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The combined effects of post-spinel and post-garnet phase transitions on mantle plume dynamics

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ABSTRACT

Mineralogical studies indicate that two major phase transitions occur near the depth of 660 km in the Earth's pyrolitic mantle: the ringwoodite (Rw) to perovskite (Pv) + magnesiowüstite (Mw) and the majorite (Mj) to perovskite (Pv) phase transitions. Seismological results also show a complicated phase boundary structure at this depth in plume regions. However, previous geodynamical modeling has mainly focused on the effects of the Rw–Pv+Mw phase transition on plume dynamics and has largely neglected the effects of the Mj–Pv phase transition. Here, we develop a 3-D regional spherical geodynamic model to study the combined influence of these two phase transitions on plume dynamics. Our results show the following: (1) A double phase boundary occurs in the high-temperature center of the plume, corresponding to the double reflections in seismic observations. Other plume regions feature a single, flat uplifted phase boundary, causing a gap of high seismic velocity anomalies. (2) Large amounts of relatively low-temperature plume materials can be trapped in the transition zone due to the combined effects of phase transitions, forming a complex truncated cone shape. (3) The Mj–Pv phase transition greatly enhances the plume penetration capability through 660-km phase boundary, which has a significant influence on the plume dynamics. Our results provide new insights which can be used to better constrain the 660-km discontinuity variations, seismic wave velocity structure and plume dynamics in the mantle transition zone. The model can also help to estimate the mantle temperature and Clapeyron slopes at the 660 km phase boundary.

1. Introduction

Seismologically defined mantle transition zone boundaries are present at 410 and 660 km, which correspond to several mineralogical phase transitions in the Earth's pyrolite model (Duffy and Anderson, 1989). The exothermic phase change of olivine (Ol) to wadsleyite (Wa), which has a positive Clapeyron slope, deepens the 410 km discontinuity and enhances plume ascent, while the ringwoodite (Rw) to perovskite (Pv) + magnesiowüstite (Mw) has the opposite effect on mantle plumes at the 660 km discontinuity due to its negative Clapeyron slope (Ito and Takahashi, 1989; Lebedev et al., 2002; Schmerr and Garnero, 2007; Yu et al., 2008). These two phase transitions play key roles in mantle convection and have been extensively studied with different methods (Christensen and Yuen, 1985; Tackley et al., 1993; Li et al., 1998; Lebedev et al., 2002; Herein et al., 2013). However, in the pyrolite model, olivine represents ∼60% of the upper mantle, and the non-olivine minerals contain large amounts of garnet (Ringwood, 1975; Frost, 2008). Therefore, an exothermic phase transition of majorite (Mj) to perovskite (Pv) (post-garnet) with a positive Clapeyron slope near a depth of 660 km has also been advanced by mineralogical studies (Fei and Bertka, 1999; Hirose, 2002; Yu et al., 2011), which can significantly affect plume dynamics and 660 km discontinuity variations (Hirose, 2002). Meanwhile, for the cold slab the majorite first changes to ilmenite at shallow depth, then the ilmenite transforms into perovskite close to 660 km depth area (Yu et al., 2011). Thus the former with a positive Clapeyron slope may enhance the subduction sinking while the latter with a negative Clapeyron slope could resist the slab descent. Besides, recent mineral experiments and geodynamic modeling indicate that pyroxene slowly diffuses into garnet, making the subducting slab stagnate in the mantle transition zone (Van Mierlo et al., 2013; Agrusta et al., 2014; King et al., 2015).

Global and regional seismic studies have revealed the complex morphology of the 660 km discontinuity beneath current

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hotspot locations, probably due to the co-existence of these two phase transformations. The seismic characteristics of the transition zone discontinuities beneath the 26 hotspots in the catalog of Courtillot et al. (2003) have been investigated using SS precursor data from a global data set. The results show that one-third of all hotspots have depressed phase boundaries at both the 410 and 660 km discontinuities (Deuss, 2007). In addition, double reflection peaks close to a depth of 660 km are observed under some hotspots, such as Iceland, Louisville, and others (Deuss et al., 2006; Deuss, 2007). Another global study using receiver functions to investigate hotspots (Anderson and Schramm, 2005) reached a similar conclusion, finding that although the 410 km discontinuity is deepened by ∼10 km, the thickness of the transition zone does not decrease (Tauzin et al., 2008). The researchers attributed this pattern to the effect of the post-garnet phase transition. Regional seismic studies provide more detailed information on the transition zone structure at the base of hotspot areas. For example, both the 660 km discontinuity and the 410 km discontinuity beneath Iceland have been shown to be depressed by Jenkins et al. (2016). The Rw–Pv+Mw phase transition cannot on its own explain the deepened 660 km discontinuity; therefore, these seismic observations have been associated with the post-garnet phase transition.

The effects of the phase transitions on the mantle convection and plume dynamics have been investigated by many geodynamic models. When the Clapeyron slope of the post-spinel transition is large enough, mantle upwelling and downwelling can be trapped near a depth of 660 km, forming a slab avalanche or secondary plumes (Tackley et al., 1993; Brunet and Yuen, 2000; Bossmann and van Keken, 2013). In particular, layered mantle convection can form in numerical models under the combined effects of a high Rayleigh number and a post-spinel phase transition (Christensen and Yuen, 1985; Herein et al., 2013). Tosi and Yuen (2011) found that the combination of the post-spinel phase transition and a horizontal viscosity contrast will produce elongated channel flow near a depth of 660 km and form secondary plumes. Bossmann and van Keken (2013) indicated that the plume shape can be controlled by different Clapeyron slopes. For example, ring-shaped secondary plumes occur when the magnitude of the Clapeyron slope is intermediate (-2.85 ± 0.05 MPa/K $\geq \gamma_{660} \geq -3.05 \pm 0.05$ MPa/K). The effect of the post-spinel phase transition on the surface dynamic topography has also been investigated by Leng and Zhong (2010) and can explain the surface subsidence before the eruption of flood basalts.

Nevertheless, these geodynamic models have mainly focused on the influence of the olivine system phase transitions on mantle convection and plume dynamics, largely ignoring the garnet system. Here, we integrate both the post-spinel and post-garnet phase transformations into our geodynamic model to investigate their effects on mantle plume structure and dynamics.

2. Method

We use CitcomCU, a geodynamic model with a 3-D regional spherical geometry (Zhong, 2006; Leng and Zhong, 2008), along with incompressible fluids and an extended Boussinesq approximation, to study the combined effects of the Rw–Pv+Mw and Mj–Pv phase transitions on plume dynamics. The non-dimensional governing equations are identical with that of Zhong (2006). Our model dimensions are 0° to 55.3° in the longitudinal (φ) direction (comprising 224 elements), 65° to 115° in the co-latitudinal (θ) direction (comprising 240 elements), and 0 km to 2866.5 km in depth (r) (comprising 256 elements). Additionally, we refined the grids between the depths of 600 km and 700 km in the vertical direction to a resolution of 5 km to ensure accurate identification for the topographic fluctuation of the 660 km discontinuity. The depth-dependent initial temperature is given as a mantle adiabat (Turcotte and Schubert, 2002):

Table 1
Model parameters with reference values.

Parameters	Values
Earth radius R_e	6370 km
Mantle thickness d	2866.5 km
Surface thermal expansivity α[a]	4e−5 (°C)$^{-1}$
Surface thermal diffusivity κ[a]	1e−6 m^2/s
Surface density ρ	3400 kg/m^3
Specific heat C_p	1000 J/kg/K
Gravitational acceleration g	10 m/s^2
Surface temperature T_s	273 K
Temperature contrast $\triangle T$	3500 K
Reference viscosity η_0	1e22 Pa s
Dissipation number D_i	2.6
Activation energy E	335 kJ/mol
Density jump for post-spinel[b]	7.9%
Density jump for post-garnet[b]	11.1%
Density jump for 410 km[c]	5%
Clapeyron slope for 410 km[c]	2.7 MPa/K
Phase transition width of post-spinel	30 km
Phase transition width of post-garnet	60 km
Phase transition width of Ol–Wa	30 km

[a] Thermal diffusivity increases by a factor of 2.18 from the surface to the CMB, while thermal expansivity decreases by a factor of 5 from the surface to the CMB.
[b] Yu et al. (2011).
[c] Yu et al. (2008).

$$\frac{dT_{adi}}{dz} = \frac{\alpha g T_{adi}}{C_p} \tag{1}$$

where T_{adi} is the adiabatic temperature; z is the depth; α is the thermal expansion; g is the gravitational acceleration; and C_p is the specific heat. The non-dimensional depth-dependent mantle viscosity is as follows:

$$\eta(T,z) = \eta_r(z)\exp\left[-A\left(T - T_{adi}(z)\right)\right] \tag{2}$$

where η is mantle viscosity; T is temperature; A is activation energy; and η_r is a reference viscosity, which is 1/30 between 100 and 660 km depth and 1.0 otherwise. We also apply depth-dependent thermal expansion and thermal diffusivity in our model (Table 1). All the related parameters are presented in Table 1. Mechanically, free-slip boundary conditions are applied to all the boundaries. Meanwhile, isothermal boundary conditions are used at the uppermost boundary and at the core–mantle boundary (CMB), while the lateral boundaries are thermally insulated. Initially, a thermal anomaly with a height of 100 km is located at the CMB ($0° < \varphi < 2°$, $88° < \theta < 92°$) to trigger the plume, and its temperature is equal to the CMB.

To incorporate both the post-spinel and post-garnet phase transitions into our model, we start from the phase diagram constructed by Hirose (2002) for the pyrolitic mantle (Fig. 1a). By ignoring the minor phase of ilmenite (Il) at shallow depth and by retaining the major phase boundaries of Mj-out and Rw-out close to the 660 km discontinuity, we obtain the simplified phase diagram that is used in our model (Fig. 1b). Meanwhile, the phase transition width of post-spinel and post-garnet are regarded as 30 km and 60 km (Akaogi and Ito, 1999; Ye et al., 2014). In this simplified diagram, we consider the pyrolitic mantle to be composed of 60% Rw and 40% Mj before applying the phase transitions close to a depth of 660 km. Along a relatively cold mantle geotherm (the red line), Rw+Mj transforms to Pv+Mw at the Rw-out boundary. However, when the mantle geotherm is higher (the purple line) than a nominal critical temperature of 1750 °C (Tc, blue circle, Fig. 1b), the 60% Rw first undergoes the post-spinel phase transition at the Rw-out boundary, while the remaining 40% Mj undergoes the post-garnet phase transition at the Mj-out boundary (Fig. 1b). The effect