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Joint seismic-geodynamic-mineral physical modelling of African geodynamics: A reconciliation of deep-mantle convection with surface geophysical constraints

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Abstract: Recent progress in seismic tomography provides the first complete 3-D images of the combined thermal and chemical anomalies that characterise the unique deep mantle structure below the African continent. With these latest tomography results we predict flow patterns under Africa that reveal a large-scale, active hot upwelling, or 'superplume', below the western margin of Africa under the Cape Verde Islands. The scale and dynamical intensity of this West African superplume (WASP) is comparable to that of the south African superplume (SASP) that has long been assumed to dominate the flow dynamics under Africa. On the basis of this new tomography model, we find the dynamics of the SASP is strongly controlled by chemical contributions to deep mantle buoyancy that significantly compensate its thermal buoyancy. In contrast, the WASP appears to be entirely dominated by thermal buoyancy. New calculations of mantle convection incorporating these two superplumes reveal that the plate-driving forces due to the flow generated by the WASP is as strong as that due to the SASP. We find that the chemical buoyancy of the SASP exerts a strong stabilising control on the pattern and amplitude of shallow mantle flow in the asthenosphere below the southern half of the African plate. The asthenospheric flow predictions provide the first high resolution maps of focussed upwellings that lie below the major centres of Late Cenozoic

volcanism, including the Kenya domes and Hoggar massif that lies above a remnant plume head in the upper mantle. Inferences of sublithospheric deformation from seismic anisotropy data are shown to be sensitive to the contributions of chemical buoyancy in the SASP.

Prof. Claude Jaupart
Editor
Earth and Planetary Science Letters

21 August 2008

Dear Claude,

Enclosed please find our paper entitled "African mantle flow is driven by two superplumes: Implications for asthenospheric flow and driving forces below the African plate" that we are pleased to submit to EPSL for consideration.

We believe that our paper clarifies and provides a new understanding of an important and extensively debated issue in the Earth Sciences, namely: the detailed spatial connection between mantle convection under the African plate and fundamental surface processes such as volcanic activity, interior basin dynamics, lithospheric deformation and the overall movement of the plate itself.

In a series of papers published since the advent of global tomography over 20 years ago, it has long been held that the large seismically-inferred high-temperature anomaly in the deep mantle under southern Africa is a dominant contributor to the convective flow dynamics under the African plate. Indeed, since the first tomography-based flow models by Hager et al. were published in 1985, the 'superplume' below southern Africa has been widely regarded as the single most important contributor to African mantle flow and plate driving force.

In our paper we argue, for the first time, that there is a second major superplume structure under the Cape Verde Islands whose contributions to African plate movement and the underlying convective transport of mass and heat are comparable to those of the southern African superplume (SASP). The heretofore unrecognised dynamical significance of the west African superplume (WASP) under Cape Verde is now revealed through recent advances in tomographic mapping of both thermal and chemical anomalies throughout the mantle under the African plate. We have obtained a new tomography model that shows the WASP is almost entirely dominated by positive thermal buoyancy, in marked contrast to the strong negative chemical buoyancy that compensates thermal buoyancy in the SASP

These discoveries also provide a new understanding of the connection between the stabilising effect of deep seated chemical buoyancy and shallow mantle flow under the African plate. We find that seismic inferences of sublithospheric deformation under southern Africa, measured in terms of azimuthal anisotropy, are sensitive to the presence of chemical buoyancy and hence may be used as a constraint on the strength of compositional heterogeneity in the deep mantle.

The resolution of 3-D structure provided by the new tomography model also yields the first detailed maps of shallow mantle flow which clearly connect Late Cenozoic volcanic structures and adjacent basins to asthenospheric upwellings and downwellings, respectively. We find, in particular, strong asthenospheric upwellings under the Hoggar massif and Kenya domes and focussed downwellings are driving the topographic depressions associated with the Congo and offshore Somali basins.

We anticipate that these new findings will be of interest to colleagues in a broad spectrum of Earth Science disciplines.

In regard to the possibility of conflicts of interest, we request that Mike Gurnis and Clint Conrad should be excluded as potential reviewers who may not provide objective or impartial assessments of our work. Our recent exchanges with these individuals has reinforced this view and we hope you will honour our request.

Sincerely Yours,
Alessandro Forte

African mantle flow is driven by two superplumes: Implications for asthenospheric flow and driving forces below the African plate

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Abstract

Recent progress in seismic tomography provides the first complete 3-D images of the combined thermal and chemical anomalies that characterise the unique deep mantle structure below the African continent. With these latest tomography results we predict flow patterns under Africa that reveal a large-scale, active hot upwelling, or 'superplume', below the western margin of Africa under the Cape Verde Islands. The scale and dynamical intensity of this West African superplume (WASP) is comparable to that of the south African superplume (SASP) that has long been assumed to dominate the flow dynamics under Africa. On the basis of this new tomography model, we find the dynamics of the SASP is strongly controlled by chemical contributions to deep mantle buoyancy that significantly compensate its thermal buoyancy. In contrast, the WASP appears to be entirely dominated by thermal buoyancy. New calculations of mantle convection incorporating these two superplumes reveal that the plate-driving forces due to the flow generated by the

WASP is as strong as that due to the SASP. We find that the chemical buoyancy of the SASP exerts a strong stabilising control on the pattern and amplitude of shallow mantle flow in the asthenosphere below the southern half of the African plate. The asthenospheric flow predictions provide the first high resolution maps of focussed upwellings that lie below the major centres of Late Cenozoic volcanism, including the Kenya domes and Hoggar massif that lies above a remnant plume head in the upper mantle. Inferences of sublithospheric deformation from seismic anisotropy data are shown to be sensitive to the contributions of chemical buoyancy in the SASP.

Keywords:

Africa, Cape Verde, Hoggar, volcanism, superplumes, asthenosphere, seismic tomography, mantle convection, thermal buoyancy, chemical buoyancy, seismic anisotropy

1 Introduction

An outstanding problem in African continental dynamics is the delineation of the mantle convective flow below the African plate and its relationship to widespread Late Cenozoic hotspot volcanic activity, unique basin and swell topography, and ongoing rifting in East Africa (Burke 1996; Ebinger & Sleep 1998). Over the past two decades a wide variety of seismic tomography models have consistently revealed long wavelength images of a large low-velocity (and presumably high-temperature) anomaly below southern Africa extending from the core-mantle boundary to the mid mantle. This deep-mantle seismic anomaly has been interpreted as the possible origin of the African 'superswell': the large-scale anomalously high topography that extends from southern African to the Red Sea along the East African Rift Valley (Nyblade & Robinson 1994). This hypothesis has been supported by independent mantle flow calculations of the origin of African superswell topography using long wavelength global tomography models (Hager et al. 1985; Lithgow-Bertelloni & Silver 1998; Gurnis et al. 2000). Initial estimates of the time-dependent evolution of the dynamic topography of Africa have also been modelled using these tomography-based mantle convection models (Gurnis et al. 2000; Conrad & Gurnis 2003). The most direct expression of the dynamical interaction between the mantle flow under the African continent and associated lithospheric deformation rates have been explored using long wavelength tomography-based mantle flow calculations (Forte et al. 2002; Behn et al. 2004).

To date, tomography based numerical investigations of mantle convection below Africa have used long wavelength global tomography models (e.g. Ritsema et al. 1999), that resolve structures with scale lengths generally in excess of 1000 km. This spatial resolution is insufficient to establish a detailed connection between the surface manifestations of African hotspot magmatism and related topographic anomalies (e.g. the late-Cenozoic volcanic domes, African Rift topography) and the sublithospheric mantle flow pattern below the African plate. A significantly greater horizontal resolution is necessary to discern the asthenospheric flow patterns below the Rift Valley system and the major volcanic domes (e.g. Hoggar, Kenya) that characterise Africa's unique physiography (Fig. 1).

Substantial progress has recently been made in deriving seismic tomography models that approach the horizontal resolution needed to address the modelling challenges outlined above (Priestley et al. 2006; Simmons et al. 2007; Fishwick et al. 2007). In this study we focus on the geodynamic implications of a new joint inversion of combined global seismic and surface geodynamic data sets, in which mineral physical constraints on mantle thermal properties are also included (Simmons et al. 2007). These tomographic inversions yield 3-D distributions of mantle density anomalies that include both thermal and compositional heterogeneity and therefore allow us to explicitly incorporate, for the first time, the stabilising effect of compositional buoyancy in the continental tectosphere and in the lower mantle. We employ these high resolution inferences of mantle density heterogeneity to provide new insights into the origin of the driving forces acting on the African plate and the implications for shallow asthenospheric mantle flow and associated deformation induced anisotropy below the African continent. This new tomography-based model of thermochemical convective flow provides a mapping of the spatial relationship between Late Cenozoic African volcanic activity (Thorpe & Smith 1974; Burke 1996; Ebinger & Sleep 1998) and asthenospheric upwellings below Africa.

2 Tomography based mantle flow model

We determine the convective flow below the African plate using a Newtonian viscous flow model of the mantle (Richards & Hager 1984) that incorporates internal buoyancy forces derived from seismic tomography. The flow predictions are based on a gravitationally consistent, compressible version of the governing fluid momentum equation in a spherical shell in which surface tectonic plates are coupled to the internal buoyancy-driven flow rather than being imposed *a-priori* (Forte & Peltier 1991; Forte 2007).

These flow calculations require two fundamental inputs, namely the rheological structure of the mantle which we represent in terms of a depth-dependent effective viscosity and mantle density perturbations.

The depth-dependent effective viscosity (Fig. 2c) was derived in a joint inversion of global convection-related observables and glacial isostatic adjustment (GIA) data associated with the response of the Earth to melting of the Laurentian and Fennoscandian ice loads (Mitrovica & Forte 2004). A significant characteristic of the profile, in the context of the discussion of shallow mantle flow below Africa, is the relatively weak ($\sim 2 \times 10^{20}$ Pa s) viscosity in the asthenospheric mantle. Despite the nearly three order of magnitude increase in viscosity from the base of the lithosphere to the mid lower mantle, the average viscosity in the top ~ 1000 km of the mantle is close to 10^{21} Pa s, in accord with the Haskell constraint (Mitrovica 1996).

The presence of lateral temperature variations associated with mantle convection will affect the microphysical mechanisms (e.g. diffusion) governing mantle creep rates (Poirier 1985), thereby leading to large amplitude lateral viscosity variations (LVV) which will be superimposed on the effective radial variations we have inferred. A complex numerical treatment of buoyancy induced flow with 3-D viscosity variations shows that the impact of global-scale LVV on predicted convection-related surface observables (e.g. dynamic topography and geoid variations) is relatively modest in magnitude and of the order of current uncertainties in the seismic tomography models (Moucha et al. 2007). The impact of the LVV on mantle flow velocities will be somewhat stronger, mainly leading to a more sharply focussed pattern of upwellings and downwellings than is predicted with only radial viscosity variations. Numerical simulations show, however, that the locations and relative amplitudes of these vertical convective motions are essentially controlled by the distribution of mantle buoyancy and hence their geometry can be robustly mapped out with a simpler flow theory that assumes a depth-dependent viscosity (Moucha et al. 2007).

Density perturbations within the mantle (Fig. 2a,b) were derived through a joint inversion of global seismic and geodynamic data sets in which mineral physical constraints on the thermal dependence of seismic wave velocities and density were explicitly incorporated (Simmons et al. 2007). The model is parameterised into spatial blocks defined by 22 layers extending from the core-mantle-boundary to the surface (with thicknesses ranging from 75 km to 150 km) and lateral dimension ~ 250 km. The geodynamic data sets include global free-air gravity anomalies, crust-corrected inferences of dynamic surface topography, horizontal divergence of tectonic plate motions and the excess or dynamic ellipticity of the core-mantle boundary. Further details concerning these convection-related data sets may be found in Forte & Perry (2000) and Perry et al. (2003). These geodynamic data are jointly inverted with seismic data that include about 46,000 residual travel time measurements associated with seismic S, ScS, sS, sScS, SKS and SKKS phases as well as multi-bounce surface multiples and shallow-turning triplicated phases (Grand 2002).

The joint seismic-geodynamic inversion for mantle heterogeneity satisfies both seismic constraints and geodynamic constraints equally well. This joint model yields mantle convection predictions that fit the observed free-air gravity, dynamic topography, and plate divergence data (up to spherical harmonic degree 16) to a variance reduction of 90%, 94%, and 76%, respectively. The global seismic travel time constraints are satisfied to within 96%.

The global seismic data employed in these joint inversions include seismic phases measured in temporary seismic deployments in southern Africa (the Kaapvaal array), Tanzania and Ethiopia. The waves recorded by these African stations are of key importance because they propagate through the African superplume structure and thereby provide enhanced constraints on this significant lower mantle feature which is known to possess extreme lateral velocity gradients and other complexities (Ritsema et al. 1999; Ni et al. 2002; Ni et al. 2005).

The joint seismic-geodynamic inversions are formulated such that the scaling coefficient between perturbations of density and seismic shear wave velocity varies both radially and laterally thereby allowing an explicit mapping of the 3-D contributions to mantle density anomalies that have both thermal and chemical origins (Simmons et al. 2007). The core of the African superplume structure is characterised by a positive chemical density anomaly that counterbalances the thermally-induced density perturbations (Fig. 2a,b). This compositional density anomaly therefore reduces the total buoyancy of the superplume, although the structure remains positively buoyant throughout.

Within the African superplume, the buoyancy ratios (i.e. the relative amplitude of chemical versus thermal density anomalies) are within the range $0.3-0.6$ and are characterised by an increase with distance above the base of the mantle. The $\sim$0.3 buoyancy ratio at the base of the African superplume is in accord with previous geodynamic inferences of deep mantle buoyancy (Forte & Mitrovica 2001). Numerical and laboratory simulations of thermochemical convection have demonstrated how large scale flow sweeps chemical heterogeneity at the base of the mantle into upwellings (Tackley 1998; Davaille 1999; McNamara & Zhong 2005). The amount of chemical heterogeneity that is entrained upwards is sensitive to the buoyancy ratio and for intermediate values (in the range inferred here) the upwellings develop complex time-dependent morphologies marked by oscillatory rising and sinking motions (Kumagai et al. 2007a; Kumagai et al. 2007b).

For the purpose of the mantle flow calculations, the total (thermal plus chemical) density anomalies and the corresponding buoyancy-driven flow are represented, at all depths, in terms of a spherical harmonic expansion up to degree and order 128. The minimum horizontal scale resolved by this harmonic expansion is $\sim$160 km at the surface, thereby allowing a full resolution of the fine-scale structural variations in the tomography model. The radial variation in the mantle flow field is parameterised in terms of Chebyshev polynomials up to order 65, yielding a maximum radial resolution of $\sim$70 km at mid-mantle depth.

3 Superplume generated mantle flow and African plate motion

The mantle flow driven by the buoyancy of the south African superplume (SASP) is plotted on two orthogonal cross-sections: one following the SW-NE axis of the African Rift system (Fig. 3a) and the other following a W-E traverse of the Kalahari craton (Fig. 3b). The central axis of the large-scale upwelling originating deep in the lower mantle appears to lie directly below the Kalahari craton and this flow then diverges laterally around the cratonic root as it enters the upper mantle (Fig. 3b). We note that it is the combination of the northeasterly tilt of the SASP and its compositional buoyancy at mid-mantle depths (Fig. 3a) that results in the most active centre of vertical buoyancy below South Africa rather than a more northerly location, such as the East African Plateau. The geometry of the flow field driven by the SASP is essentially sub-horizontal throughout most of the upper mantle below the African Rift system (Fig. 3a) and it is characterised by flow rates that are much greater than those of the overlying African plate motion. This marked contrast between the observed surface tectonic plate movement and the sublithospheric flow field is controlled by the substantial reduction of viscosity in the asthenospheric mantle (Fig. 2c).

The character of the flow field changes substantially in the W-E equatorial section passing through the East African Plateau (Fig. 3c). Here we note that deep-seated thermal buoyancy in the mid mantle is again offset by compositional buoyancy and, as a result, the most significant vertical flow rates are confined to the upper mantle, above $\sim$400 km depth. An edge-driven style of convection (King & Ritsema 2000) in the shallow mantle, west of the African cratonic lithosphere, is evident in the predicted flow field (Figs. 3b,c). This near-surface flow field constitutes a second scale of convection that is superimposed on the dominant large-scale flow driven by the deep-mantle superplume. The most significant activity (Fig. 3c) is focussed below the eastern flank of the East African Plateau, under the Eastern Rift, where the vertical flow is strongest. As discussed further below, this focussed shallow upwelling appears to be the source region for the Kenya domes. A particularly noteworthy aspect of the flow field is the strong, eastward dipping mantle downwelling that extends deep under the Somali basin in the Indian Ocean (Fig. 3c). This quasi-linear downwelling, which behaves similarly to a nascent subduction zone, is accommodating the opening of the East African Rift.

A second major mantle upwelling, with a scale and intensity rivalling that of the SASP, is localised below west Africa (Fig. 3d). In the tomography-driven flow the central axis of this west African superplume (WASP) lies below the Cape Verde Islands. The upwelling driven by the WASP diverges laterally upon reaching the base of the west African cratonic root, driving a strong sub-horizontal flow eastward. A remarkable aspect of the convective flow below northern Africa is the large plume-like structure that appears to lie below the Hoggar massif (possibly extending to the Tibesti dome). This 'Hoggar plume' lies below a region of significant thinning of the continental lithosphere (Fig. 3d) and it has been suggested that this is analogous to the thermal structure of mid-oceanic (e.g. Bermuda) swells (Crough 1981). The eastward moving Hoggar plume head appears to be detached from a source region in the lower mantle which may have been the same as that currently feeding the WASP. A possible connection between the source region of the North African volcanic domes and the source of volcanic activity on the Cape Verde and perhaps Canary Islands has been inferred previously on the basis of geochemical analyses of basalts extracted from these localities (Allegre et al. 1981).

The mantle cross-sections reveal a distinctive pattern of heterogeneity under Africa characterised by two separate plume-like structures at upper- and mid-mantle depths under northern and equatorial Africa (Figs. 3c,d) that appear to converge into a single structure (the SASP) under southern Africa (Fig. 3b). The geographical location and horizontal configuration of this V-shaped pattern of plume-related thermal heterogeneity closely resembles the doublet of lower-mantle 'hotlines' generated beneath the African plate in time-dependent numerical convection models that incorporate the past 120 Ma of plate tectonic evolution (Quéré & Forte 2006). These theoretical convection simulations suggest that the far-field effect of a long-lived history of circum-Pacific slab subduction may play a key role in organising the location and evolution of these hotlines under the African plate.

It thus appears that mantle flow dynamics below the African plate are dominated not by a single superplume, the SASP as is generally assumed, but the combined contributions from SASP and WASP. To further investigate the dynamical importance of these two superplumes we consider their contributions to the driving forces responsible for African tectonic plate motion. The plate motions resulting from the mantle flow generated by all buoyancy sources in the mantle are shown in Fig. 4 (black arrows). The mantle flow contributions to African plate motion resulting from the SASP may be tested by removing all buoyancy in this superplume, in a region extending vertically from the core-mantle boundary (CMB) to the lithosphere and extending horizontally from the southern tip of Africa to the Red Sea (i.e. the red-yellow coloured region in Fig. 3a). The consequences for African plate motion are shown in Fig. 4 (blue arrows) and the corresponding perturbation in the rotation rate vector of the African plate is 35%. We note that the motion of the Arabian plate is strongly impacted by the removal of the SASP buoyancy. If we instead remove all buoyancy in the WASP (red-yellow coloured region in Fig. 3d below the Cape Verde Islands that extends down to the CMB) the impact on the surface plate motion is shown in Fig. 4 (red arrows) where the change in the African plate rotation vector is 31%. The dynamical impact of WASP and SASP buoyancy on African surface plate motion are comparable and this underlines the heretofore unrecognized importance of the WASP on African mantle dynamics.

4 Impact of deep-mantle chemical buoyancy on asthenospheric flow

The dynamic importance of the WASP (Fig. 3d) is dependent on its strong thermal buoyancy, in contrast to the opposing chemical buoyancy which instead characterises the SASP (Figs. 3a,b). To quantify the strong stabilising control of the chemical component of SASP buoyancy on mantle flow below Africa, we have carried out a convection simulation in which all density perturbations in the SASP due to chemical heterogeneity (Fig. 2b) are set to zero. As expected, the impact on deep-mantle flow dynamics is strong (compare Figs. 5c and d), to the extent that the lower-mantle upwelling due to the SASP is strongly amplified and dominates the WASP in the absence of chemical buoyancy. The dynamical control of deep-mantle chemical buoyancy also extends to the asthenosphere (Figs, 5a,b), with the strongest impact evident on the horizontal pattern of asthenospheric flow under most of Africa. In the absence of opposing chemical buoyancy, the asthenospheric flow radiates outward in all directions from a region in the shallow mantle under southern Africa that lies above the central portion of the SASP (Fig. 5b), similar to previous tomography-based flow results (Behn et al. 2004).

The predicted convective flow in the asthenosphere (Fig. 5a, see also Fig. 6) shows detailed correlations with all major centres of Late Cenozoic volcanic activity on the African continent (Thorpe & Smith 1974; Burke 1996). Our ability to clearly reproduce these short wavelength aspects of sublithospheric flow is due to two factors: the low asthenospheric viscosity inferred from the joint convection and GIA data (Fig. 2c); the high tomographic resolution of upper-mantle structure below Africa. The strongest centres of vertical upwelling below the African Rift Valley system lie directly below the Ethiopian Plateau and the Kenya Dome, east of the Tanzania Plateau. These two upwellings are clearly separated by a gap that appears to lie under the Turkana depression (Fig. 1). The shallow upwelling centres are part of a much larger scale pattern of flow that is driven by the SASP (Fig. 5a). It is noteworthy that the amplitude of the asthenospheric upwelling below the East African Rift system is comparable to that below the mid-Atlantic ridge and that it can be clearly delineated southward until it intersect the location of the Africa-Antarctica plate boundary. Clearly defined upwelling centres are also evident under the Hoggar and Tibesti massifs in North Africa (Fig. 1), the Cape Verde and Canary Islands, the West African Rift system (e.g. under Cameroon), and a region extending from southern Angola to northern Namibia.

The pattern of asthenospheric flow reveals that the shallow mantle under the Congo Basin is almost entirely surrounded by mantle upwellings. This quasi-circular pattern of upwelling flow drives a well defined sublithospheric downwelling (also seen in Fig. 3c) below the Congo Basin. This downwelling flow and the associated surface dynamic stresses should provide strong control on the evolution and depth of this sedimentary basin, in accord with previous geodynamic hypotheses (Sahagian 1993; Hartley & Allen 1994).

5 Implications for shallow sublithospheric deformation and anisotropy

Studies of mantle seismic anisotropy under the African continent and surrounding oceans provide important constraints on mantle flow patterns and regional variations in tectonic setting (Vinnik et al. 1995; Silver 1996; Barruol & Ben Ismail 2001). Indeed, the geodynamic significance of these seismic constraints has motivated previous tomography-based convection simulations of the flow-induced deformation of the shallow mantle under Africa (Behn et al. 2004) The two principal seismic techniques employed to map African anisotropy are shear wave splitting analyses (Vinnik et al. 1995; Barruol & Ben Ismail 2001; Silver et al. 2001; Gashawbeza et al. 2004; Kendall et al. 2005; Hansen et al. 2006) and azimuthal anisotropy inferred from surface waves (Hadiouche et al. 1989; Sebai et al. 2006) that, respectively, provide detailed local-scale and longer wavelength inferences of flow-induced orientation of mantle fabric.

As a simplified proxy for seismic anisotropy in the mantle, we employ the maximum axis of the strain rate tensor (Gaboret et al. 2003). This axis corresponds to the present-day direction of maximum flow-induced extension or stretching of mantle rocks and it will provide a good first-order estimate of preferred orientation (Gaboret et al. 2003; Behn et al. 2004), except in those regions of the mantle that may be undergoing complex, rapidly changing deformation histories. We predict a pattern of maximum horizontal stretching in the sublithospheric mantle that shows complex regional changes across the African plate (Fig. 6a). The most distinctive feature is the deformation under the East African Rift system that is characterised, as expected, by a local correlation between mantle upwelling and maximum horizontal extension that is everywhere orthogonal to the axis of the rift valleys. This rift-related deformation, which is entirely analogous to that predicted under the mid-Atlantic ridge (Fig. 6a), continues under the southern Indian Ocean and extends to the Africa-Antarctica plate boundary. This rift-related sublithospheric deformation field is orthogonal to that inferred by local shear wave splitting studies (Gashawbeza et al. 2004; Kendall et al. 2005; Hansen et al. 2006) which instead show a pattern of anisotropy that is clearly parallel to the rift axes. One explanation (Gashawbeza et al. 2004; Kendall et al. 2005) for this discrepancy is the impact of volcanic activity in the form of shallow rift-aligned magmatic dykes and eruptive segments on the fast directions of seismic shear wave propagation.

Previous inferences of deformation under southern Africa from seisimc shear wave splitting have been interpreted in terms of present-day mantle flow (Vinnik et al. 1995) or in terms of preserved structures in the cratonic lithosphere (Silver et al. 2001). If seismic surface wave inferences of anisotropy (Hadiouche et al. 1989; Sebai et al. 2006) have sufficient depth resolution, they can potentially discriminate between shallow fossil anisotropy and deeper flow-related deformation. The predicted pattern of sublithospheric deformation under southern Africa (red lines, Fig. 6a) is characterised by the near absence of horizontal extension in the portion of the Kalahari craton that lies directly above the deep upwelling driven by the SASP. We interpet this null in the flow-induced deformation pattern in terms of the intrinsic positive chemical buoyancy that contributes to the stabilisation of the cratonic root below southern Africa. This region of null horizontal deformation, which marks a transition between dominantly E-W deformation on the southern coastal margin of Africa and dominantly N-S deformation to the north of the Kalahari craton, is also evident in long wavelength surface wave inferences (Sebai et al. 2006) of sublithospheric anisotropy (Figs. 6b,c).

Lower-mantle chemical buoyancy in the SASP has a significant impact on the pattern of predicted mantle deformation under the southern portion of the African plate (Fig. 6a). The sublithospheric deformation axes below southeastern Africa predicted in the absence of deep-mantle chemical buoyancy (black lines, Fig. 6a) have higher amplitudes and in some locations nearly orthogonal orientations relative to the prediction that incorporates lower-mantle chemical buoyancy (red lines, Fig. 6a). These calculations suggest that seismic anisotropy is a sensitive probe for the dynamical effect of chemical buoyancy in the deep mantle below the African plate.

6 Conclusions

It has long been assumed that large-scale dynamics under the African plate are dominated by the influence of a single deep-mantle superplume under southern Africa (Hager et al. 1985; Silver et al. 1988; Lithgow-Bertelloni & Silver 1998; Behn et al. 2004), namely the SASP (Figs. 3a,b). Recent progress in joint seismic-geodynamic mapping of the 3-D distribution of chemical heterogeneity in the mantle (Fig. 2b) has allowed us to re-examine the mantle dynamic importance of the SASP relative to a second large-scale buoyant upwelling under western Africa, the WASP (Fig. 3d), whose dynamical significance has until now been unrecognised. We find that the negative chemical buoyancy inferred within the core of the SASP partially cancels its positive thermal buoyancy and thereby exerts a strong stabilising control on the mantle flow driven by this plume (Fig. 5). This chemical stabilisation has important consequences for the relative importance of the African plate driving force generated by the SASP, which is now found to be comparable to that generated by the WASP (Fig. 4).

An important characteristic of the chemical heterogeneity in the SASP is its rather remarkable vertical extent (Fig. 2b), such that significant compositional buoyancy is inferred more than a 1000 km above the CMB. This distribution of chemical heterogeneity, in particular the tilted aspect of the SASP and the associated 'tendrils' or 'blobs' of chemically distinct mantle that appear to be shedding away from the main upwelling centre (for example in Fig. 3b), is very similar to that found in the most recent laboratory experiments of thermochemical convection (Kumagai et al. 2007a; Kumagai et al. 2007b) that have been carried out with intermediate buoyancy ratios similar to those we infer for the SASP. These fluid-mechanical experiments suggest that the unique compositional heterogeneity within the SASP will imply a thermal, chemical and dynamical evolution which will differ markedly from that of the WASP whose dynamics is dominated by thermal buoyancy. Prepared by LLNL under Contract DE-AC52-07NA27344.

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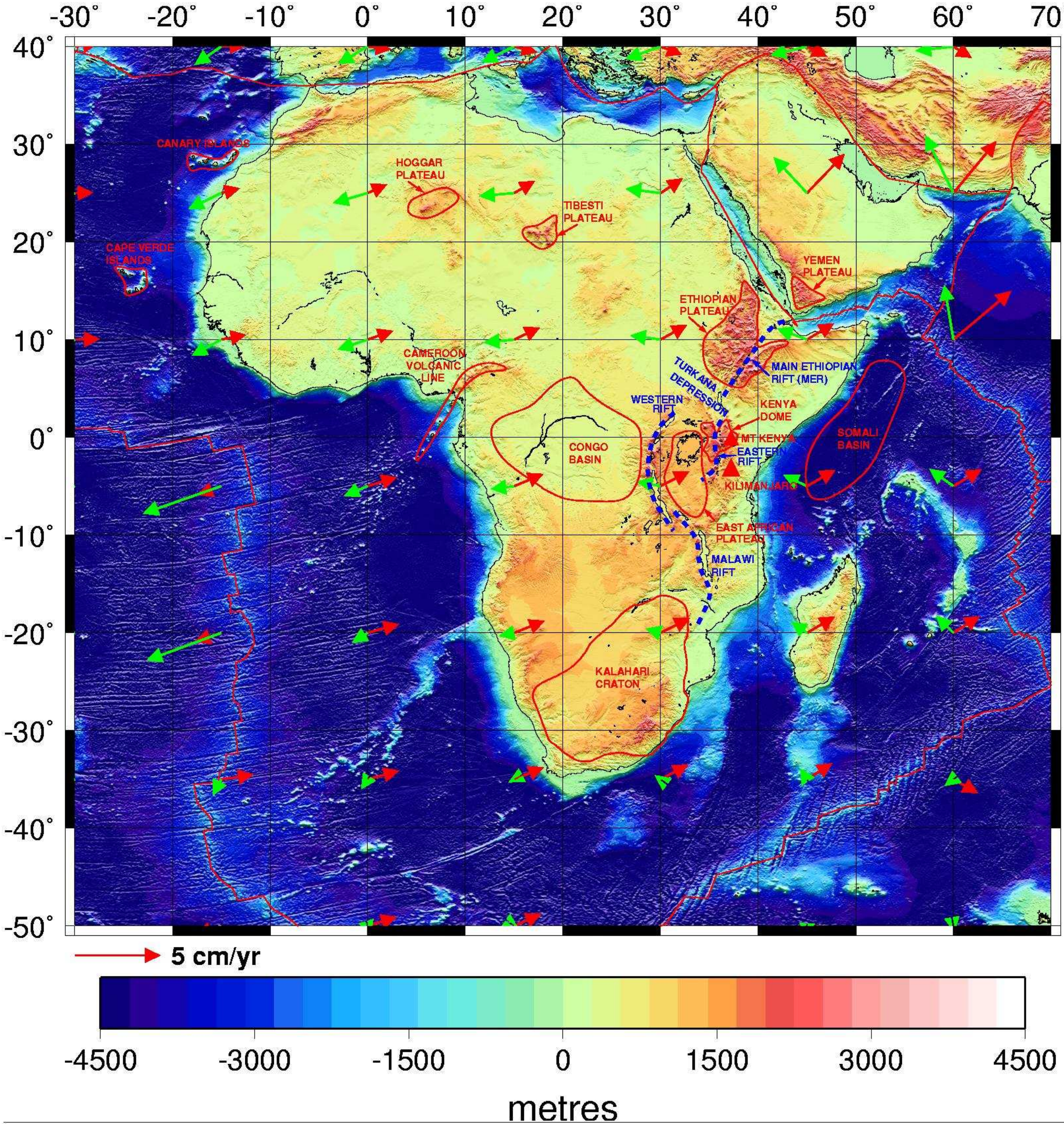

Figure 1. Topography, bathymetry and velocity of the African plate illustrating the surface physiography and tectonic structures of the African continent and adjoining oceans. The major volcanic edifices, large basins and plateaus are outlined and labelled in red. The major features of the East African rift system are indicated by the blue coloured dashed lines and labels. The associated volcanic peaks (Mt's Kenya & Kilimanjaro) are identified by red triangles. The green arrows indicated absolute plate velocities in a reference frame dominantly determined by Pacific hotspot tracks (Gripp & Gordon 2002). The red arrows show absolute plate velocities in the Indo-Atlantic hotspot reference frame (Quéré et al. 2007).

Figure 2
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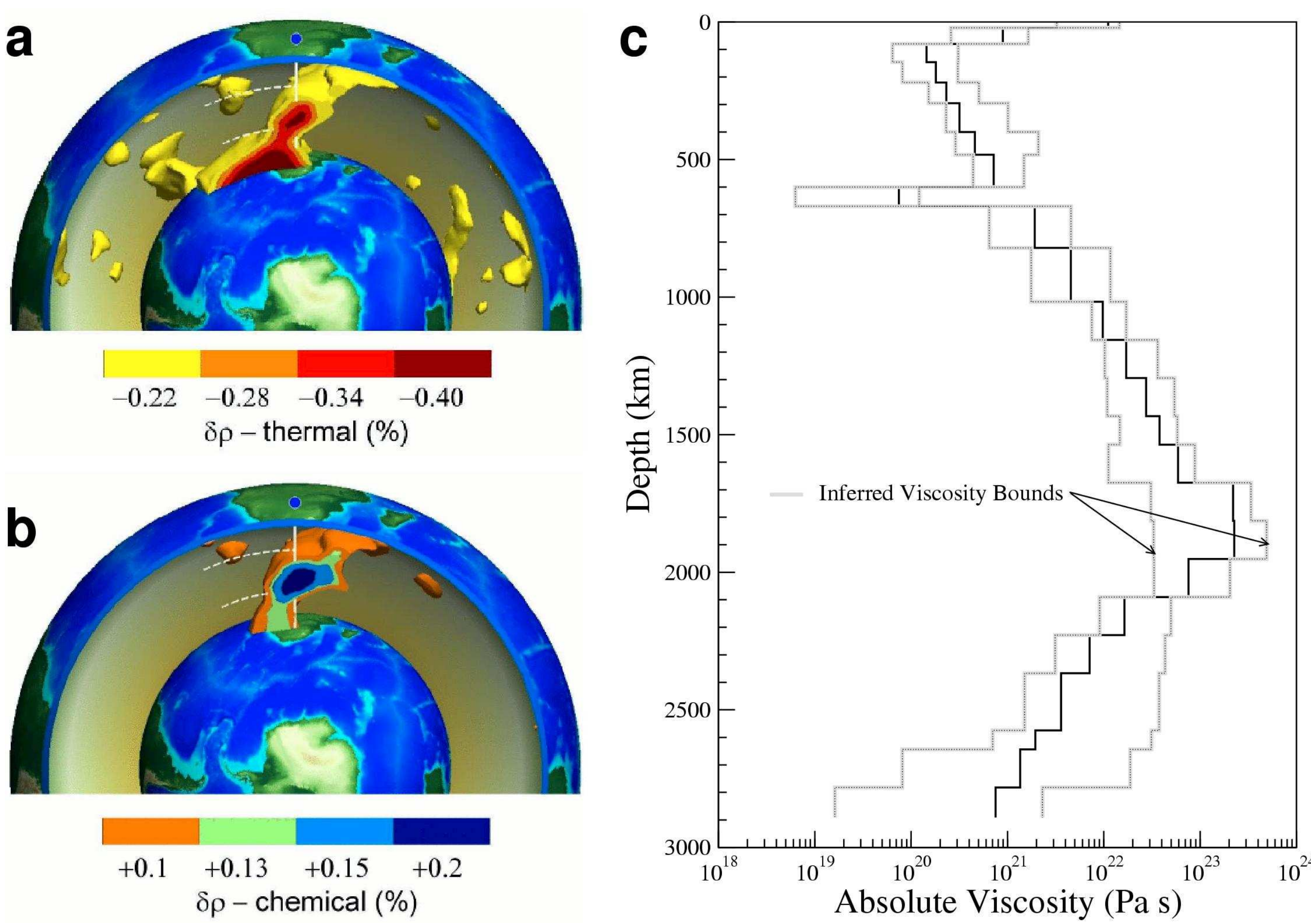

Figure 2. Mantle density and viscosity structure employed in calculating mantle convective flow. (a) Isocontours of thermally induced density field within the African superplume region (Simmons et al. 2007). The Earth is sliced open and surface topography is projected onto the CMB for perspective. The 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. For display purposes, model values south of 55°S and above 700 km depth are excluded. (b) As in (a), except the chemical (non-thermal) contributions to mantle density are shown (Simmons et al. 2007). (c) Depth-dependent effective viscosity (dark solid line) derived in Occam-style inversions of combined glacial isostatic adjustment and convection-related data sets (Mitrovica & Forte 2004). The dashed grey lines illustrate the uncertainty in the viscosity inference determined by varying the smoothing weights in the Occam inversions.

Figure 3
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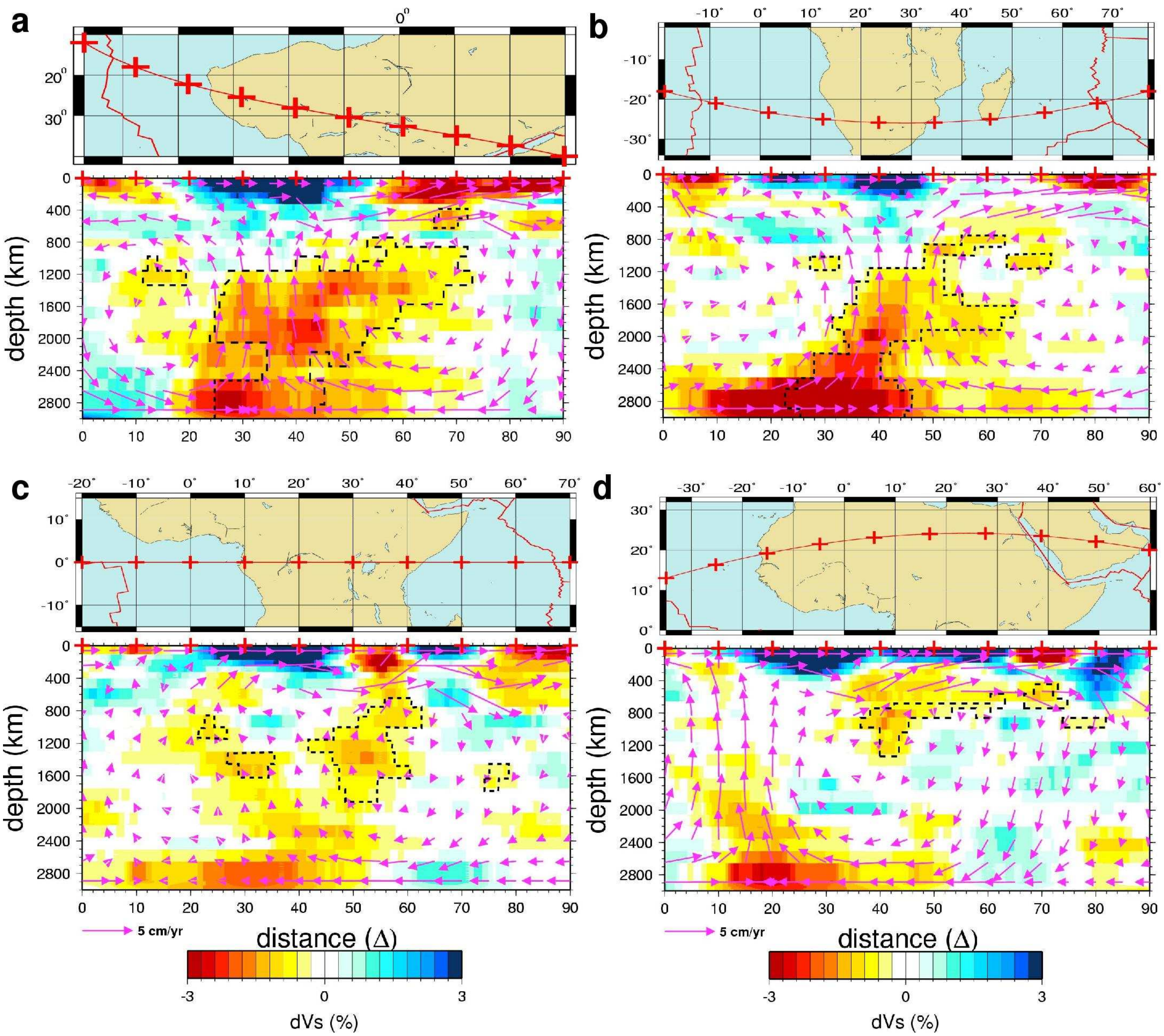

Figure 3. Mantle convective flow below the African plate. Each frame (a–d) contains a vertical mantle cross-section passing through the African continent. The geographic location of each cross section is shown by the red curve in the superimposed map frames and the red crosses spaced at 10° intervals mark the surface locations shown in the underlying cross-section frames. The coloured blocks in the cross-sections (colour scale at bottom) show the seismic shear velocity anomalies from the joint seismic-geodynamic tomography model (Simmons et al. 2007). The dashed black lines enclose mantle regions in which the chemical density anomaly (Fig. 2b) exceed $+0.1\%$. The magenta arrows superimposed on the seismic velocity anomalies show the mantle flow velocities (arrow scale at bottom left) predicted on the basis density and viscosity structures in Figure 2. Note: the vertical depth scale is exaggerated ($\times$ 13) relative to the horiztonal scale.

Figure 4
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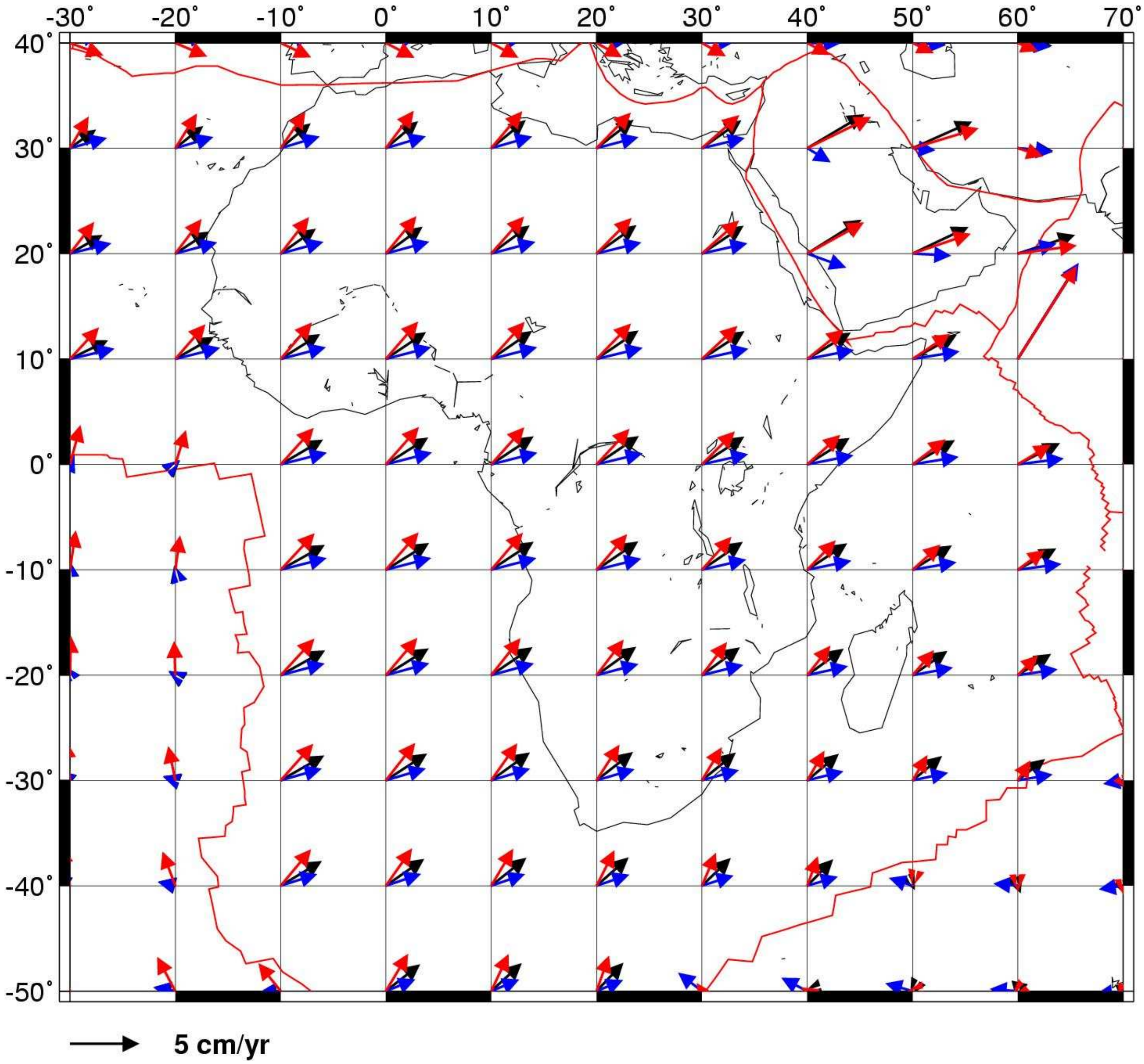

Figure 4. Impact of superplume-driven mantle flow on African plate motion. The black arrows represent the plate motion driven on the basis of the total (thermal and chemical) mantle density and viscosity structures shown in Figure 2. The red arrows represent the plate motion after removing the mantle flow contributions due to the buoyancy of the West African Superplume (WASP) shown in Figure 3d. The plate motion resulting from the removal of the buoyancy of the South African Superplume (SASP) shown in Figures 3a,b is represented by the blue arrows. In these calculations of African plate motion we ignore the small relative motion between the Nubian and Somali plates and assume both plates are rigidly attached. In all cases the plate rotations are expressed in the global no-net rotation frame of reference.

Figure 5
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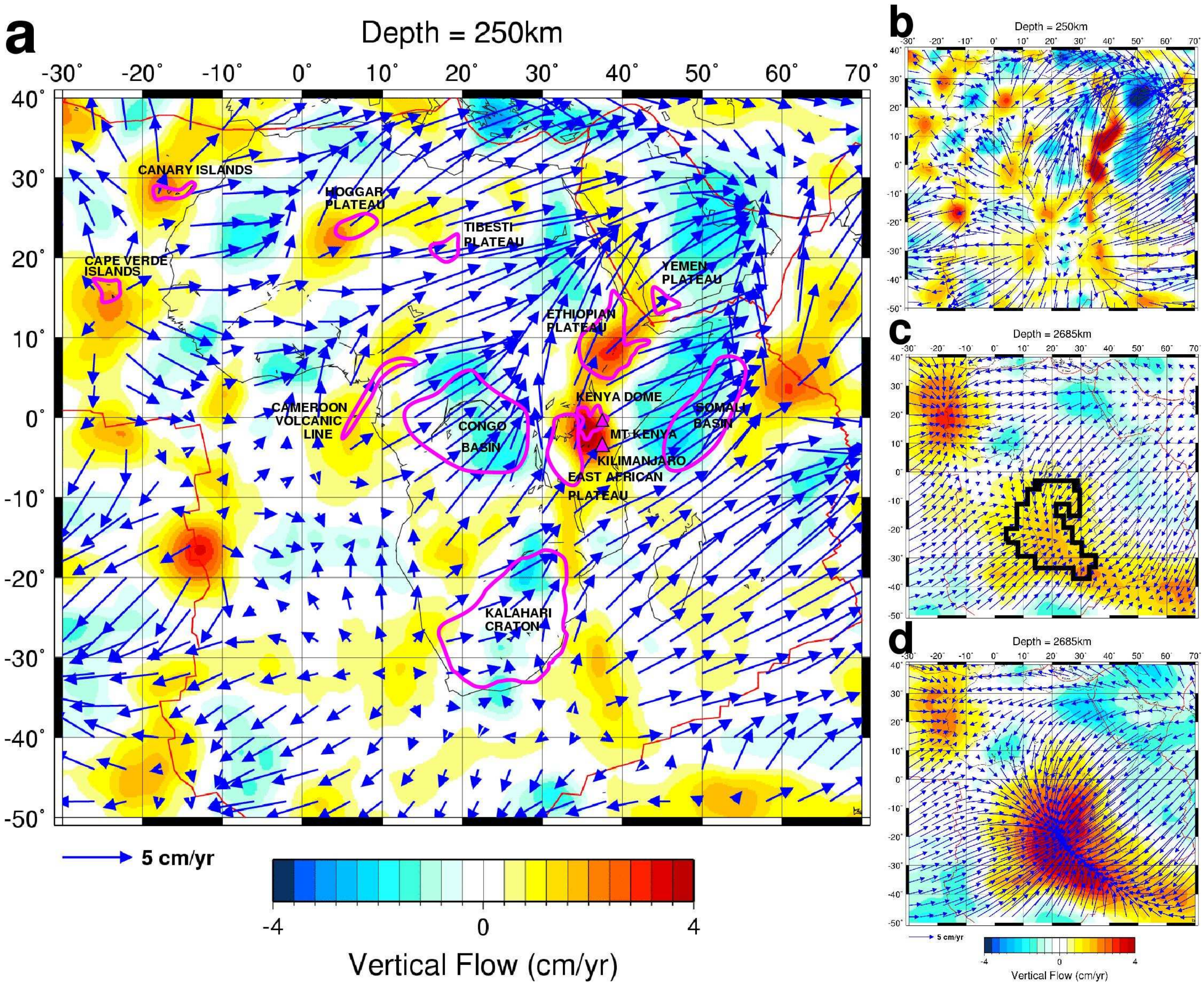

Figure 5. Predicted mantle convective flow below the African plate. **(a)** The predicted rates of horizontal (arrows) and vertical (contours) flow at a depth of 250 km are obtained from the same viscous flow calculation shown in Figure 3. The major surface physiographic features (volcanic plateaus, basins) identified in Figure 1 are outlined in magenta. **(b)** Flow predicted at 250 km depth when all chemical buoyancy in the SASP (Fig. 2b) is set to zero. **(c)** As in (a), except the flow is shown at a depth 2685 km (a couple of hundred kilometres above the CMB). The dark black polygon encloses those portions of the mantle in which the chemical density anomaly (Fig. 2b) exceeds $+0.1\%$. **(d)** Flow predicted at 2685 km depth when all chemical buoyancy in the SASP is set to zero.

Figure 6
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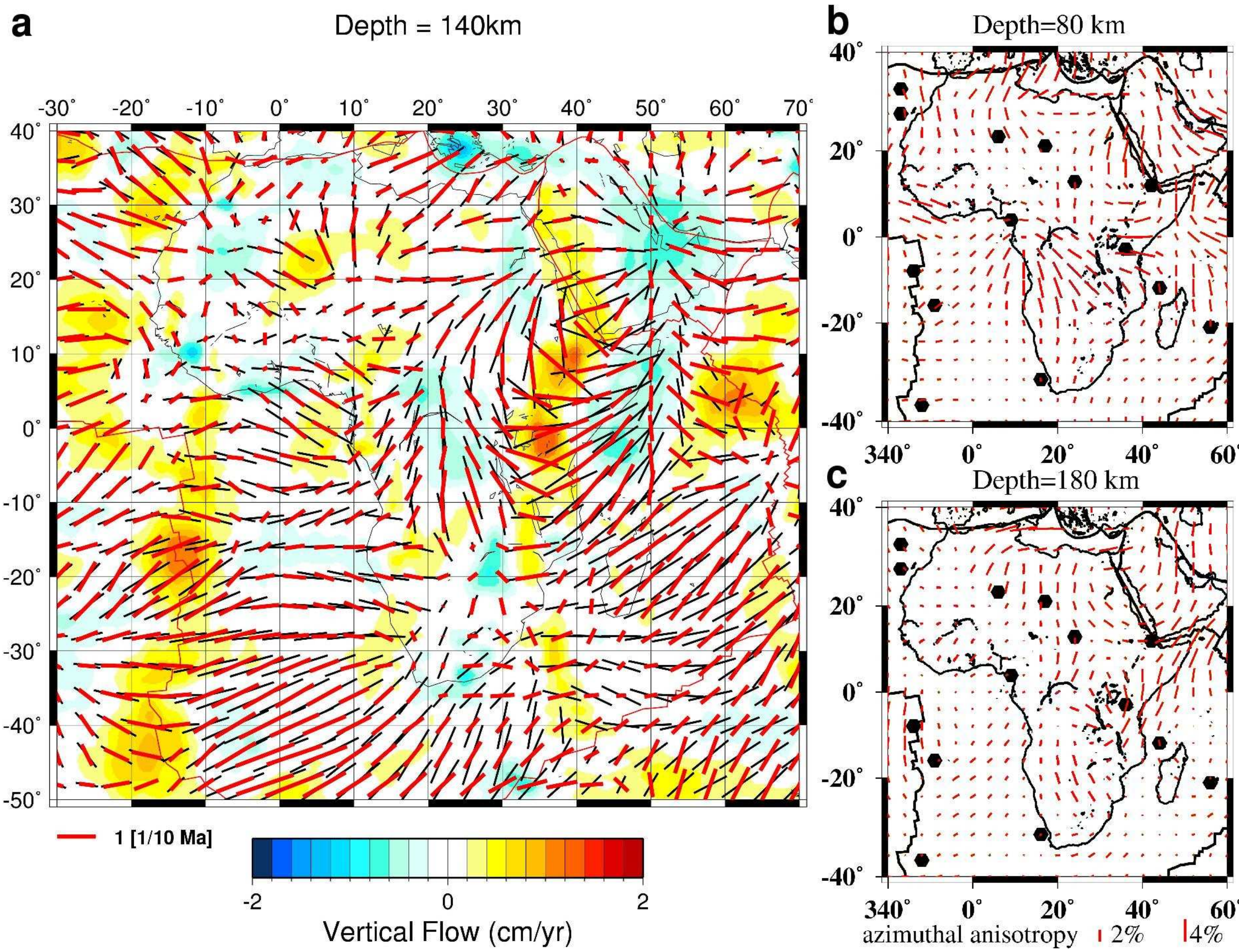

Figure 6. Convection induced deformation below the African lithosphere. (a) The horizontal components of the maximum stretching rates (red lines, scale shown at bottom left of map) are predicted at 140 km depth using the same flow calculation in Figure 3. The vertical flow rates are represented by the colour contours (scale at bottom). Black lines show predictions of maximum stretching rates when all chemical buoyancy in the SASP is set to zero. The stretching axes are used as proxies for interpreting seismic anisotropy. The maps shown in frames **(b)** and **(c)** are seismic surface wave inferences of azimuthal anisotropy (Sebai et al. 2006) at depths above and below the predictions in map (a).