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Parameters of plumes of North Asia

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Abstract

This paper presents the thermal and hydrodynamic structure of the conduit of a thermochemical mantle plume based on the results of experimental and theoretical modeling of thermochemical plumes. The basic relations for determining the thermal power and diameter of plumes are given. Depending on the geodynamic setting of eruption, the following types of plumes are distinguished: plumes responsible for the formation of large igneous provinces (LIP); plumes with a mushroom-shaped head, responsible, in particular, for batholith formation; and plumes producing rift zones. Using geological data (extent of magmatism, age of igneous provinces, and sizes of igneous areas), we estimated the parameters of plumes in Siberia and its folded framing: mass flow rate of melt, thermal power, depth of origin, and diameters of plume conduits and heads. The plumes responsible for the formation of the Siberian LIP (relative thermal power Ka = 114.9) and the West Siberian rift system (Ka = 37.8 for each of the three plumes) originated from the core–mantle boundary and erupted in the presence of a refractory layer in the lithosphere. The Vilyui plume (Ka = 27.3) originated from the core–mantle boundary and caused the formation of a rift system in the absence of a refractory layer. The plumes that produced the Hangayn (Ka = 6.8) and Hentiyn (Ka = 5.5) batholiths were initiated at the core–mantle boundary and had mushroom-shaped heads. The plumes responsible for the formation of rift zones might have originated from the 670 km discontinuity.

Keywords: experimental and theoretical modeling; thermochemical plumes; free-convection flows; thermal power; large igneous provinces; batholiths; rift zones

Introduction

Heat- and mass-transfer processes at the core–mantle boundary largely determine the operation of the thermochemical machine of the Earth. Thermochemical mantle plumes form at this boundary. The tectonics of the hot fields directly related to mantle plumes largely governs the global geodynamics of the Earth (Dobretsov et al., 1993, 2001, 2005; Kuz'min, 2014; Maruyama, 1994; Zonenshain and Kuzmin, 1983, 1993; Zonenshain et al., 1991).

Considerable attention has been given to the numerical simulation of the formation and dynamics of thermochemical plumes (Kotelkin and Lobkovsky, 2007; Lin and van Keken, 2006; Trubitsyn and Kharybin, 2010; Yang and Fu, 2014; and others). By a thermochemical plume is meant an upwelling free-convection flow (a thermal), with density changes due to composition variations taken into account. In some model experiments, mantle plumes are generated by injection of a low-density low-viscosity fluid into a high-density high-viscosity surrounding fluid, and the simulated plume rises due to the density difference between the plume material and the surrounding fluid (Olson and Singer, 1985; Whitehead and Luther, 1975). In the simulation of so-called starting plumes, the simulated plume, continuously fed by a light fluid, consists of a relatively narrow feeder conduit and a large head (Coulliette and Loper, 1995; Griffiths and Campbell, 1990; Schubert et al., 2001; and others).

A model of a thermochemical plume originating at the core–mantle boundary in the presence of heat flow from the outer core and a local supply of a chemical dope decreasing the melting temperature of the mantle has been proposed (Dobretsov et al., 2003; Kirdyashkin et al., 2004). Data of laboratory and theoretical modeling of thermochemical plumes from their origin to melt eruption from the plume conduit and the conduit configuration in relation to thermal power of the plume source have been presented (Dobretsov et al., 2006, 2008; Gladkov et al., 2012; Kirdyashkin et al., 2005, 2012). Based on the modeling and petrological data, the presence of a refractory layer in the lithosphere at a depth of

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about 100 km has been shown and estimates of some parameters of the Tunguska syneclise have been obtained (Dobretsov et al., 2008; Gladkov et al., 2012).

This paper presents estimates for plume parameters in North Asia based on the thermochemical plume model being developed. The formation of within-plate igneous provinces of North Asia is associated with the activity of mantle plumes (Dobretsov et al., 2013; Kovalenko et al., 2009; Yarmolyuk et al., 2013). Furthermore, the relationship between mantle-plume magmatism and the formation of copper-nickel and noble and rare metal deposits has been revealed (Dobretsov et al., 2010; Kuzmin and Yarmolyuk, 2014; Yarmolyuk and Kuzmin, 2012). Analysis of geochemical and isotopic results taking into account geophysical data for Central Mongolia indicates the plume nature of magmatic activity in Central Asia (Savatenkov et al., 2010). In particular, geological and geophysical data suggest mantle plume activity beneath the Hangayn, and the presence of the Paleozoic Hangayn batholith in the area of the Cenozoic Hangayn Uplift may indicate that the plume activity is inherited from the Late Paleozoic (Mordvinova et al., 2015).

An important element of the geological characterization of the Siberian Platform as one of the most typical regions of continental within-plate magmatism is quantitative estimates of the area of igneous rocks and the extent of magmatism (Vasil'ev et al., 2000; Zolotukhin and Al'mukhamedov, 1991). A review of within-plate magmatism in Siberia and its folded framing is given in (Kuzmin et al., 2010; Kuz'min et al., 2011); the latter paper also presents quantitative data on the time of eruption, the area of igneous rocks, and the volume of erupted magma.

Next we describe the thermochemical plume model, consider its thermal and hydrodynamic structure, give the basic relations for determining its thermal power and diameter, and present estimates for the parameters of plumes in North Asia such as the melt mass flow rate, thermal power, and the diameters of the conduit and head based on geological data on the extent of magmatism for each plume separately and the eruption pattern of the magmas formed by the plumes.

Thermochemical plume model

Analysis of free-convection heat transfer in the outer core based on the model of a horizontal viscous fluid layer heated from below and cooled from above has shown that for the physical properties of the outer core and a heat flux at the core–mantle boundary $q_1 = 10q = 0.6$ W/m^2 (q is the average heat flux on the Earth's surface), the superadiabatic temperature gradient between the top and bottom of the outer core is 0.3 °C (Dobretsov et al., 2001). The outer core is characterized by small superadiabatic temperature gradients and hence small temperature variations. Long existence of high superadiabatic temperature gradients at the core–mantle boundary is impossible because of intense free convection in the liquid outer core. Small temperature gradients in the outer core at the core–mantle boundary make impossible the formation of purely thermal sources responsible for manifestations of modern plumes with a thermal power $N \sim 10^8$ kW (Dobretsov et al., 2006). In connection with the indicated magnitude of the thermal power, we note that the estimated thermal power of the Hawaiian plume source is 3×10^8 kW, and that of the Iceland plume is 3.8×10^8 kW (Dobretsov et al., 2005).

The core–mantle boundary is the region of complex interaction processes between the outer core and the lower mantle: this region includes zones of melting and chemical reactions and may contain significant compositional inhomogeneities (Brandon and Walker, 2005; Garnero and McNamara, 2008; and others) According to the model of thermochemical plume formation (Dobretsov et al., 2003, 2008; Kirdyashkin et al., 2004), a decrease in the melting temperature of the lower mantle near the core–mantle boundary is possible with to a local supply of a chemical dope. A thermochemical plume forms at the core–mantle boundary where the chemical dope decreasing the melting temperature to a value T_{mc} is localized. A decrease in the melting temperature of the mantle below the temperature of the core–mantle boundary leads to melting in the mantle and plume formation. The source of the chemical dope may be the reactions of iron-bearing minerals of the lower mantle (perovskite, magnesiowustite) with hydrogen and/or methane released at the core–mantle boundary (Dobretsov et al., 2003; Kirdyashkin et al., 2004). Hydrogen and methane, having high solubility in an iron + nickel liquid melt can accumulate in the axial part of the funnel-shaped vortices generated by the Coriolis force in the boundary layer of the outer core at the core–mantle boundary (Dobretsov and Kirdyashkin, 2000; Dobretsov et al., 2001). The presence of a chemical dope is suggested, for example, by the fact that the igneous rocks of plumes having thermal power an order of magnitude lower than that of the Hawaiian plume and responsible for the formation of kimberlite pipes (explosion pipes) contain a large amount of CO_2 (12.8–20.5%) (Dawson, 1980). The explosive nature of magma discharge from such plumes indicates a large amount of in plume eruption to the surface, but this amount is difficult to estimate (Dawson, 1980; Fedortchouk et al., 2010). The heat source is the outer liquid core, whose temperature in the area of local chemical doping is higher than the melting temperature of the mantle (Kirdyashkin et al., 2004).

Thus, the conditions for the existence of a thermochemical plume formed at the core–mantle boundary are: (1) the presence of a heat flow from the outer core to the mantle; (2) local supply of a chemical dope from the outer core, which decreases the melting temperature of the mantle to a value T_{mc} lower than the temperature of the core–mantle boundary T_1. Due to the low viscosity and high thermal conductivity of the outer core, intense free-convection flows are produced in the core near the plume base located at the core–mantle boundary. Under the conditions indicated above, these flows provide the heat supply needed to melt the mantle and form the plume conduit. The melt in the plume conduit is a heterogeneous mixture in which the proportion of melt is φ and the proportion of the solid phase is $1 - \varphi$. The heat flow