The influence of interior mantle temperature on the structure of plumes: Heads for Venus, Tails for the Earth

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[1] To form mantle plumes with large heads and narrow trailing conduits requires large (>10^2) viscosity variations within the hot thermal boundary layer at the plume source. However, new and published data from laboratory experiments show that if a layer of fluid with a temperature-dependent viscosity is heated from below and cooled from above, convection occurs beneath a stagnant lid, and the interior fluid temperature remains close to that of the hot boundary. Consequently, the viscosity reduction across the hot thermal boundary layer is always <10 and upwellings take the form of discrete plume heads (thermals). Subduction of the stagnant layer (equivalent to recycling lithospheric plates on the Earth) will cool the interior of the mantle, thus increasing the viscosity ratio. Hence, the existence of Earth-like mantle plumes may be a consequence of plate tectonics. An absence of plate tectonics on Venus may lead to upwellings composed of thermals, the surface expression of which are coronae, as well as a smaller core heat flux than on Earth. *INDEX TERMS:* 5430 Planetology: Solid Surface Planets: Interiors (8147); 5418 Planetology: Solid Surface Planets: Heat flow; 8120 Tectonophysics: Dynamics of lithosphere and mantle—general; 8121 Tectonophysics: Dynamics, convection currents and mantle plumes; 8130 Evolution of the Earth: Heat generation and transport

1. Introduction

[2] Flood basalts and associated hotspot tracks on the Earth are thought to be related to mantle plumes constructed of large heads and narrow underlying conduits (i.e. tails). Laboratory [*Whitehead and Luther*, 1975; *Olson and Singer*, 1985; *Griffiths and Campbell*, 1990; *Jellinek et al.*, 1999] analytical [*Loper and Stacey*, 1983], and numerical [*Sleep et al.*, 1988] studies of the dynamics of mantle plumes indicate that in order for plumes to form persistent stable conduits, the viscosity variations within the hot thermal boundary layer must be >10^2. Large viscosity ratios imply that fluid rising within low viscosity conduits ascends much faster than fluid upwelling into the more viscous interior fluid and, thus, that conduits control the buoyancy flux from the hot boundary. Indeed, numerical studies of plume formation [*Farnetani*, 1997], analyses of hotspot swells [*Sleep*, 1990], and the geochemistry of associated basalts [*Schilling*, 1991] indicate that temperature differences between plumes and ambient mantle are a few hundred degrees, implying that the there may be more than a factor of 100 reduction in viscosity across the hot thermal boundary layer in the plume source. However, the origin of large viscosity contrasts at the base of the Earth's mantle is puzzling. In a review paper written more than a decade ago, this issue is highlighted by *Nataf* [1991, page 367]: "what we know of temperature-dependent viscosity convection indicates that the viscosity drop across the lower thermal boundary layer should *never* be larger than a factor of 100, whereas plume models require a viscosity contrast from 100 to 10^4 to form".

[3] Using two-dimensional numerical calculations *Lenardic and Kaula* [1994, page 15,697] argue that the "introduction of [mobile] plate-like behavior in a convecting temperature-dependent medium... can increase the temperature drop across the lower boundary layer." These authors go on to speculate that: 1) the resultant increase in viscosity variations therein causes a change in the morphology of buoyant upwellings; and 2) that the nature of mantle convection in one-plate planets will be different than that in planets with active plate tectonics. In this paper we address both inferences, as well as extend previous theoretical, experimental and numerical studies, by performing and analyzing experiments with time-dependent, three-dimensional convection with both free-slip and no-slip lower boundaries. We suggest that the large viscosity ratios required to form Earth-like mantle plumes are a direct consequence of unusually strong cooling due to mantle stirring driven by plate subduction. In contrast, we argue that weaker cooling associated with an absence of plate tectonics on Venus [cf. *Solomatov and Moresi*, 1996; *Solomatov and Moresi*, 2000] forces the viscosity contrast across the hot boundary layer to be small (order 1). Consequently, convection driven by core cooling is expected to be in the form of discrete plume heads with no persistent tails. The structure of this flow and the resultant heat transfer may explain both the occurrence of corona on Venus' surface as well as the absence of a planetary magnetic field.

[4] For the forthcoming discussion it is useful to distinguish "plumes" from "thermals" (Figure 1). Herein, we use "plume" to describe buoyant upwellings that are constructed of large spherical heads and narrow underlying tails (conduits) [e.g. *Richards et al.*, 1989]. Plume conduits remain connected to the hot boundary layer for time scales that are long in comparison to the time for an upwelling to ascend from a hot boundary through the full depth of an overlying fluid layer. Conversely, "thermal" is used to indicate a discrete buoyant upwelling that is similar in form to a plume head [*Griffiths*, 1986; *Bercovici and Kelly*, 1997].

2. Experiments

[5] Our convection experiments are performed using the apparatus of *Schaeffer and Manga* [2001]. In all of our experiments a layer of Chevron Oronite 16500 Polybutene oil, which has a Newtonian viscosity that decreases approximately exponentially with increasing temperature, is heated from below and cooled from above under conditions of thermal equilibrium. Time-lapse video, shadowgraphs, still photographs and measurements of the surface heat flux, surface temperature and interior temperature as a function of time are used to characterize flows quantitatively. Thermal equilibrium is indicated by constant and equal heat fluxes at the roof and floor of the tank and by an interior fluid temperature that is statistically constant in time.

[6] In all of the experiments the Rayleigh number (Ra = $\rho g \alpha \Delta T H^3/\mu\kappa$) is large ($1 \times 10^7 <$ Ra $< 1 \times 10^9$), and the Prandtl number (Pr = $\mu/\rho\kappa > 10^4$) is sufficiently large that inertial forces are negligible (i.e. the Reynolds number is less than 1). Hence, although the convection is in thermal equilibrium, flows are

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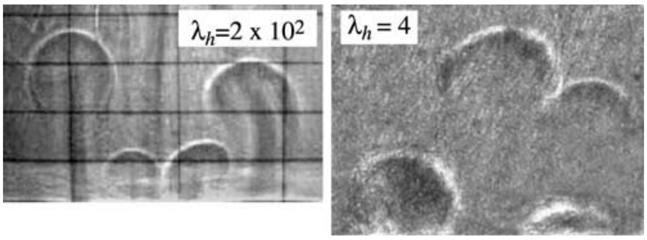

Figure 1. Shadowgraphs showing (left) plumes and (right) thermals. Plumes with large heads and persistent, narrow trailing conduits form when the viscosity ratio λ_h is larger than about 100. Discrete thermals form when λ_h is order 1.

time-dependent, composed predominantly of blobs ascending (or descending) from the hot (or cold) boundaries [*Manga and Weeraratne*, 1999]. The variable H is the height of the fluid layer, g is the acceleration due to gravity, ΔT is the temperature difference across the height H, ρ is the fluid density, α is the coefficient of thermal expansion, μ is the viscosity of the interior fluid, and κ is the thermal diffusivity. In addition to Ra and Pr, it will be convenient for our discussion to introduce the dimensionless temperature $\theta_i = (T - T_c)/\Delta T$, the total viscosity ratio $\lambda = \mu_c/\mu_h$, and the viscosity ratio across the hot thermal boundary layer at the base of the fluid layer $\lambda_h = \mu_i/\mu_h$. Here, the subscripts i, c and h indicate quantities evaluated in the fluid "interior", and at the "cold" and "hot" boundaries, respectively. Because much of the fluid forming the upper cold thermal boundary layer comprises a "stagnant lid" [*Ogawa et al.*, 1991; *Davaille and Jaupart*, 1993; *Solomatov*, 1995] in our experiments, flows are relatively insensitive to the mechanical boundary condition at the top of the tank [*Christensen*, 1984; *Weinstein and Christiansen*, 1991]. Flow ascending from the hot thermal boundary layer, however, may be influenced by the mechanical coupling to the lower boundary. Accordingly, in one series of "no slip" experiments, the oil was in direct contact with the rigid hot boundary. In a second type of "free slip" experiment, a 0.5 cm high layer of relatively dense, less viscous water separated the oil from the rigid boundary. A combination of the consumption of latent heat released on boiling and turbulent mixing in the water layer is employed to maintain an effectively isothermal bottom boundary condition.

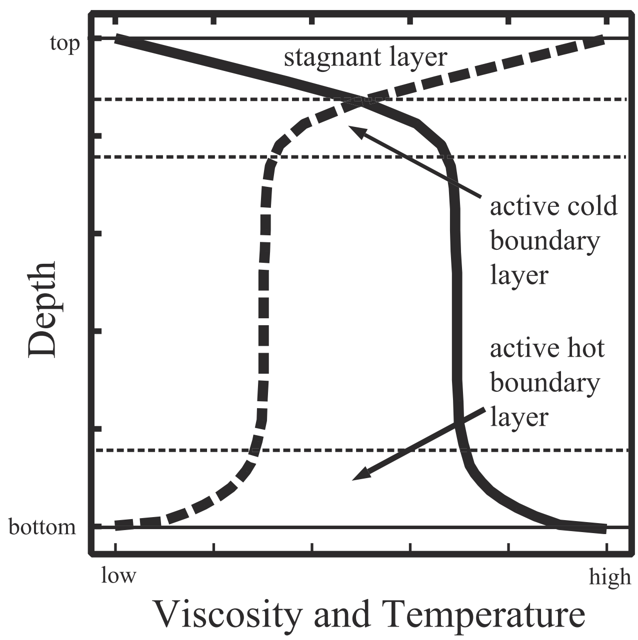

Figure 2. A schematic illustration of the horizontally averaged variation of temperature (solid line) and viscosity (heavy dashed line) with depth during one of our experiments. Also shown are the active thermal boundary layers (thin dashed lines) at the top and bottom of the fluid layer. The high viscosity of the coldest region makes the upper part of the cold thermal boundary layer stagnant. Resultant weak cooling keeps the actively convecting region nearly isothermal and, in turn, the viscosity ratio across the hot thermal boundary layer small.

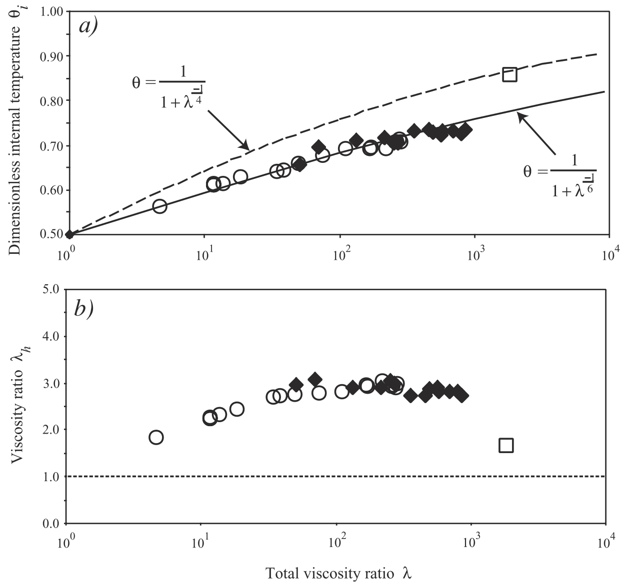

Figure 3. The variation of the (a) dimensionless internal temperature θ_i and (b) viscosity ratio λ_h as a function of the total viscosity ratio λ. Open circles are data from *Schaeffer and Manga* [2001]; diamonds are data from our "no-slip" experiments. The open square is a datum from our "free slip" experiment. Solid and dashed curves in (a) are theoretical predictions for θ_i assuming steady flow and a no slip and free slip lower boundary condition, respectively [*Morris and Canright*, 1984; *Solomatov*, 1995; *Manga and Weeraratne*, 1999].

3. Results

[7] Figure 2 shows schematically the horizontally averaged variation of temperature and viscosity with depth during an experiment. Convection from the cold upper boundary occurs beneath a stagnant lid of relatively viscous fluid, and involves only a fraction of the temperature drop across the cold thermal boundary layer [*Stengel et al.*, 1982; *Richter et al.*, 1983; *Christensen*, 1984; *Giannandrea and Christensen*, 1993; *Solomatov*, 1995; *Moresi and Solomatov*, 1995; *Solomatov and Moresi*, 1996; *Trompert and Hansen*, 1998]. Viscosity varies by at most a factor of 5–10 across the active or convecting part of the cold thermal boundary layer [*Davaille and Jaupart*, 1993; *Deschamps and Sotin*, 2000]. Because thermal equilibrium requires that the heat fluxes at the roof and floor must balance, the temperature difference carried by descending plumes determines the interior temperature and, hence, the temperature and viscosity gradient across the hot thermal boundary.

[8] Our and published data presented in Figure 3a show that $\theta_i \rightarrow 1$ as the total viscosity ratio λ becomes large, regardless of the boundary condition at the base of the tank. Published theoretical scalings for θ_i, which assume that the flow is steady and that the total viscosity ratio $\lambda \rightarrow 1$, capture the overall trend of the data

Figure 4. Cartoons showing (a) stagnant lid convection in the mantle of Venus and (b) mantle convection in the Earth. Relatively strong cooling due to plate subduction results in large viscosity variations in the hot thermal boundary layer at the base of the Earth's mantle. In turn, core cooling gives rise to plumes with large heads and persistent tails. Note that the cold plumes in (a) are continuous downwellings because the viscosity variations in the active part of the cold boundary layer are order 10 ratio $\lambda_c \approx 0.1$ [*Olson and Singer*, 1985; *Davaille and Jaupart*, 1993; *Jellinek et al.*, 1999]. The tails do not persist longer than the time for the plume to descend the layer depth.

well [*Solomatov*, 1995]. As a result, it appears that the time-dependence of the flow does not significantly influence the depth-averaged temperature distribution in our experiments.

[9] Figure 3b shows that the viscosity ratio across the hot thermal boundary layer $\lambda_h \rightarrow$ constant of around 3 (no slip experiments) or potentially about 1.5 (free slip experiments) as λ becomes large, which is consistent with theoretical predictions [*Morris and Canright*, 1984] as well as experimental studies [*Manga et al.*, 2001]. The key implication of all of the experiments and numerical results is that the dynamics associated with large viscosity variations in the cold thermal boundary layer lead to weak convective cooling that, in turn, limits λ_h to order 1.

4. Discussion

[10] A significant consequence of the data shown in Figure 3 is that Earth-like mantle plumes cannot be produced with stagnant lid convection in the diffusion creep limit, even if the flows are time-dependent and three-dimensional. It is also clear that to obtain viscosity ratios sufficiently large to form plumes with large heads and persistent tails an unusually large temperature difference must be carried into the interior fluid by the convection from the cold boundary (Figure 4b). It has been suggested that large viscosity ratios may be due to transient thermal inversions resulting from the ponding of cold lithosphere [*Lenardic and Kaula*, 1994] or, more likely, to cooling of the interior mantle by subduction and subsequent mantle stirring [*Lenardic and Kaula*, 1994; *Meriaux et al.*, 1998]. Indeed, the persistence of low viscosity plume tails over the full depth of the mantle requires that this cooling be distributed over the full depth of the mantle. Therefore, the formation of Earth-like mantle plumes probably *requires* plate tectonics.

[11] In the absence of plate tectonics, our experiments show that the viscosity ratio across the hot thermal boundary layer will be order 1. Hence, we expect that convection driven by core cooling in one-plate planets such as Venus [*Kaula*, 1994] is predominantly in the form of ascending thermals, the surface expression of which may be the nearly circular coronae (Figure 4a). An origin by discrete thermals is consistent with the topography of these features [*Koch and Manga*, 1996; *Smrekar and Stofan*, 1997; *Herrick*, 1999]. In addition, assuming that the surface of Venus is at least 500 Ma old [*Nimmo and McKenzie*, 1998], the observation that coronae are generally around a few hundred kilometers in diameter [*Copp et al.*, 1998] implies that they do not grow with time, suggesting that these features do not overlie plume conduits. If convection is by thermals, the average diameter d of coronae will be approximately twice the thickness of the thermal boundary layer at the base of the mantle. Assuming d = 200 km, say, and taking a viscosity ratio of order 1 to imply a temperature difference across the hot thermal boundary layer ΔT of around 100 degrees [cf. *Koch and Manga*, 1996], we can use our results to constrain the heat flux $q \approx K\Delta T/d$ from the core of Venus. Applying a thermal conductivity $K = 5$ w m^{-1} K^{-1}, the heat flux is around 3×10^{-3} W m^{-2}, which is around an order of magnitude smaller than estimates inferred for the core heat flux in the Earth [e.g. *Davies*, 1988; *Sleep*, 1990]. Indeed, this reduced heat flux may explain the absence of a dynamo in Venus' core [*Stevenson et al.*, 1983].

[12] Not all upwellings on Venus can be attributed to thermals. In particular, some of the younger and more active features on the surface of Venus such as Alta and Beta Regio may be the surface expressions of Earth-like plumes [see the review by *Nimmo and McKenzie*, 1998]. On the one hand, this may imply that coronae are not formed by thermals originating in the hot thermal boundary layer at the base of the mantle, but are instead related to an entirely different process [e.g. *Tackley and Stevenson*, 1993; *Smrekar and Stofan*, 1997]. Alternatively, a Ra sufficiently low [see *Manga and Weeraratne*, 1999] or internal heating can permit large-scale flows to coexist with upwelling thermals, which may be consistent with studies of the gravity and topography of Venus [e.g. *Simons et al.*, 1997]. Another possibility, which is the subject of a numerical investigation currently underway, is that Earth-like plumes result from local thermal anomalies at the base of the mantle, formed as a consequence of strong core cooling due to an overturning and nonuniform ponding [cf. *Jellinek et al.*, 1999] of cold lithospheric material at the core-mantle boundary >500 Myr ago [e.g. *Schaber et al.*, 1992; *Turcotte*, 1993]. In this case, local temperature variations along the core-mantle boundary could cause $\lambda_h > 10^2$. However, the decay of such a thermal transient, and reestablishing of rigid lid convection with $\lambda_h = O(1)$, will be on the time scale for thermal diffusion across the lithosphere thickness h, which is O(100 Myr).

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