Sharp 660-km seismic discontinuity explained by extremely narrow binary post-spinel transition

The 660-km seismic discontinuity (D660) is the globally observed boundary between the Earth's upper and lower mantles. Geophysical observations characterize D660 as follows. (a) The global average depth is 660±10 km, corresponding to 23.4±0.4 GPa in pressure. (b) The changes in compressional and shear velocities at the boundary are both 6%. (c) The strong reflection of short-period P waves suggests that the thickness of D660 is less than 2 km (0.1 GPa in pressure), which is in striking contrast to the 7-km-thick 410-km discontinuity [1]. (d) The topography of the discontinuity up to ±20 km has been locally observed. (e) Seismic tomography mappings show high-velocity anomalies around the D660 beneath subduction zones, some of which seem to indicate stagnation of subducted slabs (e.g., [2]). From the above features, D660 is considered one of the most important boundaries in the mantle, especially in terms of mantle dynamics.

It has been suggested that the Earth's upper mantle consists of *ca.* 60 atom% $(Mg_{0.9}Fe_{0.1})_2SiO_4$ polymorphs (olivine, wadsleyite, and ringwoodite) coexisting with *ca.* 40 atom% pyroxene and garnet. In contrast, most parts of the lower mantle are constituted of *ca.* 70 atom% $(Mg,Fe)SiO_3$ bridgmanite with *ca.* 20 atom% ferropericlase and *ca.* 10 atom% calcium perovskite. At a pressure near that at D660, ringwoodite decomposes to bridgmanite + ferropericlase, which is called the post-spinel transition. Because of the agreement of the post-spinel transition pressure with the D660 pressure (e.g., [3]) and the high elastic wave velocities of the post-spinel phase against those of ringwoodite, it is usually considered that the post-spinel transition is the cause of the formation of D660. Whether or not the post-spinel transition can explain D660 will determine the chemical structure of the mantle (homogeneous *vs* chemically layered mantle) and the type of mantle convection (whole-mantle *vs* layered-mantle convection). If the D660 is due to the post-spinel transition, slabs could be subducted to the lower mantle because the mantle would be homogenous across D660, leading to whole-mantle convection. However, if the D660 is not due to the transition, compositionally distinct upper and lower mantles are required to explain the sharp D660, which should imply layered-mantle convection.

If the thickness of D660 primarily corresponds to the pressure interval of the three-phase coexistence of ringwoodite + bridgmanite + ferropericlase in the Mg-Fe binary post-spinel transition, this binary loop must be extremely narrow and have a pressure interval of less than 0.1 GPa. However, such a narrow binary loop has never been demonstrated by high-pressure experiments owing to the following experimental difficulties. (a) The experimental uncertainties in pressure are larger than 0.1 GPa, indicating there is no pressure resolution suitable for evaluating the pressure interval. (b) Sample pressures drop by 0.5–2.0 GPa despite a constant press load and temperature. Such a pressure drop may have led to serious overestimation of the pressure interval [3] because the post-spinel phase remains even in a ringwoodite-stability field owing to the sluggish reversal reaction. Thus, these reasons have made the precise estimation of an extremely narrow pressure interval impossible. An experimental approach with pressure precision better than 0.1 GPa and precise control of a target pressure is essential to examine whether the binary loop is narrow enough to account for the sharp D660.

We determined the phase relations in the system Mg_2SiO_4–Fe_2SiO_4 at around 23 GPa and 1700 K with a combination of advanced multianvil techniques and *in situ* X-ray diffraction using the Kawai-type

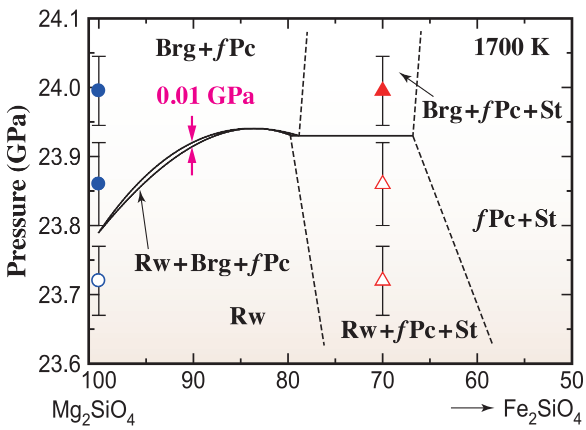

Fig. 1. Phase relations in the system Mg_2SiO_4–Fe_2SiO_4 at 1700 K. The compositions of the three phases (Rw, Brg, and *f*Pc) are shown by solid lines. Dashed lines are rough drawings of the phase boundaries in this system. Open and solid circles indicate the stable phases are Rw and Brg + Pc, respectively. Open and solid triangles indicate that stable phases are Rw + *f*Pc + St and Brg + *f*Pc + St, respectively. Pressures were calculated with the MgO scale using the equation of states reported in Ref. 5. Brg: bridgmanite, *f*Pc: ferropericlase, Rw: ringwoodite, St: stishovite.

multianvil press SPEED-Mk.II at SPring-8 **BL04B1** [4]. We improved the pressure precision to 0.05 GPa by obtaining a wide X-ray path to samples. We also suppressed a pressure decrease by increasing the press load during heating. Two samples with bulk compositions of Mg_2SiO_4 and $(Mg_{0.7}Fe_{0.3})_2SiO_4$ were loaded in a single-cell assembly to simultaneously determine their transition pressures. Since the binary loop of ringwoodite + bridgmanite + ferropericlase ends near the $(Mg_{0.7}Fe_{0.3})_2SiO_4$ composition, this procedure constrains both ends of the binary loop. In combination with thermochemical calculation, we estimated the entire shape of the binary loop to estimate the pressure interval at $(Mg_{0.9}Fe_{0.1})_2SiO_4$.

The binary phase relations determined at 1700 K are shown in Fig. 1. A striking feature is that the difference between the transition pressures in Mg_2SiO_4 and the four-phase coexistence (ringwoodite, bridgmanite, ferropericlase, and stishovite) boundary is 0.14 GPa. The geometry of the phase diagram shows that the pressure interval of the binary loop at $(Mg_{0.9}Fe_{0.1})_2SiO_4$ should be much smaller than this pressure difference. The pressure intervals at $(Mg_{0.9}Fe_{0.1})_2SiO_4$ were quantitatively estimated at 1700 K using compositions of the three phases (bridgmanite, ferropericlase, and ringwoodite) between the Mg endmember and the four-phase coexistence boundary calculated with available thermodynamic data. The pressure interval was found to be 0.012±0.008 GPa at a bulk composition of $(Mg_{0.9}Fe_{0.1})_2SiO_4$ at 1700 K (Fig. 1). This pressure interval corresponds to a depth interval of only 100–500 m, which is one order of magnitude smaller than the observable thickness of D660 (less than 2 km). The pressure interval at an expected mantle temperature (2000 K) was evaluated by the same procedure. We obtained a pressure interval of 0.003±0.002 GPa at 2000 K, which is even smaller than that at 1700 K. Thus, the seismically observed sharpness of D660 is in excellent agreement with our experimental results. This circumstance does not require chemical stratification of the upper and lower mantles, supporting a compositionally homogenous mantle throughout the present-day mantle and whole-mantle convection.

Using available thermodynamic data, we also estimated the possible expansion of the binary post-spinel transition interval up to 7 km owing to the latent heat of the phase transition when mantle flow crosses D660 (Fig. 2). We suggest that global mapping of the sharpness of D660 should be carried out to assess the presence of vertical flows that are faster than thermal diffusion. The present study encourages global seismologists to revisit this topic to obtain new insights into mantle dynamics.

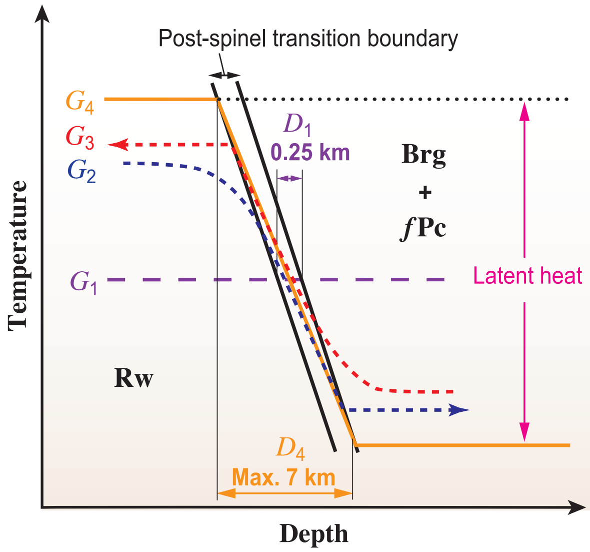

Fig. 2. Expansion of discontinuity thickness of the post-spinel transition boundary owing to latent heat of post-spinel transition. The black solid line is the phase boundary of the post-spinel transition. The isothermal geotherm is shown as G_1 (dashed line), providing a transition thickness of D_1 (0.25 km). The complete adiabatic geotherm is shown as G_4 (yellow solid line), forming D_4 (7 km at most) owing to latent heat (30–90 K). If the geotherm is under intermediate conditions (G_2 and G_3 dashed curves), the latent-heat effect should be smeared out and provide the D660 thickness between D_1 and D_4 (D_2 and D_3) depending on the flow direction. Brg: bridgmanite, fPc: ferropericlase, Rw: ringwoodite.

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