AGU PUBLICATIONS

Geochemistry, Geophysics, Geosystems

RESEARCH ARTICLE

10.1002/2013GC005089

Bayesian noise-reduction in Arabia/Somalia and Nubia/Arabia finite rotations since ~20 Ma: Implications for Nubia/Somalia relative motion

Giampiero Iaffaldano[1], Rhys Hawkins[1], and Malcolm Sambridge[1]

[1]Research School of Earth Sciences, Australian National University, Canberra, Australian Capital Territory 0200, Australia

Key Points:

- Bayesian inference to reduce finite-rotation noise
- Reconstruction of Nubia/Somalia motion since ~20 Ma
- Nubia/Somalia relative motion changed at ~11 Ma

Correspondence to:
Giampiero Iaffaldano,
giampiero.iaffaldano@anu.edu.au

Citation:
Iaffaldano, G., R. Hawkins, and M. Sambridge (2014), Bayesian noise reduction in Arabia/Somalia and Nubia/Arabia finite rotations since ~20 Ma: Implications for Nubia/Somalia relative motion, *Geochem. Geophys. Geosyst.*, *15*, 845–854, doi:10.1002/2013GC005089.

Received 9 OCT 2013
Accepted 28 DEC 2013
Accepted article online 4 JAN 2014
Published online 2 April 2014

Abstract Knowledge of Nubia/Somalia relative motion since the Early Neogene is of particular importance in the Earth Sciences, because it (i) impacts on inferences on African dynamic topography; and (ii) allows us to link plate kinematics within the Indian realm with those within the Atlantic basin. The contemporary Nubia/Somalia motion is well known from geodetic observations. Precise estimates of the past-3.2-Myr average motion are also available from paleo-magnetic observations. However, little is known of the Nubia/Somalia motion prior to ~3.2 Ma, chiefly because the Southwest Indian Ridge spread slowly, posing a challenge to precisely identify magnetic lineations. This also makes the few observations available particularly prone to noise. Here we reconstruct Nubia/Somalia relative motions since ~20 Ma from the alternative plate-circuit Nubia-Arabia-Somalia. We resort to trans-dimensional hierarchical Bayesian Inference, which has proved effective in reducing finite-rotation noise, to unravel the Arabia/Somalia and Arabia/Nubia motions. We combine the resulting kinematics to reconstruct the Nubia/Somalia relative motion since ~20 Ma. We verify the validity of the approach by comparing our reconstruction with the available record for the past ~3.2 Myr, obtained through Antarctica. Results indicate that prior to ~11 Ma the total motion between Nubia and Somalia was faster than today. Furthermore, it featured a significant strike-slip component along the Nubia/Somalia boundary. It is only since ~11 Ma that Nubia diverges away from Somalia at slower rates, comparable to the present-day one. Kinematic changes of some 20% might have occurred in the period leading to the present-day, but plate-motion steadiness is also warranted within the uncertainties.

1. Introduction

The geological setting of continental Africa has received much attention in recent years, chiefly owing to the fact that it is regarded as the archetype setting emerging from the interaction between deep mantle processes and surface tectonics [e.g., *Braun*, 2010]. *Nyblade and Robinson* [1994] first noted the anomalously shallow bathymetry of the ocean floor surrounding southern Africa and named it, together with the high African lands (i.e., the Ethiopian, East and South African Plateaus, the Angola Mountains, the Congo-Cameroom Atlantic Swell), the *African Superswell*. *Lithgow-Bertelloni and Silver* [1998] were the first to link the high African elevation to vertical stresses generated at the lithosphere base by flow within the buoyant mantle—a mechanism commonly referred to as *dynamic topography*. In this context, numerous studies [e.g., *Cadek et al*., 1995; *Gurnis et al*., 2000; *Simmons et al*., 2007; *Moucha and Forte*, 2011] resorted to geodynamic modeling to explore the links between sub-African mantle flow and associated uplift history of the lithosphere above, which left the most recent imprint in the stratigraphic, magmatic, and rift records from the Oligocene/Miocene [e.g., *Janssen et al*., 1995; *Walford and White*, 2005; *Manga*, 2008; *Jelsma et al*., 2009].

The notion of a dynamically sustained high relief of Africa requires that torques generated by deep mantle flow at the lithosphere-base balance those associated with shallower processes, such as lithospheric flexure, gravitational lateral spreading of the African high lands, and the frictional interaction of Nubia and Somalia with each other as well as with the surrounding plates. By virtue of Newton's second law of motion, plate kinematics are the most compelling evidence of such a balance, and therefore, the most powerful probe into the relative importance of the dominant controls. Temporal changes in plate motions arise from variations of forcing conditions upon plates that have already been balanced, because the time plates take to readjust their kinematics can be readily shown to be vanishingly small compared to geological time (see *Ricard* [2009], for a comprehensive review). Reconstructing the geologically-recent motions between Nubia and Somalia is therefore a key to unraveling the history of the past and present dynamic topography of Africa, among others.

The contemporary Nubia/Somalia relative motion is well constrained through geodetic and seismological observations. A number of studies [e.g., *Stamps et al*., 2008; *Argus et al*., 2010; *Altamini et al*., 2012; *Saria et al*., 2013] indicate that the Nubia/Somalia Euler pole is located a few degrees north of the Andrew Bain Transform Fault Complex, with the relative rotation rate being around 0.7°/Myr. The relative motion in the recent geological past (i.e., since ~3.2 Ma) is also known with confidence from paleo-magnetic observations of the ocean floor in the vicinity of the Andrew Bain Transform Fault Complex and the Southwest Indian Ridge, along the Nubia-Antarctica-Somalia circuit of adjacent plates [*Horner-Johnson et al*., 2007]. Confidence in such a reconstruction stems from the ability to close the Somalia-Antarctica-Nubia-Arabia circuit. These two independent estimates agree remarkably well and suggest that the Nubia/Somalia motion remained essentially stable since ~3.2 Ma.

Unfortunately, we currently do not possess sufficiently accurate observations of the ocean floor as old as ~3–20 Myr in the vicinity of the Andrew Bain Transform Fault Complex and the Southwest Indian Ridge to infer the Nubia/Somalia motion further back into the Miocene. The fact that the Southwest Indian Ridge spread slowly poses a significant challenge to the precise identification of paleo-magnetic lineations on the ocean floor. At present, little is known about the Nubia/Somalia motion prior to ~3.2 Ma—something that hampers our ability to derive precise inferences on the dynamics of Nubia/Somalia separation. The only two available studies constraining the total relative rotation since ~11 Ma [*Lemaux et al*., 2002; *Royer et al*., 2006] have both been challenged on account that either they are biased by a misinterpretation of the ocean-floor magnetization pattern [*Patriat et al*., 2008], or imply a history of rifting in East Africa that stands at odds with the continental record, as noted by *Molnar and Stock* [2009]. The implications of such a gap in knowledge are far more significant if one considers that the Nubia/Somalia relative motion allows linking the kinematic histories of Indian realm and Central/South Atlantic domain, for instance in reconstructions of the motion of India toward Eurasia—which remain controversial still today [e.g., *Molnar and Stock*, 2009; *Copley et al*., 2010; *Iaffaldano et al*., 2013]. Nonetheless, important steps in this direction are currently being taken [*DeMets et al*., 2013] and kinematic reconstructions of the Antarctic ocean floor are expected in the near future.

Meanwhile, the only viable alternative remains to reconstruct the past Nubia/Somalia motions from the circuit through the Arabian plate—that is, crossing the Gulf of Aden and Aden-Owen-Carlsberg Triple Junction as well as the Red Sea. Here we do so starting from existing finite rotations. First, we reduce noise in high-temporal-resolution finite rotations of the Arabia/Somalia paleoposition since ~20 Ma [*Fournier et al*., 2010] by making use of an extended formulation of the Bayesian framework [e.g., *Malinverno*, 2002; *Bodin et al*., 2012]. Recently, *Iaffaldano et al*. [2012, 2013] showed this to be a useful step to infer reliable plate kinematics. Second, we combine those kinematics with the ones derived from earlier reconstructions of the paleodistance between Arabia and Nubia, to obtain the Nubia/Somalia past motions. While the latter ones [*Joffe and Garfunkel*, 1987; *Le Pichon and Gaulier*, 1988; *Chu and Gordon*, 1998] come with no estimate of the associated uncertainty, they feature a lower temporal resolution, and therefore a smaller noise-to-signal ratio, compared to the reconstruction of *Fournier et al*. [2010]. This makes them less prone to noise when converted into plate kinematics. We verify such a statement and quantify the relatively small influence of noise in Nubia/Arabia finite rotations assuming three putative, yet realistic uncertainty levels in our Bayesian formulation. In order to test the reliability of our approach, we show that the resulting stage Euler vectors for the past ~3.2 Myr compare well with the independent estimate obtained by *Horner-Johnson et al*. [2007], using data from the Southwest Indian Ridge. Finally, we discuss the temporal variations of surface velocity and direction of Nubia/Somalia relative motion, and their implications for understanding the controlling dynamics, implied by our reconstructed kinematics.

2. Data and Methods

Fournier et al. [2010] determined the finite rotations for the paleoposition of Arabia with respect to Somalia since the Early Neogene (~20 Ma) from magnetic and satellite-altimetry data collected in the Gulf of Aden as well as in the region of the Aden-Owen-Carlsberg Triple Junction. Finite rotations, when differentiated according to the algebra of rotation matrices, provide stage Euler vectors for the average instantaneous

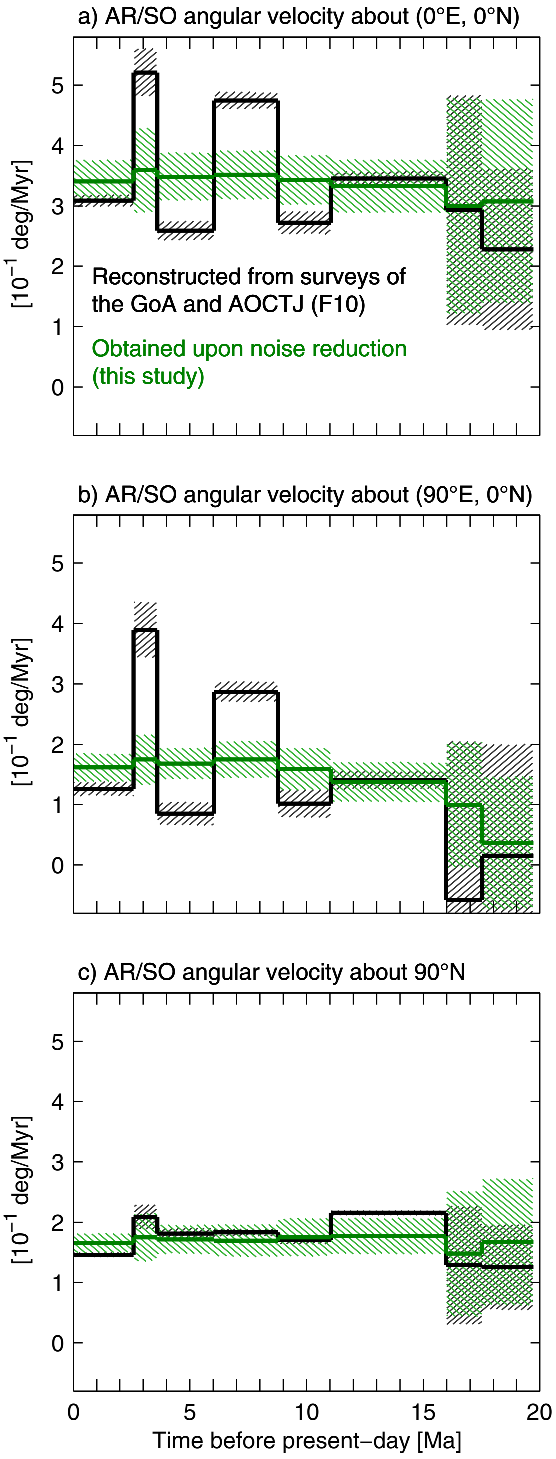

Figure 1. (a) Cartesian component along the *x* axis (0°E, 0°N) of the relative motion between Arabian (AR) and Somalia (SO) plates since ~20 Ma. AR rotates with respect to SO. Black envelope is the angular velocity obtained from differentiating finite rotations of *Fournier et al.* [2010] (F10), which are reconstructed from magnetic and satellite-altimetry surveys of the Gulf of Aden (GoA) and Aden-Owen-Carlsberg Triple Junction (AOCTJ). Green envelope is the angular velocity obtained upon noise reduction in the finite rotations of *Fournier et al*. [2010]. This is achieved through Bayesian Inference (see text for details). Striped areas are confidence ranges. (b) Same as Figure 1a, along the *y* axis (90°E, 0°N). (c) Same as Figure 1a, along the *z* axis (90°N).

rotation over the associated temporal stage [e.g., *Cox and Hart*, 1986]. These are also referred to as Euler vectors. In Figure 1, we show the temporal evolution of Euler vectors for the Arabia/Somalia relative motion since ~20 Ma, derived from the finite-rotation data set of *Fournier et al*. [2010] (in black). Plots a, b, and c report the Euler-vector Cartesian components about the $\hat{x}$ (0°E, 0°N), $\hat{y}$ (90°E, 0°N), and $\hat{z}$ (90°N) axes, respectively. It is evident that the reconstructed motions feature rapid and somewhat erratic speedups and slowdowns through time. It is difficult to imagine geological processes capable of generating such a kinematic pattern. Rather than being the result of large-scale processes controlling plate-motion changes, these features arguably arise from noise in finite-rotation data sets—similarly to the cases of other adjacent plates reconstructed at high temporal resolution [*Iaffaldano et al*., 2012].

Noise is the unknown component of finite rotation that in reality is unrelated to plate motions. It is rather due to the difficulty of (i) identifying in detail the ocean-floor magnetic lineations, particularly along short segments of slowly spreading ridges (such as the one within the Gulf of Aden); and (ii) accurately establishing the geomagnetic reversal time scales [e.g., *Cande and Kent*, 1995; *Lourens et al*., 1995]. A simple example clarifies how the influence of noise in computing Euler vectors becomes progressively more important as the temporal resolution of finite-rotation reconstructions increases. Let θ_1 and $\theta_2 > \theta_1$ be two finite rotations derived from ocean-floor observations, constraining the relative paleoposition of two spreading plates at times t_1 and t_2. For simplicity, the axis about which plates rotate, as well as the spreading center separating them, are both assumed to remain fixed from t_1 to t_2. This allows using scalar algebra, rather than the algebra of rotation matrices. Nonetheless, the main inferences from this example demonstrably hold true also for rotations about non-fixed axes. The two plates accrue an angle equal to $(\theta_2 - \theta_1)$ in the interval of time between t_1 and t_2. Instead, $(t_2 - t_1)$ is a measure of the temporal resolution of the reconstruction. Further, let $\Delta\theta$ be the amount of noise present in both θ_1 and θ_2—that is, the random departure from the true angles. Because this noise arises chiefly from the challenge of identifying accurately magnetic lineations of the ocean floor, $\Delta\theta$ does not depend on the particular resolution of the reconstruction. The *reconstructed* angular velocity of the Euler vector describing the relative motion from t_1 to t_2 is simply $\omega_r=(\theta_2-\theta_1)/(t_2-t_1)$. However, the presence of noise implies that the *true* angular velocity is in fact $\omega_t=(\theta_2-\theta_1)/(t_2-t_1)\pm 2\Delta\theta/(t_2-t_1)$. The last term of ω_t measures the departure of the *reconstructed* angular velocity from the *true* one. It is then evident that the mistake made increases for finer temporal resolution of reconstructions. In this example, we have explicitly not considered the additional noise associated with the particular geomagnetic reversal time scale [e.g., *Cande and Kent*, 1995; *Lourens et al*., 1995], which arises from dating basalts samples and ocean-floor sediments along spreading ridges through radiochronology and paleontology. In reality, this also contributes to our ignorance of the reconstructed kinematics. Nonetheless, geomagnetic reversal time scales benefit from precise astronomical calibration [e.g., *Shackleton et al*., 1990] back to ~25 Ma. For this reason, noise in finite rotations younger than that owes much to the identification of ocean-floor magnetic lineations.

Iaffaldano et al. [2012, 2013] for the first time adopted the trans-dimensional hierarchical Bayesian Inference to reduce noise in finite-rotation data sets and retrieve actual temporal changes in plate motions. The details of such a method have been previously discussed, and applications are appearing in a range of areas [*Malinverno*, 2002; *Malinverno and Briggs*, 2004; *Sambridge et al*., 2006; *Bodin and Sambridge*, 2009; *Gallagher*, 2012]. The effectiveness of Bayesian Inference in reducing finite-rotation noise has been verified through synthetic tests [*Iaffaldano et al*., 2012]. Its essence is best explained through an analogy with repeated measurements of a given observable. In estimating the most representative value of an observable, one typically repeats the same measurement for a statistically significant number of times. The most representative value for the measured observable is not any particular one of these measurements, nor the most certain one. Rather, it is the weighted average, which takes into account the uncertainty of each single measurement, but weighing more the more certain ones. Similarly, in Bayesian Inference one deals with a number of models generated by Monte Carlo algorithms and distributed according to any prior expectations one may have. Each of these models is then assigned with a probability of being a faithful realization of the truth, given the noisy data available. The probability of each model is proportional to the distance of the same model from the noisy data. In estimating such a distance, the nominal uncertainty on the noisy data is taken into account. By generating an ensemble of millions of models and including prior expectations, one is able to sample the posterior distribution of probability—that is, the probability of a given model after having compared it to the data—within the model ensemble explored. Further, Markov Chain methods allow sampling of the model ensemble in a computationally efficient manner. As with repeated measurements of observables, one is not encouraged to pick any single one of these models as the most representative, but rather compute the weighted average model according to the sampled posterior probability. It is also well established that trans-dimensional hierarchical Bayesian Inference follows the principle of *natural parsimony* [*Malinverno*, 2002], where preference always falls on the least complex explanation of observations. The synthetic test performed by *Iaffaldano et al*. [2012] demonstrated that results are closer to the truth than the noisy data. Lastly, from the millions of models generated, one can readily compute model covariances.

3. Results

In Figure 1 (in green), we report the Cartesian components of Arabia/Somalia Euler vectors since ~20 Ma, once noise is reduced through Bayesian Inference from the data set of *Fournier et al*. [2010]. We built on our previous work [*Iaffaldano et al*., 2012] and employed unobtrusive a priori knowledge by setting our prior to uniform distribution with relatively wide bounds. This effectively means that, before looking at the noisy data, we have no particular expectation as to the actual kinematic pattern. It is evident that most of the large and erratic changes derived from simple differentiation of finite rotations are in fact due to the influence of noise. Upon noise reduction, one can see that relative motion remained remarkably stable back to ~15 Ma. Some kinematic changes occurred from 15 to 20 Ma, but we concede that uncertainties are such that steadiness back to 20 Ma is also warranted.

We derive Euler vectors for the relative motion between Arabia and Nubia from previously published finite rotations, reconstructed from observations of the Red Sea ocean floor. We use finite rotations for the paleoposition of Arabia with respect to Nubia from *Joffe and Garfunkel* [1987]—at ~20 Ma—and *Le Pichon and Gaulier* [1988]—at 4.7 and 13 Ma. We also include the record from the MORVEL kinematic model [*DeMets*

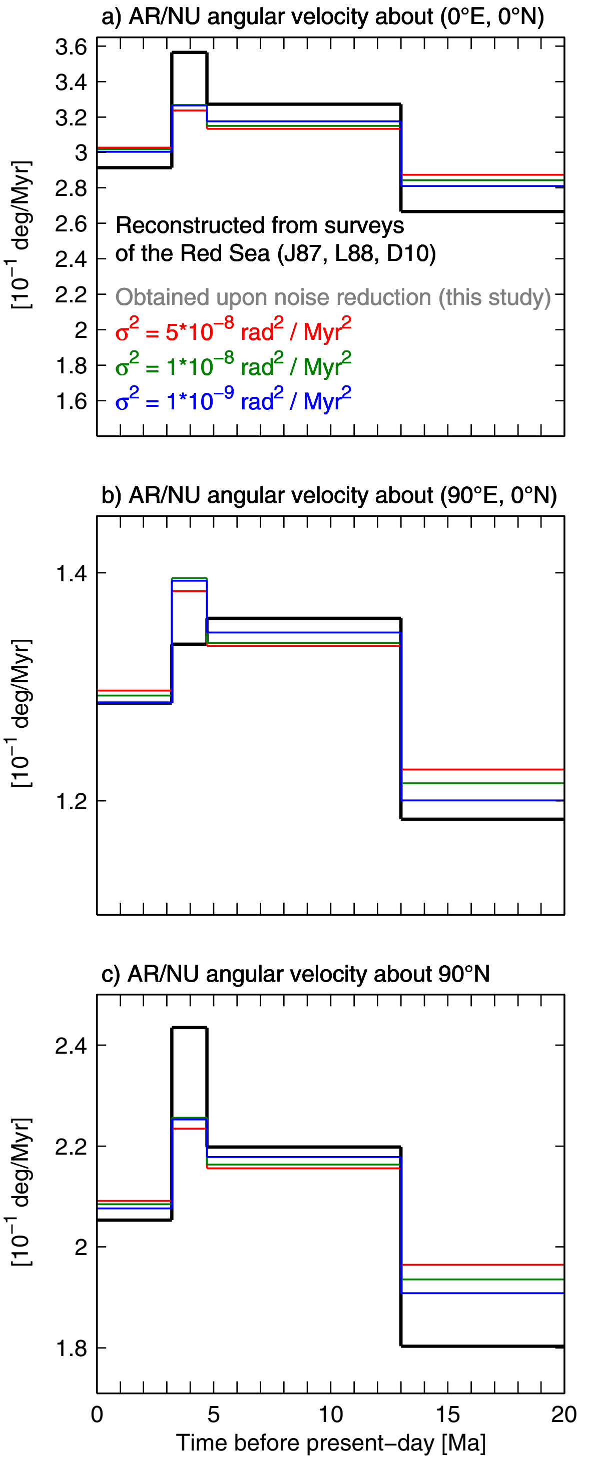

Figure 2. (a) Cartesian component along the *x* axis (0°E, 0°N) of the relative motion between Arabian (AR) and Nubia (NU) plates since ~20 Ma. AR rotates with respect to NU. Black envelope is the angular velocity obtained from merging finite rotations of *Joffe and Garfunkel* [1987] (J87), *Le Pichon and Gaulier* [1988] (L88), and *DeMets et al*. [2010] (D10). No uncertainties are provided in the first two studies. Colored envelopes are angular velocities obtained upon Bayesian noise reduction in these finite rotations. We assumed variance (σ^2) to be 5×10^{-8} (red), 1×10^{-8} (green), and 5×10^{-9} (blue) rad^2/Myr^2 (see text for details). (b) Same as Figure 2a, along the *y* axis (90°E, 0°N). (c) Same as Figure 2a, along the *z* axis (90°N).

et al., 2010] for the past 3.2 Myr, which is based predominantly on the reconstruction of *Chu and Gordon* [1998]. Other data at 9.9, 20.2, and 20.6 Ma are available from the Earthbyte repository (see www.earthbyte.org). However, *Dyment et al*. [2013] recently reevaluated finite rotations between Arabia and Nubia using data from a new aeromagnetic survey of the Red Sea. They found that the original reconstructions by *Le Pichon and Gaulier* [1988] and *Joffe and Garfunkel* [1987] are indeed consistent with these new data, and thus hold valid. The Cartesian components of the Euler vectors derived from these finite rotations are in Figure 2 (in black). Because the temporal resolution of such a reconstruction is lower than that of the Arabia/Somalia motions, one may argue that the influence of noise is of less concern in this case. Nonetheless, we explore also how noise impacts on the Arabia/Nubia Euler vectors. Since no covariances are provided for the finite rotations mentioned above, the only alternative we have is to assign putative values within reasonable ranges. We elect to assign the same numeric value (σ^2) to the diagonal of the covariance matrix (*C*), and zero to nondiagonal entries. That is, $C = \sigma^2 \cdot I$, where *I* is the 3 × 3 identity matrix. We then explore three different possible values of σ^2 that are roughly in the same range of covariances associated with Arabia/Somalia finite rotations from *Fournier et al*. [2010]. They are 5×10^{-8}, 1×10^{-8}, and 5×10^{-9} rad^2/Myr^2. Colored envelopes in Figure 2 show the Cartesian components of the Arabia/Nubia Euler vectors upon noise reduction, each obtained using either of the σ^2 values mentioned above. A comparison of the resulting Euler vectors with the original ones indicates that (i) in the case of Arabia/Nubia plate motions, noise is of less concern, due to the lower temporal resolution of the reconstruction. It also indicates that (ii) upon noise reduction, the resulting kinematics do not differ significantly for different values of the assumed uncertainty on the original finite rotations (σ^2). In this case, the covariances on the noise-reduced Euler vectors would depend directly on the values we chose for the uncertainty associated with the original finite rotations. While the latter are plausible, they carry little

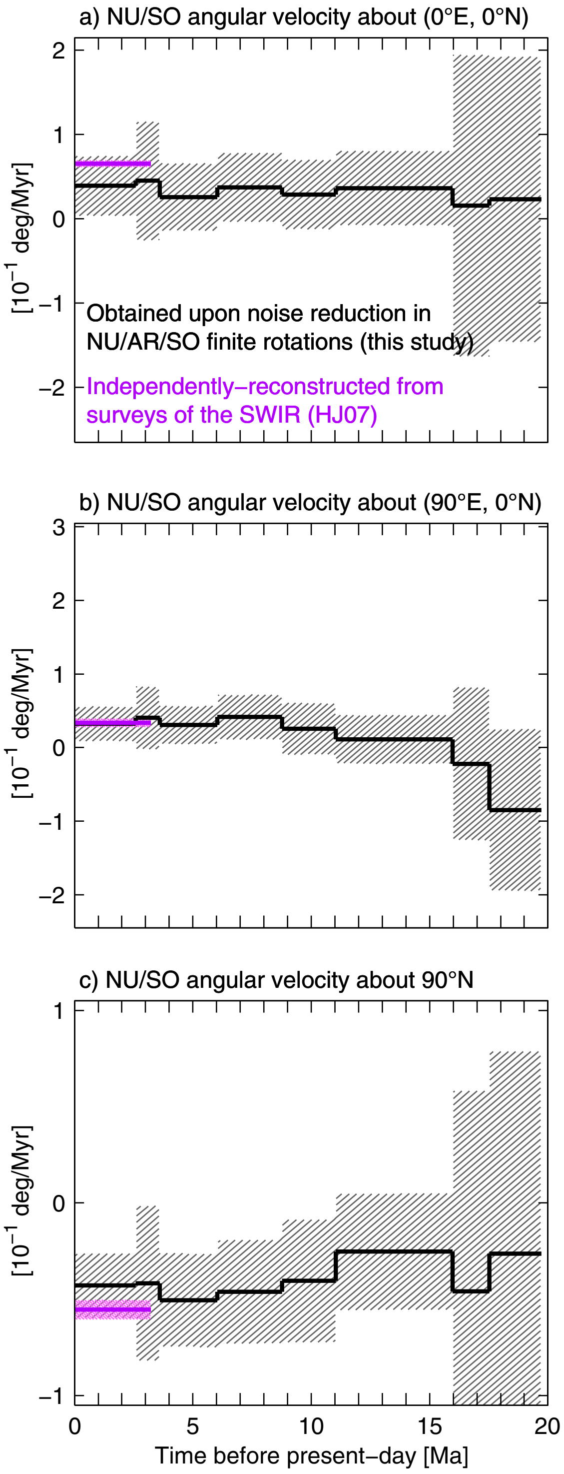

Figure 3. (a) Cartesian component along the *x* axis (0°E, 0°N) of the relative motion between Nubia (NU) and Somalia (SO) plates since ~20 Ma. NU rotates with respect to SO. Black envelope is the angular velocity obtained by combining the relative motions of AR/SO (in black in Figure 1) and AR/NU (in green in Figure 2) obtained upon Bayesian noise reduction. In magenta is the independent record for the past ~3.2 Ma obtained by *Horner-Johnson et al*. [2007], reconstructed from the Nubia-Antarctica-Somalia plate circuit. Striped areas are confidence ranges. (b) Same as Figure 3a, along the *y* axis (90°E, 0°N). (c) Same as Figure 3a, along the *z* axis (90°N).

statistical meaning; thus we refrain from estimating them.

We combine the kinematics inferred upon noise reduction in Arabia/Somalia and Arabia/Nubia ($\sigma^2 = 1 \times 10^{-8}$ rad^2/Myr^2) finite rotations to obtain Euler vectors for the Nubia/Somalia relative motion since ~20 Ma. We do so at the higher temporal resolution associated with Arabia/Somalia Euler vectors. Figure 3 (black envelope) shows Cartesian components of the resulting Euler vectors, as well as the associated uncertainties obtained from covariances. Results indicate that since ~16 Ma the rigid rotation between Nubia and Somalia remained remarkably stable within the uncertainty range. Some kinematic variability is evident prior to this stage, but we concede that uncertainties for the older stages are such that steadiness back to ~20 Ma could be equally warranted.

Horner-Johnson et al. [2007] derived the Nubia/Somalia relative motion since ~3.2 Ma from data collected along the Nubia-Antarctica-Somalia plate circuit. We use their result as an independent test for the validity of our approach in reducing finite-rotation noise along the alternative circuit Nubia-Arabia-Somalia. In Figure 3 (in magenta), we report the Cartesian components of the Euler vector provided by *Horner-Johnson et al*. [2007], together with the associated uncertainties. A comparison of our and their reconstructions over the past ~3.2 Myr indicates they agree within the uncertainty ranges, therefore allowing increased confidence in our reconstruction over the earlier stages. To enforce this point, we note in Figure 4 that using Euler vectors derived from original finite rotations—that is, without reducing noise in the inferred kinematics—would imply a more erratic Nubia/Somalia kinematic pattern over the past ~20 Myr. Most importantly, it would yield a record for the past ~3.2 Myr significantly different than the reliable estimate of *Horner-Johnson et al*. [2007]. Euler vectors for the Nubia/Somalia relative motion since ~20 Ma are in Table 1.

4. Discussion

It is productive to derive the temporal pattern of rate/direction of motion between Nubia and Somalia since the Early Neogene implied by our Euler vectors. In Figure 5, we

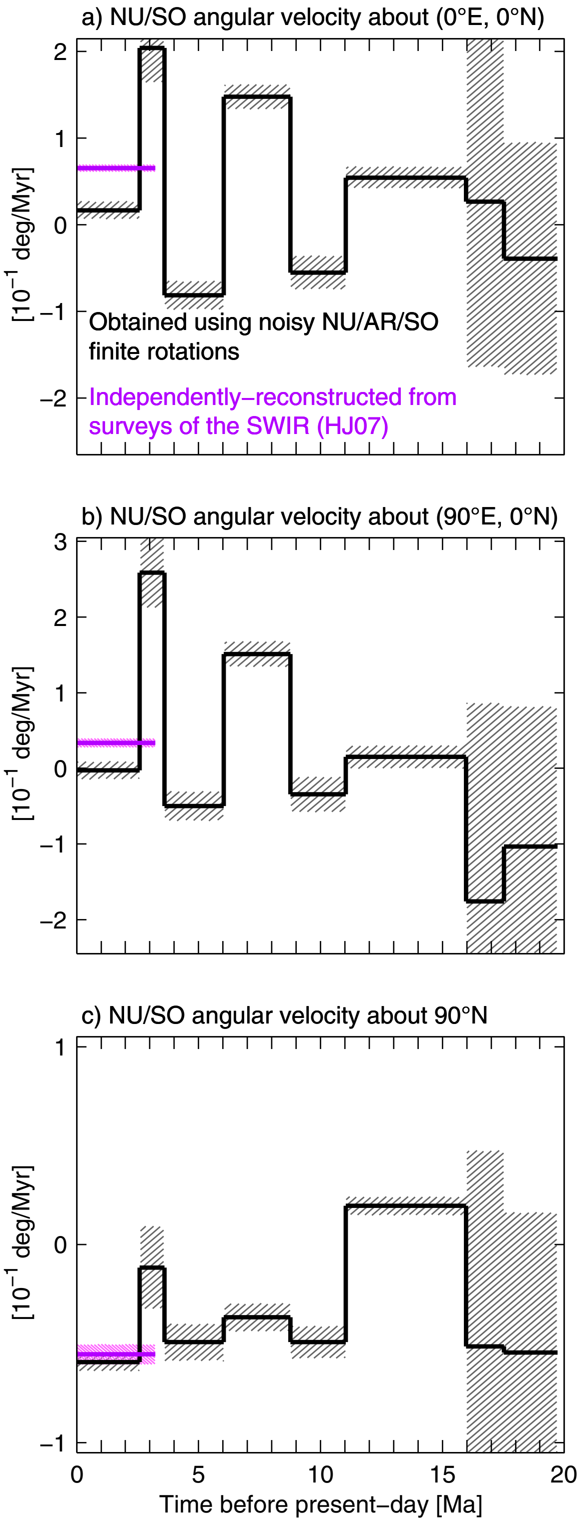

Figure 4. Same as Figure 3, but using Euler vectors derived from differentiation of noisy finite rotations for the relative paleoposition of Arabia with respect to Nubia and Somalia. Note that the ranges of vertical axes are the same of Figure 3.

compute the magnitude of the surface velocity (a) as well as its direction (b) at a position (35.2°E, 18°S), which is at the present-day halfway along the Nubia/Somalia margin (see inset in Figure 5a). Because the relationship between Euler vector and surface velocity/direction is nonlinear (i.e., it involves the computation of norm and arctangent), one cannot easily infer confidence regions for the latter ones by propagating covariances of Euler vectors, which are available from the ensemble considered in Bayesian Inference (see section 3.). Our preference is to derive the uncertainties on magnitude and direction of the surface velocity numerically. For each temporal stage of the reconstructed Nubia/Somalia plate motion, we draw 10^4 Euler vectors from the confidence regions of Cartesian components shown in Figure 3. The components of these Euler vectors are correlated with each other according to the covariance values between the nominal Euler-vector components (see Table 1). We then compute surface velocity and azimuth (angle clockwise from the local North) for each of the 10^4 Euler vectors drawn. Bold lines in Figure 5 are the stage averages, while the confidence region indicates the interval around the averages where 95% of the 10^4 estimates fall. This corresponds to a confidence level of about two standard deviations.

Figure 5a shows that during Early Neogene the total Nubia/Somalia motion was likely faster than at the present-day, although it remains difficult to determine precisely by how much, due to the confidence regions associated with Nubia/Somalia Euler vectors at early stages. Some kinematic variations of ~20% might have occurred during the more recent stages (i.e., since ~11 Ma), but steadiness of the Nubia/Somalia total motion is also warranted. More interesting is the pattern of direction of Nubia/Somalia relative motion in Figure 5b. It is evident that Nubia changed significantly its direction of motion with respect to Somalia over the past ~20 Myr. Our reconstruction indicates it is only since ~11 Ma that the relative motion is directed roughly westward (−60 to −100° clockwise from local North), generating the rifting in continental Africa that is observed today. Instead, at earlier stages relative motion was directed north-northwestward (−20 to −40° clockwise from local North), implying a significant strike-

Table 1. NU/SO Euler Vectors for Relative Motion Since ∼20 Ma, Obtained Upon Noise Reduction[a]

Stage (Ma)		Euler vector (°/Myr)			Covariances (10^{-8}·rad^2/Myr^2)					
From	To	ω_x	ω_y	ω_z	C_{xx}	C_{xy}	C_{xz}	C_{yy}	C_{yz}	C_{zz}
0	2.581	0.039	0.032	−0.043	39	11	11	17	18	9
2.581	3.596	0.045	0.040	−0.042	150	60	64	55	30	49
3.596	6.033	0.026	0.031	−0.050	49	18	20	21	9.3	18
6.033	8.769	0.037	0.041	−0.046	51	17	7	8	9	10
8.769	11.040	0.029	0.025	−0.040	53	95	14	38	56	31
11.040	15.974	0.037	0.011	−0.025	60	15	21	34	10	28
15.974	17.533	0.016	−0.022	−0.046	980	370	440	330	190	330
17.533	19.722	0.023	−0.085	−0.036	870	290	370	370	150	340

[a] The Nubia plate rotates with respect to Somalia. For each temporal stage, Cartesian components along the *x* (0°E, 0°N), *y* (90°E, 0°N), and *z* (90°N) axes are provided.

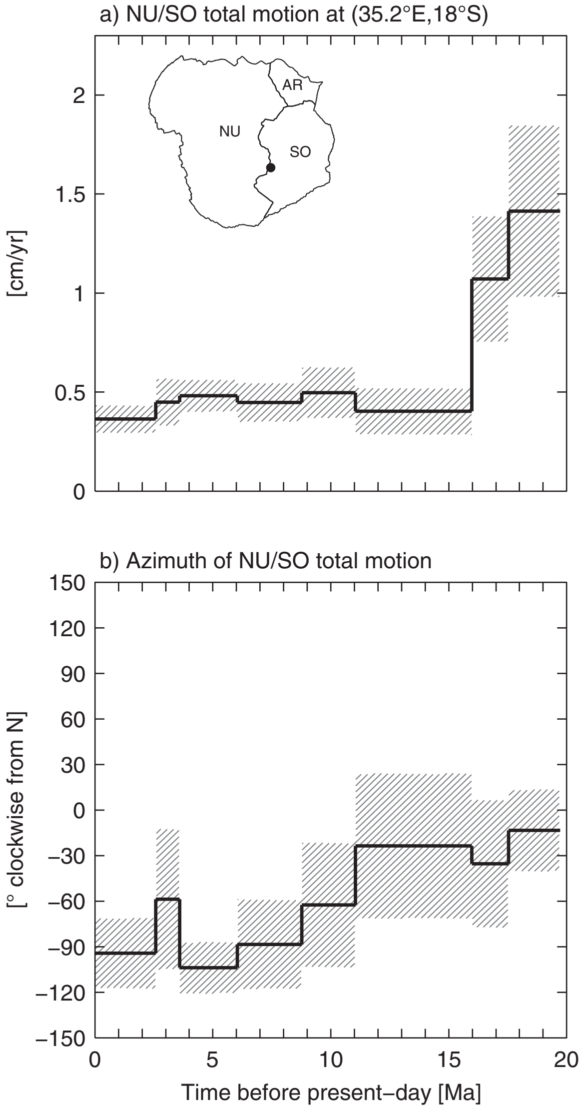

Figure 5. (a) Total surface velocity and (b) azimuth of the relative motion of Nubia (NU) with respect to Somalia (SO) obtained from NU/SO Euler vectors upon Bayesian noise reduction (see Figure 3—black envelopes). Surface motion is computed at a point along the NU/SO margin (see inset in Figure 4a—AR is Arabian plate). Striped areas are confidence ranges computed numerically (see text for details).

slip component along the Nubia/Somalia margin. One should keep in mind that observational constraints on Nubia/Somalia azimuth are somewhat weaker than those on the relative-motion rate. This is because the former ones come from the relatively short boundaries in the Gulf of Aden and Red Sea, and suffer from scarcity of fracture zone segments. Instead, rates of relative motion come from the angular distances between conjugate isochrons on either sides of spreading centers. Nonetheless, such a kinematic pattern is consistent with evidence from the geological record of the African continent. A number of studies reported structural, petrological, and geochronological data from the East African Rift suggesting that divergence between Nubia and Somalia began near 11 Ma [e.g., *Woldegabriel et al.*, 1990; *Wolfenden et al.*, 2004; *Bonini et al.*, 2005; *Pik et al.*, 2008; *Corti*, 2009]. At the same time, these studies found no indication for a different spreading regime or for stronger rifting activity since then. For the sake of comparison, we show in Figure 6 total Nubia/Somalia relative motion and azimuth obtained from the noisy Euler vectors in Figure 4. This time the kinematic pattern at the surface is too erratic, particularly in terms of direction of relative motion, to represent the result of geological processes providing torque upon the Nubia and Somalia plates.

Our findings, therefore, imply Nubia/Somalia kinematic steadiness and offer the opportunity to speculate on the character of the dominant controls on African geodynamics since the Neogene. The short time scales (i.e., few Myr) involved in changes of the Nubia/Somalia relative motions would not be surprising if they were caused by shallow tectonic forces emplaced along plate margins [e.g., *Iaffaldano and Bunge*, 2009]. In the context of deep-rooted forces that act upon the African lithosphere, however, this evidence might suggest intriguing temporal changes in the large-scale mantle convection pattern, which are only beginning to be explored (L. Colli et al., Rapid South Atlantic spreading changes and coeval vertical motion in surrounding continents: Evidence for pulsating pressure-driven upper mantle flow, submitted to *Tectonics*, 2014). Bayesian Inference applied to finite rotations of tectonic plates [*Iaffaldano et al.*, 2012] proved able to overcome the influence of noise and unravel past plate-motion changes in a precise manner. It stands as a promising technical advance to make geodynamic inferences.

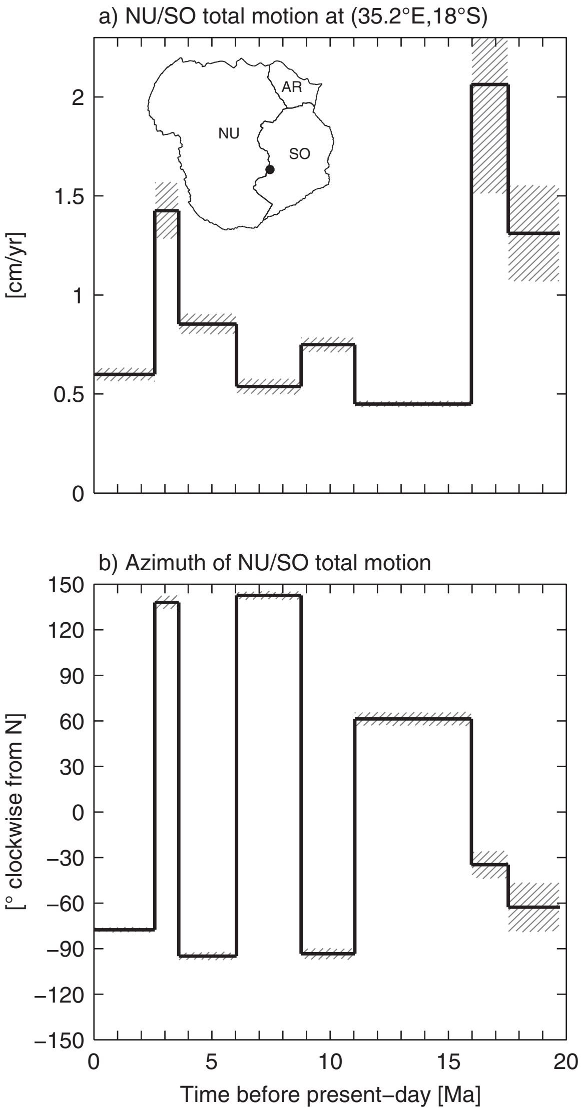

Figure 6. Same as Figure 5, but using Euler vectors derived from noisy finite rotations for the relative paleoposition of Arabia with respect to Nubia and Somalia.

5. Conclusions

We utilized the trans-dimensional hierarchical Bayesian Inference to reduce noise in finite rotations for the relative paleoposition of Arabia with respect to Somalia and Nubia. We used these results to reconstruct the relative motion between Nubia and Somalia since ∼20 Ma, from the circuit of adjacent plates Nubia-Arabia-Somalia. Our reconstruction compares well with the independent estimate available for the past ∼3.2 Myr, which is obtained through the Nubia-Antarctica-Somalia plate circuit. On the basis of this agreement, we were able to confidently compute the relative surface velocity at a position along the Nubia/Somalia margin. Results indicate that, prior to ∼11 Ma, the Nubia/Somalia relative motion was faster than today, and featured a significant strike-slip component. Nubia has since then diverged westward from Somalia, at rates that might have been ∼20% larger than those of the present-day. Kinematic steadiness since ∼11 Ma is, however, also consistent with the uncertainties. Our reconstructed pattern of relative motions agrees well with geological records previously inferred from continental Africa.

Acknowledgments
G.I. acknowledges support from the Ringwood Fellowship at the Australian National University. Authors acknowledge support from the AuScope-AGOS Inversion Laboratory. AuScope Ltd is funded under the National Collaborative Research Infrastructure Strategy (NCRIS) and the Education Infrastructure Fund (EIF), both Australian Commonwealth Government Programmes. This study indeed benefits from careful comments by Jérôme Dyment, Graeme Eagles, and by the editor Thorsten Becker.

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