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Magnetic Anomalies of the African Red Sea Shelf and Their Implications for the Anomalies of Atlantic Continental Margin

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Abstract: Marine geomagnetic measurements on the African shelf of the Red Sea between 17 and 19° N indicate a sea-floor spreading origin for this area. The spreading rates were somewhat lower than those found by Girdler and Styles for the more southern Red Sea but the crustal ages agree. Model computations require a magnetization much higher than normal for oceanic crust of the same age. Consequently, in the first stage of continental separation, crust with a higher magnetization may be produced. If this is true, it could lead to a better understanding of the slope anomalies which are found at the Atlantic continental margins.

Key words: Red Sea – Atlantic continental margin – Magnetic anomalies – Slope anomaly.

1. Introduction

The Red Sea consists of mildly deformed shelves and marginal zones and a deeper axial trough. A sea-floor spreading origin was soon accepted for the axial trough (Vine, 1966). The nature of the crust under the shelves and marginal zones remained doubtful until the discovery of extremely clear magnetic lineations in the area of the Dahlak Islands on the African shelf of the Red Sea (Girdler and Styles, 1974). So, at least partly, the shelves and marginal zones are created by sea-floor spreading, in accordance with the refraction seismic evidence that much more than the axial trough is underlain by crust with a seismic velocity which is characteristic of oceans (Davies and Tramontini, 1970).

During Valdivia cruise VA 01 in 1971, magnetic measurements were made over the axial trough and some parts of the shelves (Fig. 1). The results of the axial trough survey will be published elsewhere[1]. The measurements over the shelves were restricted to fairly small areas by the coral reefs which make navigation hazardous in most parts of the southern Red Sea. The region marked in Fig. 1 by the bold rectangle is the only one where a good coverage is possible. The reason for the absence of coral from only this region is not known. It is possible that the surveyed part of the shelf may be not typical, not only with regard to the present day topography but also with regard to its past history.

[1] Geologisches Jahrbuch, Reihe D, 1975.

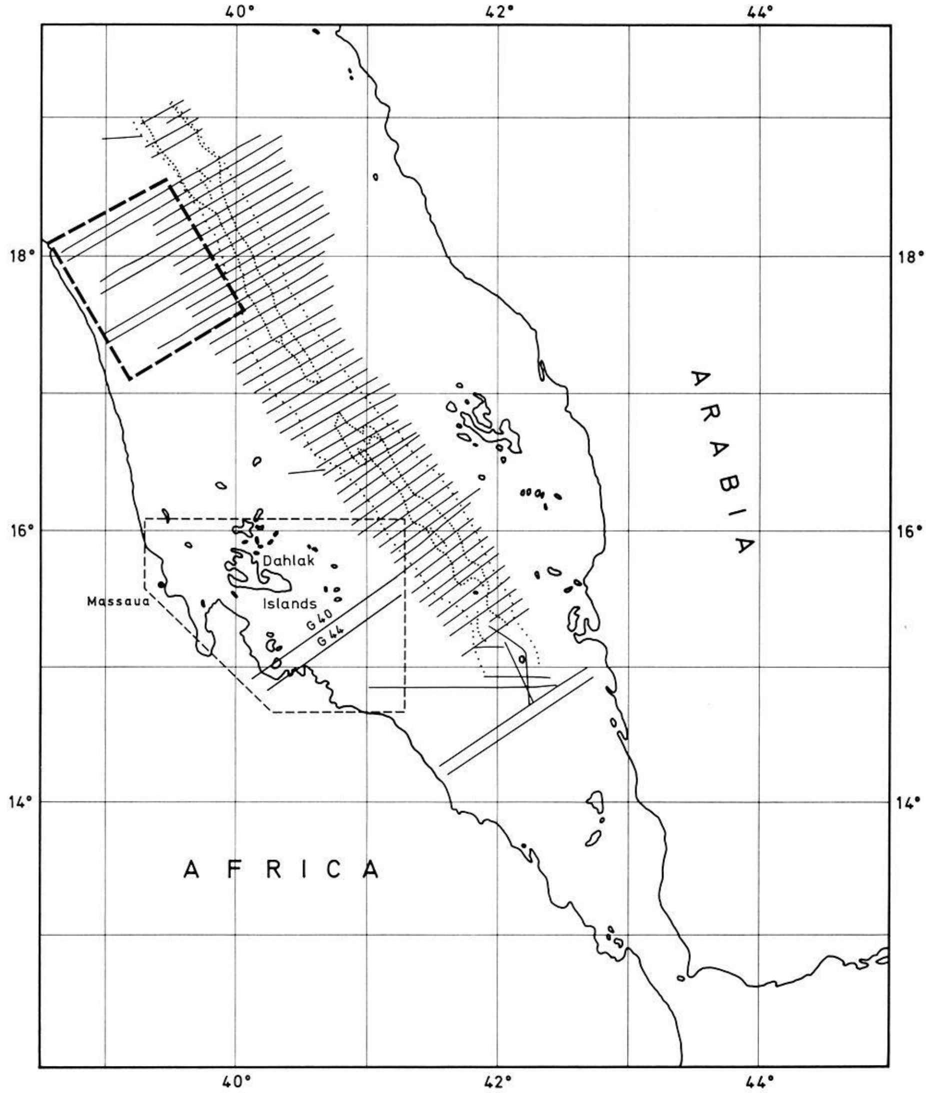


Fig. 1. Magnetic profiles of the Valdivia cruise VA 01 in the southern Red Sea (in 1971). Bold rectangle: area of Fig. 2. The dashed line near Massaua surrounds the area of the Gulf survey interpreted by Girdler and Styles (1974). The profiles G 40 and G 44 are included in Fig. 2. Dotted lines: Edges of the axial through and the axial rough zone

2. Sea-Floor Spreading Origin of the Crust under the Shelf Profiles

Fig. 2 shows the observed anomalies of the total intensity of the earth's magnetic field for the region of the bold rectangle of Fig. 1, and profiles G 40 and G 44 (latitude 15° to 15°40′ N, see Fig. 1) of Girdler and Styles (1974) which are plotted at the proper scale and distance from the Red Sea axis (only shifted

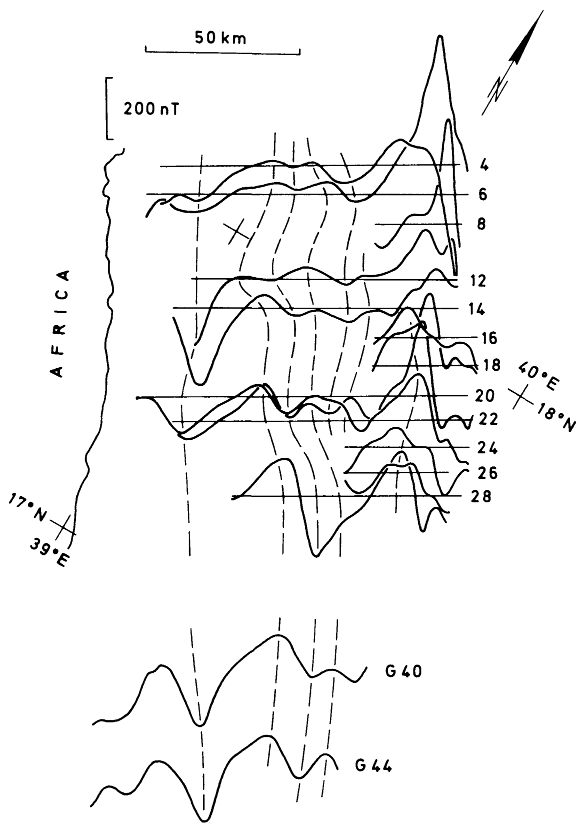


Fig. 2. Magnetic anomalies along the Valdivia profiles on the African shelf. The profiles are slightly straightened. G 40 and G 44: Profiles adapted from Girdler and Styles (1974). These profiles are shifted northwestward along the axis of the Red Sea

along the axis). It is not only possible to identify the anomaly sequence of Girdler and Styles but also is apparent that the distances from the Red Sea axis agree. Hence, the observed anomalies are probably of sea-floor spreading origin, and the crust in this area is of the same age as that under the Dahlak Islands.

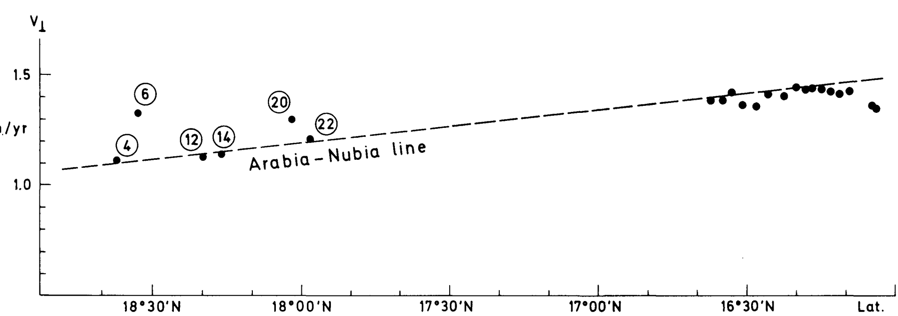


Fig. 3. Spreading for the Valdiva profiles and the northern part of the profiles of Girdler and Styles (1975). The "Arabia-Nubia" line shows the spreading-rates which could be expected for the separation of Arabia and Nubia (Girdler and Styles, 1975). Encircled numbers: Profile numbers of the Valdiva profiles

Spreading rates can be calculated using the anomaly ages determined by Girdler and Styles (1974) (Fig. 4, models). The rates are shown in Fig. 3 together with the "Arabia-Nubia" line of Fig. 8 of Girdler and Styles (1975). The scatter of the spreading rates of the Valdivia profiles is caused by the apparent irregularity of the sea-floor spreading process in this area. All spreading rates are less than those which Girdler and Styles found for the same anomalies between 16° and 16°40′ N. Although the pole or rotation for the Arabia-Nubia line is not exactly confirmed, it is clear that the spreading rate at 17° N is significantly smaller than that observed by Girdler and Styles (1975) at 16.5° N.

3. Analysis of the Anomaly Amplitude

Typical oceanic crust consists of a more or less thick layer of sediments ("layer 1") overlying "layer 2" which has a mean thickness of 1.4 km and seismic velocities between 3.4 and 6.0 km/sec. Underneath is "layer 3" which is about 4.7 km thick and has a median velocity of 6.8 km/sec (Fig. 7–8 of Wyllie, 1971). The lower boundary of layer 3 is the Moho discontinuity. Talwani *et al.* (1971) modified this model. They divided layer 2 into an upper part 2A (0.4 km thick) and a lower part 2B and stated that only layer 2A is strongly magnetized whereas layer 2B and layer 3 are magnetized so weakly that they do not contribute significantly to the observed magnetic anomalies.

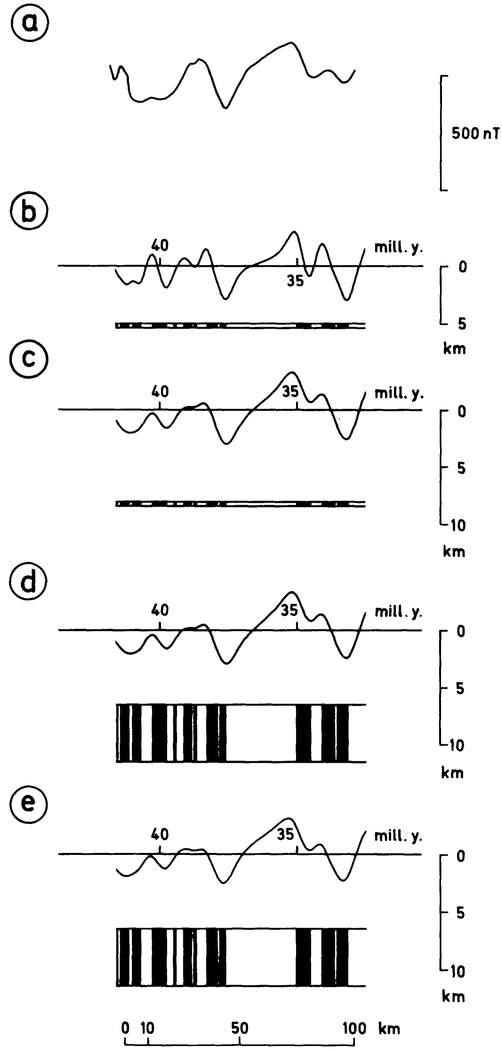
The model computations (Fig. 4) deal with profile G 40 (Fig. 4a) of Girdler and Styles (1975) instead of our profiles which are not regular enough. With one exception, the dip of the remanent magnetization is assumed to be 30° (the dip of the field of a centred dipole directed along the axis of rotation of the earth). The reversal time scale is that of Heirtzler *et al.* (1968).

According to the borehole data which Girdler and Styles (1975) report, the surface of layer 2A lies about 5 km below the survey level. With a magnetization of $\pm$ 20 amp/m ("+" and "−" mean parallel and antiparallel, respectively, to the field of a centred dipole) we get the model curve of Fig. 4b whose amplitudes are similar to those of the observed profile. The anomaly character is much different as the peaks of the model curve are too sharp. Fig. 4c matches the anomaly character better; here, the surface of layer 2A is assumed to be 8 km deep and the necessary magnetization is ± 40 amp/m.

This apparent depth discrepancy is encountered in the interpretation of many surveys of *old oceanic crust*. Cox and Blakely (1973) suggested that perhaps not only layer 2A is magnetized but also layer 3. For young oceanic crust the magnetization of layer 2A would dominate, but when the crust gets older the magnetization of this layer would decrease fairly soon whereas the magnetization of layer 3 would be more stable. The result would be that the main sources of the magnetic anomalies would lie much deeper than the surface of layer 2.

Thus the next model (Fig. 4d) assumes a magnetization of ± 3.5 amp/m for rocks at depths between 6.5 and 11 km (the depth range of layer 3). This magnetization value is near the upper limit which is possible for layer 3 (4 amp/m) according to the extensive model calculations for the anomalies of the central trough of the Red Sea (Roeser, 1975). The model matches the amplitude as

Fig. 4. Models for profile G 40 of Girdler and Styles (1975). (a) Observed profile; (b–e) All models use the Heirtzler time scale (Heirtzler *et al.*, 1968), spreading rates are 1.2 cm/year, declination 0°. (b) Layer 2A model: Magnetic layer of thickness 400 m with its surface in 5 km depth; magnetization ±20 amp/m, dip 30°; (c) Layer 2A model: Magnetic layer of thickness 400 m with its surface in 8 km depth; magnetization ±40 amp/m, dip 30°; (d) Layer 3 model: Magnetic layer of thickness 5 km with its surface in 6.5 km depth; magnetization ±3.5 amp/m, dip 30°; (e) Layer 3 model: Magnetic layer of thickness 5 km with its surface in 6.5 km depth; magnetization ±4 amp/m, dip 15°



well as the character of the observed curve. The curve form is somewhat different. Assuming a smaller dip of the magnetization (15°) would make the model curve more similar to the observed curve (Fig. 4e). There are serious arguments, however, against layer 3 contributing to the magnetic anomalies resulting from seafloor spreading (Vine and Wilson, 1965; Vine and Moores, 1974; Roeser, 1975).

A difference between the character of an observed curve and that of its computed model exists also for *young oceanic crust* (Matthews and Bath, 1967; Talwani *et al.*, 1971 (Fig. 8); and Roeser, 1975 (Fig. 4)). Generally it is barely noticed because it is overshadowed by other problems. Also, the anomaly scale (cm per nT) is commonly chosen so large that the differences can hardly be seen.

Therefore, it seems more probable (although it cannot be proved) that layer 2A (at 5 km depth) produces the observed anomalies. The magnetization of

20 amp/m necessary for this model (Fig. 4b) is surprisingly high. Talwani *et al.* (1971) calculated 7 to 12 amp/m for oceanic crust 8 to 10 million years old.

Only for the central block of the ridge did they find 30 amp/m. In the Red Sea axial trough, the necessary magnetization for a 0.4 km thick layer at a depth of 2 km is 20 amp/m, for the older parts (4 to 5 million years old) possibly somewhat less. In part, the central block has higher magnetization. These values are in accordance with those of Talwani *et al.* (1971). Thus in the second stage of spreading of the Red Sea floor, the magnetization values are not significantly higher than those of the Reykjanes Ridge, for example.

For the first stage, the model calculations indicate that more magnetic material or material of higher magnetization was produced than the model of Talwani *et al.* (1971) predicts. Furthermore, the magnetic stability must have been high enough to preserve a considerable part of the magnetization for more than about 35 million years.

4. The Magnetic Anomalies of the Continental Slopes of the Atlantic Ocean

The geophysical processes at the beginning of sea-floor spreading are not known. Until now, we have attempted to extrapolate the processes which are observed at the midoceanic ridges to the whole spreading history. However, it is quite clear that this extrapolation must be modified at the very beginning of the sea-floor spreading as it should make a difference whether or not the mantle material comes up in the immediate neighbourhood of continental crust. The Red Sea is at an early stage of sea-floor spreading. Consequently, it is easier to study all those problems which can be investigated at the Atlantic continental margins only with great difficulty because of the great depth to layers 2 and 3. One important problem concerns the nature of the strong magnetic "slope anomalies" of many parts of the Atlantic Ocean continental margins. Even today, 20 years after the discovery of the slope anomaly along the United States Atlantic coast by Keller *et al.* (1954), it is a matter of dispute whether the slope anomaly lies over crust of continental or oceanic origin.

5. The Origin of Slope Anomalies

Seaward, the slope anomalies are often followed by smaller amplitude anomalies or magnetic quiet zones. At least in some cases the low amplitude anomalies are due to magnetic aging and the great depth of the magnetic horizon. This is a possible argument against a sea-floor spreading of the slope anomaly. The data from the Red Sea shed new light on the problem of why the slope anomaly is so much greater than the anomalies immediately seaward of it. In the area of the Dahlak Islands, an extremely clear sea-floor spreading pattern is found. The absence of any disturbance shows that no continental fragments are included in the crust. Real oceanic crust and not a transitional type of crust has been formed. The spreading process lasted only for a few million years. During this time, crust with a higher than normal magnetization was produced. The amplitudes of the anomalies over the present axial trough are quite normal for young crust produced by sea-floor spreading. This may indicate that crust with normal magnetic properties would have been produced had the former episode of spreading continued. If so, the picture which we observe at the Atlantic continental margins could have been produced, that is, a 50–100 km broad strip with mostly one or two strong anomalies, and smaller amplitude anomalies on the seaward side of the strip.

The symmetry between some parts of the African and the United States coastal anomalies (Roeser *et al.*, 1971) is in agreement with the above concept. Also, the different form of the slope anomalies along the different shelves would be readily explained: As the breakup of Gondwanaland did not start at the same time on the whole length, we must expect different anomaly configurations to have formed.

Of course, it is speculative to draw such far-reaching conclusions from the data of a small area of the Red Sea shelf. However, this speculation is justified by the probability that now and for the next years there will not be much better information on this problem which is of great scientific relevance.

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References

Allan, T.D.: Magnetic and gravity fields over the Red Sea. Phil. Trans. Roy. Soc. London Ser. A **267**, 153–180, 1970

Cox, A., Blakely, R.J.: Identification of short polarity events from marine magnetic anomalies. Paper presented at the second general scientific assembly of the International Association of Geomagnetism and Aeronomy, Kyoto 1973

Davies, D., Tramontini, C.: The deep structure of the Red Sea. Phil. Trans. Roy. Soc. London Ser. A **267**, 181–189, 1970

Girdler, R.W., Styles, P.: Two stage Red Sea floor spreading. Nature **247** (5435), 7–11, 1974

Girdler, R.W., Styles, P.: The relevance of magnetic anomalies over the southern Red Sea and Gulf of Aden to Afar. In the press, 1975

Heirtzler, J.R., Dickson, G.O., Pitman III, W.C., Herron, E., Le Pichon, X.: Marine magnetic anomalies, geomagnetic field reversals, and motions of the ocean floor and continents. J. Geophys. Res. **73** (6), 2119–2136, 1968

Keller, F.J., Meuschke, L., Alldredge, L.R.: Aeromagnetic surveys in the Aleutian, Marshall and Bermuda Islands. Trans. Am. Geophys. Union **35** (4), 558–572, 1954

Matthews, D.H., Bath, J.: Formation of magnetic anomaly pattern of Mid-Atlantic Ridge. Geophys. J. **13** (1/3), 349–357, 1967

Roeser, H.A.: A detailed magnetic survey of the southern Red Sea. Geol. Jahrb. D, in the press, 1975

Roeser, H.A., Hinz, K., Plaumann, S.: Continental margin structure in the Canaries. In: The Geology of the East Atlantic Continental Margin (ed. F.M. Delany). Inst. Geol. Sci. Rpt. No. 70/16, 27–36, 1971

Talwani, M., Windisch, C.C., Langseth, M.G., Jr.: Reykjanes Ridge crest: a detailed geophysical study. J. Geophys. Res. **76** (2), 473–517, 1971

Vine, F.J.: Spreading of the ocean floor: New evidence. Science **154** (3755), 1405–1415, 1966

Vine, F.J., Moores, E.M.: A model for the gross structure, petrology, and magnetic properties of oceanic crust. In: Studies in earth and space sciences, 195–205. Geol. Soc. of Am., Boulder, Colorado, 1972

Vine, F.J., Wilson, J.T.: Magnetic anomalies over a young oceanic ridge off Vancouver Island. Science **150** (3695), 485–489, 1965

Wyllie, P.J.: The Dynamic Earth: Textbook in Geosciences, 416 p., New York, London, Sydney, Toronto: John Wiley & Sons, Inc. 1971

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