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Key Points:

- Weak continental faults and basal drag resist GPE gradients in East African Rift
- Shear tractions play a minor role in present-day Nubia-Somalia plate divergence

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Role of mantle flow in Nubia-Somalia plate divergence

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Abstract Present-day continental extension along the East African Rift System (EARS) has often been attributed to diverging sublithospheric mantle flow associated with the African Superplume. This implies a degree of viscous coupling between mantle and lithosphere that remains poorly constrained. Recent advances in estimating present-day opening rates along the EARS from geodesy offer an opportunity to address this issue with geodynamic modeling of the mantle-lithosphere system. Here we use numerical models of the global mantle-plates coupled system to test the role of present-day mantle flow in Nubia-Somalia plate divergence across the EARS. The scenario yielding the best fit to geodetic observations is one where torques associated with gradients of gravitational potential energy stored in the African highlands are resisted by weak continental faults and mantle basal drag. These results suggest that shear tractions from diverging mantle flow play a minor role in present-day Nubia-Somalia divergence.

1. Introduction

Observations of the divergence between the Somalian and Nubian plates, along the East African Rift System (EARS), stand among the recent progresses in plate boundary kinematics. The most comprehensive geodetic study to date [*Saria et al.*, 2014] indicates a slow, clockwise rotation of the Somalian plate with respect to Nubia about a pole located offshore South Africa (Figure 1). Rates of relative motion along the EARS increase from south to north, with maximum opening rates of 6 mm/yr at the Afar triple junction. This is in remarkable agreement with the past 3 Myr average motion derived from paleomagnetic observations [*DeMets et al.*, 2010].

The large-scale forcings responsible for present-day rifting in the EARS remain, however, debated. For some, rifting owes primarily to basal shear tractions exerted by divergent mantle flow under Africa [i.e., *Forte et al.*, 2010; *Ghosh and Holt*, 2012]—a common feature visible in a number of mantle circulation models (MCMs) constrained by seismic tomography [i.e., *Steinberger and Calderwood*, 2006; *Conrad and Behn*, 2010; *Moucha and Forte*, 2011]. This hypothesis implies that present-day sub-African asthenospheric flow is efficiently coupled to the overlying lithosphere. For other, rifting owes to tensional deviatoric stresses arising from lateral variations of gravitational potential energy (GPE) in the African lithosphere. These GPE variations, in turn, result from the high topography of eastern Africa [*Coblentz and Sandiford*, 1994; *Stamps et al.*, 2010, 2014], which is thought to be dynamically supported by the positive thermal buoyancy of the "African Superplume" [*Nyblade and Robinson*, 1994; *Lithgow-Bertelloni and Silver*, 1998], a seismically imaged low shear wave anomaly extending from the core-mantle boundary to at least the midmantle [*Grand et al.*, 1997; *Ritsema et al.*, 1999; *Hansen et al.*, 2012]. Such a hypothesis implies either resistive drag acting at the base of the African lithosphere or an asthenospheric viscosity that is sufficiently low to decouple horizontal mantle flow from lithospheric deformation. Finally, friction on faults, which oppose resistance to plate motions, also contributes to the global torque balance, though recent numerical studies suggest even small amounts of magmatism can generate magma-assisted rifting in thinned lithosphere independent of fault strength [*Balais et al.*, 2010].

The observed opening of the EARS hence presents a unique opportunity to explore the present-day degree of mantle-plate coupling beneath Africa and surroundings. Since Nubia and Somalia are not attached to any major subducting slabs (Figure 1), the torque balance controlling their slowly diverging motion simplifies to the contributions of lithospheric deviatoric stresses and boundary forces from both basal drag and frictional forces along transform plate boundary segments. Here we test how the horizontal component

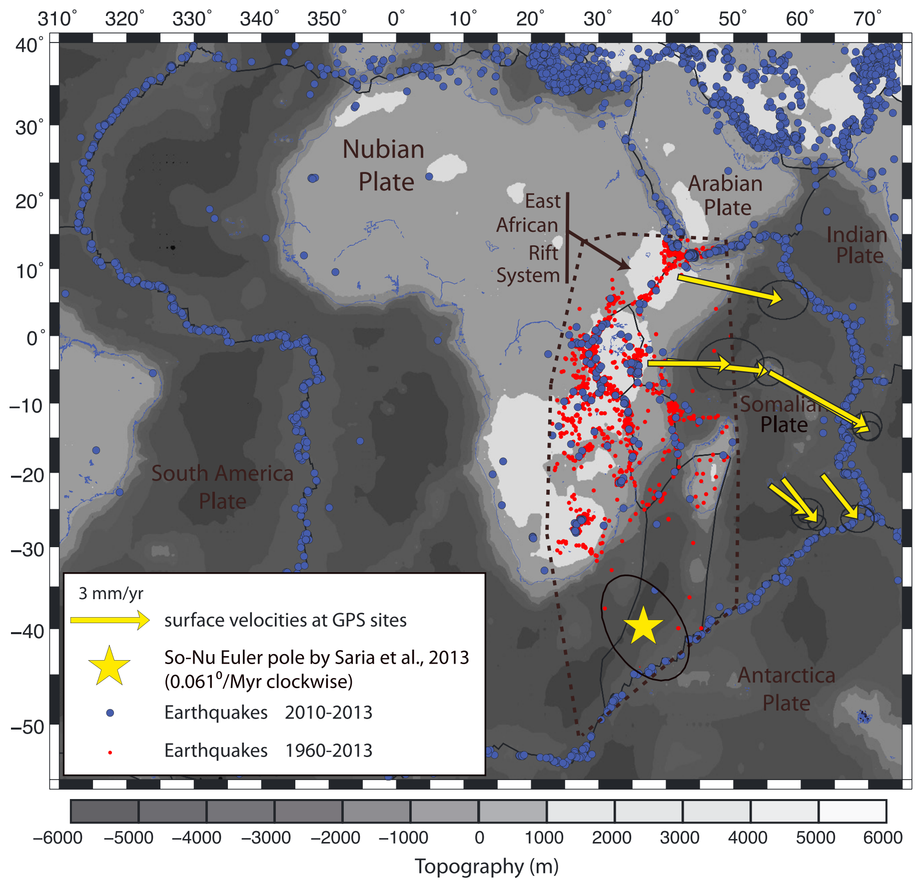

Figure 1. Tectonic setting of the Somalia-Nubia plates system. The East African Rift System (EARS: dashed black contour) is a 5000 km long divergent plate boundary between Nubia and Somalia. Blue dots are earthquake epicenters since 2010 from the U.S. Geological Survey National Earthquake Information Center catalog, and red dots are earthquake epicenters since 1960 along the EARS from the same catalog. The geodetic record [*Saria et al.*, 2014] of the Somalia-Nubia present-day relative motion is in yellow: arrows are surface velocities at GPS sites. Star indicates the pole about which Somalia rotates clockwise, in a reference frame fixed to Nubia.

of the asthenospheric flow under Africa controls present-day opening of the EARS by comparing coupled mantle-lithosphere deformation models to the most recent geodetic observations for the Nubia-Somalia plate system.

2. Geodynamic Modeling of the Mantle-Lithosphere System

We employ global asthenospheric flow fields from a series of recently published global MCMs (Figure S1 in the supporting information), in which the present-day mantle buoyancy field has been constrained either from global seismic tomography (referred to as class I models) [*Steinberger and Calderwood*, 2006; *Conrad and Behn*, 2010; *Moucha and Forte*, 2011], or from the history of subduction (referred to as class II models) [*Davies et al.*, 2012; *Schuberth et al.*, 2009] (Table S1). These two classes of MCMs represent the dominant techniques employed at present for calculating density-driven mantle flow. They also sample a range of underlying assumptions in calculating mantle flow, such as lithospheric thickness and viscosity structure (see Table S1). Regardless of the differences in initial conditions of the MCMs, each indicates divergence beneath the EARS. We couple these asthenospheric flow fields, hereafter referred to as Poiseuille flow, to Earth's lithosphere following *Iaffaldano et al.* [2006] using SHELLS [*Kong and Bird*, 1995], which models the dynamics of plates and predicts global plate motions while accounting for the present-day tectonic structure of the lithosphere (e.g., relief, thickness, configuration of plate boundaries, and their friction coefficients—see supporting information). In addition to these MCMs, we also test the hypothesis that the asthenosphere beneath Africa features a predominant Couette-type flow—that is, asthenospheric

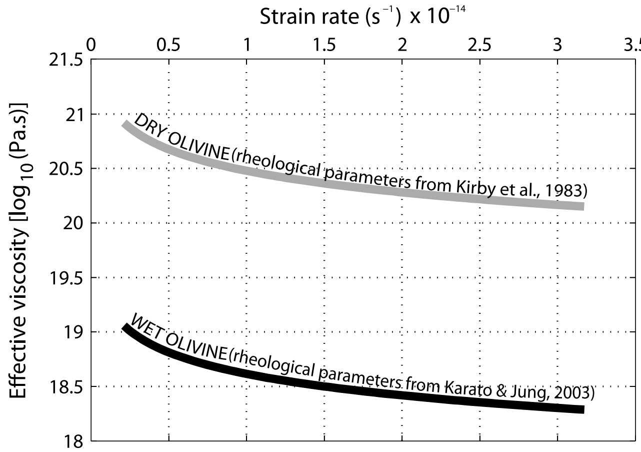

Figure 2. Effective viscosities computed for a range of strain rate values typical of plate tectonics using two sets of experimentally inferred rheological parameters of olivine (see Table S2 in the supporting information). The gray envelope corresponds to parameters inferred for dry olivine [*Kirby*, 1983], while the black one is for wet olivine [*Karato and Jung*, 2003].

shear is determined solely by the motion of plates with fixed tangential flow velocities in the underlying mantle.

The degree of mantle-plate coupling in the models is controlled by the dislocation creep of olivine [*Kohlstedt et al.*, 1995] in the lithospheric mantle. We use two end-member sets of parameters describing dry [*Kirby*, 1983] and wet [*Karato and Jung*, 2003] conditions (Table S2) in order to test the above mentioned hypotheses under the broadest range of rheological scenarios permitted by experimental results. Effective upper mantle viscosity differs by 2 orders of magnitude from dry (high viscous coupling) to wet (low viscous coupling) conditions, for a range of stain rates typical of plate tectonics (Figure 2). Similarly, we test a wide range of friction coefficients for brittle plate margins with values ranging from 0.01 to 0.2, in line with numerous laboratory- and field-based results [i.e., *Suppe*, 2007; *Di Toro et al.*, 2011; *Carpenter et al.*, 2011] (see supporting information), with most of these estimates at the lower end. Lastly, the present-day lithospheric structure and global relief, which determine lithospheric buoyancy forces, are also cast into the finite-element grid used by SHELLS (Figure S3).

From model output, we first compute the angular velocity vector for the Nubian-Somalia plate system because our calculated surface velocities are in a mantle reference frame. We only consider models in which the Somalian plate rotates clockwise with respect to Nubia. Models that do not open the EARS also predict internal deformation of the Nubian plate, which *Saria et al.* [2013] find to be rigid at the 0.6 mm/yr level (weighted root-mean-square, WRMS). In our best fit model the Nubian plate behaves rigidly with a RMS of 0.4 mm/yr (maximum residual = 1.1 mm/yr). We then score the models (Figure 3) by calculating (1) the geodesic distance between observed and modeled Somalia-Nubia Euler poles and (2) the WRMS of the modeled versus observed velocities at GPS sites (see Text S1 and Table S3).

3. Results

Among the models employing rheological parameters of dry olivine (i.e., models where plates and mantle are strongly coupled) (Figures 3a and 3b), all those employing class I as well as one class II MCMs predict unrealistic counterclockwise rotation of Somalia with respect to Nubia. This occurs regardless of the friction coefficients used. It is a consequence of the strong coupling between the lithosphere and the underlying mantle flow imposed by the dry olivine rheology. Five models employing one particular class II MCM [*Schuberth et al.*, 2009], together with low continental fault friction coefficients ($\leq$0.05), correctly predict clockwise Somalia-Nubia rotation, but greatly overestimate the associated angular velocity (Figure 3b, green). The agreement between predictions and observations improves when plates are weakly coupled (i.e., rheology constrained by wet olivine) for models employing either class I or class II MCMs (Figures 3c and 3d). Several of these models predict a Somalia-Nubia Euler pole within <2000 km of the observed one. However, they still consistently overpredict their relative rotation rate (Figure 3d; WRMS > 20 mm/yr).

In contrast, nearly all models with Couette-type asthenospheric flow yield velocity predictions consistent with observations. This holds for strong (Figures 3a and 3b) and weak (Figures 3c and 3d) mantle-plate coupling scenarios. We obtain the best match to observations for a scenario where plates are strongly coupled to the mantle and friction coefficient of continental faults along the EARS is low (0.01), regardless of the friction coefficient of submerged faults. Under this tectonic setup, the predicted Somalia-Nubia Euler pole falls within 2000 km from the observed one (Figure 3a, blue diamonds), while model velocities at GPS sites yield WRMS < 2.4 mm/yr (Figure 3b, blue diamonds).

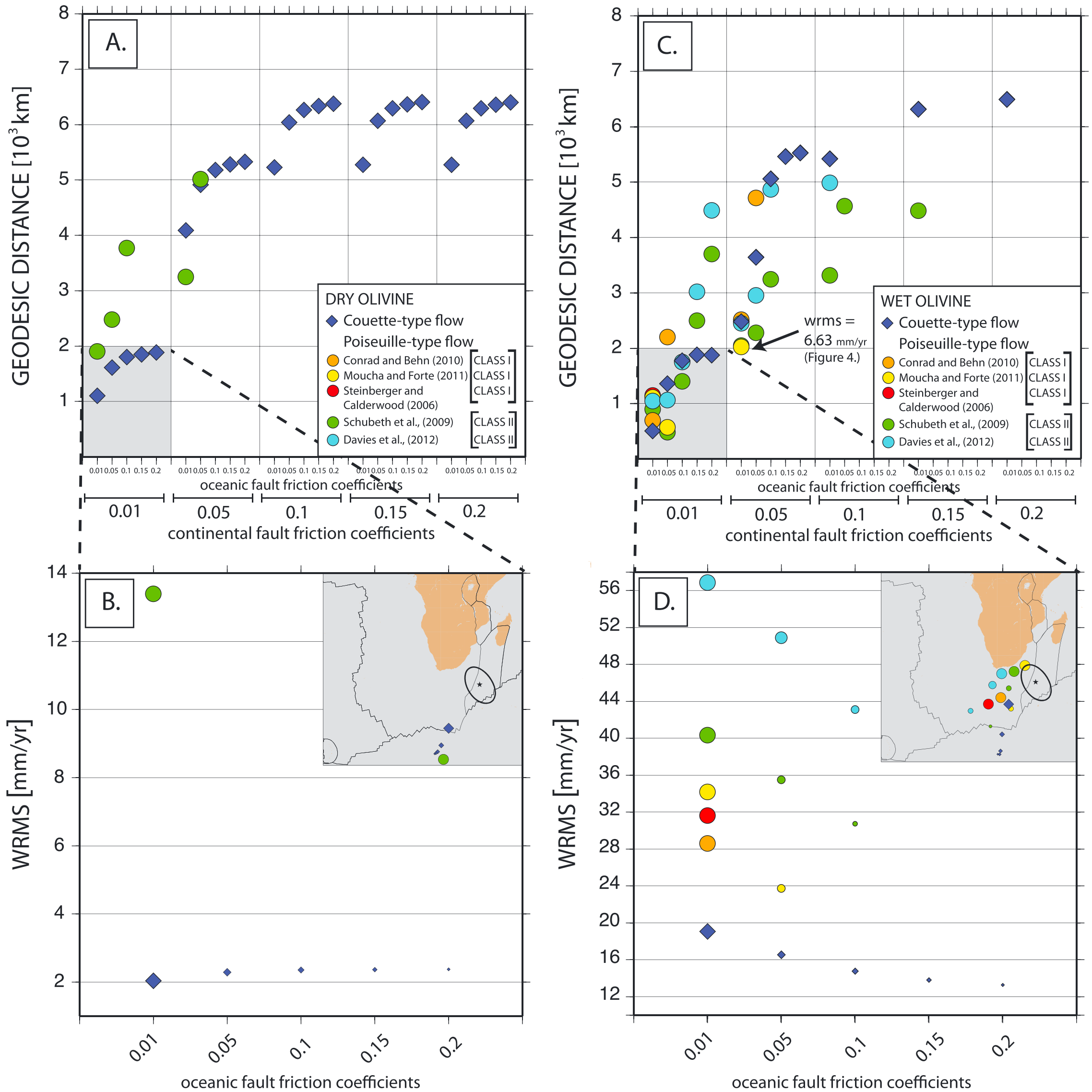

Figure 3. Scoring of model predictions against observations of Somalia-Nubia kinematics. (a) Geodesic distance (*D*) between observed and model-predicted Euler poles for the present-day Somalia-Nubia relative rotation. Models employ rheological parameters of dry olivine. (b) Weighted root-mean-square (WRMS) values for models yielding $D \leq 2000$ km. The black star in the insets shows the location of the geodetically observed Somalia-Nubia Euler pole (rotation is clockwise). Other symbols correspond to model predictions of the same pole. (c and d) Same as Figures 3a and 3b, respectively, but for models employing rheological parameters of wet olivine. Scores from models predicting a counterclockwise rotation of Somalia with respect to Nubia are opposite to observations and therefore omitted from this figure. Relative sizes of symbols in Figures 3a and 3b are reflected in the inset for identification purposes.

Recent geodynamic models using a purely viscous mantle/lithosphere system attribute Nubia-Somalia divergence to efficient viscous coupling of the plates to large-scale mantle flow [e.g., *Quéré and Forte*, 2006; *Ghosh and Holt*, 2012]. Although these models do predict divergence between Nubia and Somalia, they overpredict the current extension rate across the EARS, as in the most successful class II MCM mentioned above (Figure 3d). This may result from the fact that these purely viscous models do not account for the frictional behavior of plate boundary faults in the torque balance. Our simulations indeed show that the effect of fault friction is significant for active mantle flow models, with higher fault friction simulations matching the data better when coupling is low (Figure 3d).

Lastly, we test the impact of GPE gradients within continental Africa on the present-day Somalia-Nubia motion by simulating a uniformly elevated (100 m) continental Africa with the associated lithospheric thickness arising from isostatic balance. Under these conditions, none of the scenarios tested above yield

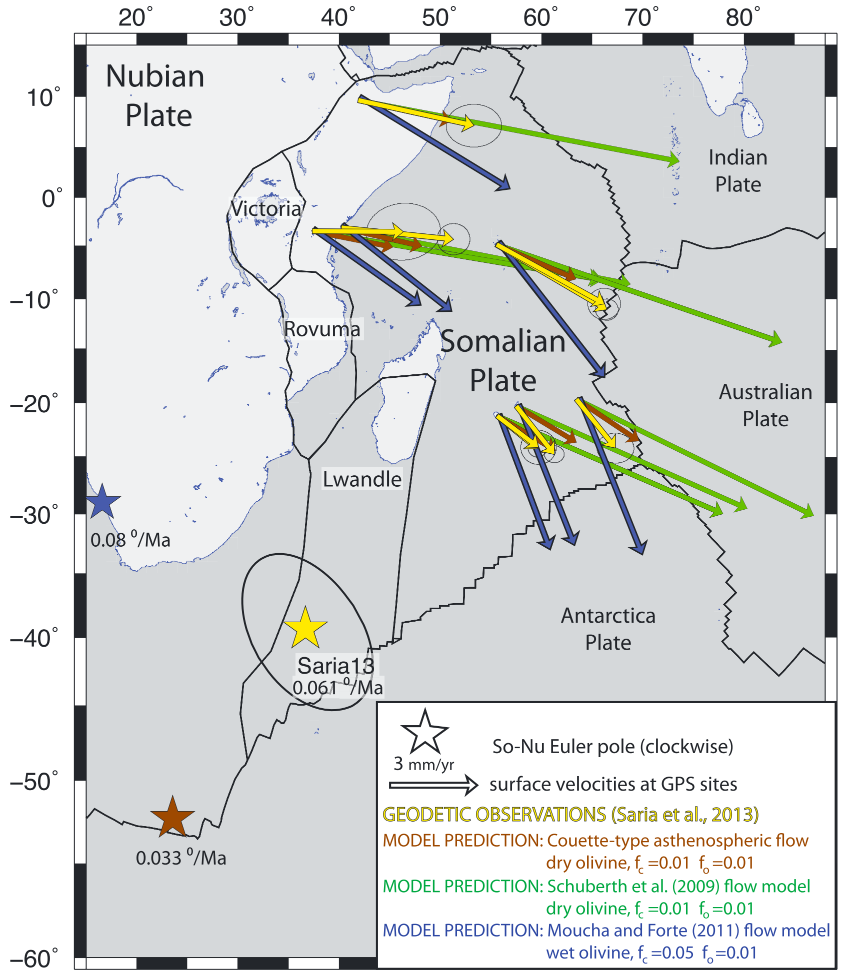

Figure 4. Comparison of kinematic observations and model predictions of Somalia-Nubia relative motion. Stars indicate observed (ellipse shows 95% confidence region) or predicted Euler poles for the clockwise rotation of Somalia with respect to Nubia using the best fit class II mantle flow model with dry rheology. Euler pole plots outside of the map region; see inset in Figure 3b. Arrows are observed or predicted surface velocities at GPS sites within Somalia, in a reference frame fixed with Nubia. In yellow is the observed geodetic record [*Saria et al.*, 2013]. In brown is the prediction from our model casting Couette-type flow within the sub-African asthenosphere with rheological parameters of dry olivine and low fault friction coefficients. In green is the model prediction using the mantle flow calculations from *Schuberth et al.* [2009], rheological parameters of dry olivine, and low friction coefficients. In blue is the model prediction using mantle flow calculations from *Moucha and Forte* [2011], rheological parameters of wet olivine, and low friction coefficients.

kinematic predictions that are compatible with the present-day geodetic observations (Figure 4). Models of this type either predict counterclockwise Somalia-Nubia rotation or feature angular velocities much larger than observations—WRMS between 7 and 15 mm/yr. This indicates that torques associated with GPE gradients in the African continent contribute significantly to the present-day torque balance of the Somalia-Nubia system [*Coblentz and Sandiford*, 1994; *Stamps et al.*, 2010].

Our best fit model results in shear tractions at the base of the African lithosphere ranging from 0.2 to 0.4 MPa, consistent with independent studies worldwide [*Bird et al.*, 2008; *Warners-Ruckstuhl et al.*, 2012; *Bokelmann and Silver*, 2002]. We computed directions of fast seismic anisotropy by taking the difference between model surface velocities and horizontal asthenospheric flow velocities (Figure S5). The fit is admittedly deceptive and similar for Couette- or Poiseuille-type models. Additional quality shear wave splitting data outside of the EARS are needed to better constraint the interpretation.

4. Conclusions

Altogether, modeling results show that the present-day balance of torques associated with buoyancy forces in the African lithosphere, weak continental faults, and Couette-type mantle flow within the sub-African asthenosphere explain plate divergence between Nubia and Somalia and hence extension across the EARS. This result is consistent with a recent study that estimated large-scale mantle tractions beneath Africa using known lithospheric GPE variations and strain rates [*Stamps et al.*, 2014] and concluded that buoyancy forces in the African lithosphere are sufficient to drive plate divergence across the EARS while additional forcing from horizontal mantle tractions overestimate the observed motions. Taken together, these two methodologically independent studies argue for a present-day opening of the EARS as a result of buoyancy forces in the African lithosphere likely to result from dynamic uplift of eastern Africa driven by the African Superplume [*Lithgow-Bertelloni and Silver*, 1998; *Gurnis et al.*, 2000; *Moucha and Forte*, 2011].

Acknowledgments

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