Composition of the Mantle Transition Region Constrained by Sound Velocity Measurements at High Pressure and Temperature

The Earth's mantle is divided into three layers, namely, the upper mantle (30 km-410 km in depth), mantle transition region (410 km-660 km), and lower mantle (660 km-2900 km), by sharp discontinuous changes in both seismic velocities (Vp and Vs) and density at depths of 410 km and 660 km. The upper mantle is known to consist of a rock called "pyrolite" (Fig. 1(a)) [1], which is composed mainly of three minerals, olivine, pyroxene, and garnet, on the basis of petrological studies of deep-seated materials delivered to the surface of the Earth via volcanic eruptions or tectonic movements. Laboratory sound velocity measurements of pyrolite also confirmed that the Vp and Vs of this rock are consistent with those observed seismologically for the upper mantle.

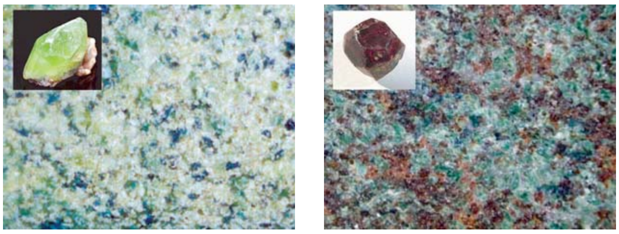

Fig. 1. Examples of mantle rocks: **(a)** pyrolite and **(b)** piclogite, where inlets are crystals of olivine and garnet, respectively, which are the predominant minerals in these rocks. Note that pyrolite and piclogite are names of hypothetical rocks, and the pictures displayed here are those of natural peridotite and eclogite rocks, which are closely related to these hypothetical rocks.

In contrast, the composition of the mantle transition region (MTR, hereafter), as well as of the lower mantle, remains unresolved. As the sources of the mantle rocks are limited to those at depths shallower than ~200 km, laboratory sound velocity measurements of the candidate materials and comparison of these results with seismic velocities are the only way to estimate the composition of the deeper part of the mantle. However, it has been difficult to precisely determine the sound velocities of high-pressure phases at pressures (13-24 GPa) and temperatures (1700-1900 K) equivalent to those of MTR.

It has been acknowledged that olivine in pyrolite composition transforms to modified spinel and spinel structures under the P, T conditions of MTR, while pyroxene dissolves in garnet, forming a high-pressure phase called "majorite." Pyrolite is composed of ~60% of the high-pressure forms of olivine plus ~40% of majorite in this region of the mantle, as confirmed by phase equilibrium studies at high pressure and high temperature. However, an alternative model composition, called "piclogite" (Fig. 1(b)) [2], has also been proposed for this region. Piclogite possesses a range of compositions with lesser amounts of the olivine relative to majorite, in contrast to pyrolite, and it has been difficult to conclude which composition is better in the light of seismological constraints, as the sound velocities of these high-pressure phases have never been measured under the P, T conditions of MTR.

We have developed techniques for precisely measuring the sound velocities at pressures up to ~20 GPa and temperatures up to ~1800 K, by a combination of synchrotron radiation and ultrasonic measurements with a large-volume multianvil apparatus at beamline **BL04B1** [3]. On the basis of these techniques, we measured the sound velocities of the spinel form of olivine (ringwoodite) [3] and majorite [4] in pyrolite composition. The results demonstrated that both Vp and Vs of majorite with the realistic mantle composition are significantly lower than the corresponding velocities of ringwoodite (Fig. 2). The Vp and Vs of the two candidates for the composition of MTR, pyrolite and piclogite, can be

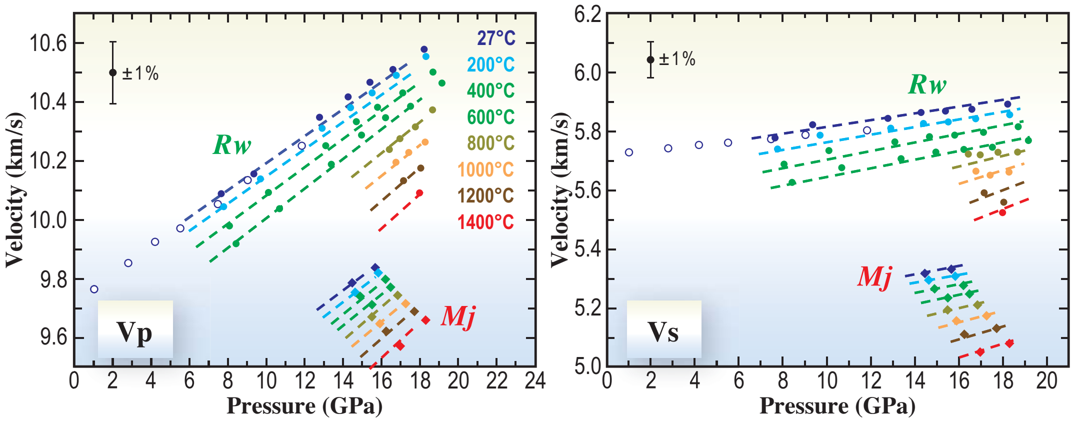

Fig. 2. Sound velocities (Vp, Vs) of ringwoodite (Rw) and majorite (Mj) at high pressure and high temperature determined by the present measurements of combined *in situ* X-ray and ultrasonic observations.

calculated using the present sound velocity data on ringwoodite and majorite, because both of these two rocks crystallize to assemblages mainly of these two high-pressure phases in different proportions.

Figure 3 illustrates the variations in Vp and Vs in pyrolite and piclogite composition based on the present measurements, which are compared with those obtained using seismological models (PREM and AK135). It is seen that the velocities of pyrolite are consistent with those seismologically observed in the upper to middle parts of MTR, while they (particularly Vs) become significantly lower than the seismological models in the lower part of this region. Piclogite yields an even lower Vs in the middle to lower parts of MTR, and is found inappropriate as the composition for this region.

Thus, the present result demonstrates that pyrolite is the best model composition for MTR except for its bottom region. We tested various compositions for this region, and found that only harzburgite, which is the main component of a sinking oceanic plate (referred to as a "subducting slab"), should have Vp and Vs consistent with those of the seismological models (Fig. 3). Thus, it is most likely that the upper mantle and upper to middle parts of this region are composed of pyrolite, while the bottom part of the latter region is made of subducted slab materials trapped around the 660 km discontinuity (Fig. 4), where the density of the surrounding mantle increases substantially.

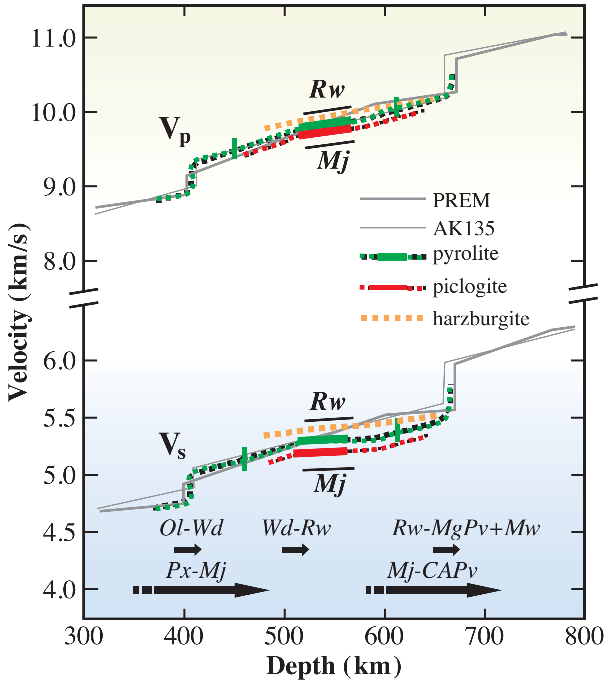

Fig. 3. Comparisons of sound velocities of pyrolite (green), piclogite (red), and harzburgite (orange) with those seismologically derived (PREM and AK135). Phase transitions in these lithologies are shown in the lower part of the figure. Ol=olivine, Wd=wadsleyite, Rw=ringwoodite, Px=pyroxene, Mj=majorite, MgPv=MgSiO$_3$ perovskite, Mw=magnesiowustite, CaPv=CaSiO$_3$ perovskite.

It has been demonstrated that some of the subducting slabs are stagnant at and around the 660 km discontinuity by some seismological observations. The fate of such "stagnant slabs" has been a matter of debate in conjunction with the possible mode of mantle convection [5]. The present study suggests that most of the slabs stagnant around this depth may form a thick (~100 km) layer of harzburgite just around the 660 km discontinuity, although some cold and thick slabs may penetrate deeper into the lower mantle and could reach the mantle-core boundary. As the thermally equilibriated harzburgite is less dense than the surrounding pyrolite mantle, once the ringwoodite to perovskite (+ magnesiowustite) transition takes place in these compositions [6], it is likely that the harzburgite layer will be gravitationally stable in the top region of the lower mantle.

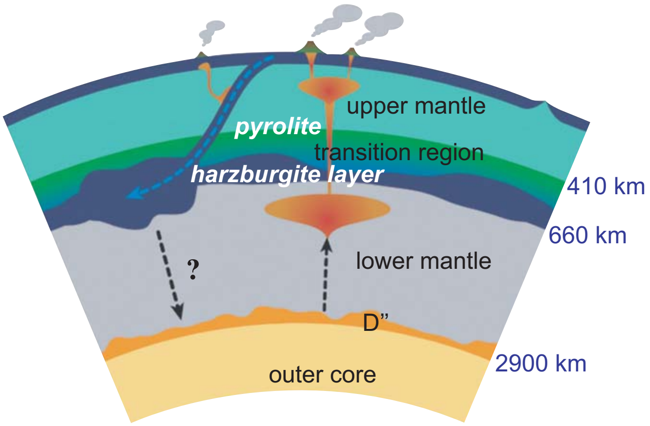

Fig. 4. Proposed model for the composition, structure, and dynamics in the mantle based on the present study, suggesting that the upper mantle and the upper to middle parts of MTR are composed of pyrolite composition, and a thick layer of harzburgite may exist near the 660 km seismic discontinuity. "Flushing" of the stagnant slab down into the lower mantle is questionable, as the harzburgite layer is gravitationally stable at the top of the lower mantle.

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