Density of carbonated peridotite magma at high pressure using an X-ray absorption method

TATSUYA SAKAMAKI,1,* EJI OHTANI,1 SATORU URAKAWA,2 HIDENORI TERASAKI,1 AND YOSHINORI KATAYAMA3

1Department of Earth and Planetary Materials Science, Tohoku University, Sendai 980-8578, Japan
2Department of Earth Sciences, Okayama University, Okayama 700-8530, Japan
3Japan Atomic Energy Agency, Hyogo 679-5143, Japan

ABSTRACT

The density of carbonated peridotite magma was measured up to 3.8 GPa and 2100 K using an X-ray absorption method. A fit of the pressure-density-temperature data to the high-temperature Birch-Murnaghan equation of state yielded the isothermal bulk modulus, \( K_0 = 22.9 \pm 1.4 \) GPa, its pressure derivative, \( K'_0 = 7.4 \pm 1.4 \), and the temperature derivative of the bulk modulus \( (\partial K_T/\partial T)_p = -0.006 \pm 0.002 \) GPa/K at 1800 K. The bulk modulus of carbonated peridotite magma is larger than that of hydrous peridotite magma. The partial molar volume of CO\(_2\) in magma under high pressure and temperature conditions was calculated and fit using the Vinet equation of state. The isothermal bulk modulus was \( K_0 = 8.1 \pm 1.7 \) GPa, and its pressure derivative was \( K'_0 = 7.2 \pm 2.0 \) at 2000 K. Our results show that the partial molar volume of CO\(_2\) is less compressible than that of H\(_2\)O, suggesting that, on an equal molar basis, CO\(_2\) is more effective than H\(_2\)O in reducing peridotite melt density at high pressure.

**Keywords:** X-ray absorption method, carbonated peridotite magma, density, high pressure, equation of state, partial molar volume of CO\(_2\);

INTRODUCTION

The density of silicate melts is an important property governing volcanic activity and differentiation of the terrestrial planets. Experimental density measurements have been carried out by several methods, including shock compression (e.g., Rigden et al. 1984) and the sink-float method using multi-anvil and piston-cylinder devices (e.g., Agee and Walker 1988; Suzuki et al. 1995).

The effects of H\(_2\)O on melt density have been examined by Matsukage et al. (2005), Sakamaki et al. (2006), Agee (2008), and Sakamaki et al. (2009) permitting determination of the partial molar volume of H\(_2\)O as a function of pressure for mafic-ultramafic compositions. Much less is known about the effects of CO\(_2\) on the densities of mantle melts. Ghosh et al. (2007) measured the density of carbonated basaltic magma at 19.5 GPa and 2573 K using the sink-float method and reported a partial molar volume of CO\(_2\) of 20.98 cm\(^3\)/mol, however, the variation in the partial molar volume of CO\(_2\) with pressure is poorly constrained.

X-ray absorption offers a complementary method for determining melt densities at high pressure and temperature (Katayama et al. 1993, 1996; Sanloup et al. 2000, 2004; Urakawa et al. 2004; Ohtani et al. 2005). Recently, Sakamaki et al. (2009, 2010) reported the densities of dry and hydrous peridotite melts up to 4 GPa by this method. In this study, we applied the same technique to measure the density of carbonated peridotite melt.

We characterize the pressure dependence of the partial molar volume of CO\(_2\) and consider the implications of these results on the density of magmas at high pressure and high temperature.

EXPERIMENTAL PROCEDURES

Starting material with a carbonated peridotite composition based on pyrolite (Ringwood 1975) was prepared as follows. Reagent-grade oxides (SiO\(_2\), MgO, FeO, and Al\(_2\)O\(_3\)) and carbonate (CaCO\(_3\)) were mixed in an agate mortar and pestle with acetone for 1 h. The mixed powder was melted at 1673 K, slightly below the quartz-fayalite-magnetite buffer regulated by a CO\(_2\)/H\(_2\) gas-mixture, and quenched to glass. We used an Fe-saturated Pt crucible to prevent loss of iron during heating. Carbon dioxide was added to glass as CaCO\(_3\) and mixed in an agate mortar and pestle for 1 h. The CO\(_2\) content of the starting material was 2.5 wt%.

The composition of the starting material is given in Table 1. The composition of the starting material was checked by sintering the powder and performing area analysis by an electron microprobe.

Density measurements were carried out using a DIA-type cubic press at the BL22XU beamline at SPring-8, Japan using 0.05 × 0.05 mm monochromate beam from an undulator source tuned to the desired energy (23 keV) using a liquid N\(_2\)-cooled Si(111) double-crystal monochromator and paralleled by two incident slits.

Details of the experimental setup are given in Sakamaki et al. (2009). The intensities of the X-ray absorption method were carried out using a DIA-type cubic press at the BL22XU beamline at SPring-8, Japan using 0.05 × 0.05 mm monochromate beam from an undulator source tuned to the desired energy (23 keV) using a liquid N\(_2\)-cooled Si(111) double-crystal monochromator and paralleled by two incident slits.

### Table 1. Chemical composition of the starting material

<table>
<thead>
<tr>
<th>Component</th>
<th>Starting material</th>
<th>Run product (3.21 GPa/2100 K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SiO(_2)</td>
<td>45.5</td>
<td>45.1 (8)</td>
</tr>
<tr>
<td>Al(_2)O(_3)</td>
<td>3.6</td>
<td>3.1 (6)</td>
</tr>
<tr>
<td>FeO</td>
<td>8.0</td>
<td>8.1 (4)</td>
</tr>
<tr>
<td>MgO</td>
<td>37.1</td>
<td>39.2 (8)</td>
</tr>
<tr>
<td>CaO</td>
<td>3.1</td>
<td>2.2 (4)</td>
</tr>
<tr>
<td>CO(_2)</td>
<td>2.7*</td>
<td>2.3*</td>
</tr>
<tr>
<td>Total (wt%)</td>
<td>100.0</td>
<td>100.0</td>
</tr>
</tbody>
</table>

* The amount of CO\(_2\) was estimated by the total deficit of the microprobe analyses.