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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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A B S T R A C T

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. We present a tomography-based model of mantle convection that provides an excellent match to fundamental surface geodynamic constraints on internal density heterogeneity that includes both compositional and thermal contributions, where the latter are constrained by mineral physics. The application of this thermochemical convection model to the problem of African mantle dynamics yields a reconciliation of both surface gravity and topography anomalies to deep-seated mantle flow under the African plate, over a wider range of wavelengths than has been possible to date. On the basis of these results, we predict flow in the African asthenosphere characterised by a clear pattern of focussed upwellings below the major centres of late Cenozoic volcanism, including the Kenya domes, Hoggar massif, Cameroon volcanicline, Cape Verde and Canary Islands. The flow predictions also reveal a deep-seated, large-scale, active hot upwelling below the western margin of Africa under the Cape Verde Islands that extends down to the core–mantle boundary. The scale and dynamical intensity of this 'West African Superplume' is comparable to the 'South African Superplume' that has long been assumed to dominate the large-scale flow dynamics in the deep-mantle under Africa. We evaluate the plausibility of the predicted asthenospheric flow patterns through a comparison with seismic azimuthal anisotropy derived from independent analyses of African shear wave splitting data.

1. Introduction

A longstanding problem in African geodynamics 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 and Sleep, 1998). A closely related problem is the development of a physical model that can reconcile the multiple surface geophysical manifestations of convection under the African plate, over a wide range of length scales, with the inferences of mantle heterogeneity provided by seismic tomography. Recent improvements in the seismic sampling of 3-D mantle structure under Africa by temporary seismic arrays (e.g. Kaapvaal, Tanzania, and Ethiopia) provide considerable impetus for the development of such a geodynamically consistent convection model. The outstanding challenge we wish to address here is the construction of a convection model that provides optimal fits to a wide suite of geodynamic data that constrain both the mantle density and viscosity structure, and to achieve this reconciliation over the widest possible range of horizontal length scales. We thereby wish to establish the predictive power of this model and explore the implications for flow dynamics below Africa.

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 and 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 and Silver, 1998; Gurnis et al., 2000). Initial estimates of the time-dependent evolution of the dynamic topography of Africa have

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also been modelled using these tomography-based mantle convection models (Gurnis et al., 2000; Conrad and Gurnis, 2003). The most direct expression of the dynamical interaction between the mantle flow under the African continent and associated lithospheric deformation rates has 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. With this spatial resolution it is difficult to establish a detailed connection between sublithospheric mantle flow patterns and surface manifestations of African hotspot magmatism and related topographic anomalies (e.g. late Cenozoic volcanic domes and massifs) 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, 2009; Fishwick et al., 2007).

In this study we focus on the geodynamic implications of a new joint inversion of global seismic and surface geodynamic data sets, in which mineral physical constraints on mantle thermal properties are also included (Simmons et al., 2007, 2009). These tomographic inversions yield 3-D distributions of mantle density anomalies that include both thermal and compositional heterogeneities. We are therefore able to incorporate, for the first time, a complete 3-D mapping of the stabilising effect of chemical buoyancy in the African lower mantle and continental tectosphere. Our first challenge is to verify the geodynamic consistency of these new inferences of mantle buoyancy through direct comparisons with surface geoid, gravity, topography anomalies and surface plate motions.

The subsequent challenge is to employ the inferred density anomalies to elucidate the influence of the buoyancy-driven mantle flow on the motion of the African plate and the implications for

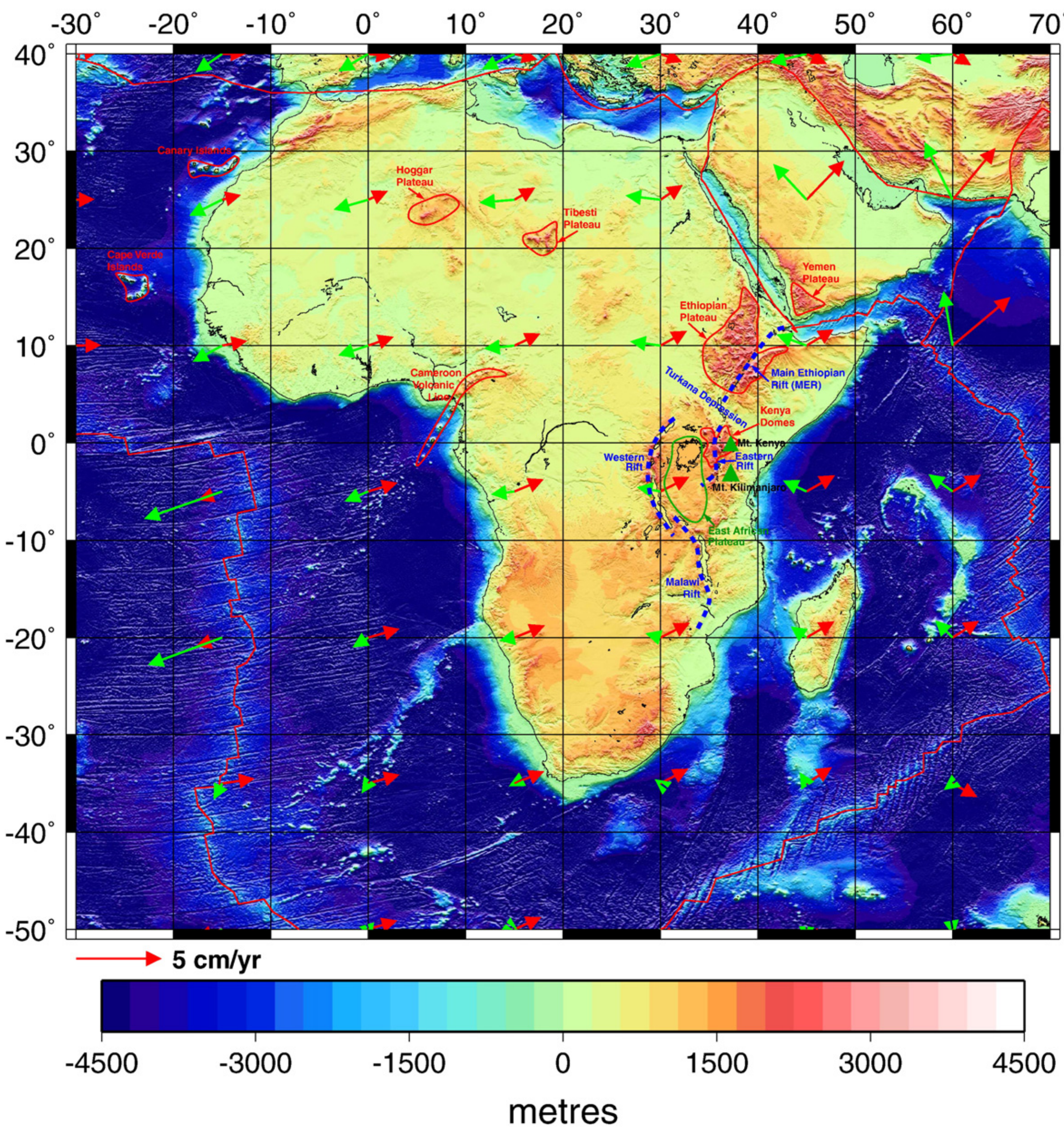

Fig. 1. Topography, bathymetry and velocity of the African plate illustrating the surface physiography and tectonic structures of the African continent and adjoining oceans. The major volcanic edifices, large basins and plateaus are outlined and labelled in red. The major features of the East African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