Geodetic constraints on present-day motion of the Arabian Plate: Implications for Red Sea and Gulf of Aden rifting


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Five years of continuously recording GPS observations in the Kingdom of Saudi Arabia together with new continuous and survey-mode GPS observations broadly distributed across the Arabian Peninsula provide the basis for substantially improved estimates of present-day motion and internal deformation of the Arabian plate. We derive the following relative, geodetic Euler vectors (latitude (°N), longitude (°E), rate (°/Myr, counterclockwise)) for Arabia–Nubia (31.7 ± 0.2, 24.6 ± 0.3, 0.37 ± 0.01), Arabia–Somalia (22.0 ± 0.5, 26.2 ± 0.5, 0.40 ± 0.01), Arabia–India (18.0 ± 3.8, 87.6 ± 3.3, 0.07 ± 0.01), Arabia–Sinai (35.7 ± 0.8, 17.1 ± 5.0, 0.15 ± 0.04), and Arabia–Eurasia (27.5 ± 0.1, 17.6 ± 0.3, 0.404 ± 0.004). We use these Euler vectors to estimate present-day stability of the Arabian plate, the rate and direction of extension across the Red Sea and Gulf of Aden, and slip rates along the southern Dead Sea fault south of the Lebanon restraining bend (4.5–4.7 ± 0.2 mm/yr, left lateral; 0.8–1.1 ± 0.3 mm/yr extension) and the Owens fracture zone (3.2–2.5 ± 0.5 mm/yr, right lateral, increasing from north to south; 1–2 mm/yr extension). On a broad scale, the Arabian plate has no resolvable internal deformation (weighted root mean square of residual motions for Arabia equals 0.6 mm/yr), although there is marginally significant evidence for N–S shortening in the Palmyride Mountains, Syria at ≤ 1.5 mm/yr. We show that present-day Arabia plate motion with respect to Eurasia is consistent within uncertainties (i.e., ±10%) with plate tectonic estimates since the early Miocene when Arabia separated from Nubia. We estimate the time of Red Sea and Gulf of Aden rifting from present-day Arabia motion, plate tectonic evidence for a 70% increase in Arabia–Nubia relative motion at 13 Ma, and the width of the Red Sea and Gulf of Aden and find that rifting initiated roughly simultaneously (±2.2 Myr) along the strike of the Red Sea from the Gulf of Suez to the Afar Triple Junction, as well as along the West Gulf of Aden at 24 ± 2.2 Ma. Based on the present kinematics, we hypothesize that the negative buoyancy of the subducted ocean lithosphere beneath the Makran and the Zagros fold-thrust belt is the principle driver of Arabia–Eurasia convergence and that resisting forces associated with Arabia–Eurasia continental collision have had little impact on plate motion. Citation: ArRajehi, A., et al. (2010), Geodetic constraints on present-day motion of the Arabian Plate: Implications for Red Sea and Gulf of Aden rifting, Tectonics, 29, TC3011, doi:10.1029/2009TC002482.

1. Introduction

During the early Miocene (~25 Ma), the Arabian plate separated from Africa along the Red Sea and Gulf of Aden riffs, roughly 10–15 Ma prior to the initiation of Arabia–Eurasia continental collision [e.g., McKenzie et al., 1970; Hempton, 1987; Joffe and Garfunkel, 1987; McQuarrie et al., 2003; Garfunkel and Beyth, 2006]. Separation from Africa resulted in the formation of ocean spreading in the Red Sea and Gulf of Aden [Chu and Gordon, 1998; Cochran, 1981] and in 200–500 km of compression along a continental collision zone in eastern Turkey, the Zagros, and the Caucasus Mountains [e.g., Jolivet and Faccenna, 2000; McQuarrie et al., 2003]. This continental collision is a major driver of the active tectonics of the eastern Mediterranean region [e.g., Sengor et al., 1985, 2003; Allen et al., 2004] and the devastating earthquakes that have affected this area throughout recorded history [e.g., Ambraseys and Jackson, 1998]. Furthermore, the kinematics of the separation of Arabia from Africa, and the continuing continental collision with Eurasia, offer opportunities to evaluate the role of different forces in driving/resisting Arabia plate motion [McQuarrie et al.,...]

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Precise constraints on Arabia plate motion are therefore important for evaluating earthquake hazards along Arabia’s plate boundaries (Red Sea/Gulf of Aden rifts, Dead Sea fault, East Anatolian fault, Zagros fold-thrust belt, Makran subduction, and Owens fracture zone), and for constraining the dynamics of plate motions.

In this paper, we present new GPS constraints on Arabia plate motion, updating previously published results. We evaluate the impact of these new constraints on fault slip rates around the periphery of the plate, focusing primarily on rifting along the Red Sea and Gulf of Aden, and strike slip motion along the southern Dead Sea fault and the Owens fracture zone (Arabia-India boundary). We compare present-day plate motions and fault slip rates to plate tectonic and geologic estimates and show that present-day motions of the Arabian plate with respect to Eurasia are consistent (±10%) with these independent estimates since separation of Arabia from Africa in the early Miocene (~25 Ma). Similarly, present-day Nubian plate motion with respect to Eurasia is equal within uncertainties to plate motions estimated for at least the past 11 Ma. Finally, we speculate on the implications of the new GPS constraints for the dynamics of Arabia plate motion and collision with Eurasia.

2. GPS Data Analysis and Euler Vector Determination

Figure 1 shows GPS velocities used in this study (decimated spatially for clarity) in and adjacent to the Arabian plate with 1-sigma confidence ellipses in a Eurasia-fixed reference frame (the full velocity field is tabulated in Data Set S1). We analyze the GPS data using the GAMIT/GLOBK software [Herring, 2004; King and Bock, 2004] in a two-step approach. The GPS solution is realized in the ITRF2005 global reference frame, and rotated into Eurasia, Nubia, Sinai, Somalia, India, and Arabia reference frames. Details of the processing strategy, error estimation, and reference frame definitions are identical to those used by Reilinger et al. [2006, Table S1] with updated velocity

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estimates and are given in the online supplementary material for that paper (ftp://ftp.agu.org/apend/jb/2005jb004051).

[5] To estimate relative Euler vectors, we use only GPS velocities at sites located more than 50 km from known plate boundaries (see Figure 2 for sites on Arabia and Data Set S1 for other plates) and search for the Euler vector that minimizes, in a least squares sense, the observed velocities within each plate interior (ts (this study) in Table 1). These Euler vectors allow us to estimate the present-day rate and direction of relative motion across the Red Sea (Arabia-Nubia) and Gulf of Aden (Arabia-Somalia) as well as the Dead Sea fault (Arabia-Sinai) and Owens Fracture zone (Arabia-India). For the Dead Sea fault and Owens fracture zone, we decompose the relative motion at the location of the plate boundary faults into fault-parallel and fault-normal components to estimate strike-slip and normal (i.e., extension or shortening) motion on the faults. We have chosen to use this approach, rather than an elastic block model [e.g., Meade and Hager, 2005; Reilinger et al., 2006] because of the concentration of GPS velocities along plate boundary faults (Figure 1). Any errors in defining the boundary fault (location, locking depth, dip) would result in mismodeling the elastic strain and could introduce spurious velocities for estimating plate motion. This approach works well for the larger plates (WRMS in Table 1), but is less reliable for the Sinai block (some sites used to define Sinai motion are less than 50 km from block boundaries) because elastic boundary deformation may affect the entire block.

[6] Figure 2 shows residual velocities within Arabia and deduced boundary fault slip rates using the GPS Euler vectors...
we estimate in this study (Table 1). Small, but significant residual velocities within the Arabian plate near the EAF are consistent with deformation due to elastic strain accumulation [Vigny et al., 2006; Reilinger et al., 2006]. Our estimated slip rates for the DSF south of the Lebanon restraining bend (4.5–4.7 ± 0.2 mm/yr, left lateral; 0.8–1.1 ± 0.3 mm/yr extension) are consistent with other geodetic estimates [e.g., Wdowinski et al., 2004; Mahmoud et al., 2005], although more tightly constrained, as well as with Late Pleistocene, geologic estimates [e.g., Klinger et al., 2000]. Similarly, our estimated slip rate for the Owens fracture zone (3.2–2.5 ± 0.5 mm/yr, right lateral, increasing from north to south; 1–2 mm/yr extension) agrees with some prior geodetic and geologic estimates, as well as with the sense of motion deduced from earthquake focal mechanisms [DeMets et al., 1994; Reilinger et al., 2006; Fournier et al., 2008]. We do not report GPS slip rates for the central and northern Dead Sea fault [see Gomez et al., 2007; Alchalbi et al., 2010], the East Anatolian fault [Reilinger et al., 2006], or the Zagros fold-thrust belt [Vernant et al., 2004; Walpersdorf et al., 2006; Tavakoli et al., 2008] since these slip rates depend on the detailed deformation of the Levant, Anatolian and Iran regions, respectively, that are not considered in this study.

### 3. Internal Deformation of the Arabian Plate

[7] Figure 2 indicates that internal deformation of Arabia is small and mostly below the resolution of our GPS observations (i.e., ~1 mm/yr). This includes sites broadly distributed around the plate from southeast Turkey (North Arabia), to central Arabia, to Oman (southeast Arabia), to Yemen (southwest Arabia). A single Euler vector accounts for almost all observed station motions (weighted root mean square (WRMS) of residual velocities for Arabian sites away from plate boundaries = 0.6 mm/yr). Exceptions to this are the three survey sites south of the Palmyride Mountains in Syria that show marginally significant northward motion relative to the plate boundaries = 0.6 mm/yr). Exceptions to this are the three survey sites south of the Palmyride Mountains in Syria that show marginally significant northward motion relative to the plate boundaries = 0.6 mm/yr).

#### Table 1. Euler Vectors for Arabia With Respect to Neighboring Plates and 1-Sigma Uncertainties From This Study and Selected Other References

<table>
<thead>
<tr>
<th>Plate Pair</th>
<th>Longitude (°E)</th>
<th>Latitude (°N)</th>
<th>Rate (°CCW/Ma)</th>
<th>WRMS of Plate 2b (mm/yr)</th>
<th>Number of Sites on Plate 2b</th>
<th>References</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR-EU²</td>
<td>17.6 ± 0.3</td>
<td>27.5 ± 0.1</td>
<td>0.404 ± 0.004</td>
<td>0.5</td>
<td>23</td>
<td>ts</td>
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<tr>
<td>AR-EU²</td>
<td>18.4 ± 1.0</td>
<td>28.4 ± 0.9</td>
<td>0.428 ± 0.009</td>
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<td>r</td>
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<tr>
<td>AR-EU²</td>
<td>18.4 ± 2.2</td>
<td>27.4 ± 1.0</td>
<td>0.40 ± 0.04</td>
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<tr>
<td>AR-EU²</td>
<td>22.87 ± 2.1</td>
<td>26.22 ± 1.2</td>
<td>0.427 ± 0.029</td>
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<td>AR-EU²</td>
<td>19.5 ± 1.4</td>
<td>27.9 ± 0.5</td>
<td>0.41 ± 0.1</td>
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<tr>
<td>AR-EU²</td>
<td>13.7 ± 5.0</td>
<td>24.6 ± 2.3</td>
<td>0.5 ± 0.05</td>
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<tr>
<td>AR-NU²</td>
<td>24.6 ± 0.3</td>
<td>31.7 ± 0.2</td>
<td>0.369 ± 0.005</td>
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<td>AR-NU²</td>
<td>25.2 ± 0.7</td>
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<td>0.393 ± 0.005</td>
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<td>0.37 ± 0.04</td>
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<td>AR-NU²</td>
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<td>31.64 ± 2.5</td>
<td>0.38 ± 0.018</td>
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<td>AR-NU²</td>
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<td>31.26 ± 1.3</td>
<td>0.400 ± 0.030</td>
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<td>AR-NU²</td>
<td>23.0 ± 2.7</td>
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<td>AR-NU²</td>
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<td>32.2</td>
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<td>26.2 ± 0.5</td>
<td>22.0 ± 0.5</td>
<td>0.404 ± 0.008</td>
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<td>0.356 ± 0.026</td>
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<td>0.423 ± 0.05</td>
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<td>0.41</td>
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<td>AR-SOM²</td>
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<td>0.423</td>
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<td>AR-SIN²</td>
<td>28.4 ± 3.7</td>
<td>32.8 ± 3.4</td>
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<td>AR-SIN²</td>
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<td>32.8</td>
<td>0.283</td>
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<td>−0.07 ± 0.01</td>
<td>1.0</td>
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<td>AR-IN²</td>
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<td>17.7 ± 4.9</td>
<td>−0.06 ± 0.01</td>
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<td>AR-IN²</td>
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<td>−0.099 ± 0.037</td>
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<td>AR-IN²</td>
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<td>19.73 ± 65.2</td>
<td>−0.035 ± 0.025</td>
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<tr>
<td>AR-IN²</td>
<td>92 ± 22.21</td>
<td>3 ± 13.9</td>
<td>−0.03 ± 0.04</td>
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<td>AR-IN²</td>
<td>91.50 ± 21.41</td>
<td>3.0 ± 13.51</td>
<td>−0.03 ± 0.04</td>
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<td>nu</td>
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<tr>
<td>AR-IN²</td>
<td>76.2</td>
<td>12.1</td>
<td>−0.102</td>
<td></td>
<td></td>
<td>f</td>
</tr>
</tbody>
</table>

²CCW, counterclockwise. Key is as follows: EU, Eurasia; NU, Nubia; AR, Arabia; SIN, Sinai; SOM, Somalia; IN, India.

²Twenty-one sites on Arabia. WRMS is for sites used in the plate stabilization; WRMS for Arabia equals 0.5 mm/yr. Plate 2 is the neighboring plate with respect to Arabia.

²References are as follows: ts, this study; chu, Chu and Gordon [1998]; f, Fournier et al. [2008]; gb, Garfunkel and Beyth [2006]; gd, Gordon and DeMets [1989]; je, Jestin et al. [1994]; jj, Joffe and Garfunkel [1987]; mc, McClusky et al. [2000]; mc1, McClusky et al. [2003]; nu, NUVEL1-A [DeMets et al., 1994]; r, Reilinger et al. [2006]; se, Sella et al. [2002]; ve, Vernant et al. [2004]; vi, Vigny et al. [2006]; wd, Wdowinski et al. [2004].

²Geodetic estimate.
et al., 1990], suggesting shortening rates of $\sim 1$ mm/yr. However, differential motions across the Palmyrides indicated by our GPS observations are either too small to be determined on a plate-wide basis or are entirely internal to the Arabian plate; that is, they do not change the overall plate configuration. If internal to the Arabian plate, any associated N-S shortening in the Palmyride Mountains is presumably balanced by N-S extension further south.

4. Geodetic Versus Geologic Relative Plate Motions and Fault Slip Rates

Plate tectonic estimates of Arabia plate motion have been reported from magnetic anomalies in the Red Sea covering the past 3 Ma [Chu and Gordon, 1998] and from broad-scale plate reconstructions for the past 59 Ma [McQuarrie et al., 2003]. The 3 Ma Euler vector (Arabia-Nubia) reported by Chu and Gordon [1998] differs insignificantly (1 sigma) in location and rotation rate from the GPS Euler vector reported here (Table 1) [see also McClusky et al., 2003]. Figure 3 shows a comparison of GPS fault slip rates derived from our block model (Figure 2) as well as from other geodetically constrained faults around the periphery of the Arabian plate, with recent geologic fault slip rates reported in the literature and covering a wide range of timescales ($10^3$–$10^7$ years). Although reported, longer-term fault slip rates vary considerably, for the most part they agree well with geodetic estimates (i.e., $\pm 10\%$). A possible exception is the Main Recent Fault (Iran) that appears to have a higher geologic than geodetic slip rate. If this result persists with improved geologic observations, it could be indicative of complex fault interaction [Walpersdorf et al., 2006; Tavakoli et al., 2008].

Figure 3. Comparison of GPS fault slip rates derived from our block model (Figure 2 and Table 1) with geologic fault slip rates reported in the literature. The shaded area indicates $\pm 10\%$ from agreement. The geodetic rates for the EAF and the Gulf of Suez are from Reilinger et al. [2006], and that for the Zagros fold-thrust belt is from Tavakoli et al. [2008]. Geologic references are as follows: Red Sea, Chu and Gordon [1998] and Joffe and Garfunkel [1987]; Gulf of Aden, Girdler et al. [1980], Laughton et al. [1970], and Cochran [1981]; Southern Dead Sea fault, Klinger et al. [2000] and Niemi et al. [2001]; Owens Fracture Zone, DeMets et al. [1994] and Fournier et al. [2008]; Main Recent fault, Authemayou et al. [2006].
width are likely to be less than the prerift crustal thickness that is not presently available. However, we estimate that errors as a proxy for the total extension across the rift [e.g., rift]
detailed knowledge of the three dimensional geometry of all
More precise estimates of total extension would require a
GPS
consider the Red Sea and Gulf of Aden rifts. Figure 5 shows
determined motions can be extrapolated to investigate the
Arabia plate motion imply that highly precise, geodetically
total extension across the rift basins. Accordingly, we estimate a 10% uncertainty on the degree to which our estimate of basin widths reflect total extension across these rifts.
[11] Figure 6 shows a plot of the width of the Red Sea and Gulf of Aden basins estimated in Figures 5a and 5b versus the observed GPS velocity with respect to Nubia (Red Sea) and Somalia (Gulf of Aden). The linear relationship between velocity and basin width is well established. Following Le Pichon and Gaulier [1988], we estimate that the increase in Nubia motion with respect to Arabia initiated at ∼13 Ma. From Figure 4, we estimate a 70% decrease in Nubia–Eurasia motion at that time (22.5 mm/yr to 6.6 mm/yr) while Arabia–Eurasia motion remained approximately unchanged. If we assume that the change in Nubia–Arabia motion was a change in rate only [McQuarrie et al., 2003, Figure S1], this implies a corresponding 70% increase in Arabia–Nubia relative motion. Total extension of the Red Sea (Nubia–Arabia boundary) will then be

\[
W(t) = W_{(pre13)} + W_{(post13)}
\]

where \(W_{(pre13)}\) and \(W_{(post13)}\) are the amount of opening of the Red Sea pre–13 Ma and post–13 Ma, \(W(t)\) is the total measured width of the Red Sea, \(V_{(gps)}\) is the present-day velocity (rate) of Arabia with respect to Nubia at the location of \(W(t)\), and \(T\) is the time of initial rifting.

[12] Solving for \(T\),

\[
T = \left( \frac{W(t)}{V_{(gps)}} - 9.1 \right) / 0.3
\]

[13] From the slope of \(W(t)\) versus \(V_{(gps)}\) in Figure 6 (∼16.4 ± 2.2 Myr), we estimate a time of initial opening of the Red Sea of ∼24 ± 2.2 Ma. While this age is uncertain because of uncertainty about the degree to which our estimates of \(W(t)\) reflect total extension, the slow rate of rifting prior to 13 Ma (and hence, \(T\) is highly sensitive to small changes in \(W_{(pre13)}\)), uncertainties about the exact timing of the change in Arabia–Nubia relative motion, and our assumption that this change occurred instantaneously, it is roughly consistent with geologic estimates for the initiation of the main phase of rifting [e.g., Omar and Steckler, 1995; McQuarrie et al., 2003; Garfunkel and Beyth, 2006], demonstrating the internal consistency of our analysis. In addition, the uncertainty on the slope of \(W(t)\) versus \(V_{(gps)}\) suggests that rifting initiated over a relatively short time (∼2.2 Myr, or ±10% of the total time of rifting) along the full length of the Red Sea rift basin, a result that is supported by fission track analyses dating the early rift flank uplifts [Omar and Steckler, 1995].

6. Discussion

[14] The geodetic–geologic comparisons presented in this paper strongly support the contention that the geodetic observations covering time spans of tens of years accurately
reflect (i.e., ±10%) fault slip rates ($10^3$–$10^6$ years) and geologic plate motions (10$^7$ years), and accordingly the long-term, geologic evolution of the Africa–Arabia–Eurasia zone of plate interaction [see also Allen et al., 2004; Reilinger et al., 2006]. Calais et al. [2003] suggest that Nubia–Eurasia relative motion has slowed by about 1 mm/yr during the past 3 Ma based on comparison of updated NUVEL-1A, geologic estimates with geodetic estimates of Nubia–Eurasia plate motion. However, owing to the present uncertainties in both the geodetic and geologic estimates used here, and the relatively slow, oblique convergence between Nubia and Eurasia (i.e., 4–5 mm/yr [McClusky et al., 2003]), a 1 mm/yr decrease in Nubia–Eurasia relative motion would not be resolvable by our analysis. However, such a small change in plate rate, if real, would be within our estimated uncertainties and would not effect our conclusions.

[15] As shown above, geologic and geodetic estimates of Arabia–Eurasia relative plate motion agree to well below the observational uncertainties for the past 22 Ma and within 95% confidence uncertainties to ~30 Ma. This timing corresponds

Figure 5. (a) GPS velocities and 95% confidence ellipses with respect to Nubia along the west coast of the Arabian plate on a bathymetric and topographic map of the Red Sea and adjacent areas. Bold lines across the Red Sea rift are estimates of basin width at the location and direction of the GPS velocities. Basin widths ($W_{(0)}$) and observed Arabia plate velocities ($V_{(gps)}$) used to estimate the age and timing of extension in Figure 6 are also shown. Base map as in Figure 1. (b) As Figure 5a with GPS velocities with respect to Somalia. Base map as in Figure 1.

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to the separation of Arabia from Africa and the initiation of rifting in the Red Sea and Gulf of Aden [e.g., Garfunkel and Beyth, 2006]. Furthermore, the present widths of the Red Sea and West Gulf of Aden are consistent with plate tectonic and geodetic estimates of Arabia-Nubia motion over the past $24 \pm 2.2$ Ma. We find no evidence that Arabia plate motion with respect to Eurasia has slowed since separation from Nubia in the early Miocene. We suggest that the apparent discrepancies between the NUVEL-1A, 3 Ma estimate of Arabia-Eurasia plate motion and geodetic estimates (i.e., Table 1) are most likely due to limitations of the geophysical observations that were used in the NUVEL model.

[16] The steady motion of the Arabian plate since separation from Nubia and the initiation of continental collision in the Late Miocene/Pliocene, the decrease in the rate of convergence between Nubia and Eurasia during this same period [McQuarrie et al., 2003] (Figure 4), and the relatively short time estimated for the development of rifting along the Arabia-Nubia and Arabia-Somalia plate boundaries have direct implications for the dynamics of plate motions in the Arabia-Africa-Eurasia zone of plate interaction. As noted by McQuarrie et al. [2003], the slowing of Africa-Eurasia convergence after separation of Arabia from Nubia in the Miocene is likely due to the loss of the subduction slab pull along the Arabia-Eurasia plate boundary, strongly supporting dynamic models for plate motion where slab pull is the dominant plate driving force [e.g., Forsyth and Uyeda, 1975; Hager and O'Connell, 1981; Conrad and Lithgow-Bertelloni, 2004]. The steady motion of Arabia before, and after the initiation of continental collision with Eurasia seems to require that the resisting forces associated with continent-continent collision are negligible in relation to the forces driving plate convergence, presumably the negative buoyancy of the subducted oceanic lithosphere. This may be due in
Figure 6. Plot of the GPS Arabia plate motion rate with respect to Nubia ($V_{\text{GPS}}$) versus the width of the Red Sea and Gulf of Aden rifts ($W_{\text{ Rift}}$) at each GPS station location (from Figures 5a and 5b). The well-defined, linear relationship between rift width and rate of extension is consistent with rifting initiating roughly simultaneously ($\pm$2.2 Myr, estimated from scatter around the straight line fit) along the Red Sea and the West Gulf of Aden at 24 $\pm$ 2.2 Ma (see text for discussion).

part to weakening of the upper plate during the long history of Tethyan subduction and related back-arc processes [Barazangi et al., 2006]. Furthermore, the absence of observable acceleration of Arabia following separation from Nubia suggests that the rate of plate motion depends primarily on the character of the subducting/subducted lithosphere and not on the dimensions of the trailing plate. Finally, the initiation of extension over a short time period along the strike of the Red Sea appears to be incompatible with dynamic upwelling associated with the Afar plume driving Arabia motion; such dynamics would more likely produce a tear that propagates from south to north [Burke and Dewey, 1973; Courtillot, 1982]. Again, we suggest that the negative buoyancy of the subducted ocean lithosphere beneath the Makran and Zagros are more likely responsible for the separation of Arabia from Nubia [Bellahsen et al., 2003]. On the other hand, the Afar plume may have weakened the lithosphere beneath the future Red Sea and Gulf of Aden rifts allowing rifting to concentrate along these structures [e.g., Garfunkel and Beyth, 2006].

7. Conclusions

[17] In this study, we determine tightly constrained Euler vectors for Arabia plate motion relative to the Nubian, Sinai, Somalian, Eurasian, and Indian plates (Table 1). A single Euler vector describes well the motion of the Arabian plate indicating that any internal deformation of the plate is below the resolution of present geodetic data (i.e., < 1.5 mm/yr, or < 10% of Arabia plate motion rate relative to Eurasia). Based on these Euler vectors, we estimate present-day slip rates for the Dead Sea fault south of the Lebanon restraining bend ($4.5 - 4.7 \pm 0.2$ mm/yr, left lateral; $0.8 - 1.1 \pm 0.3$ mm/yr extension) and on the Owens fracture zone (3.2 - 2.5 $\pm$ 0.5 mm/yr, right lateral, increasing from north to south; 1 - 2 mm/yr extension). Geodetically and geologically derived motions for Arabia and Nubia relative to Eurasia are equal within small uncertainties for at least the past 11 Ma for Nubia and > 22 Ma for Arabia, near the time when Arabia separated from Nubia in the early Miocene. We estimate the time rifting initiated in the Red Sea and the Gulf of Aden at 24 $\pm$ 2.2 Ma from the present width of the rifts, present-day Arabia plate motion rates, and plate tectonic estimates of a 70% increase in Arabia-Nubia relative motion at 13 Ma. Rifting appears to have initiated over a relatively short time ($\pm$2.2 Myr) along the full length of the Red Sea and along the West Gulf of Aden. We hypothesize that the kinematics of Arabia plate motion are most consistent with plate motion being driven by subduction processes (i.e., slab pull) along the Makran subduction zone and beneath the Zagros fold-thrust belt, and that the Afar plume served mainly to weaken the African continental lithosphere allowing deformation to concentrate along the future Red Sea and Gulf of Aden rifts.

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