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Firm mantle plumes and the nature of the core–mantle boundary region

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Abstract

Recent tomographic imaging of thick plume conduits in the lower mantle, when combined with plume buoyancy flux based on hotspot swell topography, indicates a very high plume viscosity of 10^{21}–10^{23} Pa s. This estimated plume viscosity is comparable or may even be greater than the viscosity of the bulk lower mantle, the estimate of which ranges from 2×10^{21} to 10^{22} Pa s. Here I show that both very high viscosity and large radii of lower-mantle plumes can be simultaneously explained if the temperature dependency of lower-mantle rheology is dominated by the grain size-dependent part of diffusion creep, i.e., hotter mantle has higher viscosity. Fluid-dynamical scaling laws of a thermal boundary layer suggest that the thickness and topography of the D″ discontinuity are consistent with such mantle rheology. This new kind of plume dynamics may also explain why plumes appear to be fixed in space despite background mantle flow and why plume excess temperature is only up to 200–300 K whereas the temperature difference at the core–mantle boundary is likely to exceed 1000 K.

Keywords: mantle plumes; seismic tomography; hotspot swells; diffusion creep; grain growth

1. Introduction

Seismic imaging of deep mantle plumes has long been considered as a daunting task [1] because plume conduits are believed to be a narrow feature with a radius of much less than 100 km [2,3] and the wave front healing effect makes such a small-scale feature almost invisible [4]. Traditionally, the Rayleigh–Taylor instability of a hot bottom boundary layer is thought to produce the upwelling of a less viscous plume through a more viscous overlying fluid. Viscosity contrast between a plume and the ambient mantle is typically assumed to be on the order of 10^2–10^3, and this contrast results in the formation of a large spherical head followed by a narrow conduit (Fig. 1). It is thus quite surprising that a recent finite-frequency tomography has resolved quite a few deep mantle plumes with very large radii, typically ranging

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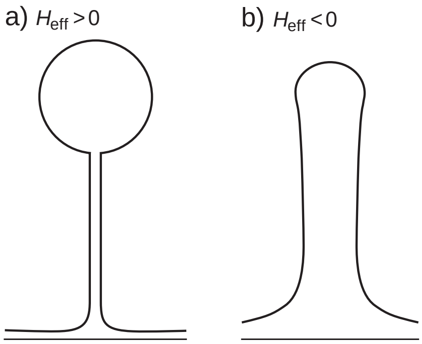

Fig. 1. The different sign of the activation enthalpy results in different plume morphology and dynamics [2,19,30]. (a) In the case of positive activation enthalpy, a less viscous plume rises through a more viscous fluid. A large spherical head forms followed by a narrow plume conduit. (b) Negative activation enthalpy results in a more viscous plume intruding in a less viscous fluid. Plume head and tail have similar radii, and upwelling is more diffuse.

from 200 to 400 km [5]. The lateral dimension of those imaged plumes is one of the most reliable features of the tomography. The reported radii are the minimum estimate based on extensive resolution tests (note: the tomographic images presented by [5] generally show larger radii than these minimum estimates because of blurring inherent in tomography); if plume conduits are narrower, even finite-frequency tomography could not image them. Although it is sometimes claimed that recent dynamic models exhibit similarly thick plumes [6], those plumes with large radii result from the use of temperature-independent viscosity and/or low Rayleigh number (i.e., very high mantle viscosity) in numerical modeling. As I will demonstrate in the following, thick plume conduits, whether created in numerical models or imaged in seismic tomography, imply a serious conflict with the surface observation of plume flux, if dynamics is properly scaled to the Earth's mantle and if plume viscosity is assumed to be lower than the surrounding mantle. The seismically imaged thick conduits, if they are indeed a solid feature as claimed by [5], may require a fundamental rethinking of plume dynamics.

2. Plume buoyancy flux and plume radius

Plume buoyancy flux [7] provides a robust constraint on the flux of hot material brought to the near surface by a plume. The buoyancy flux is calculated from swell excess topography, absolute plate velocity, and density contrast between mantle and seawater, all of which are known with reasonable accuracy. Hawaii has by far the largest buoyancy flux of 8700 kg s^{-1}; other hotspots mostly fall in the range of 1000–4000 kg s^{-1} [7]. These estimates are most likely the upper bound for thermal buoyancy flux because not all of swell topography can be attributed to the thermal buoyancy of mantle plumes. Dynamic tomography due to viscous stress [8] as well as compositional buoyancy resulting from mantle melting [9] may reduce the estimated flux. In addition, small-scale convection may facilitate the thinning of lithosphere [10], either independently of or coupled with plume influx. It is important to note that this upper bound on plume flux corresponds to the lower bound on plume viscosity estimated in the following, thus making my argument robust.

The plume buoyancy flux, $\dot{M}_A$, is related to the plume heat flux, Q, as $\dot{M}_A = \alpha^U Q / c_p^U$, where α is thermal expansivity, c_p is specific heat at constant pressure, and the superscript U indicates the upper mantle values appropriate for surface expression like swell topography. Assuming steady state, buoyancy-driven axisymmetric upwelling through a circular conduit, then, the buoyancy flux of a plume and its conduit radius (a) may be related as [3]:

$$\dot{M}_A = \frac{\pi(\alpha\rho_0\Delta T_p)^2 g a^4}{A\mu_p} \quad (1)$$

where ρ_0 is reference density, ΔT_p, is the amplitude of plume temperature anomaly, g is gravitational acceleration, and μ_p is centerline plume viscosity (much lower than ambient viscosity, μ_0, owing to temperature-dependent viscosity). In the numerical and theoretical models of [3], linear exponential viscosity is employed with a parabolic temperature distribution. The total viscosity contrast is given by $\varepsilon \equiv \mu_0/\mu_p$, and Eq. (1) is valid only when $\varepsilon \gg 1$ (ε is typically 10^2–10^3 in previous studies). The constant A is equal to $(\alpha/\alpha^U)(c_p^U/c_p)(\log(\varepsilon))^2$. The conduit radius is defined here as the radius where the temperature anomaly is one-half its centerline value [3], thus the radius a covers the dominant part of the thermal halo. Note that, because viscosity is much lower at the center of the plume conduit, the mechanical conduit is much