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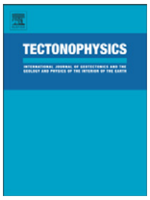

Simple shear detachment fault system and marginal grabens in the southernmost Red Sea rift

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ABSTRACT

The NNW-SSE oriented Red Sea rift, which separates the African and Arabian plates, bifurcates southwards into two parallel branches, southeastern and southern, collectively referred to as the southernmost Red Sea rift. The southern branch forms the magmatically and seismo-tectonically active Afar rift, while the less active southeastern branch connects the Red Sea to the Gulf of Aden through the strait of Bab el Mandeb. The Afar rift is characterized by lateral heterogeneities in crustal thickness, and along-strike variation in extension. The Danakil horst, a counterclockwise rotating, narrow sliver of coherent continental relic, stands between the two rift branches. The western margin of the Afar rift is marked by a series of N-S aligned right-lateral-stepping and seismo-tectonically active marginal grabens. The tectonic configuration of the parallel rift branches, the alignment of the marginal grabens, and the Danakil horst are linked to the initial mode of stretching of the continental crust and its progressive deformation that led to the breakup of the once contiguous African–Arabian plates. We attribute the initial stretching of the continental crust to a simple shear ramp-flat detachment fault geometry where the marginal grabens mark the breakaway zone. The rift basins represent the ramps and the Danakil horst corresponds to the flat in the detachment fault system. As extension progressed, pure shear deformation dominated and overprinted the initial low-angle detachment fault system. Magmatic activity continues to play an integral part in extensional deformation in the southernmost Red Sea rift.

1. Introduction

The Afro-Arabian rifts, that broke apart the once contiguous African–Arabian–Somali continental plates, comprise the Red Sea, the Gulf of Aden and the Main Ethiopian Rifts (Fig. 1) that meet at a diffuse triple junction over a mantle plume often referred to as the Afar triple junction (Hofmann et al., 1997; White and McKenzie, 1989). Since the advent of plate tectonics in the 1960s, the region has become a testing ground for models of active continental divergence (e.g., McKenzie et al., 1970). However, whether extension in the region initiated along low-angle detachments 'simple shear mode' or along steep normal faults 'pure shear mode', and the role of magmatic expansion, particularly during the initial crustal extension in the southernmost Red Sea rift remains unclear.

Based on the Eocene–Oligocene geological observations (e.g., Drury et al., 1994; Talbot and Ghebreab, 1997; Wernicke, 1985), and lithospheric-scale analog experiments (e.g., Michon, 2003) simple shear low-angle detachments accommodated the extension across the southern Red Sea rift during the initial stretching of the continental crust. Simple shear detachment fault geometry in the Red Sea region has also been utilized to explain the asymmetry (Voggenreiter et al., 1988; Wernicke, 1985), the non-uniform distribution of extension across it, igneous underplating and post rifting uplifts (Bohannon, 1986; Bohannon and Ettreim, 1991). On the other hand, based on present-day symmetric distribution of high and narrow zones of heat flow and seismicity distribution in the Red Sea, a pure shear mode of extension has been proposed (e.g., Buck et al., 1988; Cochran and Martinez, 1988). These two modes of extension occurred at different times. Extension in the southern Red Sea occurred in phases (e.g., Chorowicz et al., 1999; Ghebreab and Talbot, 2000; Hempton, 1987), with each phase experiencing different rate and magnitude of extension. In the western Afar rift margin, extension initiated on high angle normal faults that penetrated to mid or lower crustal levels followed by localized magma assisted rifting (Wolfenden et al., 2005). The role of magmatic intrusion in late stage continental breakup in the Main Ethiopian Rift (Ebinger and Casey, 2001; Kendall et al., 2005) and in the axial volcanic range in Afar (e.g. Belachew et al., 2011; Ebinger et al., 2010; Keir et al., 2013; Wright et al., 2006) is a well-documented phenomenon.

Between 11° N and 15° 30′ N latitude, two parallel NNW trending rift basins, the Afar rift and the southeastern Red Sea rift define the southernmost Red Sea rift segment (Fig. 2). The two rift basins, the Afar and southeastern Red Sea rifts, are separated by a NW trending, counterclockwise rotating continental relic known as the Danakil horst. Paleomagnetic measurements (Burek, 1970; Schult, 1974), plate reconstruction studies (Eagles et al., 2002) as well as GPS geodetic

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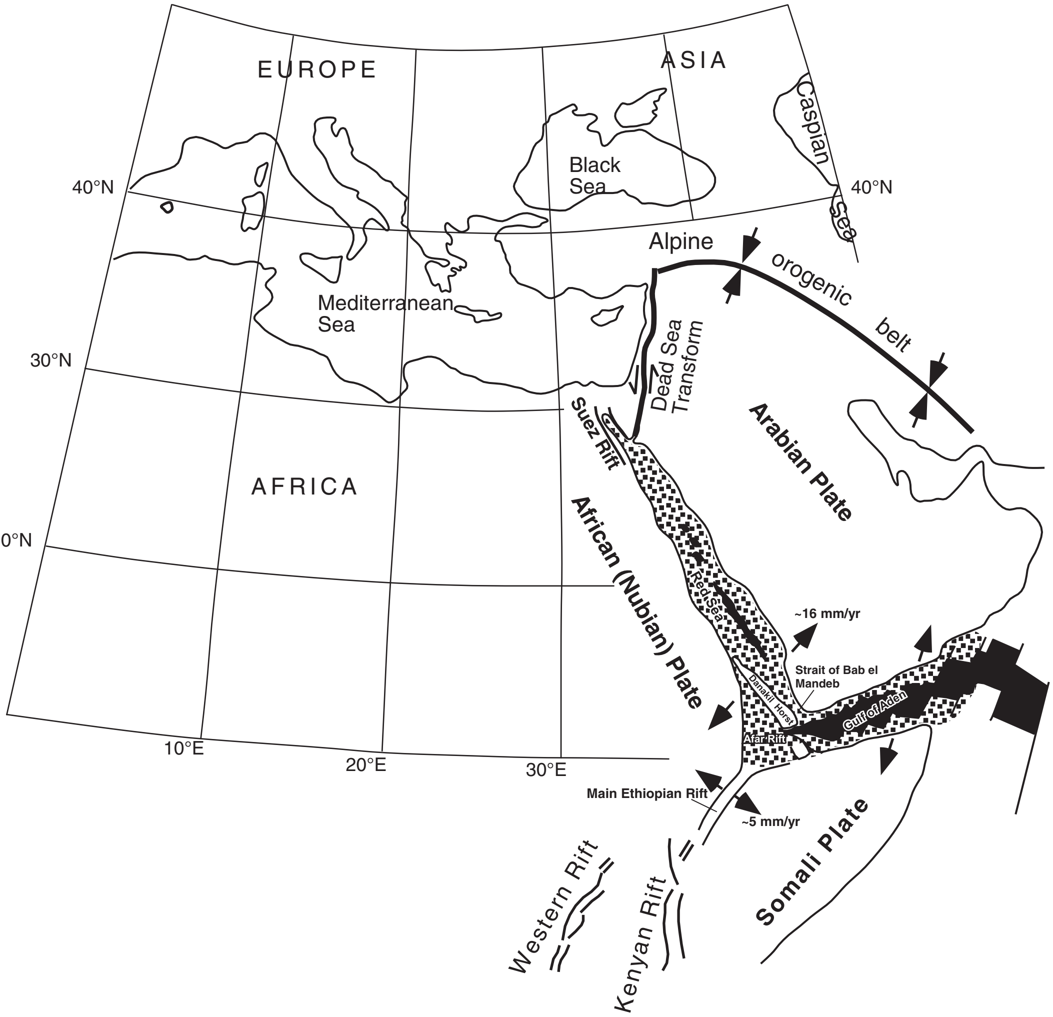

Fig. 1. Map showing distribution of oceanic and continental crust in the Red Sea and Gulf of Aden rifts. Stippled area indicates thinned continental crust and solid black is oceanic crust. The extent of oceanic crust in the Red Sea is limited to the axial trough. Note that width of the Red Sea rift increases progressively towards the south (adopted from Makris and Rhim, 1991).

investigations (e.g., McClusky, 2010), all confirm that the Danakil horst has undergone counterclockwise rotation albeit at varying rates in different time periods. The width of the two rift basins is complementary; in that where one is narrower the other becomes wider which enables the Red Sea rift to maintain its southward increasing width. Seismic data indicate that the southeastern branch of the Red Sea basin pinches out towards the Strait of Bab el Mandeb (Abouzakhm et al., 1991) where the Afar depression is at its widest (Fig. 2). Of the two rifts, the Afar rift, whose floor is exposed at the surface, is relatively well studied. A series of N-S aligned, and seismo-tectonically active marginal grabens characterize the western margin of the Afar rift (e.g., Mohr, 1974; Wolfenden et al., 2005).

There is significant lateral variation of the crustal structure and thickness in the Afar rift. The overall thickness of the crust under the rift is 20–26 km, and thins to 13–16 km beneath the narrow, seismically and magmatically active axial volcanic ranges (Dugda and Nyblade, 2006; Dugda et al., 2007; Hammond et al., 2011; Stuart et al., 2006). However, the thickness of the crust beneath the surrounding plateaus (Ethio-Eritrean, Southeastern, and Yemen plateaus) is 35–45 km (Dugda and Nyblade, 2006; Maguire et al., 2006; Stuart et al., 2006). Models proposed to explain the crustal nature of the Afar rift also vary, and include new oceanic crust (Barberi and Santacroce, 1980; Barberi and Varet, 1977), thinned continental crust (Berckhemer et al., 1975; Makris and Ginzburg, 1987; Makris et al., 1975), new igneous crust of continental affinity (Mohr, 1989), new largely mafic crust (Dugda and Nyblade, 2006), and stretched and intruded continental crust with partial melt (Hammond et al., 2011).

Modern extensional velocity varies approximately linearly along strike from ~15 mm/yr on the main Red Sea Rift north of ~16°N latitude to 20 mm/yr on the Afar rift (Danakil Depression), at ~13°N (e.g., McCluscky et al., 2010). In addition, McClusky et al. (2010) state that as the width of the Afar rift (Danakil Depression), and hence lithospheric stretching, increases from north to south, the adjacent GPS-derived velocities along the Danakil block also increases from north to south. The overall tectonic evolution, including the mode of initial stretching of the continental crust in the southernmost Red Sea rift, including the tectonic origin of the Danakil horst is less-well understood.

The objective of this study is to evaluate whether a simple shear low-angle detachment model could account for the initial breakup of the African–Arabian continental lithosphere and provide an explanation for the origin of the parallel rift basins, the Danakil horst, and the seismically active marginal grabens that are aligned along the western Afar rift margin. Digital topographic data, morphotectonic features, earthquake catalogs and previously published results supplemented with limited field observations are analyzed to assess the viability of such a model. The digital topography data used in this study include Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER) Global Digital Elevation Model (GDEM) and Shuttle Radar Topography Mission (SRTM30_PLUS) elevation and bathymetry data.