Melting phase equilibrium relations in the MgSiO₃-SiO₂ system under high pressures

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ABSTRACT

Melting relations in the MgSiO₃-SiO₂ system have been investigated at 13.5 GPa using a Kawai-type multi-anvil apparatus. The system displays eutectic melting with the eutectic point located at SiO₂/(SiO₂+MgO) = 0.61 (in mol; which is denoted by \( X_{\text{Si}} \) hereafter) and at 2350 ± 50 °C. Taking into account the eutectic compositions at lower pressures reported in previous studies, i.e., 0.556 at 1 GPa (Hudon et al. 2005) and 0.60 at 5 GPa (Dalton and Presnall 1997), the eutectic composition is slightly enriched in SiO₂ with increasing pressure. The silica-rich eutectic composition is not consistent with the present peridotitic mantle composition (\( X_{\text{Si}} = 0.43 \)). Considering Si incorporation into iron alloys in a magma ocean, however, mass-balance calculations based on an E-chondrite model demonstrate that the silicate magma ocean could have \( X_{\text{Si}} \) consistent with the present peridotitic mantle.

Keywords: Melting, high pressure, MgSiO₃-SiO₂ system, mantle, enstatite chondrite model, multi-anvil, pressure calibration, thermal expansion

INTRODUCTION

Understanding the melting behavior of silicates is essential for modeling the chemical differentiation in a deep magma ocean in the early stages of Earth’s history. Therefore, melting relations in the MgO-SiO₂ system as a representative of the mantle have been extensively studied since the pioneering work by Bowen and Andersen (1914). Furthermore, many scenarios of chemical differentiation in a magma ocean have been proposed based on the results of high-pressure melting experiments (e.g., Kato and Kumazawa 1985; Presnall and Gasparik 1990; Ito and Katsura 1992; Presnall et al. 1998). However, almost all of these works have been carried out on bulk compositions ranging from MgO to MgSiO₃, assuming that the bulk mantle composition is peridotitic.

In a multi-anvil apparatus, the sample pressure can be sub - accounted for by the mechanical weakening of the pressure medium. As shown in previous studies conducted at high temperatures (e.g., Ito and Takahashi 1989; Fei et al. 2004; Leinenweber et al. 2012), the effects of temperature at >1000 °C on the generated pressure are negligible. In this study, the sample heating was conducted from 2250 to around 3000 °C. Therefore, we also evaluate the effects of the generated pressure at such high temperatures.

In comparison with the DAC, the KMAA has remarkable advantages in investigating the high-pressure phase equilibria of silicates because a much larger sample volume is available under stable temperature conditions (e.g., Ito 2007; Xie et al. 2020). In this study, we determine the melting relations in the MgSiO₃-SiO₂ system at 13.5 GPa as precisely as possible using the KMAA. In addition, we evaluate the E-chondrite model based on the melting relations in the MgSiO₃-SiO₂ system determined in the present study combined with those determined in previous studies.

In a multi-anvil apparatus, the sample pressure can be substantially altered upon heating due to the thermal expansion and the mechanical weakening of the pressure medium. As shown in previous studies conducted at high temperatures (e.g., Ito and Takahashi 1989; Fei et al. 2004; Leinenweber et al. 2012), the effects of temperature at >1000 °C on the generated pressure are negligible. In this study, the sample heating was conducted from 2250 to around 3000 °C. Therefore, we also evaluate the effects of the generated pressure at such high temperatures.