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Key Points:
- Spreading in the Mid-Atlantic and Southwest Indian Ridges changed coevally between 8 and 5 Ma
- Relative motions of Nubia/North America and Nubia-Eurasia changed by the same amount, as may have Nubia/Antarctica and Somalia/Antarctica
- The simplest scenario explaining these records is one where North America and Antarctica changed their absolute motions between 8 and 5 Ma

Supporting Information:
- Supporting Information S1

Correspondence to:
G. Iaffaldano,
giia@ign.ku.dk

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Late Neogene changes in North America and Antarctica absolute plate motions inferred from the Mid-Atlantic and Southwest Indian Ridges spreading histories

G. Iaffaldano[1] and C. DeMets[2]

[1]Department of Geosciences and Natural Resource Management, University of Copenhagen, Copenhagen, Denmark,
[2]Department of Geoscience, University of Wisconsin-Madison, Madison, Wisconsin, USA

Abstract Reconstructions of absolute plate motions underpin our understanding of the plate torque balance, but are challenging due to difficulties in inferring well-dated rates and directions of plate movements from hot spot tracks. Useful information about plate dynamics can be inferred from rapid absolute plate motion changes, as these are linked only to the torque(s) that changed. Here we infer late Neogene changes in the absolute motions of North America and possibly Antarctica from changes in the easier-to-determine relative plate motions recorded along the Arctic, northern Mid-Atlantic and Southwest Indian Ridges. We show that Eurasia/North America and Nubia/North America motions changed by the same amount between 8 and 5 Ma, as may have Nubia/Antarctica and Somalia/Antarctica plate motions. By considering additional, independent constraints on Somalia/India plate motion, we argue that a scenario in which North America and Antarctica absolute motions changed is the simplest one that explains the observed changes in relative motions. We speculate that these changes are linked to the late Neogene dynamics of the Pacific plate.

1. Introduction

Testing hypotheses about the balance of torques that drive and resist tectonic plate motions requires detailed knowledge of absolute plate motions through geological time (i.e., plate motions relative to the deep mantle) and constraints on the parameters that are needed to estimate the torques, whether shallow- or deep-seated [e.g., *Bird*, 1998]. Unfortunately, reconstructions of absolute plate motions since the Cretaceous typically average plate velocities over intervals of 10–15 Myr due to the difficulties inherent in estimating plate motions from hot spot tracks and/or paleomagnetic data [e.g., *Gordon and Jurdy*, 1986; *Müller et al.*, 1993; *Torsvik et al.*, 2010; *Doubrovine et al.*, 2012]. Efforts to resolve variations in plate torques, which can occur over periods of just a few Myr, are thus impeded. This limitation applies also to the recent geological past: for instance, while a change in Pacific absolute plate motion between 10 and 6 Ma has been well documented [e.g. *Cox and Hart*, 1985; *Wessel and Kroenke*, 2000; *Cande and Stock*, 2004], very little is known about other absolute motion changes during this time, thus limiting the reconstruction of lithosphere dynamics. An alternative means of studying plate dynamics, one that circumvents the problem described above, is to focus on periods when more precise estimates of relative plate motions indicate that significant changes have occurred, with a goal of isolating the torque variation(s) responsible for these changes [e.g., *Iaffaldano and Bunge*, 2015]. Such an approach takes advantage of the high-resolution oceanic record of marine magnetic reversals that can, in theory, be used to reconstruct the relative positions and velocities of the major plates at roughly million-year intervals for much of the past 180 Myr. In particular, one can differentiate time series of finite rotations, which quantify how much one plate has rotated with respect to another from some time in the past to the present, to derive a time progression of stage rotations and thus stage Euler vectors (i.e., stage poles and angular velocities) that describe the average relative motion between two plates over temporally consecutive stages [see *Cox and Hart*, 1986].

Recent progress in reconstructing relative plate motions at 1 Myr or better resolutions [e.g., *Croon et al.*, 2008; *Merkouriev and DeMets*, 2006, 2008, 2014a, *Eagles and Wibisono*, 2013], together with the emergence of numerical tools for mitigating the impact of noise in marine magnetic data [*Iaffaldano et al.*, 2012, 2014], now permit the timing and magnitude of changes in relative plate motions to be described more accurately than before. Here we use high-resolution sequences of finite rotations that quantify Nubia/North America (NB/NA) and

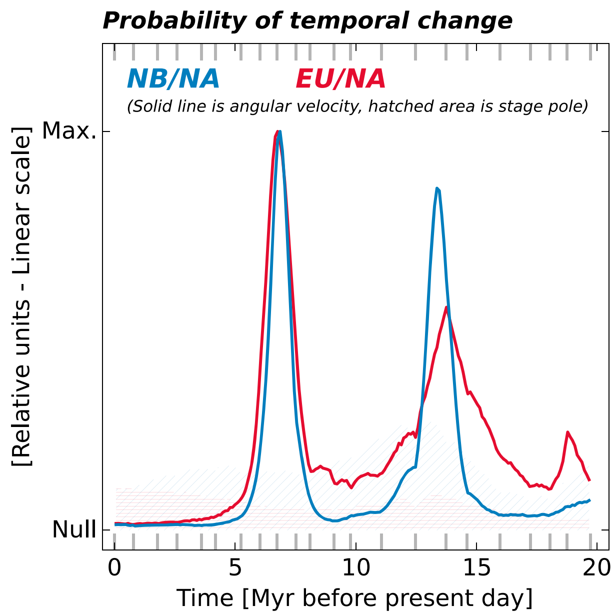

Figure 1. Normalized probability of a change in NB/NA (in blue) and EU/NA (in red) relative motions through geological time, mapped using the Redback software. Solid lines refer to changes in angular velocities, while hatched areas refer to changes in stage Euler poles. Grey ticks on horizontal axes indicate the times for which finite rotations are available.

Eurasia/North America (EU/NA) plate motions since 20 Ma from the well-mapped magnetic reversals flanking seafloor spreading centers in the Arctic and North Atlantic Basins [*DeMets et al.*, 2015a] and high-resolution rotations that describe motion between the Nubia and Somalia (SO) plates relative to Antarctica (AN) across the Southwest Indian Ridge [*DeMets et al.*, 2015b] to infer temporal changes in absolute plate motions. We present evidence that NB/NA and EU/NA relative motions changed coevally by the same amount and additional, albeit weaker evidence for similar, coeval changes in NB/AN and SO/AN plate motions. We show, for the first time, that the simplest and thus most likely scenario explaining such evidence is one where these events are attributable to changes in the absolute motions of NA and AN, for which we estimate mean values and confidence intervals. Lastly, we speculate on a possible, common cause for these changes.

2. Late Neogene Changes in Spreading of the Mid-Atlantic and Southwest Indian Ridges

DeMets et al. [2015a] have recently put forth high-resolution, independent Neogene/Quaternary reconstructions of the EU/NA and NB/NA plate motions that build on the previous work of *Merkouriev and DeMets* [2014a, 2014b], but benefit from noise reduction through the Redback open-source software [*Iaffaldano et al.*, 2014]. Redback implements Bayesian inference [*Bayes*, 1763] in the transdimensional hierarchical fashion [e.g., *Malinverno and Briggs*, 2004; *Sambridge et al.*, 2006], which has been applied to a wide range of geoscientific problems [e.g., *Bodin and Sambridge*, 2009; *Gallagher*, 2012; *Tkalčić et al.*, 2013; *Iaffaldano et al.*, 2013; *Baumann and Kaus*, 2015]. Among the advantages of Bayesian inference is the ability to map the probability density of changes in a generic time series. In the context of plate reconstructions, Redback estimates the probability that a true (as opposed to noise-related) kinematic change occurred at a particular time.

In Figure 1, we show the probabilities estimated by Redback for changes in NB/NA (in blue) and EU/NA (in red) plate motions determined using stage Euler vectors and Redback parameter values from *DeMets et al.* [2015a]. Solid and hatched profiles show the probability of a change in angular velocity of relative motion and location of the stage Euler pole, respectively. Figure 1 indicates that while rates of angular rotations changed significantly at distinct times, stage poles migrated more gradually, because their probabilities of change remain more or less constant but are not null. More specifically, highly-probable changes in both the NB/NA and EU/NA angular velocities occurred around 8–5 Ma and less probable, though still significant, changes in the

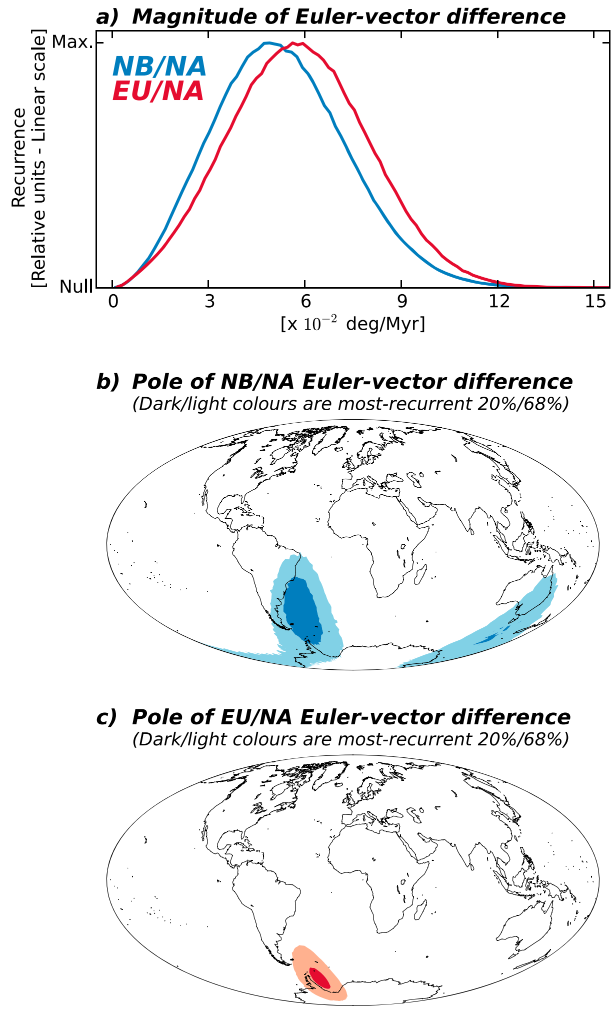

Figure 2. Comparison of the distributions of the ensembles of NB/NA (in blue) and EU/NA (in red) Euler vector differences (see text for details) from the stage bounded by geomagnetic reversals 4n.2o (8.108 Ma) to 4n.1y (7.528 Ma) to that bounded by 3An.1y (6.033 Ma) to 3n.4o (5.235 Ma). (a) Comparison of the magnitude of the Euler vector difference. (b) Distribution of pole of the NB/NA Euler vector difference. The more darkly colored patch shows the region where the most probable 20% of samples fall, whereas the lighter patch encompasses the most probable 68% of the samples. (c) Similar to Figure 2b but for the distribution of samples of EU/NA Euler vector difference.

NB/NA and EU/NA angular velocities also appear to have occurred at 15–12 Ma. Here we focus on the more recent time stage, given the likelihood that the similarly-timed changes had a common cause. An analysis of the latter, less robustly determined changes is reserved for a future study.

The striking coincidence in the NB/NA and EU/NA plate motion changes at 8–5 Ma motivated us to investigate whether the two relative motions changed by the same amount during this period. From the noise-reduced NB/NA stage Euler vectors and associated covariances of *DeMets et al.* [2015b], we draw 1 million samples of the Euler vector of relative motion during the stage between reversals 4n.2o (8.108 Ma) and 4n.1y (7.528 Ma), which marks the beginning of the high-probability interval in Figure 1. Similarly, we draw an equally large ensemble of samples of the NB/NA stage Euler vector between reversals 3An.1y (6.033 Ma) and 3n.4o (5.235 Ma), which instead marks the end of the high-probability interval. We refer to the former ensemble as $\vec{\omega}_{NB/NA}(1)$ and to the latter as $\vec{\omega}_{NB/NA}(2)$. Next, we calculate an ensemble of samples of difference between stage Euler vectors, $\Delta\vec{\omega}_{NB/NA} = \vec{\omega}_{NB/NA}(2) - \vec{\omega}_{NB/NA}(1)$. Such an ensemble can be reexpressed recalling that, in general, the Euler vector of relative motion between two plates equals the difference between Euler vectors of absolute motions. Therefore, $\vec{\omega}_{NB/NA}(1) = \vec{\omega}_{NB}(1) - \vec{\omega}_{NA}(1)$ and $\vec{\omega}_{NB/NA}(2) = \vec{\omega}_{NB}(2) - \vec{\omega}_{NA}(2)$. Consequently, $\Delta\vec{\omega}_{NB/NA} = \Delta\vec{\omega}_{NB} - \Delta\vec{\omega}_{NA}$ expresses the change in stage Euler vector from the older to the

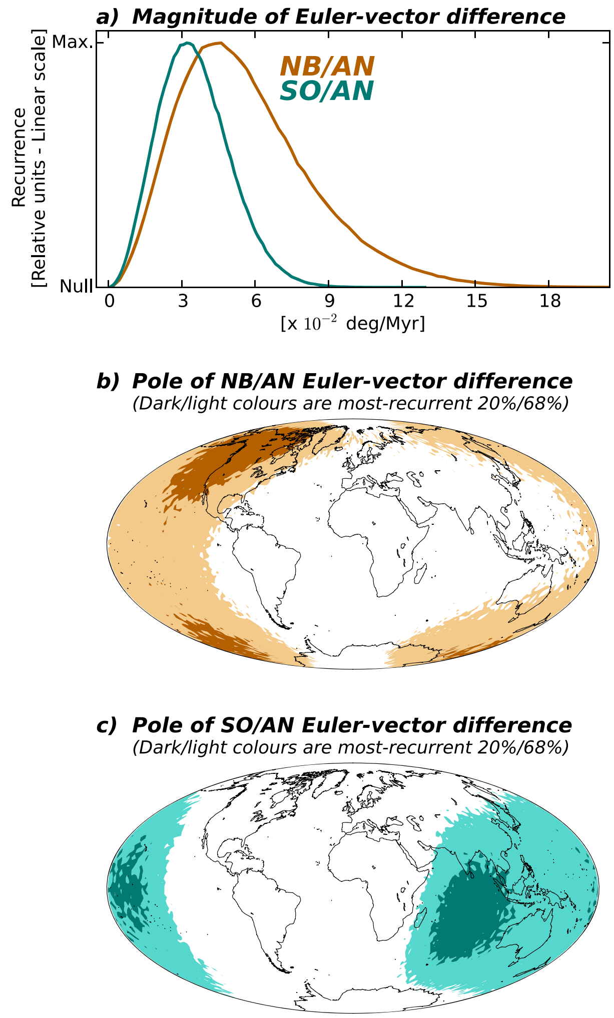

Figure 3. Same as Figure 2 but for the samples of Euler vector difference of NB/AN (in brown) and SO/AN (in green) relative motions.

younger stage, such that $\vec{\omega}_{NB/NA}(6.033 - 5.235 \text{ Ma}) = \vec{\omega}_{NB/NA}(8.108 - 7.528 \text{ Ma}) + \Delta\vec{\omega}_{NB/NA}$. We similarly sampled the noise-reduced EU/NA stage Euler vectors during the same stages in order to calculate the ensemble of samples $\Delta\vec{\omega}_{EU/NA} = \Delta\vec{\omega}_{EU} - \Delta\vec{\omega}_{NA}$.

Figure 2 shows the distribution of the ensembles $\Delta\vec{\omega}_{NB/NA}$ (in blue) and $\Delta\vec{\omega}_{EU/NA}$ (in red) expressed in spherical coordinates, which include the magnitude of the Euler vector difference (Figure 2a)—that is, $|\Delta\vec{\omega}_{NB/NA}|$ and $|\Delta\vec{\omega}_{EU/NA}|$—and the poles of the same vector differences—that is, where the unit vectors $\Delta\vec{\omega}_{NB/NA}/|\Delta\vec{\omega}_{NB/NA}|$ (Figure 2b) and $\Delta\vec{\omega}_{EU/NA}/|\Delta\vec{\omega}_{EU/NA}|$ (Figure 2c) intersect Earth's surface. The magnitudes and poles of the Euler vector differences are almost indistinguishable, a remarkable outcome given that the reconstructions for these two plate pairs are derived from entirely independent data. We conclude that the two plate pairs experienced the same kinematic change between 8 and 5 Ma. In quantitative terms, it means $\Delta\vec{\omega}_{NB/NA} = \Delta\vec{\omega}_{EU/NA}$ or $\Delta\vec{\omega}_{NB} - \Delta\vec{\omega}_{NA} = \Delta\vec{\omega}_{EU} - \Delta\vec{\omega}_{NA}$.

Along the Southwest Indian Ridge, which separates the NB, SO, and Lwandle plates north of the ridge from AN south of it, *DeMets et al.* [2015b] recently derived similar high-resolution reconstructions of NB/AN and SO/AN plate motions, including noise-reduced stage Euler vectors from the Redback software. From these, they inferred significant changes in NB/AN and SO/AN plate motions between ~8 and ~5 Ma [see *DeMets et al.*, 2015b, Figure 26], coeval with the NB/NA and EU/NA changes described above. Using the same sampling procedure as is described above, we tested whether NB/AN and SO/AN plate motions changed by the same amount between 8 and 5 Ma. Figure 3 compares ensembles of Euler vector differences $\Delta\vec{\omega}_{NB/AN}$ (in brown) and $\Delta\vec{\omega}_{SO/AN}$ (in green). The distributions of magnitude and pole are similar: the magnitudes of the change for

Table 1. Inferred Changes of Absolute Motions of North America (NA) and Antarctica (AN) From Before 8 Ma to After 5 Ma[a]

Plate	$\Delta\vec{\omega}_x$	$\Delta\vec{\omega}_y$	$\Delta\vec{\omega}_z$	c_{xx}	c_{xy}	c_{xz}	c_{yy}	c_{yz}	c_{zz}
NA	−6.351	10.091	46.126	14	−9	−2	9	3	15
AN	10.306	−2.184	−0.156	13	4	1	18	−5	48

[a]Changes ($\Delta\vec{\omega}$) are expressed in Cartesian coordinates, where $\hat{x}$, $\hat{y}$, and $\hat{z}$ intersect Earth's surface at (0°E, 0°N), (90°E, 0°N), and (90°N), respectively. For either plate, $\vec{\omega}$(after 5 Ma) = $\vec{\omega}$(before 8 Ma) + $\Delta\vec{\omega}$. Units of vector components $\Delta\vec{\omega}_{i=x,y,z}$ are 10^{-3}×°/Myr. Units of the covariance matrix c are $10^{-8} \times (\text{rad/Myr})^2$.

the two plate pairs are almost the same, and the most recurrent 68% of the poles fall within similar regions of Earth's surface. Our analysis thus suggests that $\Delta\vec{\omega}_{NB/AN} = \Delta\vec{\omega}_{SO/AN}$, although this inference is less compelling than the case for $\Delta\vec{\omega}_{EU/NA} = \Delta\vec{\omega}_{NB/NA}$ (Figure 2). Assuming $\Delta\vec{\omega}_{NB/AN} = \Delta\vec{\omega}_{SO/AN}$ to be true, it follows that $\Delta\vec{\omega}_{NB} - \Delta\vec{\omega}_{AN} = \Delta\vec{\omega}_{SO} - \Delta\vec{\omega}_{AN}$.

3. Synthesis and Discussion

Since SO is separated from India (IN) by the Carlsberg Ridge, the evidence described above for coeval changes in seafloor spreading across the northern Mid-Atlantic and Southwest Indian Ridges motivated us to also consider independent, high-resolution Neogene and Quaternary reconstructions of the motion between SO and IN across the Carlsberg Ridge [*Merkouriev and DeMets*, 2006]. Efforts by the authors to extend the analysis of magnetic anomalies to other major tectonic boundaries that involve some of the plates considered here are currently underway. The analysis of IN/SO motion by *Merkouriev and DeMets* [2006] shows no evidence for a change in either the rate of angular rotation or the stage Euler pole since 9 Ma. In quantitative terms this means that between 8 and 5 Ma $\Delta\vec{\omega}_{SO/IN} = \vec{0}$ or that $\Delta\vec{\omega}_{SO} = \Delta\vec{\omega}_{IN}$. Together with the results from the previous section, the following equations must be verified simultaneously:

$$\begin{cases} \Delta\vec{\omega}_{NB} - \Delta\vec{\omega}_{NA} = \Delta\vec{\omega}_{EU} - \Delta\vec{\omega}_{NA} \\ \Delta\vec{\omega}_{NB} - \Delta\vec{\omega}_{AN} = \Delta\vec{\omega}_{SO} - \Delta\vec{\omega}_{AN} \\ \Delta\vec{\omega}_{SO} = \Delta\vec{\omega}_{IN} \end{cases} \tag{1}$$

Such a system comprises three equations constraining four parameters: $\Delta\vec{\omega}_{EU}$, $\Delta\vec{\omega}_{NB}$, $\Delta\vec{\omega}_{SO}$, and $\Delta\vec{\omega}_{IN}$ ($\Delta\vec{\omega}_{NA}$ and $\Delta\vec{\omega}_{AN}$ may, in fact, be eliminated by addition of a common term). The system is underdetermined and thus has a family of possible solutions, rather than a unique one. Satisfying all three equations simultaneously requires that $\Delta\vec{\omega}_{EU} = \Delta\vec{\omega}_{NB} = \Delta\vec{\omega}_{SO} = \Delta\vec{\omega}_{IN}$, regardless of the values of $\Delta\vec{\omega}_{NA}$ and $\Delta\vec{\omega}_{AN}$. Therefore, if the absolute motion of any among EU, NB, SO, and IN changed between 8 and 5 Ma, then the other three plates must also have coevally changed their motions by the same amount. Such a scenario is unlikely, given that the absolute motion of each plate is controlled by a different set of forces. However, a particular solution from the family of possible ones, namely, $\Delta\vec{\omega}_{EU} = \Delta\vec{\omega}_{NB} = \Delta\vec{\omega}_{SO} = \Delta\vec{\omega}_{IN} = \vec{0}$, does not require simultaneous, equal changes in the absolute motions of all four plates. *Occam's razor* favors this scenario as the most likely. By implication, the results shown in Figures 2 and 3 map the respective distributions of $-\Delta\vec{\omega}_{NA}$ and $-\Delta\vec{\omega}_{AN}$. In other words, changes in NA and AN absolute motions are revealed by the high-resolution reconstructions of seafloor spreading across the northern Mid-Atlantic, Carlsberg, and Southwest Indian Ridges. In Table 1 we report mean and covariances of $\Delta\vec{\omega}_{NA}$ and $\Delta\vec{\omega}_{AN}$ obtained from the distributions in Figures 2 and 3. We use these results in conjunction with estimates of the present-day stage Euler vectors of North America and Antarctica [*DeMets et al.*, 2010; *Torsvik et al.*, 2010] to map the absolute velocities of the two plates before 8 Ma and after 5 Ma (Figure 4). In North America, absolute velocities decreased by around 5 mm/yr. At the location of the Yellowstone hotspot, for instance, the absolute velocity decreased from 24 to 20 mm/yr, while the direction of motion remained steady at 100°W. Furthermore, motion at the location of the San Andreas Fault decreased from 24 to 19 mm/yr, while the direction of motion remained steady at 107°W. Furthermore, motion at the location of the San Andreas Fault decreased from 3.2 to 1.9 cm/yr and rotated from 95°W to 107°W. These inferences might contribute to ongoing debates concerning, for instance, the long-term seismic potential of faults in the western United States [e.g., *Bird*, 2009] or even the long-term climate, since the vertical motions of the Antarctic bedrock that arise from its passage over buoyant mantle structures contribute to the stability of the Antarctic ice sheet [e.g., *Austermann et al.*, 2015].

The similar timing of the changes in the absolute motions of NA and AN suggests, although does not require, a common origin for those changes. For example, both plates share long boundaries with the Pacific (PA)

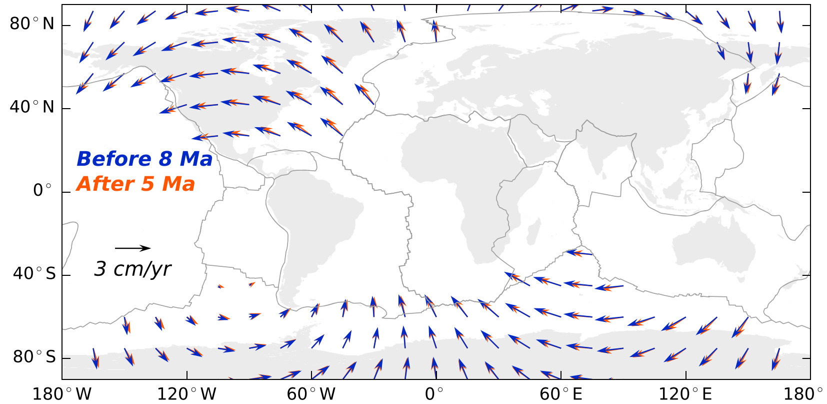

Figure 4. Absolute velocities of North America and Antarctica before 8 Ma (in blue) and after 5 Ma (in orange). Absolute velocities after 5 Ma are determined by summing the stage Euler vectors for Antarctica/Nubia and North America/Nubia motions from the MORVEL model of *DeMets et al.* [2010] to the vector for Nubia absolute motion since 10 Ma of *Torsvik et al.* [2010]. Absolute velocities before 8 Ma are determined by modifying the estimates above by the $\Delta\vec{\omega}$ described in the text and shown in Figures 2 and 3. Plate margins are in dark grey, continents in light grey.

plate, whose absolute motion rotated clockwise between 10 and 6 Ma [e.g. *Cox and Hart*, 1985; *Wessel and Kroenke*, 2000; *Cande and Stock*, 2004]. *Austermann et al.* [2011] describe evidence from geomechanical modeling that a change in forces acting on PA due to the collision between the north Melanesian arc and the Ontong Java Plateau in the western Pacific Basin was sufficient to cause the observed change in PA absolute motion. We speculate that the change in PA absolute motion reoriented the stresses acting along the PA/NA and PA/AN plate interfaces enough to alter the associated torques, which—by virtue of Newton's third law of motion—contribute also to the absolute motions of NA and AN. One aspect of our hypothesis is that the dynamic coupling between PA and AN, meaning the amount of force that the two plates mutually exchange, is less than for the PA/NA plate pair, because the latter boundary is mostly transform or convergent, wherease the former is predominantly divergent. Since the thermal regime of ridges [e.g., *Stein and Stein*, 1992] makes them significantly weaker than transform and convergent margins, most PA/AN coupling is likely to be concentrated along the PA/AN rise transform faults, whose net 3100 km length is less than a third of the >11,000 km combined length of the transcurrent and convergent faults that comprise the PA/NA plate boundary. It follows that a change in PA absolute motion would induce a larger torque variation on NA than on AN. Considering that the surface areas of NA and AN are nearly the same (5.5×10^7 km^2 versus 5.8×10^7 km^2, respectively), the fact that absolute velocities in North America changed by 1 to 1.5 cm/yr while those in Antarctica did by 0.5 to 1 cm/yr lends some support to our hypothesis. By the same logic, the late Neogene rotation of PA absolute motion should have impacted the motion of the Australian Plate, with which it shares a long convergent/transcurrent margin, but not too much that of the Nazca plate, whose 4500 km long boundary with PA consists dominantly (>80%) of ridge segments.

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Erratum

In the originally published version of this article, a formatting error in the script used to generate figure 4 was discovered. Figure 4 was replaced with a corrected version. Also, in section 3 "In North America, absolute velocities decreased by at least 1 cm/yr and up to 1.5 cm/yr. They also rotated by 5 to 10°. At the location of the Yellowstone hot spot, for instance, the absolute velocity decreased from 3.4 to 2.0 cm/yr, while the direction of motion rotated by ∼11° counterclockwise, from 88°W to 99°W. Furthermore, motion at the location of the San Andreas Fault decreased from 3.2 to 1.9 cm/yr and rotated from 95°W to 107°W. The absolute velocities of Antarctica exhibit a similar pattern, although in this case implied slowdowns are smaller, between 0.5 and 1 cm/yr." This text was changed to: "In North America, absolute velocities decreased by around 5 mm/yr. At the location of the Yellowstone hotspot, for instance, the absolute velocity decreased from 24 to 20 mm/yr, while the direction of motion remained steady at 100°W. Furthermore, motion at the location of the San Andreas Fault decreased from 24 to 19 mm/yr, while the direction of motion remained steady at 107°W." The following have since been corrected and this version may be considered the authoritative version of record.