Curved post-garnet phase boundary and its implications for mantle dynamics

Recent seismic tomography studies have revealed that slabs stagnate at 660–1000 km depths in many subduction zones [1] and that plumes from the lowermost mantle become invisible at a depth above 1000 km [2]. One explanation for this is that a phase transition below the 660-km discontinuity decelerates slab subduction and accelerates plume upwelling in the upper part of the lower mantle. To achieve this, the sign of the Clapeyron slope must change with temperature because a positive Clapeyron slope enhances mantle convection (plume acceleration), whereas a negative slope impedes it (slab stagnation).

Garnet, a major mantle mineral, transforms into a bridgmanite-bearing assemblage at a depth of ~700 km. This is called the post-garnet transition and only occurs in the upper part of the lower mantle. Thus, determining the Clapeyron slope of the post-garnet transition is essential for understanding the dynamics of the upper part of the lower mantle.

The most accurate and precise method to determine the Clapeyron slope of a mineral phase transition is *in situ* X-ray diffraction with a multianvil press. Our recent studies highlighted two potential problems in accurately and precisely determining phase boundaries, namely the pressure change during heating and the sluggish kinetics of the investigated phase transitions [3,4]. An inevitable rapid pressure change upon heating hampers the accurate determination of the transition pressures. Although phase stability must be determined by observing pairs of normal and reversed reactions, this has not been confirmed in most previous studies. Thus, most previous studies have misinterpreted the phase relationships.

In this study, we have rigorously determined the boundary of the post-garnet transition in $Mg_3Al_2Si_3O_{12}$ (pyrope to bridgmanite+corundum transition), a major component of garnet, was determined using multianvil techniques combined with *in situ* X-ray diffraction using the Kawai-type multianvil press SPEED-Mk.II at SPring-8 **BL04B1** [5]. The strategy for establishing the phase boundary was as follows: (1) phase stability was continuously determined from the lowest temperature applied after sufficient annealing to release most deviatoric stresses, avoiding substantial pressure changes during phase identification; (2) the low- (pyrope) and high-pressure (bridgmanite + corundum) phases always coexisted during the experiments to monitor the direction of the reaction; and (3) the peak intensity change with time was monitored using X-ray diffraction patterns of the sample taken under the same conditions to identify a stable phase (Fig. 1). These experimental treatments resulted in a precise and accurate phase identification without rapid pressure changes or sluggish kinetics.

The phase relations in the $Mg_3Al_2Si_3O_{12}$ system were determined at 25.5–26.5 GPa and 1350–2100 K (Fig. 2). The transition pressure changed nonlinearly with increasing temperature, resulting in a downward boundary shape. The Clapeyron slope

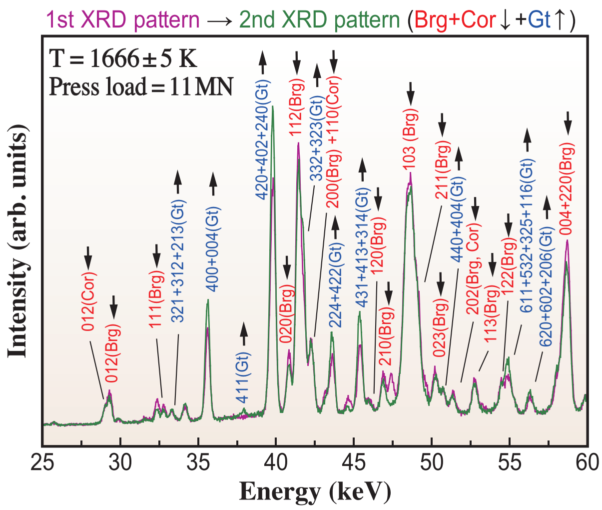

Fig. 1. An example of the accurate determination of phase stability between garnet (Gt) and bridgmanite (Brg) plus corundum (Cor) at 25.93(5) GPa and 1666 K. The Gt peaks are stronger in the second diffraction (green) than in the first (purple), whereas those of Brg and Cor are weaker, indicating that Gt is stable.

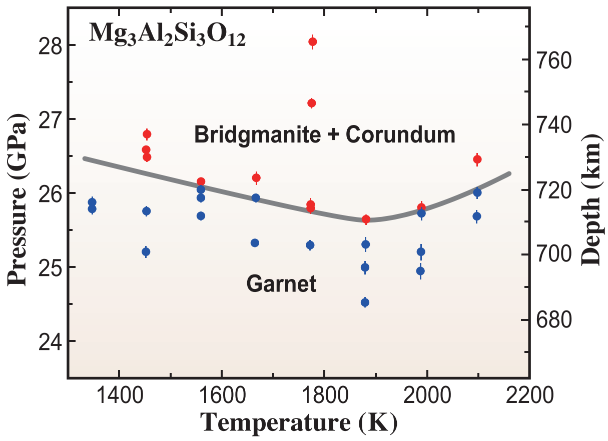

Fig. 2. Phase relations of the post-garnet transition in $Mg_3Al_2Si_3O_{12}$. The blue and red circles indicate the stable phases of garnet and bridgmanite plus corundum, respectively.

had a negative value of −1.5 MPa/K at 1400–1800 K, and a positive value of +2.5 MPa/K at 1900–2100 K. A change in the slope from positive to negative was first discovered during the phase transitions of mantle minerals. The Clapeyron slope is defined as the ratio of the entropy change (ΔS_{tr}) to the volume change (ΔV_{tr}) associated with the phase transition: $dP/dT = \Delta S_{tr}/\Delta V_{tr}$. As ΔV_{tr} is negative and only changes slightly with temperature, ΔS_{tr} is essential in forming the nonlinear boundary. Based on previously reported heat capacity data, we proposed an increase in the pyrope heat capacity at >1300 K. This can be explained by the possible disorder among the crystallographic sites in the $^{VIII}Mg_3{}^{VI}Al_2{}^{IV}Si_3O_{12}$ pyrope, as in the $^{VIII}Mg_3{}^{VI}[Mg,Si]^{IV}Si_3O_{12}$ majorite.

The curved post-garnet boundary explains the dynamics in the upper part of the lower mantle. In a cold subducting region, the post-garnet boundary has a negative slope (Fig. 3), which could stagnate a slab or decelerate the slab motion after crossing the 660-km discontinuity. This may result in a tomographic snapshot of the apparent slab stagnation below the 660-km discontinuity [1]. Slabs stagnating below the 660-km discontinuity are further promoted to subduct into deeper regions after being heated by the surrounding mantle because the Clapeyron slope of the post-garnet transition approaches zero with an increase in the average temperature (Fig. 3). In a hot upwelling region, the post-garnet boundary has a positive slope, which can accelerate plume upwelling (Fig. 3), resulting in plume thinning and reduced visibility in seismic tomography. This scenario may explain why tomographic images show indistinct plume traces below a depth of 1000 km [2]. The two types of seismic observations of slab stagnation and plume upwelling can be consistently interpreted based on the curved boundary of the post-garnet transition.

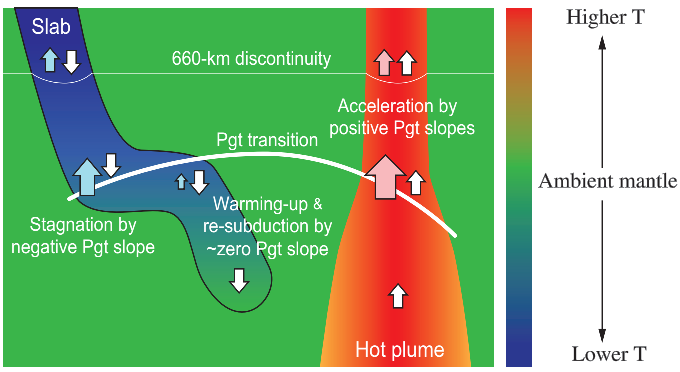

Fig. 3. Mantle dynamics in the upper part of the lower mantle controlled by phase transitions. The bold solid line is the post-garnet (Pgt) transition boundary determined in this study. Blue arrows show the positive buoyancies in a slab caused by the negative slopes of the post-spinel and Pgt transitions. Pink arrows indicate the positive buoyancies in a plume by the positive slopes of the Pgt transition. The main phase transition in a plume around a depth of 660-km is the Pgt transition. The arrow sizes express buoyancy magnitudes.

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