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GEOPHYSICS

Evolution of Thermal Plumes in the Earth's Mantle

A. T. Ismail-Zadeh[a], A. I. Korotkii[b], D. P. Krupsky[a], I. A. Tsepelev[b], and G. Schubert[c]

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Thermal plumes in the Earth's mantle are formed at the core/mantle or upper/lower mantle boundary as a result of gravity instability in the thermal boundary layer (TBL), which can exist at these boundaries. At the same time, recent seismic tomography studies of the Earth's mantle [1] show clear evidence for low velocity anomalies (associated with individual mantle plumes) extending down to mid-mantle depths. The origin of mantle plumes at these depths is problematic because no TBL feeding the plumes has thus far been observed in the mid-mantle. In the present paper, we propose that plumes formed at the core/mantle boundary lose their tails (vertical conduits for hot material) during the thermal evolution of plumes.

Despite the fact that the lifetime of some mantle plumes exceeds 150 Ma, they are short-lived structures [2]. The ascent and evolution of thermal plumes depend generally on the physical and chemical properties of the TBL, as well as viscosity [3] and thermal conductivity of the mantle [4, 5] surrounding the rising plumes. The properties of the TBL determine the structure and viscosity of the mantle plume. The structure of the plume, velocity of its ascent, and thermal flux depend on the properties of not only the TBL but also the plume-hosting mantle. Physicochemical properties of the mantle change only slightly during approximately 100–150 Ma (mean lifetime of plumes), whereas properties of the boundary layer vary significantly during this period of time because the TBL (source of the plumes), which supplies hot mantle material to the plumes, is depleted. This occurrence is related to the fact that the TBL is formed as a result of conductive heat transfer, and the time for its replenishment exceeds significantly the time of its depletion as a result of advective heat-and-mass transfer by the mantle plumes.

Total depletion of the TBL under a rising plume practically separates this plume from its source. The subsequent evolution of the plume is most interesting. The results of our numerical experiments show that a plume separated from the source begins to disappear from the bottom to top as a result of thermal diffusion. This is the most probable explanation for mid-mantle plumes distinguished recently based on global seismic tomography of the Earth's mantle [1, 6]. Seismic tomography allows us to get images and study mantle plumes, i.e., negative anomalies of seismic velocities, which are associated to a greater extent with high temperature (however, they can also be related to variations in the mantle composition). Numerical experiments are performed to study the dynamics of mantle plumes.

In this paper, the evolution of mantle plumes appearing at the core/mantle boundary has been modeled numerically in a rectangular parallelepiped (height 2800 km, length and width 8400 km) filled with Newtonian viscons incompressible fluid. The fluid is heated from below, and thermoconvective currents are controlled by specifying the Rayleigh number Ra = $\frac{\alpha\rho_0 g\Delta T h^3}{\eta_0\kappa}$, where $\alpha = 3 \cdot 10^{-5}$ K^{-1} is the coefficient of thermal expansion, $\rho_0 = 4000$ kg $\cdot$ m^{-3} is the typical density of the mantle, $g = 9.8$ м $\cdot$ s^{-2} is acceleration due to gravity, $\Delta T = 3000$ K is the temperature difference between the upper and lower boundaries of the model region, h is depth of the model region (2800 km), $\eta_0 = 8 \cdot 10^{22}$ Pa $\cdot$ s is the typical viscosity of the mantle, and $\kappa = 10^{-6}$ m^2 $\cdot$ s^{-1} is the coefficient of thermal diffusion. The equations of conservation of mass, momentum, and energy are solved at the infinite Prandtl number and in the Boussinesq approximation [7, 8]. Free slip conditions are specified at the boundaries of the

[a] *International Institute of Earthquake Prediction Theory and Mathematical Geophysics, Russian Academy of Sciences, Varshavskoe sh. 79/2, Moscow, 113556 Russia; e-mail: aismail@mitp.ru*

[b] *Institute of Mathematics and Mechanics, Ural Division, Russian Academy of Sciences, ul. Sof'i Kovalevskoi 16, Yekaterinburg, 620219 Russia*

[c] *Department of Earth and Space Sciences, UCLA, 2810 Geology Bl, 595 E Circle Drive, Los Angeles, CA 90095-1567, USA*

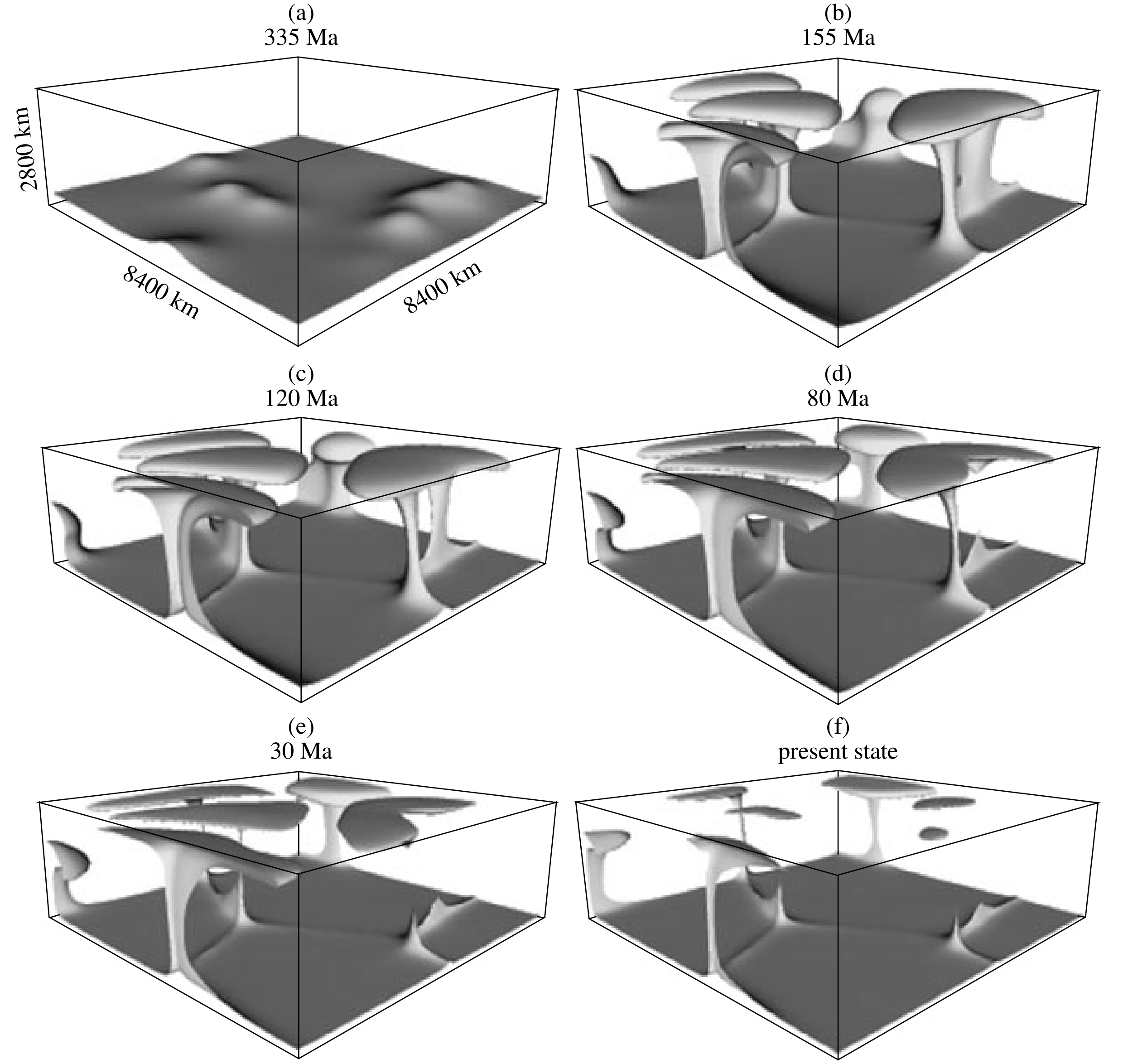

Fig. 1. Evolutionary stages of mantle plumes in the numerical experiment (Ra = $9.5 \cdot 10^5$). The plumes are presented using isothermal surfaces 3000 K.

model region. Zero heat flux is specified at the vertical boundaries. Constant temperatures are specified at the upper and lower boundaries. It is assumed that the temperature in the model region at the initial time moment linearly depends on depth. The system of equations (with respect to two-component vector potential of velocity and temperature) with the corresponding boundary and initial conditions is solved using the methods of finite elements and finite differences [8].

The model region is divided into $50 \times 50 \times 50$ rectangular finite elements for approximation of the velocity potential vector by tricubic splines. A regular $148 \times 148 \times 148$ grid (the grid for determination of finite elements is three time smaller) is used for approximation of temperature, viscosity, and velocity by trilinear functions. Numerical calculations were performed using a multiprocessor computer.

The mantle material behaves like a viscons fluid in the geological time scale. We assume that the viscosity of the mantle η depends on temperature:

$$\eta(T) = \exp\left(\frac{M}{T+G} - \frac{M}{0.5+G}\right),$$

where $M = \frac{225}{\ln(r)} - 0.25\ln(r)$, $G = \frac{15}{\ln(r)} - 0.5$, $r = 20$ (r is the ratio between viscosities at the upper and lower boundaries of the region) [9]. The evolution time of mantle plumes in numerical models is normalized as $\dfrac{h^2}{\kappa}$.

Mantle plumes are generated in the model at the TBL boundary (2520 km) using an arbitrary temperature perturbation of this boundary (Fig. 1a). Vertical ascent of hot material is concentrated in the low-viscous channels around the centers of rising plumes. The ascending mantle material (Fig. 1b) forms plumes with distinct reservoirs of hot material (plume heads) and vertical channels (plume tails), which connect the TBL with plume heads. In the course of time, the hot material of the TBL, which feeds the plumes, is depleted almost completely (Fig. 1c) and thermal plumes begin to shrink. As this takes place, the tails disappear more rapidly than the heads (Figs. 1c–1f). At different stages of thermal diffusion of plumes, one can observe completely isolated plume heads, plume heads with reduced tails, and plume heads connected with tails. The figures show a hot isothermal surface, which characterizes the mantle plume. If we consider a colder surface, the diffusive disappearance of plumes would happen later. However, the character of their disappearance would not change in this case; i.e., plume tails would disappear earlier than heads. The results of numerical simulation are confirmed by recent laboratory experiments on the modeling of plumes and their diffusive disappearance at later evolutionary stages [10].

Thermal diffusion of various (in geometry) mantle plumes requires different time periods. The heat loss in flat tails (Figs. 1b–1f, right-hand zone) is higher than in cylindrical tails (Figs. 1b–1f, left zone). Tails of cylindrical plumes are still observed after 120 Ma of their thermal diffusion (Figs. 1e–1f, left zone). During this time, flat tails of plume disappear almost completely (Figs. 1e–1f, right zone) and only their heads remain in the upper mantle. Fast thermal diffusion of flat tails as compared to cylindrical ones can be explained by conductive transfer of heat in the horizontal direction in bodies of various geometrical shapes.

On the basis of numerical experiments (and analysis of seismic tomography), it is possible to distinguish three main stages in the evolution of a mantle plume: (1) generation and ascent of a vertical plume; (2) interaction of the plume with the lithosphere, gravity spreading of the plume head beneath the lithosphere floor, and retardation of the plume; and (3) change in the shape (destruction) of the plume due to its thermal diffusion and possible mantle currents.

Numerical experiments with mantle plumes show that the lifetime of a plume decreases and the tails of rising hot plumes become thinner when the Rayleigh number increases. At Ra > 10^7, the heads of thermal plumes are separate from their tails [11]. Plume tails can also be separated from the heads due to strong currents in the mantle induced by the motion of the lithosphere. At the same time, recent data on the diffusion of mantle plumes under the influence of induced currents show that mantle currents do not change the character and sequence of the diffusive disappearance of plumes: tails of plumes disappear before the disappearance of their heads [12].

Thus, hot mantle material of the TBL intrudes into the relatively cold mantle owing to instability of the TBL and generates a rising mantle plume. During a certain period of time, mantle plumes are fed from this source, which weakens with time. As this takes place, the ascent of the plume becomes slower and convective transfer of heat and mass decreases. However, convective transfer of heat from the plume to the surrounding mantle increases. Numerical experiments carried out in this work showed that plumes begin to dissolve in the surrounding mantle. First, tails of plumes disappear at mid-mantle depths. The successive diffusion of plume tails and heads is related to the geometry of mantle plumes.

The numerical experiments did not take into account internal heat sources in the mantle, the phase boundary between the upper and lower mantle, and variation in the coefficient of heat conductivity in the lower mantle. Accounting for these and other factors would undoubtedly refine the evolutionary models of mantle plumes. Nevertheless, the experimental results presented in this paper point to an important role of thermal diffusion in the evolution of mantle plumes and explain the morphological diversity of mantle plumes recorded by seismotomography [1, 6].

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