# Geodetic constraints on Rupturing of Continental Lithosphere along the Red Sea

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Our project uses the Global Positioning System (GPS) to monitor and quantify patterns and rates of tectonic and magmatic deformation associated with active rifting of the continental lithosphere in the northern Red Sea and the transition to sea floor spreading in the central Red Sea. Figure 1 shows the current network and preliminary velocities for GPS sites with sufficient observations, together with GPS-velocities from our broader collaborative project (*Reilinger et al., 2006*). As briefly described here, these new data allow us to: 1) identify, and quantify present-day motion of the Sinai micro-plate that is distinct from both Nubia and Arabia; 2) determine more precisely the motion of the Arabian plate relative to Nubia and Eurasia (Euler vectors); 3) establish baseline observations to quantify the spatial distribution of deformation associated with rupturing of the continental lithosphere as a function of the stage of rifting (i.e., along strike of the rift); and 4) quantify the relationships between deformational processes around the periphery of the Arabian plate to provide new constraints on the dynamics of Arabia plate motion and associated rifting along the Red Sea. In addition, independent but coordinated observations in Eritrea are beginning to quantify bifurcation of rifting in the southern Red Sea near the Afar Rift/Rift/Rift Triple Junction, promising to provide powerful new constraints on the dynamics of Red Sea rifting and the influence of rheology on the kinematic response of the lithosphere.

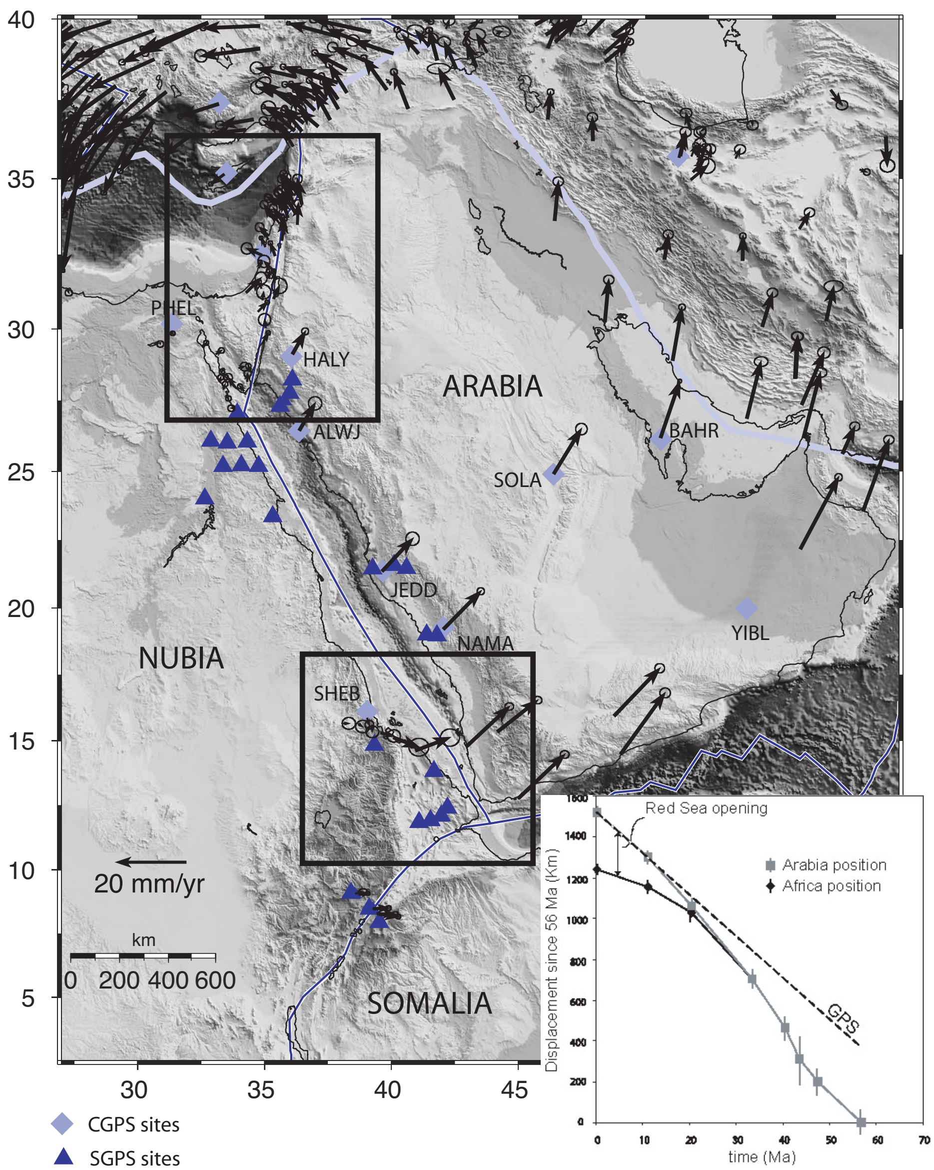


*Figure 1. Red Sea and surroundings showing idealized plate boundaries (Arabia-Nubia-Somalia, dark blue; Arabia and Nubia-Eurasia, light blue) and GPS-derived velocities relative to Eurasia with 1-sigma error ellipses. The boxes show the locations of Figures 2 (north) and 3. The inset, modified from McQuarrie et al. (2003), shows the motion of Arabia and Nubia relative to Eurasia since 56 Ma along with the GPS-derived motion for Arabia extrapolated to this time interval.*

## Sinai Micro-plate [*Mahmoud et al., 2005*]

GPS survey sites in the Sinai Peninsula show northerly motion relative to Africa (Nubia) at 1.4 ± 0.8 mm/yr north and 0.4 ± 0.8 mm/yr west (Figure 1). Continuous IGS GPS sites in Israel, west of the Dead Sea fault [*Wdowinski et al., 2004*] show a similar northerly sense of motion relative to Nubia (2.4 ± 0.6 mm/yr north and 0.04 ± 0.7 mm/yr east), suggesting that the entire Sinai Block south of Lebanon is characterized by northward translation relative to the Nubian plate. We develop an elastic block model constrained by the GPS results that is consistent with regional tectonics and allows us to estimate slip rates for Sinai bounding faults (Figure 2). The substantial, and perhaps unanticipated left-lateral strike-slip motion within the Gulf of Suez is supported by geologic analyses that indicate a late Pleistocene change in the regional stress field from rift-normal to N-S extension [*Bosworth and Strecker, 1997*]. These observations indicate that the Sinai Peninsula and Levant region comprise a separate sub-plate sandwiched between the Arabian and Nubian plates. The relatively recent change in Gulf of Suez extension provides an important new constraint on the dynamics of rifting in the N Red Sea.

## Arabia Plate Motion

The separation of Arabia from Nubia and associated extension in the Red Sea initiated in the Miocene roughly simultaneously with the onset of continental collision between Arabia and Eurasia along the Bitlis-Zagros suture zone (inset, Figure 1). Collision continues today as evidenced by the intense seismic activity along the borders of the Arabian plate. We initiated GPS observations in the Kingdom of Saudi Arabia by establishing 5 continuously recording stations (Figure 1). These stations, IGS stations in Bahrain and Damascus, and survey sites in SE Turkey, Oman, and Yemen, constrain Arabia motion and provide boundary conditions on the distribution of extension along the Red Sea plate boundary. The GPS velocities are consistent with coherent motion of the Arabian plate with internal deformation below the current resolution of our measurements (~ 1-2 mm/yr). The GPS-determined Euler vectors for Arabia-Nubia, and Arabia-Somalia relative motions are indistinguishable from geologic Euler vectors determined from marine magnetic anomalies in the Red Sea and Gulf of Aden [*Chu and Gordon, 1998, 1999*], implying that, to the resolution of our observations, spreading in the central Red Sea is primarily confined to the central rift (±10-20%). This contrasts with the N Red Sea and Gulf of Suez where extension appears more spatially distributed. Furthermore, Arabia-Eurasia relative motion from GPS is equal within uncertainties to relative motion determined from plate reconstructions suggesting that Arabia plate motion has remained constant (±10%) during at least the past ~10 Ma (Figure 1, inset). The new constraints on Arabia motion provide corresponding strong constraints on slip rates for the faults bounding the plate, including the Red Sea rift, Dead Sea fault, Makran subduction, faults along the Zagros Mountains, and the East Anatolian Fault (EAF) that separates the Arabian and Anatolian plates. Surprisingly, we find that while the EAF is characterized by predominantly left-lateral strike slip, it also shows a small component of extension. Likewise we find extension in the direction of relative plate motion north of the Arabian plate in the Lesser Caucasus. These observations appear to be incompatible with classic "indentor/extrusion" models for present-day deformation within this continental collision zone.

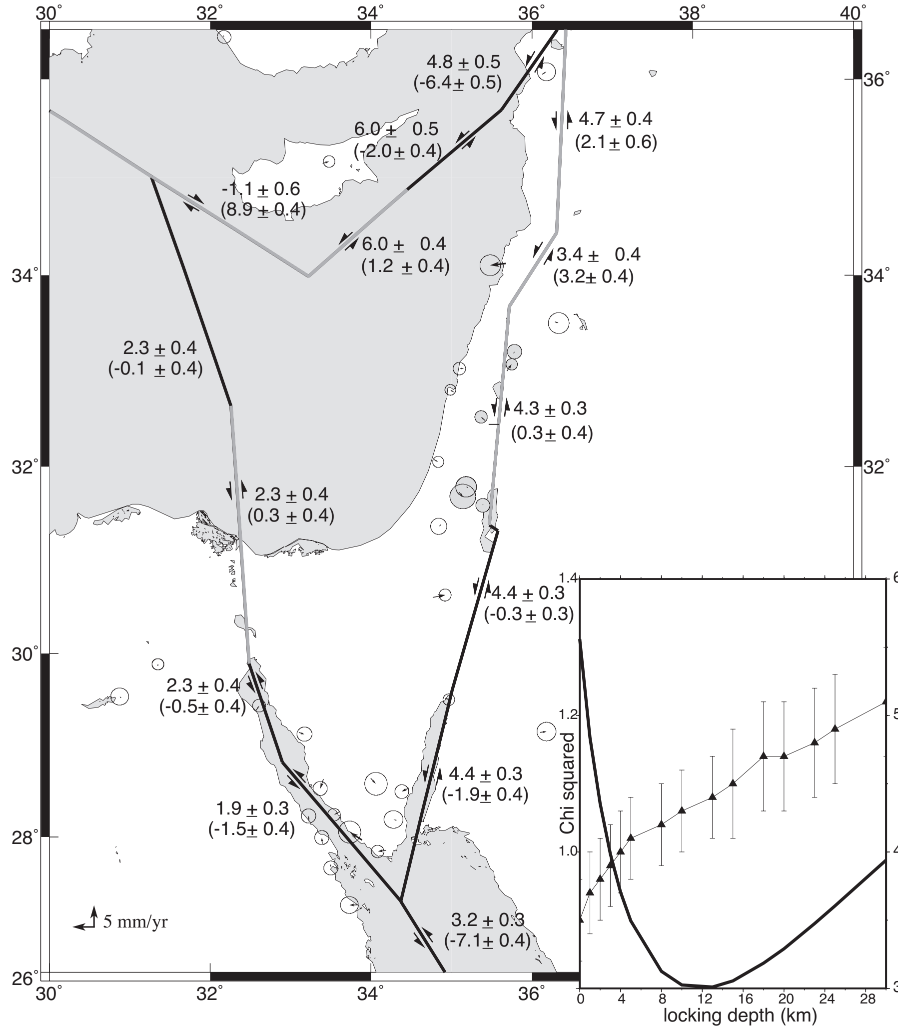


*Figure 2. Elastic block model for the Sinai micro-plate showing residual GPS velocities and 95% confidence ellipses, and fault slip rates (fault-normal slip rates in brackets, positive for left lateral and compression). The inset shows the trade-off between locking depth and slip rate for the model, indicating the best fit for a slip rate of 4.3 mm/yr and a 13 km locking depth for the central DSF (see Mahmoud et al., 2005 for details).*

## Baseline Measurements of the Spatial Character of Extension Along the Red Sea

Figure 1 shows survey sites established along profiles perpendicular to the Red Sea spreading axis in Egypt (collected and analyzed by the National Research Institute of Astronomy and Geophysics -

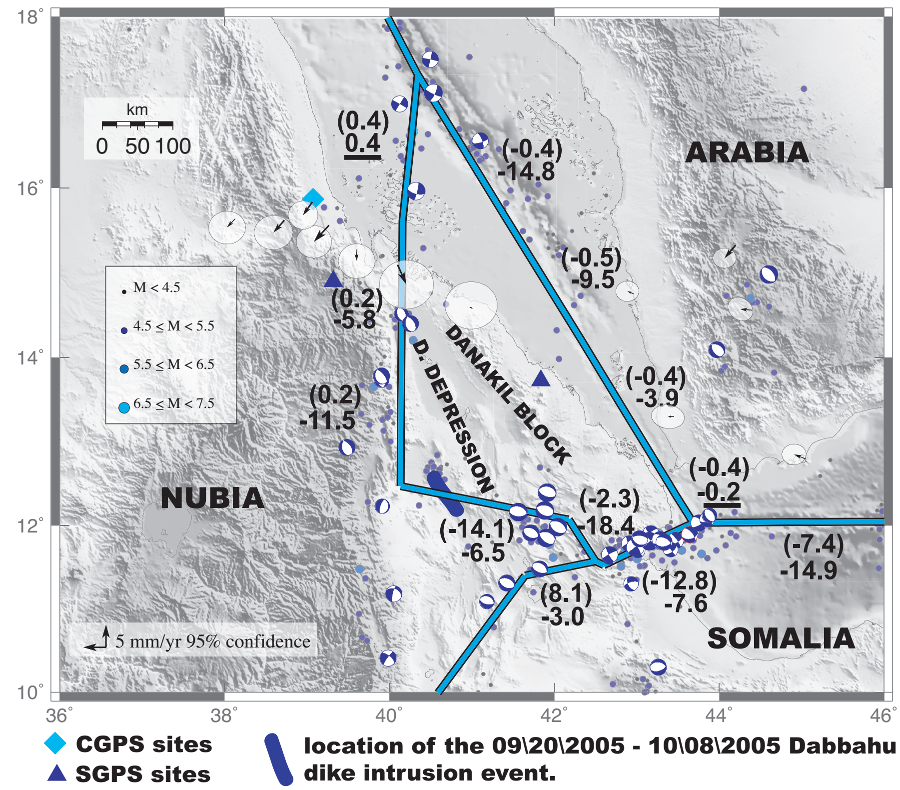


*Figure 3. Elastic block model for the S Red Sea and Afar region. The model is highly idealized and still poorly constrained by GPS. The model involves coherent rotation of the Danakil micro-plate with extension increasing from N-S on the western plate boundary and decreasing from N-S along the Red Sea.*

NRIAG), Saudi Arabia, and Eritrea. Except in the vicinity of the Sinai Peninsula/northernmost Red Sea and in the southern Red Sea adjacent to Eritrea, the survey sites have an insufficient observation history to determine reliable velocities. In addition, we anticipate small strains along the coast for the central Red Sea based on the approximate coincidence of GPS-plate motion and seafloor spreading estimates of spreading rates (< ~2mm/yr). More definitive conclusions about the distribution of extension will require repeat surveys over sufficient time for the anticipated small signals to emerge from the GPS uncertainties.

## Plate Dynamics and Rupturing of the Continental Lithosphere

An overarching objective of our geodetic research is to establish an observational basis to constrain better the dynamics of plate motions and continental deformation. This is a difficult problem involving trade-offs between driving forces and rheology that has occupied Earth scientists since the advent of Plate Tectonics. However, we believe that the fundamentally new kinematic observations provided by space-based geodesy, new quantitative geological techniques that allow precise dating of tectonic events, and advances in seismology that are quantifying lithospheric and mantle structure and anisotropy, provide powerful new constraints on dynamic and rheological Earth models.

We alluded above to the implications of Arabia-Anatolia relative motion for the extrusion model [*Reilinger et al., 2006*]. For the Red Sea, a fundamental question concerns the relative importance of ridge "push" by the Red Sea and Gulf of Aden ridges and the Afar hot spot, and slab "pull" along the Makran subduction zone (and Zagros?) for driving the separation of NU and AR and the collision of AR with Eurasia. In the case of ridge push, we would expect intra-plate, ridge-normal compression within Arabia, while slab pull would induce trench-normal extension. While at present we prefer models where subduction dominates the dynamics, we continue to develop the geodetic observations necessary to quantify present-day strain of Arabia to evaluate better the importance of different plate driving forces.

## Bifurcation of Rifting in the Southern Red Sea

Although our MARGINS project is confined to the simpler part of the rift in the northern and central Red Sea, our Eritrean partners have taken the initiative to extend our geodetic network to the southern Red Sea (Figure 1). This part of the Nubia-Arabia plate boundary includes the Danakil Block and adjacent Depression that appear to result from bifurcation of the rift north of the Afar plume (Figure 3). This extension of our network is highly valuable in that it provides a basis to investigate further the influence of lithospheric rheology on rifting processes.

Spreading in the southern Red Sea is thought to deviate towards the west, south of about 17°N, forming the Danakil Depression that is separated from the Red Sea proper by the intervening NW-SE striking Danakil Block [e.g., *Chu and Gordon, 1998*] (Figure 3). The Red Sea rift and Danakil Depression do not appear to be connected by a transform fault as is typical for offset ridges in more mature ocean basins. We propose a kinematic model for the S Red Sea that includes a "Danakil micro-plate", as hypothesized by *Chu and Gordon* [1998], and shown in Figure 3. The model involves linearly increasing spreading rates from N to S within the Depression and linearly decreasing rates along the Red Sea rift such that their sum is equal to the full Arabia-Nubia spreading rate. While the model is very preliminary and poorly constrained by the available GPS data, it has a number of interesting features, including: 1) the proposed Danakil micro-plate boundaries correspond well with seismic activity; 2) the "junction" where the Red Sea rift "bifurcates" at ~ 17°N involves negligible deformation of the SW Red Sea, consistent with the absence of any well defined tectonic features on the sea floor; 3) the model results in coherent rotation of the Danakil block, consistent with its geological structure and aseismic character, and 4) the model involves coherent rotation of the Arabian plate, consistent with the absence of tectonic deformation or significant seismic activity in Yemen. Interestingly, the width of the Danakil depression at the latitude of the Afar triple junction (~12°N) is roughly 300 km. Arabia-Nubia relative plate motion at this latitude is about 17 mm/yr. If AR-NU relative motion has been roughly constant since the initiation of Red Sea rifting, as indicated by geological studies (Figure 1 inset), the depression would develop in ~18 Myr, roughly the time that Arabia is thought to have separated from Nubia (*McQuarrie et al., 2003*). This implies that the Danakil micro-plate has been an integral part of rifting/triple junction processes throughout the history of separation of the Arabian and Nubian plates.

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A MARGINS Interdisciplinary Mini-Workshop

## Seismogenesis and Subduction Fluxes in the Middle America Subduction Zone: The role of IODP and ORION

AGU Fall Meeting, 2006, Mon., 11 Dec., 8 pm onward, Salon A3, San Francisco Marriott

**Conveners: K. Brown (University of California, San Diego), N. Bangs (U. Texas at Austin), S. Schwartz (U. California, Santa Cruz)**

This public mini-workshop will focus on interconnections between the dynamics of both seismic and aseismic slip processes and along-strike variations in subduction fluxes (fluids, sediments, and chemical species) through the Middle America arc and fore-arc. How do the physical and hydrologic structure and composition of the incoming plate and fore-arc control both fluxes and seismogenic processes along the Middle America Trench? Can these controls be quantified sufficiently to make predictions from Central America to other non-accretionary subduction zones? Topics addressing these questions will include: physical, geophysical and hydrological properties of the system; material/chemical fluxes; integration of onland and offshore studies; relation of laboratory and numerical studies to field observations; and development of new technologies and methodologies.

This mini-workshop immediately follows the MARGINS Izu-Bonin-Marianas mini-workshop in the same location. Food and drink will be provided at both events.