Physics of the Earth and Planetary Interiors 236 (2014) 109–116

Contents lists available at ScienceDirect

Physics of the Earth and Planetary Interiors

journal homepage: www.elsevier.com/locate/pepi

Thermochemical piles in the lowermost mantle and their evolution

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ARTICLE INFO

Article history:
Received 31 December 2012
Received in revised form 28 February 2014
Accepted 19 April 2014
Available online 9 May 2014
Edited by M. Jellinek

Keywords:
LLSVPs
Thermochemical pile
Entrainment rate
Plume
Morphology

ABSTRACT

Two Large Low Shear-wave Velocity Provinces (LLSVPs) lie beneath Southern Africa and Southern Pacific Ocean. These LLSVPs may be thermochemical in origin. Studying the dynamic evolution of these thermochemical piles will help us understand the earth's present structure and history. We investigate the entrainment and evolution of an initially isolated high viscosity thermochemical pile in detail. The entrainment rate of the dense pile increases with time until it being totally entrained. The pile's survival time does not monotonically varies with its viscosity. The chemical pile obstructs the horizontal flow along CMB and turns it into upwelling flow. This may help explain the observation of plume generation zones. The morphology and location of the dense pile oscillate with time. A high viscosity pile can keep its location and morphology roughly unchanged for hundreds of millions years if the convective structure in the surrounding mantle keeps steady.

1. Introduction

Two large Low Shear wave Velocity Provinces (LLSVPs) have been detected lying in the lowermost mantle beneath Africa and South Pacific Ocean for decades (Grand et al., 1997; Masters et al., 1996; Ritsema et al., 2011; Su et al., 1994). It is suggested that these two LLSVPs are chemical in origin (He et al., 2006; Kennett et al., 1998; Ni and Helmberger, 2003; Ni et al., 2002; Wang and Wen, 2004, 2007) and very likely to be denser than the surrounding mantle (Ishii and Tromp, 1999; Trampert et al., 2004). Torsvik et al. (2006) and Burke et al. (2008) further suggested that (1) Large Igneous Provinces' (LIPs) eruption sites in the past 300 Myrs and the most active deep rooted hotspot volcanoes today lie vertically above the plume generation zones bounding these LLSVPs. (2) These plume generation zones have remained fixed for the past 300 Myrs. By considering the eruption sites of Phanerozoic kimberlites, Torsvik et al. (2010) extends this 'fixity time' to 540 Ma.

Because the dynamics of these dense piles is important for our understanding of the earth's structure and evolution, many numerical and laboratorial experiments have been conducted to study the entrainment rate (Huang, 2008; Huang et al., 2010; Lin and van Keken, 2006; Sleep, 1988; Zhong and Hager, 2003), morphology evolution (Bower et al., 2013; Deschamps and Tackley, 2008, 2009; McNamara et al., 2010; McNamara and Zhong, 2004b, 2005; Tackley, 1998; Tackley and Xie, 2002; Zhang et al., 2010) or both (Davaille, 1999; Gonnermann et al., 2002) of a dense pile.

The upwelling flow in the mantle may have two different kinds of regimes: conduit flow and broad-scale flow (Sleep, 1988). Ideally, numerical experiments on the entrainment of a dense pile should be taken under full three-dimensional spherical geometry and include both regimes above. Yet, due to the limited computational resources, axisymmetric geometry are often invoked (Huang, 2008; Huang et al., 2010; Lin and van Keken, 2006; Zhong and Hager, 2003). These experiments shed lights on the entrain dynamics of a dense layer in the conduit flow regime (plumes). To give a more precise evaluation of the entrainment rate, experiments under more complete dynamics is still needed. On the other hand, laboratory experiments have been able to approach the real dynamics of the compositionally dense layer in a convecting system (Davaille, 1999; Gonnermann et al., 2002; Jellinek and Manga, 2004), but they are unable to detect the full parameter space (e.g. depth or temperature dependent viscosity).

Intrinsic density increase and viscosity contrast are two of the most important parameters that control the entrainment rate and morphology evolution of dense piles (Davaille, 1999; Deschamps and Tackley, 2009; Deschamps et al., 2007; McNamara and Zhong, 2004b). The intrinsic density increase of the LLSVPs is usually reckoned to be within the range of 1–6% (Deschamps and Tackley, 2009; Simmons et al., 2007; Tackley and Xie, 2002). The viscosity contrast of the LLSVPs, on the other hand, is of large uncertainty. Previous studies often assume the piles less viscous than the surrounding mantle (McNamara and

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http://dx.doi.org/10.1016/j.pepi.2014.04.006
0031-9201/

Zhong, 2005; Zhang et al., 2010), due to their high temperature. However, the grain size, which may affect the viscosity strongly (Karato and Wu, 1993), has not been considered in these models. Hot LLSVPs may have several orders higher viscosity than the surrounding mantle if they are primordial and have large grain size (Korenaga, 2005; Solomatov, 1996; Solomatov and Reese, 2008). On the other hand, the cold downwelling flow may have lower viscosity than the surrounding mantle (Ammann et al., 2010; Karato and Li, 1992).

In this paper, we investigate the dynamics of a high viscosity dense pile with high resolution numerical simulations. First we investigate the survival time of a dense pile in full dynamic regime. Then we observe the morphology and location evolution of the dense pile.

2. Models and method

2.1. Governing equations

We consider thermochemical convection of a Boussinesq, infinite Prandtl number fluid in a 2D Cartesian rectangular box. The non-dimensional equations for the conservation of mass, momentum, and energy and the advection equation are listed as below:

$$u_{i,j} = 0 \tag{1}$$

$$-P_{,i} + [\mu(u_{i,j} + u_{j,i})]_{,j} - (Ra \cdot T - Rc \cdot C) * g_i = 0 \tag{2}$$

$$\dot{T} + u_i \cdot T_{,i} = T_{,ii} \tag{3}$$

$$\dot{C} + u_i \cdot C_{,i} = 0 \tag{4}$$

Here u_i is velocity, P is dynamic pressure, μ is viscosity, T is temperature, C is chemical composition, $g_i = (0, 1)$ is gravitational acceleration, X_i, $\dot{X}$ are the spatial and time derivative of X, respectively. Ra, Rc are thermal and compositional Rayleigh numbers respectively, and are given by

$$Ra = \frac{\rho_0 g \alpha \Delta T h^3}{\kappa \eta_0}, \quad Rc = \frac{\Delta \rho g h^3}{\kappa \eta_0}$$

The values on the right-hand are dimensional, their definitions and values are listed in Table 1.

Divide Rc by Ra defines buoyancy number, B, which is the ratio of the chemical to thermal buoyancy:

$$B = \frac{Rc}{Ra} = \frac{\Delta \rho}{\rho_0 \alpha \Delta T}$$

The no dimensional governing equations are solved with the finite element code Citcom (Moresi and Solomatov, 1995). The evolution of composition field is predicted by the tracer ratio method (Tackley and King, 2003). The tracer ratio method utilizes two set of particles, representing background mantle material (particle type is 0) and dense pile material (particle type is 1), respectively. The position of each tracer at each time step is predicted with 2nd order Runge–Kutta method (McNamara and Zhong, 2004a).

Table 1
Symbols and values of physical parameters in this article.

Parameters	Symbols	Values
Mantle thickness	h	2890 km
Thermal diffusivity	κ	1E−6 m^2/s
Reference density	ρ_0	3.3E3 kg/m^3
Thermal expansivity	α	3E−5
Gravitational acceleration	g	9.8 m/s^2
Reference temperature	ΔT	2500 K
Rayleigh number	Ra	1E7

2.2. Model parameter

To reduce the effect of the side boundaries on the evolution of the dense piles, the aspect ratio of the box is set 3. The box is evenly divided into 128 elements in the vertical direction (the corresponding grid space is 22.58 km). The horizontal direction has the same resolution. Initially, each element has 24 randomly distributed tracers.

Free-slip boundary condition is applied to all the sides of the domain. Constant zero and unity temperature are assigned to the top and bottom boundaries, respectively. Thermal insulating boundary condition is assigned to the side walls. The initial temperature field was established based on the horizontal average of a steady temperature field from a corresponding pure thermal convection model.

Initially, the dense pile is represented by a block with 2% volume percent of the model box (Fig. 1). This is about the total volume percent of the Africa and Pacific LLSVPs (Burke et al., 2008; Wen, 2001).

The mantle viscosity is a complex function of temperature and grain size (diffusion creep). In this paper, we consider neither of them. Instead, we use a simple depth and composition dependent viscosity to represent the integral effect:

$$\eta(C) = \eta_0(z)(1 + \eta_c C)$$

where η_0 is a prefactor depending on depth and is 1, 0.01, 0.1, 1 for the lithosphere, asthenosphere, transition zone, and lower mantle respectively. Viscosity ratio η_c is the ratio of viscosity between anomaly and ambient mantle.

We keep other parameters earthlike (Table 1) while changing the viscosity ratio η_c from 10 to 500 and buoyancy ratio B from 0.2 to 0.8 (corresponding to 1.5–6% density increase) to investigate the effect of the viscosity contrast and buoyancy ratio on the dynamics of the chemical piles. The readers may refer Table 2 and Fig. 4 for all the models calculated.

2.3. Survival time

We define the characteristic mass decay time T_h (the time when the residual mass of the maximum chemical pile is $1/e$ its initial. Here, e is the base of the natural logarithm.) to study the effect of viscosity ratio and buoyancy ratio on the survival time of a chemical pile. The mass of the maximum chemical block in each time step is determined by:

1. Find the compositional different elements (Fig. 2b) from the compositional field (Fig. 2a). Whether an element is compositional different is judged under the following criterions:
   (a) Elements with composition larger than C_{c1} = 0.9 are always assumed to be compositional different.
   (b) Elements with composition larger than C_{c2} = 0.1 and in connection with at least one compositional different element are assumed to be compositional different. The compositional different elements are searched by the labyrinth algorithm.
2. Cluster these compositional different elements into different blocks. The initially single block may be dispersed into separated piles by the mantle flow. We use hierarchical clustering method to classify the compositional different elements into separated piles and find the maximum pile (Fig. 2c).
3. Calculate the mass of the maximum dense pile. The mass of the maximum dense pile is calculated by: