Akimotoite-bridgmanite phase transition explains depressed 660-km seismic discontinuity in subduction zones

The seismic wave velocities abruptly increase at depths around 660 km in the Earth's interiors, referred to as the 660-km seismic discontinuity, separating the Earth's upper and lower mantles. One of the prominent features of the 660-km discontinuity suggested by seismology is significant depression down to 750 km structure beneath cold subduction zones [1]. This discontinuity is interpreted as the dissociation of $(Mg,Fe)_2SiO_4$ ringwoodite to (Mg,Fe) SiO_3 bridgmanite plus (MgFe)O ferropericlase. An earlier study reported that this reaction boundary has a negative slope, and the depression of the 660-km discontinuity in cold regions was orthodoxly interpreted by this slope [2]. However, a later study demonstrated that the slope of the ringwoodite dissociation is very gentle and cannot explain the significant depression in cold regions [3]. Thus, another phase transition with a steep negative slope is required to interpret the discontinuity depression. We hypothesized that the akimotoite-bridgmanite in $(Mg,Fe)SiO_3$ transition can cause the 660-km discontinuity depression in cold regions because akimotoite is a dominant mineral in cold regions of the bottom of the upper mantle.

In the current study [4], we determined the boundaries of the ringwoodite dissociation to bridgmanite plus periclase and akimotoite–bridgmanite phase transition in the MgO-SiO_2 system over a temperature range of 1250–2085 K using advanced multi-anvil techniques with *in situ* X-ray diffraction at SPring-8 **BL04B1** and P61B at DESY. In these experiments, we first synthesized higher-pressure assemblages (bridgmanite and bridgmanite plus periclase) at the lowest possible temperature in separate runs, and these assemblages were partially converted at the beginning of synchrotron experiments to lower-pressure assemblages also at the lowest possible temperature (Fig. 1). This method provided coexisting higher- and lower-pressure assemblages synthesized at the lowest temperature, which is essential because silicates become very inert once high-temperature conditions are experienced. Then, we observed the higher- and lower-pressure assemblages using *in situ* X-ray diffraction at spontaneously and gradually decreasing pressure and a constant temperature in a multi-anvil press. Stable assemblies were determined based on the relative increases/decreases in the ratio of their diffraction intensities (Fig. 1). Examples of the change in intensity ratio are shown in Fig. 2. We repeated this procedure with 50-K steps to determine the transition boundaries tightly. Since this strategy strictly follows the principle of phase equilibrium, problems in determining phase stability caused by sluggish kinetics and surface energy are excluded.

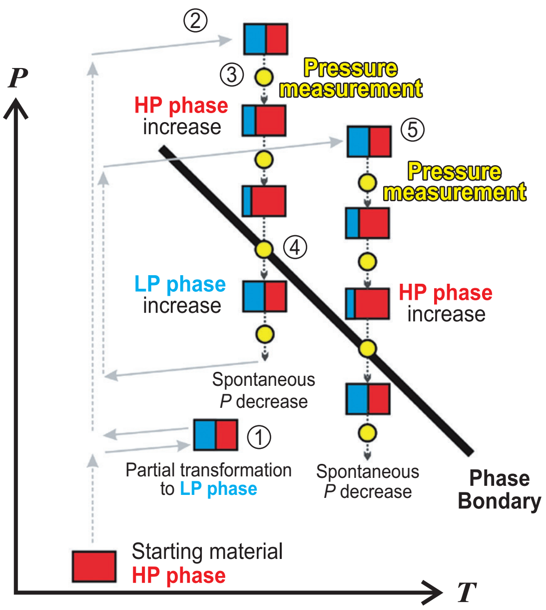

Fig. 1. Experimental strategy. The pressure spontaneously and gradually decreases while keeping the temperature and press load constant. In the high-pressure (HP) and low-pressure (LP) phase stability fields, the HP and LP phases increase with time to bracket the phase boundary. The numbers in the circles indicate the step numbers in the new strategy explained above.

The experimental results showed that the ringwoodite-dissociation boundary has a slightly concave curve, whereas the akimotoite-bridgmanite boundary has a steep convex curve (Fig. 3). The ringwoodite-dissociation boundary is located at pressures of 23.2–23.7 GPa in the temperature range of 1250–2040 K. Its slope varies from –0.1 MPa/K at temperatures less than 1700 K to –0.9 MPa/K at 2000 K with an averaged value of –0.5 MPa/K. The ringwoodite-dissociation boundary was thus found in agreement with previous experiments [3]. The slope of the akimotoite-bridgmanite boundary gradually changes from –8.1 MPa/K at low temperatures up to 1300 K to –3.2 MPa/K above 1600 K. The akimotoite-bridgmanite boundary intersects with the ringwoodite-dissociation boundary at 1260 K and around 24 GPa, which corresponds to 660 km depth (Fig. 3). Based on these findings, we predict that, beneath cold subduction zones, ringwoodite should first dissociate into akimotoite plus periclase at around 660 km depth, and then akimotoite transforms to bridgmanite at greater depth. Furthermore, seismological studies also reported that the 660-km discontinuity is doubled in cold regions such as Tonga subduction zone, which is interpreted by the succession of dissociation of ringwoodite to akimotoite plus periclase and the akimotoite-bridgmanite transition (Fig. 3). Beneath warm subduction zones such as Peru, ringwoodite dissociates into bridgmanite plus periclase (Fig. 3).

The current results also have significant geodynamic implications since steep phase transition boundaries produce large buoyancy in slab dynamics [5]. When the upward buoyancy produced by the negative phase boundary exceeds the downward force due to the thermal expansion, mantle flows are hampered, and slabs stagnate above the 660-km discontinuity. Therefore, the steep negative boundary of the akimotoite-bridgmanite transition should result in cold-slab stagnation, which is supported by the seismological observations beneath cold (e.g., Tonga, Izu-Bonin) subduction zones.

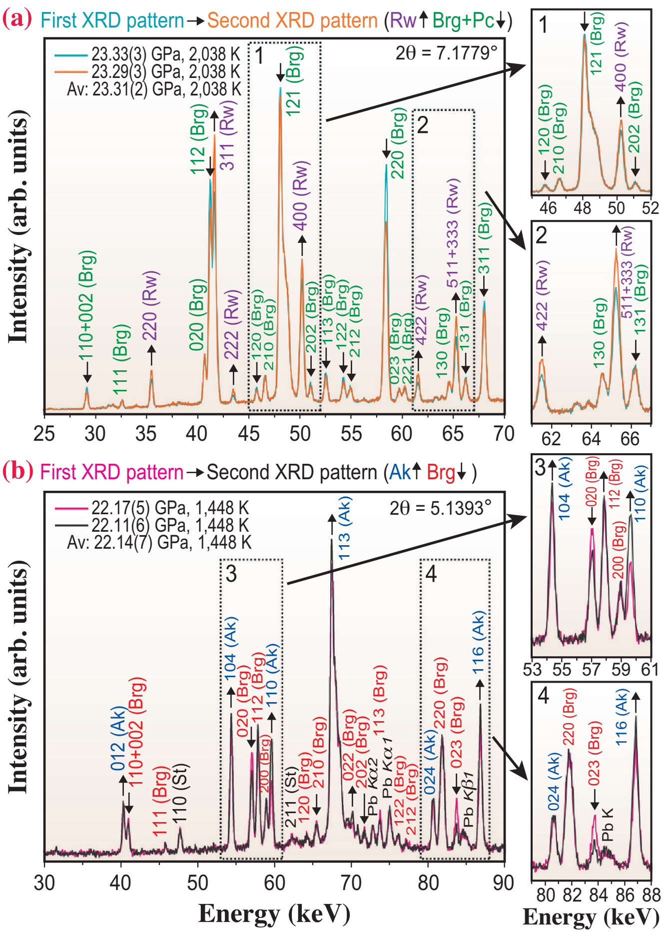

Fig. 2. **(a)** An example of the change of intensity ratio between ringwoodite and bridgmanite plus periclase at 2038 K and 23.31(2) GPa. **(b)** An example of the change of intensity ratio between akimotoite and bridgmanite at 1448 K and 22.14(7) GPa. The first diffraction patterns are shown in (a) blue and (b) pink, and the second patterns are displayed in (a) orange and (b) dark gray. The upward and downward arrows, respectively, indicate the peaks with increased and decreased intensities in the second diffraction patterns.

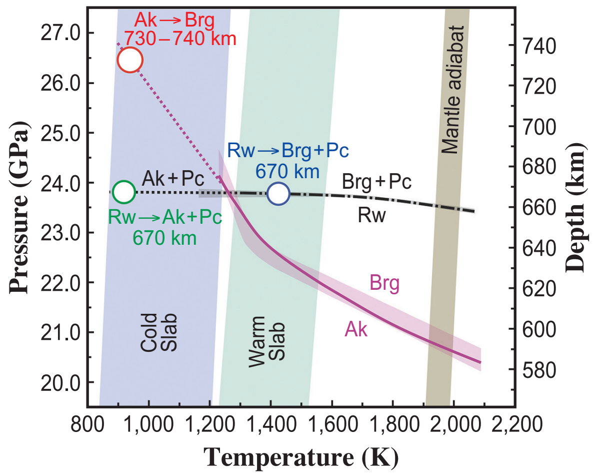

Fig. 3. Comparison of the ringwoodite dissociation and akimotoite–bridgmanite phase transition boundaries. Ak–$MgSiO_3$ akimotoite, Brg–$MgSiO_3$ bridgmanite, Pc–MgO periclase, Rw–Mg_2SiO_4 ringwoodite. Green, blue and red circles indicate Rw→Ak+Pc dissociation at 670 km depth, Rw→Brg+Pc dissociation at 670 km depth and Ak→Brg transition at 730–740 km depth, respectively.

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