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Thermochemical structure and dynamics of the African superplume

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[1] We present a new three-dimensional (3-D) model of the thermochemical structure of the African superplume region obtained from simultaneous inversion of global seismic and convection-related data. Convection-related observations include the global free-air gravity field, tectonic plate motions, dynamic surface topography and the excess ellipticity of the core-mantle boundary. A 3-D image of the chemically-induced density perturbations provides direct evidence that intrinsically-dense material is entrained within the superplume and concentrated into a rounded structure ~1000 km above the core-mantle boundary. The thermally-induced density perturbations are greater in magnitude than the chemically-induced implying overall positive buoyancy throughout the superplume. The observed morphology and density signatures are consistent with a thermochemical plume that has risen from a compositionally-distinct 'pile' at the base of the mantle and may be currently deforming under the influence of its intrinsic negative chemical buoyancy. **Citation:** Simmons, N. A., A. M. Forte, and S. P. Grand (2007), Thermochemical structure and dynamics of the African superplume, *Geophys. Res. Lett.*, *34*, L02301, doi:10.1029/2006GL028009.

1. Introduction

[2] The African 'superplume' is a large-scale structure near the base of the mantle centered beneath South Africa that exhibits complex seismic characteristics [e.g., *Ritsema et al.*, 1998, 1999; *Ishii and Tromp*, 1999; *Masters et al.*, 2000; *Ni et al.*, 2002, 2005; *Ni and Helmberger*, 2003a, 2003b]. The superplume is most notably characterized by slow shear (S) wave speeds. Detailed waveform analyses have revealed that the superplume possesses a ridge-like morphology and abrupt wave speed reductions near its boundaries [*Ni et al.*, 2002; *Ni and Helmberger*, 2003a, 2003b]. Slow seismic wave speeds may indicate high temperatures [*Karato*, 1993]; however, the morphology and abrupt velocity jumps associated with the structure cannot be easily attributed to temperature variations alone implying a potential chemical origin. This hypothesized chemical component could have considerable consequences for the dynamics of the mantle and, therefore, has led to numerical models and scaled experiments with compositional variations [*Thompson and Tackley*, 1998; *Kellogg et al.*, 1999; *Ni et al.*, 2002; *Tackley*, 2002; *Davaille et al.*, 2003; *McNamara and Zhong*, 2005; *Tan and Gurnis*, 2005].

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[3] Integrated approaches considering both seismic and geodynamic constraints are necessary to provide insight on the relative chemical and thermal contributions to mantle heterogeneity [e.g., *Forte*, 2000; *Forte and Mitrovica*, 2001; *Trampert et al.*, 2004; *Simmons et al.*, 2006]. A recent integrated tomographic study by *Simmons et al.* [2006] simultaneously considered seismic data and a large suite of convection-related geodynamic constraints including global free-air gravity, dynamic topography, tectonic plate divergence and the flow-induced excess ellipticity of the CMB. This study concluded that mantle models that are consistent with both geodynamic and seismic constraints could be found while assuming a dominance of thermal effects on mantle heterogeneity. The models found were reasonable in that, relative to a purely seismically-derived model, no significant increase in model roughness was required to explain the combined observations. However, no attempt was made to model the chemical contributions to the mantle's density field. We have thus expanded on this approach of simultaneously inverting multiple geophysical constraints including those directly sensitive to density perturbations to explore the structure of the African superplume in detail.

2. Thermal Contributions to Mantle Heterogeneity

[4] Our integrated approach involves linearly relating seismic velocity structure ($\Delta \boldsymbol{m}$) to our seismic observations ($\boldsymbol{r}$) as well as the geodynamic observations ($\boldsymbol{s}$). The seismic data set consists of ~46,000 shear wave travel time residual measurements including multi-bounce S-waves, shallow-turning triplicated phases, as well as core reflections and phases traversing the outer core [e.g., *Grand*, 2002]. The convection-related geodynamic observations include the global free-air gravity, tectonic plate divergences and excess ellipticity of the CMB. In addition, we employ dynamic surface topography estimated by removal of the crustal isostatic topography component [*Forte and Perry*, 2000]. These observations are represented as spherical harmonics up to degree 16 and are linearly related to density perturbations via viscous flow theory calculations [*Richards and Hager*, 1984]. The simplified forward model setup can be represented as follows:

$$\begin{bmatrix} \mathbf{L} \\ \mathbf{G}\left(R_{\rho/s}\right) \end{bmatrix} \Delta \boldsymbol{m} = \begin{bmatrix} \boldsymbol{r} \\ \boldsymbol{s} \end{bmatrix} \qquad (1)$$

where we wish to solve for the seismic heterogeneity model ($\Delta \boldsymbol{m}$, slowness perturbations) using iterative inversion techniques. In this relationship, $\mathbf{L}$ is the seismic sensitivity matrix (ray path lengths) and $\mathbf{G}$ is the viscous flow response matrix based on the radially-symmetric viscosity profile developed by *Mitrovica and Forte* [2004]. One of the

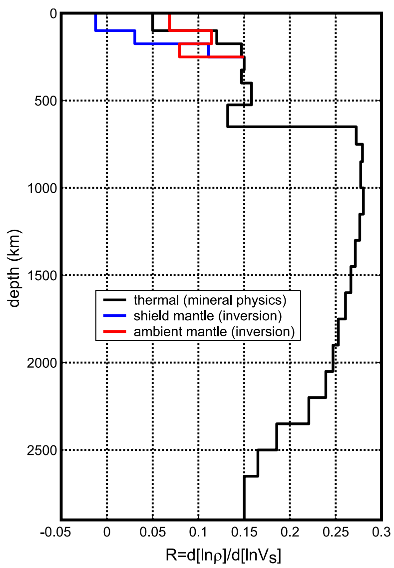

Figure 1. Relationship between shear-wave velocity and density perturbations presented in terms of $R_{\rho/s} = d[\ln\rho]/d[\ln V_s]$. The black line corresponds to values obtained from recent mineral physics estimates for thermal contributions (see text). The blue and red curves are inversion results for mantle corresponding to shield and ambient mantle domains in the upper 250 km.

controlling variables is the scaling between seismic velocity heterogeneity and density perturbations ($R_{\rho/s}$) which is defined as the ratio of relative density (ρ) to shear wave velocity (V_S) heterogeneity by: $R_{\rho/s} = d[\ln\rho]/d[\ln V_S]$. We tested a wide range of radially-symmetric scaling profiles derived from recent mineral physics estimates based on the assumption of thermally-dominated heterogeneity in the mantle [*Karato and Karki*, 2001; *Cammarano et al.*, 2003]. The thermal velocity-density relationship ($R_{\rho/s}^{thermal}$) that yielded the most successful fit to the combined data set after joint inversion was selected (Figure 1). The mantle heterogeneity model $\Delta\boldsymbol{m}^{thermal}$ corresponding to the $R_{\rho/s}^{thermal}$ profile provides an equivalent level of match to the shear-wave seismic data as the purely seismically-derived model. In addition, the jointly-derived model is consistent with the geodynamic constraints; with the exception of dynamic surface topography which is less well fit (Table 1).

[5] Given the likelihood that continental shield roots are chemically- and thermally-distinct relative to the mantle beneath ocean basins [*Jordan*, 1981], we defined the Archean/Proterozoic shield regions [*Mooney et al.*, 1998] in the model parameter space and solved for individual 1-D profiles for the shield ($R_{\rho/s}^{shield}$) and ambient mantle domains ($R_{\rho/s}^{ambient}$) within the upper 250 km (Figure 1). Treating these chemically-distinct mantle domains independently yields an increased fit to the estimated dynamic surface topography (Table 1). Incorporating this simplified, regionalized representation of shallow lateral variations in the density-velocity scaling into the joint inversion also provides for a high degree of reconciliation of all other geodynamic data fields demonstrating the dominance of thermal variations to heterogeneity below ~250 km.

[6] Translating the resultant velocity structure into thermally-induced density perturbations in the lower mantle can be achieved with the relationship: $(\delta\rho/\rho)^{thermal} = R_{\rho/s}^{thermal}(\delta V_s/V_s)$ as per our forward model assumptions. One of the most prominent features of this new joint model (Figure 2) is the African superplume consisting of a low-velocity (low-density) zone at the base of the mantle with a tilted upward extension into the mid-mantle similar to previous seismic models [e.g., *Ritsema et al.*, 1999; *Ni et al.*, 2002]. The deepest part of the structure covers a vast area beneath most of the African continent and has a northwest-southeast trending ridge-like structure extending into the southwest Indian Ocean. This joint solution is generally in accord with previous detailed seismic studies of the region [*Wen*, 2001; *Ni and Helmberger*, 2003a, 2003b]. In addition to the broad basal structure, a low-velocity upward extension directly beneath South Africa reaches distances of ~1500 km above the CMB and displays a quasi-bulbous morphology that may be interpreted as a large plume head that has risen from the basal structure.

3. Chemical Contributions to Mantle Heterogeneity

[7] The thermal modeling results suggest that density perturbations in the mantle are primarily due to lateral temperature variations. However, there still exist significant residual misfits to the dynamic topography, free-air gravity and plate motion observations. This suggests the presence of residual density anomalies that cannot be directly attributed to variations in temperature. Therefore, compositional heterogeneity in the mantle may be an important contributor to the overall density field. In order to account for the combined thermal and chemical density field, we allow the density-velocity scaling $R_{\rho/s}$ to vary laterally, thus creating a fully 3-D relationship between density and shear wave velocity ($R_{\rho/s}^{3D}$). Any significant deviations from the optimal 1-D thermal relationship ($R_{\rho/s}^{thermal}$) can be considered a departure from an isochemical mantle and therefore represents lateral compositional variations.

[8] A 3-D density-velocity relationship including both thermal and chemical contributions, $R_{\rho/s}^{3D}$, must satisfy the following forward model:

$$\mathbf{G}(\Delta m)R_{\rho/s}^{3D} = s\,. \tag{2}$$

Rather than finding a new seismic model, we fixed the seismic model to that obtained by joint inversion of seismic

Table 1. Data Variance Reductions for Joint Seismic-Geodynamic Models

Density/Velocity Conversion (R)	Seismic, %	Free-Air Gravity, %	Plate Divergence, %	Dynamic Topography, %	CMB Excess Ellipticity, km
Simple 1-D	95.8	78	80	44	0.4
1-D with shields	95.8	80	80	64	0.4
3-D	95.8	90	94	76	0.4

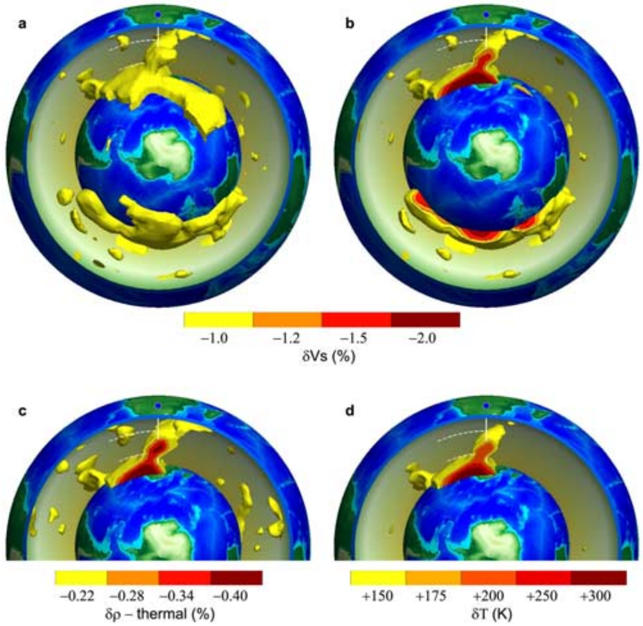

Figure 2. Isocontours of the velocity, thermally-induced density, and temperature fields within the African superplume region. The Earth is sliced open and surface topography is projected onto the CMB for perspective. The white vertical line is for spatial reference and intersects the southern African continent at 25°S latitude and 25°E longitude. The dashed lines correspond to 1000 and 2000 km depths. (a) Shear-wave velocity perturbation field determined by simultaneous inversion of seismic and geodynamic data. (b) Internal view of the shear-wave perturbation field. (c) Internal view of the thermally-induced density field found by converting the velocity field with the velocity-density relationship in Figure 1. (d) Temperature variations derived using recent estimates of the coefficient of thermal expansion [*Karki et al.*, 2001] and the thermally-induced density field. For display purposes, model values south of 55°S and above 700 km depth are excluded.

and geodynamic data considering only thermal contributions discussed above ($\Delta \boldsymbol{m}^{thermal}$, Figure 2) and inverted for $R^{3D}_{\rho/s}$. It should be noted that where seismic constraints are lacking, there should be no significant deviation from the 1-D density-velocity scaling relationship since the joint inversion will attempt to satisfy the geodynamic constraints while assuming only thermal variations. The resultant total (thermal + chemical) density perturbation field becomes: $(\delta\rho/\rho)^{total} = R^{3D}_{\rho/s}(\delta V_s/V_s)$. This acquired total density field provides an excellent fit to the employed geodynamic constraints (Table 1).

[9] The compositional contributions to mantle density heterogeneity are estimated as the residual field obtained by removing the thermal density anomalies from the total density field: $(\delta\rho/\rho)^{chemical} = (\delta\rho/\rho)^{total} - (\delta\rho/\rho)^{thermal}$. These chemically-induced density anomalies are characterized by amplitudes that are very small relative to the thermal density field throughout the majority of the lower mantle. The only exception to this generality is the African superplume region where we detect significant chemically-induced density heterogeneity (Figure 3). Specifically, we find that the African superplume structure requires a positive chemical density anomaly (particularly at mid-mantle depths) that opposes the thermally-induced density anomalies. These characteristics are not found anywhere else in the mid-mantle making this a globally unique feature based on our models. The highest concentration of intrinsically-dense material is detected at about 1000 km above the CMB where we also observe large negative thermal density anomalies and, therefore, higher than average temperature. This positive density component is lower in amplitude than the thermal component and it effectively reduces the total buoyancy of the superplume,

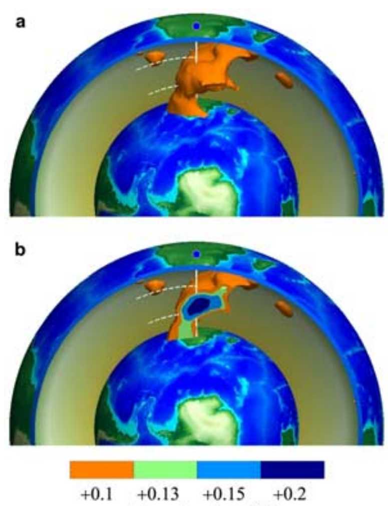

Figure 3. Positive chemically-induced density determined by allowing for a fully 3-D density-velocity relationship ($R_{\rho/s}{}^{3D}$). (a) View of the African superplume region exhibiting a plume-like morphology with a large-volume rounded structure centered at ~1800 km depth directly beneath the southern African continent. (b) View of the internal domain of the positive chemical density field.

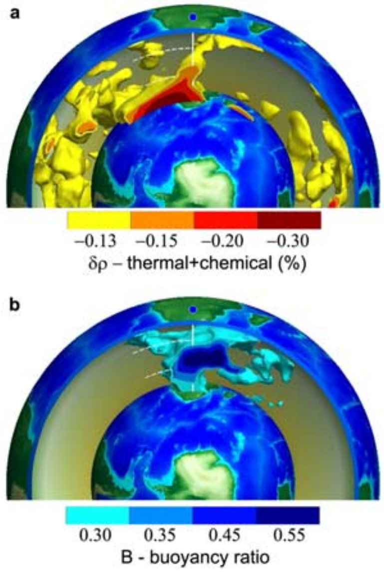

Figure 4. Total density perturbation field and buoyancy ratio $B = |\delta\rho^{chemical}/\delta\rho^{thermal}|$ within the African superplume region. (a) Summation of the thermally- and chemically-induced density fields yields negative density (positive buoyancy) of the superplume structure. (b) The buoyancy ratio field reveals that the superplume buoyancy is strongly reduced by the positive-density chemical component near 1800 km depth. The superplume structure appears to bend eastward within the same region as a response to buoyancy deficiency.

although the structure remains positively buoyant throughout.

[10] The fluid dynamical impact of the effective chemical contribution to the density field can be quantified using the buoyancy ratio: $B = |\delta\rho^{chemical}/\delta\rho^{thermal}|$. Within the African superplume, we find buoyancy ratios within the range 0.3–0.6 with a general increase with distance above the base of the mantle (Figure 4). Buoyancy ratio mapping also reveals that the mid-mantle extension of the superplume (~1800 km depth) may be succumbing to the positive chemical density component and folding eastward, demonstrating a significant loss of positive buoyancy near this depth range and possible stagnation of parts of the upwelling. The high-density chemical component may gradually overcome the thermally-induced buoyancy and ultimately cause collapse of the structure towards the CMB.

[11] When 3-D density-velocity scaling is introduced, significant improvement in fit to the dynamic surface topography (Table 1) is obtained. This improvement is mainly due to inference of compositional heterogeneity in the shallow mantle, especially in the subcontinental tectosphere [e.g., *Forte and Perry*, 2000]. However, it is possible that the acquired shallow mantle heterogeneity affects the outcome of the mid-mantle heterogeneity and thereby dynamic topography could be an indirect contributor to the superplume density heterogeneity. To test this, we performed the entire inversion process by excluding dynamic topography as a constraint and found only slight variations in the mid-mantle heterogeneity models. Therefore the dynamic topography constraint is not a primary contributor to the compositional densities detected in the mid-mantle superplume structure.

4. Conclusions

[12] Our results indicate that the African superplume is an active, buoyant upwelling consistent with the uplift of the African continent [*Lithgow-Bertelloni and Silver*, 1998] and previous mantle flow studies [*Gurnis et al.*, 2000; *Forte and Mitrovica*, 2001]. Active upwelling from the base of the mantle beneath Africa is also supported by study of seismic anisotropy demonstrating an onset of vertical flow in this same region [*Panning and Romanowicz*, 2004]. The morphology of the base of the superplume region is found to be ridge-like with steeply dipping sides based on our joint inversion solutions. Deep mantle ridge-shaped structures, such as the one observed extending into the Indian Ocean, are indicative of compositional variability at the base of the mantle and have been mimicked successfully by numerical flow models with an intrinsically-dense basal layer [*Tackley*, 2002; *McNamara and Zhong*, 2005]. The shape and locations of observed ridge structures in the deep mantle could be primarily a product of past subduction processes acting to sweep dense material into these linear ridge-like piles [*McNamara and Zhong*, 2005; *Quéré and Forte*, 2006].

[13] A large-scale buoyant upwelling rising well above the basal structure is observed directly beneath South Africa. This feature is plume-like and rises at least 1500 km above the CMB. Significant positive chemical density signatures that tend to oppose the thermally-induced density anomaly are found within the upwelling. This substantial chemical density anomaly is not found elsewhere in our global model making this a unique feature in Earth's mid-mantle region. Without sufficient seismic resolution in the region, the compositional effects would not be detected since the joint inversion procedure assuming only thermal contributions (1-D scaling model) would nullify any disagreement between the seismic and geodynamic data sets. It may be that the lack of seismic resolution in other mid-mantle regions (such as beneath the Pacific Ocean) prevents the detection of other significant compositional anomalies.

[14] The density characteristics and morphology of the rounded mid-mantle structure beneath Africa are indicative of an actively rising thermochemical plume that has entrained intrinsically-dense material from a pile at the base of the mantle similar to numerical simulations [e.g., *Ni et al.*, 2002; *Tackley*, 2002]. Additionally, the observed tilting and asymmetry of the upward flow are possibly the response to large-scale ambient flow and the relative motion of the African plate [*Ni et al.*, 2002]. Sweeping of compositionally-distinct mantle material into discontinuous piles coupled with large-scale plumes actively rising from the piles provides a plausible framework for the heterogeneity and dynamics of the African superplume region. An alternative view is that this structure is a manifestation of a 'doming' event where a heated dense layer (discontinuous in this case) ascends and descends through the mantle in a cyclic manner [*Davaille et al.*, 2003]. A potential problem with each of these scenarios is the small amplitude of the

intrinsic chemical density we find in the basal layers. These small amplitudes could be the result of the lessened sensitivity of the geodynamic observables or the underestimation of the thermal density contribution in the basal layers. Future application of the general methodology presented here in conjunction with numerical and physical modeling will help to unravel the source of the intrinsically-dense material observed in the African superplume. Future investigations should include lateral, temperature-dependent viscosity variations in the forward model assumptions and determine its influence on mantle density heterogeneity in and around the superplume structures.

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