Opening of the Red Sea: from Afar to Suez

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Extended Abstract

For over two billion years the Earth's internal engine has triggered a cyclical process, whereby continents assemble in a single " Supercontinent", and then gradually fragment and disperse again. An even cursory look at a globe shows that at present we are in a phase when a number of continental blocks are scattered seemingly at random on the surface of our Planet. Reconstructions of the geological past suggest that the last time interval when continental masses were assembled in a single Supercontinent, called Pangea, lasted roughly from 250 to 150 million years ago. An entire cycle of continental break up, dispersal and reassembly lasts roughly 500 million years. A fundamental step in this "Wilson Cycle" (named after the great Canadian earth scientist Tuzo Wilson, a key figure in the Plate Tectonics scientific revolution) is the splitting of a continent and the birth and growth of a new ocean.

Nowhere in today's Earth is this event better displayed than in the Red Sea region where Arabia is the process of splitting from Africa. In fact, three major rifts (or "cracks") of the Earth solid external layer meet in this region. One is the East African Rift, a linear "crack" that cuts through the African continent ending up in the Afar region of Eastern Ethiopia. The other is the Gulf of Aden, an oceanic rift that started over 15 million years ago, propagating gradually from east to west: today it impacts against the African Continent, again in the Afar region. The third is the Red Sea-northern Afar rift, where the transition from a continental to an oceanic rift has barely started.

Understanding the processes that occur during the transition from a continental to an oceanic rift, the earliest stages of seafloor spreading, and the formation of passive margins, has been for years a major challenge in the Earth sciences. The Red Sea/Gulf of Aden system is an ideal "natural laboratory" where this challenge can be addressed. Together with the East African

and the Afar Rifts, we have within the same region a network of rift zones in different stages of evolution (Fig. 1), from fully continental (East African), to “pre-oceanic” (Afar and northern Red Sea), to oceanic (southern Red Sea and Gulf of Aden). Plate tectonic reconstructions suggest that, while emplacement of oceanic crust initiated as early as 15 Ma in the Gulf of Aden, it started more recently (~ 5 Ma) in the Southern Red Sea, but has not yet started in the northern Red Sea. Although different parts of this system have been the object of many studies, a number of key aspects remain poorly known.

We are addressing in this work a number of issues, namely: (a) Does the initial break of the continental lithosphere and oceanic accretion occur in discrete axial cells, and, if so, why ? (b) To what extent is the opening of the Red Sea normal to the rift, and how is it affected by oblique motion (i.e., Dead Sea Fault direction) ? (c) How do crust-forming melts evolve during the transition from continental to oceanic rift and during the first stages of sea floor spreading? (d) How do melting processes in a young oceanic rift (Red Sea) differ from melting below a mature Mid Ocean Ridge? (e) Is there a systematic change in melt composition along the Red Sea axis, that parallels the presumed south to north propagation of the oceanic rift? (f) Does underplating of thinned-extended continental crust by basaltic melts preceed initiation of sea floor spreading? (g) To what extent is the break up of the continental lithosphere in the Red Sea region related to a mantle plume? Addressing these questions should lead ultimately to a better understanding of changes in thermal structure and composition of the upper mantle as it upwells beneath rifts that evolve from continental to oceanic.

The Red Sea occupies a 2000-km long rift bounded depression. The rift shoulders average between 1000 m and 3000 m in elevation and expose a variety of Pan-African (late Proterozoic) granitic, metamorphic and mafic igneous rocks (Shackleton et al., 1980; Stern, 1994). Uplifting and unroofing began almost simultaneously along the entire Red Sea ~34 Ma while the main phase of rifting began at ~22 Ma, according to fission track data (Omar and Steckler, 1995). The onset of rifting in the Red Sea was preceded by massive basaltic volcanism in Ethiopia and southern Yemen around 30 Ma (Hofmann et al., 1997; Coulie et al., 2003), attributed to impingement of the Afar plume head on the lithosphere (Richards et al., 1989). After a perhaps 10 Ma-long interval of stretching of the continental crust , oceanic crust started to form in the southern Red Sea about 5 Ma.

The axial zone of the Red Sea displays a different geotectonic signature moving from South to North (Fig. 1) (Searle and Ross, 1975; Pautot et al., 1983; Bonatti, 1985 Cochran, 2005). South of 19° 30’N the axis of the Red Sea rift is displaced inland in the Afar rift

(Ethiopia and Eritrea), a spectacular region of active seismicity, volcanism and hydrothermalism. Between 19° 30' and 16°N we observe a relatively continuous axial rift valley with Vine-Matthews linear magnetic anomalies. Moving north (from 19º 30'N-22ºN) we have a complex pattern of axial trough segments, some with hydrothermal circulation. We then observe a "transition zone", with a number of discrete, regularly spaced axial oceanic troughs (Fig. 1). North of 24º N the Red Sea is carpeted probably by thinned continental crust injected by scattered basaltic intrusions: we observe a few isolated deeps, some exposing basalt, but no evidence of "ordered" centers of sea floor spreading, although some, i.e. Shaban Deep (Haase er al., 2000) are carpeted by fresh basalt.

Vine-Matthews-type magnetic anomalies indicate initiation of sea-floor spreading by injection of basaltic crust in a narrow axial zone starting about 5 Ma, at around 17º N, but more recently to the north and south, in a pattern suggesting axial rift propagation. Spreading rates appear to decrease northward, from about 16 mm/a at 18° N to 10 mm/a at 25 °N (Chu and Gordon, 1998). The initial emplacement of oceanic crust may occur in the Red Sea in regularly spaced discrete "cells" (Bonatti, 1985) serving as nucleii for axial propagation of the zone of oceanic accretion, that evolves then in linear segments of spreading. This segmentation could derive either from regularly spaced nucleii of upwelling asthenosphere, or from an initial structural segmentation inherited from pre-existing structural "accommodation zones", as observed in the East African Rift (Bosworth, 1989; Makris and Rhim, 1991; Ghebreab, 1998).

The two northernmost "oceanic" segments of the "transition zone", with axial troughs carpeted by MORB-type fresh volcanics and with Vine-Matthews magnetic anomalies, are called Thethis and Nereus (Fig. 2). North of these oceanic segments a major fracture zone (Zabargard Fracture Zone), intersects the Red Sea N-S at 23ºN-25ºN (Fig. 2) (Ligi et al., 2012). The Island of Zabargad, an uplifted block of sub-Red Sea lithosphere, lies at the SW end of this structure (Bonatti et al., 1981; 1984). A probably extensional basin (Mahabiss Deep) lies at the NE end of the Zabargad FZ. We suspect the Zabargad Fracture Zone is a "prototransform" that, if the Red Sea were to continue its opening, might develop into an "initial" major oceanic transform, similar to those offsetting today the equatorial Mid Atlantic Ridge.

The small islands of the Brothers in the Northern Red Sea at about 26° N provides a remarkable exposure of microgabbros dissected by doleritic dykes. Similar material is exposed on Zabargad island. These rocks might represent uplifted fragments of basaltic melts underplating thinned and extended continental crust before initiation of sea floor spreading (Bonatti and Seyler, 1987).

Alfred Wegener, who early in the last century pionereed the concept of Continental Drift, realized that the Red Sea is a young oceanic rift formed by the separation of Arabia from Africa. He further understood that the Afar Triangle does not belong in attempts to fit the African and Arabian Red Sea coastlines; he suggested therefore that the Afar region must have developed by volcanism that took place during the separation of the two continental blocs: a remarkable intuition, particularly since at that time the information on the geology of Afar was very scant.

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Figure 1. *Satellite image of the Red Sea/Gulf of Aden region and East African and Afar rifts zones.*

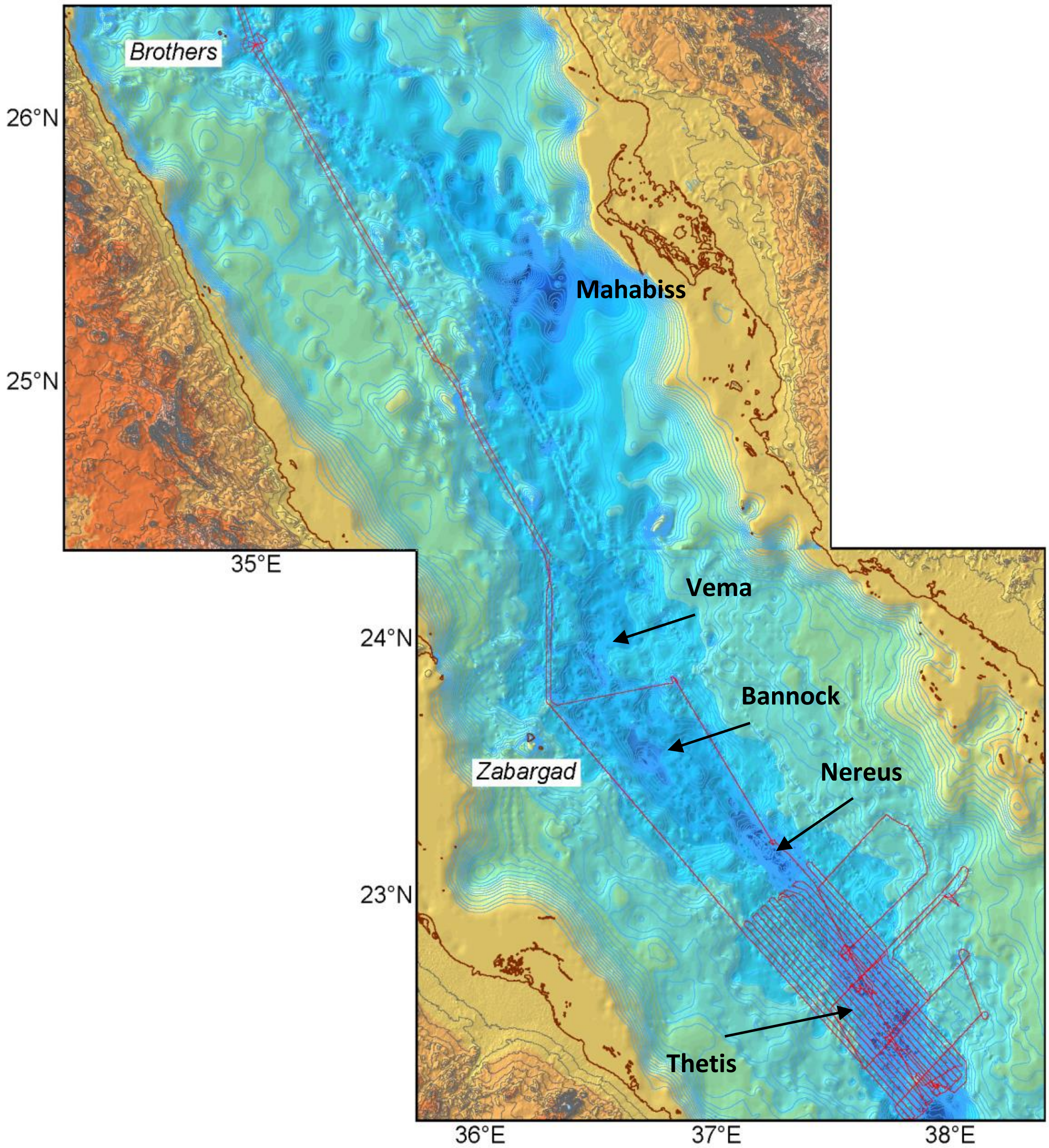

Figure 2. *Shaded relief image of the Northern Red Sea region showing the two northernmost oceanic deeps (Nereus and Thetis deeps). Brothers and Zabargad islands and the Zabargad Fracture Zone are also shown.*