PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES

An Aeromagnetic Survey of the Junction of the Red Sea, Gulf of Aden and Ethiopian Rifts -- A Preliminary Report [and Discussion]

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Phil. Trans. R. Soc. Lond. A 1970 **267**, 359-368
doi: 10.1098/rsta.1970.0041

Phil. Trans. Roy. Soc. Lond. A. **267**, 359–368 (1970) [359]
Printed in Great Britain

An aeromagnetic survey of the junction of the Red Sea, Gulf of Aden and Ethiopian rifts—A preliminary report

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An aeromagnetic survey over the junction region of the Gulf of Aden and Red Sea fault troughs was carried out from February to April 1968. A brief geophysical and geological background to the survey is given. The planning of the survey is discussed and a summary of the main results is given.

1. Introduction

In 1965, a proposal was made to the British Upper Mantle Panel that an aeromagnetic survey should be made over the critical junction region of the Gulf of Aden, Red Sea and Ethiopian rifts. The region (shown in figure 1) is of special interest as it is one of the places where the oceanic rift system intersects a continental landmass.

Most of the region is low lying, some of it being below sea level. It is formed by the westward extension of the Gulf of Aden trough and the southward extension of the Red Sea trough (figure 1). The Gulf of Aden has oceanic structure (Laughton *et al.* this volume, p. 227). This has been deduced from the presence of positive Bouguer gravity anomalies, large magnetic anomalies and the fact that all seismic refraction profiles (figure 1) give velocities appropriate to oceanic crust. The seismicity and magnetic anomalies indicate a sea-floor spreading mechanism for its evolution.

The southern part of the Red Sea is much more complicated. Seismic refraction profiles (figure 1) indicate there are some areas where there is continental crust. In addition, there are some regions with large thicknesses of evaporites which obscure the underlying structure. The evidence to date suggests that in this region there is a mixture of continental and oceanic crust (Drake & Girdler 1964; Girdler 1969).

The geological history of the region is dominated by the fact that there was a land barrier in the neighbourhood of the Straits of Bab el Mandeb until about 6 or 7 Ma ago cutting off the Red Sea from the Gulf of Aden and Indian Ocean. Before this time, the Red Sea was open to the Mediterranean via the Gulf of Suez and the greatest build up of evaporites through the Miocene occurred in the closed southern part of the Red Sea.

At the southern end of the Red Sea, there has been much basaltic volcanism and there are still active centres (figure 1). The total crustal separation in this region perpendicular to the Red Sea axis has been estimated as 240 km at 14.5° N (Girdler 1966). Sialic crust is known to be present, for example, the Danakil horst. It seems that fragments of crust were left behind when Africa and Arabia broke up and separated.

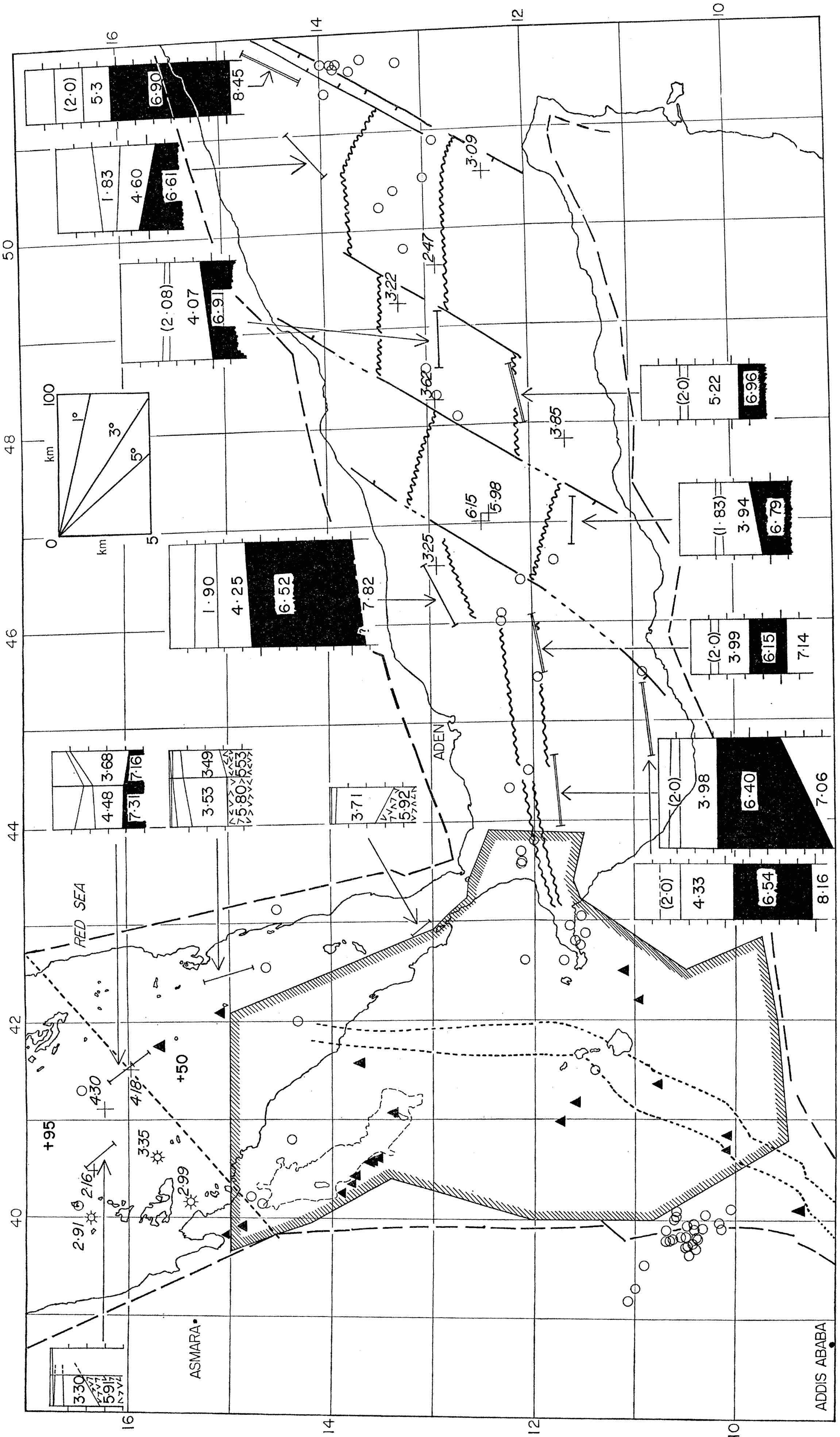

FIGURE 1. The location of the survey area at the junction of the Red Sea and Gulf of Aden. Other information includes the location of volcanic centres (▲), the location of earthquake epicentres (○), heat flow measurements and seismic refraction profiles. The dashed lines across the survey area mark the position of Mohr's 'Wonji fault belt'.

2. Objectives of the survey

The present survey had the following objectives:

First, it is known that large magnetic anomalies with amplitudes of several hundreds of nanoteslas (gammas) continue east–west from the Gulf of Aden into the Gulf of Tadjoura (Girdler & Peter 1960; Laughton *et al.*, this volume, p. 227). These anomalies are typical of the axial rift zone in the sea floor and the question arises as to what happens to them over the neighbouring land to the west.

Secondly, the deep, axial trough of the Red Sea also has associated magnetic anomalies (Drake & Girdler 1964) and it is not known what happens to these south of latitude 15° N where the Red Sea narrows. It is also not known, if, how and where these anomalies join with the Gulf of Aden anomalies.

Thirdly, the results of marine magnetic surveys over the last ten years have shown the oceanic crust to have magnetic anomalies of a very different character from the continental crust. It should therefore be possible to map the locations of relics of continental crust in the region.

3. Previous surveys

In 1966, U.S. *Project Magnet* flew about 4700 km of track based on Aden. This was in the form of eight profiles, seven parallel to the southwestern Red Sea shore with an average spacing of 90 km and one at right angles. The profiles (total field) were flown at different heights, the heights increasing from the sea, inland. Copies of the magnetometer records were made available and these were read and plotted on topographic maps. A summary map is shown in figure 2 where all the profiles are reduced to the same scale and are plotted together with an earlier *Project Magnet* profile across the Gulf of Aden and Somalia.

The survey is of value in that several tracks extend over the neighbouring plateau areas. It is seen that the magnetic field over these areas is very different in character from the magnetic field over the low lying junction area. The magnetic field is either very smooth or has high-frequency anomalies. The survey also reveals the existence of impressive long wavelength anomalies over the low lying area which are similar in character to the anomalies over the Gulf of Aden. The spacing of the profiles makes it difficult to establish any magnetic trends and this was one of the main objectives of the present survey.

4. Planning the survey

The flight plan for the present survey is shown in figure 3. Permission was granted to fly over Ethiopia and Afars and Issas but not over Somalia or the Yemen. The total length of track is nearly 24 000 km.

In the southern half, the main flight direction was 150° N which was chosen for mapping the possible extension of the Gulf of Aden ENE trending anomalies and for revealing possible NE transform faults. In the northern half, the main flight direction was 100° N which was chosen for mapping three possible trends: the NW Red Sea trend, the ENE Gulf of Aden trend and the NE transform fault trend. The arrangement of the two flight directions allowed for very good coverage of the region north of the Gulf of Tadjoura where it seemed possible the Gulf of Aden and Red Sea magnetic trends might intersect. It was expected the magnetic

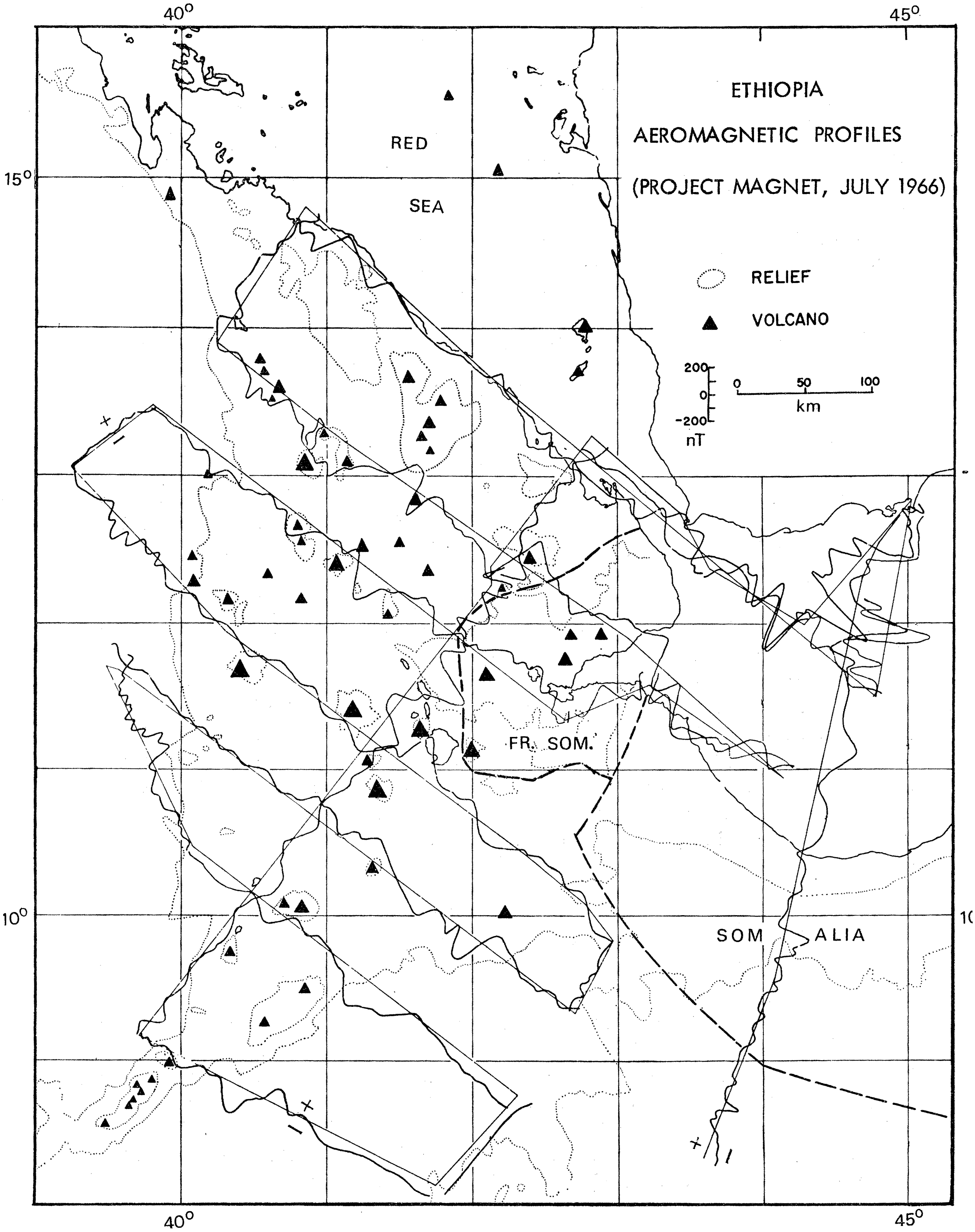

FIGURE 2. Map showing the total intensity magnetic profiles of *Project Magnet* together with volcanic centres (▲).

anomalies might here be very complicated. It turned out that the magnetic pattern in this region is surprisingly simple.

All flying was at a height of 1.83 km (6000 ft) and the flight line spacing was nearly always 10 km with 15 tie lines. Each flight line has a positional accuracy of ± 0.5 to 1.0 km.

The survey was flown by Hunting Geology and Geophysics Ltd using a DC 3 aircraft. The scientific equipment included a Gulf Mark III fluxgate magnetometer, radio-altimeter, synchronous survey camera and Doppler recorder. Most of the survey was flown from February to April 1968 from Djibouti where the time variations of the magnetic field were monitored.

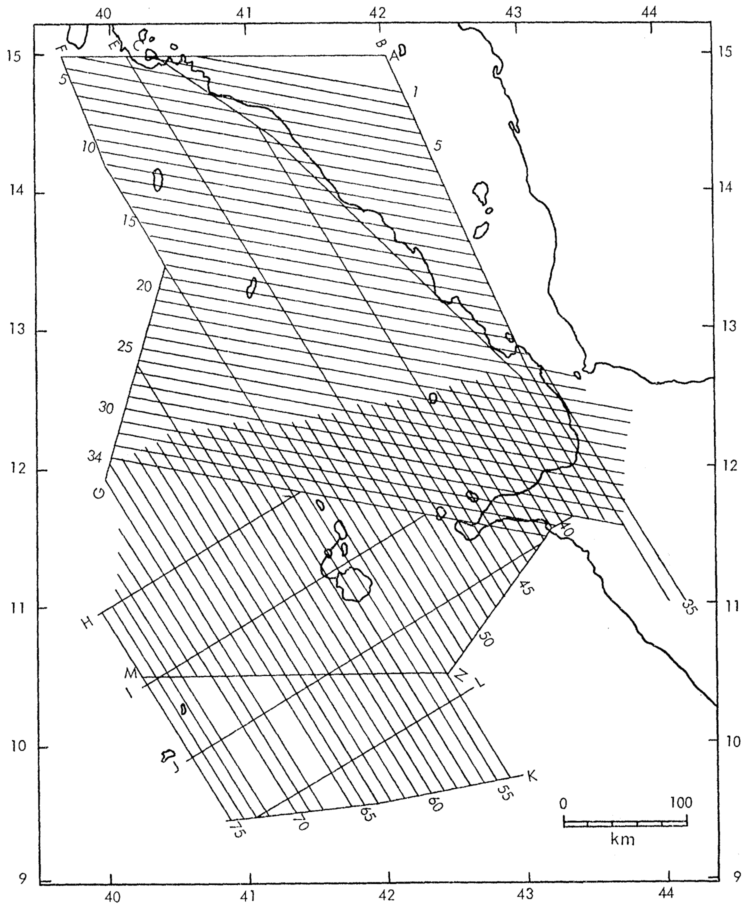

FIGURE 3. Flight plan of the aeromagnetic survey flown from February to April 1968.

5. MAIN RESULTS

Two total intensity magnetic anomaly charts, dividing the region at 12.5° N were prepared with contour interval 50 nT (gammas) and scale 1:500 000. The charts are too large to reproduce here and the main results are summarized in figures 4 and 5.

In figure 4, the magnitudes of the anomalies are presented in histogram form. The peak to trough amplitude is commonly 400 nT (flight height 1.83 km) and the largest maximum anomaly is greater than 500 nT and the largest minimum is more than 1000 nT.

Of greatest interest is the trends of these anomalies. These are presented in summary form in figure 5 which has been prepared from the large charts by drawing lines of maxima and minima through the peaks and troughs. The main anomalies are shown by solid lines. The broken lines indicate weak or discontinuous anomalies. In the extreme north, the trends from a neighbouring survey by the Gulf Oil Company have been included.

The map reveals three interesting features:

(*a*) South of 12.75° N (which is approximately the western extension of the northern margin of the Gulf of Aden) the anomalies are most impressive and continue westwards from the Gulf of Aden to intersect the north–south rift scarp in the west. The earthquakes also lie along this trend and it is interesting to compare figure 5 with figure 8 of Fairhead & Girdler (this volume p. 56).

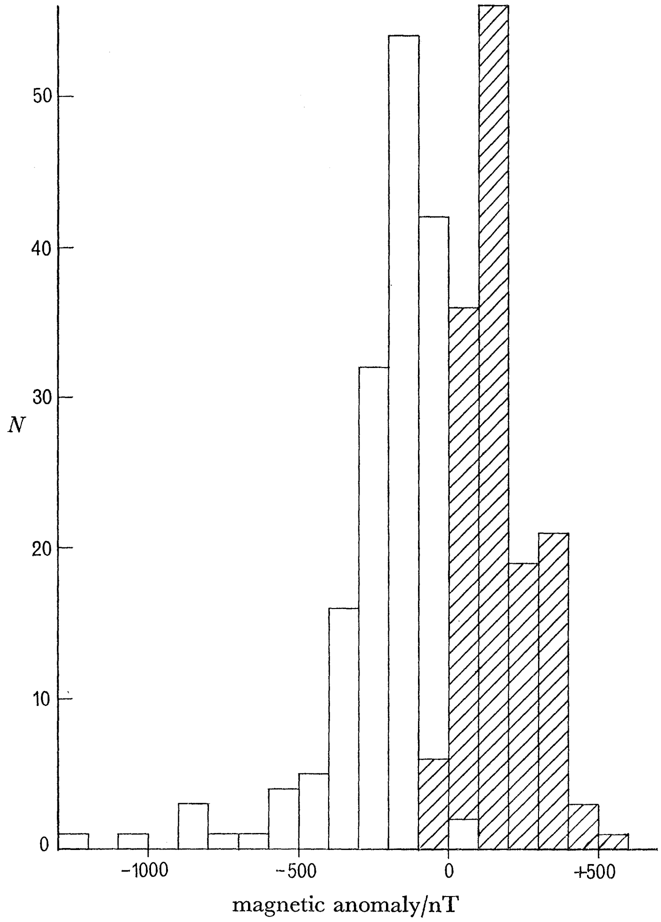

FIGURE 4. Histogram of the magnitudes of the magnetic anomalies mapped from a flight height of 1.83 km. ▨, Positive anomalies; □, negative anomalies.

(*b*) North of 12.75° N, the anomalies are less impressive and trend NW rather than parallel to the NNW Red Sea trend.

(*c*) It is seen that there are some areas which are relatively void of large anomalies, the most impressive being at about latitude 14° N and corresponding in part to the Danakil horst.

The survey data are now being digitized for computer studies. The anomalies will be studied in profile form and a much fuller report of the results of the survey will appear later.

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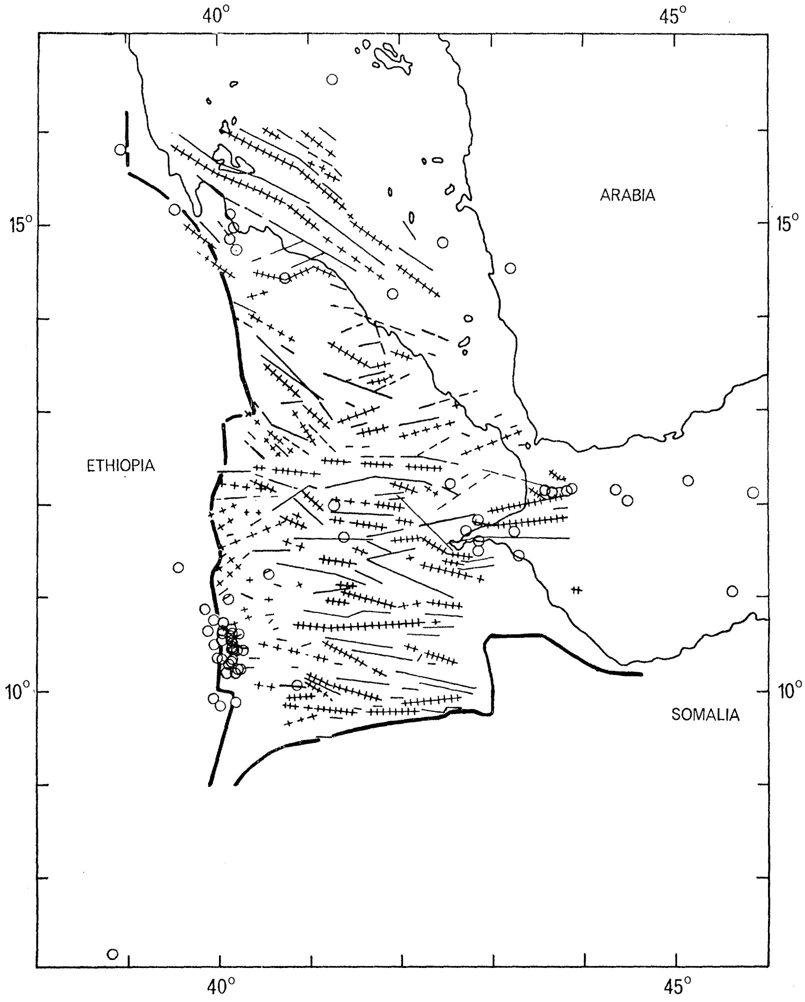

Figure 5. Map showing the main magnetic trends throughout the region together with earthquake epicentres for January 1955 through June 1968 (○). ———, present scarp line; ┼┼┼┼, trend of maximum magnetic anomalies; ——, trend of minimum magnetic anomalies.

I am most grateful to Dr H. Stockard of the U.S. Naval Oceanographic Office for making available the *Project Magnet* data and to the Gulf Oil Company for their data. I am also very grateful to Dr David Boyd and Mr Derek Morris of Hunting Geology and Geophysics Ltd for their patient help in planning the survey which was financed by the Natural Environment Research Council.

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Discussion

I. L. Gibson (*University of Leeds*). In attempting to explain the observed pattern of magnetic anomalies in Afar, Dr Girdler postulates above that the formation of the essentially oceanic crust in Afar has taken place in two important stages. While evidence of the sediment distribution in the Gulf of Aden (Laughton *et al.* this volume, p. 227) does suggest that the motion of Arabia was discontinuous, there is no evidence which indicates that the direction of movement has changed significantly. The transform faults which accommodated both the older and the more recent movements are approximately linear features.

In seeking an alternative explanation for the magnetic anomaly pattern in Afar, it is perhaps relevant to emphasize that this is an embryonic oceanic region. The pattern of seafloor spreading may thus depart from the model derived from the study of mature mid-oceanic ridge systems

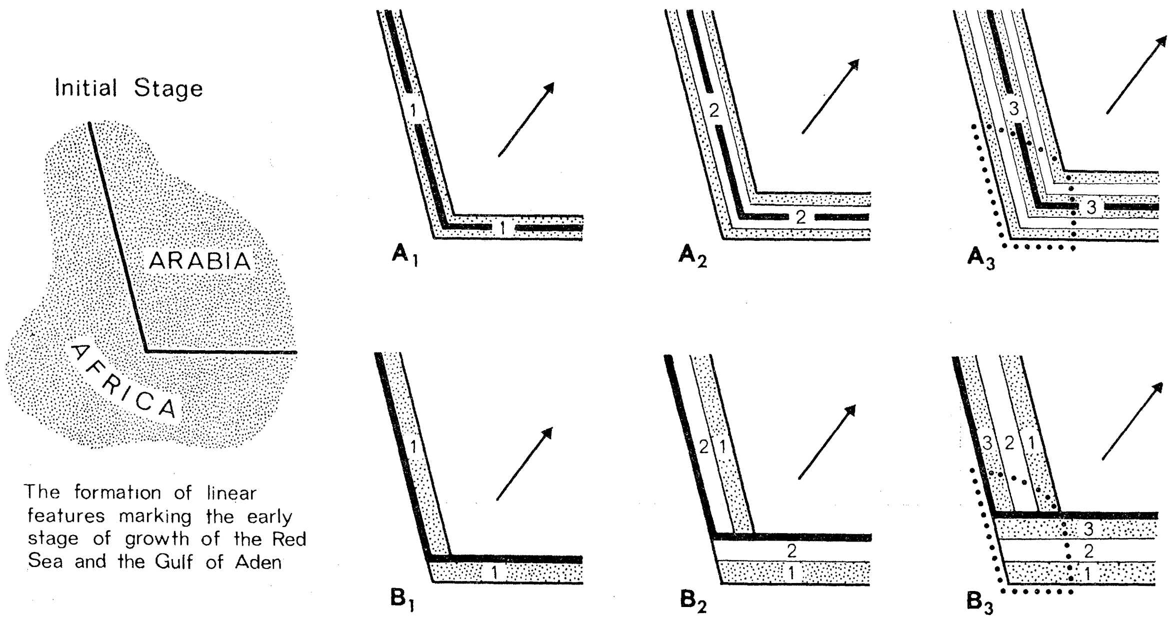

Figure 6. Two possible models for the formation of the magnetic anomalies in Afar. In both models three stages in the development are shown and in both cases Afar is shown as the region bounded by the dotted line at the junction of the 'Red Sea' and 'Gulf of Aden'. Model A: the zone of generation of new crust occupies a central position between the continental blocks. Model B: The generation of new crust occurs only on one side of each axial zone. The arrows are intended to indicate the direction of movement of Arabia relative to Africa which is assumed fixed.

such as the Mid-Atlantic Ridge. Laughton *et al.* (this volume) have noted two important ways in which the initial stages of spreading in the Gulf of Aden are unusual. The axial anomaly is not normal to the transform faults and does not occupy a central position within the growing region of oceanic crust. When these two factors are considered, an alternative explanation for the magnetic anomaly pattern in Afar becomes possible, involving only one movement direction for Arabia relative to Africa.

Two simple models for the formation of the Afar region, both involving the separation of Africa and Arabia in a constant direction, are considered. The models only involve two major crustal blocks; the aeromagnetic map shows that the size and perhaps the importance of the Danakil and Aisha Horsts may have been over-emphasized. Relative movement along the

Ethiopian Rift is also ignored, as it is small in comparison with the amount of opening in the Gulf of Aden and the Red Sea.

In the first model (A in figure 6) Arabia is assumed to have moved in a NNE direction away from Africa with new oceanic crust forming progressively. The zone of generation of new crust occupies an approximately central position in the new oceans. Three stages in the development are shown.

The second model (B in figure 6) involves the separation of Africa and Arabia in the same sense and direction as in the first model. However, in this case the zone of generation of new oceanic crust is away from the central region. The E–W trending zone of growth is assumed to occupy a position close to the Arabian block, with crustal growth taking place only on the southern side, whereas the NNW trending zone is assumed to be close to the African block with growth only on the eastern side. It can be seen that the pattern of anomalies produced by this second model is very different. Here a series of E–W trending anomalies characterize the southern part of the region, while NNW trending anomalies occur to the north.

As noted, Laughton *et al.* (this volume, p. 227) have already shown that the Sheba Ridge is displaced laterally towards the north in the sense postulated in model B above. Hutchinson & Engels (this volume, p. 313) have emphasized the asymmetric nature of northern Afar and the particular significance of the western marginal area. These observations and the agreement between the observed magnetic anomalies and model B pattern suggest that lateral asymmetry could well be a significant feature in the development of this embryonic oceanic area.

R. W. Girdler (*written reply*). The two models (A and B) proposed by Dr Gibson both give rise to anomaly patterns which differ from the observed (figure 5). Further, it is difficult to see how model B works; it is to be expected that asymmetric spreading in the Red Sea should be consistent with that in the Gulf of Aden, i.e. if the new crust in the Gulf of Aden is evolving in the north, the new crust in the Red Sea should be evolving in the *east* (assuming, as Dr Gibson does, only two plates and the vector shown in figure 6B).

It should be noticed that the Gulf of Aden and Red Sea are only slightly asymmetric. The epicentres in the Gulf of Aden are slightly to the north of centre and in the Red Sea *possibly* just to the east of centre (Fairhead & Girdler, this volume, figures 8 and 9, pp. 56 and 58). Magnetic anomalies (Laughton *et al.* this volume) are observed on both sides of the seismically active zone and there is no justification for Dr Gibson's assumption that the zone of growth occupies 'a position close to the Arabian block'.

In seeking a full explanation of the magnetic anomaly patterns in Afar, several possibilities have to be considered. A full discussion of these will appear in the final report of the survey, but as they were mentioned in the lecture and Dr Gibson picks on one of them, it seems worthwhile to list them here.

First, the seismicity of the region helps to define where new crust is forming and from this and the magnetic anomalies, it seems the main feature is the Gulf of Aden trend and its westward extension across Afar.

Secondly, the possibility of three discrete plates (Arabia, Nubia and Somalia) must be considered and the relationships of the Red Sea and Gulf of Aden troughs to the Kenya–Ethiopia rift (omitted from Dr Gibson's diagrams).

Thirdly, it can be shown that the pole of rotation for Arabia–Nubia differs from the pole for Arabia–Somalia by at least 10° (Fairhead & Girdler, this volume, figures 16 and 17, p. 69).

This is not insignificant. It implies that the spreading direction in the southern Red Sea differs from that in the Gulf of Aden by about 17°. This is a little less than the observed differences of about 21° and deserves more careful study.

Fourthly, there is the possibility (criticized by Dr Gibson) that the direction of movement between the pairs of plates may have differed before and after the well-established quiet period of about 15 Ma throughout much of the Miocene. Although this is possible, it seems unlikely to be very important for mechanical reasons. Further, although we express caution concerning the fault-plane solutions, it *may be* significant that the *recent* fault movements near the centre of the Red Sea are consistent with the pole deduced from the fit of the shorelines. This suggests that the *direction* of movement has changed little since the formation of the Red Sea trough some 25 to 30 Ma ago.

Lastly, the anomaly patterns (and spreading directions) may be locally influenced by the sialic relics.

All these have to be taken into account and their relative importance assessed. At present, it seems to the author that the consideration of the Afar region as a triple junction is the most important.

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