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Changes in African topography driven by mantle convection

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The topography of the African continent is characterized by large-scale extensional features such as the East African Rift, widespread volcanic activity, and anomalously subsided basins and uplifted domes. These enigmatic surface features have long suggested that the African continent is shaped by significant dynamic forcing originating in the underlying mantle. Here we simulate mantle convection backwards in time to reconstruct the evolution of dynamic topography of Africa over the past 30 million years. We show that the current high topography of the East African Rift system is due to the southward propagation of a topographic swell that encompassed the western margin of Arabia and the Afar region before 30 million years ago. We suggest that this dominant swell formed in response to the upwelling of the African superplume and the relative northward motion of the African tectonic plate over it. We also find that the adjacent Congo Basin has gradually subsided over the same time period in response to convective drawdown in the mantle. We conclude that much of Africa’s recent geological history is driven by buoyancy forces in the mantle. Our findings have important implications for African volcanism, erosion, sediment transport and river-basin drainage patterns.

Subject terms: Geodynamics • Seismology • Structural geology

At a glance
Previous tomography-based investigations of mantle convection below Africa\textsuperscript{7, 8, 9, 10} are based on long-wavelength global tomography models\textsuperscript{11} that resolve structures with scale lengths generally in excess of 1,000 km. A better horizontal resolution is necessary to discern the asthenospheric flow patterns below the East African Rift (EAR) system, major basins (for example Congo, Angola) and volcanic domes (for example Hoggar, Tibesti) that characterize Africa’s unique physiography. Substantial progress has recently been made in deriving regional and global tomography models that approach the horizontal resolution needed to address these modelling challenges\textsuperscript{12, 13, 14, 15}.

This progress in seismic imaging has permitted the construction of a new model of mantle flow driven by thermochemical density variations inferred from recent global joint inversions of seismic and geodynamic data\textsuperscript{14, 16}. These flow predictions provide the first high-resolution connection between focused upwellings in the asthenosphere and the major Late Cenozoic volcanic domes in Africa\textsuperscript{16}. (See the Methods Summary and Supplementary Information for details concerning the convection model.)

In this study we focus on the time-dependent geodynamic implications of these new predictions of present-day mantle heterogeneity and flow. We employ a time-reversed global convection calculation (see Supplementary Information) to reconstruct mantle heterogeneity and flow over the past 30 million years, starting from the present day (Fig. 1a). We then compute the corresponding changes in convection-driven dynamic topography (rock uplift/subsidence) of the African continent and evaluate their compatibility with geological constraints. Inferences of palaeo-elevation from geological observations such as thermochronometry and river incision are sensitive to topography changes and thus provide constraints on past surface elevation.

Figure 1: Present-day and 30-Myr-before-present mantle temperature structure, calculated flow and African dynamic topography.
Our objective is a detailed reconstruction of the history of uplift/subsidence of the African continent, in particular the EAR system, the Congo–Angola margin and the Congo Basin, starting with the reconstructed dynamic topography at 30 Myr before present as a reference base level (Fig. 1d).

We employ the term ‘dynamic topography’ to refer to topography that is supported by convectively maintained stresses generated by viscous flow throughout the mantle and buoyancy variations in the lithosphere. This differs from previous studies that remove up to 600 km of upper-mantle heterogeneity and consequently miss the topography contributions from the upper mantle and thermal isostasy of the stable lithosphere. We also note that although the results presented here focus on the African region, they are derived from a fully global backwards convection model as opposed to previous backwards convection simulations that were...
limited to a regional ‘box’ model with imposed side and surface boundary conditions. Our simulations are therefore consistent with the global mantle flow (including the far-field effects from deep flow outside of the African plate) and they are unbiased by the imposition of a priori, prescribed plate velocities.

Our calculations of the convection-driven topography changes also include important dynamical effects from compositional heterogeneity in the mantle. In particular, the joint seismic–geodynamic inference of the density structure of the lithosphere under ancient cratons is chemically distinct from the oceanic lithosphere, and thus it is almost neutrally buoyant\textsuperscript{13, 14, 18}. Moreover, the chemically distinct portions within the deep-mantle upwellings under Africa act in opposition to their thermal buoyancy\textsuperscript{16} and the backwards evolution in time of this chemical heterogeneity is also included.

To rigorously model the evolution of surface topography, we would require the complete knowledge of the pre-existing topography at 30 Myr. However, over time, this past topography would be modulated by the effects of erosion, sediment transport and any other near-surface process that cannot be modelled by mantle convection, such as crustal deformation and lithospheric modification. For this reason, we present the change in dynamic topography (Fig. 2) relative to the modelled dynamic topography at 30 Myr (Fig. 1d) and thus only quantify the amount of rock uplift/subsidence originating from changes in mantle buoyancy over this time.

\textbf{Figure 2: Reconstructed African dynamic topography with respect to 30 Myr.}
Evolution of African dynamic topography in a Africa-fixed reference frame, relative to the predicted topography at 30 Myr (Fig. 1d), for a, 25 Myr, b, 20 Myr, c, 15 Myr, d, 10 Myr, e, 5 Myr, and f, 0 Myr (present day). Results are shown for the V2 viscosity model (see Supplementary Information) and the TX2008 density model.

Starting at 25 Myr (Fig. 2a), the high topography associated with rifting in the vicinity of the future Red Sea (Fig. 1d) rapidly progresses southward, first raising the Ethiopian plateau, followed by the East African plateau. The progression of this topographic swell is due to the combination of changes in mantle flow driven by the deep-seated African superplume and the relative northward motion of the African plate over it (Fig. 1). Thus the present-day dynamic topography high
associated with the EAR has developed over the past 30 Myr and is consistent with a number of palaeo-altimetry inferences\textsuperscript{19,20}. For example, the palaeo-slope of the East African plateau must have existed before 15 Myr to facilitate the 13.5 Myr Yatta lava flow in Kenya\textsuperscript{20}. Our model suggests that by 15 Myr, the maximum uplift of the East African plateau reached \( \sim 500 \) m and by 10 Myr this increased to \( \sim 1,000 \) m. Moreover, the coeval growth of topography and post-30 Myr volcanism within the EAR zone\textsuperscript{21} is not a mere coincidence. There clearly exists a relationship between plume-driven uplift, melting and volcanism, but additional modelling of the different processes involved is needed to further clarify this relationship.

Coinciding with the uplift of the EAR system is the subsidence of the regions that flank it. There is subsidence of the northern portion of the Arabian plate in conjunction with the uplift of the Red Sea Rift as the Arabian plate tilts northward in accord with regional geodynamic models\textsuperscript{22} and geological observations\textsuperscript{23,24}. West of the EAR there is subsidence in the Congo Basin. Remarkably, over the past 30 Myr, the uplift associated with the EAR does not cross into the present-day Congo drainage basin, but rather surrounds its north-eastern edge. The result is a line of uplift along the EAR system where the main Ethiopian rift section is oblique to the Red Sea rift and the Kenyan portion of the EAR (Fig. 2e,f). These peculiar oblique characteristics are directly linked to the buoyancy-driven uplift in the convection model and are not the result of any imposed surface boundary conditions.

The most recent uplift, occurring over the past 10 million years, is shown in Fig. 3. The most conspicuous prediction over this time interval is the relative subsidence of the western half of the Arabian plate in contrast to the continuing uplift of the Ethiopian and East African plateaux. Other areas of uplift include the Hoggar plateau and the Angola coastal margin. Although the predicted \( \sim 150 \) m uplift of the Angolan margin is less than the \( \sim 400 \) m inferred from offshore stratigraphy\textsuperscript{25}, it is temporally consistent with the latter. Additional subsidence within the Congo Basin in the past 10 Myr is concomitant with the surrounding uplift in the EAR and the Angolan margin. We also find that further uplift along the EAR system shows the development of two separate domes during this time interval, corresponding to the Ethiopian and Kenyan plateaux.

Figure 3: Reconstructed African dynamic topography with respect to 10 Myr.
Recent evolution of African dynamic topography in an Africa-fixed reference frame, relative to topography at 10 Myr, for a, 5 Myr and b, 0 Myr (present day). Results are again shown for the V2 viscosity model (see Supplementary Information) and the TX2008 (ref. 14) density model.

We summarize the uplift and subsidence histories and their uncertainties, with respect to the dynamic topography existing at 30 Myr, for three different regions of the African continent in Supplementary Fig. S2. A considerable increase in uplift of the East African and Ethiopian plateaux is observed at about 15 Myr. The total uplift of these plateaux over 30 Myr is in the range of 400–1,200 m, depending on the mantle density and viscosity model used (see Supplementary Information for model uncertainties). In contrast, the approximate 500 m of subsidence in the Congo Basin seems to be independent of the models.

The present-day dynamics of the Congo Basin and the implications for its recent history have also been the focus of two recent studies\(^\text{26, 27}\). Analyses of stratigraphic sequences indicate that the Congo Basin has accumulated about 1 km of sediments since the early Cretaceous, with only a few hundred metres of accumulation in the Late Cenozoic\(^\text{28-30}\). Two geodynamic scenarios have been proposed to explain the present-day low Congo topography and corresponding negative free-air gravity anomaly. The first scenario\(^\text{26}\) involves an anomalously high-density object, most likely of compositional origin, within the lithosphere as the driving force for the downward deflection of the lithosphere. In contrast, the second scenario\(^\text{27}\) suggests that even though such a mechanism could be consistent with the gravity data it would be gravitationally unstable and would not have survived for the duration of the basin’s history. This scenario thus proposes a convective drawdown resulting from the surrounding mantle upwellings associated with the EAR (shown in ref. 16) in conjunction with the dynamics of a slightly denser anomaly in the lithosphere below the Congo Basin, in the manner of the first scenario\(^\text{26}\).

To test these two hypotheses and isolate the cause of Congo subsidence, we remove from the tomography model (by an iterative area-depth averaging) the cold (dense) anomaly that is clearly visible below the Congo Basin in the mantle cross-sections (Fig. 1). The region of interest that delineates the Congo anomaly is between the depths of 100 and 400 km and has an areal extent of about $5 \times 10^6$ km$^2$ (see Supplementary Fig. S3). The result of this averaging applied to the seismic-geodynamic density model TX2008 (ref. 14) is shown in the cross-sections in Supplementary Fig. S3 and its effect on the subsidence of the Congo basin is summarized in Supplementary Fig. S2d. As expected, the large-scale asthenospheric flow field is minimally perturbed by the removal of the cold dense anomaly, but the effect on the Congo basin subsidence is more pronounced. By removing the anomaly in both the TX2007 (ref. 13) and TX2008 (ref. 14) density models, we have reduced the amount of subsidence by 25% and 70%, respectively. We also note that the removal of this anomaly would significantly misfit the observed free-air gravity anomaly over the Congo\(^\text{26}\). The convective drawdown that accommodates the onset of asthenospheric upwelling below the East African Rift contributes to the subsidence of the Congo Basin, but the total amount is subject to uncertainties in the joint seismic–geodynamic constraints on the mantle density models (see Supplementary Information for a detailed discussion of the uncertainties).

In conclusion, we have developed a novel time-dependent convection model, based on high-resolution mantle density anomalies from seismic-geodynamic inversions, that provides a
detailed reconstruction of the changing dynamic topography of Africa over the past 30 Myr. We find that the high topography of the EAR system is driven by the upper-mantle buoyancy forces originating in the deep-seated African superplume that we tracked over the past 30 Myr, starting from the Ethiopian plateau and extending southward towards the East African plateau. The total predicted uplift of the two distinct plateaux may be as high as 1,200 m. Juxtaposed to this uplift is the corresponding gradual subsidence of the Congo Basin by as much as 500 m; in part due to the dense anomaly in the deep lithosphere beneath the Congo Basin and also due to the convective drawdown driven by surrounding deep mantle upwellings. The magnitude of this subsidence, in conjunction with the small amount of Late Cenozoic sediments, suggests that the Congo Basin was at a higher elevation at 30 Myr. This is not unusual, as the Congo Basin seems to have experienced a unique history characterized by past episodes of tectonic uplift and erosion, as documented by depositional hiatuses and erosion.

Methods

The mantle convective flow is calculated with a gravitationally consistent, compressible version of the governing fluid mechanical equations in a spherical shell, on which the surface tectonic plates are coupled to (and driven by) the internal mantle flow, rather than being imposed or specified a priori (see ref. 16 and Supplementary Information for details). 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 that provide the buoyancy forces driving the mantle flow.

The radial profiles of mantle viscosity that we employ are inferred from joint inversions of convection-related observables (global plate velocities, global gravity anomalies, global crust-corrected dynamic topography, core–mantle boundary ellipticity) and a suite of glacial isostatic adjustment (GIA) data associated with the response of the Earth to melting of the Laurentian and Fennoscandian ice loads (see ref. 16 and Supplementary Information for details).

The mantle density perturbations 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 incorporated13, 14. These inversions are solved iteratively, with a starting model that assumes purely thermal anomalies. This constraint is then relaxed in subsequent iterations, when lateral variations in the density–velocity scaling are introduced, until an optimal reconciliation between the seismic and geodynamic constraints is obtained. Chemical or non-thermal contributions to mantle density anomalies are then inferred in terms of the deviations from a purely thermal scaling between seismic and density anomalies (for further details, see ref. 14 and Supplementary Information).

The backwards convection calculations are based on a high-Rayleigh approximation to the time-dependent equation for conservation of (thermal) energy. In this approximation the temperature variation due to thermal diffusion in upwelling and downwelling plumes is treated as negligible compared with the effect of heat transport by advection, where the latter is a reversible process. We evaluate the uncertainties associated with the neglect of thermal diffusion and establish a conservative time window of 30 million years over which irreversible diffusion effects are acceptably small. See Supplementary Information for a detailed evaluation of the uncertainties in the backwards convection procedure, including the uncertainties in the viscosity and mantle density structure.

It is worth noting the fundamental importance of using a geodynamically consistent model of present-day mantle convection to ensure the success of the time-reversed, backwards
convection modelling presented herein. The predicted present-day convective flow must provide the best possible fit to surface geodynamic data sets (for example free-air gravity anomalies, crust-corrected dynamic topography, and tectonic plate velocities) that are sensitive to both mantle density anomalies and viscosity structure. This density and viscosity structure controls the amplitude and pattern of the mantle flow velocities that determine the critically important starting trajectory of the time-reversed convection model. We therefore underline that the convection model employed here has been extensively validated against a wide suite of surface geodynamic constraints on mantle density and viscosity structure.\textsuperscript{16}

References


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Contributions

R.M. and A.M.F. both developed the scientific concepts presented herein, and jointly wrote the paper. R.M. created the figures.

Competing financial interests

The authors declare no competing financial interests.

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Supplementary information

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