Solubility of silicon and oxygen in liquid iron coexisting with (Mg,Fe)SiO₃-perovskite and implications for core formation

T. Kawazoe* and E. Ohtani Tohoku University, Sendai, Japan,
Email: kawazoe@ganko.tohoku.ac.jp

Summary

Solubilities of silicon and oxygen in liquid iron coexisting with Mg-perovskite were investigated at 27 GPa and 2320-3040 K to discuss a core formation process and light elements in earth’s core. The earth’s core contains light elements and these light elements were dissolved into liquid iron to form the core during core formation process. A reaction between the liquid iron and Mg-perovskite must have occurred at a base of a deep magma ocean and could have provided silicon and oxygen as the light elements into the liquid iron. In this study, high pressure and temperature experiments were conducted with a Kawai-type multi-anvil apparatus. The liquid iron reacted with Mg-perovskite to form the magnesiowustite and silicon and oxygen dissolved into the liquid iron at temperatures above 2640 K. The solubility of silicon in the liquid iron decreases, whereas that of oxygen increases with increasing oxygen fugacity, and both increase with increasing temperature. This implies a possibility that silicon and oxygen are the light elements in the earth’s core.

Introduction

The light elements were dissolved into liquid iron to form the Earth’s core during the core formation process. A terrestrial magma ocean is likely to have extended to the lower-mantle depth in the core formation stage (Ohtani et al., 1997; Li and Agee, 2001). Liquid iron separated in the magma ocean ponded at the base, and segregated to form the core. A reaction between the liquid iron and (Mg,Fe)SiO₃-perovskite (hereafter called Mg-perovskite), the most dominant mineral in the lower mantle, may have occurred at the base of the deep magma ocean and it may have provided silicon and oxygen for the light elements in the core. The dissolution of silicon also makes it possible to explain a depletion of silicon in the primitive mantle compared with CI chondrite (McDonough and Sun, 1995; Allegre et al., 2001) without enrichment of silicon in the lower mantle. Another importance of this reaction is that it may occur at the core-mantle boundary throughout the core formation stage. Results of previous studies on this reaction using a laser-heated diamond anvil cell (LH-DAC) (Knittle and Jeanloz, 1989, 1991; Hillgren and Boehler, 2000) were controversial perhaps because of a large temperature gradient in the sample and possible difference in the I/O₂ conditions. In this study, equilibrium experiments between liquid iron and Mg-perovskite have been conducted with a Kawai-type multi-anvil apparatus at 27 GPa and up to 3040 K in order to obtain more reliable results on this reaction and solubilities of silicon and oxygen in the liquid iron.

Experimental Method

Experiments were performed with a Kawai-type multi-anvil apparatus at Tohoku University, using WC anvils with 2.0-mm truncated edges and a semi-sintered (Mg,Co)O pressure medium. Pure iron (99.99 wt% purity) rod was packed into a synthesized MgSiO₃ or (Mg₀.₉,Fe₀.₁)SiO₃ capsule. The sample was heated at a high temperature by a Re cylindrical heater and a LaCrO₃ thermal insulator system. Generated temperature was calibrated with a relation between an input power to the heater and a melting temperature of Mg-perovskite (Zerr and Boehler, 1993) and a eutectic temperature in the Fe-FeO system (Boehler, 1993). Temperatures monitored outside the heater with a W₉₇Re₃-W₇₅Re₂₅ thermocouple were also taken into account. Especially in the run 83 quenched at 3040 K and 27 GPa, Mg-perovskite
was molten in the outer part of the capsule contacting with the Re heater. Generated pressure was calibrated with the pressure of the phase transformation boundary from ringwoodite to Mg-perovskite and periclase in Mg$_2$SiO$_4$ (Fei et al., 2004) and that from pyrope garnet to aluminous Mg-perovskite and corundum in Mg$_3$Al$_2$Si$_2$O$_{12}$ (Hirose et al., 2001) (corrected to an equation of state of MgO (Speziale et al., 2001) by Fei et al. (2004)) at 1873 K. Quenched liquid iron was analyzed with an electron probe micro-analyzer (EPMA) with the wave length dispersive mode (JEOL JXA-8200, 8800). The chemical compositions of Mg-perovskite and magnesiowüstite were analyzed with an EPMA with the energy dispersive mode (JEOL JSM-5410). An oxygen fugacity (fO$_2$) relative to the Iron-Wüstite buffer (ΔlogfO$_2$ (IW)) was estimated by thermodynamic calculations (Hillgren et al., 1994) and partitioning of FeO between Mg-perovskite and magnesiowüstite.

**Results**

The quench texture of liquid iron was similar to that of melting experiments in the Fe-FeO system at 16 GPa (Ringwood and Hibberson, 1990), except for a precipitation of stishovite and blobs composed of SiO$_2$ and FeO. At lower oxygen contents in the liquid iron, quench products were iron crystal, sub-micron wüstite and blobs composed of SiO$_2$ and FeO. At higher oxygen contents in the liquid iron, quench products are wüstite dendrite, sub-micron wüstite and blobs composed of FeO and Fe. The quench textures of the liquid iron in runs 83 and 102 are shown in Figures 1 and 2, respectively. These quench products are interpreted to be dissolved in liquid iron at high temperatures and pressures and formed by precipitation from the liquid iron during rapid quenching (Ringwood and Hibberson, 1990, 1991). A reaction between liquid iron and Mg-perovskite to form magnesiowüstite was clearly observed in runs 83 and 86 quenched at 3040 K and 2640 K at 27 GPa, respectively. We could not observe magnesiowüstite and confirm the reaction in the other runs, although dissolution of Si into liquid iron was observed. Back-scattered electron images of run 83 quenched at 3040 K at 27 GPa are shown in Figure 1.

![Figure 1. Back-scattered electron images of run 83 quenched at 3040 K and 27 GPa. (a) Mg-perovskite (dark gray) reacted with liquid iron (white) to form magnesiowüstite (light gray) at a boundary between Mg-perovskite and the liquid iron. This reaction provides silicon and oxygen as “light elements” in liquid iron. A black crack between the liquid iron and a reaction zone was formed during decompression. (b) Needle-like stishovite (black) was grown over iron crystals (white) and many sub-micron wüstite (gray area) were formed between the iron crystals. Silicon and oxygen contents in the liquid iron were 1.70 wt% and 2.3 wt%, respectively.](image-url)
Figure 2. Back-scattered electron image of run 102 quenched at 2830 K and 27 GPa. Ionic blob (gray, spherule) and dendritic wüstite (gray) were observed homogeneously in liquid iron. Black grains were Mg-perovskite. Silicon and oxygen contents in the liquid iron were 0.18 and 7.52 wt%, respectively.

Discussion

In a core formation stage, liquid iron descended in the magma ocean, then ponded at its bottom and subsequently descended through the solid mantle composed of Mg-perovskite and magnesiowüstite to the center of the proto-Earth. As the depth of the magma ocean increased, pressure and temperature at the bottom of magma ocean increased along the mantle solidus (Zerr et al., 1998). According to recent studies on partitioning of siderophile elements between liquid iron and magma or magnesiowüstite (e.g., Gessmann and Rubie, 2000; Li and Agee, 2001), the magma ocean could have extended to the upper part of the lower mantle and ΔlogO₂ (IW) of the magma ocean was in the range between -2.5 and -2.1. In the case that the magma ocean had extended to the pressure of 27 GPa in this study, the temperature at the bottom of the magma ocean was between 2430 and 2840 K (Zerr et al., 1998). The liquid iron ponded at the bottom could contain several wt% silicon and about 1 wt% oxygen in such conditions of oxygen fugacity and temperatures. Rubie et al. (2004) suggested that oxygen solubility in liquid iron could increase with increasing pressure at the bottom of the magma ocean beyond 27 GPa because a positive effect of temperature is larger than a negative effect of pressure in this region. The liquid iron could contain several wt% silicon when the depth of the magma ocean increased, taking into account of a positive temperature effect found in this study and an estimated negative pressure effect (Gessmann et al., 2001). Thus silicon and oxygen explaining the density deficit of the present core (Anderson and Isaak, 2002; Hirao et al., 2004) could be transported by liquid iron into the center of the Earth during the core formation stage.

Conclusion

Solubilities of silicon and oxygen in liquid iron coexisting with Mg-perovskite were investigated at 27 GPa and 2320-3040 K to discuss the core formation process and light elements in earth’s core. The liquid iron reacted with Mg-perovskie and silicon and oxygen dissolved into the liquid iron at temperatures above 2640 K. Silicon and oxygen contents in liquid iron were 1.70 wt% and 2.3 wt%, respectively, in the run made at 3040 K and 1.70 log units below IW buffer. They were 0.18 wt% and 7.5 wt%, respectively, in the run made at 2800 K and -0.79 log units above IW buffer. The solubility of silicon in the liquid iron decreases, whereas that of oxygen increases with increasing oxygen fugacity, and both increase with increasing temperature. This implies a possibility that silicon and oxygen are the light elements in the earth’s core.
References


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