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Earth and Planetary Science Letters 6825 (2003) 1–12
www.elsevier.com/locate/epsl

Evidence for a post-3.16-Ma change in Nubia–Eurasia–North America plate motions?

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Received 8 April 2003; received in revised form 9 July 2003; accepted 11 July 2003

Abstract

We combine updated GPS velocities from the Nubian (NU), Eurasian (EU), and North American (NA) plates with 500 new 3.16-Myr-average seafloor spreading rates and nine transform fault azimuths from the northern Atlantic and Arctic basin seafloor spreading centers to estimate and test for changes in the relative motion between these plates. The numerous new seafloor spreading rates and GPS velocities improve our ability to detect recent changes in the relative motions of these plates. The angular velocity vector that best fits the EU–NA GPS velocities lies significantly north of the 3-Ma-average pole, in accord with previously published geologic evidence that the EU–NA pole has migrated northward since ~3 Ma. Although we also find evidence for a significant post-3-Ma change in NU–NA motion, it is less compelling because the Nubian plate GPS velocity field is sparse and NU–NA seafloor spreading rates appear to have remained steady within the 1 mm yr^{-1} uncertainties if we systematically decrease the seafloor spreading rates to correct for outward displacement of seafloor spreading magnetic lineations. The NU–EU pole derived from GPS site velocities lies more than 30 angular degrees south of the tightly constrained 3-Ma-average estimate and predicts significantly slower and more oblique present-day NU–EU convergence in the Mediterranean. Both models for NU–EU motion pass a key test for their accuracy, namely, they correctly predict strike-slip motion along the well-mapped Gloria fault east of the Azores. The change to more oblique NU–EU motion may reflect increasing difficulty in maintaining margin-normal convergence within this continent–continent collision zone.

Keywords: plate motions; GPS; Eurasia; Nubia; North America

1. Introduction

Changes in plate motions over geologically brief intervals in the geologic past are well documented from analysis of the seafloor spreading record (e.g., [1–4]) and may reveal fundamental properties of the dynamics of plate motions. Such changes have been interpreted either as the result of changes in plate boundary forces due to

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0012-821X/03/$ – see front matter © 2003 Published by Elsevier B.V.
doi:10.1016/S0012-821X(03)00482-5

evolving plate boundaries [5,6], or as the result of buoyancy instabilities in mantle convection [7]. A key goal of geodetic measurements of plate velocities is to extend our knowledge of such changes to the present.

Toward this goal, estimates of recent plate velocities derived from early geodetic measurements and geologic data such as seafloor spreading rates derived from marine magnetic anomalies and transform fault azimuths have been shown to agree well, suggesting that plate motions have been essentially steady over the last 3 Myr [8]. In the past decade, as the geographic distribution of permanent geodetic stations and the reliability of global geodetic reference frames have improved, geodetic estimates of the instantaneous motions of most tectonic plates have become increasingly well-constrained (e.g., [9,10]). With uncertainties in both geologic and geodetic estimates of plate motions now approaching 1–2 mm yr^{-1}, it is possible in principle to detect relatively small changes in plate motion (2–3 mm yr^{-1}). Detecting changes this small however requires well-constrained geodetic and geologic estimates for the plates in question and careful examination of potential sources of systematic error in either estimate. In Section 4, we describe the effects of several potential sources of systematic error, most notably displacement of seafloor spreading magnetic lineations away from the axis of seafloor spreading due to extrusion and intrusion of newly magnetized crust over adjacent older crust during emplacement of new seafloor along a spreading axis (hereafter referred to as ‘outward displacement’) and imperfectly known motion of the geocenter in terrestrially based geodetic reference frames.

Herein, we employ new geodetic and geologic observations from the boundaries and interiors of the Eurasian (EU), North American (NA), and Nubian (NU) plates to test whether their relative motions have changed in the past 3 Myr. Numerous magnetic and bathymetric surveys of the seafloor spreading centers in the North Atlantic and Arctic basins over the past 40 years allow us to derive well-constrained angular velocity vectors to describe the relative motions of these three plates since 3 Ma. Coupled with widespread geodetic coverage of the Eurasian and North American plate interiors, this allows for a strong test for recent changes in the EU–NA relative motion. Sparser geodetic coverage of the Nubian plate, which presently has fewer than 10 continuously operating GPS stations, allows for a somewhat weaker but nonetheless useful test for recent changes in the NU–NA and NU–EU relative motion. Improved geologic and geodetic estimates for Nubian plate motion are particularly relevant because the NUVEL-1 and NUVEL-1A plate motion models [11,12] treat Africa as a single plate instead of separate Nubian and Somalian plates, thereby giving a biased estimate of its long-term motion [13]. Prior comparisons of geodetic estimates for Nubian plate motion (e.g., [10,14]) to the NUVEL-1A prediction for Africa include this small bias.

2. Geological and geodetic data

Our geologic estimates of NU, EU, and NA motions are derived from 500 seafloor spreading rates from the Arctic basin and mid-Atlantic ridges (Figs. 1 and 2) and nine transform fault azimuths taken from the NUVEL-1A data set. Individual seafloor spreading rates are derived from original shipboard and airborne magnetic anomaly profiles from the Arctic and North Atlantic seafloor spreading centers. The best-fitting rate for each magnetic profile was derived via cross-correlation of its anomaly 2A sequence (3.58–2.58 Ma) with a series of synthetic magnetic anomaly profiles that use different assumed spreading rates. Each rate thus averages motion since ∼3 Ma. A more detailed description of these seafloor spreading rates will be provided by one of us (C.D.) in a future publication.

We inverted the new geologic data using fitting functions and procedures described by [11] to determine new best-fitting NU–NA and EU–NA angular velocity vectors (Table 1). The uncertainties assigned to the numerous seafloor spreading rates were adjusted to reflect their dispersion relative to the predictions of their best-fitting angular velocity vectors. The uncertainties in the angular velocity vectors thus accurately represent the random

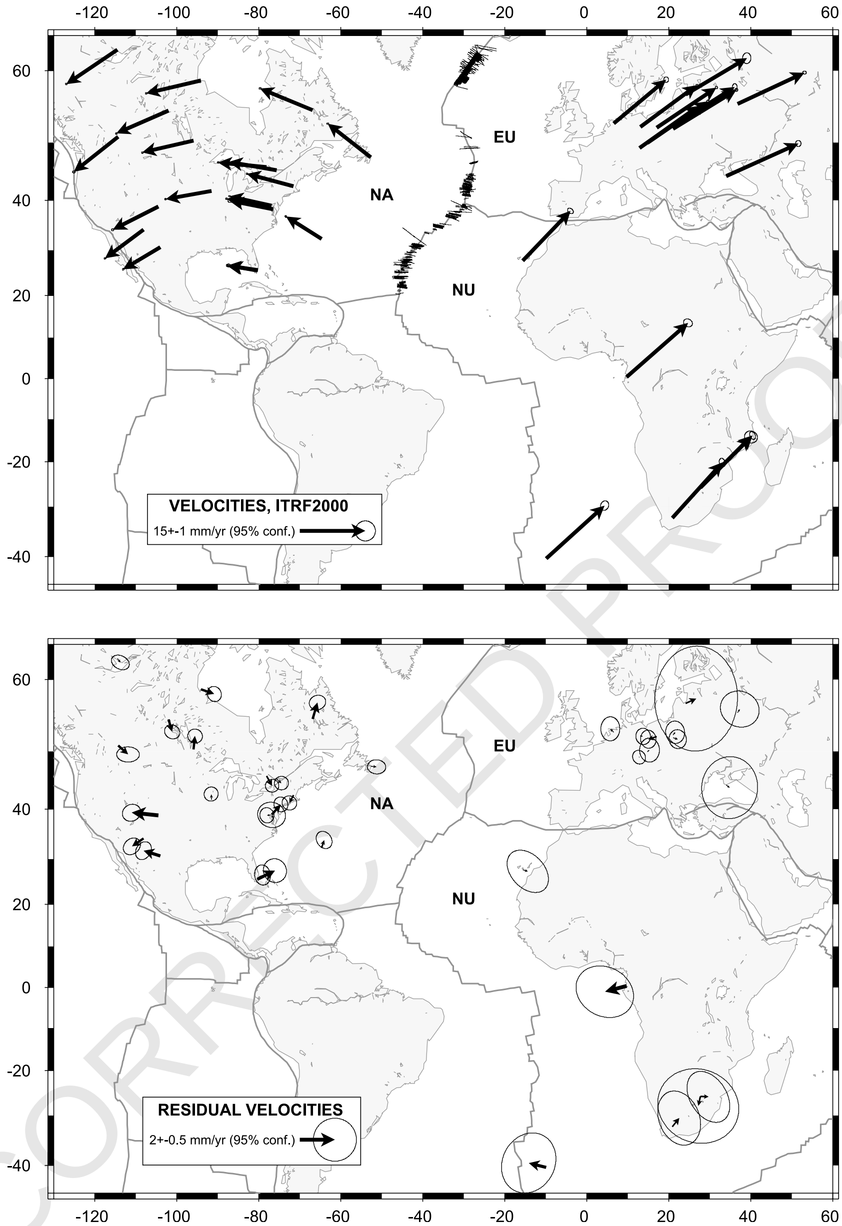

Fig. 1. (Top) Locations of airborne and shipboard magnetic profiles (thin lines) used to derive new seafloor spreading rates and GPS velocities used to describe the relative velocities of the EU, NA, and NU plates. GPS velocities are shown relative to ITRF2000. Airborne and shipboard profile locations north of Iceland are not shown. (Bottom) Residual GPS velocities for EU, NA, and NU plates are removing velocities predicted by the angular velocity vectors that best fit the GPS velocities for these three plates (shown in upper panel).

noise in the spreading rates. The NU–EU angular velocity vector and its uncertainties are derived from the NU–NA and EU–NA angular velocities and their covariances (Table 1).

GPS velocities for the Nubian and North American plates are derived from the International GPS Service (IGS) combined solution updated for GPS week 1186 (Sept. 29, 2002). This solution

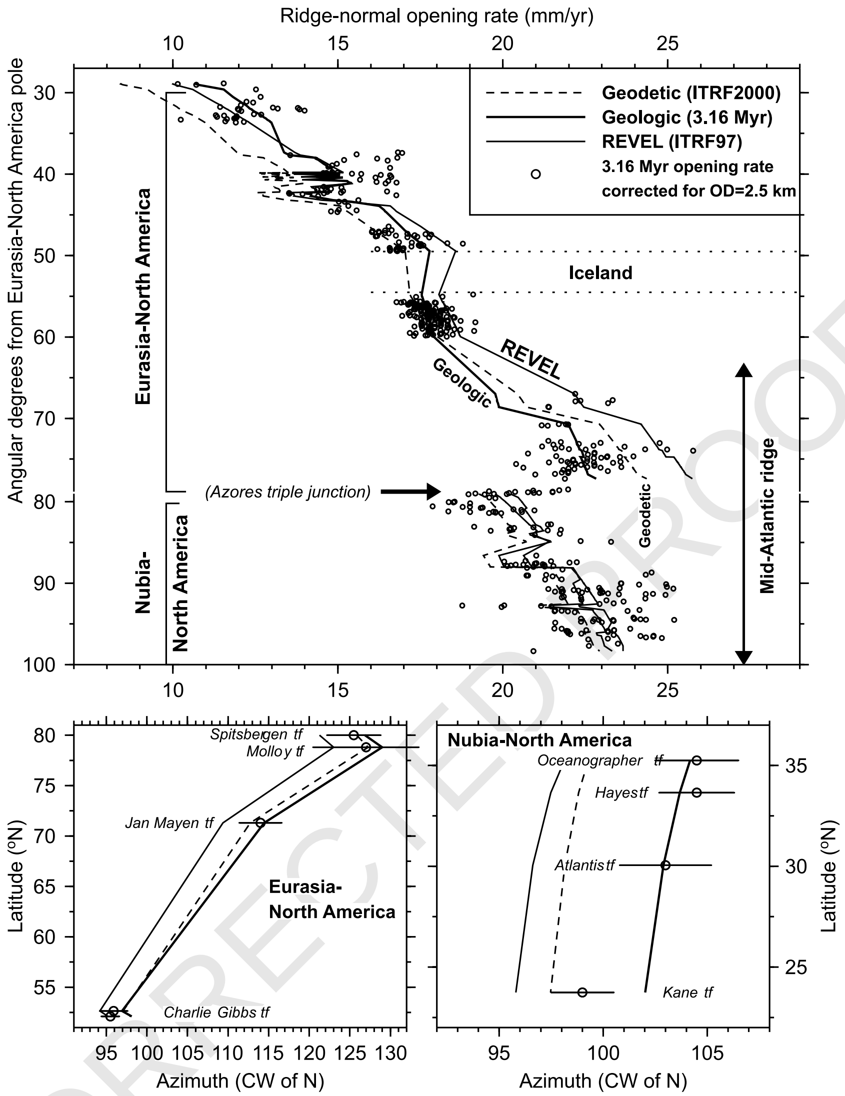

Fig. 2. EU–NA and NU–NA 3.16-Myr-average seafloor spreading rates and directions versus the predictions of the best-fitting geologic (bold line), best-fitting geodetic (dashed), and REVEL geodetic (thin line) models [10]. The REVEL model employs an earlier geodetic reference frame ITRF97. All rates are corrected downward by 0.8 mm yr^{-1} to compensate for the effect of outward displacement. See text for further discussion.

is a combination of weekly global solutions provided by seven data analysis centers. It contains site positions and velocities in ITRF2000 (International Terrestrial Reference Frame [15]) with their full associated covariance matrix. For the Eurasian plate, we combined three additional solutions in order to densify the site distribution [16]. We selected sites with standard horizontal velocity deviations that are less than 1 mm yr^{-1} (Fig. 1, top). In order to find the sites that best satisfy the condition of plate rigidity for each of the Nubian, Eurasian, and North American plates, we repeatedly inverted horizontal GPS velocities for each of these plates while searching for the combination of site velocities that are best fit by a single angular velocity vector, using χ^2 tests and minimal variance criteria [16,17]. By doing so, we obtain angular velocity vectors for all three plates relative to both ITRF2000 and each other (Table 1). Fig. 1 (bottom) shows that the residual velocities we obtain are less than 1 mm yr^{-1} at the 6, 22, and 12 sites we used to define Nubia, North America, and Eurasia angular velocity vectors.

3. Testing for changes in motion

3.1. Eurasia–North America

Relative to the 20 seafloor spreading rates that are used to define EU–NA motion in the NUVEL-1 and NUVEL-1A models, the 341 new rates represent a 12-fold increase. Inversion of these numerous new seafloor spreading rates along with five transform fault azimuths taken from the NUVEL-1 data yields a best-fitting EU–NA geologic pole that lies significantly south of our new best-fitting geodetic pole (Fig. 3). The location of the new geologic pole is close to that of the NUVEL-1A EU–NA pole, but has much smaller confidence limits that reflect the significant increase in the number of data used to derive the new angular velocity vector. The northerly location for the new best-fitting geodetic pole is similar to previously published GPS- and VLBI-based models for EU–NA motion [10,15,18,19].

This persistent difference between the locations of the ∼3-Ma-average geologic poles and the instantaneous-average geodetic poles, as defined by this and previous studies, suggests that the EU–NA pole has migrated northwards by ∼900 km since 3 Ma. Geologic evidence that Quaternary sedimentary basins aligned along the EU–NA plate boundary in the Cherskiy range of northern Siberia experienced a change from opening to east–west compression in the past few Myr is interpreted by [20] as indirect evidence for a post-3-Ma northward migration of the EU–NA pole of rotation. Our results support their hypothesis.

The new geodetic model predicts seafloor spreading rates along the EU–NA plate boundary that are ∼1 mm yr^{-1} systematically slower than predicted by the REVEL geodetic model (Fig. 2). The discrepancy between our geodetic estimates and REVEL may be due to different processing strategies, data time spans included in the solution, different release of the terrestrial geodetic reference frames (ITRF97 for REVEL versus ITRF2000 for this study), and finally the distribution of sites used to define the rigid plate motions. The small, but systematic difference in the geodetic predictions is evidence that systematic errors can be introduced into geodetic estimates of relative plate motion via the terrestrial geodetic reference frame that is used for a given analysis. We return to this issue later in the paper.

Table 1
Angular velocities for NU–NA, EU–NA, and NU–EU

Data set	Lat. (°)	Long. (°)	Rate (°/Ma)	1−σ error ellipse ε_{maj}	ε_{min}	Azim.	σ rate (°/Ma)
EU–NA							
GPS	70.1	129.2	0.236	2.2	1.0	134.4	0.005
Geologic	60.1	133.6	0.217	0.5	0.4	N03°W	0.001
Geologic_C	61.4	133.5	0.211	0.6	0.5	N04°W	0.001
NU–NA							
GPS	80.9	82.9	0.213	1.4	1.3	114.4	0.003
Geologic	77.3	70.1	0.228	2.3	1.0	N62°W	0.003
Geologic_C	77.7	66.2	0.221	2.5	1.0	N66°W	0.003
NU–EU							
GPS	−10.3	−27.7	0.063	10.3	3.3	52.0	0.004
Geologic	19.3	−19.0	0.103	3.2	1.0	N59°W	0.007
Geologic_C	18.5	−18.9	0.099	3.4	1.1	N59°W	0.007

'GPS' is derived only from GPS velocities described in the text; 'Geologic' is derived from seafloor spreading rates and transform fault azimuths described in the text; 'Geologic_C' is derived from the same rates and transform azimuths, but with a downward rate adjustment to compensate for outward displacement (see text).

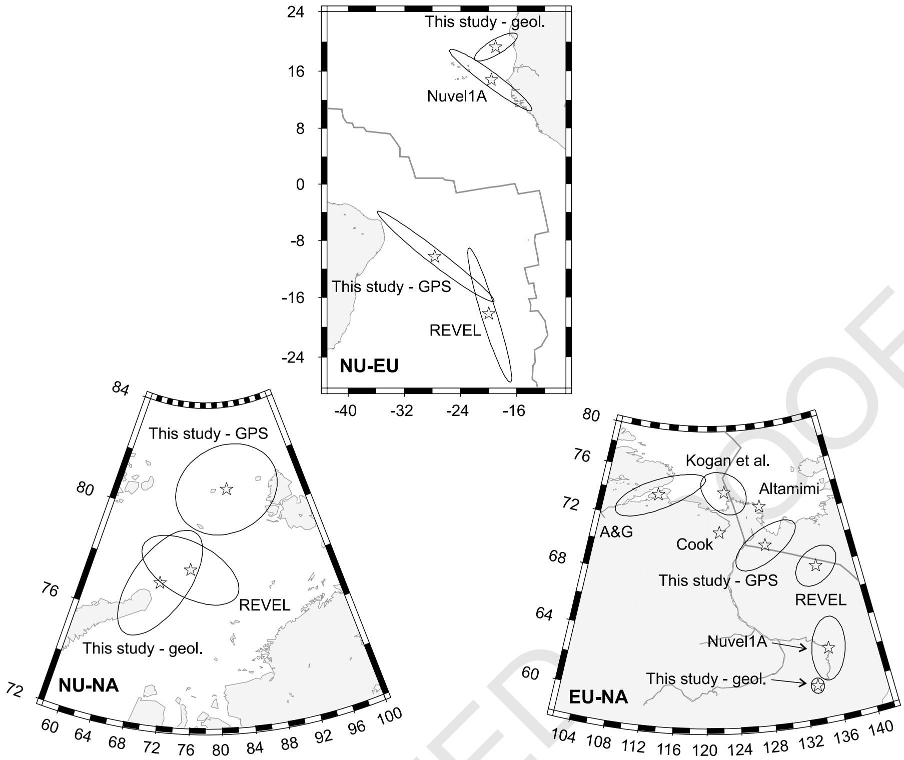

Fig. 3. Geologic and geodetic Euler poles derived in this and previous studies. REVEL poles are taken from [10]. Pole labeled 'Cook' is taken from [20], 'A and G' represents pole from [18], and 'Altamimi' pole from [15]. Uncertainty ellipses show 2-D, 95% confidence limits.

Due to the post-3-Ma northward migration of the EU–NA pole, the new geodetic angular velocity vector (and the REVEL model) misfit the gradient in the 3-Myr-average rates along the EU–NA plate boundary (Fig. 2). Similarly, the new 3-Myr-average angular velocity vector misfits the observed directions of motion at the Eurasian GPS sites (Fig. 4). We tested whether these misfits are statistically significant (and hence whether EU–NA motion has changed since 3 Ma) by using the *F*-ratio test to compare the least-squares fits of two models. We first inverted the 341 geologic data and 34 EU–NA GPS site velocities separately to determine the least-squares misfit for the angular velocity that best fit each set of data. We then combined the two sets of data and inverted them simultaneously. The least-squares fits of the former model and latter model differ at a confidence level much greater than 99.99%. The geodetic and geologic estimates of EU–NA motion thus differ significantly. This implies that EU–NA motion has changed since ∼3 Ma or, if motion has remained constant, that unrecognized systematic errors (discussed below) affect one or both sets of data.

3.2. Nubia–North America

Simultaneous inversion of the GPS velocities from the Nubian and North American plates yields a best-fitting instantaneous angular velocity vector that predicts ridge-normal seafloor opening rates along the Mid-Atlantic ridge (Fig. 2) that are ∼1–2 mm yr^{-1} slower than the 3.16-Myr-average opening rates whether or not we adjust the latter rates for the effects of outward displacement (described below). The new geodetic model predicts slip directions that are ∼5° counter-clockwise from the azimuths of three out of the four well-mapped NU–NA transform faults (Fig.

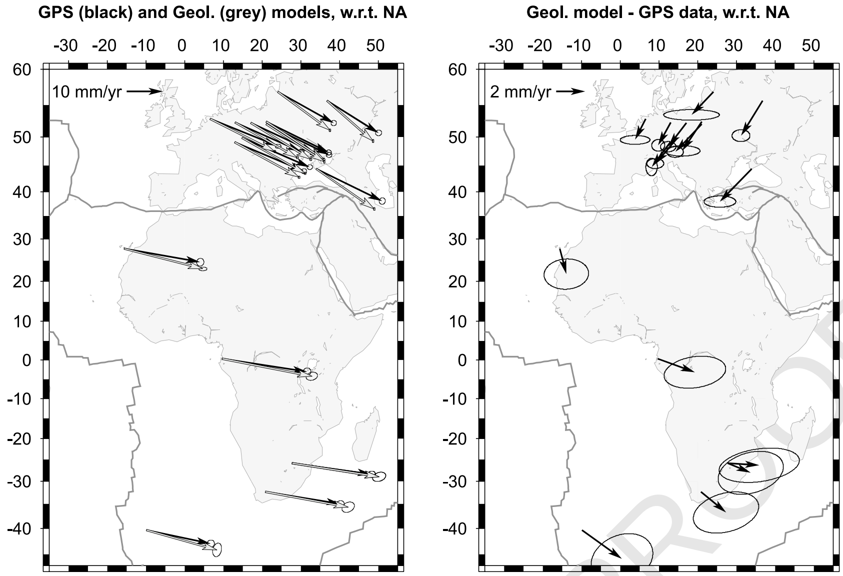

Fig. 4. (Left) Predictions of geologic and geodetic NU–NA and EU–NA angular velocity vectors at GPS sites from the Nubian and Eurasian plates. North American plate is fixed. (Right) Residual velocities of GPS sites on the Nubian and Eurasian plates with respect to velocities predicted by the NU–NA and EU–NA geologic angular velocity vectors. North American plate is fixed.

2). Similarly, the observed GPS velocities are 1–3 mm yr^{-1} slower than predicted by the geologic model (Fig. 4).

We tested whether the geologic and geodetic data are consistent with the hypothesis of steady motion since 3 Ma by simultaneously inverting the 28 Nubian and North American GPS site velocities and the 168 geologic observations that constrain NU–NA motion (i.e., NU–NA seafloor spreading rates and transform fault azimuths) to determine a single NU–NA angular velocity and its associated least-squares misfit. We then compared this misfit with the summed least-squares misfit for the angular velocity vectors that separately best fit the same geologic and geodetic data. We find that the geologic and geodetic data are inconsistent at confidence levels much greater than 99.99%. We note, however, that the Nubian plate geodetic velocity field is both more sparse and less mature (i.e., GPS sites have shorter time series) than the GPS velocity fields for Eurasia and North America. There is thus a greater likelihood that the true uncertainty in our geodetic estimate of Nubian plate motion is significantly greater than the formal uncertainty we derive from the handful of Nubian plate GPS velocities we use. In addition, systematic biases (discussed below) may affect one or both of the geologic and/or geodetic data. For these reasons, we consider the above evidence for a recent change in NU–NA motion to be preliminary.

3.3. *Nubia–Eurasia*

A test of the accuracy of the new geologic and geodetic models for NU–EU motion is whether they predict strike-slip motion along the Gloria fault, a ∼350-km-long transcurrent fault that accommodates NU–EU motion east of the zone of highly oblique rifting near the Azores islands [21]. Although neither the geologic nor geodetic model was derived using Gloria fault azimuths, both correctly predict the azimuths of the principal strands of the Gloria fault (Fig. 3), even though they average motion over different time intervals and are derived from independent data.

The best-fitting geodetic rotation pole lies ∼30 angular degrees south of the geologic pole (Fig. 3), mirroring a similar difference between the REVEL geodetic pole and the NUVEL-1A geologic pole. We tested whether the apparent change in NU–EU motion is significant by inverting the

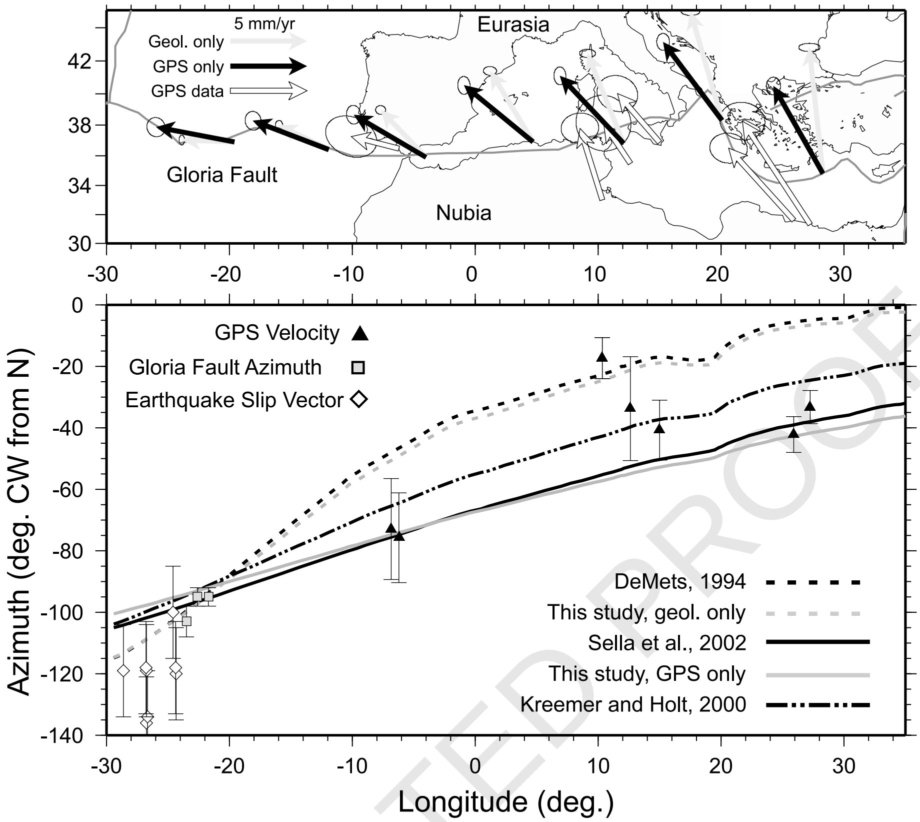

Fig. 5. Velocities predicted by geodetic and geological NU–EU angular velocity vectors along the Nubia–Eurasia plate boundary from the Azores to the eastern Mediterranean. Azimuths for the Gloria fault are measured from [21] and earthquake slip directions represent horizontal slip for oblique normal faulting earthquakes taken from Harvard centroid moment tensor solutions. The slip direction is averaged for the two nodal planes.

geologic data that constrain EU–NU motion (i.e., the EU–NA and NU–NA seafloor spreading rates and transform fault azimuths) and the GPS velocities from the Nubian and Eurasian plates separately and simultaneously and comparing their least-squares misfits. The difference in the least-squares fits of the combined-fit and separate-fit models is significant at confidence levels much higher than 99.99%. The geodetic and geologic estimates of NU–EU motion thus differ significantly.

The ∼3500 km southward migration of the NU–EU Euler pole over the past 3 Myr (Fig. 3) implies that NU–EU relative motion has recently become more oblique to the plate boundary trace, particularly in the Mediterranean (Fig. 5), where the new geodetic model predicts motion 10°–35° more oblique to the plate boundary than does the geologic model. The velocity directions at continuous GPS sites near the plate boundary in northern Africa, southern Spain, Sardinia, and Sicily (Fig. 5), and at GPS sites in Egypt (not shown, but described by [22]) are consistent with the directions predicted by the geodetic model, offering independent evidence that the present convergence direction is more oblique than in the recent geologic past.

The geodetic model also predicts a more uniform rate of motion than does the geologic model, averaging 6 ± 1 mm yr^{-1} everywhere along the boundary (Fig. 5). In contrast, the geologic model predicts convergence of 8 ± 0.6 mm yr^{-1} in the eastern Mediterranean, changing gradually to highly oblique opening of 4 ± 0.6 mm yr^{-1} at the western end of the plate boundary.

4. Discussion: Effects of possible systematic errors

The possibility that systematic biases are responsible for the apparent changes in motion within this plate circuit is an important concern, particularly given that the apparent changes are small (< 3 mm yr^{-1}). We discuss three possible sources of systematic error: (1) possible displacement of magnetic reversals away from the axis of seafloor spreading due to emplacement and extrusion of younger seafloor onto older adjacent seafloor along a seafloor spreading center [23], (2) a systematic bias in all of the GPS velocities due to a possible error in the geocentral translation rates underlying ITRF2000, (3) possible biases in one or more of the best-fitting GPS angular velocity vectors due to the sparseness of available velocities for the Nubian plate or possibly our selection of GPS sites to represent the motions of stable Eurasia, Nubia, or North America.

A likely source of systematic error in seafloor spreading rates results from the displacement of magnetic reversal edges away from the axis of seafloor spreading due to the finite width of magma emplacement during seafloor spreading. Studies of deep-tow magnetic profiles demonstrate that reversal transition widths, defined as the zone within which 90% of a magnetic reversal transition occurs, are typically 1–5 km for a wide range of seafloor spreading rates [24]. An underway study of seafloor spreading centers where opening rates have remained constant for the past few Myr indicates that the outward bias of the midpoint of a single magnetic reversal is 1–1.5 km along most seafloor spreading centers where opening rates are slower than ∼60 mm yr^{-1} (DeMets and Wilson, unpublished work, 2003). This outward bias represents an approximate estimate of the half-width of the total reversal transition zone, thereby implying an approximate total width of 2–3 km. The kinematic estimate thus agrees well with the reversal transition zone widths that are estimated from deep-tow magnetics.

Given that outward displacement increases seafloor spreading rates relative to the true rate of crustal accretion, we examined the effect of adjusting the 3.16-Myr-average NU–NA and EU–NA opening rates downward to compensate for an assumed 1.25 km of outward displacement of anomaly 2A on each side of the seafloor spreading axis. Adjusting the rates downward to compensate for 2.5 km of total outward displacement reduces each rate by 0.8 mm yr^{-1}. Along the NU–NA plate boundary, this downward adjustment eliminates half of the 1.5 mm yr^{-1} difference that existed between the geologic and geodetic model predictions. It is unclear whether the small remaining difference is caused by additional systematic errors (such as outward displacement that differs significantly from the value we assumed) or is instead evidence for a significant post-3-Ma change in NU–NA motion.

No systematic correction for outward displacement is capable of eliminating the difference in the opening gradients predicted by the EU–NA geologic and geodetic angular velocity vectors. Similarly, the NU–EU angular velocity vector is relatively insensitive to systematic adjustments of the EU–NA and NU–NA seafloor spreading rates for outward displacement, mainly because outward displacement affects rates along both seafloor spreading centers in a similar manner and hence largely cancels as a significant source of error upon summation of the EU–NA and NU–NA angular velocity vectors.

A second potential source of systematic bias, one that affects geodetic site velocities, comes from the requirement that the motion of the Earth's center of mass or geocenter be specified in order to define the terrestrial reference frame for a geodetic velocity solution [25]. Errors in the imperfectly known motion of the origin introduce systematic errors in GPS and other geodetic site velocities. For example, any error in the geocentral velocity component along the polar axis (90°N) will impart a mostly vertical systematic error to the velocities for geodetic sites at high latitudes and a mostly horizontal, north- or south-directed velocity bias for sites at lower latitudes. Such velocity biases do not cancel out when estimating relative plate motions because the magnitude and direction of the systematic velocity bias for a GPS site depend on the site location.

An inter-comparison of geocentral translation rates derived from the satellite laser ranging and very-long-baseline-interferometric solutions that are used to define ITRF2000 [15] suggests that errors in the geocentral translation rates used for ITRF2000 are smaller than 1 mm yr^{-1}. An independent way to estimate the potential magnitude of any biases in the geocentral translation rates is to treat them as adjustable parameters in a global velocity solution that attempts to minimize differences between long-term and geodetic estimates of plate velocities. Ongoing work by one of us (C.D.) using this technique also suggests that any geocentral rate biases in ITRF2000 are smaller than 1 mm yr^{-1}. Uncertainties related to geocentral translation rates thus appear unlikely to bias geodetic estimates of plate velocities at a level greater than 1 mm yr^{-1} and if so, are not a major limiting factor in attempts to detect recent changes in plate motion.

Finally, the possibility remains that the formal errors in our geodetic estimates of EU–NA–NU motion do not fully reflect the uncertainties engendered by our choice of geodetic velocities to represent the motions of these three plates. This seems less likely for the Eurasian and North American plates, for which the definition of the stable plate interiors is now relatively well understood thanks to the numerous, long-operating continuous geodetic stations on both plates (e.g., [16,17,26]). We also note that our results and those of the REVEL geodetic model [10] agree well, even though the underlying data, processing strategies, data time spans, and sites used to define the Eurasian and North American plates all differ. As a further test, we inverted our GPS velocities using the same sites employed to derive the REVEL model for these plates. The resulting angular velocity vectors are statistically indistinguishable from REVEL. The evidence thus suggests that our geodetic angular velocity vectors for the Eurasian and North American plates are not biased by the particular sites we selected to represent the motions of these plates.

It is more difficult to assess the reliability of our model for Nubian plate motion. The subset of GPS sites we used to define Nubian plate motion (GOUG, HARB, NKLG, MASP, HRAO, SUTH) are highly consistent with each other, with residual velocities smaller than 0.7 mm yr^{-1} (Fig. 1). Using alternative, smaller subsets of these sites yields similar estimates for Nubian plate motion and does not significantly alter any of the results presented herein. Unfortunately, there are relatively few stations, some operating for relatively short time spans (a few years or less). There is thus a greater possibility that longer time intervals for the existing stations and the addition of new continuous sites in the Nubian plate interior will lead to significant future revisions in our estimates of the angular velocity vector for this plate.

5. Conclusions

We conclude that the Nubia–Eurasia and Eurasia–North America motion have both changed significantly since ~3 Ma, even if we allow for possible systematic biases that affect the data from which these models were derived. More observations and a better understanding of possible systematic biases in the geologic and geodetic data are required to establish whether apparent changes in Nubia–North America motion are real.

Our results suggest that the new GPS-based angular velocity vector for present-day Nubia–Eurasia relative motion be used instead of the NUVEL-1A estimate as a boundary condition for lithospheric deformation along the Africa–Eurasia plate boundary zone (e.g., [27]).

The geodetic velocities suggest that the direction of Nubia–Eurasia convergence has rotated roughly 20° counter-clockwise in the past few Myr along the Mediterranean collision zone, reflecting significant southward migration of the rotation pole during this period. Our new model also predicts that NU–EU convergence rates have decreased by roughly 25% in the eastern Mediterranean over the past 3 Myr, with a relative plate motion direction becoming more oblique.

This change in the direction of the Nubia–Eurasia plate motion is consistent with the Pliocene to Quaternary counter-clockwise rotation of the compression direction inferred for northern Algeria by [28]. Other reports of recent changes in the strain regime along the Nubia–Eurasia plate boundary in the Mediterranean include the onset of widespread extension in the Apennines in the late Pleistocene (∼800 ka) [29] and the onset of the rapid phase of extension in the Hellenic arc in the Pleistocene (∼1 Ma) [30]. These latter two examples are however difficult to unambiguously link to changes in the Nubia–Eurasia relative plate motion because both areas involve an independent microplate, the Adriatic microplate in the case of the Apennines, and the Anatolian microplate in the case of the Aegean.

The post-3-Ma decrease in convergence rate and more oblique motion between Nubia and Eurasia found here may reflect increasing difficulty in maintaining north-directed convergence within the largely continent–continent collision zone between the two plates. During the same period, the Eurasia–North America pole migrated northwards toward the Arctic basin, in accord with independent geologic evidence [20].

Our kinematic analysis leaves unanswered important questions about what forces are responsible for the observed changes in the relative motions within this plate circuit. For example, did the forces acting on a single plate such as Eurasia change its absolute motion, thereby changing its motion relative to both Nubia and North America? Or did a change in the forces acting along the Nubia–Eurasia collisional boundary in the Mediterranean change the motions of both of these plates relative to the North America and possibly other neighboring plates?

Acknowledgements

We thank the U.S. National Science Foundation for funding (EAR-9902818) that supported some of this work and the French Ministry for Research for funding E.C. and J.M.N. through the program 'Prévention des Catastrophes Naturelles'. We thank R. Armijo and an anonymous reviewer for their helpful comments.***[VC]***

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