Earth and Planetary Science Letters 500 (2018) 86–96

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

The influence of deep mantle compositional heterogeneity on Earth's thermal evolution

Mingming Li [a,*], Allen K. McNamara [b]

[a] Arizona State University, School of Earth and Space Exploration, PO Box 876004, Tempe, AZ 85287-6004, USA
[b] Michigan State University, Department of Earth and Environmental Sciences, Natural Science Building, East Lansing, MI 48824, USA

ARTICLE INFO

Article history:
Received 5 November 2017
Received in revised form 16 June 2018
Accepted 5 August 2018
Available online xxxx
Editor: B. Buffett

Keywords:
thermal evolution
compositional heterogeneity
thermochemical piles
lowermost mantle

ABSTRACT

The seismically-observed large low shear velocity provinces in the Earth's lowermost mantle have been hypothesized to be caused by thermochemical piles of compositionally distinct, more-primitive material which may be remnants of Earth's early differentiation. However, one critical question is how the Earth's thermal evolution is affected by the long-term presence of the large-scale compositional heterogeneity in the lowermost mantle. Here, we perform geodynamical calculations to investigate the time evolution of the morphology of large-scale compositional heterogeneity and its influence on the Earth's long-term thermal evolution. Our results show that a global layer of intrinsically dense material in the lowermost mantle significantly suppresses the CMB heat flux, which leads to faster cooling of the background mantle relative to an isochemical mantle. As the background mantle cools, the intrinsically dense material is gradually pushed into isolated thermochemical piles by cold downwellings. The size of the piles also decreases with time due to entraining of pile material into the background mantle. The morphologic change of the accumulations of intrinsic dense material eventually causes a gradual increase of CMB heat flux, which significantly reduces the cooling rate of Earth's mantle.

1. Introduction

Understanding the Earth's thermal evolution is one the most important problems in Earth Sciences. The thermal evolution of Earth's mantle dictates the partial melting and degassing processes occurring in the uppermost mantle which have great influences on climate change and atmospheric evolution. One key factor that controls the thermal evolution of the Earth's mantle is the core–mantle boundary (CMB) heat flux, which is largely determined by the lowermost mantle structure and dynamics.

Seismic observations have revealed two large low shear velocity provinces (LLSVPs) in Earth's lowermost mantle, surrounded by regions with much higher seismic velocities that are suggested to be ancient subducted cold slabs (e.g., Li and Romanowicz, 1996; Ritsema et al., 2004). One hypothesis for the origin of LLSVPs is that they are caused by large-scale, compositionally-distinct material that may be remnants of Earth's early differentiation (e.g., Labrosse et al., 2007). The large-scale compositional heterogeneity may have been pushed by convection into hot but intrinsically dense thermochemical piles that cause the LLSVPs (Davaille, 1999; Li and Zhong, 2017; McNamara and Zhong, 2005; Tackley, 1998; Zhang et al., 2010). The thermochemical piles are expected to act as thermal insulators (Nakagawa and Tackley, 2004), beneath which the CMB heat flux is much lower than that outside piles (Zhang and Zhong, 2011). Thus, the lateral extent of thermochemical piles on the CMB significantly controls the CMB heat flux.

The morphology of thermochemical piles is expected to change with time. Firstly, changing mantle convection currents will act to push the piles away from regions of downwelling and into regions of upwelling. Furthermore, and of specific relevance to this paper, the total geographic area of core–mantle boundary surface that thermochemical piles will cover is expected to decrease with time. This primarily occurs for two reasons that control topographic relief of piles (lower topographic relief leads to a more layer-like morphology that covers more CMB surface area, and vice versa). Firstly, as the Earth cools and the mantle's effective Rayleigh number becomes smaller, piles are more viscously coupled to background mantle flow and therefore obtain higher topographic relief (e.g., Tackley, 1998). Secondly, as time passes, the effective density difference between thermochemical piles and the background mantle decreases, making the piles effectively less-dense and therefore obtain higher topographic relief. This occurs for two reasons. With time, thermochemical piles and background mantle continually exchange material via entrainment (e.g., Davaille, 1999; Deschamps et al., 2011; Li et al., 2014), which acts to reduce

* Corresponding author.
E-mail address: Mingming.Li@asu.edu (M. Li).

https://doi.org/10.1016/j.epsl.2018.08.009

the intrinsic density contrast between them (and incidentally also makes piles smaller with time (e.g., Davaille, 1999; Li et al., 2014)). Also, cooling is more efficient for background mantle than for thermochemical piles. If starting with an initially hot temperature for the entire system, an increasing temperature differential between piles and background mantle develops through time because the background mantle cools faster. Therefore, the difference in thermal expansion between piles and background mantle increases with time (i.e., the background mantle gets thermally denser than piles), which acts to reduce the effective density contrast between them.

Here, we investigate how the presence of thermochemical piles in the lowermost mantle can affect the Earth's thermal evolution. In an isochemical convection system that lacks thermochemical piles, the temperature of the entire mantle is predicted to generally decrease in a monotonic manner as a function of time for most of Earth's history (e.g., Christensen, 1985; Davies, 1993; Honda, 1995; McNamara and Keken, 2000; Schubert et al., 1980). This is due to the decreasing concentrations of radioactive heat-producing elements and secular cooling of the mantle through time. Note that this monotonic temperature decrease can sometimes be preceded by an early, transient temperature increase, particularly for relatively low initial temperatures (e.g., Christensen, 1985; Davies, 1980; Franck, 1998). In this study, we introduce a denser mantle component in the lowermost mantle of an initially uniform hot Earth. We find that this denser material will evolve from a flat layer to discrete thermochemical piles as the mantle cools with time. We find that although the initial global layer of intrinsically dense material on the CMB significantly reduces the CMB heat flux, which leads to rapid cooling of Earth's background mantle, the transition of this dense layer to discrete thermochemical piles and the reduction of pile size due to entrainment lead to eventual increases of CMB heat flux, which in turn cause a reduction of cooling rate and possibly temperature increase of Earth's upper mantle with time. Thus, the presence of a thermochemical layer may initially cool the upper mantle quicker than would be expected for an isochemical mantle. This is followed by a reduced cooling rate or possibly heating up of the upper mantle as the dense layer transitions into discrete thermochemical piles.

2. Method

We perform both isochemical and thermochemical numerical calculations to study thermal evolution of Earth's mantle. The following non-dimensional equations of conservation of mass, momentum and energy are solved under the Boussinesq approximation:

$$\nabla \cdot \vec{u} = 0, \tag{1}$$

$$-\nabla P + \nabla \cdot (\eta \dot{\epsilon}) = \xi^{-3} Ra (T - BC)\hat{r}, \tag{2}$$

$$\frac{\partial T}{\partial t} + (\vec{u} \cdot \nabla)T = \nabla^2 T + Q, \tag{3}$$

where, $\vec{u}$ is the velocity, P is the dynamic pressure, η is the viscosity, $\dot{\epsilon}$ is the strain rate, Ra is the Rayleigh number, T is the temperature, B is the buoyancy number, C is the compositional concentration, $\hat{r}$ is the unit vector in radial direction, t is the time, and Q is the internal heat generating rate. The spatial dimension is non-dimensionalized by the Earth's radius, not mantle thickness. Therefore, we include $\xi = D/R_e$, where D is the thickness of Earth's mantle and R_e is the Earth's radius. All parameters in equations (1)–(3) are non-dimensional. The above equations are solved using the CitcomCU code (Zhong, 2006).

The Rayleigh number Ra in equation (2) is defined as:

$$Ra = \frac{\rho g \alpha \Delta T D^3}{\eta_0 \kappa}, \tag{4}$$

Table 1
Physical parameters and reference values.

Parameters	Symbol	Value
Earth's radius	R	6370 km
Thickness of Earth's mantle	D	2890 km
Gravitational acceleration	g	9.8 m/s^2
Density of background mantle	ρ	3300 kg/m^3
Thermal expansivity	α	1×10^{-5} K^{-1}
Temperature difference between CMB and surface	ΔT	2500 K
Reference viscosity	η_0	2×10^{20}, 4×10^{20} Pa s
Thermal diffusivity	κ	1×10^{-6} m^2/s

where, ρ, g, α, ΔT, η_0 and κ are dimensional parameters for density of the background mantle, gravitational acceleration, thermal expansivity, potential temperature difference between CMB and surface, reference viscosity at temperature $T = 0.6$ (non-dimensional), and thermal diffusivity, respectively. Table 1 lists the reference values of physical parameters used in this study.

The buoyancy number B in equation (2) is defined as the ratio between intrinsic density anomaly and density anomaly due to thermal expansion:

$$B = \frac{\Delta \rho}{\rho \alpha \Delta T}, \tag{5}$$

where, $\Delta\rho$ is intrinsic excess density of pure pile material with respect to background mantle material. Using reference values in Table 1, the buoyancy number of 0.4, 0.8 and 1.2 are scaled to intrinsic density anomalies of 1%, 2% and 3%, respectively. The composition concentration C in equation (2) represents the concentration of the intrinsic dense material within one element of the computational domain in this study. The background mantle regions have $C = 0$, regions with pure intrinsic dense material have $C = 1$, and regions with a mixture of background mantle material and intrinsic dense material have $0 < C < 1$.

The viscosity depends on both temperature and depth. The temperature dependent viscosity is $\eta_T = \exp[A(0.6 - T)]$, where A is activation parameter which controls the amount of viscosity changes due to changes in temperature. For most of our cases, A is 9.21 in both upper and lower mantles, which leads to 10,000 viscosity contrast between lowest ($T = 0$) and the highest temperature ($T = 1$). In addition, there is a 50× viscosity increase from upper mantle to lower mantle across the 670-km discontinuity.

The whole mantle dynamics is modeled in a spherical annulus geometry (Hernlund and Tackley, 2008). The radius of inner (representing the CMB) and outer (representing the surface) layer of the model domain are $r_i = 0.55$ and $r_o = 1.0$, respectively. The model domain is divided into 1280 × 128 (longitudinal and radial, respectively) elements. Both the surface and the CMB have free-slip velocity boundary condition. The temperature boundary condition is isothermal on the surface ($T = 0$) and the CMB ($T = 1$). The model is both internally and basal heated.

The temperature initial condition for most cases is $T = 0.72$ throughout the domain with small sinusoidal perturbations superimposed to enhance convection at the beginning. For thermochemical models, we also initially introduced a global layer of intrinsically dense material at the bottom the mantle. The composition advection is performed using ∼3.28 million tracers (∼20 tracers per element on average) using the ratio tracer method (Tackley and King, 2003).

The Earth's thermal evolution is influenced by factors such as the internal heating rate, vigor of mantle convection, the nature of plate motion in the early Earth (e.g., Davies, 2009; Korenaga, 2006), phase transition at Earth's transition zone (Davies, 2008), surface magmatism (e.g., Nakagawa and Tackley, 2012), and the supercontinent cycles (e.g., Coltice et al., 2007; Lenardic et al., 2011;