Metastable superplumes and mantle compressibility

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[1] Seismically, the African superplume is known to have a sharp lateral transition in V_S and an interface between seismic anomalies with high relief. Such a structure is usually unstable in conventional thermo-chemical convection models. Using a compressible thermo-chemical convection model in which each material has a distinct equation of state, we find an expanded regime of metastable superplumes. In the preferred model, superplume material has a bulk modulus 6% higher and density 2.25% higher than ambient mantle. The inferred physical properties of the superplume are consistent with subducted oceanic crust, simultaneously satisfying seismological, geodynamical, mineralogical and geochemical constraints. **Citation:** Tan, E., and M. Gurnis (2005), Metastable superplumes and mantle compressibility, *Geophys. Res. Lett.*, *32*, L20307, doi:10.1029/2005GL024190.

1. Introduction

[2] The African and Pacific superplumes are the most prominent features in the lower mantle. Both superplumes have low shear velocity (V_S), large shear to compressional velocity (V_P) heterogeneity ratio ($\delta V_S/\delta V_P > 2.5$) [*Su and Dziewonski*, 1997], anti-correlated bulk sound velocity (V_Φ) and V_S [*Masters et al.*, 2000], and sharp lateral V_S transition [*Wen*, 2001; *Wen et al.*, 2001; *Ni et al.*, 2002; *To et al.*, 2005]. Together, these observations indicate that superplumes are compositionally distinct [*Karato and Karki*, 2001; *Wen et al.*, 2001; *Ni et al.*, 2002]. The superplumes are expected to be warmer than background mantle, as inferred from their low shear velocity, correlation with hotspots and the restored position of Large Igneous Provinces [*Burke and Torsvik*, 2004], and anti-correlation with regions of long term subduction (cool mantle). The confinement of chemical anomalies at the base of upwellings is consistent with the dynamics of thermo-chemical convection [*Gurnis*, 1986; *Jellinek and Manga*, 2002].

[3] From seismological observations, the African superplume has a sharp lateral boundary extending steeply above the CMB for 1000 km and has a $\sim$1000 km width in the mid-mantle [*Ni and Helmberger*, 2003; *Wang and Wen*, 2004; *To et al.*, 2005]. Geodynamic models suggest that high Rayleigh number, thermo-chemical convection is required in order to reproduce such sharp lateral boundaries. Moreover, high relief (steep sides) and a broad width have only been found for unstable structures. Our former conclusion that the African superplume is a hot, chemical anomaly that is unstable and short-lived [*Ni et al.*, 2002] is, however, unsatisfying. The conclusion implies that two mantle layers are being stirred together, which raises questions on the origin and uniqueness of the layers: If the density difference between layers is only marginal stable, how could the dense layer form? Are we observing a turnover event, potentially geologically unique, in which an old dense layer is overturning? Given these problems, a new formulation of compressible convection is advanced that provides an alternative dynamic route to metastability consistent with observed structure.

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2. Analytical Prediction

[4] The stability of a dense layer below ambient mantle has been investigated [*Hansen and Yuen*, 1988; *Davaille*, 1999; *Tackley*, 1999; *Jellinek and Manga*, 2002; *Ni et al.*, 2002; *McNamara and Zhong*, 2004], mostly under the assumption that the density difference between the materials, $\Delta\rho_{ch}$, is depth-independent. Considering a chemical structure with an isothermal interior, because of the depth dependence of thermal expansion, the lower portion of the structure would be denser than the surrounding mantle while the upper less dense. The upper portion will rise and become a plume, while the lower portion will sink and become a flat layer with cusps. It is difficult to produce stable thermo-chemical structures with high topography and steep sides when thermal expansion decreases with depth. Past models of stable superplumes all assumed constant thermal expansion [*Davaille*, 1999; *McNamara and Zhong*, 2004]. On the other hand, if $\Delta\rho_{ch}$ is not constant, but decreases with depth, the upper portion of the chemical structure can become denser and stable, while the lower less dense and unstable. Under this scenario, a heated dense material can form a metastable superplume with high topography.

[5] Seismological observations provide hints that $\Delta\rho_{ch}$ may decease with depth. Inside the African superplume, the average V_S reduction is -3%, but the average V_P reduction is -0.5% [*Ni and Helmberger*, 2003; *Wang and Wen*, 2004]. A V_S reduction of similar amplitude is found inside the Pacific superplume [*To et al.*, 2005], but the V_P reduction and vertical extent of the Pacific superplume remain poorly constrained. The density structure of the African superplume is not well constrained by seismology [*Ishii and Tromp*, 1999; *Romanowicz*, 2001], but is unlikely to be 1% denser than the ambient mantle due to the observed high topography. A simple calculation of the shear and bulk moduli (μ and K_S) anomalies (Table 1) shows that unless the African superplume has very low density ($<-2\%$), which has previously been explored [*Ni et al.*, 2002] and will not be considered further in this paper, its K_S must be larger than the values in PREM [*Dziewonski and Anderson*, 1981]. Materials with different K_S have different adiabatic density profiles. The adiabatic density profile of ambient mantle

Table 1. Estimates on the Elastic Moduli[a]

$\delta\rho$	1%	0%	−1%	−2%
$\delta\mu$	−5%	−6%	−7%	−8%
δK_S	3%	2%	1%	0%

[a]From the δV_S and δV_P observations, $\delta\mu$ and δK_S of the superplume material can be estimated by assuming $\delta\rho$ (based on V_S and V_P of PREM model at 2500 km depth). The bulk modulus observed in seismology underestimates the bulk modulus at normal geotherm, because of the elevated temperature inside the superplume.

(material 1), $\rho_{1,ad}$, can be calculated by integrating the equations for self-compression:

$$dP_H = -\rho_{1,ad} g dz$$
$$d\rho_{1,ad} = \frac{Di}{\gamma}\frac{\rho_{1,ad}}{K_{S1}} dP_H \quad (1)$$

where P_H is the hydrostatic pressure; g is the gravity; Di is the dissipation number; γ is the Grüneisen parameter; K_{S1} is the adiabatic bulk modulus of the ambient material. A compositionally distinct material (material 2) with a bulk modulus K_{S2} will have an adiabatic density, $\rho_{2,ad}$, given by:

$$d\rho_{2,ad} = \frac{Di}{\gamma}\frac{\rho_{2,ad}}{K_{S2}} dP_H \quad (2)$$

The compositional density anomaly, $\Delta\rho_{ch}$, is the difference between $\rho_{2,ad}$ and $\rho_{1,ad}$, and can decrease with depth if K_{S2} is significantly higher than K_{S1} (Figure 1). The thermal density anomaly is $\Delta\rho_{th} = -\rho\alpha dT$, where dT is the excess temperature and α is the coefficient of thermal expansion and is depth dependent. We define a "height of neutral buoyancy" (HNB) as the height above the core-mantle boundary where the density is neutral, i.e. $\Delta\rho_{total} = \Delta\rho_{ch} + \Delta\rho_{th} = 0$. By assuming a constant dT with depth (Figure 2), we can calculate HNB and predict the stability of the dense layer for range of zero-pressure densities and bulk moduli.

3. Numerical Method

[6] We modified the finite-element code ConMan [*King et al.*, 1990], using the Truncated Anelastic-Liquid Approximation [*Ita and King*, 1994] for the governing equations. The algorithm and benchmark are described separately (E. Tan and M. Gurnis, manuscript in preparation, 2005). The interface of distinct materials is traced by a marker chain [*Sidorin and Gurnis*, 1998]. The non-dimensional parameters used in the models are: Rayleigh number ($Ra = \rho g\alpha\Delta T h^3/\kappa\eta = 2.2 \times 10^5$ to 2.2×10^6), dissipation number ($Di = \alpha g h/C_P = 0.4$), Grüneisen parameter ($\gamma = \alpha K_S/\rho C_P = 1.333$), normalized surface temperature ($T_0/\Delta T = 0.75$), fraction of density change due to thermal expansion ($\varepsilon_T = \alpha\Delta T = 0.054$), initial thickness of dense layer ($d_0 = 0.08$ to 0.125), and rate of internal heating of the anomalous material ($H = 0$ to 100). The coefficient of thermal expansion is $(1 + 3.2(1 - z)^{8.5})^{-1}$ for most cases, which is obtained from thermodynamic calculation [*Sidorin and Gurnis*, 1998], or is linear in z in some cases. The viscosity is temperature dependent (changing by a factor of 100) and mildly depth dependent (to compensate for the adiabatic temperature gradient). The side walls have reflecting boundary conditions. The horizontal boundaries have free-slip and isothermal boundary conditions. The initial temperature is an adiabatic temperature gradient with small perturbations.

4. Results

[7] We computed a series of 2D thermo-chemical convection models, in which the zero-pressure density anomaly, $\Delta\rho_0$, and bulk modulus, K_{S2}, of the chemically distinct material is systematically varied between $\Delta\rho_0$ of 0.0 and 0.04 and K_{S2} between 1.0 and 1.08. We find a wide range of

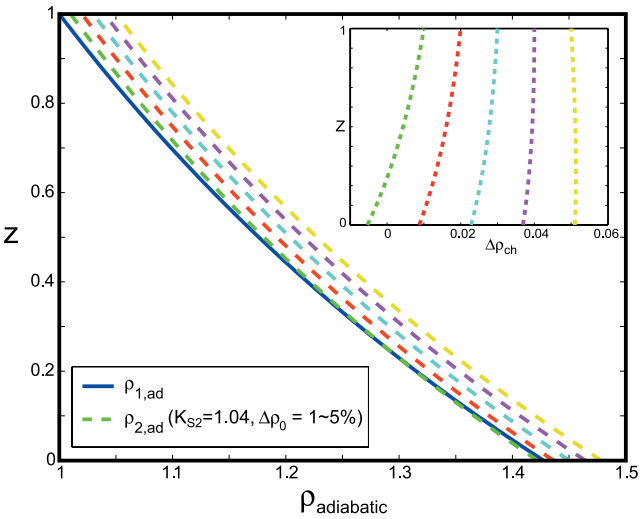

Figure 1. The solid line is the adiabatic density profile of ambient mantle ($K_{S1} = 1$, $\rho_0 = 1$). The dashed lines are adiabatic density profiles of superplume material for $K_{S2} = 1.04$, but variable $\Delta\rho_0$ (1%–5%). The inset shows the chemical density anomaly (compared to ambient mantle) of the superplume material.

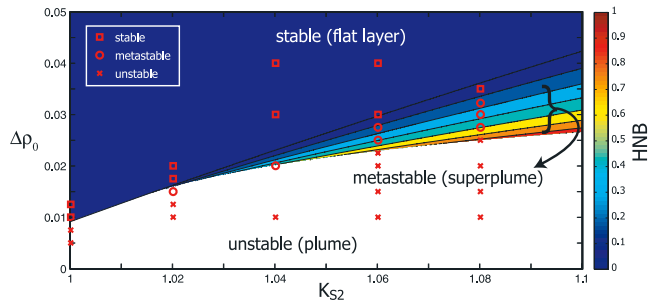

Figure 2. Predicted (color contours) and calculated (symbols) domains for stability of thermo-chemical convection with two materials of differing equations of state. Assuming the excess temperature of the anomalous material $dT = 0.7$, the predicted height of neutral buoyancy (HNB) is contoured. For $K_{S2} < 1.02$, all of the contours converge, such that the transition between stability and instability is abrupt. For $K_{S2} > 1.02$, a domain of metastability becomes possible and expands with higher K_{S2}. Outcomes of finite amplitude calculations in which the convective mode and stability are inferred from morphology and density structure are plotted as symbols.

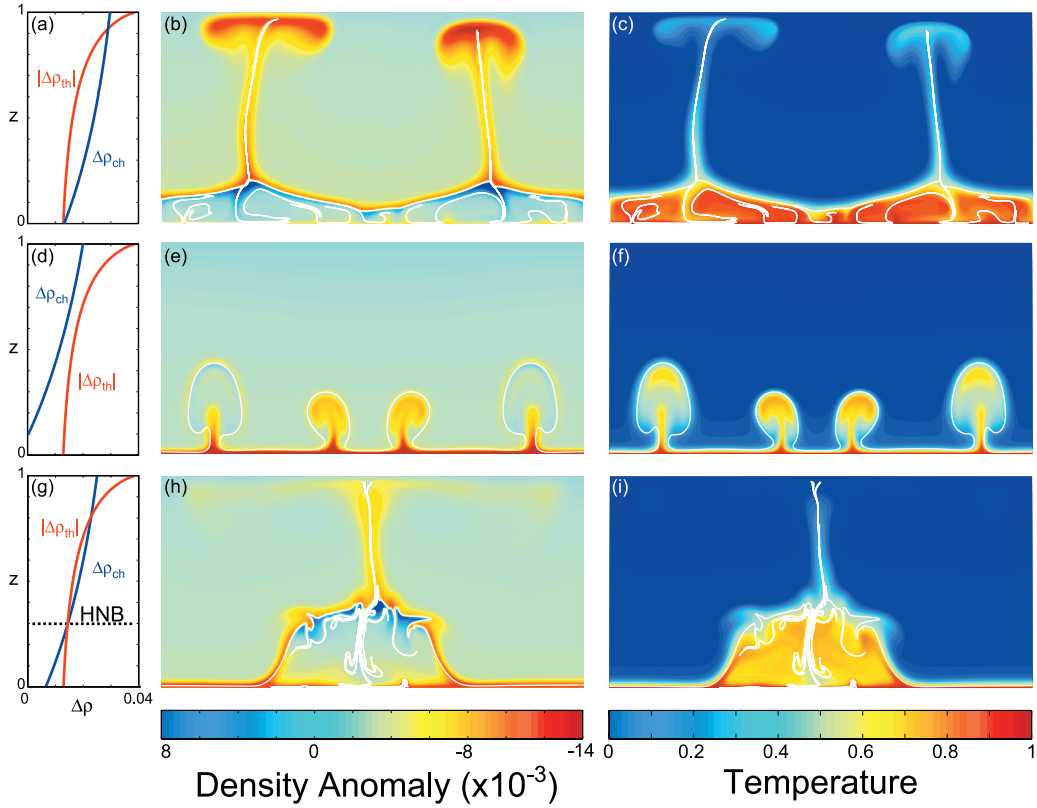

Figure 3. Three calculations with K_{S2} = 1.06 and variable $\Delta\rho_0$. Top row: $\Delta\rho_0$ = 0.03; middle row: $\Delta\rho_0$ = 0.02; bottom row: $\Delta\rho_0$ = 0.025. Left column: predicted thermal (red) and chemical (blue) density anomalies; central column: density anomaly field; right column: temperature field. (a–c) The anomalous material forms a flat layer with cusps. These structures occur within the stable domain. (d–f) The anomalous material forms several plumes. These structures occur within the unstable domain. (g–i) The anomalous material forms a superplume with steep sides. These structures occur within the metastable domain.

thermo-chemical structures that we classify in terms of the morphology and evolution (Figure 2).

[8] First, when $\Delta\rho_0$ is sufficiently large for all K_{S2} investigated, the anomalous material forms a layer with small relief in which sharp cusps occur at the highest elevations of the layer interface (square symbols in Figures 2 and 3a–3c). The HNB is either too low (lower than the initial layer thickness) or non-existent ($\Delta\rho_{total}$ is always positive). In no cases has the layer been regionally swept off the bottom. This structure is stable with the most significant exchange occurring at the aforementioned cusps. This is a dynamic mode previously well studied since it occurs even when the bulk moduli of the two materials are identical. This domain is judged to be stable.

[9] Second, when $\Delta\rho_0$ is sufficiently small for all K_{S2} investigated, even for moderate fractions of overturn times, the lower layer becomes quickly stirred into the upper layer (cross symbols in Figures 2 and 3d–3f). The HNB is non-existent because $\Delta\rho_{total}$ is always negative. A range of morphological states can be found during a period when the dense layer is swept off of the bottom. Some of the morphology resembles that of a metastable superplume (Figure 3h) but can be distinguished by the unstable density structure. This regime has also been studied previously since it is well expressed when the bulk moduli of the two material are identical.

[10] Finally, for K_{S2} larger than 1.02, as $\Delta\rho_0$ is systematically increased, we find a zone of metastability between the two aforementioned states (circle symbols in Figures 2 and 3g–3i). The dense layer is regionally swept off of the base and into a single superplume with steep sides and a roughly flat top slightly higher than the HNB. Thermal plumes emerge from the top of the superplume and entrain some of the anomalous material. The thermal plumes root either along the top of the superplume or along its edge, depending on initial conditions. Because $\Delta\rho_{ch}$ dominates over $\Delta\rho_{th}$ at depths above the HNB, the anomalous material near the top is denser and tends to descend to the HNB, while the opposite is true at the base of the superplume as the anomalous material tends to rise upward. The dynamic effect stabilizes the height of the superplume near the HNB and keeps the average density of the superplume close to neutral. Although the height of the superplume rises and lowers by about 10% as a function of time, the oscillation is not nearly as large as that found in the plume mode and so does not cause the two layers to rapidly stir together. There is a trade-off between $\Delta\rho_0$ and K_{S2}. Similar HNB and superplume morphology can be found by varying the two parameters simultaneously (Figure 2).

[11] We find that Rayleigh number, initial thickness and the rate of internal heating of the dense layer do not substantially influence the stability of the layer. The effect

of internal heating is to increase the internal temperature of the superplume and, therefore, raise the HNB. Even for cases with substantial internal heating, the superplume remains metastable and only raises the level of its top surface. This means that superplumes can be metastable for a wide range of temperatures and persist for long periods of geological time as the mantle temperature and rate of internal heat generation decrease.

[12] For a given $\Delta\rho_0$ and K_{S2}, the domain of metastability is greatly expanded compared with that from models with constant thermal expansion, in which the metastable regime exists only when thermal and chemical density anomalies nearly cancel each other. However, the metastable regime we find is particularly sensitive to the depth dependence of the coefficient of thermal expansion, $\alpha(z)$. Using different $\alpha(z)$, in some cases the metastable regime shrinks and only exists when K_{S2} is greater than 1.1, while in other cases the metastable regime broadens, and metastable superplumes reach almost to the top of the convecting box.

5. Conclusion

[13] From the dynamics, it seems likely that a range of lithologies might satisfy the increased density and bulk modulus we require. We show that the inferred physical properties of superplume material are plausible. For example, pyroxenite, commonly associated with subducted oceanic crust [*Hauri*, 1996], has been shown to be 2% denser with a 5% higher K_S than the PREM value under high pressure-temperature conditions [*Lee et al.*, 2005]. The trade-off between $\Delta\rho_{ch}$ and K_{S2} in our dynamic model and the uncertainty in the high pressure experiment preclude us from uniquely identifying pyroxenite as the material of superplumes. However, if superplumes consist of subducted oceanic crust, it could explain the spatial correlation of superplumes with the DUPAL geochemical anomaly [*Hart*, 1984]. In order for a large mass of oceanic crust to have accumulated at the core mantle boundary without mixing with oceanic lithosphere, an efficient mechanism for the separation of oceanic crust with lithosphere is required [*Christensen and Hofmann*, 1994]. The hypothesis that superplumes consist of subducted oceanic crust can satisfy seismological, geodynamical, mineralogical and geochemical constraints simultaneously.

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