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# Present-day stress fields of the Gulf of Suez (Egypt) based on exploratory well data: Non-uniform regional extension and its relation to inherited structures and local plate motion

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ABSTRACT

The Gulf of Suez is the prototype model of a failed or aborted continental rift. However, the basin is seismically active and the footwalls of several major extensional faults continue to rise at the present time. Furthermore, decadal-length Global Positioning System (GPS) datasets demonstrate that the Sinai micro-plate continues to separate from Africa in a northerly direction at ~0.15 cm/yr with a Gulf of Suez rift-normal component of ~0.05 cm/yr. Geologic and GPS observations both indicate that the rift is now undergoing highly-oblique extension. Previous interpretations of borehole breakouts in industry exploration wells suggested that the minimum horizontal stress ($S_{hmin}$) in the southern Gulf of Suez is presently aligned ~015°. New subsurface data from the accommodation zone boundary between the Central and Darag (northern) sub-basins similarly identifies an extension direction of approximately N-S. By contrast, in the Central sub-basin itself breakout and drilling-induced fracture (DIF) data indicate NE-SW extension, or rift-normal movement that is similar to the documented older Miocene history of the entire basin. Based on these observations the present-day stress field of the Gulf of Suez is spatially non-uniform. Variations are also present in local and teleseismic datasets. The northern Gulf of Suez shows relatively less seismicity, with very few events greater than $M = 3$. The central sub-basin is very active, with 17 events $M \geq 3$ during the past 45 years, and these suggest NE-SW extension similar to the breakout data. The southern Gulf of Suez is the most seismically active and merges with an area of significant seismicity in the northern Red Sea. In the southern Gulf of Suez the seismicity is complex but focal plane analyses of the two largest historical events indicated NNE-SSW extension, in agreement with the breakout data. Differing interpretations have been proposed for the smaller magnitude seismicity. We suggest that each of the three sub-basins of the Gulf of Suez, whose fault geometries are inherited from the main phase of Miocene continental rifting, are now subject to differing shallow crustal stress fields with variation in orientation and perhaps magnitude of the principal stresses. We do not know what the long-term implications for displacement fields throughout the rift might be, but along-strike variation in extension has been suggested in other ancient continental rift settings. This study also highlights the danger in assuming that fault populations with different kinematics must represent different times in a region's geologic evolution.



## 1. Introduction

The interpretation of present-day stress fields has become a mainstay of structural and tectonic studies throughout our planet (Zoback and Zoback, 1989; Zoback, 1992; Engelder, 1993; Heidbach et al., 2008; and references therein). As more data have become available it is clear that some lithospheric plates display broad areas of relatively consistent stress orientations, but many areas show more localized secondary complexities that were not always anticipated. The African plate fits this general scenario.

A large part of the interior of the African plate is presently experiencing compression with approximately E-W maximum

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horizontal stress ($S_{Hmax}$; Fig. 1; Zoback, 1992; Bosworth, 2008). This interpretation is supported by thrust and strike-slip earthquake focal mechanisms in West Africa (Ayele, 2002; Delvaux and Barth, 2010), normal and strike-slip solutions in the Sudan (Giardini and Beranzoli, 1992; Gaulon et al., 1992; Delvaux and Barth, 2010), strike-slip faulting in southern Egypt (Badawy, 2001; Hussein et al., 2013), and normal and oblique-slip solutions in the northern Eastern Desert of Egypt (Abou Elenean and Hussein, 2008; Abdel-Fattah et al., 2011). Borehole breakout interpretations from exploration wells in the Mesozoic Sudan rifts similarly show very uniform E-W $S_{Hmax}$ (Bosworth et al., 1992). Zoback (1992) attributed this intra-plate compression to the first-order effects of ridge push at the Central and South Atlantic and Indian Ocean spreading centers. Bosworth (2008) referred to this very broad region of relatively uniform E-W $S_{Hmax}$ as the Central African Intra-plate (CAIP) stress field (Fig. 1).

The CAIP stress field switches to north-south compression in the Mediterranean realm due to the convergence of Africa and Eurasia and the development of a complex multiple arc/subduction zone plate boundary (Mediterranean Convergence Zone, MCZ; Fig. 1). The Mediterranean is covered by many present-day stress field interpretation data points (Heidbach et al., 2008). Focal mechanisms along the northern edge of the African plate are generally reverse/thrust fault solutions with $S_{Hmax}$ perpendicular to the local arc/subduction zone segment. Stress fields in Europe and continental North Africa are much more complex. Internal details of the North Africa "transition zone" (Fig. 1) have yet to be resolved (Bosworth, 2008).

The eastern branch of the East African Rift System (EARS) east of Lake Victoria is presently undergoing NW-SE extension based on integration of neotectonic outcrop fault kinematics, aligned young volcanic vents, and borehole breakout studies (NE-SW $S_{Hmax}$; Fig. 1; Strecker et al., 1990; Bosworth et al., 1992; Chorowicz, 2005). This has been attributed to the interplay of mantle-derived buoyancy forces with the far-field E-W plate-scale compression (Zoback, 1992). Inversion of a robust set of earthquake focal mechanisms does not clearly support the NE-SW $S_{Hmax}$ interpretation (Delvaux and Barth, 2010). As discussed below for the southern Gulf of Suez this may reflect differences between shallow and intermediate crustal stress fields. The same focal mechanism inversion suggests that $S_{Hmax}$ varies rapidly along strike in the western branch of the EARS, with extension generally approximately normal to local rift axes (Fig. 1; Delvaux and Barth, 2010).

Stress fields in southern Africa are complex (Bird et al., 2006; Heidbach et al., 2008) and there is also uncertainty in where to place the plate boundary between the African and Somalia/West Indian Ocean plates (Fig. 1). An area of consistent NNW-SSE $S_{Hmax}$ occurs along the west coast of South Africa and Namibia, referred to

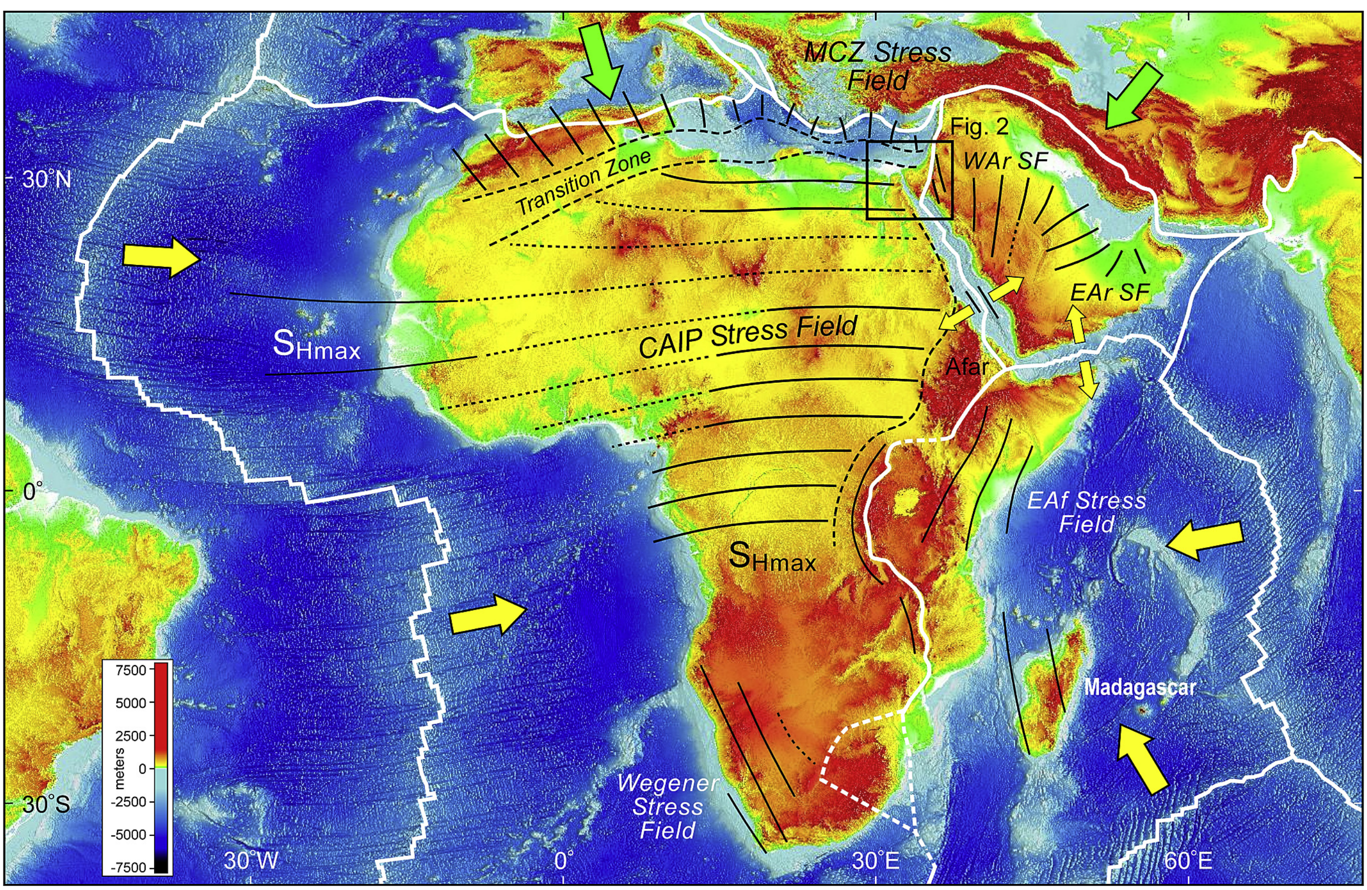


**Fig. 1.** Regional stress fields ($S_{Hmax}$ trajectories; black lines) and plate boundaries (heavy white lines) of Africa. Arrows give principal plate boundary forces affecting the Africa plate: yellow = ridge push; green = compression due to continental collisions. Size of the arrows are not to a set scale except that ridge push in the southern Red Sea and Gulf of Aden are shown smaller as these spreading centers are young and of short lengths. Plate boundaries are from USGS (2016) with modifications from Viti et al. (2011) in the Central Mediterranean (dashed where uncertain). Sources of stress field interpretations: East Africa (EAf) – Bosworth et al., 1992; Delvaux and Barth, 2010; Madagascar – Delvaux and Barth, 2010; Wegener – Bird et al., 2006; Mediterranean convergent zone (MCZ) and Central Africa intra-plate (CAIP) – Bosworth, 2008; East Arabia (EAr) – Ameen et al., 2010. West Arabia (WAr) is based on N-S alignment of young volcanic cones. All areas are corroborated with the World Stress Map database release 2008 (Heidbach et al., 2008). Complexities of Afar and much of southern Africa are not shown. Base is Etopo merged bathymetry and elevations model (NOAA, 2016). Location of Fig. 2 is shown by box. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

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