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The development of extension and magmatism in the Red Sea rift of Afar

Derek Keir [a,*], Ian D. Bastow [b,1], Carolina Pagli [c], Emma L. Chambers [a]

[a] National Oceanography Centre Southampton, University of Southampton, Southampton, SO14 3ZH, UK
[b] School of Earth Sciences, University of Bristol, Bristol, BS8 1RJ, UK
[c] School of Earth and Environment, University of Leeds, Leeds, LS2 9JT, UK

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ABSTRACT

Despite the importance of continental breakup in plate tectonics, precisely how extensional processes such as brittle faulting, ductile plate stretching, and magma intrusion evolve in space and time during the development of new ocean basins remains poorly understood. The rifting of Arabia from Africa in the Afar depression is an ideal natural laboratory to address this problem since the region exposes subaerially the tectonically active transition from continental rifting to incipient seafloor spreading. We review recent constraints on along-axis variations in rift morphology, crustal and mantle structure, the distribution and style of ongoing faulting, subsurface magmatism and surface volcanism in the Red Sea rift of Afar to understand processes ultimately responsible for the formation of magmatic rifted continental margins. Our synthesis shows that there is a fundamental change in rift morphology from central Afar northward into the Danakil depression, spatially coincident with marked thinning of the crust, an increase in the volume of young basalt flows, and subsidence of the land towards and below sea-level. The variations can be attributed to a northward increase in proportion of extension by ductile plate stretching at the expense of magma intrusion. This is likely in response to a longer history of localised heating and weakening in a narrower rift. Thus, although magma intrusion accommodates strain for a protracted period during rift development, the final stages of breakup are dominated by a phase of plate stretching with a shift from intrusive to extrusive magmatism. This late-stage pulse of decompression melting due to plate thinning may be responsible for the formation of seaward dipping reflector sequences of basalts and sediments, which are ubiquitous at magmatic rifted margins worldwide.

1. Introduction

Rifting and breakup of the continents can occur by extensional faulting, as well as by ductile stretching and thinning of the continental lithosphere (e.g., McKenzie, 1978). Thinning of the lithosphere results in adiabatic decompression of the underlying asthenosphere, which can result in the production of large volumes of molten rock if the rate and extent of thinning are sufficiently high and if the thermo-chemical state of the mantle is conducive to it (Bown and White, 1995; Shillington et al., 2009; White and McKenzie, 1989). Intrusion of melt into the lithosphere can also achieve extension, without marked plate thinning (e.g., Mackenzie et al., 2005; Thybo and Nielsen, 2009), but with important implications for the thermal structure and strength of the extending plate (e.g., Bialas et al., 2010; Ebinger, 2005). The breakup of continents therefore occurs by the interplay between structural and rheological changes to the lithosphere due to mechanical deformation, heating, and magmatism.

Once a continent has successfully broken apart and seafloor spreading has commenced along a new mid-ocean ridge, the architecture of the once-active continental rift remains frozen beneath the conjugate passive continental margins. Study of passive margin geology, combined with wide-angle seismic imaging of crustal structures and rift stratigraphy provided a primary framework from which to infer the extensional mechanisms and mantle conditions that characterised breakup (e.g., White, 1988; White et al., 2008; Whitmarsh et al., 2001). However, it is difficult to interpret the geological record unambiguously because the tectonic activity that characterised breakup has long-since ceased and the continent–ocean transition (COT) is sometimes masked by up to several kilometres of late-to-syn rift interbedded basalt flows and sediments (often evaporites). These so-called seaward-dipping reflector sequences reflect back a large proportion of the seismic energy used to image beneath them in controlled-source experiments (Maresh and White, 2005; Mutter, 1985; Mutter et al., 1982; White et al., 2008).

Tectonically active continental rifts and recently developed mid-ocean ridges provide snapshots of rift development. Study of the rift system in Ethiopia is particularly useful because it exposes

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[*] Corresponding author. Tel.: +442380593786.
E-mail address: D.Keir@soton.ac.uk (D. Keir).

[1] Now at Department of Earth Science and Engineering, Imperial College, London, London, SW7 2AZ, UK.

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subaerially several stages of magmatically active rift sector development from immature continental rifting in the East African rift to incipient oceanic spreading in the Red Sea and Gulf of Aden (e.g., Barberi et al., 1972; Ebinger, 2005; Hayward and Ebinger, 1996; Makris and Ginzburg, 1987; Mohr, 1967) (Fig. 1). It therefore provides a unique opportunity to develop an understanding of the evolution from mechanical continental rifting to magmatic extension in mid-ocean ridges. Here we synthesise constraints from the southern Red Sea rift in Afar on along-rift variations in crustal structure, style of surface volcanism, shallow magmatic plumbing, surface morphology, and active deformation constrained by seismicity and geodesy. These constraints provide fundamental information on the spatial and temporal evolution of deformation and magma-supply during the late-stages of continental breakup.

2. Tectonic background

2.1. Rifting

2.1.1. Rift initiation

Afar marks a triple junction between the Nubian, Somalian, and Arabian plates, which are diverging due to extension in the Red Sea, Gulf of Aden and East African rifts (e.g., Beyene and Abdelsalam, 2005; Ghebreab, 1998; McKenzie et al., 1970; Mohr, 1970; Tazieff et al., 1972) (Fig. 1). The excellent fit of the southern coast of Arabia into the Horn of Africa was amongst the earliest case studies used to substantiate plate tectonic theory (e.g., McKenzie et al., 1970). Border faults on the SE and SW flanks of the Afar depression mark the abrupt transition from rift valley floor to the 2–3 km high Ethiopian

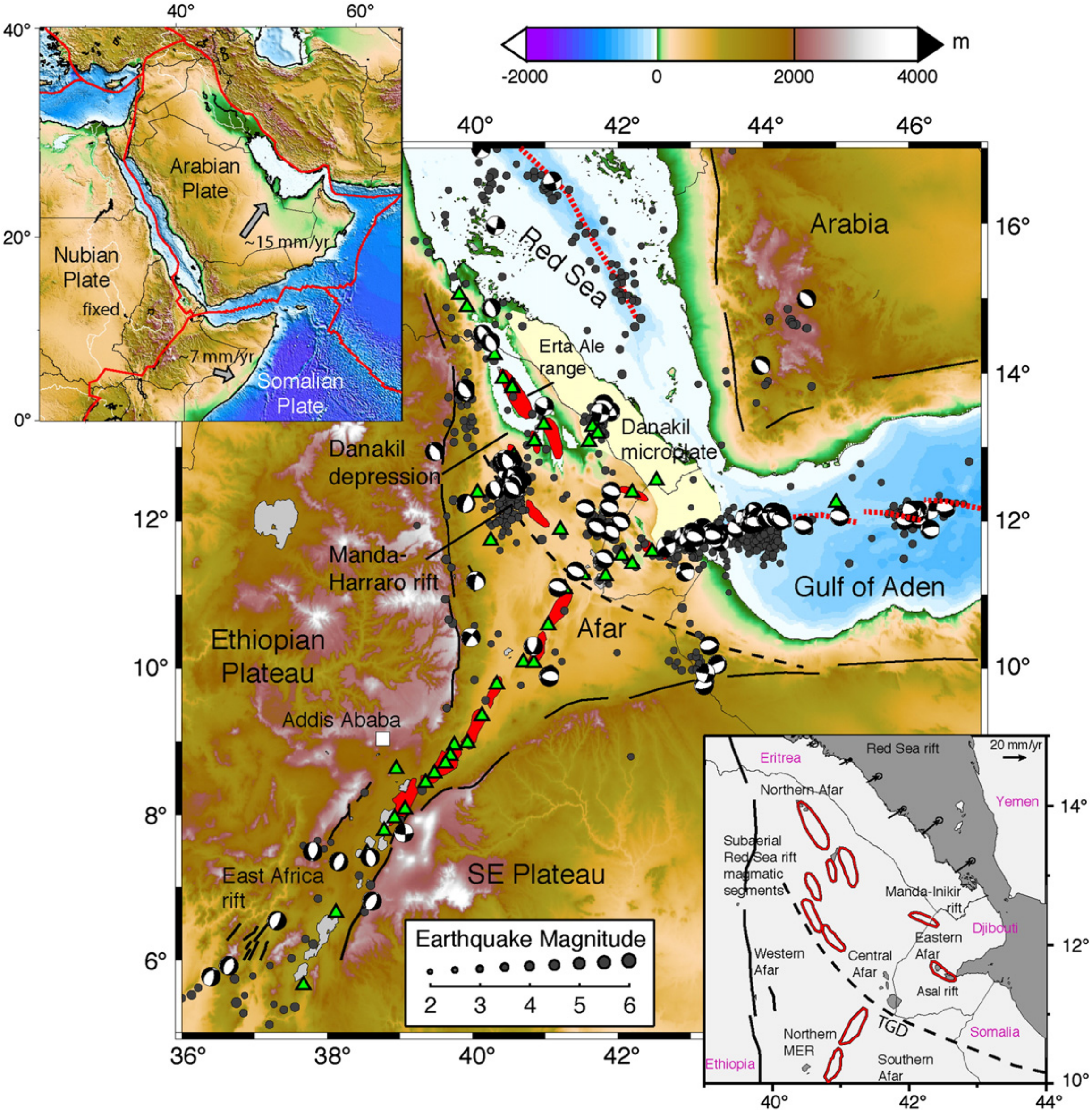

Fig. 1. Tectonic setting of the Afar depression (modified after Keir et al., 2011b). Solid black lines show Oligocene–Miocene border faults of the Red Sea, Gulf of Aden Aden, and East African rifts. Red segments show the Quaternary–Recent subaerial rift axes, and green triangles show Holocene volcanoes. Dashed lines show the Tendaho–Goba'ad Discontinuity (TGD). The Danakil microplate is shaded yellow. Gray circles show large earthquakes during 1973–2012 sourced from the National Earthquake Information Centre (NEIC) catalog. Earthquake focal mechanisms are from the Global Centroid Moment Tensor (CMT) catalogue. Top left inset: topography of NE Africa and Arabia. Gray arrows show plate motions relative to a fixed Nubian plate (ArRajehi et al., 2010). Bottom right inset: zoom of Oligocene–Miocene border faults (black) and Quaternary-Recent subaerial rift axes (red lines) with arrows showing motion of the Danakil microplate (McClusky et al., 2010).