Complete agreement of the post-spinel transition pressure with the 660-km seismic discontinuity depth

The 660-km seismic discontinuity is a global feature dividing the Earth's upper and lower mantle. Geophysical observations of this discontinuity have revealed the following features. (1) The reported global average depth of this discontinuity is 660 km, corresponding to a pressure of 23.4 GPa (e.g., [1]). (2) The jumps of the compressional and shear velocities are both 6%. (3) The 660-km discontinuity has a topography of ±20 km. In particular, the 660-km discontinuity is depressed under the circum-Pacific subduction zones [1]. (4) The 660-km discontinuity produces strong reflection. The reflection of short P waves suggests that the thickness of the discontinuity is less than 2 km [2]. (5) Seismic tomography studies observed the stagnation of subducted slabs around the 660-km discontinuity (e.g., [3]). These observations should be interpreted in terms of mineral physics. Mg_2SiO_4 olivine is the most abundant mineral in the Earth's upper mantle, which transforms to a high-pressure polymorph of ringwoodite at pressures corresponding to the base of the upper mantle. At a pressure near that at the 660-km discontinuity, ringwoodite decomposes to bridgmanite + periclase, which is called the post-spinel transition. Therefore, the post-spinel transition is commonly accepted to be the cause of the 660-km discontinuity.

Since the late 1990s, the post-spinel transition pressure in Mg_2SiO_4 has been investigated using a combination of Kawai-type multi-anvil presses and synchrotron-based *in situ* X-ray diffraction, which enabled the most precise and accurate determination of the phase boundary. Nevertheless, these studies have located the post-spinel transition at pressures of 21.4–22.9 GPa at temperatures of 1900–2000 K (the geotherm at a depth of 660 km [3]), which are 0.5–2.0 GPa lower than the actual pressure at a depth of 660 km. This discrepancy is distinctive considering the pressure precision in a Kawai-type multi-anvil press. If these results were correct, the 660-km discontinuity could not be attributed to the post-spinel transition. Consequently, ringwoodite and bridgmanite + periclase would not be the dominant minerals in the transition zone and lower mantle, respectively. This is highly unlikely because, if this were the case, the mantle composition would be completely different from those suggested on the basis of geochemical and petrological observations, such as the ferromagnesium silicates $(Mg,Fe)_2SiO_4$ and $(Mg,Fe)SiO_3$. Therefore, the discrepancy between the reported results and expected pressures requires critical experimental investigations.

We revisited the PSp transition pressure in Mg_2SiO_4 at 1700 K by employing a combination of advanced multi-anvil techniques and *in situ* X-ray diffraction using the Kawai-type multi-anvil press SPEED-Mk.II at SPring-8 **BL04B1** [4]. This approach is, for the most part, identical to that followed in previous studies. However, we detected a significant drop in pressure in the samples after reaching the target temperature. This finding suggests a likely cause of the unexpectedly low transition pressures reported in previous studies. Accordingly, we minimized this decrease in pressure by increasing the press load during heating (forced pumping), something that no other research group has yet attempted.

We performed seven runs to determine the transition pressure at 1700 K. The PSp transition pressure at 1700 K was constrained to be between 23.72 GPa and 23.86 GPa (Fig. 1) according to the MgO scales based on the equations of states reported in Ref. 5 (hereafter the Tange MgO scales). Our results showed 0.5–2 GPa higher transition pressures than those previously determined.

We examine the correspondence of the post-spinel transition with the 660-km discontinuity using the new transition pressures obtained in this study. The temperature at the 660-km discontinuity is estimated to be 1900–2000 K [3]. The transition pressure was extrapolated to 2000 K using the Clapeyron slope of Ref. 5 corrected by the Tange MgO scale (–0.0016 GPa/K), which gave 23.4 GPa at 2000 K (Fig. 1). Given these facts, the present findings are entirely consistent with the depth of the 660-km discontinuity.

Previous studies likely underestimated the transition pressure owing to insufficient pressure control at high temperatures. The phase transition is completed within minutes after the target temperature is reached. Reference 6 reported a typical pressure decrease of ~0.5 GPa at a constant temperature of 1873 K; however, having adopted the final pressure before quenching in order to constrain the phase boundary, the authors significantly underestimated the transition pressure. We avoided a pressure drop at a high temperature via forced pumping and, therefore, obtained a more accurate transition pressure. Therefore, the forced-pumping technique is essential to determine a phase boundary. Notably, we observed a lower transition pressure (22.8 GPa) in preliminary experiments without the forced pumping techniques.

The problem of pressure drops is obvious when a Kawai-type multi-anvil press is combined with *in situ* X-ray diffraction at high temperatures, even though it is in fact attributable to the high precision of the Kawai-type multi-anvil press experiments. Experiments in a laser-heated diamond anvil cell would therefore encounter similar difficulties. This issue has never been seriously considered when investigating phase relations at high pressures and high temperatures. Therefore, there is a pressing need to reinvestigate every high P–T phase boundary that has been determined by X-ray diffraction without considering this problem. In particular, the determination of mantle mineral phase boundaries that are inseparably linked to other seismic discontinuities should be carefully investigated to improve our knowledge of the structure of the mantle.

Thus, owing to our innovation of the Kawai-type multianvil technology, we obtained a transition pressure that is in complete agreement with that of the 660-km discontinuity. The present study validates the applicability of widely accepted mantle compositional models such as the pyrolite and CI chondrite models.

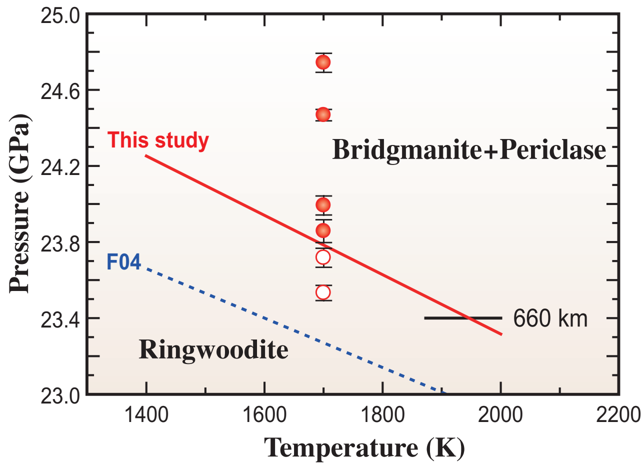

Fig. 1. Phase boundaries of the post-spinel transition in Mg_2SiO_4. Data points were calculated on the basis of the Tange MgO scale (red circle). Open and solid circles with error bars identify the stable phases as ringwoodite and bridgmanite+periclase, respectively. The black solid line is the expected condition of the 660-km discontinuity. The red solid line is a phase boundary evaluated using the fixed points obtained in this study and the Clapeyron slopes of Ref. 6 after recalculation with the Tange MgO scale. The blue dashed line (F04) is the phase boundary determined by Ref. 6 using MgO scale. The recalculated boundaries of the previous study with the Tange MgO scale are shifted to an even lower pressure.

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