

Phase transformations in model mantle compositions and nature of the 410 km and 660 km seismic discontinuities

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Phase transformations in model mantle materials have been extensively studied over the last few decades to elucidate the composition and constitution of the Earth's deep mantle. In these studies, it has been a common practice to study the phase transformations in mantle minerals, such as olivine, pyroxene and garnet separately, and discuss the plausible phase changes in more complex systems related to the actual mantle compositions by combining these results because of some technical problems both in high pressure experiments and in preparation of suitable starting materials. However, it was suggested that the chemical interaction among these mineral phases may significantly change the stability and chemical compositions of these phases, yielding quite different phase changes in the complex systems from those estimated based on the phase transformations of the individual phase (Irifune, 1994; Wood and Rubie, 1996). Here, I summarize our recent experimental study on a model mantle composition, and discuss the mineral constitution of the deep mantle and the nature of the two major seismic discontinuities at 410 km and 660 km depths in the light of these and other available data.

Experimental

Pyrolite starting material was prepared from a mixture of oxides and gels, which was sintered at 1000°C in an evacuated silica tube. Thus prepared sample, mostly consisted of poorly crystallized olivine, pyroxene, and plagioclase, was crushed into fine powder and sealed in a capsule of Au₇₅/Pd₂₅ alloy. Some additional runs were also conducted with a different starting material of pyrolite composition, that is a mixture of 'pyrolite minus olivine' and natural San Carlos olivine possessing Mg# (= 100Mg/(Mg+Fe)) of 89, to ensure the equilibrium of the phases.

High pressure and high temperature runs were conducted with a multianvil 6-8 system (ORANGE-2000) at Ehime University. The truncations (TEL) of the second-stage cube anvils were either 5.0 mm (5

GPa < P < 20 GPa) or 1.5 mm (20 GPa < P), and semi-sintered magnesia was used as a pressure medium and pyrophyllite as gaskets. Pressure was estimated from the calibration curves based on the phase transformations in some reference materials, while temperature was measured with a W₉₇Re₃-W₇₅Re₂₅ thermocouple. Quenching method was adopted, and the recovered sample was examined by a micro-focus X-ray powder diffractometer as well as an electron microprobe analyzer. The run durations were typically 30 minutes to several hours, and experiments were conducted at pressures between 5 and 28 GPa, along a representative mantle geotherm. Additional experiments at pressures between 20 and 24 GPa are currently being pursued.

Results

Figure 1 shows the mineral proportion changes in pyrolite as a function of pressure at temperatures close to the typical mantle geotherm, on the basis of mass balance calculations using the chemical compositions of the coexisting phases at each P/T condition in the present experiments. Parts of the results were already reported elsewhere (Irifune, 1994; Irifune and Isshiki, 1998). The gross nature of the phase transformations in this composition was found to be consistent with that estimated by combining the results of the experiments on 'pyrolite minus olivine' and those of the olivine component (e.g. Irifune, 1987), except for the presence of a small amount of magnesiowüstite observed at pressures 17–20 GPa in the present study.

It was shown that all of the coexisting phases in pyrolite became Mg-rich with increasing pressure between 9 and 15 GPa, where pyroxenes dissolved into a garnet structure and the formation of majorite garnet proceeded (Irifune and Isshiki, 1998). It was also noted that the Mg#s of MgSiO₃-rich perovskite and magnesiowüstite approached each other with increasing pressure, presumably caused by the occurrence of ferric iron in the former phase

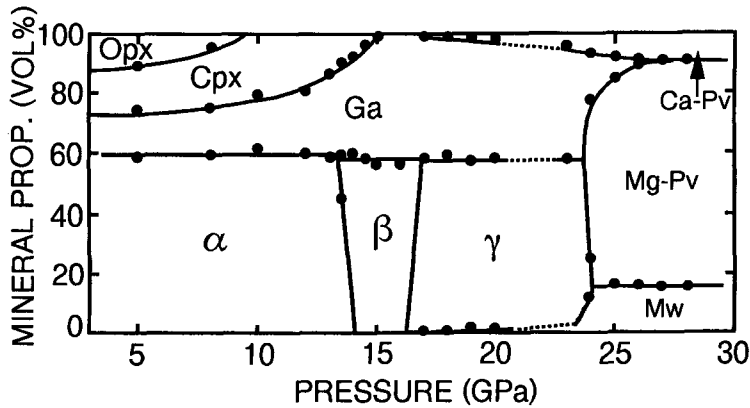


FIG. 1. Mineral proportions in pyrolite as a function of pressure along a representative geotherm (i.e. $\sim 1400^{\circ}\text{C}$ at 14 GPa and $\sim 600^{\circ}\text{C}$ at 24 GPa). Opx, orthopyroxene; Cpx, clinopyroxene; Ga, (majorite) garnet; α , olivine; β , modified spinel; γ , spinel phases of $(\text{Mg,Fe})_2\text{SiO}_4$; Ca-Pv, CaSiO_3 perovskite; Mg-Pv, MgSiO_3 perovskite; Mw, magnesiowüstite.

associated with the increasing alumina content with pressure (Wood and Rubie, 1996; McCammon, 1997).

Discussion

It has been demonstrated that the 410 km seismic discontinuity is sharper than ever thought in some localities (e.g., Benz and Vidale, 1993), which is inconsistent with the sharpness of this discontinuity expected from the olivine to modified spinel transformation of a fixed composition $(\text{Mg}_{0.89}\text{Fe}_{0.11})_2\text{SiO}_4$. The present results, however, suggest that this transformation may cause sharper change in seismic velocities in pyrolite composition as compared to the case of the isochemical transformation because of the changes of Mg#s of the olivine component in pyrolite (i.e. Mg# of olivine is about 92–93 before the transformation, while it is about 88–89 for modified spinel phase immediately after the transformation is completed) upon the transformation (see, Irifune and Isshiki, 1998). Thus the above problem in pyrolite mantle hypothesis may be resolved or at least be reduced significantly. This chemical composition change in olivine component associated with the olivine to modified spinel transformation in pyrolite should reduce the magnitude of the seismic velocity jump at 410 km depth, which is also consistent with the idea of the pyrolite mantle that indicates this transformation to be the main cause of the 410 km seismic discontinuity.

It was found that MgSiO_3 -rich perovskite in pyrolite contains about 3–4 wt.% of Al_2O_3 when it first appeared at about 24 GPa, and most of majorite

garnet transformed to the perovskite structure at this pressure where the spinel form of olivine completely transformed to perovskite + magnesiowüstite (the postspinel phases). Thus only a small amount of garnet was left after the spinel–postspinel transformation was completed at this pressure, which further persisted to higher pressures but gradually transformed to the perovskite structure by about 26 GPa (Fig. 1). This nature of the phase transformations in pyrolite is also consistent with the observed seismic velocity profiles near the 660 km depth; the velocity and the density change sharply around this depth due to the spinel–postspinel transformation that occurs in a very limited pressure range, followed by their gradual changes in the uppermost part of the lower mantle caused by the smeared-out transformation of the small amount of garnet into the perovskite structure. In conclusion, the nature of the phase transformations in pyrolite generally matches that of the seismologically derived velocity/density profiles, from a viewpoint of high pressure phase equilibria based on quench experiments.

References

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