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The Geologic Enigma of the Red Sea Rift

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1 Introduction

The Red Sea is a narrow 1920 km long trough extending from the Sinai Peninsula at 27°40′N to the Straits of Bab al Mondab at 12°40′N. It is part of an extensive rift system that extends from southern Africa to the Afar depression from which the Red Sea and the Gulf of Aden bifurcate (Fig. 1; Hötzl 1984). The Afar depression is partially blocked from the Red Sea by a northwest trending basement high, the Danakil horst which Le Pichon and Francheteau (1978) believe is a microplate. It probably formed as a result of reorganization of the plate boundaries at the triple junction of the African, Arabian, and Somalian plates (see Engeln et al. 1988; Schouten et al., in press, for microplate formation resulting from spreading center reorganization.) In the Afar depression, tectonic and volcanic activity occurred in taphrogenetic phases of short duration at the boundaries of the Oligocene and Miocene, Miocene and Pliocene, during middle and upper Pliocene, and early Pleistocene (Pilger and Rösler 1976). Within the depression are a series of northwest trending en echelon active tectono-volcanic axes that may be considered emerged sea-floor spreading centers (Stieltjes 1973).

At its northern end the Red Sea splits into the Gulf of Suez, a tensional rift structure, and the Gulf of Aqaba, part of the Dead Sea left lateral shear. The edges of the Red Sea are marked by a pronounced 1000 to 3000-m-high basement hinge facing seaward along which Pan-African granites, metamorphics, and volcanic rocks and accreted exotic terrains including ophiolites are exposed (Stern et al. 1984; Stoeser and Camp 1985). From the mouth of the Gulf of Suez at 27°50′N to 24°N for a distance of about 460 km the coastlines of the Red Sea are straight and parallel and are about 190 km apart. Farther south the coastlines are more irregular, widening to 350 km between 16°N and 17°N narrowing from there to 40 km at the Straits of Bab al Mandab. The floor of the Red Sea consists of narrow shelves, a main trough at a depth of 600 to 1200 m which at its southern end from 20°N to 15°N is entrained by a less than 20 km wide and up to 2000 m deep axial trough. South of about 20°N on the east and 17°N on the west side, reefs and carbonate banks have prograded seaward almost completely filling in the main trough (Martinez and Cochran, in press). Toward the northwest the main trough terminates on a series of northeast trending asymmetric rhombal half grabens in an en echelon pattern formed by motion along the "leaky" Dead Sea transform (Ben-Avraham 1985).

The axial trough is underlain by oceanic crust and well-developed magnetic anomalies as old as anomaly 3 (about 5 Ma old) from 16°N to 23°N (Roeser 1975). Marginal to the axial trough are sediments accumulations 4 to 5 km thick including 3 to 4 km of middle and late Miocene evaporites. The nature of basement beneath

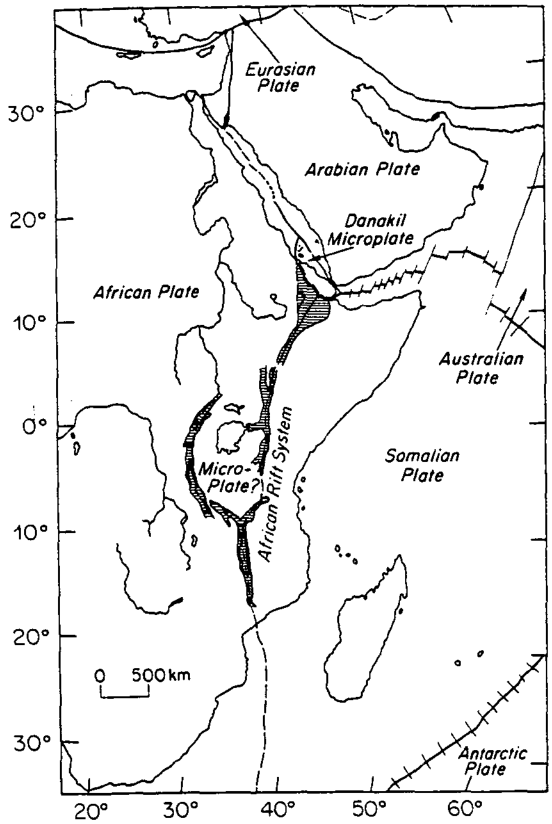

Fig. 1. Plate boundaries and associated structures in the general area of the Red Sea. Modified from Pilger and Rösler (1976) using data from Fig. 2, Emery and Uchupi (1984, p 113) and Rosendahl (1987)

the sediments is the subject of considerable controversy, a controversy illustrated by the three models that have been proposed for the origin of the Red Sea. One hypothesis, which we call the oceanic crustal model, suggests that the whole Red Sea is underlain by oceanic crust. In the second hypothesis, the intermediate model, the main trough is underlain by oceanic crust and the area landward of the trough by intruded attenuated continental crust. Proponents of the third hypothesis, which we call the attenuated continental crustal model, believe that most of the Red Sea is underlain by continental crust and that oceanic crust is restricted to the axial trough, and a few isolated depressions immediately north of the trough.

2 The Oceanic Crustal and Intermediate Models

Advocates of the oceanic crustal model for the Red Sea believe that the rift is underlain by oceanic crust from shore to shore (Girdler and Styles 1974, 1976; Styles and Hall 1980); others have even proposed that oceanic crust extends inshore in southern Arabia (Gettings 1977; Girdler and Underwood 1987). Such an interpretation appears to be supported by seismic refraction velocities of about 6.7

km/s in the inner half of the main trough between 22°N and 23°N (Tramontini and Davies 1969; Davies and Tramontini 1970) and the presence of linear magnetic anomalies in parts of the main trough which are believed to be of seafloor spreading origin (Girdler and Styles 1974, 1976; Styles and Hall 1980). Girdler (1983) has described the plate setting of the Gulf of Aden, Red Sea and the Gulfs of Suez (Clysmic rift), and Aqaba to the propagation of rifting westwards through the Gulf of Aden and then northwards through the Red Sea terminating north of the present Gulf of Suez, seafloor spreading and separation of the Gulf of Aden and Red Sea beginning 25 Ma ago and 62 km left lateral motion along the Dead Sea shear, and a second cycle of seafloor spreading in the Red Sea that began about 5 Ma ago with a further 45 km movement along the Dead Sea shear. In a combined study of gravity, magnetic and seismic refraction data from the southeast margin of the Red Sea extending from 16.3° to 17.3°N and 41.6°E to 43.1°E, Girdler and Underwood (1985) state that a model where the oceanic-continental boundary might be 35 km inland from the coast and 8 km from the Precambrian shield satisfies all the geological and geophysical measurements. The implication from their model is that little continental crustal extension took place and the decoupling of the continental lithosphere was fairly clean. For example, the presence of positive Bouguer anomalies on the coastal plain in a region of large unconsolidated sediment thickness where one would expect negative values suggests that the sediments might be underlain by heavy oceanic lithosphere rather than light sialic continental crust. The magnetic field over the region displays high frequency small anomalies over the Precambrian shield and long wavelength, large amplitude linear anomalies in the coastal plain; a similar pattern also is found on the opposite side of the Red Sea. Gravity data would indicate that these are not due to basement relief. Thus they postulate that the magnetic lineations were formed by seafloor spreading. Seismic refraction measurements also suggest that the crustal transition may take place some 25 km inland from the coast. Bohannon (1986) states that the geometric configuration of the Arabian passive margin constrained by seismic refraction measurements predicted by an oceanic model indicates a 35 to 40 km shoreline overlap. A continental crustal model predicts a minimum divergence of 320 km resulting in a narrow gap between the shorelines. According to Bohannon this minimum is not realistic because oceanic rocks are known from the margin. Thus, the shoreline overlap described by Girdler and Underwood (1985) may be real.

In another publication Girdler (1985) suggested that the Red Sea may have evolved in three phases. In phase one in the Oligocene during which continental rifting took place, the Gulf of Suez opened up. In the second phase from ?latest Oligocene to early Miocene the first 62-km movement along the Dead Sea left-lateral shear occurred and sea-floor spreading began in the Red Sea. The third phase took place during the second 45-km motion of the Dead Sea shear in the Plio-Pleistocene. Lack of clear magnetic lineations of seafloor spreading in origin in the northern Red Sea is believed to be due to a combination of large thickness of salt, high temperatures, and slow spreading rates as the region is near the pole of rotation at 36.5°N, 18.0°E.

In a recent publication based on bathymetric, gravity and magnetic profiles recorded between the Sinai Peninsula and 19°N Girdler and Southern (1987) also proposed a similar three stage development for the Red Sea. They are (1) a "Gulf of Suez" stage in the Oligocene during which the continental crust was attenuated by faulting to form an early "Red Sea-Gulf of Suez" graben 30 Ma ago with an average crustal extension of 60 km; (2) an "early Dead Sea" stage in the Miocene 25 to 15 Ma ago accompanied by slow seafloor spreading and 62 km left lateral motion along the Dead Sea shear; and (3) a recent "Dead Sea" stage again with slow seafloor spreading and 45 km left lateral motion along the Dead Sea shear from 4.5 Ma ago to the present. They further suggested that gabbro on the borehole 55 km off the Egyptian coast at about 25.8° N would indicate that the oceanic/continental crystal boundary lies between 25 and 55 km offshore. During the 10 Ma long seafloor spreading hiatus from 15 to 4.5 Ma ago circulation in the Red Sea was restricted leading to the accumulation of the middle and late Miocene evaporites. When seafloor spreading began again the earlier oceanic crust was cut in two to form the deep axial trough and evaporite deposition ended as a connection with the Gulf of Aden was established.

Labrecque and Zitellini (1985) also believe that sea floor spreading extends the length of the Red Sea. In their reconstruction, (intermediate model) however, oceanic crust is restricted to main trough. They state that the oldest magnetic anomaly that they can correlate with the reversal scale is anomaly 5C along the landward flank of the main trough. The 50 km wide zone between anomaly 5C and the continental basement hinge basement they state is composed of stretched continental crust intruded by basaltic dikes. Basement seaward of anomaly 5C is a quasi-oceanic crust composed of a higher percentage of lava flows than normal oceanic crust, a stratoid crust comparable to the crust in the Afar depression (Barberi et al. 1976).

3 Continental Crust Attenuation Model

The first seismic refraction measurements (Drake et al. 1959; Drake and Girdler 1964; Girdler 1969) appear to verify the concept that the Red Sea is underlain by continental crust (Drake and Girdler 1964; Girdler 1969; Coleman 1974). More recent geophysical measurements, however, have been interpreted as indicating that the regions is underlain by oceanic crust. This new interpretation has not met with universal approval. As pointed out by Cochran (1983): (1) the magnetic anomalies in the marginal areas of the Red Sea are smooth, low-amplitude without any distinguishing characteristics and are unlike the seafloor spreading anomalies within the axial trough; Cochran was also able to demonstrate that the magnetic anomaly sequence found in the marginal areas could be generated as a result of normal faulting of continental basement using a susceptibility value of 0.002 emu; well within the range of values reported for granites; (2) the presence of pre-rift crystalline rocks on St. John and possibly on The Brothers suggest that basement beneath the main trough is continental; the fresh peridotite on St. John and the gabbro in the borehole 55 km off Egypt may represent intrusives into attenuated continental crust. Based on a structural and kinematic analyses of the peridotites in Zabargad Island, Nicolas et al. (1987) believe that they represent asthenospheric diapirism emplaced during the early phases of rifting of the Red Sea; (3) a seismic reflection line along the western edge of the axial trough outside the region of high-amplitude magnetic anomalies shows that the crust with a velocity of 5.91 km/s is block-faulted in a manner characteristic of attenuated continental crust; (4) crustal seismic velocities considered diagnostic of continental rocks are found in a number of locations under the main trough. The "oceanic" crustal velocities encountered in one region in the main trough may be Neogene intrusions or Precambrian or early Paleozoic mafic and ultramafics such as those described from Arabia and Nubia. Similarly, the ophiolite complex at base of the basement hinge near 17°N (Tihama Asir igneous complex; Coleman et al. 1975, 1979) in southern Saudi Arabia and several locations between the Yemen border and Ad Bard at 17° 45′N may represent massive intrusions into continental crust.

The model described by Girdler and Underwood (1985) for the southern Red Sea also implies that little continental crustal attenuation took place prior to seafloor spreading, a concept that appears to be verified by a crustal geometric configuration constrained by seismic refraction measurements (Bohannon 1986). Yet all passive margins of the Atlantic pull-apart type (not translation margins such as the southwest Grand Banks margin, the Gulf of Guinea margin and the Benue trough, and the margin of southern Africa where crustal extension is minimal) appear to have undergone long periods of crustal extensions (Uchupi, in press; references therein), an extension that lasted 30 to 47 Ma in the northern North Atlantic, 75 Ma in the southern North Atlantic, 68 to 53 Ma years in the Equatorial Atlantic and 77 to 68 Ma in the South Atlantic. This extension resulted in a 100 to 250 km wide rift system. The fundamental structure of the Atlantic rift is a half graben with a geometry ranging from overlapping, partially overlapping, to non-overlapping half-grabens. In the non-overlapping pattern the half graben is fronted by a platform (i.e., Baltimore trough, Reguibat Massif). Where the boundary faults overlap a set of cross trending normal faults they form accommodation faults. When continental decoupling occurred the plane of separation apparently was closer to the platform. Thus most of the extended continental crust is only found next to the boundary fault. Only when two half-grabens face each other or where the fundamental structure is graben did continental de-coupling take place in the center of the rift.

It is these reservations that have led some geologists to propose the attenuated continental crustal model for the origin of the Red Sea (Lowell and Genik 1972; Ross and Schlee 1973). In this model the basement hinge bordering the Red Sea is a series of master normal faults that define a chain of half-grabens and opposing platforms. The main boundary faults are not restricted to one hinge, but probably occur along both yielding a tectonic style comparable to the East African rift of nonoverlapping, partially overlapping, and facing half-grabens. Along the master normal faults are subsidiary faults dipping toward or away from the master fault breaking up basement into a series of blocks. The bathymetric terraces in the marginal areas of the northern Red Sea represent such a series of rotated fault blocks (Cochran and Martinez, in press). A set of cross-trending normal faults connecting partially overlapping master faults form accommodation zones in the manner described by Rosendahl (1987) for the East African rift system. Such a geometry is present in the Gulf of Suez with the accommodation zones being oriented oblique and orthogonal to the boundary faults (M. Steckler in Martinez and Cochran, in press).

Rifting in the Red Sea may have been preceeded by arching in the Oligocene (Lowell and Genik 1972). Using fission track ages from Precambrian apatites, Kohn and Eyel (1981) determined that domal uplift in the Sinai peninsula began 26.6 ± 3 Ma ago and continued for most of the Miocene. The uplift amounted to at least 5 km, 3 km of which has taken place since 9 Ma ago. Uplift was greater parallel to the Gulf of Suez, an area of extension, and less parallel to the Gulf of Aqaba along the Dead Sea shear along which there has been 105 km of left lateral motion during the last 22 Ma. Steckler (1985), however, believes that this doming was not a pre-rift event, but developed during the main phase of rifting. Absence of Oligocene sediments, generally cited as evidence of uplift, Steckler (1985) states is probably the consequence of a major northwards regression. Jarride et al. (1986) postulate that the tectonic style in the Gulf of Suez and the northwest edge of the Red Sea is controlled by two events; a strike-slip displacement that produced antithetic tilted blocks 24 to 20 Ma ago, and a second phase that began 20 Ma ago and still developing now when synthetic normal movements formed a horst and graben pattern.

Rifting in the Red Sea region was underway by the start of the Miocene and initially the Gulf of Suez formed part of the Red Sea. Subsequent 105 km left lateral motion along the Dead Sea shear and opening of the Gulf of Aqaba has led to further extension in the Red Sea proper. Extension in the central Gulf of Suez has been estimated to be 27 to 25 km (Steckler 1985) and in the northern Red Sea 135 km (Cochran 1983). On the rift were deposited a thick sequence of Miocene volcanics and clastics and middle and late Miocene evaporites. About 5 to 4 Ma ago a spreading axis was established near Lat. 17°N and that axis propagated to the north and south until it extended from Lats. 20°N to 15°30′N, the drift zone of Fig. 2. From 20°N to 23°30′N is a series of large deeps spaced at intervals of about 50 km floored by oceanic crust. This area is presently changing from continental extension to a sea-floor spreading mode. Lineated magnetic anomalies indicate that seafloor spreading in this transitional zone (Fig. 2) was possibly initiated in the southern deeps and is propagating northward (Martinez and Cochran, in press). One, possibly two, of the deeps in the rifted continental terrain have high amplitude dipolar magnetic anomalies which are believed to be the result of intrusions into attenuated continental crust (Pautot et al. 1986; Cochran 1983; Cochran et al. 1986). Intrusion may be a consequence of extension and crustal thinning being concentrated in the main trough during the late phase of rifting with points of injection being controlled by periodically spaced gravitational instability of the asthenosphere (Bonatti 1985; Whitehead et al. 1984). With continuing intrusion and extension these deeps may develop into isolated cells of seafloor spreading which in time will coalesce to form a continuous seafloor spreading axis (Martinez and Cochran, in press).

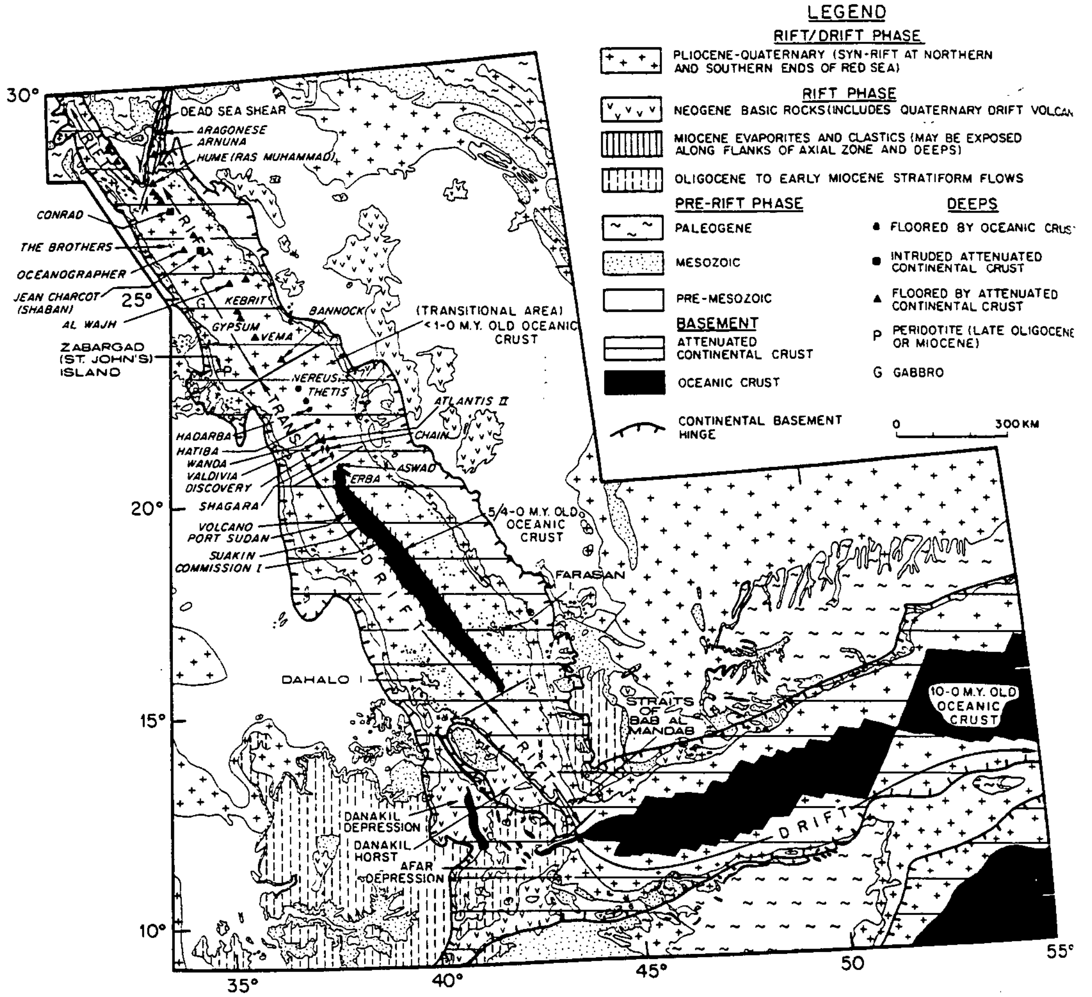

Fig. 2. Tectonic map of the Red Sea region based on the attenuated continental crustal model. In the oceanic crustal model most of the area between the basement hinges will be floored with oceanic crust, and in the intermediate model the main trough is underlain by oceanic crust landward of which is a intruded rifted continental crust. Compiled from data obtained during the present investigation, Nesteroff (1955); Association of African Geological Societies and UNESCO (1963, 1968); Laughton (1970); Gass et al. (1973); Ross and Schlee (1973); Barberi et al. (1974); Searle and Ross (1975); Civetta et al. (1978); Heezen et al. (1978); Ben-Avraham et al. (1979); Cochran (1981); Beydoun (1982); El Shazley (1982); Bartholomew and Son (1983); Bonatti et al. (1983); Cochran (1983); Pautot and Guennac (1984); Girdler and Southern (1987); Nicolas et al. (1987); Martinez and Cochran (in press)

4 Conclusion

The data available to date does not make it possible to determine the validity of the three models that have been proposed for the origin of the Red Sea rift. No borehole data are available as to the nature of the crust beneath the main trough. As a result of the acoustic impedence of the Miocene evaporites multi-channel seismic profiles have provided little information as to the tectonic style of basement in the main trough from which inferences could be made regarding its origin. Gravity and magnetic measurements are too ambiguous and can be interpreted as due to either continental or oceanic crustal sources. The oceanic crustal model implies that rifting in the Red Sea was minimal to non-existent, a conclusion contrary to observations in the Atlantic Ocean where seafloor spreading was preceded by a long period of continental crustal extension. If continental rifting did take place in the Red Sea, it was of much shorter duration lasting less than 20 Ma ago, whereas in the Atlantic rifting may have lasted in places as much as 77 Ma. Rift basins in the Atlantic also rarely exceed 200 km (from basement hinge to basement hinge) in width, yet in the Red Sea the rift basin in places exceeds 400 km in width. The two regions also may vary in the tectonic style. In the Atlantic, continental separation appears to have been asymmetrical with the plane of separation between accomodating zones being located closer to the platforms opposing the half-grabens. Only in regions of facing half-grabens and grabens is the plane of separation located along the axis of the rift. In the Red Sea, however, the plane of separation delineated by the axial deep is along the axis of the rift. This would suggest that the Red Sea lost its assymetry during its evolution as described by Martinez and Cochran (1988).

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