Rapid decrease of MgAlO$_{2.5}$ component in bridgmanite with pressure

Z. Liu$^1$*, T. Ishii$^1$, T. Katsura$^1$

Abstract

The solubility of the MgAlO$_{2.5}$ component in bridgmanite was measured at pressures of 27, 35 and 40 GPa and a temperature of 2000 K using an ultra-high pressure multi-anvil press. Compositional analysis of recovered samples demonstrated that the MgAlO$_{2.5}$ component decreases with increasing pressure, and approaches virtually zero at 40 GPa. Above this pressure, the MgAlO$_{2.5}$ component, i.e. the oxygen-vacancy substitution, becomes negligible, and Al is incorporated in bridgmanite by the charge-coupled substitution only. These results are supported by the volume change associated with the change from the oxygen-vacancy substitution to charge-coupled substitution. The present result may explain the seismically observed slab stagnation in the mid-lower mantle. Although bridgmanite has been put forward as a potential host for water and argon in the lower mantle by trapping them in oxygen vacancies, such capabilities will rapidly decrease with depth and be lost in regions deeper than 1000 km.

Introduction

Aluminium (Al) is the fifth most abundant element in the Earth’s mantle (McDonough and Sun, 1995). Under the Earth’s lower mantle conditions, Al$^{3+}$ is mainly accommodated in bridgmanite in a pyrolite mantle (Irifune, 1994). Al substitution in the Mg, Si or both sites modifies the crystal chemistry of bridgmanite, and thereby changes the physical properties of bridgmanite (Zhang and Weidner, 1999; Brodholt, 2000). Therefore, understanding the Al substitution mechanism is essential to investigating the mineralogy and dynamics of the lower mantle.

Two competing Al substitution mechanisms occur in bridgmanite (Hirsch and Shankland, 1991). One is the charge-coupled substitution (Mg$^{2+}$ + Si$^{4+}$ = Al$^{3+}$ + Al$^{3+}$; components along the MgSiO$_3$–Al$_2$O$_3$ binary system), where two Al cations substitute for one Mg with the roughly 8-fold coordination (A site) and one Si with the 6-fold coordination (B site). The other mechanism is the oxygen-vacancy substitution (2Si$^{4+}$ + O$_2$– = 2Al$^{3+}$ + V$_O$, where V$_O$ is an oxygen vacancy; components along the MgSiO$_3$–MgAlO$_{2.5}$ binary system), where two Al cations replace two Si in the B sites and one oxygen vacancy forms to compensate for the excess negative charges. The oxygen vacancies in bridgmanite have special importance for understanding lower mantle processes because oxygen vacancies may induce water ($V_O$ + O$_2$– + H$_2$O = 2OH$^-$, Shcheka and Kepleller, 1999) and noble gases into bridgmanite (Shcheka and Kepleller, 1999). One is the oxygen-vacancy substitution to charge-coupled substitution. The present result may explain the seismically observed slab stagnation in the mid-lower mantle. Although bridgmanite has been put forward as a potential host for water and argon in the lower mantle by trapping them in oxygen vacancies, such capabilities will rapidly decrease with depth and be lost in regions deeper than 1000 km.

Earlier theoretical calculations investigated whether oxygen vacancies exist in bridgmanite (Brodholt, 2000; Yamamoto et al., 2003; Akber–Knutson and Bukowski, 2004). Brodholt (2000) suggested that oxygen-vacancy substitution should dominate at pressures up to 30 GPa. Yamamoto et al. (2003) argued oxygen-vacancy substitution should be unfavourable in the entire lower mantle. Furthermore, energetic calculations by Akber–Knutson and Bukowski (2004) suggested that oxygen-vacancy substitution could only account for 3–4 % and less than 1 % of Al substitutions in the shallower and deeper parts of the lower mantle, respectively.

High pressure and high temperature synthesis (Navrotsky et al., 2003) and nuclear magnetic resonance (NMR) spectroscopy (Stebbins et al., 2003) suggested that oxygen-vacancy substitution dominates in bridgmanite with 5–10 mol. % MgAlO$_{2.5}$ at 27 GPa and 1873 K. On the other hand, X-ray diffraction measurements in a laser-heated diamond anvil demonstrated that bridgmanite coexisted with periclase from a glass starting material with a composition of 90 mol. % MgSiO$_3$ and 10 mol. % MgAlO$_{2.5}$ at 40 ± 10 GPa and 2000–2500 K (Walter et al., 2006), indicating that the MgAlO$_{2.5}$ component was not present in bridgmanite and thereby oxygen-vacancy substitution was unfavoured under these conditions. Note that pressure and temperature uncertainties in this study were relatively large, and the composition of bridgmanite was not determined owing to its very small sample size. Thus, it is still uncertain whether MgAlO$_{2.5}$ can be a dominant component in bridgmanite in the lower mantle.

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Here, we investigate the solubility of the MgAlO$_{2.5}$ component in bridgmanite as a function of pressure from 27 to 40 GPa at a constant temperature of 2000 °K and discuss water and noble gas storage capacities in the lower mantle.

## Experimental Methods

The starting materials were glasses with En$_{90}$Brm$_{10}$ (En: MgSiO$_3$; Brm: MgAlO$_{2.5}$ mol. %) and En$_{95}$Cor$_{5}$ (Cor: Al$_2$O$_3$) compositions (see section S-1 in the Supplementary Information for synthesis details and Table S-1 for their compositions). High pressure and high temperature experiments were conducted using ultra-high pressure multi-anvil technology with carbide anvils (Ishii et al., 2016), and detailed techniques can be found in Figures S-1 and S-2 in the Supplementary Information. As shown in Table 1, bridgmanite samples with En$_{90}$Brm$_{10}$ and En$_{95}$Cor$_{5}$ compositions were first synthesised at 27 GPa and 2000 °K for 3 hours. These samples were annealed at pressures of 35 and 40 GPa and a temperature of 2000 °K for 2 and 3 hours. The recovered samples were analysed by X-ray diffraction (XRD), scanning electron microscopy (SEM), and electron probe microanalysis (EPMA) (see section S-2 in the Supplementary Information for analytical analyses).

## Results

XRD patterns of bridgmanite with the En$_{90}$Brm$_{10}$ starting composition synthesised at 27, 35 and 40 GPa are shown in Figure 1, while those for En$_{95}$Cor$_{5}$ composition are shown in Figure S-3. All diffraction peaks of the sample for the En$_{90}$Brm$_{10}$ composition synthesised at 27 GPa were assigned to those of bridgmanite (Ito and Matsui, 1978), indicating the formation of a single phase bridgmanite. The diffraction peaks of the En$_{90}$Brm$_{10}$ bridgmanite sample annealed at 35 GPa were also assigned to bridgmanite. For the sample annealed at 40 GPa, the majority of its peaks were assigned to bridgmanite, except for three extra weak peaks with \(d\)-spacings of 2.11 (\(2\theta = 50.3^\circ\)), 2.80 (\(2\theta = 37.5^\circ\)) and 3.15 (\(2\theta = 32.9^\circ\)) Å. The peak with \(d\)-spacing of 3.15 Å was suggested to result from the presence of a superstructure (Navrotsky et al., 2003). The weak peak with \(d\)-spacing of 2.11 Å may correspond to (200) of MgO (periclase), which indicates the coexistence of a trace amount of periclase with bridgmanite at 40 GPa and 2000 °K as consistent with the observation by Walter et al. (2006). The sample decomposed to periclase and aluminous bridgmanite, suggesting a lower solubility of the MgAlO$_{2.5}$ component with increasing pressure.
Textural observations by SEM showed that all samples consist of a single phase. Although the XRD patterns showed the presence of periclase for the sample annealed at 40 GPa, this phase was not detected by back scattered electron (BSE) observations in Figure 2. Compositions of bridgmanite with grains larger than 3 µm were analysed by EPMA and shown in Table 1, where the total cation numbers were normalised to two to show clearly the variation of oxygen number with pressure.

Figure 2  Representative BSE images of $\text{En}_{90}\text{Brm}_{10}$ subjected to (a) 27 GPa, (b) 35 and (c) 40 GPa and 2000 °K.
The number of oxygen atoms in bridgmanite from the En$_2$Brm$_{10}$ and En$_3$Cor$_5$ compositions is 2.973 ± 0.004, which is slightly lower than those in Navrotsky et al. (2003) and Kojitani et al. (2007) and substantially lower than that of En$_3$Cor$_5$ bridgmanite. This value shows clearly the presence of oxygen vacancies as consistent with ²⁷Al NMR observations by Stebbins et al. (2003). However, the number of oxygen in bridgmanite for the En$_3$Brm$_{20}$ composition monotonically increases to 2.984 ± 0.007 at 35 GPa, and finally reaches 2.993 ± 0.004 at 40 GPa, which is within the uncertainties of En$_3$Cor$_5$ bridgmanite at the same pressure, indicating almost no oxygen vacancies at 40 GPa.

Figure 3b shows the variation in the Mg/Si cation ratio in these two kinds of aluminous bridgmanite against pressures. At 27 GPa, the ratio of the sample from the En$_2$Brm$_{10}$ composition was 1.06 ± 0.01, which lies between the ideal compositional lines associated with the oxygen-vacancy and charge-coupled substitution. With increasing pressure, it decreases to 1.03 ± 0.02 at 35 GPa, and then to 1.01 ± 0.02 at 40 GPa, which finally lies on the ideal composition line of the charge-coupled substitution for the case of En$_3$Cor$_5$ bridgmanite.

Figure 3c shows the ratios of Al at the A and B sites (Al$_B$/Al$_A$) in bridgmanite. This ratio of the sample for En$_2$Brm$_{10}$ decreases from 3.82 ± 0.53 at 27 GPa to 1.23 ± 0.38 at 40 GPa, which is finally within the uncertainties of unity, the expected result of the charge-coupled substitution. In contrast, this ratio for En$_3$Cor$_5$ bridgmanite remains almost unchanged with increasing pressure and lies on the line associated with the charge-coupled substitution.

The mass balance calculation implies that 1.2 ± 0.2 and 1.9 ± 0.4 wt. % periclase should coexist with bridgmanite for the En$_2$Brm$_{10}$ composition at 35 and 40 GPa, respectively. However, XRD patterns exhibited only one peak of periclase from the sample at 40 GPa, and that of the sample at 35 GPa and SEM showed no evidence for the coexistence of periclase. No observation of periclase by SEM could be explained by polishing out tiny interstitial grains.

The results of these observations can be summarised such that the proportion of the MgAlO$_2$ component in bridgmanite decreases with increasing pressure: 5.7 ± 0.6 mol. % at 27 GPa, 3.2 ± 1.8 mol. % at 35 GPa, and 1.1 ± 1.0 mol. % at 40 GPa (see the detailed calculation in section S-6 in the Supplementary Information). Thus, this component should become negligible at pressures above 40 GPa. Theoretically, the proportion of the MgAlO$_2$ component should decrease more rapidly than demonstrated in this study because our starting sample was not ideally saturated with this component (see section S-6 in the Supplementary Information). It is noted that the oxygen fugacity has a negligible effect on the oxygen vacancy for Fe-free minerals (e.g., Smyth and Stocker, 1975; Stocker and Smyth, 1978). Compositions of synthetic Al-bearing bridgmanite being consistent with each other by using different metal capsules (such as gold and rhenium) and also comparable to those of the glass starting materials in the present and previous studies (Navrotsky et al., 2003; Kojitani et al., 2007) further confirms this point. Therefore, pressure is the only factor to result in this rapid decrease of the MgAlO$_2$ component in bridgmanite.

The present conclusion can be understood by a simple volume comparison based on the following reaction:

$$2\text{MgAlO}_2 (\text{Brg}) = \text{Al}_2\text{O}_3 (\text{Brg}) + 2\text{MgO} (\text{Per})$$ Eq. 1

The molar volume of periclase (Per) under ambient conditions is 11.27 cm$^3$/mole. The molar volumes of the hypothetical end members of MgAlO$_2$ and Al$_2$O$_3$ bridgmanite (for Al cation number of 0.1 per formula unit) under ambient conditions are estimated to be 24.50 and 24.54 cm$^3$/mole, respectively, from the volume composition data in Figure S-4 and Liu et al. (2016). Therefore, the molar volume of the left hand side component of Equation 1 is larger than that of the right hand side components by 1.92 cm$^3$/mole, suggesting that the MgAlO$_2$ component becomes unstable with increasing pressure (see Fig. S-5).

### Geochemical Implications

Although the water storage of the lower mantle is uncertain, it has significant impacts on the chemical evolution of the mantle. The oxygen vacancy substitution, one of the most likely mechanisms, in aluminous bridgmanite may provide suitable storage sites to incorporate water in the shallower part of the lower mantle (e.g., Navrotsky, 1999; Brodholt, 2000) according to the following reaction:

$$2\text{MgAlO}_2 (\text{Brg}) + \text{H}_2\text{O} (\text{fluid}) = 2\text{MgHAlO}_3 (\text{Brg})$$ Eq. 2

Although the volume of the MgHAlO$_3$ component in bridgmanite is unknown, we could assume that it has a similar volume with the MgAlO$_2$ component because of an actually zero volume of the proton (Hernández et al., 2013). Hence, H$_2$O is expected to be incorporated in bridgmanite as MgHAlO$_3$ in the lower mantle because of high pressures. Murakami et al. (2002) and Litaso et al. (2003) reported that synthetic Al-Fe-bearing bridgmanite in mantle peridotite can contain 1000–2000 ppm water at 26 GPa and 1500–1923 °K, which is significantly higher than that of synthetic MgSiO$_3$ bridgmanite at 24–25 GPa and 1573–1873 °K (Boffan-Casanova et al., 2000).

### Table 1 Experimental conditions, run products, and phase compositions.

<table>
<thead>
<tr>
<th>Start Comp</th>
<th>Phases</th>
<th>MgO</th>
<th>Al$_2$O$_3$</th>
<th>SiO$_2$</th>
<th>Total</th>
<th>O</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRIS333 (27 GPa, 2000 °K; 3 hours)</td>
<td></td>
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<tr>
<td>En$<em>2$Brm$</em>{10}$</td>
<td>Brg [n = 40]</td>
<td>39.82 (23)</td>
<td>5.13 (15)</td>
<td>55.92 (24)</td>
<td>100.86 (14)</td>
<td>2.973 (4)</td>
<td>0.979 (5)</td>
<td>0.100 (3)</td>
<td>0.922 (4)</td>
</tr>
<tr>
<td>En$_3$Cor$_5$</td>
<td>Brg [n = 26]</td>
<td>37.93 (22)</td>
<td>5.11 (12)</td>
<td>56.31 (3)</td>
<td>99.35 (55)</td>
<td>2.908 (2)</td>
<td>0.952 (5)</td>
<td>0.101 (2)</td>
<td>0.948 (4)</td>
</tr>
<tr>
<td>IRIS357 (35 GPa, 2000 °K; 2 hours)</td>
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<tr>
<td>En$<em>2$Brm$</em>{10}$</td>
<td>Brg [n = 52]</td>
<td>39.11 (52)</td>
<td>5.19 (13)</td>
<td>56.38 (45)</td>
<td>100.69 (25)</td>
<td>2.984 (7)</td>
<td>0.970 (13)</td>
<td>0.102 (2)</td>
<td>0.938 (7)</td>
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<tr>
<td>En$_3$Cor$_5$</td>
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<tr>
<td>IRIS351 (40 GPa, 2000 °K; 3 hours)</td>
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<tr>
<td>En$<em>2$Brm$</em>{10}$</td>
<td>Brg [n = 55]</td>
<td>38.01 (40)</td>
<td>5.09 (12)</td>
<td>56.01 (46)</td>
<td>99.11 (65)</td>
<td>2.995 (4)</td>
<td>0.955 (8)</td>
<td>0.101 (2)</td>
<td>0.944 (4)</td>
</tr>
<tr>
<td>En$_3$Cor$_5$</td>
<td>Brg [n = 20]</td>
<td>38.44 (32)</td>
<td>5.12 (16)</td>
<td>57.37 (55)</td>
<td>100.92 (72)</td>
<td>2.999 (3)</td>
<td>0.949 (6)</td>
<td>0.100 (3)</td>
<td>0.950 (3)</td>
</tr>
</tbody>
</table>

Oxide analyses are reported in wt %. n: number of analysis points.

*: temperature was evaluated from a calibrated power curve derived from a lower temperature of 1500 °K.

Number in parentheses represents standard deviation for the last digit(s). Abbreviation: Brg, bridgmanite.
Figure 3  Plots of (a) oxygen number, (b) Mg/Si ratio, and (c) Al ratio in A and B sites (Al\textsubscript{B}/Al\textsubscript{A}) in bridgmanite for En\textsubscript{90}Brm\textsubscript{10} and En\textsubscript{95}Cor\textsubscript{5} versus pressure. The black lines represent the compositions associated with the oxygen-vacancy substitution mechanism (OVM) and charge-coupled substitution mechanism (CCM) for bridgmanite. The red line is the least squares fitting (Mg/Si = A_{exp}(–P/B) + C, where \( P \) is pressure) of the present data.
Litasov et al., 2003). Following Equation 2, the amount of 2.2 mol. % MgAlO$_2$ in bridgmanite can explain those reported high water amounts in bridgmanite. In contrast, Bolfan-Casanova et al. (2003) and Panero et al. (2015) showed that Al-Fe-bearing bridgmanite had a very low water content (<10 ppm) at 24–26 GPa and 1600–2000 °K. Even though bridgmanite contained these amounts of water in their experimental conditions, the water solubility should rapidly decrease with increasing pressure due to a rapid decrease of MgAlO$_2$ component in bridgmanite. Since bridgmanite has a negligible MgAlO$_2$ component at pressures above 40 GPa, no water could be stored in regions deeper than 1000 km depth, i.e. in the majority of the lower mantle. Furthermore, the ambient lower mantle temperatures (Katsura et al., 2010) are too high for hydrous minerals (Walter et al., 2015), therefore, we conclude that the majority of lower mantle is dry.

Shcheka and Kepller (2012) showed that MgSiO$_3$ bridgmanite contained ~1 wt. % argon at 25 GPa and 1873–2073 °K dissolved through oxygen-vacancy substitution. Theoretically, Al-bearing bridgmanite may accommodate larger amounts of argon than MgSiO$_3$ bridgmanite because of the higher proportion of oxygen vacancies in the uppermost part of the lower mantle. With increasing depths, the incorporation capacity of argon quickly diminishes, due to the rapidly decreasing oxygen vacancies in aluminous bridgmanite, and finally vanishes at depths deeper than 1000 km. Therefore, the explanation for the xenon anomaly in the Earth’s atmosphere given by Shcheka and Kepller (2012) needs to be further investigated.

Bridgmanite, the most abundant phase in the lower mantle (80 vol. %; Irfune, 1994), dominates the viscosity of this region (Girard et al., 2016). Seismic observation suggests that some slabs stagnate at 600–1000 km depths (Fukao and Obayashi, 2013). Since there are no phase transitions in this region, some special explanations are required. One explanation is the increase of viscosity with depth in this region. Since the viscosity of minerals is controlled by atomic diffusivity (Karato and Wu, 1993), the decrease of oxygen vacancies in aluminous bridgmanite, will cause a decrease in element diffusivity. Therefore, the expected decrease in diffusivity for aluminous bridgmanite should cause a high viscosity, which may explain this mid-lower mantle slab stagnation.


References


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Additional Information

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Z. Liu$^{1,*}$, T. Ishii$^{1}$, T. Katsura$^{1}$

**Supplementary Information**

The Supplementary Information includes:

1. Glass Preparation
2. High Pressure Technique in Kawai-type Multi-anvil Apparatus
3. Analytical Methods
4. XRD of En$_{95}$Cor$_{5}$-bridgmanite at 27 and 40 GPa and 2000 °K
5. Unit Cell Volume of Bridgmanite
6. Calculation of the Solubility of the MgAlO$_{2.5}$ Component in Bridgmanite
7. The Variation of Molar Volume for Equation S-1
   Figures S-1 to S-5
   Tables S-1 to S-3
   Supplementary Information References

1. Glass Preparation

Besides with En$_{90}$Brm$_{10}$ and En$_{95}$Cor$_{5}$ glass, En$_{100}$ glass is also prepared for the standard for composition comparison. All glasses were prepared from oxide mixtures using reagent grade chemicals: MgO, SiO$_2$, and Al$_2$O$_3$, fused and homogenised at least two times at 2000 °K for one hour, and finally quenched into water. After that, the glasses were finely ground into powder, then checked by powder X-ray diffraction to confirm absence of solid phases. They were finally kept in a high vacuum box before experiments. Based on the compositions in Table S-1, the total cation number is normalised to two to see oxygen vacancies clearly in the starting material. Therefore, the composition of the En$_{90}$Brm$_{10}$ glass is Mg$_{0.982}$±0.006Al$_{0.101}$±0.001Si$_{0.918}$±0.003O$_{2.969}$±0.003, which clearly deviates from the Al$_2$O$_3$ stoichiometry and is deficient in oxygen. This glass starting material contains about 6.4 ± 0.9 mol. % MgAlO$_{2.5}$ and 1.9 ± 0.5 mol. % AlO$_{1.5}$, which is slightly smaller than that with the nominal MgAlO$_{2.5}$ component of En$_{90}$Brm$_{10}$. Therefore the starting material is not ideally saturated with MgAlO$_{2.5}$ as En$_{90}$Brm$_{10}$. Here, we approximated this non-stoichiometric glass starting material with Mg$_{0.982}$±0.006Al$_{0.101}$±0.001Si$_{0.918}$±0.003O$_{2.969}$±0.003 as En$_{90}$Brm$_{10}$-glass. The En$_{100}$ and En$_{95}$Cor$_{5}$ glasses have the intended compositions within analytical errors.

**Table S-1** Chemical compositions of the starting glass material.

<table>
<thead>
<tr>
<th>Starting material</th>
<th>MgO</th>
<th>Al$_2$O$_3$</th>
<th>SiO$_2$</th>
<th>Total</th>
<th>O</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>En$<em>{90}$Brm$</em>{10}$ (n = 25)</td>
<td>39.49 (18)</td>
<td>5.11 (5)</td>
<td>55.08 (37)</td>
<td>99.68 (40)</td>
<td>2.969 (3)</td>
<td>0.982 (6)</td>
<td>0.101 (1)</td>
<td>0.918 (3)</td>
</tr>
<tr>
<td>En$<em>{95}$Cor$</em>{5}$ (n = 15)</td>
<td>38.42 (29)</td>
<td>5.10 (5)</td>
<td>57.47 (48)</td>
<td>100.99 (52)</td>
<td>3.002 (7)</td>
<td>0.948 (9)</td>
<td>0.100 (2)</td>
<td>0.951 (7)</td>
</tr>
<tr>
<td>En$_{100}$ (n = 12)</td>
<td>40.03 (50)</td>
<td>–</td>
<td>59.48 (60)</td>
<td>99.39 (36)</td>
<td>2.998 (3)</td>
<td>1.001 (9)</td>
<td>–</td>
<td>0.999 (7)</td>
</tr>
</tbody>
</table>

Oxide analyses are reported in wt. %. n: number of analysis points. Number in parentheses represents standard deviation and is placed in the last digit (s).
2. High Pressure Technique in Kawai-type Multi-anvil Apparatus

Bridgmanite samples were first synthesised at a pressure of 27 GPa and a temperature of 2000 °K for 3 hours using a 7/3 (OEL/TEL = octahedral edge length of pressure medium/truncated edge length of anvil) cell assembly (Fig. S-1a) in a Kawai-type multi-anvil apparatus (IRIS-15) with a DIA-type guide block and a maximum press load of 15 MN in Bayerisches Geoinstitut, University of Bayreuth, Germany. After that, the bridgmanite samples were cut into two parts for X-ray diffraction, scanning electron microscopy and electron probe microanalysis, respectively.

Furthermore, two annealing high pressure experiments are conducted at pressures of 35 and 40 GPa, respectively, and a temperature of 2000 °K for 2 and 3 hours using a synthetic single phase non-stoichiometric bridgmanite (hereafter as En90Brm10-Brg), which was synthesised from the starting En90Brm10 glass at 27 GPa and 2000 °K, as a starting material in a 5.7/1.5 cell assembly (Fig. S-1b) by means of the ultra-high pressure multi-anvil technology (Ishii et al., 2016). The 7/3 and 5.7/1.5 cell assemblies are shown in Figure S-1, and LaCrO3 and rhenium (Re) were used for the heaters in these two cell assemblies, respectively. Pressure calibrations of these two cell assemblies at room temperature and high temperature were reported by Ishii et al. (2016), and also shown in Figure S-2 based on the Al2O3 solubility in bridgmanite. Temperature was measured with a W97Re3–W75Re25 thermocouple adjacent to the sample capsules. In experiments where no direct temperature reading from the thermocouple was obtained, temperatures were estimated using power-temperature relationships established by preceding runs.

3. Analytical Methods

Phases in recovered samples were identified using a micro-focused X-ray diffractometer with a Co anode operated at 40 kV, 500 µA. MgSiO3 bridgmanite, synthesised in the IRIS333 run (Table S-2), was used as the external standard to calibrate the Bragg angle (2θ) of the instrument. XRD profiles were collected for about one hour. Electron back scattered images were collected by a LEO1530 scanning electron microscope operating at an acceleration voltage of 15 kV and a beam current of 10 nA. Chemical compositions were determined by a JEOL JXA-8200 electron probe microanlyser (EPMA) operating at 15 kV and 5 nA with standards of enstatite for Mg and Si, and pyrope for Al.
Figure S-3 XRD patterns of the recovered sample for En$_{95}$Cor$_5$ composition at 27 (a) and 40 GPa (b) under 2000 °K, respectively. Number in parentheses represents the index of bridgmanite.

Table S-2 The experimental condition and composition of MgSiO$_3$ bridgmanite.

<table>
<thead>
<tr>
<th>Starting material</th>
<th>Phases</th>
<th>MgO</th>
<th>Al$_2$O$_3$</th>
<th>SiO$_2$</th>
<th>Total</th>
<th>O</th>
<th>Mg</th>
<th>Al</th>
<th>Si</th>
</tr>
</thead>
<tbody>
<tr>
<td>IRIS33 (27 GPa, 2000 °K; 3 hours)</td>
<td>En$_{100}$</td>
<td>Brg (n = 25)</td>
<td>40.16 (37)</td>
<td>–</td>
<td>59.72 (37)</td>
<td>99.88 (35)</td>
<td>2.999 (7)</td>
<td>1.000 (3)</td>
<td>–</td>
</tr>
</tbody>
</table>

Oxide analyses are reported in wt. %. n: number of analysis points. Number in parentheses represents standard deviation and is placed in the last digit (s). Abbreviation: Brg, bridgmanite.

4. XRD of En$_{95}$Cor$_5$-bridgmanite at 27 and 40 GPa and 2000 °K

Figure S-3a shows XRD patterns for synthetic En$_{95}$Cor$_5$-bridgmanite at pressures of 27 GPa and 2000 °K, and Figure S-3b shows that for the annealing sample for En$_{95}$Cor$_5$-bridgmanite at 40 GPa and 2000 °K. Their compositions are almost consistent with that of starting glass, indicating that bridgmanite is the only phase in these recovered samples.

5. Unit Cell Volume of Bridgmanite

Figure S-4 shows unit cell volumes of bridgmanite along the system MgSiO$_3$–Al$_2$O$_3$ and MgSiO$_3$–MgAlO$_{2.5}$ in the present and previous studies (Ito and Matsui, 1978; Weng et al., 1981; Iritune et al., 1996; Kubo and Akaogi, 2000; Navrotsky et al., 2003; Walter et al., 2004, 2006; Kojitani et al., 2007). In the present study, unit cell volumes of the recovered bridgmanite for the En$_{90}$Brm$_{10}$ composition at 35 and 40 GPa are slightly lower than those at 27 GPa under the same temperature of 2000 °K, but comparable with those of bridgmanite for En$_{95}$Cor$_5$ composition within analytical uncertainties in the present study. This may be caused by the slight change of the crystal chemistry for bridgmanite or the stress in these recovered samples at different pressures. Moreover, these volumes of the recovered bridgmanite for the En$_{90}$Brm$_{10}$ composition in the present study are comparable to those of previous studies on the same composition within analytical uncertainties (Navrotsky et al., 2003; Walter et al., 2006; Kojitani et al., 2007), which is also within uncertainties of bridgmanite for En$_{95}$Cor$_5$ composition in previous studies (Navrotsky, 1981; Iritune et al., 1996; Kubo and Akaogi, 2000; Walter et al., 2004). The largely scattered value for bridgmanite with the same composition may be caused by the different synthesis conditions, quench history, and analytical methods.
6. Calculation of the Solubility of the MgAlO\textsubscript{2.5} Component in Bridgmanite

It is known that both MgAlO\textsubscript{2.5} (the oxygen-vacancy substitution) and AlO\textsubscript{1.5} (the charge-coupled substitution) are competing with each other in aluminous bridgmanite in both systems MgSiO\textsubscript{3}–MgAlO\textsubscript{2.5} and –AlO\textsubscript{1.5}, therefore, the composition of bridgmanite can be represented by the following reaction:

\[
\text{Mg}_x\text{Al}_y\text{Si}_6\text{O}_{18+2y} = y\text{ MgSiO}_3 + (x-y)\text{ MgAlO}_{2.5} + (2-x-y)\text{ AlO}_{1.5}
\]

Following this equation, the composition of bridgmanite in Table S-2 can be well calculated using the MgAlO\textsubscript{2.5} component.

It is noted that the equilibrated proportion at 27 GPa could be higher because our sample at this condition was not ideally saturated with the MgAlO\textsubscript{2.5} component for the glass starting material. On the other hand, the equilibrated proportion at 35 and 40 GPa could be lower, because the starting material was bridgmanite that had more MgAlO\textsubscript{2.5} component than the present run products. Therefore the proportion of the MgAlO\textsubscript{2.5} component should decrease more rapidly than demonstrated in this study.

7. The Variation of Molar Volume for Equation 1

Considering Al cation number of 0.1 for the Equation 1 in the main text based on the present and previous studies, the Eq. 1 can be represented by the following chemical equation:

\[
\text{MgAl}_{0.1}\text{Si}_{0.9}\text{O}_{2.95}(\text{Brg}) + 0.05\text{ MgSiO}_3(\text{Brg}) = \text{Mg}_{0.95}\text{Al}_{0.1}\text{Si}_{0.9}\text{O}_3(\text{Brg}) + 0.1\text{ MgO (Per) Eq. S-2}
\]

Pressure and temperature effects on molar volume are calculated using the third order Birch–Murnaghan equation:

\[
P = \left(\frac{3K_T}{2}\right) \left\{\frac{V_0}{V}\right\}^7 - \left\{\frac{V_0}{V}\right\}^5 \left[1 + \frac{3}{4} (K'_T - 4) \left\{\frac{V_0}{V}\right\}^2 - 1 \right]\]

\text{Eq. S-3}

where \(K_T\), \(V_0\), \(V\), and \(K'_T\) are the isothermal bulk modulus, zero pressure molar volume, high pressure molar volume and pressure derivative of bulk modulus. The temperature effects for \(K_T\) and \(V_0\) are given by:

\[
K_T = K_0 + \left(\frac{\partial K_T}{\partial T}\right)_p (T - T_0)
\]

\text{Eq. S-4}

\[
V_0 = V_0 \exp \int_{T_0}^{T_p} \alpha_0 dT
\]

\text{Eq. S-5}

where \(\left(\partial K_T/\partial T\right)_p\), \(T_0\), \(V_0\) and \(\alpha_0\) are the temperature derivatives of the bulk modulus, reference temperature, molar volume and volumetric thermal expansion at ambient pressure, respectively. Thermal expansion \(\alpha\) is empirically represented by:

\[
\alpha_T = \alpha_0 + \alpha_1 T + \alpha_2 T^2
\]

\text{Eq. S-6}

The experimental thermoelastic parameters of these mantle minerals used in Equation S-2 are shown in Table S-3.

The calculated \(\Delta V\) as a function of pressure is shown in Figure S-5 under 300 and 2000 °C, respectively. It is seen that the values of \(\Delta V\) are minus at both temperatures at 27–50 GPa, suggesting the pressure would enhance both Equations 1 and S-2 from the left to right direction. Therefore, the pressure will decrease the component of MgAlO\textsubscript{2.5} in bridgmanite.

Figure S-4 Unit cell volumes of bridgmanite along the system MgSiO\textsubscript{3}–Al\textsubscript{2}O\textsubscript{3} and MgSiO\textsubscript{3}–MgAlO\textsubscript{2.5} in the present and previous studies. The solid line presents the linear fitting results on values for bridgmanite along the system MgSiO\textsubscript{3}–Al\textsubscript{2}O\textsubscript{3} (Liu et al., 2016).
Table S-3  Elastic properties of minerals related with Eq. S-2 used for thermodynamic calculations.

<table>
<thead>
<tr>
<th>Phase</th>
<th>MgSiO$_3$-Brg</th>
<th>Mg$<em>{0.95}$Al$</em>{0.1}$Si$_{0.95}$O$_3$-Brg</th>
<th>MgAl$<em>{0.1}$Si$</em>{0.9}$O$_{2.95}$-Brg</th>
<th>MgO</th>
</tr>
</thead>
<tbody>
<tr>
<td>$V_0$ (cm$^3$/mol)</td>
<td>24.44 (1)$^a$</td>
<td>24.54 (1)$^a$</td>
<td>24.50 (1)$^f$</td>
<td>11.27 (1)$^b$</td>
</tr>
<tr>
<td>$\Delta H_0$ (KJ/mol)</td>
<td>10.79 (196)$^b$</td>
<td>16.44 (88)$^b$</td>
<td>10.24 (428)$^f$</td>
<td>36.48 (50)$^b$</td>
</tr>
<tr>
<td>$\Delta S_0$ (KJ/mol)</td>
<td>0.063$^b$</td>
<td>0.058$^b$</td>
<td>0.073$^f$</td>
<td>0.026$^b$</td>
</tr>
<tr>
<td>$K_{T298}$ (GPa)</td>
<td>256.7 (15)$^a$</td>
<td>239 (1)$^p$</td>
<td>259 (8)$^g$</td>
<td>160.9$^b$</td>
</tr>
<tr>
<td>$K_T$</td>
<td>4.09 (6)$^a$</td>
<td>4$^e$</td>
<td>4$^e$</td>
<td>4.35 (10)$^b$</td>
</tr>
<tr>
<td>$(\partial K/\partial T)_P$ (GPa/K)</td>
<td>-0.035 (2)$^c$</td>
<td>-0.057 (1)$^e$</td>
<td>-0.057 (1)$^*$</td>
<td>-0.0272$^h$</td>
</tr>
</tbody>
</table>

$\alpha_T = \alpha_0 + \alpha_1 T + \alpha_2 T^{-2}$ (oK$^{-1}$)

| $\alpha_0 \times 10^8$ | 1.982$^d$ | 2.08 (26)$^a$ | 2.08 (26)$^*$ | 3.38$^b$ |
| $\alpha_1 \times 10^8$ | 0.818$^d$ | 2.21 (67)$^a$ | 2.21 (67)$^*$ | 12.52$^a$ |
| $\alpha_2 \times 10^{-10}$ | -4.740$^d$ | 0           | 0           | -19.13$^b$ |

$C_P = A + BT^{-0.5} + CT^{-2}$ (oK$^{-1}$)

| $A \times 10^{-2}$ | 1.769$^d$ | 1.769$^h$ | 1.769$^*$ | 0.66$^i$ |
| $B \times 10^{-3}$ | -1.565$^d$ | -1.565$^g$ | -1.565$^*$ | -0.36$^i$ |
| $C \times 10^{-6}$ | 0          | 0         | 0         | -0.61$^i$ |

a: Tange et al. (2012)  
b: Akaogi and Ito (1999)  
c: Katsura et al. (2009)  
d: Funamori et al. (1996)  
e: Zhand and Wiedner (1999)  
f: Navrotsky et al. (2003)  
g: Walter et al. (2006)  
h: Kono et al. (2010)  
i: Kojitani et al. (2012)  
j: the same value with that of MgSiO$_3$-Brg.  
k: the same value with that of Mg$_{0.95}$Al$_{0.1}$Si$_{0.95}$O$_3$-Brg  
Abbreviation: Brg: bridgmanite.  
Number in parentheses represents standard deviation and is placed in the last digit (s).

Figure S-5 The calculated molar volume change of Eq. S-2 in the text along 300 and 2000 °K, respectively.
Supplementary Information References


