===== **GEOPHYSICS** =====

Diameter and Formation Time of Plume Head at the Base of Refractory Lithospheric Layer

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Received August 28, 2005

Estimation of the growth time and dimension of plume head (PH) ascent from the deep mantle toward the lithosphere is an important problem of geodynamics, towards the solution of which an active search is presently being carried out. An experimental and theoretical model of the plume that spreads at the lithosphere base is presented in [1]. This model envisages the ascent of a purely chemical plume driven by a density difference between the low-viscous plume material and the high-viscous ambient massif. Results of the numerical modeling presented in [2] are related to the development of a thermal PH that approaches the lithosphere base when the density difference between the plume material and the ambient massif is caused by a variation of temperature without additional melting. Estimates of the PH dimension based on geological data are given in [3–6].

The thermochemical plumes, the most important regulators of the Earth's thermochemical engine, are formed at the core/mantle boundary in the presence of a heat flow from the outer core and the local delivery of a chemical dope that depresses the melting temperature at the lower mantle base [7–10]. According to [8–10], the melting temperature in the presence of the chemical dope is $T_{cm} = T_{dm} - kc_2$, where T_{dm} is the melting point of "dry" lower mantle massif without a dope, coefficient k [°C/%] is a parameter that sets the decrease in melting temperature owing to the dope, and c_2 is the dope concentration at the plume–ambient mantle massif boundary. The site of dope delivery is marked by the melting of plume channel and the ascent of plume. As has been shown in [11], two refractory layers may exist in the upper mantle. Having reached a refractory layer (RL), the plume spreads beneath the RL with the formation of a mushroom-shaped head. Such a situation may arise in two cases [11]: (a) at a depth of ~650 km under conditions of a certain relationship between the melting temperature of the ambient massif (the authors

of [11] considered the experimental curve of peridotite KLB-1 melting reported in [12]) and variation of the melt temperature adjacent to the plume roof in the course of its ascent and (b) in the vicinity of the lithosphere base at a depth of 100–200 km, if the lithospheric mantle is largely composed of dunite–harzburgite material at a certain relationship between the melting temperature of the depleted mantle and the melt temperature adjacent to the plume roof.

The objective of this study is to establish the dependence of the PH diameter at the RL base on the time and thermal power of source. We propose a model of evolution of the thermochemical PH adjacent to the RL base. As the diameter of PH increases, the heat flow in the lithosphere above the plume roof decreases. The PH diameter as a function of the thermal power of plume source and time t has been estimated from the balance of heat flows in the PH. We have found that the time of the PH growth at the RL base is commensurable with the time of the secondary plume ascent within the RL.

The heat from the plume source delivered to the plume roof at the RL base is transferred to the lithosphere and consumed for the melting of the ambient massif; i.e., $N = N_l + N_m$, where N is the thermal power supplied to the plume roof, N_l is the power transferred to the lithosphere, and N_m is the power consumed for melting. The melting occurs along the RL base, and the melt–ambient massif interface propagates along the base with velocity v. As a result, the PH diameter D increases (Fig. 1).

Let us assess diameter D as a function of thermal power N of thermochemical plume. The following thermal balance is fulfilled at all times t counted out from the adjacent to when the plume has reached the RL base: heat Q supplied by plume over time t equals the sum of the heat transferred to the lithosphere (Q_l) and the heat consumed for the heating of the ambient massif and its melting (Q_m):

$$Q = Q_l + Q_m. \qquad (1)$$

where $Q = Nt$. The heat transferred to the lithosphere is

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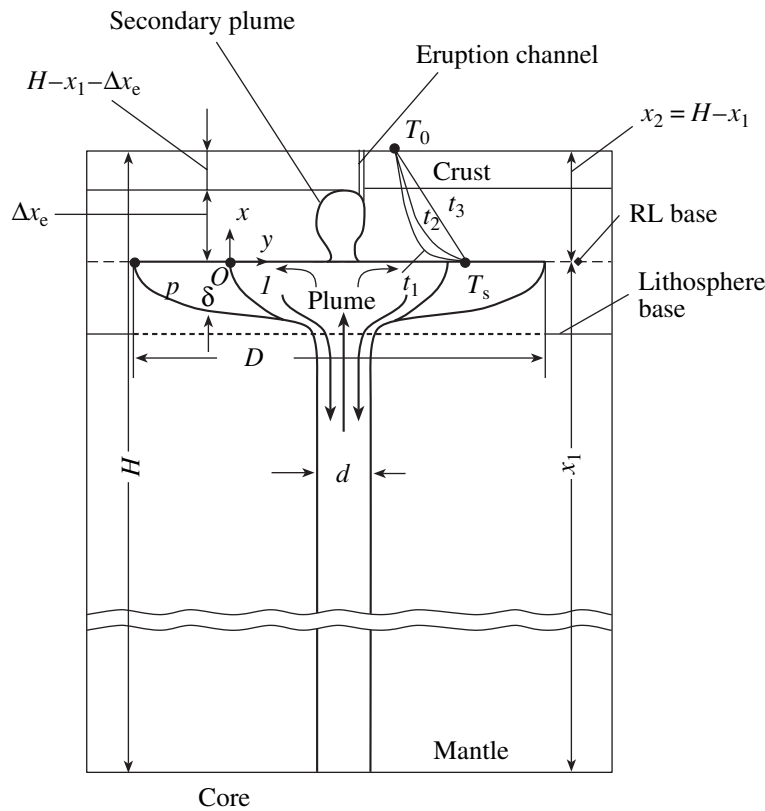*e-mail: aak@uiggm.nsc.ru*

Fig. 1. Schematic evolution of PH that reached the RL. ($x_2 = H - x_1$) the depth of the RL base; (Δx_e) the height of the secondary plume ascent; ($H - x_1 - \Delta x_e$) the height of the eruption channel. The diagram shows temperature profiles across the RL x_2 at moments $t_1 < t_2 < t_3$. (1, 2) Locations of the PH at moments t_1 and t_2, respectively. Free convection currents within a plume are indicated.

$$Q_1 = \frac{\pi D^2}{4} \bar{q} t, \tag{2}$$

where $\bar{q}$ is the heat flow from the plume roof to the lithosphere averaged over the time t. The heat consumed for heating of the massif surrounding the PH and its melting is equal to

$$Q_m = \rho \frac{\pi D^2 \delta}{4} [B\varphi + C(T_{ph} - T_{am})], \tag{3}$$

where δ is the average thickness of the PH commensurable with diameter d of the plume channel; ρ is the density of ambient massif adjacent to the PH; B is the heat of melting; φ is the degree of melting in the PH; C is the heat capacity; T_{ph} is the melt temperature in the PH; and T_{am} is the temperature of ambient massif. Assuming $\delta \approx d$, we obtain from (1)–(3)

$$Nt = \frac{\pi D^2 \rho d}{4} [B\varphi + C(T_{ph} - T_{am})] + \frac{\pi D^2 \bar{q} t}{4}. \tag{4}$$

The diameter of the PH obtained from (4) is

$$D = \left[\frac{4Nt}{\pi \rho d [B\varphi + (T_{ph} - T_{am})] + \pi \bar{q} t} \right]^{1/2}. \tag{5}$$

In order to determine the $\bar{q}$ value, let us place the origin of coordinates O at the PH boundary (Fig. 1) that moves along the RL base with velocity v. When estimating the intensity of heat transfer in the lithosphere, velocity v is accepted as the average velocity $v_0 =$ const. Furthermore, we neglect term $\frac{\partial^2 T}{\partial y^2}$, which is much less than term $\frac{\partial^2 T}{\partial x^2}$, where x is the vertical coordinate counted out from the RL base and y is the horizontal coordinate counted out along the RL base. If the system of coordinates is fixed, the lithosphere may be regarded as moving with velocity $v_0 =$ const. In this case, the heat transfer in the lithosphere above the plume roof is described by equation

$$v_0 \frac{\partial T}{\partial y} = a \frac{\partial^2 T}{\partial x^2}. \tag{6}$$

If coordinate $y = v_0 t$, Eq. (6) is transformed into

$$\frac{\partial T}{\partial t} = a \frac{\partial^2 T}{\partial x^2}. \tag{7}$$

Owing to the relatively high velocity of the plume ascent and the great thermal inertia of the lithosphere, one can accept that, at the initial adjacent to $t = 0$, the temperature at the RL base instantly changes from the average temperature T_1 of the lithosphere to the solidus temperature T_c at the plume roof. Therefore, the following boundary conditions should be set in order to estimate the intensity of heat transfer at the plume roof:

$$T = T_1 \quad \text{at} \quad x > 0 \quad \text{and} \quad t = 0;$$

$$T = T_s \quad \text{at} \quad x = 0 \quad \text{and} \quad t > 0; \qquad (8)$$

$$T \to T_1 \quad \text{at} \quad x \to \infty \quad \text{and} \quad t > 0,$$

where $T_1 = \dfrac{T_{ds} + T_s}{2}$ is the average temperature in the lithosphere above the PH and T_{ds} is the temperature of day surface (Fig. 1).

According to [13], Eq. (7) with boundary conditions (8) can be solved as

$$q = \frac{\lambda(T_s - T_1)}{(\pi a t)^{1/2}}, \qquad (9)$$

where λ is the thermal conductivity of the lithosphere.

The heat flow averaged over time is $\bar{q} = \dfrac{1}{t}\displaystyle\int_0^t q\,dt.$ From (9), we obtain the average (by time) value

$$\bar{q} = \frac{2\lambda(T_s - T_1)}{\sqrt{\pi a t}}, \qquad (10)$$

where $T_s - T_1 = \dfrac{T_s - T_{ds}}{2}$.

The plume can erupt at the surface according to the following scenario. When the plume roof reaches the RL base, material along the base is melted. Consequently, the plume/RL boundary is marked by the formation of a purely chemical (secondary) plume (Fig. 1) owing to the density difference between the plume melt and rocks above the plume roof. The secondary plume ascends within the RL from its base to the Δx_e level of plume eruption at the surface (Fig. 1). The height of eruption channel $(H - x_1 - \Delta x_e)$, where H is the distance from the core–mantle boundary to the day surface and x_1 is the distance from the core–mantle boundary to the RL base, was assessed in [11].

Owing to the eruption of plume (Fig. 1), the further growth of its head may cease. Substituting heat flow $\bar{q}$ from (10) into (5), we obtain

$$D$$
$$= \left[\frac{4Nt}{\pi \rho d[B\varphi + C(T_{ph} - T_{am})] + \dfrac{2(\pi t)^{1/2}\lambda(T_s - T_1)}{a^{1/2}}}\right]^{1/2}. \quad (11)$$

Let us estimate the time interval t from the adjacent to when the plume roof reaches the RL base to the adjacent to of plume eruption. To do this, it is necessary to find the velocity of the secondary plume ascent. In the case of the plume ascending from the core/mantle boundary, the secondary (chemical) plume is formed at the plume roof under a pressure that exceeds the lithostatic pressure and equals [11]

$$\Delta P = \rho_0 g x_1 \beta (T_m - T_0)\left(\frac{d}{D}\right)^2, \qquad (12)$$

where ρ_0 is the density of the mantle massif surrounding the plume channel, g is the acceleration of gravity, x_1 is the coordinate of the RL base, β is the coefficient of thermal expansion of melt in the plume channel, T_m is the temperature of melt in the plume channel averaged over the channel height, T_0 is the average temperature of the ambient mantle massif, and d is the diameter of the mantle plume channel. ΔP varies from 10^9 to $1.4 \cdot 10^9$ N/m^2 [11]. As follows from (12), ΔP decreases with increasing diameter D. Further, we find the average $\overline{\Delta P}$ value when the diameter of the PH changes from d to D_{max}:

$$\overline{\Delta P} = \frac{1}{1-f}\int_f^1 s^2 \rho_0 g x_1 \beta (T_m - T_0)\,ds$$

$$= \frac{1 + f + f^2}{3}\rho_0 g x_1 \beta (T_m - T_0), \qquad (13)$$

where $s = \dfrac{d}{D}$, D is the increasing diameter of the PH at the RL base, $f = \dfrac{d}{D_{max}}$, and D_{max} is the maximum diameter of the PH. Let us introduce parameter $\xi = \dfrac{1}{3}(1 + f + f^2)$. At $f = 1$, $\xi = 1$. At $f = 0$, $\xi = \dfrac{1}{3}$.

The diameter of the secondary (chemical) plume is commensurable with the diameter of the mantle plume channel d or with the thickness of the PH that propagates along the RL base (Fig. 1). Let us estimate the velocity of the secondary plume ascent based on the assumption that this plume at a first approximation is a sphere and the secondary plume ascends within the RL according to the Stokes formula for a sphere moving in a high-viscous liquid [14]:

$$W = 6\pi\eta u_0 r, \qquad (14)$$

where W is the friction resistance of the moving sphere (secondary plume, in this case), η is the dynamic viscosity of RL, u_0 is the velocity of the secondary plume ascent, and $r = \dfrac{d}{2}$ is its radius. The friction resistance of the ascending secondary plume is estimated from the relationship $W = \overline{\Delta P}\pi r^2$. In this case, we obtain from (13) and (14)

$$u_0 = \frac{\overline{\Delta P} r}{6\eta} = \frac{\xi\rho_0 g x_1 \beta (T_m - T_0) r}{6\eta}. \qquad (15)$$

Using (15), we can find the time of ascent t of the secondary plume from the RL base to the height Δx_e:

$$t = \frac{\Delta x_e}{u_0} = \frac{6\Delta x_e \eta}{\xi\rho_0 g x_1 \beta (T_m - T_0) r}. \qquad (16)$$

The time of growth of the main (thermochemical) PH is commensurable with the time of the secondary plume ascent. Now, we can find the diameter of the main PH, taking into account expression (16) in relationship (11).

Accepting the parameters $\rho_0 = 4500$ kg/m^3, $x_1 \approx H = 2.8 \cdot 10^6$ m, $T_m - T_0 = 310°C$ [11], $\eta = 5 \cdot 10^{21} - 10^{22}$ H · s/m^2, $r = 5 \cdot 10^4$ m, $\beta = 3 \cdot 10^{-5}$ °C^{-1}, $f = \dfrac{d}{D_{max}} = \dfrac{1}{6}$, and $\xi = 0.398$ from [15], we find that the velocity of the secondary plume ascent is $u_0 = 1.2-2.4$ cm/yr. The velocity u_0 is much lower than the velocity of the main plume ascent from the core/mantle boundary, which is estimated at 0.6–1.1 m/yr [9]. At $\dfrac{d}{D_{max}} < 1$, the plume may erupt at the surface from the lower crustal level [11]. Therefore, we suppose that the plume erupts at $H - x_1 - \Delta x_e \approx 30$ km. The RL base may occur at a depth of $H - x_1 = 100-200$ km, and $\Delta x_e \approx 70-170$ km. At $u_0 = 1.2$ cm/yr, according to (16), the time of the secondary plume ascent from the base of RL to the height of Δx_e is $t = \dfrac{\Delta x_e}{u_0} = 5.8-14.2$ Ma. At $u_0 = 2.4$ cm/yr, $t = \dfrac{\Delta x_e}{u_0} = 2.9-7.1$ Ma. As follows from [12], the temperature of peridotite melting at the RL base at depths of 100 and 200 km is 1500 and 1800°C, respectively. For $T_{ds} = 0$, $T_s - T_{ds} = 1500$ and 1800°C and $T_s - T_1 = \dfrac{T_s - T_{ds}}{2} = 750$ and 900°C. In addition, the following values are accepted to estimate the PH diameter from relationship [11]: $\rho = 3430$ kg/m^3, $B = 2.1 \cdot 10^3$ J/kg, $\varphi = 0.3$, $C = 10^3$ J/kg · °C, $T_{ph} - T_{am} = 100°C$, $\lambda = 3$ W/m · °C. The relationship between the PH diameter D and the thermal power N of the plume source at the core/mantle boundary is presented in Fig. 2 for $t = 2.9-14.2$ Ma, $d =$
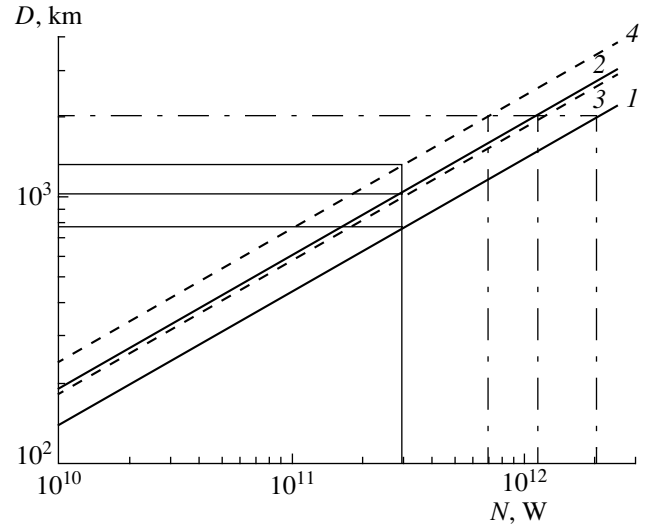

Fig. 2. Diameter of the PH vs. its thermal power at $d = 100$ km, degree of melting (φ) = 0.3, and dynamic viscosity of RL $\eta = 5 \cdot 10^{21} - 10^{22}$ N · s/m^2. (*1*) $x_2 = 100$ km, $\Delta x_e = 70$ km; $\eta = 5 \cdot 10^{21}$ N · s/m^2; $t = 2.9$ Ma; (*2*) $x_2 = 200$ km, $\Delta x_e = 170$ km; $\eta = 5 \cdot 10^{21}$ N · s/m^2; $t = 7.1$ Ma; (*3*) $x_2 = 100$ km, $\Delta x_e = 70$ km; $\eta = 10^{22}$ N · s/m^2; $t = 5.8$ Ma; (*4*) $x_2 = 200$ km, $\Delta x_e = 170$ km; $\eta = 10^{22}$ N · s/m^2; $t = 14.2$ Ma.

100 km, and $\Delta x_e = 70$ and 170 km. As follows from Fig. 2, at plume power $N = 3 \cdot 10^{11}$ W, which corresponds to the power of the Hawaiian plume [9], and at a viscosity of the RL of $5 \cdot 10^{21} - 10^{22}$ N · s/m^2, diameter D that provides for the eruption of the plume may be 770–1310 km. At $N = 10^{11}$ W, $D = 450-770$ km. According to the estimates published in [6], the PH diameter is ~2000 km for two of the largest continental igneous provinces (Mackenzie and CAMP), the largest of their kind in the world, and for the Ontong-Java and Manihiki oceanic lava plateaus. A thermal power of the plume source of $7 \cdot 10^{11} - 2 \cdot 10^{12}$ W should correspond to such a diameter.

REFERENCES

1. R. W. Griffiths and I. H. Campbell, J. Geophys. Res. **96** (B11), 18 295 (1991).

2. E. d'Acremont, S. Leroy, and E. B. Burov, Earth Planet. Sci. Lett. **206**, 379 (2003).

3. R. White, and D. McKenzie, J. Geophys. Res. **94** (B6), 7685 (1989).

4. R. I. Hill, Earth Planet. Sci. Lett. **104**, 398 (1991).

5. M. F. Coffin and O. Eldholm, Geology **21**, 515 (1993).

6. R. E. Ernst and K. L. Buchan, J. Geodynam. **34**, 309 (2002).

7. N. L. Dobretsov, A. A. Kirdyashkin, and A. G. Kirdyashkin, *Deep Geodynamics* (GEO Branch of the Siberian Division of the Russian Academy of Sciences, Novosibirsk, 2001) [in Russian].

8. N. L. Dobretsov, A. A. Kirdyashkin, and A. G. Kirdyashkin, Dokl. Akad. Nauk **393**, 797 (2003) [Dokl. Earth Sci. **393A**, 1319 (2003)].

9. N. L. Dobretsov, A. A. Kirdyashkin, and A. G. Kirdyashkin, Geol. Geofiz. **46**, 589 (2005).

10. A. A. Kirdyashkin, N. L. Dobretsov, and A. G. Kirdyashkin, Geol. Geofiz. **45**, 1057 (2004).

11. A. A. Kirdyashkin, N. L. Dobretsov, A. G. Kirdyashkin, *et al.*, Geol. Geofiz. **46**, 891 (2005).

12. C. Herzberg and J. Zhang, J. Geophys. Res. **101** (B4), 8271 (1996).

13. D. L. Turcotte and G. Schubert, *Geodynamics: Applications of Continuum Physics to Geological Problems* (Wiley, New York, 1982; Mir, Moscow, 1985).

14. G. Shlikhting, *Theory of Boundary Layer* (Nauka, Moscow, 1969) [in Russian].