

1 Kinematics of the southern Red Sea-Afar Triple Junction and implications for plate
2 dynamics

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Abstract

GPS measurements adjacent to the southern Red Sea and around the Afar Triple Junction (Red Sea Rift/Gulf of Aden Rift/East African Rift), 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° Azimuth) and the other oriented more N-S, traversing the Danakil Depression. These two rift branches account for the full Arabia-Nubia relative motion. Within the resolution of our observations, the partitioning of extension between rift branches varies linearly along strike; north of ~ 16°N latitude, extension (~ 15 mm/yr) is all on the main Red Sea Rift while at the latitude of the Asab, Eritrea GPS station (~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 $1.9 \pm 0.1^\circ/\text{Myr}$ around a pole located at $17 \pm 0.2^\circ\text{N}$, $39 \pm 0.2^\circ\text{E}$, accommodating extension along the rifts and developing the roughly triangular geometry of the Danakil Depression. Based on the present geometry of the Danakil Depression, we suggest that the location of the Danakil Block-Nubia pole of rotation has migrated approximately 200 km north during the past few Ma. 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 ~40 % increase in the rate of Nubia- Arabia relative motion.

Index Terms: 8105, 8109, 8120, 8158, 8159

Introduction

The Afar Rift-Rift-Rift 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; Garfunkel and Beyth, 2006). 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, and references therein), 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).

In this paper we present new geodetic constraints on the spatial distribution (kinematics) 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 of present-day motions and tectonic structures suggests that rifting associated with the

62 separation of Arabia from Nubia initiated along the southern extension of the main Red
63 Sea rift. The rift bifurcated around 9 ± 4 Ma, with extension being partitioned between
64 the two rift branches, roughly as observed at present. We suggest here that the change
65 from extension principally confined to the main Red Sea Rift to the partitioning of
66 extension between the main Red Sea Rift and the Danakil Depression was associated
67 with the change in Arabia plate motion around 11 Ma (Le Pichon and Gaulier, 1988;
68 McQuarrie et al., 2003) and was facilitated by weakening of the Nubian continental
69 lithosphere due to heating from the Afar Hot Spot.

71 GPS Data Analysis and Present-day Deformation

72 Details of the GPS observations presented here, and those used to estimate Nubian,
73 Arabian, and Somalian reference frames are given in Supplementary Table 1S. The GPS
74 observations were processed with the GAMIT/GLOBK software suite (King and Bock,
75 2004; Herring, 2004), and uncertainties were estimated following standard procedures
76 described in Reilinger et al. (2006).

78 Figure 1 shows, and Table 1S lists GPS-determined surface velocities and their 95%
79 confidence ellipses with respect to Eurasia used in this study. Also shown on Figure 1 are
80 the residual velocities from a block rotation model for Arabia, Nubia, and Somalia using
81 the relative Euler vectors for these plates determined here and given in Table 1. As
82 reported previously (e.g., McClusky et al., 2003; Reilinger et al., 2006; Stamps et al.,
83 2008; ArRajehi et al., 2009), all three plates move coherently at the level of precision of
84 the GPS observations.

85

86 Figure 2 shows a close up view of the GPS velocity field around the southern Red Sea
87 and Danakil/Afar Depression, plotted with respect to Nubia. The bifurcation of rifting
88 identified earlier on the basis of seismicity (Chu and Gordon, 1998) is clearly indicated
89 by the increase in velocities along the west side of the Red Sea (i.e., along the Danakil
90 Block) from 15.5°N to the latitude of the junction of the Red Sea and Gulf of Aden
91 (~12°N). North of the Danakil block (~16°N), Nubia-Arabia motion is accommodated
92 completely by extension confined to the Red Sea. At the latitude of GPS station ASAB
93 (~13°N), Nubia-Arabia extension is completely accommodated within the Danakil/Afar
94 Depression west of the Danakil Block.

95

96 Prior studies have shown that the Arabian Plate has been moving at a roughly constant
97 rate relative to Eurasia, consistent with the present-day GPS rate, since at least 21 Ma
98 (McQuarrie et al., 2003; McClusky et al., 2003; Reilinger et al., 2006) and possibly since
99 the initiation of the Afar Triple Junction dated at 25 – 30 Ma (ArRajehi et al., 2009).
100 These same studies indicate that Nubia Plate motion relative to Eurasia has been constant
101 since 11 Ma while the rate from 21 – 11 Ma was approximately 40% faster than the 11 -
102 0 Ma rate, implying an increase of the rate of Nubia-Arabia relative motion of this same
103 amount (Le Pichon and Gaulier, 1988; McQuarrie et al., 2003; Garfunkel and Beyth,
104 2006). ArRajehi et al. (2009) further show that present-day motion of the Arabian plate
105 relative to Nubia and Somalia, including a 40% increase in Arabia-Nubia relative motion
106 at 11 Ma (i.e., due to the slowing of Nubia plate motion with respect to Arabia), would
107 develop the present morphology of the Red Sea and Gulf of Aden rifts in about **30 ± 3**

108 **Ma**, roughly consistent with geologic estimates for the initiation of rifting. On this basis,
109 ArRajehi et al. (2009) suggest that the GPS-derived motions reflect the long-term
110 evolution of these rifts.

112 A Simple Block Rotation Model

114 Given the present-day, roughly coherent rotation of the Danakil Block (Figure 2), and the
115 well established, coherent motions of the Arabian, Nubian, and Somalian plates, we
116 develop a block rotation model constrained by GPS to quantify active deformation in and
117 around the Afar Triple Junction. Figure 3 shows one such model including the Nubian,
118 Arabian, and Somalian lithospheric plates and a Danakil micro-plate (Chu and Gordon,
119 1998) that primarily accommodates the bifurcation of extension along the southernmost
120 Red Sea segment of the Triple Junction. We locate block boundaries based on tectonic
121 morphology (Red Sea, EAR, and the Gulf of Aden Rift and its westward extension into
122 the Afar), and earthquake epicenters. The configuration of block boundaries is well
123 constrained on major active tectonic structures, but less so within the Danakil Depression
124 where it is difficult to identify a localized boundary, and where geodetic constraints are
125 lacking. Active deformation within the Danakil Depression may be distributed spatially,
126 or the position of the boundary within the Depression may vary with time (note in Figure
127 3 the location of the 2005 Dabbahu dike intrusion event [Wright et al., 2006] off our
128 proposed central Danakil Depression spreading boundary). In the absence of direct
129 constraints, we have chosen to locate the western boundary of the Danakil micro-plate
130 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 times).

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 are given along with relative Euler vectors in Table 1. Overall, the sense of slip on the modeled faults is consistent with earthquake focal mechanisms (Figure 3); Extension and right-lateral strike slip deformation along the western extension of the Gulf of Aden Rift, N-S extension along the southern boundary of the Danakil Block as well as the central Gulf of Aden, and ~E-W extension along the western Danakil micro-plate boundary. 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.

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., $10^{\circ}/1.9^{\circ}/\text{Myr} - 25^{\circ}/1.9^{\circ}/\text{Myr}$), or 9.3 ± 4 Ma.

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).

Discussion

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 al., 2002). Although still speculative, 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 (which remained connected across the EAR) due to subduction of the Neotethys ocean lithosphere along the Bitlis-Zagros and the Makran subduction zones (Le Pichon and Gaulier, 1988; Bellahsen et al., 2003). 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, initiating counterclockwise rotation of the Danakil Block with respect to Nubia. Such a scenario is consistent with the notion that slab pull is the primary driving force for plate motion (e.g., Elsassner, 1971; Forsyth and Uyeda, 1975; Hager and O'Connell, 1981; Conrad and 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; Reilinger et al., 2009) and the Lesser Caucasus region (Reilinger et al., 2006) provide further evidence that the continental lithosphere maintains strength under extreme tectonic/magmatic conditions.

200

201 Conclusions

202 Geodetic observations along the Danakil Block and Afar Triple Junction indicate present-
203 day, coherent, counterclockwise rotation of the Block with respect to the Nubian Plate
204 around a pole of rotation located in the central Red Sea at $\sim 17^\circ\text{N}$ latitude (Figure 4,
205 Table 1). We estimate the age of initiation of Danakil Block rotation at 9 ± 4 Ma based
206 on present-day rotation rates and the width of the Danakil Depression that was created by
207 block rotation. This interpretation implies that the Danakil Depression is completely
208 composed of new area (within reported uncertainties), created by mantle intrusion. We
209 relate the initiation of Danakil Block rotation to the change in Arabia-Nubia relative
210 motion at ~ 11 Ma, which in turn we relate to the initiation of ocean spreading in the Gulf
211 of Aden that reduced the northward pull on Somalia from subduction of the Neotethys
212 oceanic lithosphere along the Bitlis-Zagros and Makran subduction zones. To the extent
213 that these events are causally related, they provide an observational basis to constrain
214 quantitative models for plate driving forces and the rheology of the lithosphere.

215

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Figure and Table Captions:

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. Relative Euler vectors for the rotation parameters are given in Table 1. Topography and bathymetry from SRTM30 PLUS (http://topex.ucsd.edu/WWW_html/srtm30_plus.html). Plate boundaries are shown schematically.

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.

Figure 3. A simple block/plate rotation model constrained by GPS motions including the Nubian, Arabian, and Somalian plates, and a Danakil micro-plate. 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. Base map as in Figure 1. Focal mechanisms as in Figure 2.

338

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

345

346 Table 1. Rotation parameters (relative Euler vectors) for the plate pairs reported here.

347	Plate pair	Lat	+-	Lon	+-	Rate	+-	Correlations		
348		°		°		°/ma				
349	AFRICA-DANAKIL	17.0	0.2	39.7	0.2	1.9	0.1	0.708	0.851	0.830
350	ARABIA-DANAKIL	13.4	0.2	42.9	0.2	1.5	0.1	0.093	-0.231	-0.530
351	SOMALIA-DANAKIL	15.3	0.2	39.6	0.2	1.9	0.1	0.502	0.532	0.833

352 Table 1S. GPS velocity components and associated 1-sigma uncertainties in Eurasian,
353 Nubian, Somalian, and Danakil reference frames (see Table 1 for relative Euler vectors).







