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Key Points:
- A three-component mantle is used to investigate thermal evolution
- Primordial layering is needed to explain core thermal evolution
- The viscosity formulation strongly influences structures

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Influence of combined primordial layering and recycled MORB on the coupled thermal evolution of Earth's mantle and core

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Abstract A thermo-chemical mantle convection model with both primordial compositional layering and recycling of mid-ocean ridge basalt (MORB) coupled to a parameterized core heat balance model is used to investigate how the thermo-chemical evolution of the mantle affects the thermal history of the core including primordial material proposed by early Earth hypotheses. The viscosity formulation has been improved from our previous works. The amount of MORB that accumulates above the CMB is strongly dependent on effective Rayleigh number, such that more accumulates at higher Ra (lower viscosity), but a continuous layer of MORB is not obtained here. With initial primordial layering, large-scale thermo-chemical anomalies are found in the deep mantle, which are generated mainly by the primordial material with small amount of segregated basaltic material on top of it, localized in the hot upwelling region. A successful core evolution can only be obtained when initial primordial layering is present. In conclusion, primordial material above the CMB originated from early mantle differentiation might be needed to construct a realistic model of a coupled mantle and core evolution. However, in the current study, the convective vigor is lower than realistic and we only consider the case that primordial material is denser than MORB.

1. Introduction

There are several mechanisms that may have caused Earth's mantle to become compositionally layered very early in Earth's history, including magma ocean crystallization [*Solomatov*, 2007], overturn of an early crust [*Tolstikhin and Hofmann*, 2005], basal magma ocean crystallization [*Labrosse et al*., 2007], and "upside-down differentiation" [*Lee et al*., 2010]. The latter two hypotheses are based on the density cross over between silicate melt and solid silicate found from high pressure experiments [e.g., *Ohtani and Maeda*, 2001] and theory [*de Koker et al*., 2013]. The hypothesis of a deep, primordial layer has been motivated partly by trying to reconcile the trace element composition of the MORB source region with that of chondritic material [e.g., *Corgne et al*., 2005; *McDonough and Sun*, 1995]. Such a dense layer sets the "initial condition" for subsequent long-term evolution over billions of years. It is also possible that more than one of these processes may have operated, which, when combined with long-term differentiation associated with MORB production, subduction of segregation, would have led to a mixture of materials accumulating above the CMB, which has been termed a "basal melange" (BAM) [*Tackley*, 2012].

Studies of mantle thermo-chemical evolution have normally studied either the case of a deep primordial layer, or the case in which a deep layer builds up over time by segregation of subducted mid-ocean ridge basalt (MORB), but not both simultaneously. Such a deep layer has a very strong influence on core evolution, as demonstrated by our previous studies of the coupled evolution of the core and mantle, which focused on the influence of a basal layer formed by recycled MORB [*Nakagawa and Tackley*, 2004a, 2005, 2010, 2013] except for one case with an initial layer and no recycling [*Nakagawa and Tackley*, 2004b; *McNamara and Zhong*, 2004]. We found that the core cools too rapidly when there is no basal layer (resulting in a larger-than-observed inner core), but too slowly when there is a global basal layer (resulting in a CMB heat flux too low to drive the geodynamo). Our "best fit" scenarios featured a spatially intermittent basal layer, as also indicated by present-day seismological observations, which appears to be the best way of avoiding too much core cooling while allowing a sufficiently high heat flux to drive the geodynamo, although some radiogenic heating in the core also helps. The recently found high core thermal conductivity further reduces the parameter space for a "successful" evolution [*Nakagawa and Tackley*, 2013].

For the case of a primordial origin of deep-mantle compositional anomalies, several attempts have been made to explain present-day deep mantle seismological structure and its linkage to geochemical

Table 1. Physical Parameters for Multicomponent Phase Changes Taken From *Nakagawa and Tackley* [2011]

#	Depth (km)	Temperature (k)	$\Delta\rho_{ph}$ (kg m^{-3})	γ_{ph} (MPa/K)	Width (km)
Olivine-Spinel-Perovskite-Postperovskite					
1	410	1600	280	+2.5	30.0
2	660	1900	400	−2.5	30.0
3	2740	2650	60	+12.0	30.0
Pyroxene-Garnet-Perovskite-Postperovskite					
1	60	0	350	0	30.0
2	400	1600	100	+1.0	75.0
3	720	1900	500	+1.0	75.0
4	2700	2650	60	+12.0	30.0

constraints [e.g., *Nakagawa and Tackley*, 2004b; *McNamara and Zhong*, 2005; *Deschamps and Tackley*, 2008, 2009; *Deschamps et al*., 2011; *Davaille et al*., 2005; *Tan et al*., 2011]. However, those studies did not investigate the influence of primordial material on the thermal evolution of Earth's mantle and core, which has been studied only for the case of basalt-harzburgite differentiation [e.g., *Nakagawa and Tackley*, 2005, 2010, 2013], except for one case in *Nakagawa and Tackley* [2004a]. Here we expand our previous coupled core-mantle evolution calculations to include three bulk compositional components (harzburgite, MORB, and primordial material) to constrain the viable range of density and other parameters leading to a "successful" evolution, in the sense of matching the present-day inner core size while maintaining a geodynamo over geological history. We also characterize structures arising from the interaction of primordial material and subducted MORB in the CMB region.

2. Model Description

The model is very similar to that used in our previous papers [particularly *Nakagawa and Tackley*, 2010, 2012, 2013], to which the reader is referred for full details. As in these previous papers we assume that normal (pyrolitic) mantle material is a mechanical mixture of 80% harzburgite and 20% MORB, but here add primordial material that is initially located above the core-mantle boundary (CMB). We include the main phase changes in the olivine and pyroxene-garnet systems (parameters listed in Table 1) and the bulk composition gives the relative fractions of olivine:pyroxene-garnet (pyrolite = 60:40, basalt = 0:100, harzburgite = 75:25). The CMB temperature decreases as heat is extracted according to a parameterized heat balance based on *Buffett* [2002] and *Lister* [2003]. The viscosity formulation is the same as in *Nakagawa and Tackley* [2011], and is given by

$$\eta_m = A_0 \prod_{ij} \Delta\eta_{ij}^{\Gamma_{ij} f_j} exp\left(\frac{E+E'd}{T}\right)$$
$$\eta_Y = \frac{\sigma_0+\sigma_1 d}{2\dot{e}} \tag{1}$$
$$\eta = \left(\frac{1}{\eta_m}+\frac{1}{\eta_Y}\right)^{-1}$$

where A_0 is the prefactor defined by the viscosity having a particular reference value at zero depth and a temperature of 1600 K, $\Delta\eta_{ij}$ is the viscosity jump caused by phase transition (i, j), Γ_{ij} is the phase function for each phase, f is the fraction of phase system j (olivine or pyroxene-garnet), d is the depth of mantle, E is the activation energy, E' is the rate of change of activation enthalpy with depth, T is the temperature, σ is the yield stress at the surface, σ_t is the yield stress gradient, and $\dot{e}$ is the second invariant of the strain-rate tensor. The activation energy E and its depth derivative E' are based on estimates for perovskite by *Yamazaki and Karato* [2001], with E being 290 kJ/mol, and $E + E'd$ increasing to 520 kJ/mol at the CMB, which (for comparison) corresponds to an average activation volume of about 1.7 cm^3/mol.

Reference density, thermal expansivity, and thermal diffusivity are functions of depth while heat capacity and acceleration due to gravity are assumed constant. Those properties are calculated using the approach of *Tackley* [1996], i.e., by integrating

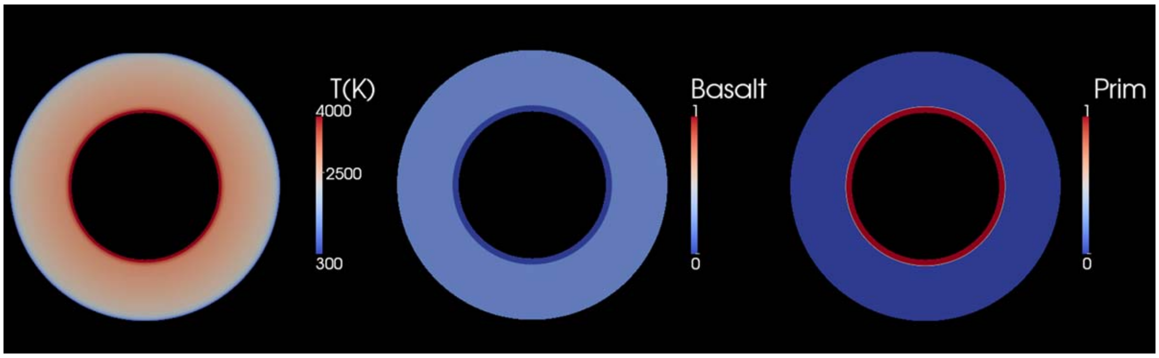

Figure 1. (left) Initial condition for temperature, (middle) MORB fraction, and (right) primordial material fraction.

$$\frac{\partial \rho}{\partial r} = -\frac{\alpha g}{\gamma c_p} \rho \quad (2)$$

with g and c_p constant and:

$$\alpha = \alpha_0 exp \left[-4.29 \left(1 - \left(\frac{\rho_0}{\rho} \right)^{1.4} \right) \right] \quad (3)$$

$$\gamma = \gamma_0 \left(\frac{\rho_0}{\rho} \right) \quad (4)$$

$$\kappa = \kappa_0 \left(\frac{\rho}{\rho_0} \right) \quad (5)$$

where γ is the Gruneisen parameter. Included in the density profile is the effect of phase transitions. The result of this is shown in Figure 2 and is reasonably close to PREM.

The initial condition for temperature and composition is shown in Figure 1. The initial temperature is adiabatic with a potential temperature of 2000 K, plus thermal boundary layers at top and bottom, which approximates the profile for fully developed convection in order to minimize artificial initial transients, while the initial cold thermal boundary layer also avoids a near-surface magma ocean. The initial CMB temperature is assumed to be 6000 K. The composition is initially homogeneous pyrolite except for a 289 km thick layer of primordial material above the CMB. The basaltic oceanic crust is generated by the partial melting of the shallow mantle. Possible melting of primordial material that is entrained to the shallow mantle is not treated here. Since the composition and material properties of primordial material are unclear, we simply assume that its density profile is similar

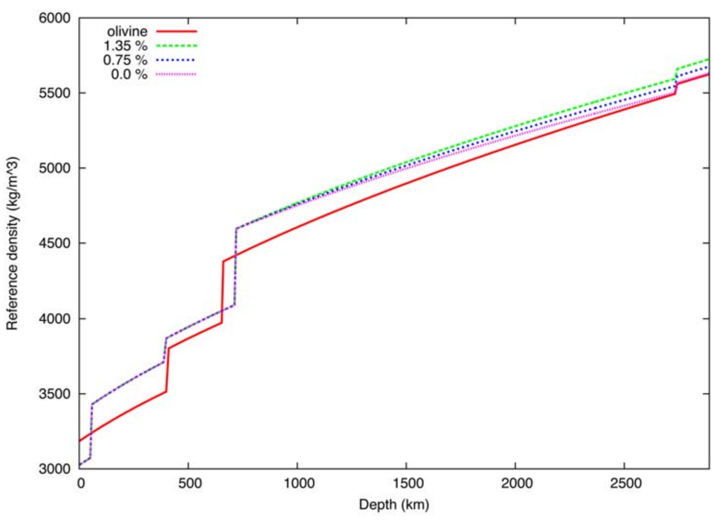

Figure 2. Density-depth profiles for both olivine and pyroxene-garnet phase systems (MORB is pure pyroxene-garnet but harzburgite is 75% olivine + 25% pyroxene-garnet). The labels give the density difference between olivine and pyroxene-garnet systems at the CMB.

Table 2. Mantle Model Physical Parameters[a]

Symbol	Meaning	Dimensional Value
η	Reference viscosity	1.4×10^{22} or 1.4×10^{21} Pa s
$\Delta\eta$	Viscosity jump at 660 km	30
σ_b	Yield stress at surface	50 MPa
σ_d	Yield stress gradient	38.21 Pa m^{-1}
ρ	Reference (surface) density	3300 kg m^{-3}
g	Gravity	9.8 m s^{-2}
α	Reference (surface) thermal expansivity	5×10^{-5} K^{-1}
κ	Reference (surface) thermal diffusivity	7×10^{-7} m^2 s^{-1}
γ	Reference (surface) Gruneisen parameter	1.3
ΔT_{sa}	Temperature scale	2500 K
T_s	Surface temperature	300 K
L_m	Latent heat	6.25×10^5 J kg^{-1}
τ	Half life	2.43 Gyrs
k_0	Reference (surface) thermal conductivity	3 W m^{-1} K^{-1}

[a] $Ra_0 = \rho_0 g \alpha_0 \Delta T_{sa} d^3 / \kappa_0 \eta_0$. Reference viscosity is defined at $T = 1600$ K and surface position ($d = 0$ km) in equation (1).

to that of MORB plus a depth-independent density offset described by $B_{prim} = \Delta\rho_{prim}/\rho_0\alpha_0\Delta T_{sa}$ where B_{prim} is the buoyancy ratio of primordial material, $\Delta\rho_{prim}$ is the density difference between the primordial material and MORB, ρ_0 and α_0 are reference density and thermal expansivity and ΔT_{sa} is the temperature scale. The density profiles of the olivine and pyroxene-garnet phase systems (harzburgite = 75:25 and MORB = 0:100 olivine:pyroxene-garnet) are shown in Figure 2. The density profile of basalt in the upper mantle is the same for all cases, but in the lower mantle three different values of compressibility are assumed in order to vary the density anomaly of basalt near the CMB. The maximum density contrast between olivine and pyroxene-garnet systems at the CMB is 1.8%, corresponding to a MORB-harzburgite contrast of 1.35%.

The numerical code StagYY [*Tackley*, 2008] is used, in a 2-D spherical annulus geometry [*Hernlund and Tackley*, 2008]. The numerical resolution and model geometry are the same as our previous study on the effect of different core thermal conductivities on its thermal evolution [*Nakagawa and Tackley*, 2013], which is, 1024 cells in the azimuthal direction by 128 in the radial direction, plus 4 million tracers to track composition and melt fraction. Time integration is performed to 4.5 Gyrs. All physical parameters used here are listed in Table 2 for mantle convection and Table 3 for core evolution.

3. Results

3.1. Without Primordial Layering

Figure 3 shows thermo-chemical structures at $t = 4.5$ Gyrs for cases without a primordial layer for two reference Rayleigh numbers ($Ra_0 = 10^7$ and 10^8, based on physical properties at the surface and (for viscosity) a temperature of 1600 K) and three values of basalt-harzburgite density difference: 0, 0.75, and 1.35% at the CMB. The compositional field for the lower Ra shows that only small piles of segregated basalt accumulate

Table 3. Physical Parameters for the Core Heat Balance[a]

Symbol	Meaning	Value
r_{CMB}	Radius of the core	3486 km
ρ_c	Initial density of core	12,300 kg m^{-3}
ρ_{iron}	Density of pure iron	12,700 kg m^{-3}
ρ_{li}	Density of light elements	4950 kg m^{-3}
$\Delta\rho_{IC}$	Density difference	400 kg m^{-3}
ΔS	Entropy change	118 J kg^{-1} K^{-1}
$C_l(t = 0)$	Initial concentration of light elements	0.035
C_p	Heat capacity of the core	800 J kg^{-1} K^{-1}
α_c	Thermal expansivity of the core	10^{-5} K^{-1}
C_K	Radioactive potassium in the core	400 ppm
$T_L(r = 0, C_l(t = 0))$	Melting temperature at the center	5600 K
k_c	Thermal conductivity of core	100 W m^{-1} K^{-1}

[a]The value of entropy change is taken from [*Labrosse*, 2003]. The melting temperature at the Earth's center is taken from [*Lister*, 2003]. All other values are taken from *Buffett et al*. [1996].

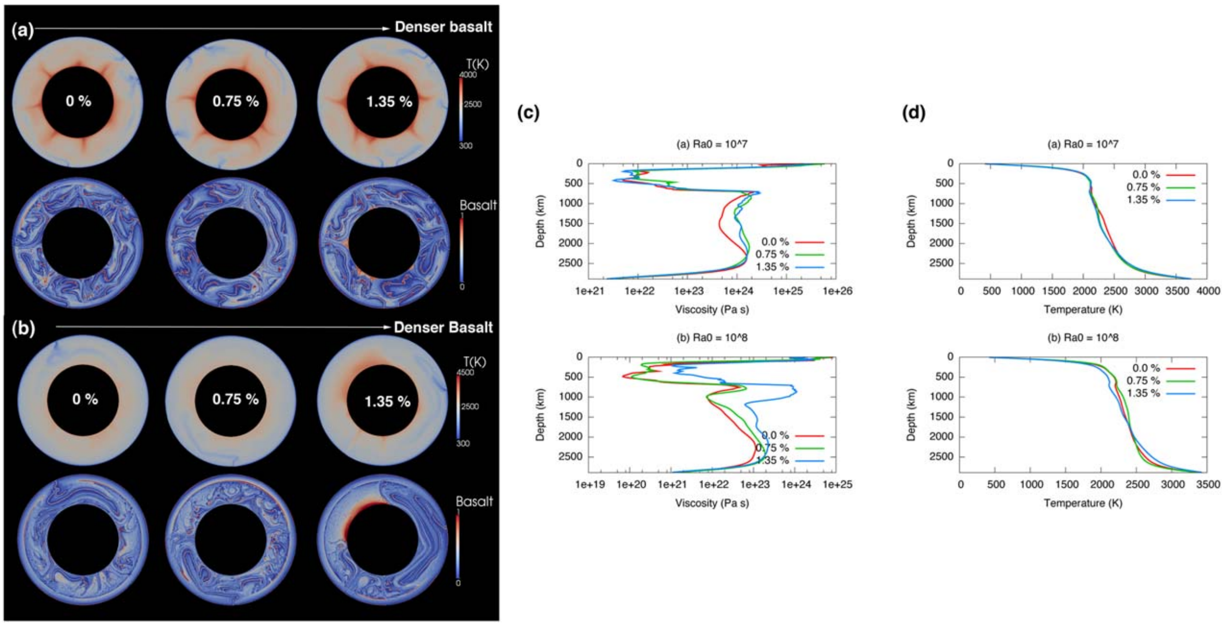

Figure 3. Thermo-chemical structures at $t = 4.5$ Gyrs for cases without a primordial layer and, three different values of deep-mantle MORB-harzburgite density difference and (a) $Ra_0 = 10^7$ and (b) $Ra_0 = 10^8$. (c) Profiles of azimuthally averaged viscosity for these cases. (d) Profiles of azimuthally averaged temperature for these cases. Note that, in cases with $Ra_0 = 10^8$ and density different 0% and 0.75%, thermo-chemical structures are taken at $t = 3.2$ Gyrs because the inner core has completely grown up to the size of the core.

above the CMB even if the basalt-harzburgite density difference is 1.35%. For the higher Ra, when the basalt-harzburgite density difference is 1.35% a large-scale basaltic pile above the CMB is obtained, but this does not develop for the lower density differences. For the larger Ra, both convection and magmatism are more enhanced than for the smaller Ra. This is caused by the more MORB settling down in the deep mantle for the higher Ra.

The viscosity profiles indicate that the upper mantle viscosity is $\sim 10^{22}$ Pa s for $Ra_0 = 10^7$ and $\sim 10^{21}$ Pa s for $Ra_0 = 10^8$. Both of these are higher than estimates of Earth's upper mantle viscosity, but the $Ra_0 = 10^8$ is closer to Earth. A similar observation can be made for lower mantle viscosity. Therefore the $Ra_0 = 10^8$ case is more representative of Earth and it is likely that higher Ra_0 would be more realistic. Hereafter, for the cases with primordial layering we show only the higher Ra cases. In 1-D viscosity profiles, those profiles have a peak below the 660 km viscosity jump. This is because near-horizontal cold slabs tend to build up in that region, which affect the viscosity profile much more than the temperature profile because viscosity is exponentially dependent on temperature.

Figure 4 shows the thermal evolution of Earth's core for both Ra_0. For the lower Ra_0, the present-day size of the inner core is more than 2000 km corresponding to a CMB temperature of 3750 K, the CMB heat flow starts extremely high and drops monotonically to a present-day value of around 15 TW, and ohmic dissipation caused by the magnetic field indicates a magnetic field generated by dynamo action for the entire history. At the higher Ra_0 the CMB heat flux is generally higher, resulting in a lower final CMB temperature (from 3100 K with no layering to 3500 K with 1.35% basalt-harzburgite density contrast) and a larger inner core (3000 km or more), although during the final stages this low CMB temperature can result in a CMB heat flow lower than the adiabat one, as indicated by zero magnetic dissipation. These cases are not realistic for Earth.

The small amount of MORB segregation observed here may appear at odds with our previous studies in which much more basalt segregation occurred for the same density profiles (the maximum density contrast here corresponds to that in *Nakagawa and Tackley* [2012, 2013] and the "intermediate" density contrast in *Nakagawa and Tackley* [2010]). The likely explanation is, lower viscosities in these previous papers due to the different viscosity law assumed (the viscosity law assumed here is chosen because it gives a realistic temperature-dependence, unlike in most of our previous papers). In *Nakagawa and Tackley* [2011], we used the same viscosity law as here and also obtained only a small amount of basalt segregation in 3-D

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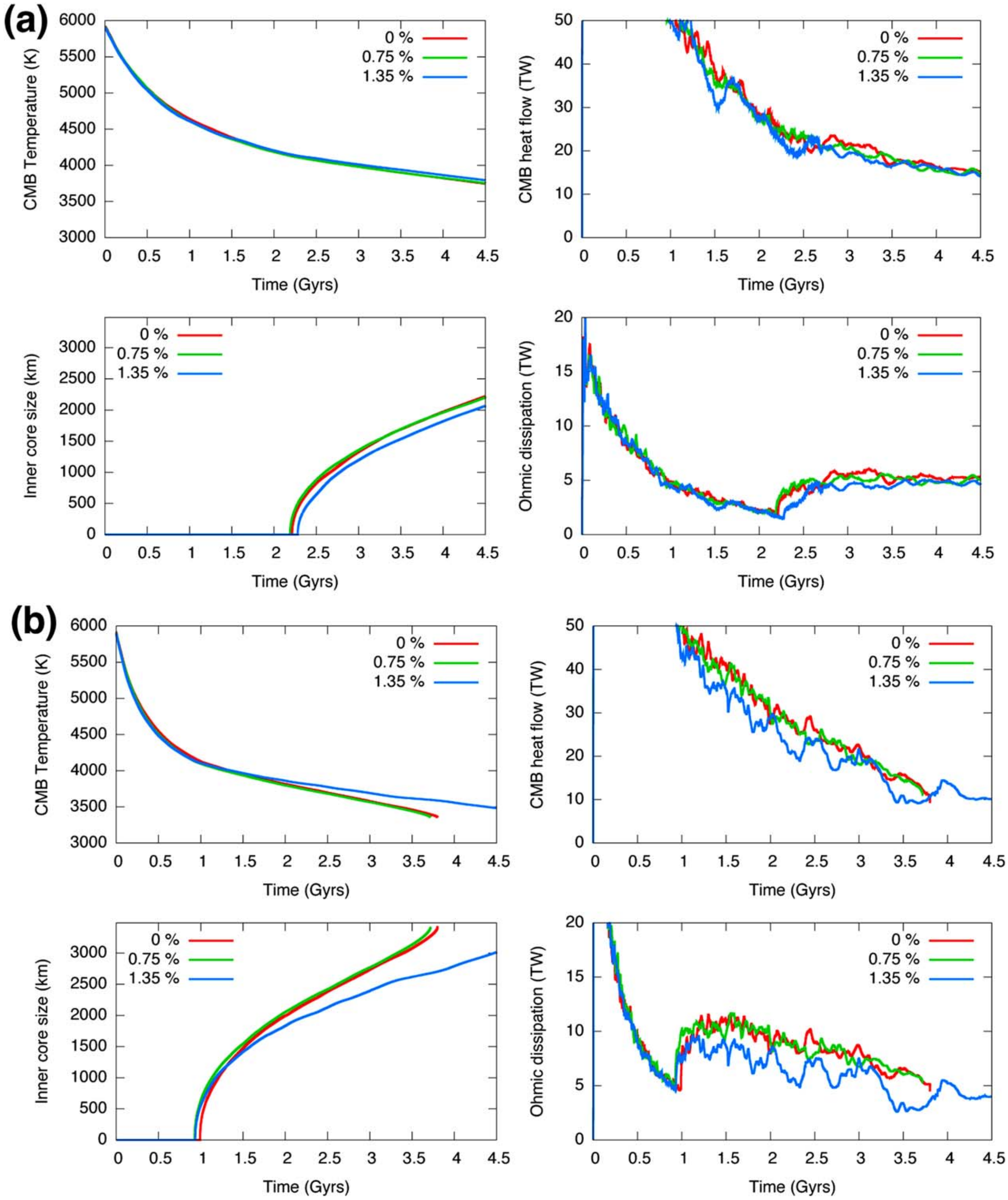

Figure 4. Core evolution diagnostics (CMB temperature, CMB heat flow, inner core size, and magnetic dissipation) for cases with (a) $Ra_0 = 10^7$. (b) $Ra_0 = 10^8$. For 0% and 0.75% density difference of basaltic material, the core completely solidified before 4 Gyrs; thus diagnostics were not plotted after this.

calculations. In contrast, in *Nakagawa and Tackley* [2012] the viscosity profiles in Figure 1 show values of $O(10^{20})$ Pa s in the upper mantle and $O(10^{22}-10^{23})$ Pa s in the lower mantle, almost an order of magnitude lower than those found here, which is because the reference viscosity was defined at midmantle depth rather than zero pressure leading to $\sim$2 orders of magnitude lower viscosity; the same viscosity law was used in *Nakagawa and Tackley* [2013]. In *Nakagawa and Tackley* [2010, 2005], the reference viscosity was

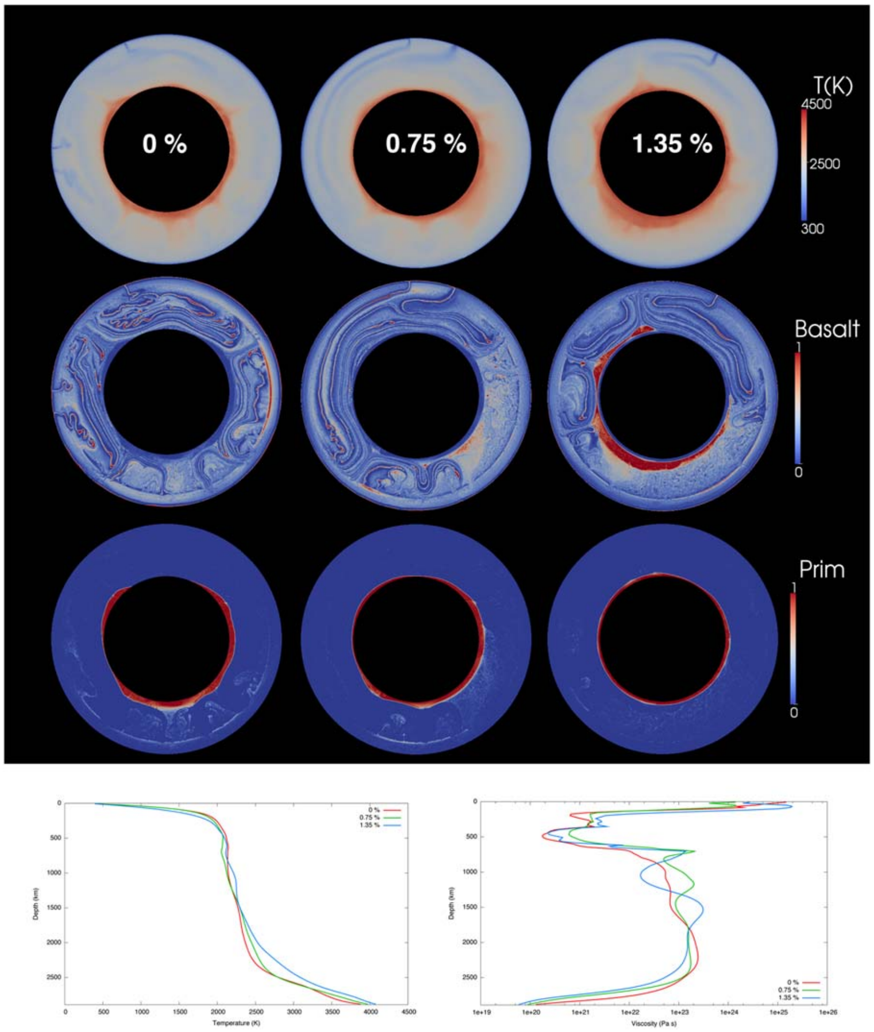

Figure 5. (top) Thermo-chemical structures at $t = 4.5$ Gyrs for cases with a primordial layer and three different values of deep-mantle MORB-harzburgite density difference. The primordial-MORB density difference is fixed at 165 kg/m^3 (about 3% at the CMB). (bottom left) Horizontally averaged temperature at $t = 4.5$ Gyrs. Bottom right: Profiles of azimuthally averaged viscosity at $t = 4.5$ Gyrs corresponding the thermo-chemical structures shown in the top part.

defined at zero pressure but the increase of viscosity with depth was smaller. Thus, it appears that lower viscosity favors greater basalt segregation, something that should be systematically checked in the future. This trend does seem consistent with the small amount of basalt segregation obtained in the numerical thermo-chemical convection simulations of *Li and McNamara* [2013], in which the viscosity is relatively high and has a temperature-dependence much lower than realistic. It is also consistent with the calculations of *Davies* [2007], which were at higher Ra than used here. In any case, we do here obtain basaltic piles above the CMB with a 1.35% basaltic-harzburgite density contrast when the reference Ra is set as O(10^8).

3.2. With Primordial Layering

3.2.1. Influence of MORB Density Contrast

Figure 5 shows thermo-chemical structures at $t = 4.5$ Gyrs for the three basalt-harzburgite density differences (0%, 0.7%, and 1.35%). B_{prim} is 0.4, corresponding to a density offset relative to MORB of 165 kg/m^3 (about 3% at CMB pressure). In all cases most of the primordial material remains in the layer above the CMB and covers most or all of the CMB. A small fraction of it is entrained, and tends to get trapped below the 660 km discontinuity because of its density anomaly.

The behavior of recycled MORB differs greatly between cases. For 0% basalt-harzburgite density difference, recycled basalt is well-mixed in the entire mantle except for strips of crust that have not yet been stirred in.

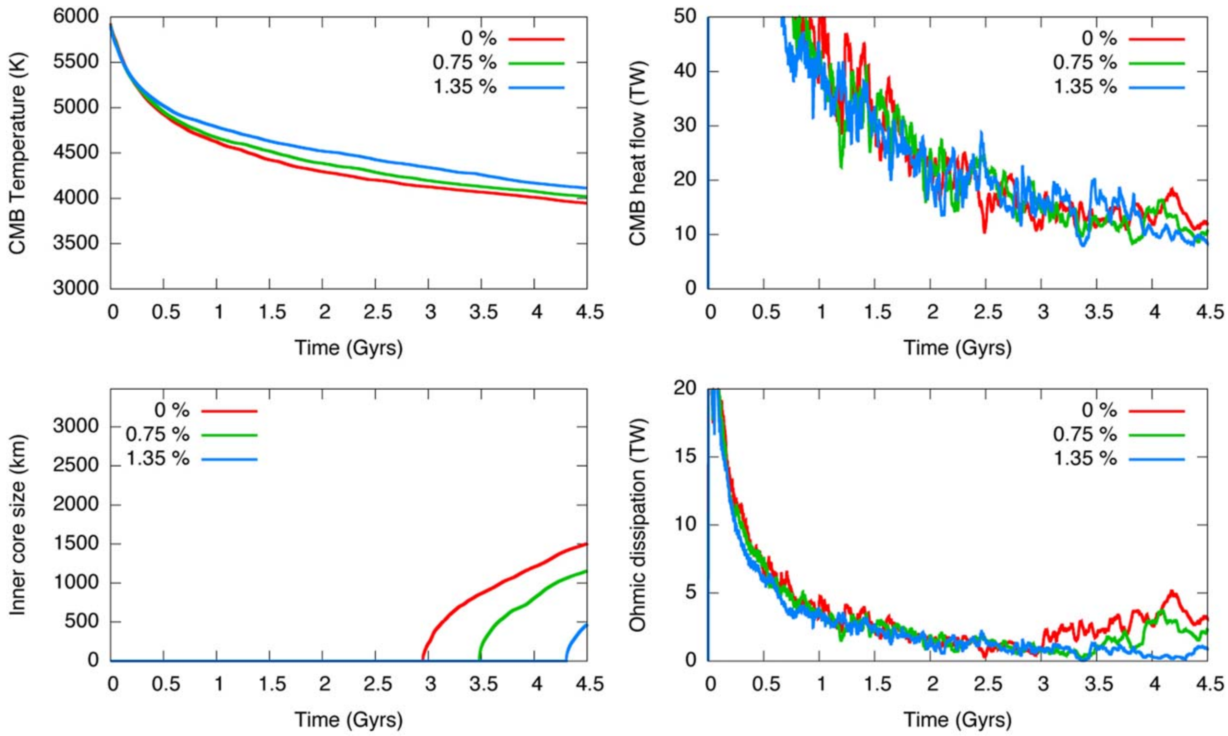

Figure 6. Core evolution diagnostics for the cases shown in Figure 5.

For the 1.35% density contrast case, the recycled MORB forms an almost continuous layer on top of the primordial material, although it is thicker on one side and is associated with hot upwelling regions. For the case with 0.7% basalt-harzburgite density difference, there is a small region where basalt is concentrated above the primordial layer, again in a hot upwelling region.

The viscosity profiles for these cases (Figure 5, bottom) indicate an upper mantle viscosity of O(10^{21}) Pa s and a lower mantle viscosity of O(10^{23} Pa s), similar to the cases with no primordial layer.

Figure 6 shows the time evolution of the core for these cases. They match the Earth much better than the cases with no primordial layer, with a present-day inner core size of between 500 km (for the 1.35% MORB density contrast) and 1500 km (for 0% MORB density contrast), bracketing the correct value of 1220 km. This corresponds to a final CMB temperature of $\sim$4000 K. This 2000 K cooling over 4.5 Gyrs corresponds to an average of 444 K/Gyr, but it is much higher near the beginning and reduces to $\sim$200 K/Gyr near the end. The age of the inner core is less than or equal to 1.6 Gyrs. The CMB heat flow toward the end in all cases fluctuates in the range 8–15 TW, which is consistent with our previous studies [*Nakagawa and Tackley*, 2013] and observational constraints [*Lay et al*., 2008]. The magnetic dissipation is positive over the whole evolution time, indicating the existence of a geodynamo. Thus, these cases can be regarded as successful in terms of matching both the constraint of inner core size and continuous existence of a geodynamo for as long as records exist.

Figure 7 shows thermo-chemical structures with various values of density difference between primordial material and MORB. The density difference between harzburgite and MORB is fixed at 0.75%. As B_{prim} increases, features of the primordial material can be classified as three types: completely entrained ($B_{prim} = 0.0$), large-scale piles ($B_{prim} = 0.2$ and 0.3), and continuous layer with large-scale topography ($B_{prim} = 0.4$ and 0.5). Regarding MORB, for $B_{prim} = 0.2$ and 0.3, large-scale basaltic piles are found on top of the primordial material. In addition, for $B_{prim} = 0.4$, somewhat smaller piles are also found, while for $B_{prim} = 0.5$ only one fairly small basaltic pile forms. The horizontal length scale of basaltic piles thus seems to be dependent on B_{prim}. Wide basaltic piles occur where the primordial layer is thickest. If the primordial layer is so dense that its thickness hardly varies then basaltic piles are suppressed.

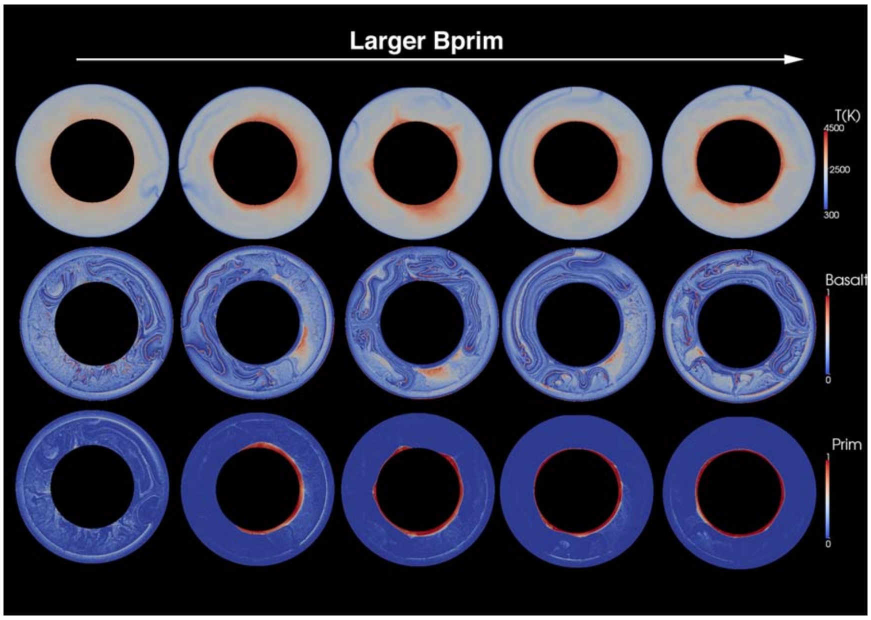

Figure 7. Thermo-chemical structures at $t = 4.5$ Gyrs for different values of B_{prim}, which increases from left to right as 0.0, 0.2, 0.3, 0.4, and 0.5, corresponding to dimensional density anomalies of up to 206 kg/m^3. Note that, for $B_{prim} = 0.0$, thermo-chemical structure is taken at $t = 3.7$ Gyrs because the inner core has completely grown up to the core size at that time.

For all these cases except $B_{prim} = 0$, primordial material is denser than MORB. This explains why MORB never sinks to the CMB and never displaces or mixes with the primordial layer. In the $B_{prim} = 0$ case, neither MORB nor primordial material is dense enough to remain above the CMB. Thus, a basal melange (BAM) [*Tackley*, 2012] cannot form with these compositional densities. It would be interesting to investigate cases in which MORB is denser than primordial material, but this is left to a future study.

The time evolution of the core for these cases is shown in Figure 8. As the density of primordial material increases the amount of core cooling is less, with a higher final CMB temperature and a smaller and younger final inner core. Except for the case with zero primordial density contrast, the CMB temperature cooling rate is similar to the cases shown in Figure 6. The preferred scenario for obtaining the correct inner core size is $B_{prim} \sim= 0.4$, which gives an inner core age of 1 Gyr. The final CMB heat flow fluctuates from ~8 to 15 TW, except for the case with zero primordial density anomaly, in which core became completely frozen around 3.7 Gyr. The magnetic dissipation plot indicates a geodynamo over the full 4.5 Gyrs for the preferred model.

The time evolution of thermo-chemical structure for the best-fit model (0.7% basalt-harzburgite density contrast and 3.0% primordial-basalt density contrast) is shown in Figure 9. In the early stage (up to 1.5 Gyrs; the two leftmost columns), there are many subduction zones and many plumes, resuting in small-scale and chaotic structures; however, the primordial layer is still stable and has small-scale topography. From $t \sim=$ 2.5 Gyrs (center and rightmost two columns), there are typically only one or two subduction zones, and small-scale basaltic piles start to accumulate on top of the primordial material. The basaltic piles are easily moved by the strong subducting slabs. At $t = 4.5$ Gyrs (right), large-scale thermo-chemical structure in the deep mantle is found, consisting of a continuous layer of primordial material with long-wavelength thickness variation, plus small-scale basaltic piles in the hot upwelling region.

Figure 10 shows the time-dependent heat budget for the best-fit model (0.7% basalt-harzburgite density difference and 3.0% primordial-basalt density difference) shown in Figures 7–9. Surface conductive and CMB heat flow and volume averaged mantle temperature are plotted separately. The upper plot shows that magmatic heat transport is the dominant mechanism for transporting heat from the interior to the surface for for the first ~2 Gyrs, after which conductive heat transport becomes important, consistent with our previous studies [e.g., *Nakagawa and Tackley*, 2012]. The conductive surface heat flow for the present day is about 30 TW, which is slightly smaller than the 40 TW observed [e.g, *Jaupart et al.*, 2007] but similar to our

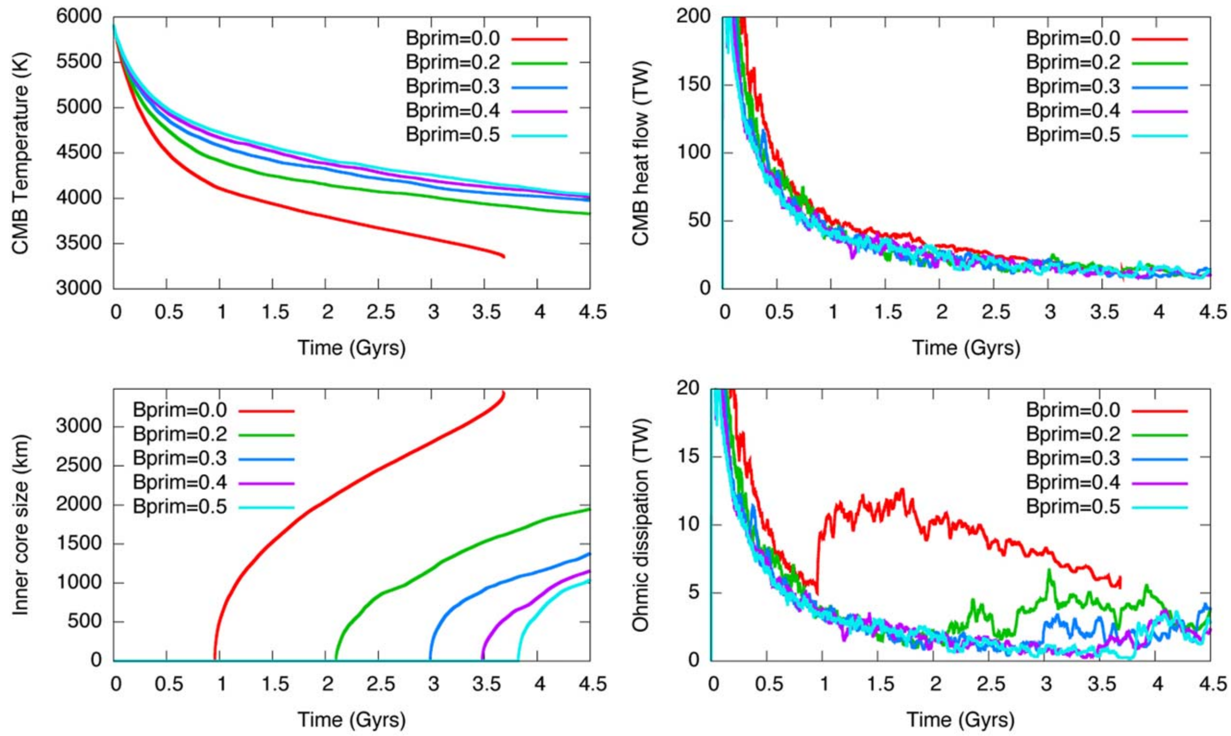

Figure 8. Core evolution diagnostics for the cases shown in Figure 7.

previous study looking at the surface heat flow contribution [*Nakagawa and Tackley*, 2012]. The contribution of magmatic heat flow (red line) is in this case around O(10) TW, which helps to bridge this discrepancy, although *Jaupart et al*. [2007] did not include magmatic transport in their estimate.

The volume averaged mantle temperature indicates an average mantle cooling of 300 K/4.5 Gyrs (around 65 K/Gyr). This is similar value to that estimated from petrological measurements [e.g., *Abbott et al*., 1994] as well as our previous study [*Nakagawa and Tackley*, 2012]. One mechanism that is thought to be important in regulating a planet's cooling history is the feedback between temperature in viscosity, which is realistically strong in this present study, whereas it was reduced in some of our previous papers [e.g., *Nakagawa and Tackley*, 2012, 2013].

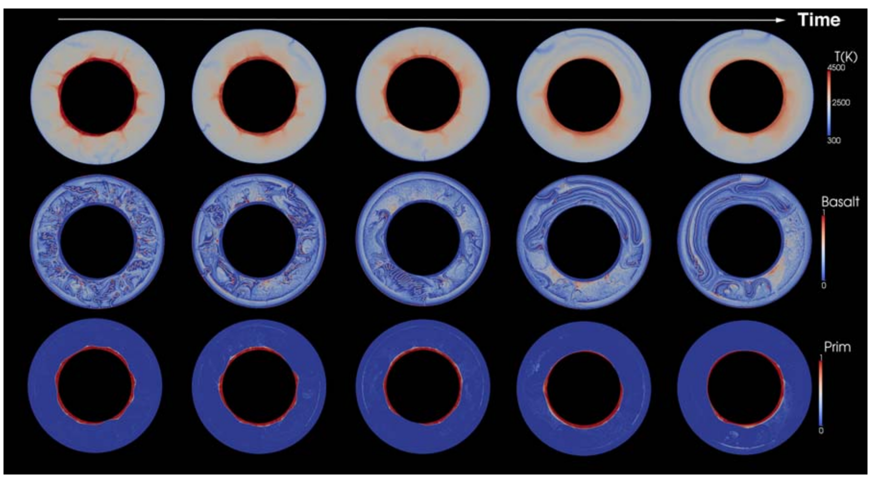

Figure 9. Time evolution of thermo-chemical structure for the best-fit model (0.75 % MORB-harzburgite and 3% primordial-MORB density differences). The plotted times are (left) 0.5 Gyrs to (right) 4.5 Gyrs in 1 Gyrs intervals.

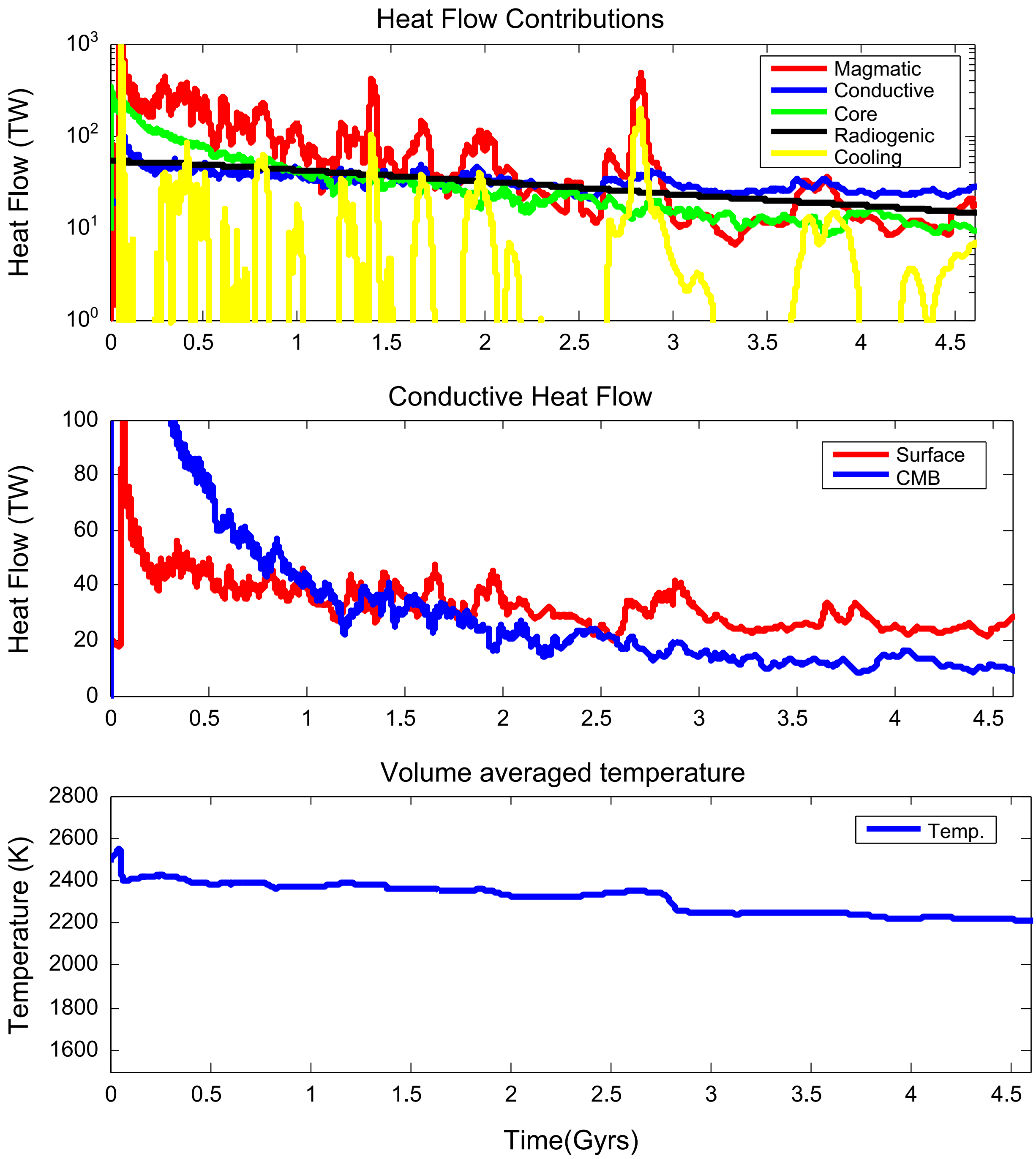

Figure 10. Heat budget for the "best fit" case shown in Figure 9.

4. Discussion and Summary

4.1. Findings

In this study, we find that the combination of a primordial layer and recycling of basalt has several significant consequences for the thermal evolution of the coupled mantle and core:

1. When the primordial material is initially inserted above the CMB and subducted MORB is less dense than it, the subducted MORB may accumulate on top of the primordial layer, with the exact form determined by

primordial layer density (see Figures 5 and 7). MORB tends to accumulate where the primordial layer is thicker, corresponding to an upwelling region. If the primordial layer is so dense that its thickness hardy varies, this can suppress MORB segregation. In this study, we consider only cases in which the primordial material is denser than MORB, which does not allow for mixing of the two materials necessary to form a basal melange (BAM) [*Tackley*, 2012].

2. Regarding the thermal evolution of Earth's core, it is very difficult to find a successful scenario (in the sense of obtaining both the correct present-day inner core size and a geodynamo throughout Earth history) when there is no primordial material (see Figure 4) because of rapid core cooling caused by high CMB heat flux before any basal layering builds up. On the other hand, when a primordial layer is included a successful evolution is easily obtained (Figures 5 and 8). There is most likely a range of parameters for which this is the case [as in our earlier study *Nakagawa and Tackley*, 2010]. From Figure 8, the best example in this study is with a 0.75% MORB-harzburgite density difference and a 3% primordial-MORB density difference, which leads to the correct inner core size and an age of 1.0 Ga. The basic mechanism is that the primordial layer reduces CMB heat flux, preventing excessive core cooling. In our previous study [*Nakagawa and Tackley*, 2013] (which focused on the influence of core thermal conductivity) a successful evolution was found even without initial primordial layering, because a layer of subducted MORB rapidly built up, reducing core cooling. The main difference between these studies is rheology, as discussed below.

3. The thermo-chemical structure in the deep mantle, specifically the amount of recycled basalt that segregates and accumulates above the CMB, appears to be quite sensitive to rheology. The rheology assumed here gives a realistic temperature-dependence of viscosity in the lower mantle, but higher average viscosity than used in some of our previous papers [*Nakagawa and Tackley*, 2012, 2013], which appears to result in a much smaller buildup of MORB above the CMB. Higher Ra_0, meaning lower viscosity, leads to more MORB accumulation, implying that it is mainly the background viscosity value rather than its temperature-dependence that is most important. This is broadly consistent with another recent study [*Li and McNamara*, 2013] which is at relatively low effective Ra and viscosity contrast. It is also consistent with the conclusions of *Davies* [2007], who performed experiments at higher Ra than we use here. Judging from our viscosity profiles (Figures 3 and 5) an additional order of magnitude increase in Ra_0 might correspond to an Earth-like regime, at which even more basalt settling would occur. Other factors to consider are the rheological thickness of subducted lithosphere [e.g., *Grasset and Parmentier*, 1998] and the thickness of the oceanic crust. All these aspects should be checked in the future.

4.2. Is the Initial Primordial Layer Needed?

Primordial layering, if it persists to the present day, would affect the deep mantle heterogeneity as found from seismological imaging and already compared to various numerical mantle convection simulations [e.g., *Nakagawa and Tackley*, 2004b; *Deschamps et al*., 2007; *Deschamps and Tackley*, 2008, 2009; *Deschamps et al*., 2011, 2012]. *Deschamps and Tackley* [2008, 2009] found that the models that best match probabilistic tomography have very large topography, discontinuous chemical piles at the present day. None of the models in the present study display these, implying that a lower B_{prim} would be result in more Earth-like structures.

However, with the parameters assumed here a dense primordial layer appears to be necessary to obtain a successful core evolution. In our initial study on thermal evolution of Earth's core in numerical thermo-chemical convection model [*Nakagawa and Tackley*, 2004a], we found that either an initial layer or a layer of recycled MORB that builds up rapidly can lead to a successful evolution. Another possibility is an initial layer that progressively gets entrained and replaced by segregated MORB. In any case, with recent early Earth hypotheses [*Labrosse et al*., 2007; *Lee et al*., 2010; *Tackley*, 2012] there is plenty of reason to think that early layering may have existed.

4.3. Early Earth and its Influence on Later Evolution

The initial condition for solid-state long-term mantle convection after solidification of a magma ocean is not well known, so while our choice is plausible it is highly nonunique. However, at least as far as initial mantle and core temperature are concerned, our previous study [*Nakagawa and Tackley*, 2010] indicates that for most parameter combinations initial temperatures do not have much influence on the thermo-chemical mantle and core state after billions of years, because different initial states follow convergent evolutions with a time scale of O(1 Gyrs).

A recent modeling study of purely thermal convection found that over a certain parameter range either stagnant lid or mobile lid solutions could be obtained depending on the initial condition [*Lenardic and Crowley*, 2012], as also found in earlier 3-D experiments [*Tackley*, 2000]. Our initial condition biases the system toward a stagnant lid, which is present early on, but nevertheless the system changes into episodic or mobile lid mode after some time. The production of laterally heterogeneous crust by partial melting seems to be a key mechanism for initiating subduction in our presented models, which is something that was not present in the cited, purely thermal models. Indeed, model subduction is often observed to initiate in places where crust is thickened (e.g., by a plume) such that the base of it converts to eclogite, which is dense and wants to sink.

Magmatic heat loss, i.e., eruption, cooling, and solidification of magma originating from below the lithosphere, the so-called "magmatic heat pipe" mechanism, was found to be the dominant early heat loss mechanism in our previous models of stagnant lid Mars [*Keller and Tackley*, 2009], mobile-lid Earth [*Nakagawa and Tackley*, 2012], and stagnant or episodic-lid Venus [*Armann and Tackley*, 2012], and is also the dominant heat loss mechanism in the first $\sim$2 Gyrs of our current experiments (Figure 10, top; red line compared to blue line). *Moore and Webb* [2013] recently highlighted this mechanism and argued that it is consistent with the geological record.

There is currently a vigorous debate about when plate tectonics started, and whether before this the lithosphere was stagnant or had some other type of active tectonics [for recent reviews, see *van Hunen and Moyen*, 2012; *Gerya*, 2014]. In our presented cases mobile lid behaviour starts quite early, but magmatic heat transport is still dominant, implying that the two can coexist; a stagnant lid is not required for magmatic heat transport to be dominant. An approximation made in our calculations as well as those of *Moore and Webb* [2013] is that all magmatism is extrusive. If some were intrusive, then a hot, weak crust would be likely to result, which would likely be deforming not stagnant. These issues need to be studied in future calculations.

Even with an early stagnant lid, if the core starts off strongly superheated then it still cools rapidly via plumes, and once plate tectonics starts it seems likely that this early phase is "forgotten" after some period, as in *Nakagawa and Tackley* [2010]. Nevertheless, such issues should be more closely studied in the future.

4.4. Some Additional Implications Regarding Core Thermal Evolution

In this study, we assume that the thermal conductivity of Earth's core is 100 W/mK, which is taken from the lowest values estimated from first principle calculations [*de Koker et al*., 2012; *Pozzo et al*., 2012]. In our previous study [*Nakagawa and Tackley*, 2013], we found that the thermal conductivity of Earth's core does not influence thermo-chemical structure in the mantle and the main characteristics of core evolution except for the magnetic dissipation, because the thermal conductivity of Earth's core affects only the adiabatic heat flow. In our results, magnetic field generation by dynamo action started in the very early Earth. However, our mantle model is incomplete in that we do not consider the possibility of a basal magma ocean [e.g., *Labrosse et al*., 2007], which would result in rapid heat transfer from the core to the deep mantle due to the very low viscosity and vigorous turbulent convection occurring in magma-dominated regions. This can be treated using an effective thermal conductivity within a modified diffusion equation [*Abe*, 1997], and we plan to study this in the future.

5. Conclusions

In this study, we investigate the influences of combined primordial layering and recycling of MORB on the thermo-chemical evolution of a coupled mantle and core, for the case that primordial material is at least as dense as MORB. The conclusions of this study are as follows:

1. When the primordial material is initially above the CMB and subducted MORB is less dense than it, the subducted MORB may accumulate on top of the primordial layer, with the exact form determined by primordial layer density. MORB accumulation tends to be associated with regions of thicker primordial material.

2. For the parameters used here, too rapid core cooling occurs (resulting in a too-large present-day inner core) unless there is an initial primordial layer; thus, primordial layering is important for maintaining

dynamo action over geological time. It is possible that other successful solutions would be obtained if we considered a broader parameter range (such as Ra_0, density contrasts). The primordial layer reduces core cooling.

3. The viscosity formulation strongly influences deep-mantle thermo-chemical structures, as can be seen within the present results as well as comparing present results to previous ones. The dominant effect appears to be that lower viscosity favors greater basalt settling, although the effect of this compared to temperature-dependence needs to be further studied. The surface heat flow is somewhat smaller than that constrained from both geophysical and geochemical analyses [e.g., *Jaupart et al*., 2007], indicating that our effective Rayleigh number should be increased (as also indicated by the obtained viscosity profiles), which would increase the amount of MORB settling.

4. Our calculations start off with a stagnant lid, as has been proposed for early Earth, and magmatic heat loss (heat-pipe volcanism) is the dominant heat transport mechanism for the first ~2 Gyr, consistent with previous modeling studies and a recent proposal [*Moore and Webb*, 2013]. However, in our calculations mobile-lid behavior and high magmatic heat loss start approximately simultaneously at a very early state of evolution. The production of laterally heterogeneous crust, some of which is thick enough to convert to eclogite, seems to be important in initiating subduction in the presented models.

5. Regarding the onset of geodynamo and a possible subadiabatic region below the CMB caused by the high thermal conductivity of Earth's core: in these simulations a dynamo starts very early, and a subadiabatic region may be generated in the later evolution. Early core cooling might be greatly increased by a basal magma ocean [*Labrosse et al*., 2007], which we plan to consider in the future.

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