

The importance of radiative heat transfer on superplumes in the lower mantle with the new post-perovskite phase change

Ctirad Matyska^{a,*}, David A. Yuen^b

^a*Department of Geophysics, Faculty of Mathematics and Physics, Charles University, V Holešovičkách 2, 180 00 Praha 8, Czech Republic*

^b*Department of Geology and Geophysics and Minnesota Supercomputing Institute, University of Minnesota, 117 Pleasant Street, South East, 599 Walter Library, Minneapolis, MN 55455-0219, USA*

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Abstract

A new post-perovskite phase has been identified recently from both X-ray observations and first-principles calculations. This novel phase change occurs at a depth about 200 km above the core–mantle boundary for temperatures of around 2800 K. Using a two-dimensional, extended Boussinesq model, we have studied the dynamical consequences of this deep-mantle phase transition on mantle convection with particular emphasis on the effects on lower mantle plume structures. We have employed a depth-dependent viscosity with a viscosity maximum in the mid-lower mantle and two phase transitions, one at 670 km depth and the other at a depth of 2650 km. The phase transition at 670 km is endothermic, while we have examined both exothermic and endothermic possibilities for the new phase transition. Our results show the following situations favorable for the development of superplumes: (1) endothermic phase transition for both constant and radiative thermal conductivities and (2) exothermic phase transition and radiative thermal conductivity. Smaller unstable plumes are found for exothermic phase transition and constant thermal conductivity. Extremely high lateral temperature increases, exceeding 1500 degrees, are found inside the lower mantle plume for constant thermal conductivity. This lateral temperature contrast is mitigated by the presence of radiative thermal conductivity. In order for superplumes to prevail in the lower mantle with a deep exothermic phase change, we must invoke some form of radiative thermal conductivity for stabilizing and promoting large upwellings with a width exceeding at least 500 km. Strong lateral heterogeneities in both the seismic velocity and density fields can be produced in the plumes and the surrounding mantle for this new phase transition with a large Clapeyron slope, close to 10 MPa/K.

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1. Introduction

Superplumes in the lower mantle have been in the lores of geophysics for a longtime, since the pioneering studies [1,2], which revealed by long-wavelength

* Corresponding author. Tel.: +420 2 21912538; fax: +420 2 21912555.

E-mail address: Ctirad.Matyska@mff.cuni.cz (C. Matyska).

seismic tomography the presence of such superplumes in the lower mantle under the Pacific and Africa. They have also been invoked by geologists as a viable agency for tectonic events, e.g. [3]. The dynamical feasibility for generating superplumes has been investigated in [4–6], where various physical mechanisms have been invoked, which can maintain the existence of plumes with an enormous girth, exceeding around 600 km, and the stability of these singular features. Most recently inference of the roots of the superplumes were obtained by finite-frequency tomography [7] and by seismic anisotropy [8]. Superplumes caused by thermal–chemical convection have been proposed from laboratory experiments [9] and more recently been corroborated by probabilistic inversion [10].

Depth-dependent properties, such as increasing viscosity, decreasing thermal expansivity, and radiative component of thermal conductivity, are fundamental quantities resulting in stabilization of convection and generation of the superplumes [4–6,11,12]. Other plausible mechanisms, such as layering caused by endothermic phase change can also be regarded as promoting a superplume as it drives the solution to longer wavelengths [13]. Although the viscosity stratification in the lower mantle is still a matter of debate, the significant feature could be a “viscosity hill”—of two orders in magnitude or even more rise in viscosity—which was first proposed on the basis of modelling of dynamic geoid generated by mantle convection [14]. This finding has been reinforced by incorporating postglacial rebound analysis [15,16]. The presence of a viscosity hill in the lower mantle helps to facilitate the development of superplumes [6,11]. The changes of the spin state of iron [17] may also change the viscosity in the deep lower mantle.

Very recently, a new structure of MgSiO_3 perovskite has been reported from high-resolution X-ray diffraction measurements at high pressure and temperature corresponding to the conditions at the core–mantle boundary [18,19]. This pioneering result on the post-perovskite transition has been confirmed by first-principles calculations [20–22]. All these results demonstrated that the perovskite transforms to a new high-pressure form, hereafter referred to as the post-perovskite phase (PPP) at a pressure equivalent to a depth of about 2650 km. This points to the potential

importance of this phase transition on D'' dynamics and the generation of mantle plumes, since in studies of Martian convection the proximity of the spinel to perovskite transition close to the Martian core–mantle boundary (CMB) gives rise to superplumes [23–26]. According to Tsuchiya et al. [20] a new polymorph of MgSiO_3 the PPP, does form with a density change of around 1.5% and an exothermic Clapeyron slope of about 8 MPa/K, which is a factor of around 3 greater than the magnitude of the Clapeyron slopes characteristic of upper mantle phase transitions, e.g. [27]. Such a large exothermic phase transition near the bottom thermal boundary layer (D'' layer) has been proposed also from seismic wave modelling [28]. The scheme of this new view to fundamental mantle phase changes, which are able to influence mantle dynamics, is displayed in Fig. 1. This type of phase transition could be strongly destabilizing from both linear and nonlinear points of view and could destroy the coherent superplumes of the more traditional mantle convection models [5,6], which did not account for this new phase transition. How do we reconcile this new situation brought on by PPP and not have to cast away our cherished concepts of superplumes? The solution to this dilemma may be radiative thermal transfer in the lower mantle, the importance of which has been emphasized by the physical models for radiative transfer [29,30]. The importance of radiative

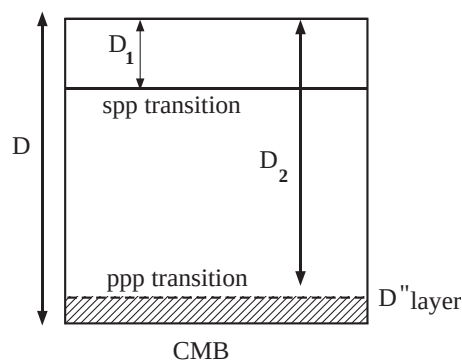


Fig. 1. Schematic figure of our two-dimensional Cartesian model. The depth of the mantle is given by D , D_1 represents the depth to the SPP (spinel to perovskite) phase transition at 670 km depth, D_2 represents the approximate depth of 2650 km to the new PPP (perovskite to post-perovskite) phase change. The D'' layer is drawn as a shaded region. The core–mantle boundary is denoted by CMB. The depth-dependencies of both thermal expansivity and the viscosity are given respectively by Eqs. (1) and (2).

heat transfer in the deep mantle, in particular for the post-perovskite phase, has been underscored emphatically on the basis of spectroscopy [31].

The purpose of this paper is to focus on the influence of the PPP transition on plume dynamics and to study the effects of radiative thermal conductivity in preserving the superplume features. Only by focusing on the range of dynamical mechanisms associated with this PPP transition with different models of radiative thermal conductivity in the lower mantle, we can arrive at a much better understanding of the dynamics of the entire mantle. In Section 2 we describe the mantle model with both the classical spinel to perovskite transition and the new PPP transition. Section 3 will report the results as a range of Clapeyron slopes, ranging from negative to strongly positive values for the PPP transition. In the final section we will discuss the geophysical implications of this new PPP transition on seismic anomalies in the deep lower mantle, superplume dynamics, and the role played by radiative thermal heat transfer.

2. Model description

We have employed here the stream-function formulation of 2-D thermal convection model in the extended Boussinesq approximation, e.g. [32], with the surface dissipation number $Di = \alpha_s q D / c_p$ (α_s is the surface thermal expansivity, g is the gravity acceleration, D is the thickness of the mantle, and c_p is the specific heat under a constant pressure) set to 0.5. Computations have been performed in a Cartesian box with an aspect ratio equal to six. The mathematical description of this finite-difference numerical model has already been published in the papers by Matyska and Yuen [12,33,34]. We note that our results have been cast in dimensionless units for the sake of universality. One can focus on a particular subset by imposing specific values for the specific heat, surface thermal expansivity, and gravity and then solving for the unknown dimensional quantity, based on the dimensionless parameter for the dissipation number, etc.

One strong endothermic change depicting the spinel to perovskite phase transition (SPP), with the buoyancy parameter in the momentum equation

$P = (\Delta\rho / \alpha_s \rho^2 g D)(dp/dT)$ equal to -0.15 has been included at the dimensionless depth $z=0.23$ where $z \in \langle 0, 1 \rangle$ is normalized by D , as shown in Fig. 1 (ρ is a reference density taken for the entire mantle, $\Delta\rho$ is the density jump due to the phase change under consideration and dp/dT is its Clapeyron slope). The second phase change has been considered at the depth $z=0.92$. Although finding by Tsuchiya et al. [20] showed that the PPP transition is exothermic, it still needs confirmation. Therefore, we have considered a whole range of values of the buoyancy parameter P at this depth, ranging from negative (endothermic) [35] to strongly positive (exothermic) values for the PPP transition.

The decrease in the dimensionless depth-dependent thermal expansivity profile has been parameterized in the same way as in [36] to

$$\alpha(z) = \frac{8}{(2+z)^3}. \quad (1)$$

The depth-dependence of viscosity is expressed by means of the relation

$$\eta_r(z) = 1 + 214.3z \exp(-16.7(0.7-z)^2), \quad (2)$$

which was first used by Hanyk et al. [37] to express analytically the profile obtained from inversion of geoid and topography data in [14]. Such a kind of viscosity depth-dependence has recently been justified by joint inversion of convection and glacial isostatic adjustment data [15,16]. Note here that this viscosity model does not contain any particularly low viscosity zone at the base of the mantle and has a local maximum in the mid-part of the lower mantle near $z=0.7$, which yields a two order of magnitude viscosity increase in the lower mantle. We have considered both constant dimensionless thermal conductivity $k=1$ and variable dimensionless thermal conductivity in the form

$$k = 1 + 10(T_0 + T)^3, \quad (3)$$

where T is the dimensionless temperature, $T=0$ at the surface and $T=1$ at the core–mantle boundary, $T_0=0.08$ is the dimensionless surface temperature. As the dimensional temperature T' is related to T by means of the temperature drop ΔT across the mantle: $T' = \Delta T(T_0 + T)$, $T_0=0.08$ corresponds to a common value of around 3600 K for the temperature drop ΔT

[38]. The second term describes the radiative transfer of heat in the same form as in [5], where we showed its importance for lateral dimensions and stability of the superplumes. The factor 10 in Eq. (3) is a measure of the importance of radiative heat transport. A detailed study on the influence of radiative to phonon thermal conductivity ratio to mantle convection models was published in [39,40]. We have fixed both the surface Rayleigh number $Ra_s \equiv \rho_s^2 c_p \alpha_s \Delta T g D^3 / \eta_s k_s = 10^7$ (η_s is the surface viscosity and k_s is the surface thermal conductivity) and the dimensionless internal heating $R \equiv Q D^2 / k_s \Delta T = 3$, where Q denotes volumetric heat sources. This value corresponds approximately to one fourth of the whole mantle chondritic heating, e.g. [41]. Greater amounts of internal heating than what is used here could raise the interior of the mantle to exceed the solidus, since the influence of the post-perovskite transition is to increase the interior temperature of the mantle by a couple of hundred degrees [42]. Time is scaled by $\rho c_p D^2 / k_s$ and typical total time of integration spans between 0.01 and 0.1 in the dimensionless unit.

3. Results

As the strong radiative heat transport enhances formation of the lower mantle superplumes [5], we have started our calculations for a thermal conductivity given by Eq. (3). In all studied cases we have obtained more or less stable superplumes, see Fig. 2a, where the typical snapshots of temperature for both strong exothermic and endothermic phase change at the depth 2650 km are presented. To enhance interaction between the deep phase change and superplumes, the values of the buoyancy parameter P considered are of extremely high absolute values in this four models (for $|(\Delta\rho/\rho)(dp/dT)| \sim 0.15$ MPa/K we get $|P| \sim 0.05$) but they do not seem to influence the state of the superplumes in any remarkable way. We can explain this behavior by the presence of radiative heat transfer, which is strongest at the CMB, thus resulting in a thicker lower boundary layer. In this situation PPP is located well within the bottom lower thermal boundary layer in a depth with very small horizontal variations in the temperature.

Consequently the dynamical effect of the PPP transition is suppressed, as the additional buoyancy

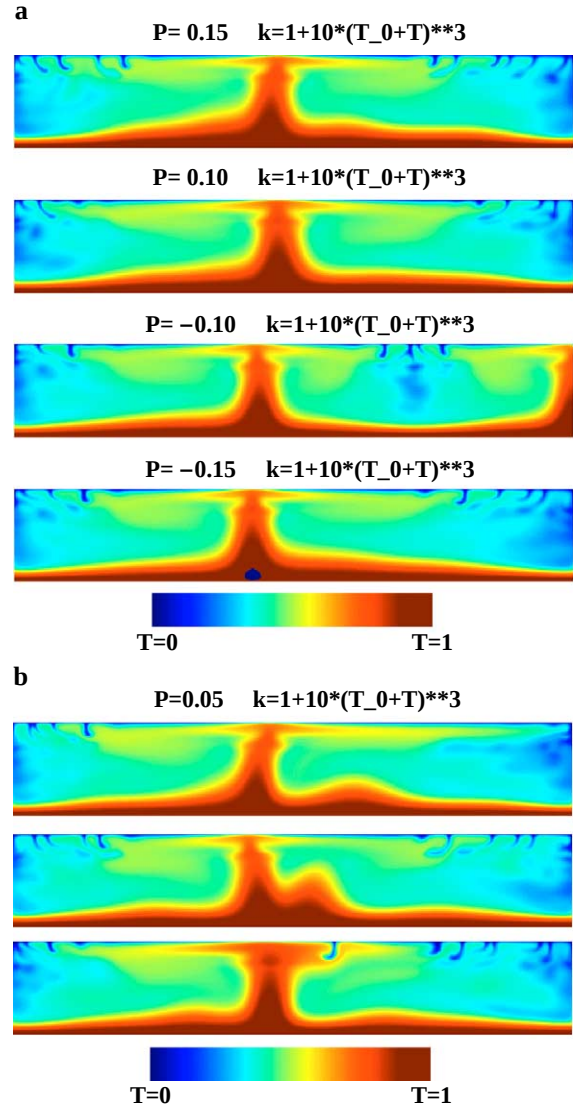


Fig. 2. Typical snapshots of the temperature field for a longtime scale under the presence of a strong radiative heat transfer and an endothermic phase change at the depth of 670 km; 769 (horizontal) $\times 129$ (vertical) evenly distributed finite-difference nodal points were included into the computational mesh. (a) The cases of extremely high absolute values of the buoyancy parameter P , where exothermic ($P=0.15$, $P=0.10$) and endothermic ($P=-0.10$, $P=-0.15$) phase changes at the depth of 2650 km has been modelled. Note that we use the periodic color scale and thus the blue spot inside the superplume root in the bottom panel marks temperatures slightly higher than 1, the temperature at the CMB. (b) The dynamics of the superplume in the presence of a weaker exothermic phase change with $P=0.05$ at the same depth.

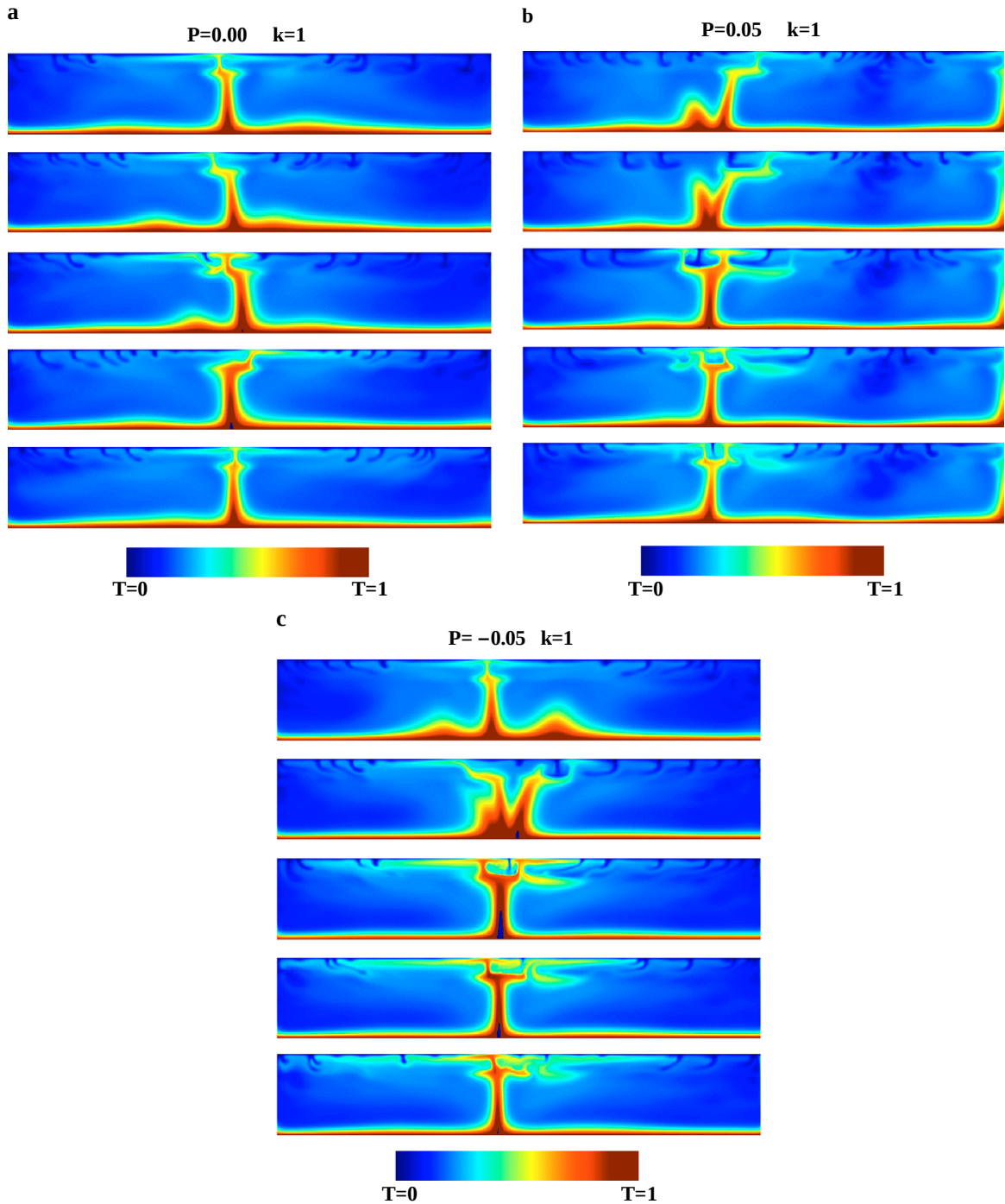


Fig. 3. Snapshots of the temperature field for a longtime scale with constant thermal conductivity. An endothermic phase change at the depth of 670 km was included. (a) The time evolution of temperature if no deep lower mantle phase change is considered. (b) The same as (a) but for an exothermic phase change with $P=0.05$ at the depth of 2650 km. (c) The same as (b) but for an endothermic phase change with $P=-0.05$. In all of the cases studied the superplume position remains more or less stable but their internal dynamics can exhibit substantial oscillations. Notice that the ambient mantle temperature is very low.

force corresponding to the undulations of the phase transition boundary is small due to the small amplitude of the undulations, see also [43]. Moreover, the buoyancy effect due to latent heat cooling (heating) if $P > 0$ ($P < 0$) of the upward flowing superplume acts against the buoyancy caused by the topographic undulations due to the phase change and is of minor importance at higher vigor of convection [44]. The latent heat together with heat dissipation can result in overheating of the superplume root centre, where temperature can exceed the CMB temperature as indicated by the blue spot in the $P = -0.15$ case, see also [45] for a more detailed description of this phenomenon.

We have also considered the three values of the buoyancy parameter: $P = 0.05$ (exothermic phase change), $P = 0.00$ (no phase change), and $P = -0.05$ (endothermic phase change) at the same depth of 2650 km. Surprisingly, in the case $P = 0.05$ we have obtained lower stability of the superplume, which is demonstrated in Fig. 2b. It exhibits pulsations, which originate from the lower boundary layer instabilities that are attracted by the superplume. This scenario helps us to understand better the physics of superplume creation. Newly created plumes are repeatedly attracted into one single location [46] forming a robust and relatively thick lower mantle superplume with a variable flow intensity. Such a scenario would produce strongly variable surface tectonic activities. The large instabilities of this highly nonlinear system, fueled by the PPP transition, may explain the creation of large igneous provinces, e.g. [47].

If only constant thermal conductivity, $k = 1$, is considered, the superplumes are smaller and less stable. Fig. 3a shows the case $P = 0.00$, i.e. no phase change at the CMB was included into modelling. This is just the classical example of creating the superplume under the presence of only the phase change at 670 km depth by incorporating decreasing thermal expansivity with depth together with the viscosity hill in the lower mantle. A strong phase change at 670 km is necessary to prevent direct interaction of plume head with the upper boundary layer, which would represent a huge tectonic event continuing for long times. It is remarkable what the effects of constant thermal conductivity have on the lower mantle superplumes. At the base of the lower mantle there develop many boundary layer instabilities, which are

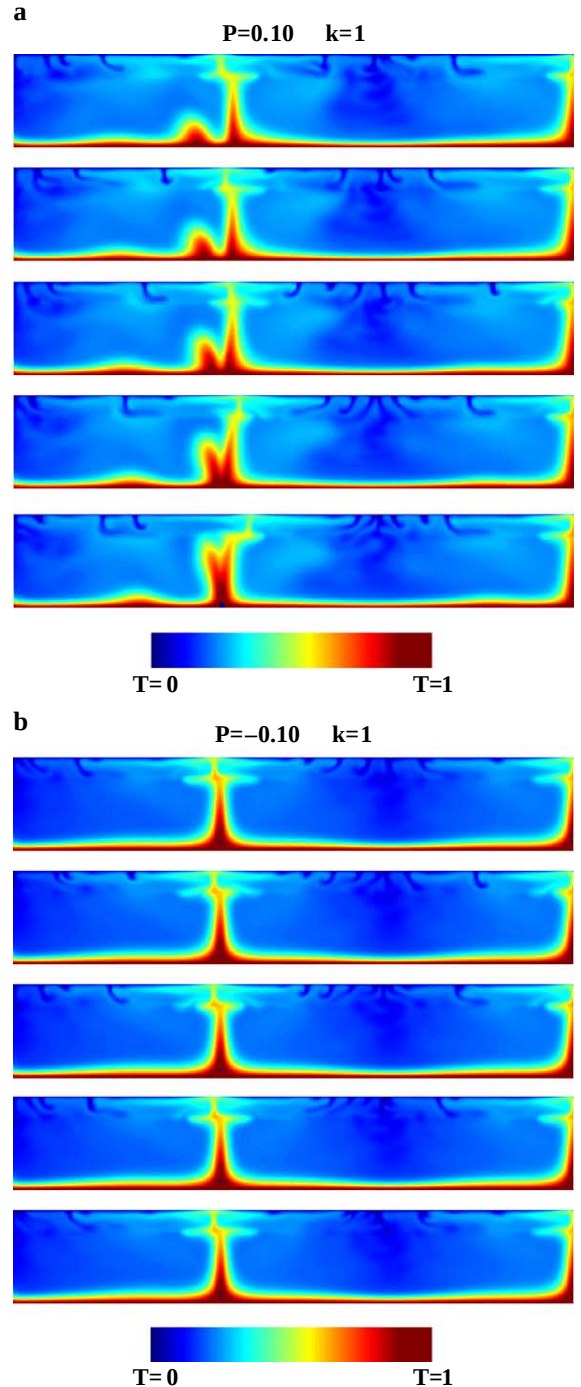


Fig. 4. The same as in Fig. 3 but for a stronger deep mantle phase change. (a) The exothermic phase change with $P = 0.10$ results in intensive plume-plume interactions. (b) The endothermic phase change with $P = -0.10$ yields a stabilized superplume.

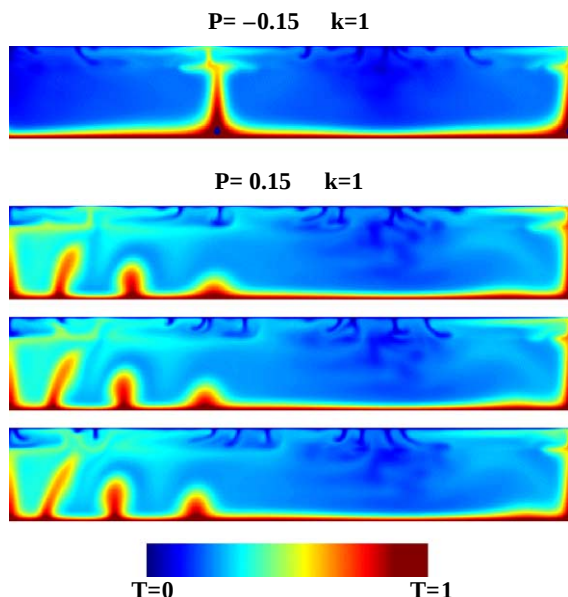


Fig. 5. The same as in Fig. 4 but for a deep mantle phase change with large absolute values of the buoyancy parameter. The endothermic deep mantle phase change with $P = -0.15$ produces a very stable superplume but an exothermic phase change with $P = 0.15$ results in a repeated generation of new plumes.

stronger than those found in the model with radiative thermal conductivity. As a consequence, outpours of hot material are periodically injected into the head of the superplume, below the transition at 670 km depth and afterwards they would penetrate into the upper mantle to the base of the lithosphere [48]. We note here that within the framework of the extended Boussinesq approximation both adiabatic and shear heatings are included with the surface dissipation number $Di = 0.5$. Therefore there is a significant cooling and weakening of the plume [36]. If an exothermic phase change with $P > 0$ is added at 2650 km, the root of the superplume is cooled by its latent heat and thus its head is also cooler, although the flushes can be even slightly stronger than in the previous case, see Fig. 3b. On the other hand, the endothermic phase change located at this depth would further increase the superplume temperature and lead to overheating the superplume core and repeated flushing of a hot material into the upper mantle (Fig. 3c).

The situation has changed for larger absolute values of the buoyancy parameter P . In Fig. 4a we

display five subsequent snapshots of temperature for the exothermic phase transition with $P = 0.10$. The resultant convection pattern is characterized by plume–plume interactions, which are similar to those depicted in Fig. 3a for $P = 0.05$. Notice that the plumes have been cooled at the CMB due to the latent heat and thus their heads are not so hot. In contrast, the endothermic phase transition with $P = -0.10$ create more stable superplume with a hotter interior, see Fig. 4b. If the magnitude of the buoyancy parameter is further increased, one can observe that in the case of $P = -0.15$ a stable lower mantle superplume is again developed, see Fig. 5, where typical snapshots of the temperature field for a long timescale are given. However, we find that for an exothermic phase transition with a large P of 0.15, the lower mantle convection becomes rather unstable (see the lower panel of Fig. 5). This again underscores the need for a significant role played by radiative thermal conductivity if one may use the presence of megaplumes as a geophysical constraint for the lower mantle today.

The presence of superplumes can change simple one-dimensional geophysical profiles, such as the resultant subadiabatic mantle geotherms (see Fig. 6), which were obtained by means of horizontal averaging of temperature fields. The physical reason is an overheating of the mantle below the 670 km interface

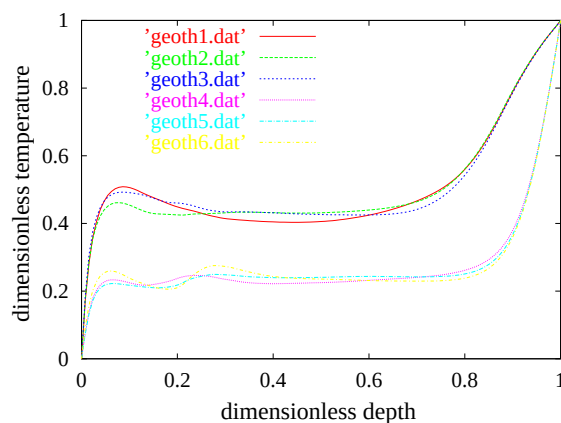


Fig. 6. Geotherms obtained by horizontal averaging of temperature fields. The same exothermic deep mantle phase change with $P = 0.05$ was chosen in all cases. The three upper geotherms were obtained from the temperature snapshots displayed in Fig. 2b (variable thermal conductivity), whereas geotherms with lower temperatures correspond to the three top panels from Fig. 3b (constant thermal conductivity).

as well as below the upper boundary layer. At this juncture we should recall that the dimensionless adiabatic temperature gradient is given by $\alpha(z)Di(T_0+T)$ [34]. However, the most remarkable feature is the substantial increase of temperature if radiative transfer of heat is included, see also [39]. If only phonon thermal conductivity is considered, the average mantle temperature is unrealistically low, which is another argument for the importance of radiative heat transfer in the lower mantle.

In Fig. 7 we plot the lateral temperature differences, ΔT , which is the quantity obtained by taking the difference between the total temperature $T(x, z, t)$ and the horizontally averaged temperature profile $\langle T \rangle(z, t)$. The cases considered have a positive Clapeyron slope with the buoyancy parameter equaling to 0.05 and the snapshots of temperature fields correspond to a box of 7000 km $\times$ 1000 km above the CMB with the superplume cores located at the center. There is a very remarkable difference in ΔT between the constant thermal conductivity and the radiative thermal conductivity cases. Very large and unrealistic lateral temperature differences, exceeding 1500 K, are found with the constant thermal conductivity, while the values are greatly moderated with $k=k(T)$. If one assumes the Clapeyron slope of around 10 MPa/K, then undulations in the phase boundary of close to 20 GPa would be found in the case of constant thermal conductivity, leading to an

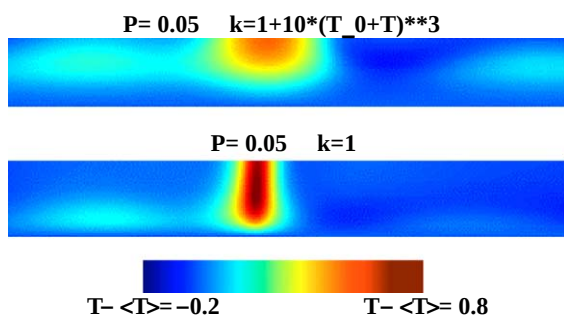


Fig. 7. Deviations of temperature from the geotherms. Only zoomed parts of the computational domain corresponding roughly to a box of 7000 km (horizontal) $\times$ 1000 km (vertical) above the CMB, where the superplumes are located, are shown. In both panels the temperature field for $P=0.05$ was used and the influence of radiative heat transfer (top panel) is compared to constant conductivity (bottom panel). Notice that the temperature under the presence of the strong radiative heating exhibits very small lateral variations in the bottom 250-km layer.

incredible depression of the PPP boundary exceeding 300 km! For variable thermal conductivity the lowering of the PPP phase boundary is much smaller and should not exceed 100 km.

4. Concluding remarks

The recent discovery [18–22] of a new transition of MgSiO_3 to post-perovskite phase change, occurring just above the CMB, is indeed very exciting news and has prompted us to look at the potential consequences this new phase transition has on the development of deep mantle plumes. This delicate situation of a phase change within a thermal boundary layer is novel in Earth mantle convection but is reminiscent of the situation in the smaller Martian mantle, where the endothermic spinel to perovskite transition is located very close to the Martian CMB and is found to exert a significant influence on the creation of a few large stable plumes [23–26]. Because of the unusual nature of the location of this phase change, we cannot employ the usual ideas of boundary layer instabilities erupted in D'' layer based on the classical theory of heated-from-below convection [44,49–51]. Hence our usual intuition of plumes developed off an unstable bottom boundary layer, as shown in laboratory experiments [52,53] or starting plume models [54,55] would not be valid and this problem must be studied with numerical simulations in the highly nonlinear regime, where the deflection from the thermodynamical and chemical nature of the phase change would play an important role.

In order to develop a better physical understanding, we have considered both exothermic and endothermic phase changes, even though the theoretical calculations [20] have indicated that the post-perovskite transition is strongly exothermic because of the large anisotropic changes in the crystal structure. For constant thermal conductivity and exothermic post-perovskite transition lower mantle convection is time-dependent and there are many unstable lower mantle plumes, which are excited globally by the exothermic character of the phase transition. In order for the lower mantle to behave in a more tranquil fashion as suggested by seismic tomography [56,57], we would need to have a strong contribution in the radiative thermal conductivity in the lower mantle.

Recent investigations [29,30,58] have argued for the importance of radiative thermal conductivity in controlling the chaotic behavior in lower-mantle convection, which was already demonstrated by means of 2-D convection calculations [5]. The same stabilizing effect arising from radiative heat transfer can be found in controlling the planforms of 3-D convection [40]. Thus under these new circumstances the putative existence of superplumes in the lower mantle would support the importance of radiative thermal conductivity. This idea is still consistent with a few isolated plume clusters with large lateral dimensions present in the lower mantle [59], which seems to be resolved under the Pacific [7].

Our results also show that very large thermal anomalies and enormous depression of the phase boundary of PPP transition is produced in the case of constant thermal conductivity, while for radiative thermal conductivity the magnitudes of lateral temperature differences are greatly reduced to a few hundred degrees, which results in a modest enough 50 km or so of the phase boundary depression above the CMB. Therefore, this argument would support the presence of chemical heterogeneities in the D'' layer for producing short-wavelength topography at the base of the mantle.

Another important ramification of this new phase transition in the deep lower mantle would be the production of strong lateral seismic and density heterogeneities within vertical flows in the lower mantle, such as plumes. Since the magnitude of the exothermic phase transition is rather large, close to 10 MPa/K, we would expect a sheath of high-velocity and high-density post-perovskite material surrounding the central portion of the plume, which has already transformed to the perovskite phase with a lower seismic velocity and lower density. The correlation between lower velocity and higher density inside superplumes [60] would imply either a substantial amount of iron enrichment inside the superplume roots, which will boost the density of the perovskite phase, or an upward deflection of the CMB due to the buoyancy forces of the superplume, which has been resolved as an additional velocity decrease and density increase in the tomographic models of the D'' layer. The idea of iron enrichment strengthens the case for chemically driven plumes [61]. Future numerical modelling should also incorporate the effects of chemical heterogeneities, see also [62,63],

in addition to considering the effects of chemistry on the radiative heat transfer and on the undulations of the phase boundary from chemical variations, such as Fe migration.

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