HOW DID THE RED SEA EVOLVE?

(N.B.) C.V. HAS BEEN REMOVED

PROJECT SUMMARY

The Red Sea is an embryonic ocean formed as a result of north-northeastward separation of the Arabian plate from the African plate. It started opening about 25Ma. Geophysics and geochronology of dredged basaltic rocks indicate that sea-floor spreading began at only about 4-5Ma. It provides as one of the classical examples of basins formed due to lithospheric stretching and has been extensively studied. But there are many questions which are still unanswered.

Two main processes of rifting are in the literature today. Active rifting, driven by mantle plume, and passive rifting as a result of lateral extension of the lithosphere leading to reactive effects in the mantle. Some studies have considered active and passive rifting modes within the context of continuous rifting since some authors have suggested that a change from passive to active mode can occur during rifting. There remains insufficient knowledge of fundamental controls on rift architecture. More complete understanding of rift evolution is contingent upon detailed knowledge of timing, geometry and kinematics of extension.

The objective of this project is to look into details of rift tectonics, and to test the two main hypotheses in literature today - the Pure Shear and Simple Shear models. Both the models explain the evolution of Red Sea based on their observation but have inconsistencies as well. The work proposed here intends to look into those inconsistencies and see which of the two works better. Also, to see if both the models could be possible, but for different parts along the Sea. And to find a composite model that can account for the evolution of the whole of the Red Sea.

TABLE OF CONTENTS

Introduction

One of the intriguing problems concerning the evolution of oceanic lithosphere is the way it begins to form when the continents break and begin to drift apart. The Red Sea, which separates the African Plate from the Arabian Plate, is an embryonic ocean, evolving as the two plates drift away from each other. It therefore provides a good model for understanding continental break up and the development of passive margins and ocean ridges.

Offshore studies of well logs and geophysics have resulted in several models for the tectonic evolution of Red Sea that differ substantially in terms of timing and mechanism. In particular there is no widely agreed model for the relative timing of volcanism, doming, extensional basin initiation, and the formation of oceanic crust (Beydoun, 1989). There is basically no dispute about the last stage of evolution in the Red Sea: a small ocean basin is developing, having a well-organized seafloor spreading center in the southern axial trough. There are, however, substantial controversies about the initial stages of development of the main trough and the way the northern part of the basin is spreading.

Modern concepts of rifting and associated volcanism reduce to two models, one where mantle processes play an *active* role in rifting by adiabatic rise and decompression melting of a mantle plume head and one where decompression melting is a *passive* response to lithospheric stretching and isostatic uplift of the asthenosphere (Sengor and Burke, 1978; Bohannon et al., 1989; Dixon et al., 1989; Hart et al., 1989; White and Mckenzie, 1989). Within the regime of passive rifting, two different models have been proposed: Pure shear model, in which crust and mantle lithosphere are attenuated uniformly along any given vertical reference line (Mckenzie, 1970), and Simple shear model, in which relative extension of crust and mantle lithosphere along any given vertical line is nonuniform (Wernicke, 1981).

The objective of the work proposed here is to test the two hypotheses stated above by running geophysical surveys (seismic reflection, gravity and magnetic surveys), making detailed geological maps and drilling cores across the Red Sea.

General Geological Setting

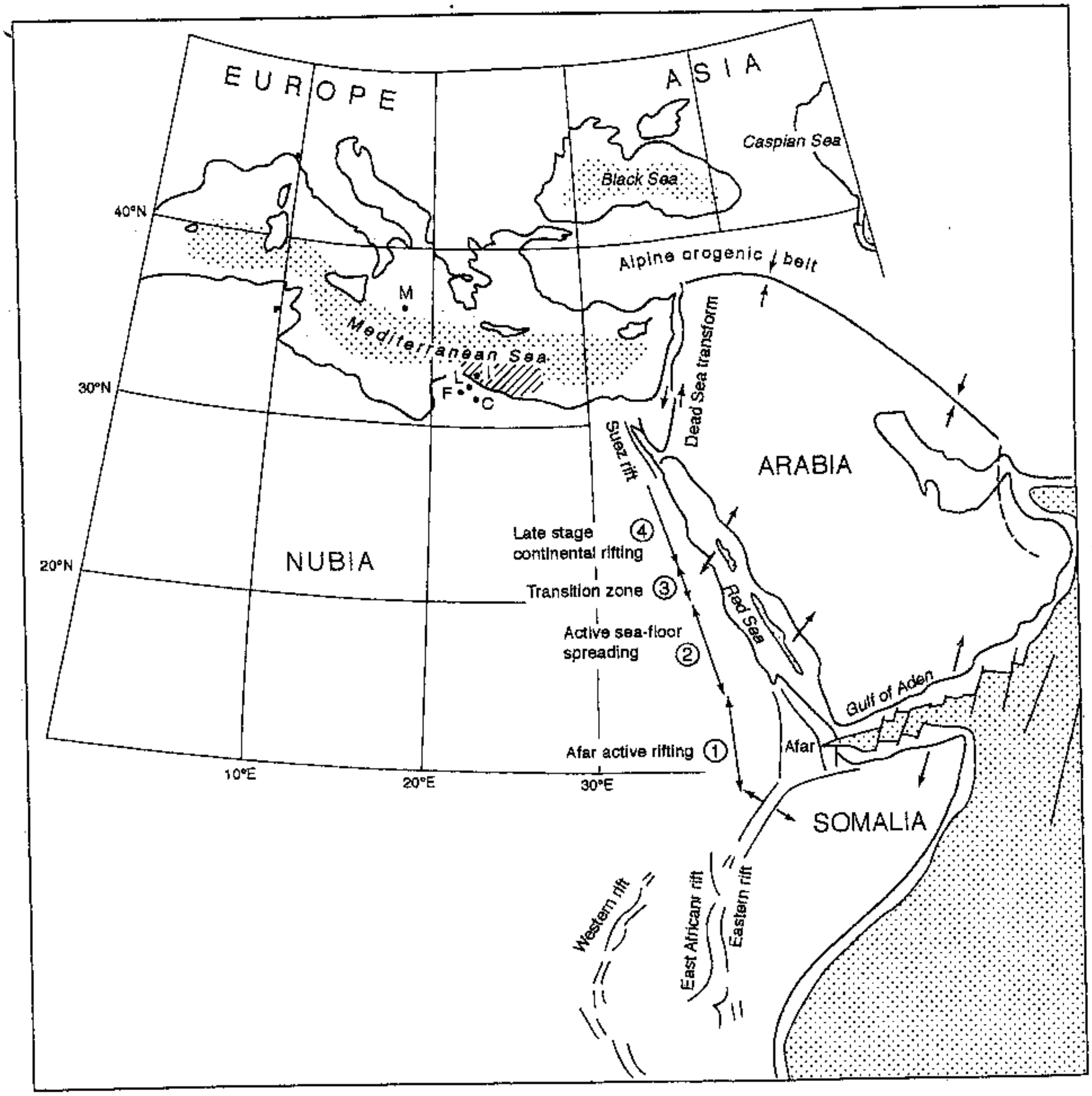

Fig 1: Physiography of Red Sea

In the north, the Red Sea bifurcates into the Gulfs of Suez and Aqaba, with the Sinai peninsula in between, and in the south joins Gulf of Aden. It occupies a long and slightly sinuous northwest-trending escarpment-bound basin, 250-450 km wide, between the uplifted shoulders of African and Arabian shields. Morphologically, the Red Sea consists of two shallow continental shelves on either side of a wide 'main trough' and narrow central 'axial trough'.

The Red Sea can be divided into three or four distinct zones each characterized by different morphology and structure which appear to represent different stages in the development of continental margin and establishment of a mid-ocean ridge spreading system (Cochran, 1983; Cochran et al., 1986). See Fig. 1. The zones are:

1. *Active sea-floor spreading (Southern Red Sea):-* It is characterized by a well-developed axial trough, which has developed through normal sea-floor spreading.

2. *Transition zone (Central Red Sea):-* In this zone, the Red Sea consists of a series of 'deeps' alternating with shallow 'intertrough zones' (Searle and Ross, 1975).

3. *Late stage continental rifting (Northern Red Sea):-* It consists of a broad trough without a recognizable spreading center, although there are a number of small isolated deeps (Cochran et al., 1986).

4. *Active Rifting:-* The future line along which the southern Red Sea is now due to propagate through the Danakil depression (Afar), may be added to the first zone.

Active and Passive rifts

The stresses responsible for rifting have been suggested to fall into a spectrum between two active and passive end members (e.g. Sengor and Burke, 1978). In the active model, deviatoric stresses responsible for rifting are imposed by upwelling mantle beneath the rift whereas passive rifting is caused by plate driving forces outside the immediate area of the rift. Volcanism precedes normal faulting and rifting in active rifts whereas the reverse holds for the passive rifts. The terms "active" and "passive" are used with respect to the mantle.

Tectonic models for the extension of the Red Sea

Many models have been proposed for the tectonic development of the Red Sea region prior to the present period of sea-floor spreading. Most of the models restricted the sea-floor spreading history to the last 10 Ma in the Gulf of Aden and to the last 5 Ma in the Red Sea.

Pure Shear Model by Mckenzie (Fig.2a)

He proposed that a period of diffuse extension prior to the beginning of sea-floor spreading is an essential part of rifting, i.e. rifting was a result of lithospheric extension by faulting followed by mantle upwelling to maintain isostatic equilibrium. He assumed that the crustal and lithospheric extension was the same (uniform stretching), the stretching being symmetrical, and hence satisfies the condition of pure shear.

Simple Shear Model by Wernicke (Fig 2b)

The model is based on a low-angle normal fault (detachment) of regional extent that breaks away at the surface on the African continent and projects to sub-lithospheric levels beneath the Arabian continent (Wernicke, 1985; Voggenreiter et al., 1988). Thus the extension is asymmetric both laterally and vertically. On the breakaway (footwall) side, deformation is intense at shallow crustal levels but crust and mantle deep beneath the detachment are not deformed. On the opposing side, the upper half of the lithosphere is undeformed whereas the deep lithosphere is highly extended by shear. This model also requires that the initial mantle upwelling be substantially offset from the surface position of the rift axis. As rifting proceeds the locus of mantle upwelling migrates up the dipping detachment surface to eventually coincide with the rift axis at the surface in the Red Sea. The position of the deep extension is eventually offset substantially from that at the surface.

Conclusions

Each of the Red Sea tectonic models makes predictions that the data may or may not support. As a result no single proven model explains the tectonic evolution of the whole length of the Red Sea. The discrepancies between the various models proposed suggests that the entire red Sea region is not tectonically homogeneous, but consists of segments with different tectonic histories and hence require combination of models.

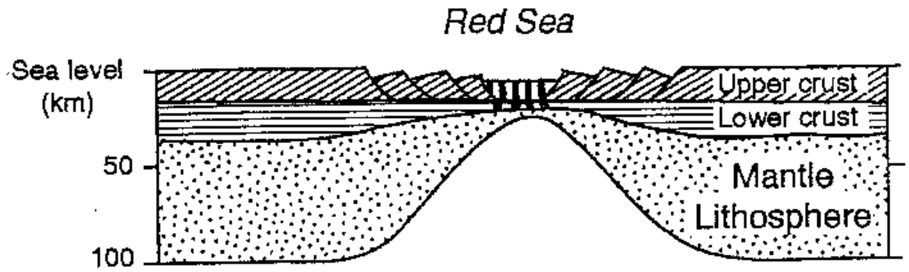

Fig 2a: Pure Shear Model by McKenzie

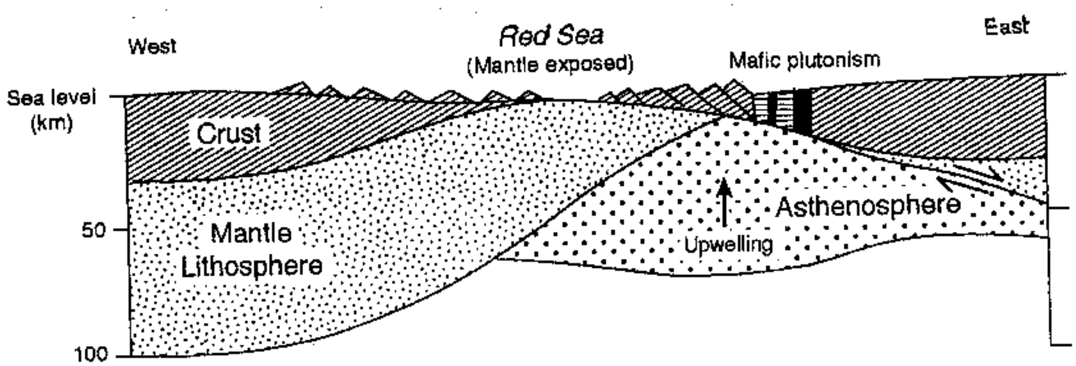

Fig 2b: Simple Shear Model by Wernicke

There is no general agreement about the timing of volcanism, uplift and extension implying that the Red Sea rifting was neither purely active nor purely passive.

Proposal

The work proposed here intends to test the two models discussed above. Both the models are based on real observations, but do not explain all of them. The Mckenzie model requires that the geological structures on either side should be correlatable. The heat flow pattern and seismicity be symmetric. The lithospheric thinning, which lifts a large amount of mantle, should result in a large amount of partial melting followed by rise of magma into thinned lithosphere.

The Wernicke model, on the other hand, requires that the geological structures, heat flow patterns, crustal thickness, etc be asymmetrical on either side of the Red Sea.

Thus the two models are based on totally different principles. To test them I propose the following:

1) Seismic reflection surveys across the length of the red Sea to look at the structure of the Moho and hence thickness of crust, configuration of deeper lithosphere to see where the maximum deformation took place. If Mckenzie model is correct, the deformation in the upper levels of crust should be intensely deformed on the breakaway side. Whereas as per the Mckenzie model, the deformation should be the same on either side. Also, at and along flanks of the ridge normal faults should be prevalent being symmetrical on either side.

2) Gravity Surveys across the ridge of the Red Sea to delineate the profile across the ridge axis. Also gravity anomaly curves would depict the nature of the crust underlying the ridge. If the Mckenzie model is to be believed, it should be oceanic crust symmetric about the axis. But there should be no oceanic crust at the ridge axis, if the Red Sea evolved as Wernicke proposed.

3) Magnetic surveys in different parts along the length of the Red Sea would help reveal the nature of sea floor spreading, i.e. whether its symmetrical or asymmetrical.

4) Mapping of geological structures on either side or then correlating them would help answers many questions. If the structures match reasonably well, it would provide a strong support for the Mckenzie model.

5) Drill cores in different part of the ridge to find out the heat flow pattern.

Plan of Study

I want to conduct my study over a period of three years, with three different field seasons each year. The first field session of each year would be to do seismic surveying and getting drill cores. This would be then followed by magnetic and gravity surveys. The third and last field session would involve geological mapping.

I would like to hire one of the faculties from the Louisiana State University specialized in Geophysical Exploration to help understand our results from the various surveys. Also, I intend to hire a couple of geologists from the local universities, who would have a profound knowledge about the geology of the area. I would hire undergraduate students to map the geological structures on either side of the Re Sea.

REFERENCES CITED

Allen, P. A., Allen, J. R., 1990. Bk Basin Analysis - Principles and Applications.

Beydoun, Z. R., 1989. The hydrocarbon prospects of the Red Sea - Gulf of Aden: A review, J. Petr. Geol., 12, 125-144.

Bohannon, R. G., 1986. Tectonic configuration of the western Arabian continental margin, Southern Red Sea. Tectonics 5 (4), 477-499.

Cochran, J. R., 1983. Model for development of the Red Sea. Am. Assoc. Pet. Geol. Bull. 67, 41-69.

Davison, I., Al-Kadasi, M., Al-Kihrbash, A., Baker, J., Blakey, S., Bosence, D., Dart, C., Heaton, R., McClay, K., Menzies, M., Nichols, G., Owen, L., Yelland, A., 1994. Structural Evolution of the southeastern Red Sea margin, Republic of Yemen. Geol. Soc. Am. Bull. 106, 1474-1493.

Dixon, T. H., Ivins, E. R., and Franklin, B. J., 1989. Topography and volcanic asymmetry around the Red Sea: Constraints on rift models. Tectonics, 8, 1193-1216.

Drake, C. L., Girdler, R. W., 1964. A geophysical study of the Red Sea. Geophysis. J. R. Astron. Soc. 8, 472-495.

Drury, S. A., Kelly, S. P., Berhe, S. M., 1994. Structures related to Red Sea evolution in Northern Eritrea. Tectonics 13, 6, 1371-1380.

Ghebraeb, W., 1998. Tectonics of the Red Sea region reassessed. Earth-Science Reviews 45, 1-44.

Girdler, M. E., Underwood, M., 1985. The evolution of early oceanic lithosphere in the northern Red Sea. Tectonophysics 116, 95-108.

Hart, W. K., Woldegabriel, G., Walter, R. C., and Mertzman, S. A., 1989. Basaltic volcanism in Ethiopia: Constraints on continental rifting and mantle interactions, J. Geophys. Res., 94, 7731-7748.

Khalil, S. M., McClay, K. R., 2002. Extensional fault-related folding, northwestern Red Sea, Egypt. Jour. Struc. Geol. 24, 4, 743-762.

Makris, M. J., Rhim, R., 1991. Shear-controlled evolution of the Red- Sea: pull-apart model. Tectonophysics 198, 441-466.

Makris, J., and Henke, C. H., 1992. Pull-apart evolution of the Red Sea. Jour. Pet. Geol. 15, (2), 127-134.

Mckenzie, D. P., Davies, D., Molnar, P., 1970. Plate Tectonics of the Red Sea and East Africa. Nature 226, 242-248.

Searle, R. C., Ross, D. A., 1975. A geophysical study of the Red Sea axial trough between 20.5 and 22N. Geophys. J. R. Astron. Soc. 43, 555-572.

Sengor, A. M. C., and Burke, K., 1978. Relative timing of rifting and volcanism on earth and its tectonic implications. Geophys. Res. Lett. 5, 419-421.

Steckler, S. M., Feinstein, S., Kohn, B. P., 1998. Pattern of mantle thinning from subsidence and heat flow measurements in the Gulf of Suez; evidence for the rotation of Sinai along-strike flow from the Red Sea. Tectonics 17, 6, 903-920.

Wernicke, B., 1985. Uniform-sense normal simple shear of the continental lithosphere. Can. J. Earth Sci. 22, 08-125.

White, R., and Mckenzie, D., 1989. Magmatism at rift zones: The generation of volcanic continental margins and flood basalts. J. Gephys. Res., 94, 7685-7729.

BUDGET

• Seismic Exploration	50,000/year for 5 surveys
• Other geophysical Explorations	50,000/year
• Travel to meetings	8000/year - for both domestic and foreign
• Publication charges	2000/year
• Salary of geologists	60,000/year - only for field seasons
• Salary of undergrad students	6000/year - only for field seasons
Total cost	176,000/year
Overhead	73,920
Total amount of this request	749,760 for three years.