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Kinematics of the southern Red Sea–Afar Triple Junction and implications for plate dynamics

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[1] GPS measurements adjacent to the southern Red Sea and Afar Triple Junction, indicate that the Red Sea Rift bifurcates south of 17° N latitude with one branch following a continuation of the main Red Sea Rift (~150° Az.) and the other oriented more N-S, traversing the Danakil Depression. These two rift branches account for the full Arabia–Nubia relative motion. The partitioning of extension between rift branches varies approximately linearly along strike; north of ~16°N latitude, extension (~15 mm/yr) is all on the main Red Sea Rift while at ~13°N, extension (~20 mm/yr) has transferred completely to the Danakil Depression. The Danakil Block separates the two rifts and rotates in a counterclockwise sense with respect to Nubia at a present-day rate of 1.9 ± 0.1°/Myr around a pole located at 17.0 ± 0.2°N, 39.7 ± 0.2°E, accommodating extension along the rifts and developing the roughly triangular geometry of the Danakil Depression. Rotating the Danakil Block back in time to close the Danakil Depression, and assuming that the rotation rate with respect to Nubia has been roughly constant, the present width of the Danakil Depression is consistent with initiation of block rotation at 9.3 ± 4 Ma, approximately coincident with the initiation of ocean spreading in the Gulf of Aden, and a concomitant ~70% increase in the rate of Nubia–Arabia relative motion. **Citation:** McClusky, S., et al. (2010), Kinematics of the southern Red Sea–Afar Triple Junction and implications for plate dynamics, *Geophys. Res. Lett.*, *37*, L05301, doi:10.1029/2009GL041127.

1. Introduction

[2] The Afar Triple Junction is a Late Oligocene - Early Miocene structure that continues to accommodate the divergent motions between the Arabian, Nubian, and Somalian plates along the Red Sea, Gulf of Aden, and the East African rifts [e.g., *McKenzie et al*. 1970; *Le Pichon and Gaulier*, 1988]. The Triple Junction lies above the Afar Hot Spot that is responsible for the voluminous volcanic activity and high elevation that has characterized the region since the Late Oligocene [e.g., *Hoffman et al*., 1997], and which continues to the present time [e.g., *Wright et al*., 2006]. Interaction between tectonic extension and the Afar Hot Spot has resulted in spatially distributed, and temporally evolving deformation around the Triple Junction [e.g., *Garfunkel and Beyth*, 2006], although Arabia–Nubia–Somalia relative plate motions have remained approximately constant since at least 11 Ma [*McQuarrie et al*., 2003; *Garfunkel and Beyth*, 2006; *ArRajehi et al*., 2009]. Better constraints on the kinematic evolution of the Triple Junction therefore promise to advance our understanding of the dynamics of Arabia–Nubia plate motion [e.g., *Bellahsen et al*., 2003] as well as interactions between mantle dynamics and crustal tectonics [e.g., *Ebinger and Casey*, 2001; *Wolfenden et al*., 2005; *Keranen and Klemperer*, 2008].

[3] In this paper we present new geodetic constraints on the spatial distribution of active deformation associated with the Afar Triple Junction. We use these constraints and the morphology of the Danakil Depression to investigate the spatial and temporal evolution of the southernmost Red Sea and the Afar Triple Junction. Our analysis suggests that rifting associated with the separation of Arabia from Nubia initiated along the southern extension of the main Red Sea Rift. The rift bifurcated around 9 ± 4 Ma, with extension being partitioned between the two rift branches, roughly as observed at present. We suggest here that the change from extension principally confined to the main Red Sea Rift to the partitioning of extension between the main Rift and the Danakil Depression was associated with the change in Arabia plate motion around 13 Ma [*Le Pichon and Gaulier*, 1988; *McQuarrie et al*., 2003], and was facilitated by weakening of the Nubian continental lithosphere due to heating from the Afar Hot Spot.

2. GPS Data Analysis and Present-Day Deformation

[4] Details of the GPS observations presented here, and those used to estimate Nubian, Arabian, and Somalian reference frames are given in the auxiliary material (Table S1).[8] The GPS observations were processed with the GAMIT/GLOBK software suite [*King and Bock*, 2004; *Herring*,

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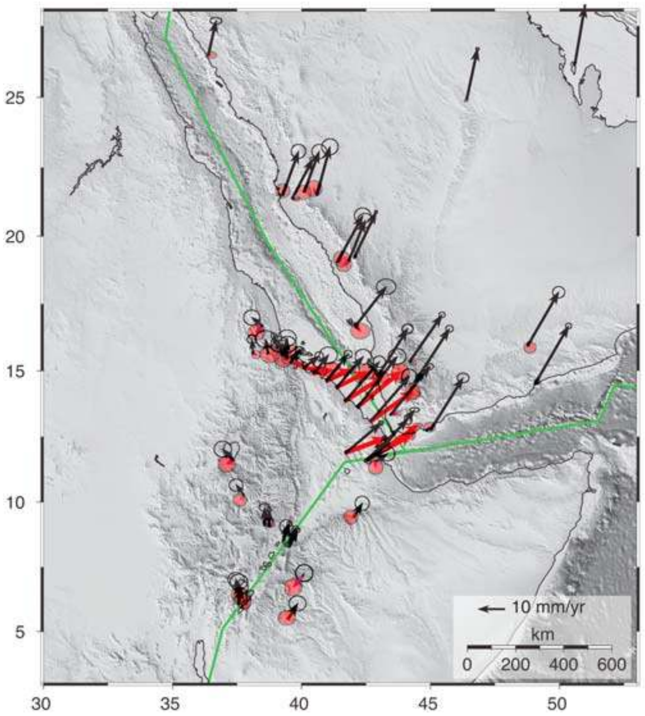

Figure 1. Map of the Nubia–Arabia–Somalia plate boundary region showing GPS-derived velocities with respect to Eurasia and 95% confidence ellipses (black arrows). Red arrows show residual velocities from a block rotation model for the Nubian, Arabian, and Somalian plates. Relative Euler vectors for the rotation parameters are given in Table 1. Topography and bathymetry from SRTM30 PLUS (see http://topex.ucsd.edu/WWW_html/srtm30_plus.html). Plate boundaries are shown schematically.

2004], and uncertainties were estimated following standard procedures described by *Reilinger et al.* [2006].

[5] Figure 1 shows and Table S1 lists GPS-determined surface velocities and their 95% confidence ellipses with respect to Eurasia and the residual velocities from a block rotation model for Arabia, Nubia, and Somalia using the relative Euler vectors for these plates determined here (Table 1). As reported previously [e.g., *McClusky et al.*, 2003; *Stamps et al.*, 2008; *ArRajehi et al.*, 2009], except for GPS sites along the W side of the S Red Sea, all three plates move coherently at the level of precision of the GPS observations.

[6] Figure 2 shows a close up view of the GPS velocity field around the southern Red Sea and Danakil/Afar Depression, plotted with respect to Nubia. The bifurcation of rifting identified earlier on the basis of seismicity [*Chu and Gordon*, 1998] is clearly indicated by the increase in velocities along the west side of the Red Sea from 15.5°N to the latitude of the junction of the Red Sea and Gulf of Aden (~12°N). North of ~16°N, Nubia–Arabia motion is accommodated by extension confined to the Red Sea, while at ~13°N Nubia–Arabia extension is completely accommodated within the Danakil/Afar Depression [*Vigny et al.*, 2007].

[7] Prior studies have shown that the Arabian Plate has been moving at a roughly constant rate relative to Eurasia, consistent with the present-day GPS rate, since at least 21 Ma [*McQuarrie et al.*, 2003; *McClusky et al.*, 2003] and possibly since the initiation of the Afar Triple Junction dated at 25–30 Ma [*ArRajehi et al.*, 2009]. These same studies indicate that Nubia Plate motion relative to Eurasia has been constant since 13 Ma but is ~70% slower than the rate from 30–13 Ma while Arabia-Eurasia motion has been largely constant. This implies a similar ~70% increase of the rate of Nubia–Arabia relative motion since 13 Ma [*Le Pichon and Gaulier*, 1988; *McQuarrie et al.*, 2003; *Garfunkel and Beyth*, 2006]. *ArRajehi et al.* [2009] further show that motion of the Arabian plate relative to Nubia and Somalia would develop the present morphology of the Red Sea and Gulf of Aden rifts in about 24 ± 2.2 Ma, roughly consistent with geologic estimates for the initiation of rifting. On this basis, *ArRajehi et al.* [2009] suggest that the GPS-derived motions reflect the long-term evolution of these rifts.

3. A Simple Block Rotation Model

[8] Given the present-day, roughly coherent rotation of the Danakil Block (Figure 2), and the coherent motions of the Arabian, Nubian, and Somalian plates, we develop a block rotation model constrained by GPS to quantify active deformation in and around the Afar Triple Junction. Figure 3 shows one such model including the Nubian, Arabian, and Somalian plates and a Danakil micro-plate [*Chu and Gordon*, 1998; *Eagles et al.*, 2002]. We locate block boundaries based on tectonic morphology, and earthquake epicenters. The configuration of block boundaries is well constrained on major active tectonic structures, but less so within the Danakil Depression where it is difficult to identify a localized boundary. Active deformation within the Danakil Depression may be distributed spatially, or the position of the boundary within the Depression may vary with time (note in Figure 3 the location of the 2005 Dabbahu dike intrusion event [*Wright et al.*, 2006] which is ~50 km west of our proposed central Danakil Depression spreading boundary). In the absence of direct constraints, we have chosen to locate the western boundary of the Danakil micro-plate along the central Danakil Depression, based on the roughly symmetric shape of the Depression that may indicate symmetric spreading about this axis (averaged over geologic time).

[9] The simple block rotation model provides a good fit to the GPS observations, accounting for the coherent motions of the Nubian, Arabian, and Somalian plates, as well as counterclockwise rotation of the Danakil Block with respect to Nubia. The rms for residual velocities on each block is

Table 1. Rotation Parameters for the Plate Pairs Reported Here[a]

Plate Pair	Latitude (°)	+/− (°)	Longitude (°)	+/− (°)	Rate (°/My)	+/− (°/My)	Correlations lat/lon, lat/rate, lon/rate
Nubia–Danakil	17.0	0.2	39.7	0.2	1.9	0.1	0.708, 0.851, 0.830
Arabia–Danakil	13.4	0.2	42.9	0.2	1.5	0.1	0.093, −0.231, −0.530
Somalia–Danakil	15.3	0.2	39.6	0.2	1.9	0.1	0.502, 0.532, 0.833

[a] Rotation parameters are relative Euler vectors.

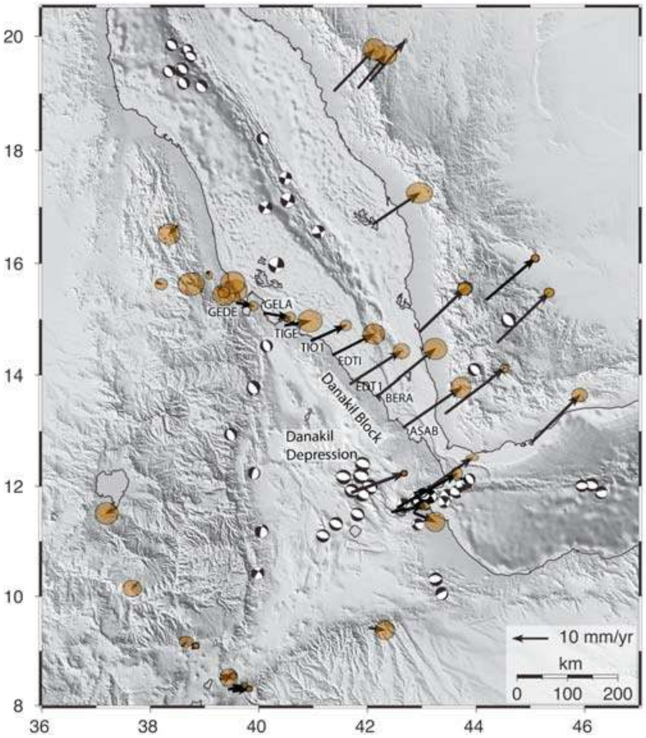

Figure 2. Map of the Afar Triple Junction showing GPS velocities and 95% confidence ellipses with respect to Nubia (see Table 1 for rotation parameters). Focal mechanisms (lower hemisphere projections) from Harvard catalog, 1976–2009. Topography and bathymetry as in Figure 1.

given along with relative Euler vectors in Table 1. The sense of slip on modeled faults is generally consistent with earthquake focal mechanisms (Figure 3). The "junction" where the Red Sea Rift "bifurcates" at ~17°N involves small left-lateral motion consistent with earthquake focal mechanisms; the small rate along this boundary is consistent with the absence of any well defined tectonic features on the Sea floor. Furthermore, the model results in coherent rotation of the Danakil Block, consistent with its geological structure and aseismic character.

[10] Figure 4 shows an attempt to "rotate back" the Danakil Block using the GPS-derived Danakil–Nubia Euler vector. Ten degrees clockwise rotation results in overlap of "unextended" terrains along the northernmost part of the Danakil Depression (~15°N) and substantial remaining opening to the south. An additional 15° of rotation are required to close the southernmost Depression. Assuming a constant rotation rate as given by GPS, these rotations imply an age for the Danakil block of 5.3–13.2 Ma (i.e., 10°/1.9°/Myr − 25°/1.9°/Myr), or 9.3 ± 4 Ma.

[11] The morphology of the Danakil Depression appears more consistent with a rotation pole located ~200 km south of the GPS pole (i.e., at the northernmost end of the Depression at about 15°N). Rotation about this pole results in a good fit between the western side of the Danakil Block and the adjacent Nubian plate with a single clockwise rotation of about 25°. It seems very likely that the rotation pole has shifted north in geologically recent times, possibly associated with the accretion of the southernmost Danakil Block to Arabia (see location of the Arabia–Danakil rotation pole about 200 km north of the S end of the Danakil Block, Figure 3) and the separation of the northern end of the Danakil Block from Nubia. In this case, the older age estimate may be more indicative of the age of initiation of Danakil Block rotation. This possibility is further supported by the relationship between the present width of the depression and GPS velocities along the Danakil block (Figure 4).

4. Discussion

[12] The bifurcation of rifting in the S Red Sea at about 9 ± 4 Ma may be related to the change in Nubia–Arabia relative motion that occurred around this same time [*Le Pichon and Gaulier*, 1988; *McQuarrie et al.*, 2003; *Garfunkel and Beyth*, 2006]. This time was also marked by the initiation of full ocean spreading in the Gulf of Aden (11–16 Ma) [*Cochran*, 1981; *Ben Avraham et al.*, 2008] and the influx of volcanics from the EAR into the Afar region [*Wolfenden et*

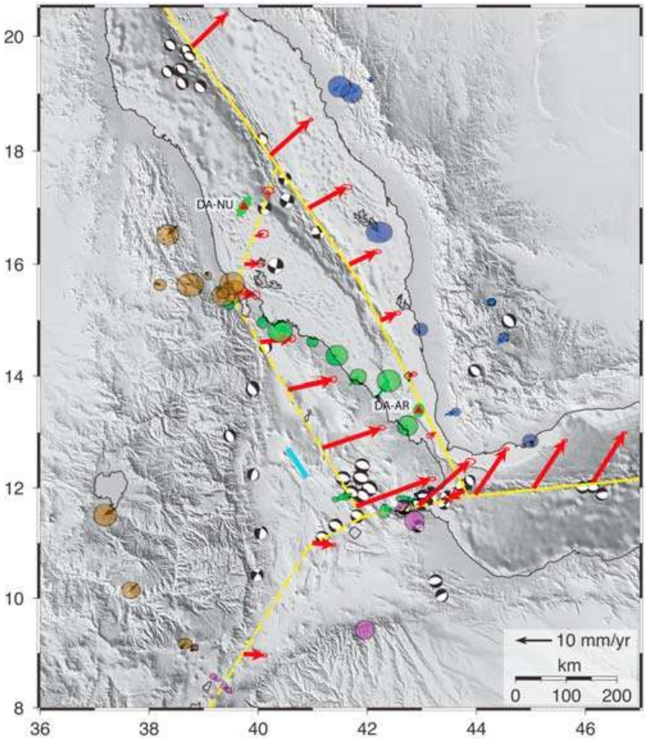

Figure 3. A simple block/plate rotation model constrained by GPS motions including the Nubian, Arabian, and Somalian plates, and a Danakil micro-plate. The western boundary of the Danakil Block is dashed indicating uncertainty in its location (see text). Residual velocities (modeled – observed; green = Danakil, purple = Somalia, brown = Nubia, blue = Arabia) and 95% confidence ellipses from this model (rotation parameters in Table 1). The red triangles and green ellipses show the location of the Danakil–Nubia and Danakil–Arabia rotation poles and 95% confidence ellipses (Table 1). Red arrows show predicted motion on block boundaries (east side with respect to west side, or north with respect to south). The light blue line shows the approximate location of the 2005–2007 Dabbahu dyke intrusion events [*Wright et al.*, 2006]. Base map as in Figure 1. Focal mechanisms as in Figure 2.

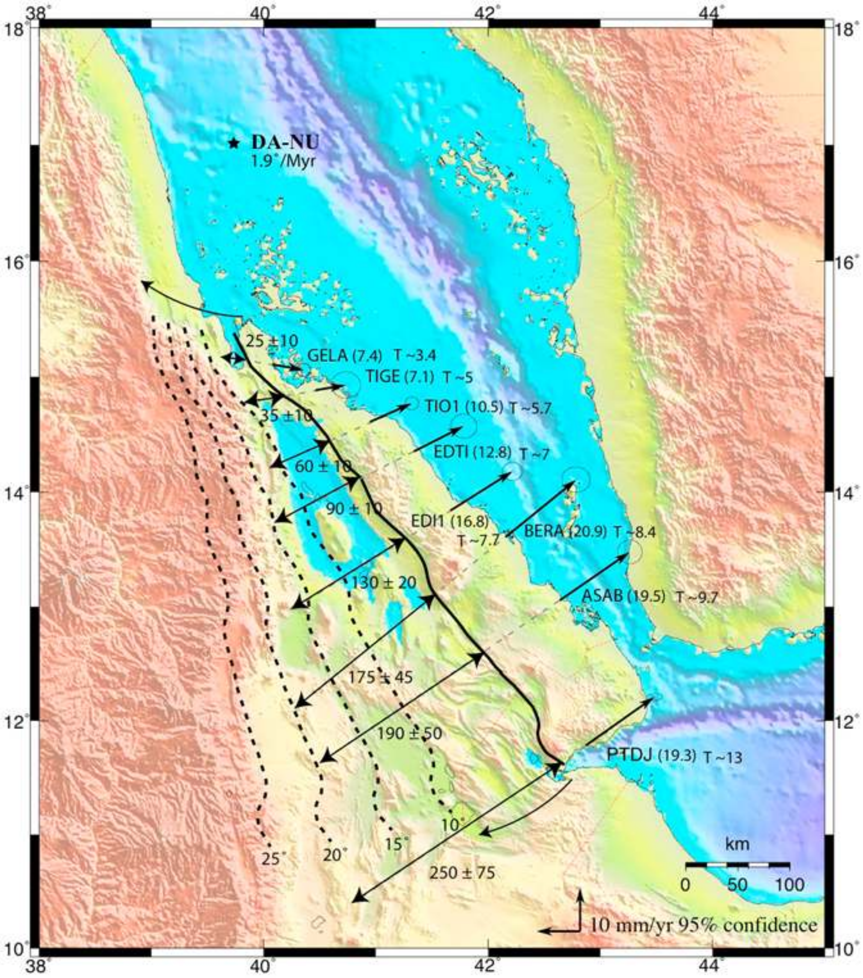

Figure 4. Back rotation of the western side of the Danakil Block around the GPS rotation pole showing initial overlap of unextended terrains in the N (15°N) after 10° rotation and closing of the S Danakil Depression at 25°. Also shown is the relationship between the estimated width of the Danakil Depression and the adjacent velocities along the Danakil Block, and the implied estimate of the progressively increasing age of the Depression from north to south.

al., 2005]. We suggest that the initiation of full ocean spreading in the Gulf of Aden essentially severed the connection between the Arabian and Somalian plates thereby reducing the pull on the Somalian and Nubian plates due to subduction of the Neotethys ocean lithosphere along the Bitlis-Zagros and the Makran subdution zones [*Le Pichon and Gaulier*, 1988; *Bellahsen et al.*, 2003 *ArRajehi et al.*, 2009]. The reduction in NNE-directed pull on Nubia and Somalia caused the plate pair to slow down with respect to Arabia resulting in an increase in the rate of Arabia–Nubia relative motion, and possibly adding an additional N-S component of motion across the Red Sea. This new geometry and increased rate of motion may have initiated the change in the configuration of deformation in the southern Red Sea that shifted extension to the east into the Danakil Depression. Such a scenario is consistent with the notion that slab pull is the primary driving force for Arabia Plate motion [e.g., *Elsasser*, 1971; *Forsyth and Uyeda*, 1975; *Hager and O'Connell*, 1981; *Conrad and Lithgow-Bertelloni*, 2002; *Bellahsen et al.*, 2003]. It also implies that the Arabian continental lithosphere is sufficiently strong in relation to plate boundaries and basal drag forces to maintain stresses over large distances (i.e., in relation to the thickness of the plate) with a minimum of internal plate deformation. We further speculate that the coherent rotation of the Danakil Block implies that continental lithosphere remains strong in relation to plate boundaries and basal drag even after extreme heating and tectonism. The present day, coherent motion of the south Aegean micro-plate [*McClusky et al.*, 2000] and the Lesser Caucasus region [*Reilinger et al.*, 2006] provide further evidence that the continental lithosphere maintains strength under extreme tectonic/magmatic conditions.

5. Conclusions

[13] Geodetic observations along the Danakil Block and Afar Triple Junction indicate present-day, coherent, counterclockwise rotation of the Block with respect to the Nubian Plate around a pole of rotation located in the central Red Sea at ~17°N latitude (Figure 4, Table 1). We estimate the age of initiation of Danakil Block rotation at 9 ± 4 Ma based on present-day rotation rates and the width of the Danakil Depression. This interpretation implies that the Danakil Depression is completely composed of new area (within reported uncertanties), created by mantle intrusion. We relate the initiation of Danakil Block rotation to the

change in Arabia–Nubia relative motion at ~11 Ma, which in turn we relate to the initiation of ocean spreading in the Gulf of Aden that reduced the northward pull on Somalia from subduction of the Neotethys oceanic lithosphere along the Bitlis-Zagros and Makran subduction zones. To the extent that these events are causally related, they provide an observational basis to constrain quantitative models for plate driving forces and the rheology of the lithosphere.

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