PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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Magnetic Anomalies in the Red Sea

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Magnetic anomalies in the Red Sea†

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[Plate 16]

Marine magnetic profiles over the Red Sea between 18° N and 25° N latitudes confirm previous hypotheses that strongly magnetic rocks underlie the axial trough. The symmetrical nature of the anomalies and their close correspondence to seafloor spreading magnetic models support a rifting origin for the trough. The dominant magnetic anomaly trends strike about N 35° W in the northern and southern parts of the trough. In the central region between 20° and 22° N the trend direction is about N 60° E. Geometrical considerations of possible spreading mechanisms suggest that the true separation direction of Africa away from Arabia near 21° N latitude is in either a N 10° E or N 60° E direction. The separation rates then are 3.2 cm a^{-1} and 2.0 cm a^{-1}, respectively.

Introduction

The intense magnetic anomalies over the axial trough of the Red Sea have been recognized for many years. These anomalies coupled with the positive Bouguer gravity anomaly and high compressional wave velocity of material observed in the axial trough led Drake & Girdler (1964) to propose that the trough was formed by the emplacement of dense, strongly magnetic rocks along tensional cracks as the continental crust rifted apart. Vine's (1966) seafloor spreading interpretation of magnetic profiles across the axial trough in the southern Red Sea has provided further evidence for a rifting origin. More recent studies describing high heat flow measurements (Erickson & Simmons 1969), transform faulting (Fairhead & Girdler, this volume, p. 49; Sykes 1968) and the strong linearity of the magnetic anomaly trends (Phillips, Woodside & Bowin 1969; Allan, this volume, p. 153) have revealed remarkable similarity between the axial trough and mid-ocean ridge crests.

The purpose of this paper is to describe marine magnetic measurements across the axial trough and present various seafloor spreading models which could account for the inferred motion.

Previous work

Although the magnetic field associated with the axial trough has been described by many, the detailed nature of the anomalies is poorly known (Drake & Girdler 1964; Allan 1964; Allan, Charnock & Morelli 1964; Knott, Bunce & Chase 1966). Maxima and minima trends in the total magnetic field intensity paralleling the axis of the trough and shorelines were first noted by Drake & Girdler (1964). However, they admitted considerable difficulty in correlating detailed features from profile to profile. Allan's (1964) preliminary magnetic anomaly contour chart of the Red Sea also showed magnetic anomalies on the order of 2000 nT (gammas) trending parallel to the axial trough. These trends are especially evident in the southern Red Sea between 16° N and 20° N latitude. Here the anomalies and axial trough trend about N 35° W.

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Between 20 and 22° N the charts of Allan and of Drake & Girdler show that the magnetic trends strike more northerly as does the axial trough. More detailed contours presented by Allan (this volume, p. 153) and Kabbani (this volume, p. 89) show strong northeasterly trends here. North of 22° N latitude the amplitude of the anomalies decreases markedly to values of less than about 500 nT (gammas) and the axial trough is absent. However, the anomaly trends become northwesterly and parallel the main trough axis.

Methods and results

During October and November 1966 (*Chain* cruise 61) several long magnetic profiles were made across the axial trough of the Red Sea between 20 and 25° N latitudes (figure 1). These supplement previous profiles made during *Chain* cruise 43 (Knott *et al.* 1966) and cruises of *Vema* and *Conrad* (Drake & Girdler 1964 and unpublished data), *Dalrymple* and *Aragonese* (Allan 1964; Allan *et al.* 1964). A detailed magnetic and bathymetric survey was also made over the hot brine deeps near 21° N (Ross, Hayes & Allstrom 1969; Phillips *et al.* 1969). A total magnetic intensity contour map for this area is shown in figure 2. Figures 3 to 5 show magnetic anomaly profiles in the central, northern, and southern Red Sea respectively. The central region is taken to lie between 20 and 22° N latitude. Navigational control for the survey of the hot brine deeps (central region) was provided by moored buoys with radar reflectors. Celestial navigation and radar sights on landmarks were the primary positioning methods for the longer *Chain* cruise 61 profiles as well as for the previous *Chain*, *Vema*, *Conrad*, and *Dalrymple* profiles. A Varian proton precession magnetometer system was employed for measurements of the total geomagnetic field intensity during *Chain* cruise 61. The sensor was towed 250 m astern. Similar magnetometers were used aboard the previous cruises of *Chain*, *Conrad*, and *Dalrymple*. The *Vema* was equipped with a fluxgate magnetometer.

The magnetic anomalies along each track (figure 1) were computed as profiles with the magnetic anomaly amplitude plotted normal to the track. Only certain of these profiles are shown in figures 3 to 5. Those omitted generally supported the trend correlations shown. However, they were removed to improve the legibility of the figures. The anomalies along the *Chain* and *Dalrymple* tracks were computed by removing the regional field proposed by Allan (1964) for the Red Sea, and updated for secular variations according to estimates provided by U.S. Hydrographic Office Chart no. 1703. The *Conrad* and *Vema* anomaly profiles were computed by using a spherical harmonic expansion estimate of the main geomagnetic field (Cain, Henricks, Daniels & Jenson 1964). The *Vema* fluxgate data were calibrated for absolute intensity using eighteen crossings with the *Dalrymple* track (Drake & Girdler 1964). Each profile was adjusted an arbitrary amount along the total magnetic anomaly scale of each straight track segment for purposes of clear illustration, in this way providing anomaly profiles easily identifiable with the respective tracks. Accordingly, the anomaly amplitudes should only be taken to indicate relative amplitudes along the tracks. Also, no attempt has been made to correct the data for diurnal variations.

The large horizontal gradients and short spatial wavelengths of the anomalies associated with the axial trough coupled with the wide track spacing prevented useful contouring of the magnetic data away from the hot brine area. Preliminary contouring attempts tended to smooth the detailed features of the profiles and did not reveal any more information than has already been shown by Drake & Girdler (1964) and Allan (1964). It was found more illuminating simply to correlate distinctive anomaly features along the tracks (figures 3 to 5) from profile to profile. Solid lines have been used to connect the most likely correlative anomalies along each track. The open arrows show the general trend of the large positive anomaly found over the axial trough. This is believed to be the central anomaly of seafloor spreading models. It must be

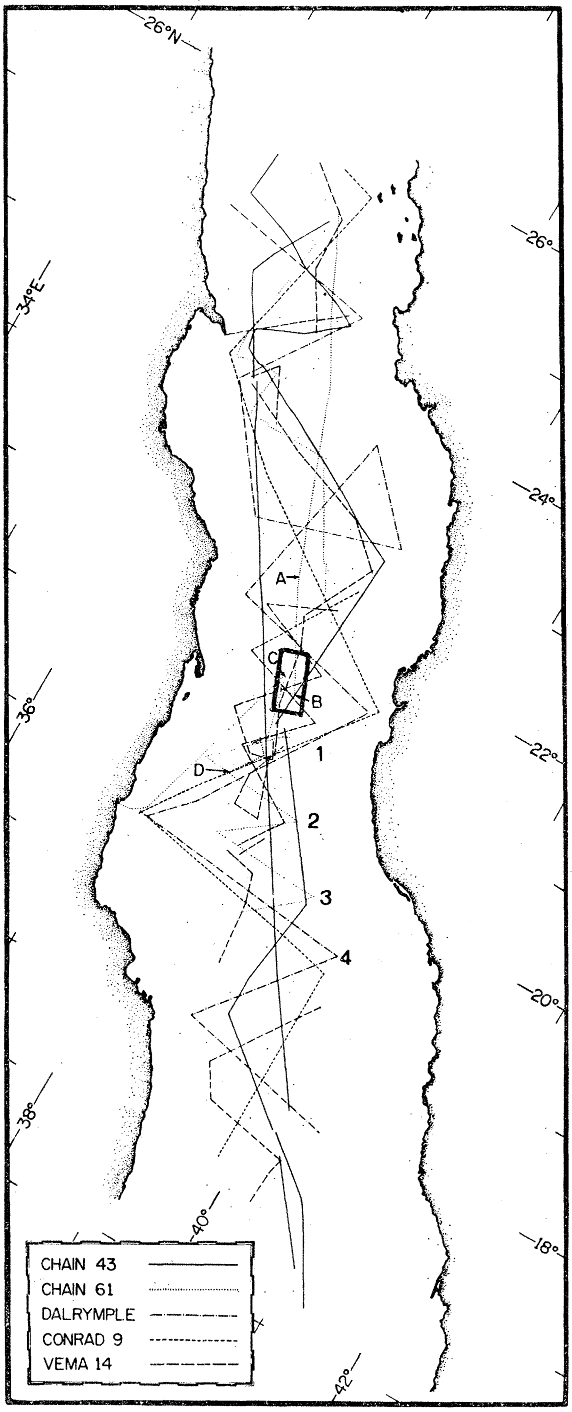

FIGURE 1. Index map showing locations of magnetic profiles in the central Red Sea. The rectangle near 21° 30′ N shows the detailed magnetic survey area over the hot brine deeps. The locations of profiles across the hot brine deeps and southern Red Sea are indicated by letters (*a*–*d*) and numbers (1–4) respectively.

recognized that this correlation techique is subjective and is strongly influenced by the orientation of ship tracks in a given area. In regions where varied track orientations are available, it is a useful procedure. For example, most of the correlations shown in figures 3 and 5 are based on several track orientations. Here the trend assignments are considered firm. However, the trends of the northern section of figure 3 and of figure 4 are considered less reliable since most of the tracks here are oriented NW–SE. This orientation unduly favours a NE–SW trend assignment.

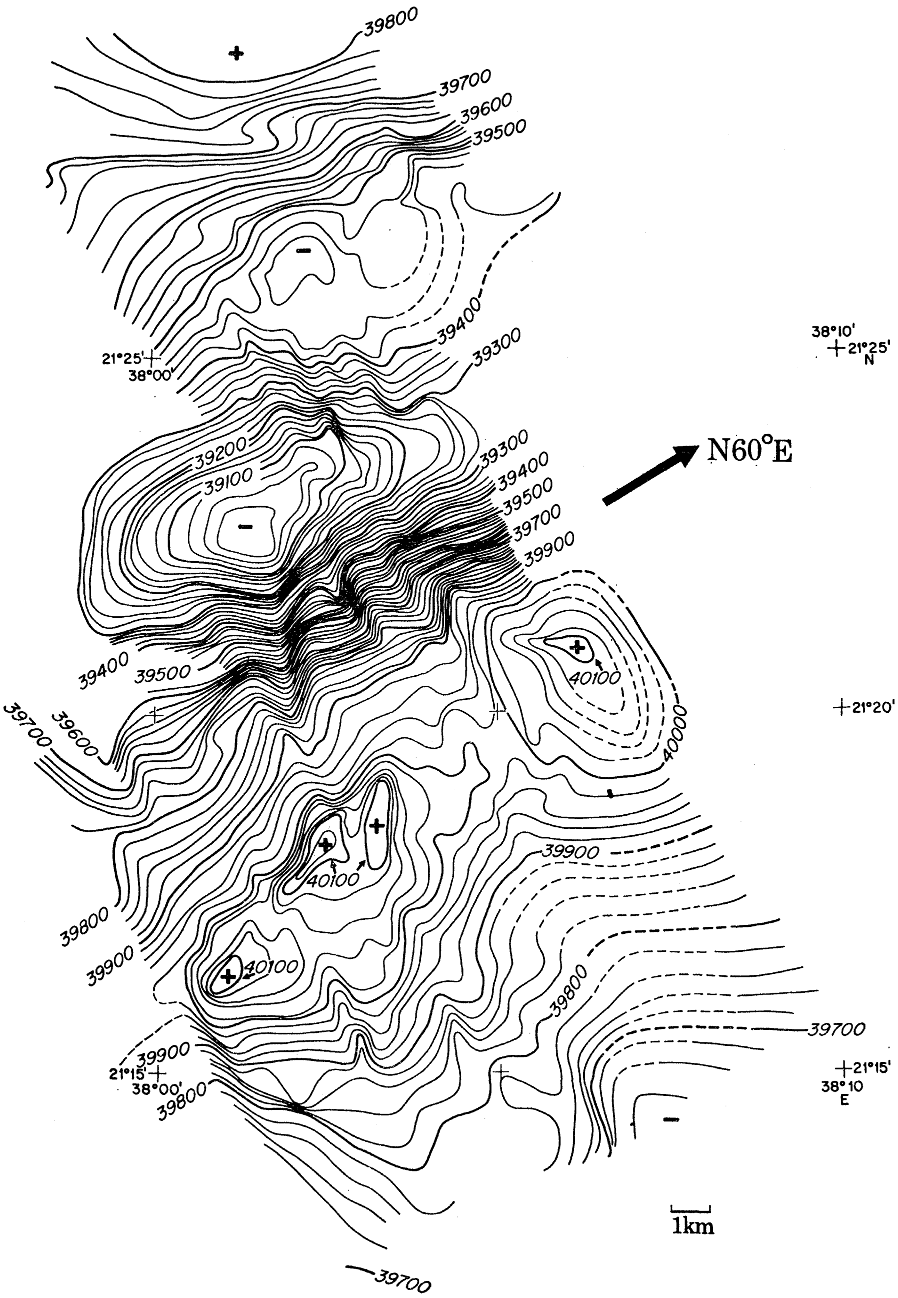

FIGURE 2. Total magnetic intensity contour map over the hot brine deeps. Contour interval 20 nT (gammas). The location of the survey is shown in figure 1.

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

Inspection of figure 3 shows that in the central Red Sea between 20 and 22° N latitudes several anomaly features trend northeasterly (say N 60° E). The large central anomaly over the axial trough near the hot brine deeps has been labelled C. The contour maps of Allan (this volume, p. 153) and Kabbani (this volume, p. 89) also show northeast striking trends in this region. North of 22° N latitude the trends appear to strike northwesterly. This trend direction is nearly parallel to anomaly trend S of the southern Red Sea, discussed later. Between

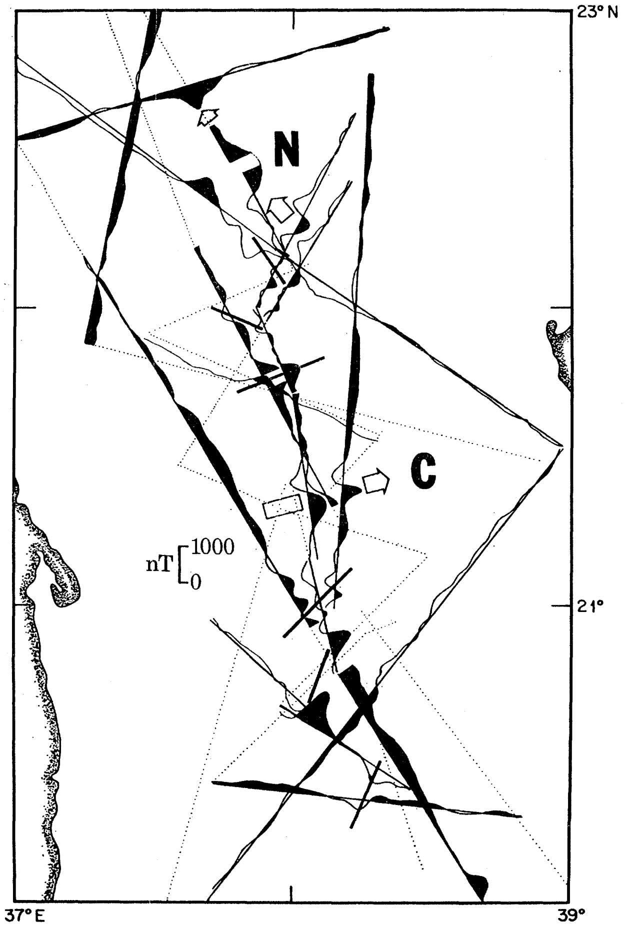

Figure 3. Magnetic anomaly profiles over the hot brine deeps and adjacent areas. The relative anomaly amplitudes have been plotted normal to certain ship tracks shown in figure 1. The positive portion of each anomaly curve has been blackened. The heavy line indicates the inferred direction of the anomaly trend. A light dotted line shows those ship tracks for which the anomaly curve has been omitted. These data were not shown in order to provide a clear illustration. The open arrow shows the trend direction of a large positive anomaly over the axial trough which is believed to be the central anomaly of seafloor spreading models.

23 and 24° N, the trend directions are again northeasterly (figure 4). NE–SW oriented tracks in the area are needed to confirm this possibility. South of 20° N latitude, in the southern Red Sea, the anomaly trends clearly strike NW–SE, striking at about N 35° W as noted by previous investigators (figure 5). This trend, labelled S is essentially normal to trend C of the hot brine area. It is the southern Red Sea trend S that Vine (1966) interpreted to result from seafloor spreading.

MATHEMATICAL, PHYSICAL & ENGINEERING SCIENCES
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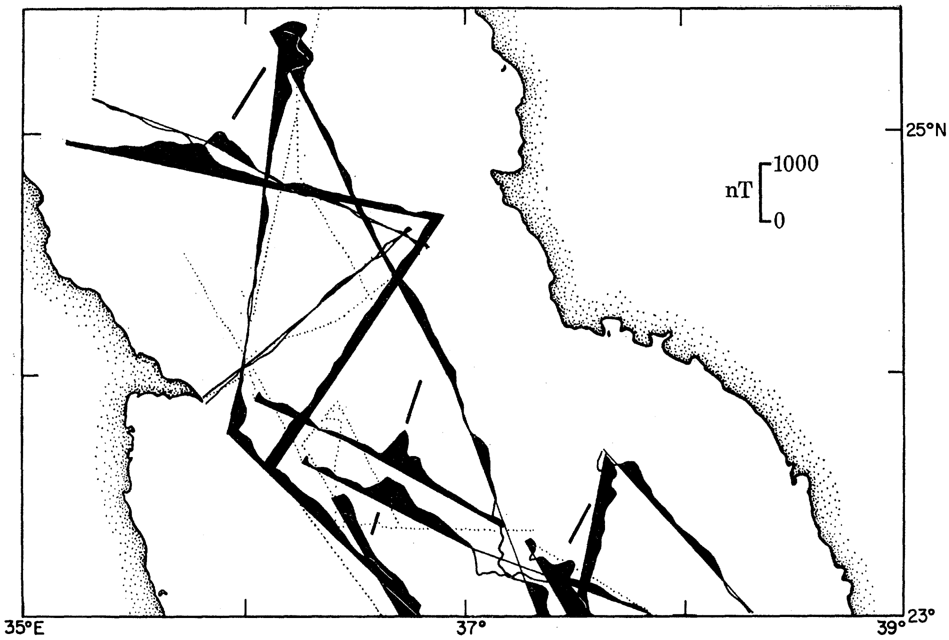

FIGURE 4. Magnetic anomaly profiles over the northern Red Sea axial trough.

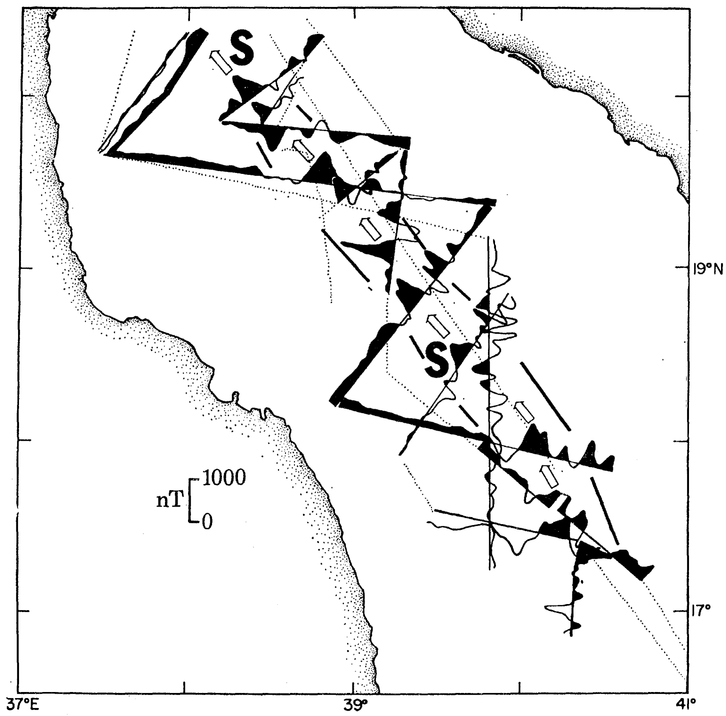

FIGURE 5. Magnetic anomaly profiles over the southern Red Sea axial trough.

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

Careful examination of the profiles near 20° N latitude (figure 6), between the regions of anomaly trends C and S reveals that the central anomalies of trend S, which have been correlated with the simulated central-type seafloor spreading anomalies, decrease in amplitude to the north. Also, the central anomaly does not appear to be continuous with any of the anomaly features of the trend C (figures 3 and 5). It seems to terminate abruptly near the *Dalrymple* profile at 21° N latitude (figure 1). The axial trough also shows an abrupt change in strike in this area to a nearly N–S direction (see bathymetry chart of Laughton in accompanying wallet).

Trend C over the hot brine deeps is best seen in the total magnetic intensity contour chart of figure 2. The positive magnetic trend is associated with the *Chain* and *Discovery* deeps (see bathymetry chart of Ross *et al.* 1969). The negative trend appears to be over the *Atlantis II* deep. These trend directions are significantly different from the general strike of trends N and S observed in other portions of the axial trough (figures 3 and 5). Phillips *et al.* (1969) noted that the large amplitude of anomaly trend C cannot be attributed to local magnetic materials associated with the heavy metal deposits. On the basis of laboratory magnetic analyses of core materials from the hot brine deeps it was found that the deposits are too weakly magnetized. It is more reasonable to consider anomaly trend C in terms of the regional anomaly field across the central Red Sea.

Discussion

The most widely accepted hypothesis proposed for the origin of the Red Sea concerns the axial trough and its similarity to the median valley of mid-ocean ridge crests. Various petrologic, thermal, seismic, gravity, paleomagnetic and magnetic characteristics have been cited as evidence for a tensional origin of the axial trough associated with the rifting apart of the African and Arabian continental blocks (Drake & Girdler 1964; Girdler 1966; Girdler 1969). Recent pre-rifting geologic reconstructions based on the inferred motions along fault trends across the region further support this idea (Laughton 1966; Freund, Zak & Garfunkel 1968; Freund, this volume, p. 107; Abdel-Gawad 1969, and this volume, p. 23; Beydoun this volume, p. 267; McKenzie this volume, p. 393). In addition, the absence from the axial trough of the Miocene evaporite layers commonly observed in seismic profiles over most of the Red Sea has been interpreted by Phillips & Ross (this volume, p. 143) to reflect the rifting apart of the evaporite sequence during formation of the trough.

The rifting hypothesis has probably received its strongest support from Vine's (1966) analysis of two magnetic profiles across the southern Red Sea. He proposed that seafloor spreading-type magnetic models already known to account for the magnetic anomalies over mid-ocean ridges also provide an explanation for certain anomalies in the Red Sea. Vine found that a spreading rate of about 1 cm a^{-1} in a N 55° E direction generated a simulated profile which closely matched observed profiles near 16 and 20° N latitudes. The results of a similar comparison of four other profiles between 18 and 20° N latitudes with a spreading model are shown in figure 6. The model suggests a 1 cm a^{-1} rate, active during the last 3 Ma, can account for the anomaly features. The seafloor spreading-type anomaly patterns appear to span the entire axial trough. The similarity of peak positions to those of the simulated profile is considered good, especially for the *Dalrymple* profile 4 (figure 6). In this, even certain shape details on the eastern side of the profile are represented in the simulated profile. However, the lack of symmetry elements about the central anomaly and the decreased amplitude and smoother character of three more northern profiles indicates that a simple spreading model cannot be used to account for all the anomalies. The difference may indicate that seafloor spreading type anomalies had begun to form earlier toward the south. This would give rise to a wider, more distinctive symmetrical pattern in the south. In the north a simple single block model, representing perhaps only the present Brunhes normal polarity epoch, could easily account for the observed profiles. Vine (1966) also implied such an explanation for a 20° N latitude profile by using a less complex

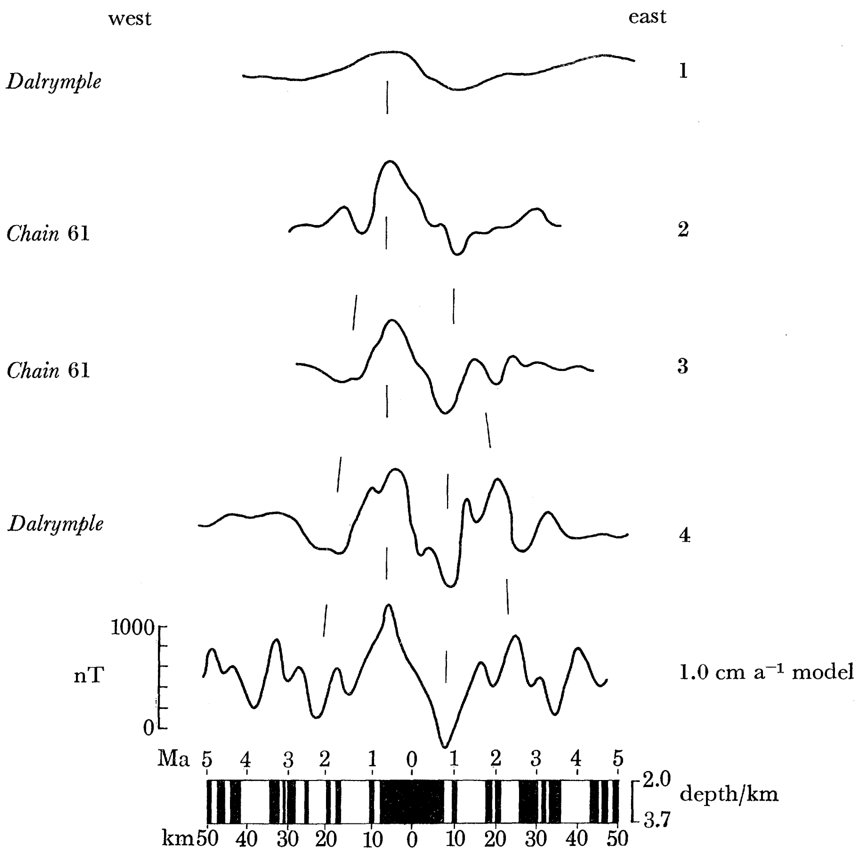

FIGURE 6. The top four curves show magnetic anomaly profiles projected normal to trend C (strike N 35° W) of the axial trough in the southern Red Sea. The locations of the profiles are shown in figure 1. The bottom curve is a simulated profile generated by the seafloor spreading model beneath it. The black blocks indicate normal magnetization. The open blocks represent reversed magnetization. Effective susceptibility is 0.01 cgs units, except for the central block which is 0.02. The assumed model parameters are 35 μT and 36° for intensity and inclination of the axial geomagnetic dipole field, respectively. The strike of the profile is N 55° E. The reversal time scale was taken from Vine (1968). The simulated magnetic profile here and in figure 8 was calculated using a computer program similar to that described by Talwani & Heirtzler (1964).

spreading model than that at 16° N latitude. Here the 1 cm a^{-1} rate need only be active during the last 1.5 Ma. However, alternative explanations are possible. For example, a markedly decreased spreading rate near 21° N as compared to that in the 16 and 18 °N latitude areas could also account for the subdued nature of the more northern profiles. The relation of a typical magnetic profile to the structure of the axial trough is shown in figure 7, plate 16.

Anomaly trend C in the central Red Sea presents a vexing problem. If a seafloor spreading origin is invoked to account for anomaly trend S of the southern Red Sea, must trend C be explained by a similar process? The symmetry aspects of observed anomaly profiles here suggest that they may indeed be related to seafloor spreading (figure 8). Also, an apparent spreading

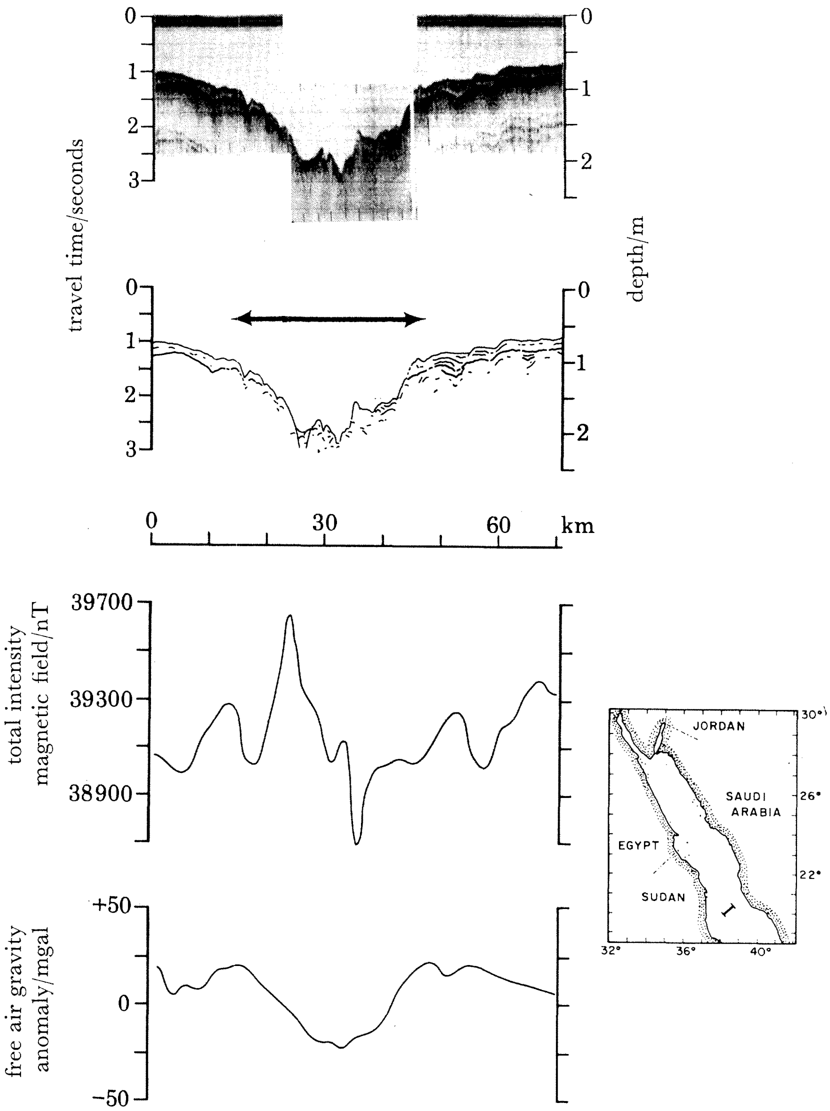

FIGURE 7. Geophysical profile across the axial trough. The top photograph is a reproduction of an original continuous seismic reflexion record. A line drawing interpretation of the record is shown beneath the photograph. The continuous heavy line about 0.3 s 'below' the seafloor traces the top of the Miocene evaporite layers on each side of the trough. The width of the trough is indicated by the arrows. Magnetic and gravity profiles are shown at the bottom of the figure. This profile is identified as *Chain* 61–2 in figures 1 and 6. Figure 6 also presents a seafloor spreading interpretation of this profile which suggests all the anomalies within the axial trough were formed in the last 2 to 3 Ma.

(*Facing p.* 212)

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

rate of 1.5 cm a^{-1} appears to provide a reasonable 'fit' of the peak positions in the observed profile with those of the simulated profile. The overall correlation is not considered very good in view of the markedly different shapes of the corresponding anomaly peaks. However, if we

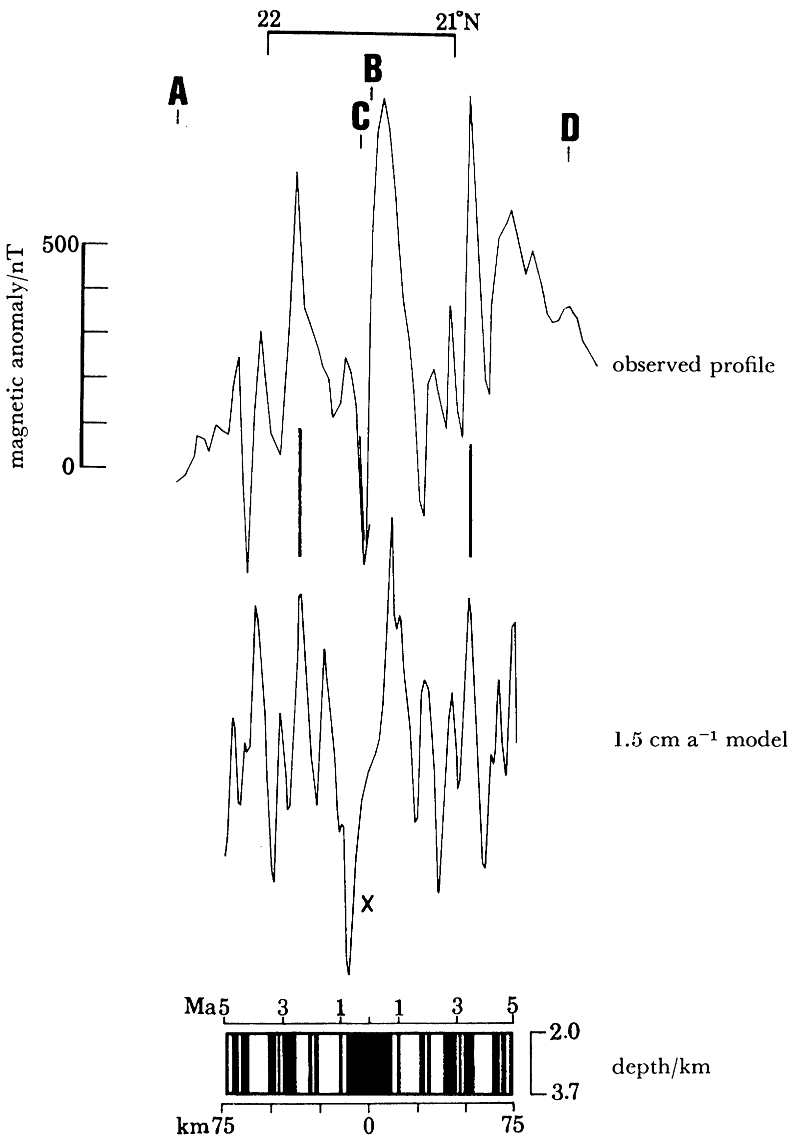

FIGURE 8. The top curve is a composite magnetic profile projected normal to the anomaly trend C in the central Red Sea. The location of the profile segments AB and CD are shown in figure 1. The bottom curve is a simulated magnetic anomaly profile generated by the seafloor spreading model shown beneath it. The model parameters are the same as those in figure 6 except the strike of the profile is N 30° W and the dip of the Earth's field is 35°. The approximate position of the *Atlantis II* hot brine deep with respect to the profile is indicated by the cross above the block model.

assume that the anomaly trend C is the locus of a spreading axis and that there is no compression nor dilatation of the seafloor and adjacent continental blocks, geometrical considerations provide some insight as to the pattern of magnetic trends which would result.

If anomaly trends C and S represent spreading axes which are joined to each other and if spreading is contemporaneous along both axes, the individual anomaly features along these axes should be continuous from one to another (figure 9*a*). Theoretically they should present a chevron-like array where the acute angle of intersection marks successive join-points of the spreading axes. The apparent spreading rates, derived for the direction normal to the magnetic trends, would be minimum values. These apparent vector directions would represent only components of the resultant vector direction of true motion. Thus the direction of separation of Africa and Arabia will be essentially E–W, say N 100° E. The rate would be about 3.2 cm a^{-1} (twice the spreading rate). The Great Magnetic Bight in the Gulf of Alaska has been postulated to result from a similar process (Pitman & Hays 1968). Unfortunately the present track coverage in the Red Sea, in the critical zone of intersection of the magnetic trends, does not allow confirmation of a chevron-like magnetic pattern. However, available data clearly show that the magnetic trends are not continuous with each other (figures 3 and 5).

If the spreading axes are not joined but are separated by transform faults (Wilson 1965), the direction of true motion will be determined by the relative positions of termini for the respective axes (figure 9*b*). That is, since the direction of true spreading must be parallel to all axes in order to conserve surface area, lines joining the eastern and western ends of the spreading axis represented by trend C with the respective ends of spreading axes N and S define the direction of true motion. Although present information does not allow precise location of the anomaly trends or their extent, a preliminary estimate of the magnetic anomaly pattern based on the data presented here can be made. The direction of true motion is essentially normal to the motion depicted in figure 9*a*, say N 10° E. This motion requires a transform fault system near 21° N latitude. The rate of separation for Arabia and Africa would again be about 3.2 cm a^{-1} over the last 3 Ma. Geologic reconstructions by Abdel-Gawad (1969) and inferred motions along the Dead Sea–Aqaba rift (Freund *et al.* 1968) also support a nearly N–S separation direction. However, first motion studies of recent earthquakes in the Red Sea axial trough suggest a more northeasterly separation direction, about N 50° E (Sykes 1968; Fairhead & Girdler, this volume, p. 49).

It should be emphasized that both of the above explanations for the arrangement of the magnetic trends assumed that trend C over the hot brine deeps represented the central anomaly of a seafloor spreading anomaly pattern extending between 21 and 22° N latitude. However, as pointed out earlier, the magnetic evidence for this is rather weak. There is only one profile available that crosses the entire region. Alternatively the anomaly trend C may simply be the trace of a transform fault between the offset NW trending spreading axes represented by anomaly trends N and S. In the NE Pacific where detailed surveys are available, linear anomalies are found to parallel the Mendocino, Murray and other fracture zones (Mason & Raff 1961). These fracture zones are generally believed to represent the traces of ancient transform faults (Menard & Atwater 1968). If a similar explanation is invoked here, the direction of true motion would indeed be northeasterly (say N 60° E) at a rate of about 2.0 cm a^{-1}, or twice the 1.0 cm a^{-1} spreading rate derived from the southern Red Sea anomaly trend S (figure 9*c*). This solution would be in better agreement with the earthquake first motion studies which also suggest a NE–SW separation.

Another method for estimating the separation directions in the Red Sea can be found by examining recent models of global tectonics (Morgan 1968; McKenzie & Parker 1967). Le Pichon & Heirtzler (1968) and Heirtzler *et al.* (1968) determined a pole of rotation for the African and Arabian plates at about 26° N–21° E, from fault trends in the Gulf of Aden. They also presented a comparison of calculated transform fault strikes (separation directions) and

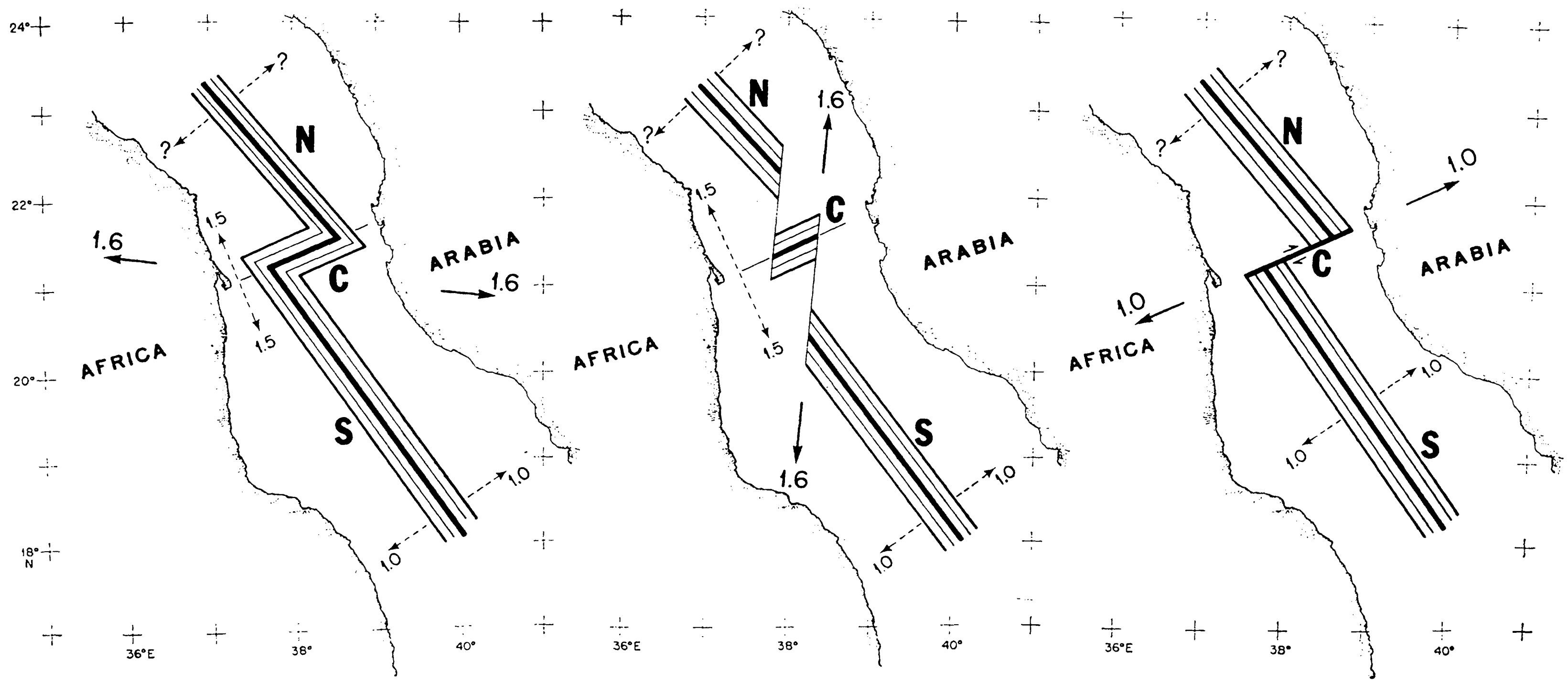

FIGURE 9. Possible seafloor spreading mechanisms to account for the magnetic anomaly trends and separation of Africa and Arabia across the central Red Sea. The black and white bands schematically represent positive and negative anomaly trends respectively which might be generated by spreading along the different axes. The light numbers and arrows refer to the rates of apparent spreading taken in directions normal to the magnetic trends. The bold arrows and numbers show the directions and rates of true spreading for Africa and Arabia away from the spreading axis. The letters represent the spreading axes which may reflect the anomaly trends shown in figures 3 to 5. The orientation of the northernmost spreading axis N near 24° N latitude is considered speculative in that track coverage here is inadequate. (*a*) Separation mechanism where the spreading axes N, C and S are joined. The relative motion of Africa away from Arabia would be about N 100° E at 3.2 cm a^{-1}, twice the true spreading rate. (*b*) Separation mechanism where the spreading axes N, C and S are not joined but are separated by transform faults. The directions normal to the magnetic trends would then be components vector directions of the true spreading direction. The resultant direction of true spreading for the relative motion of Africa and Arabia would be N 10° E at 3.2 cm a^{-1}. (*c*) Separation mechanism where anomaly trend C is interpreted to reflect a transform fault joining anomaly trends N and S. The direction normal to the anomaly trends N and S is taken to be the true spreading direction. The relative motion for the separation of Africa and Arabia is in a N 60° E direction at about 2.0 cm a^{-1}.

spreading rates resulting from rotation about this pole with transverse fractures and magnetic patterns between the Red Sea and NW Indian Ocean. The comparison was poorest for the Red Sea, in that their pole requires a true separation direction of about N 25° E at 19° N, whereas the spreading direction normal to the magnetic trends and earthquake first motion directions suggests a more northeasterly motion (N 50° E). This pole does not appear to be applicable to the Red Sea. It probably reflects only the separation of Arabia from Somalia (Horn of Africa), in that Somalia may be an independent crustal block joined to Africa along the East African rift zone (McKenzie, this volume, p. 393). The opening of the Red Sea more probably results from the separation of Arabia from Egypt and the Sudan. In this case a pole of rotation determined graphically from the curvature of the Dead Sea–Aqaba rift trend may be more appropriate. However, this pole (25° N, 31° W) suggests an even more northerly separation direction in the central Red Sea (say N 15° E). Significantly, there do not appear to be any magnetic trends normal to this direction. Of course, it may be that spreading directions need not be normal to the magnetic trends as suggested earlier (figure 9*b*).

Summary and conclusions

The symmetrical nature of magnetic profiles across the axial trough of the Red Sea and their close similarity to simulated seafloor spreading model profiles support a rifting origin for the axial trough. This rifting is believed associated with the horizontal separation (drift) of Africa and Arabia. The magnetic anomaly trends strike about N 35° W (trends N and S) in the northern and southern parts of the trough. In the central region between 20 and 22° N latitude the anomaly trends strike about N 60° E (trend C). The direction of true motion or separation of the African and Arabian crustal plates is not clear. If each of the magnetic trends represents an axis of spreading and if the spreading axes are joined, the true separation direction is about N 100° E at about 3.2 cm a^{-1} (twice the spreading rate). On the other hand, if each magnetic trend reflects a separate and distinct spreading axis bounded by transform faults, the resultant direction of true separation is N 10° E, again at a rate of 3.2 cm a^{-1}. It is also possible anomaly trend C does not reflect an axis of spreading. It may simply be an anomaly trend parallel to a transform fault joining the anomaly trends N and S which are the true spreading axes. In this case, the direction of separation would be N 60° E at a rate of about 2.0 cm a^{-1}. While independent evidence based on geologic reconstructions and inferred motion along the Dead Sea–Aqaba rift support an essentially northerly separation, equally strong evidence in the form of earthquake first motion determinations argue for the northeasterly separation. There is no evidence available to support a NW–SE separation.

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

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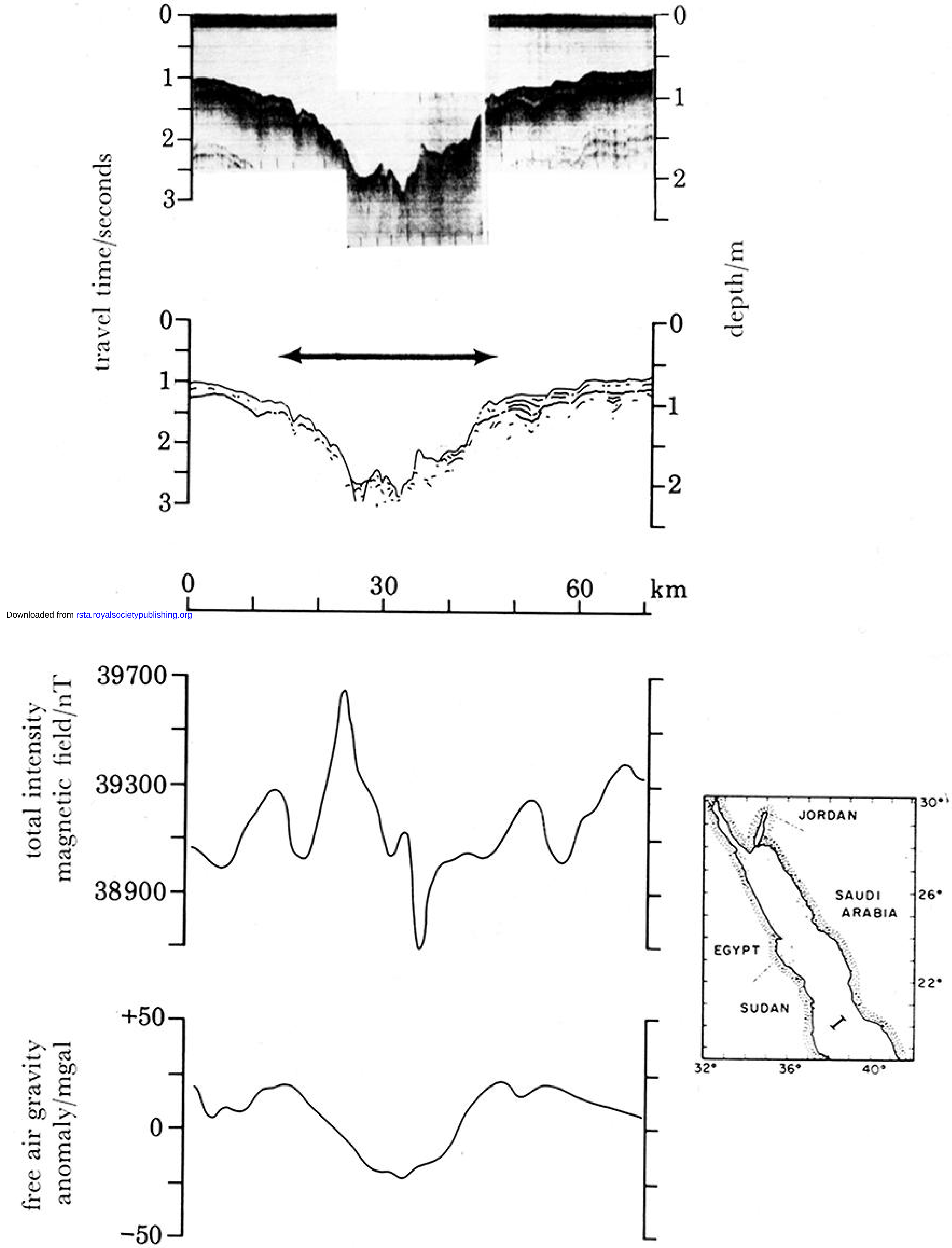

FIGURE 7. Geophysical profile across the axial trough. The top photograph is a reproduction of an original continuous seismic reflexion record. A line drawing interpretation of the record is shown beneath the photograph. The continuous heavy line about 0.3 s 'below' the seafloor traces the top of the Miocene evaporite layers on each side of the trough. The width of the trough is indicated by the arrows. Magnetic and gravity profiles are shown at the bottom of the figure. This profile is identified as *Chain* 61–2 in figures 1 and 6. Figure 6 also presents a seafloor spreading interpretation of this profile which suggests all the anomalies within the axial trough were formed in the last 2 to 3 Ma.