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The influence of post-perovskite strength on the Earth's mantle thermal and chemical evolution

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ABSTRACT

We have investigated the influence of post-perovskite (ppv) viscosity on mantle convective dynamics and stirring efficiency, using numerical modeling and simple analytical theory.

Our results show that the strength of ppv has a dramatic influence on convective dynamics. The presence of a weak ppv enhances heat transfer across the bottom thermal boundary layer, resulting in higher temperatures, lower mantle viscosities and considerably larger convective velocities. This leads to a significant increase in stirring efficiencies with decreasing the ppv strength, by at least one order of magnitude.

In addition, using a simple parameterized convection evolution that includes the influence of ppv, coupled to a mixing model, we show that during the long term history of the Earth's mantle, the presence of ppv yields systematically hotter thermal evolution and more efficient convective stirring.

Such a strong effect of ppv strength on mantle stirring efficiency suggests that the influence of ppv phase must be considered when interpreting both geochemical and geophysical observations.

1. Introduction

Constraining the efficiency of stirring processes in the Earth's mantle is essential to the interpretation of surface geochemical record. In such a context, even the deepest parts of the Earth's mantle play an important role in influencing convective dynamics. The latter tend to homogenize geochemical heterogeneities via the repeated action of stretching and folding of mantle material (Hoffman and McKenzie, 1985; Ottino, 1989).

In the last years, a perovskite (pv) to post-perovskite (ppv) phase change occurring at deep mantle pressures was discovered by Murakami et al. (2004) and was later confirmed by additional experimental studies and *ab initio* calculations (Hirose et al., 2006; Oganov and Ono, 2004, 2005). In addition to the latent heat release, the presence of this exothermic phase change affects the physical properties of deep mantle material, such as density and compressibility (Boffa Ballaran et al., 2007; Komabayashi et al., 2008), thermal expansivity (Guignot et al., 2007), or thermal conductivity (Cheng et al., 2011; Ohta, 2010), therefore suggesting the potential impact of ppv on mantle convective heat transfer and dynamics.

For these reasons, several workers have studied the influence of ppv on mantle convection using theoretical and numerical approaches including various degrees of complexity (*e.g.*, compressibility, presence of compositional heterogeneities, variable heat transport properties or depth-dependent rheologies) (Buffet, 2007; Hernlund et al., 2005; Matyska and Yuen, 2006; Monnereau and Yuen, 2007, 2010; Nakagawa and Tackley, 2004, 2006; Tosi et al., 2009). A main result of these studies is that the presence of ppv leads to higher heat flux at the core–mantle boundary and increases mantle temperatures. The occurrence of ppv lenses is also suggested as likely cause of lowermost mantle heterogeneity inferred by seismic studies (Lay et al., 2006; van der Hilst et al., 2007).

Recent studies also point out the possibility of strong viscosity differences between the perovskite and the post-perovskite phases. The magnitude and sign, however, of such a pv–ppv viscosity contrast remains debated, with studies supporting the idea of a weaker ppv (Ammann et al., 2010; Hunt et al., 2009), while others suggest that a neutrally viscous or even a stronger ppv is possible (Karato, 2011). Investigations focusing on this pv–ppv rheological differences have found that the ppv rheology has a first order influence on mantle dynamics and thermal evolution (Čižkovà et al., 2010; Nakagawa and Tackley, 2011; Tosi et al., 2010), significantly amplifying the influences already observed for ppv with neutral viscosity.

The efficiency of convective stirring is directly related to the ability of material to deform (Ottino, 1989), therefore mantle viscous rheology plays a central role in convective stirring. The effect of mantle viscosity has been the focus of various studies (Tackley, 2007; van Keken et al., 2003 and references therein). For instance, the influence of vertical viscosity contrasts due to phase changes or spin transition was investigated by means of numerical experiments (Coltice, 2005;

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Farnetani and Samuel, 2003; Naliboff and Kellogg, 2006, 2007; van Keken and Ballentine, 1998). These studies concluded that an increase in viscosity yields smaller deformation, hence larger mixing times. Even a more gradual increase in viscosity due to lithostatic pressure effects leads qualitatively to a comparable behavior (Hunt and Kellogg, 2001). Similarly, local increase of viscosity due to compositional differences was found to reduce the efficiency of stirring (Manga, 1996; Merveilleux du Vignaux and Fleitout, 2002). Other forms of local variations of viscosity, either due to temperature-dependent (Christensen and Hofmann, 1994; Samuel and Farnetani, 2003), grain size-dependent (Solomatov and Reese, 2008), or to strain rate dependent rheologies (Ten et al., 1997) can also strongly affect the efficiency of stirring.

The relationship between mantle rheology and convective stirring illustrated by these studies naturally suggests that the presence of ppv with distinct rheological properties would have a significant impact on mantle stirring efficiency. However, this hypothesis has not been previously tested nor quantified.

Therefore, we focus here on the impact of ppv strength on mantle thermal evolution and convective stirring efficiency, using both numerical modeling and analytical theory.

The paper is organized as follows: Section 2 describes the numerical models and results used to investigate the effect of ppv on mantle stirring efficiency. Section 3 presents simple scaling laws for the heat fluxes and mantle temperatures in the presence of ppv with distinct rheology. A simple mixing model in good agreement with the measured stirring efficiency is derived in Section 4. In the last Section 5 preceding the discussion and conclusions, the scaling laws for heat flow and stirring efficiency are combined to test the impact of ppv on mantle convective stirring efficiency through its long-term history.

2. Numerical experiments

2.1. Governing equations and method

We use the finite-volume code YACC (*e.g.* Tosi et al., 2010) to solve the dimensionless conservation equations of mass, momentum and thermal energy in a Cartesian domain of aspect-ratio 1:3. In the frame of the Extended Boussinesq Approximation (*e.g.* King et al., 2010), they respectively read:

$$\partial_j v_j = 0, \tag{1}$$

$$-\partial_j p + \partial_j\left(\eta\left(\partial_j v_i + \partial_i v_j\right)\right) = Ra\left(\alpha T - \frac{Ra_{\mathrm{ppv}}}{Ra}\Gamma\right)\delta_{jz}, \tag{2}$$

$$\frac{DT}{Dt} = \partial^2_{jj}T + Di\ \alpha\ v_z(T+T_s) + \frac{Di}{Ra}\Phi + Di\ \frac{Ra_{\mathrm{ppv}}}{Ra}\frac{D\Gamma}{Dt}\gamma_{\mathrm{ppv}}(T+T_s), \tag{3}$$

where v_j are the components of the velocity, p is the dynamic pressure, η the viscosity, Ra the thermal Rayleigh number, Ra_{ppv} the phase Rayleigh number associated with the pv–ppv transition, α the thermal expansivity, T the temperature, T_s the surface temperature, Di the dissipation number, Φ the viscous dissipation, γ_{ppv} the Clapeyron slope of the pv–ppv transition and Γ the phase function. Following Christensen and Yuen (1985), the latter is defined as:

$$\Gamma = \frac{1}{2}\left\{1 + \tanh\left[\frac{z_d - 1 - \gamma_{\mathrm{ppv}}\left(T - T^0_{\mathrm{ppv}}\right)}{w}\right]\right\}, \tag{4}$$

where z_d is the depth, w the width of the phase transition and T^0_{ppv} the temperature intercept of the Clapeyron curve at the core–mantle boundary. Material constants and non-dimensional scaling are chosen as in Tosi et al. (2010). Table 1 lists the values and definitions of the non-dimensional numbers and of the parameters used for the pv–ppv transition.

Velocity boundaries are impermeable and free-slip. Temperature sidewalls are reflective, and horizontal boundaries are isothermal. Depending on the ppv viscosity, up to 800×400 grid points were used to discretize the spatial domain.

We measure the convective stirring efficiency using two Lagrangian methods: the first determines the mixing time associated with different wavelengths of heterogeneity following the approach of Ferrachat and Ricard (2001). The second determines the value of the maximum Finite Time Lyapunov Exponents (FTLE), λ^+, as described in Farnetani and Samuel (2003), and measures the rate at which heterogeneities are stretched by mantle motions. These methods were applied after each experiment had reached statistical steady state. The latter is considered to be reached whenever the average mantle temperature has reached a constant value (statistically speaking), which also corresponds to similar values of surface and bottom heat fluxes.

2.2. Viscosity and thermal expansivity

The dimensionless viscosity η is assumed to be Newtonian and dependent on dimensionless temperature and depth:

$$\eta(z_d, T) = \exp(-ET)\left[1 + 214.3 z_d \exp\left(-16.7(0.7 - z_d)^2\right)\right]. \tag{5}$$

For the temperature-dependent part (exponential term), we set $E = ln(10^3)$. This relatively low value prevents the formation of a stagnant-lid. The depth-dependent part (term in square brackets) implies a viscosity maximum in the mid lower mantle at a depth of around 1800 km (Tosi et al., 2010). This is consistent with geodynamic-based inversions of the geoid combined with mineral physics (Forte and Mitrovica, 2001; Ricard and Wuming, 1991; Steinberger and Calderwood, 2006) and several lower mantle constraints (Steinberger and Holme, 2008), as well as with molecular dynamics simulations of diffusion of MgO periclase (Ito and Toriumi, 2010).

The viscosity within the ppv-phase is:

$$\eta_{\mathrm{ppv}} = \Delta\eta_{\mathrm{ppv}}\ \eta(z_d, T), \tag{6}$$

where the viscosity contrast between pv and ppv phase, $\Delta\eta_{\mathrm{ppv}}$, was varied from 10^{-4} to 10 depending on the model.

In models where the depth-dependence of the thermal expansivity is taken into account, α varies with the dimensionless depth z_d as:

$$\alpha = \begin{cases} (1 + 0.78 z_d)^{-5} & \text{if } 0 \le z_d \le 0.23 \\ 0.44[1 + 0.35(z_d - 0.23)]^{-6.5} & \text{if } 0.23 < z_d \le 1. \end{cases} \tag{7}$$

Eq. (7) implies an overall decrease of α by about one order of magnitude throughout the mantle. The exponents 5 and 6.5 are the Anderson–Grüneisen parameters for the upper and lower mantles, respectively. These values are consistent with experimental measurements on olivine (Chopelas and Boehler, 1992) and perovskite (Katsura et al., 2009).

2.3. Results

Fig. 1 displays the temperature and velocity fields for four cases with depth-dependent thermal expansivity, at statistically steady state. Panel (a) corresponds to the reference case that has no ppv, while panels (b–d) display cases with decreasing values of ppv viscosity, starting from a stronger ppv ($\Delta\eta_{\mathrm{ppv}} = 10$, panel (b)) to weak ppv ($\Delta\eta_{\mathrm{ppv}} = 10^{-2}$, panel (d)). The presence of a strong ppv leads to colder mantle (Fig. 1b), and consequently thicker ppv patches.