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かんらん岩組成融体の密度に鉄が及ぼす影響

Effect of iron on the density of peridotitic melt

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1. Introduction

Knowledge of the density of peridotitic melt is fundamental to discuss nature and dynamics of the magma ocean in the early Earth and its evolution. In particular, possible density crossover between magma and crystallized mantle minerals in the magma ocean is one of the most important issues to understand formation of basal magma ocean at the base of the Earth's mantle1). Preferential partitioning of iron in silicate melt at the deep mantle condition is considered to be the key to cause density crossover between silicate melt and mantle minerals2). Petitgirard et al. (2015)3) discussed density difference between silicate melt and bridgmanite, which is the major mineral constituent of the Earth's lower mantle, in the experimentally observed range of the partitioning coefficient of iron of ~0.1-0.5 between silicate melt and bridgmanite2,4), and suggested that silicate melt is denser than the surrounding mantle mineral in the lowermost mantle condition. However, it is important to note that effect of iron on the density of silicate melt with peridotitic composition has not been experimentally investigated. Petitgirard et al. (2015)3) used density of Fe_2SiO_4 melt calculated by first principles simulation3) to estimate effect of iron on the density of $MgSiO_3$-$FeSiO_3$ melts. Experimental determination of the effect of iron on the density of peridotitic melt is essential to clarify the possible occurrence of the density crossover between $MgSiO_3$-$FeSiO_3$ melt and bridgmanite in the deep mantle conditions.

Efforts have been made to understand the effect of major chemical compositions on the density of silicate melts6-8). However, previous density measurements were conducted for silicate samples with relatively high SiO_2+Al_2O_3 compositions (more than ~50 wt.%)6-8) such as basaltic and andesitic compositions (Fig. 1). On the other hand, densities of SiO_2-poor peridotitic melts have not been experimentally investigated, due to experimental difficulties of the high melting temperature peridotitic compositions (for example, melting temperature of Mg_2SiO_4 olivine composition at 2161 K9)). In addition, effect of iron on the density of silicate melts has not been well studied, due to experimental difficulty by high reactivity of iron with typical crucible material such as platinum. Only Guo et al. (2014)8) investigated density of iron-bearing silicate samples with basaltic compositions in molybdenum capsule.

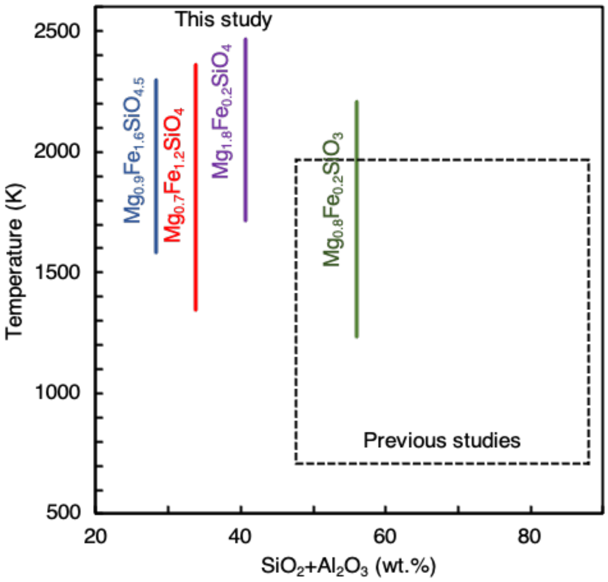

Figure 1. Sample compositions and the temperature conditions of the density measurements in this and previous studies.

Here we show density measurements of four iron-rich peridotitic melts ($Mg_{0.8}Fe_{0.2}SiO_3$, $Mg_{1.8}Fe_{0.2}SiO_4$, $Mg_{0.7}Fe_{1.2}SiO_4$, and $Mg_{0.9}Fe_{1.6}SiO_{4.5}$) at the temperature conditions up to 2465 K (Fig. 1) by using electrostatic levitation furnace (ELF) at the international space station (ISS). ELF at the ISS enables us to melt high melting temperature peridotitic compositions by laser heating, and to carry out density measurements for levitated melt samples without container material, which avoids reaction of iron in melt with capsule material. This technique opens new way to experimentally investigate density of iron-rich peridotitic melts at high temperature conditions.

2. Results and discussion

We measured densities of $Mg_{0.8}Fe_{0.2}SiO_3$ melt at 1235-2206 K, of $Mg_{1.8}Fe_{0.2}SiO_4$ melt at 1718-2465 K, of $Mg_{0.7}Fe_{1.2}SiO_4$ melt at 1348-2360 K, and $Mg_{0.9}Fe_{1.6}SiO_{4.5}$ melt at 1586-2297 K under Ar gas environment in the ELF at the ISS. Our obtained densities of $Mg_{0.8}Fe_{0.2}SiO_3$ melt at 1500 and 2200 K is 6.1 % and 7.3 % higher than those calculated by first principles simulation10), respectively. On the other hand, our obtained densities of $Mg_{0.8}Fe_{0.2}SiO_3$ melt at 1500 and 2200 K show only 0.5 % and 2.8 % differences, respectively, from those estimated by the previous density model, which is determined based on the experimental density results of basaltic compositions8). In contrast, temperature dependence of $Mg_{0.8}Fe_{0.2}SiO_3$ melt obtained in this study (-1.4×10^{-4} g/cm^3 K) is similar to that of the first principles simulation study (-1.8×10^{-4} g/cm^3 K)10), while is markedly lower than that of the previous density model (-2.3×10^{-4} g/cm^3 K)8).

In order to construct density model of peridotitic melts, we fit the experimentally observed density (ρ) of $Mg_{0.8}Fe_{0.2}SiO_3$, $Mg_{1.8}Fe_{0.2}SiO_4$, $Mg_{0.7}Fe_{1.2}SiO_4$, and $Mg_{0.9}Fe_{1.6}SiO_{4.5}$ melts at the temperature conditions of 1235-2465 K into the following equation:

$$\rho = \sum X_i M_i \Big/ \sum X_i \left[V_{i,T_{ref}} + \frac{\delta V_i}{\delta T}(T - T_{ref}) \right],$$

where X_i and M_i are the mole fraction and molecular weight of each oxide component, respectively. $V_{i,Tref}$ is the partial molar volume of each oxide component at a reference temperature condition (T_{ref}=1723 K), and $\delta V_i/\delta T$ is partial thermal expansivity of each oxide component. The partial molar volumes of SiO_2, MgO, and FeO determined from the our obtained density data of peridotitic melts are similar to those of the previous density model derived from basaltic melts data8), while the partial thermal expansivities obtained in this study are markedly lower than those of the previous density model8). The result indicates that the effect of iron on the density of peridotitic melt is similar to those of basaltic melts, while there is marked difference in the thermal expansivity between peridotitic and basaltic melts. In addition, effect of iron on the density of (Mg,Fe)SiO_3 melt calculated by first principles simulation10) is similar to that obtained in this study.

In summary, we succeeded in determining densities of SiO_2-poor and iron-rich peridotitic melts at the temperature conditions up to 2465 K. Our obtained densities of peridotitic melts are higher than those of previous studies. The new density data of iron-rich peridotitic melts provide important constraints on the density crossover between silicate melts and mantle minerals in the Earth's deep mantle.

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