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Magnetic and Gravity Fields over the Red Sea

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Magnetic and gravity fields over the Red Sea

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[Plate 15]

Strong magnetic anomalies associated with the axial trough of the Red Sea are considered to be related to a second phase of opening. Lack of magnetic expression of the first and wider separation is attributed to initial thinning and necking of the continental crust and, possibly, to a slow rate of spreading. The rise of the mantle during this first stage is reflected in the positive Bouguer gravity anomaly which extends over the whole Sea.

A displacement of the magnetic anomaly pattern and a grouping of earthquake epicentres at latitude $19\frac{1}{2}°$ N delineates a transform fault. Futher offsets in the anomaly pattern between $19\frac{1}{2}°$ N and 23° N may be related to other transform faults presently inactive.

If Sinai is treated as a separate block then the two-stage clockwise rotation of Africa to open the Red Sea leads to the southerly displacements of this block required by the geology. Negative gravity anomalies in the Gulf of Aqaba support the idea of a shear. A separate rotation of the Horn of Africa is believed to have contributed to the opening of the Gulf of Aden.

1. Introduction

During the last five years, new and convincing geophysical and geological evidence has been produced in support of continental drift. The magnetic lineations which Vine & Matthews (1963) first related to a spreading ocean floor have been observed over many parts of the world's oceans and their patterns have been used to calculate the various rates of sea-floor spreading (Heirtzler, Dickson, Herron, Pitman & Le Pichon 1968). A computer fit of the continents around the Atlantic (Bullard, Everett & Smith 1965) indicates that the original separation probably took place along the present 500 m depth contour.

Several years ago, at a time when continental drift was rejected by a majority of geophysicists, the remarkable jig-saw fit of the Red Sea shorelines compelled consideration of a possible separation of Africa and Arabia to form the Red Sea. The mode of formation of the inter-connecting series of rifts which continue from the Jordan Valley as far as Lake Nyasa has long claimed the attention of earth scientists (Gregory 1896). Willis (1928) recognized that the rifts '...are distinct structural depressions which may or may not have had similar histories'. The early observations of gravity made along the coasts and on several islands of the Red Sea by von Triulzi (1898) and the submarine pendulum observations of Vening Meinesz (1934) showed the Red Sea to be characterized by positive anomalies in contrast to the negative anomalies measured over the East African rift valleys by Bullard (1936).

Carey (1958), an early advocate of continental drift, postulated a mechanism for the opening of the Red Sea by tensional forces brought about by convection currents. The theory of a rift between Africa and Arabia was supported by Swartz & Arden (1960) who proposed a time scale based on geological evidence. They proposed that compressional forces developed in the northern region at the end of the Lower Eocene while tensional stresses developed in the south. Africa and Arabia moved apart under tension throughout the Eocene and Oligocene while the first stage of the Gulf of Aden rift took place in the early Miocene. Their model required movement between four separate blocks—the Sinai peninsula, the northeastern African block, the Horn of Africa and Arabia.

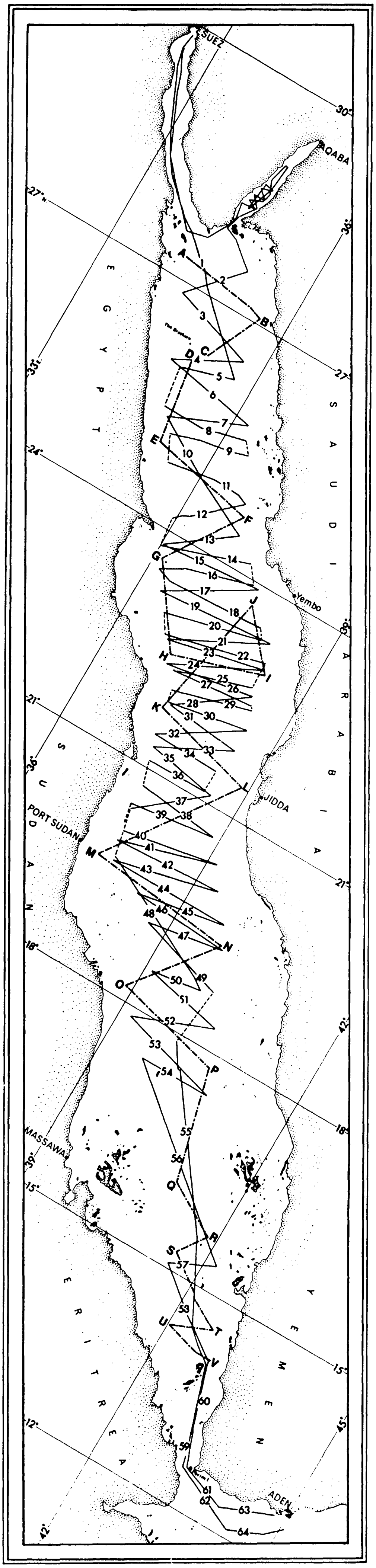

FIGURE 1. Tracks of *Aragonese* (full lines with numbers) and *Dalrymple* (dashed lines with letters) over which geophysical measurements were made. Gravity measurements were restricted to *Aragonese* tracks.

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In 1958 the first magnetic measurements were made in the Red Sea by RV. *Vema* using a fluxgate magnetometer (Drake & Girdler 1964) and in 1959 H.M.S. *Dalrymple* made some twelve long profiles across the Sea with a proton precession instrument (Allan 1960, 1964). The Nato research ship *Aragonese* completed an extensive survey of the Red Sea in the winter of 1961 making, besides magnetic measurements, the first continuous recordings of the gravity field (Allan, Charnock & Morelli 1964). The tracks of *Dalrymple* and *Aragonese* are shown in figure 1.

2. Topography

The Red Sea, which runs almost 2000 km from the Mediterranean to the Indian Ocean, lies in a fault depression in the Arabian–Nubian Shield. At its northern end it bifurcates into the Gulfs of Suez and Aqaba, the floor of the former being smooth and shallow (approximately 60 to 70 m) while, by contrast, the Gulf of Aqaba reaches a maximum depth of over 1700 m. To the south the opposite coasts of the Red Sea run straight as far as latitude 25° N with a shore-to-shore width of approximately 180 km. The sea floor forms a gently dipping trough reaching a maximum depth of approximately 1300 m. South of latitude 24° N a deep incision, referred to by Drake & Girdler as the axial trough, appears in the main trough. The existence of this trough was known even before Farquarson (1935) made the first echo-soundings over it during the *John Murray* expedition. Subsequent bathymetric profiles illustrating the width of the main and axial troughs were reported by Tazieff (1952) and Cousteau, Nesteroff & Tazieff (1953). Following the *Aragonese* expedition of 1961 a bathymetric map was produced from all the soundings available to the U.K. Hydrographic Department of the Navy plus the *Aragonese* soundings (Allan 1966). This map (C 6539) was published by the Hydrographic Department and is reproduced in figure 2. In figure 3 a detail of the area between latitude 23° to 16° N is shown.

The axial trough, which follows the sinuous coast lines, can be followed as far as 16° N where the coasts start to converge towards Bab-el-Mandeb. The appearance of coral banks in this southern area obscures the delineation of the main trough and limits navigation to a narrow channel.

Topographic sections illustrating the development and variation of the axial and main troughs are shown in figure 4.

3. Magnetic results

Description

Magnetic contour charts of the total and anomalous field over the whole of the Red Sea were constructed from the *Dalrymple* and *Aragonese* surveys and are shown in figures 5 and 6. In calculating the anomalous field a regional field with linear gradient was assumed as follows:

$$F_{\mathrm{R}}(\text{nanoteslas}) = 38200+6.750N+2.067E,$$

where N = minutes of latitude north of 17° 18′ N, E = minutes of longitude east of 40° 00′ E. Detailed charts of the most anomalous area in the Red Sea are shown in figures 7 and 8.

The magnetic anomalies are of much lower magnitude in the northern part of the Sea than over the central and southern parts. The onset of magnetic activiy more or less coincides with the appearance of the narrow axial trough at about latitude 23° N. Between 23 and 22° N anomalies of a peak-to-trough amplitude up to 1600 nT (gammas) are recorded but between 22 and 21° N the anomalies are somewhat diminished and the contours appear to turn and run at right angles to the strike of the Sea (figure 8). Large amplitude anomalies return between

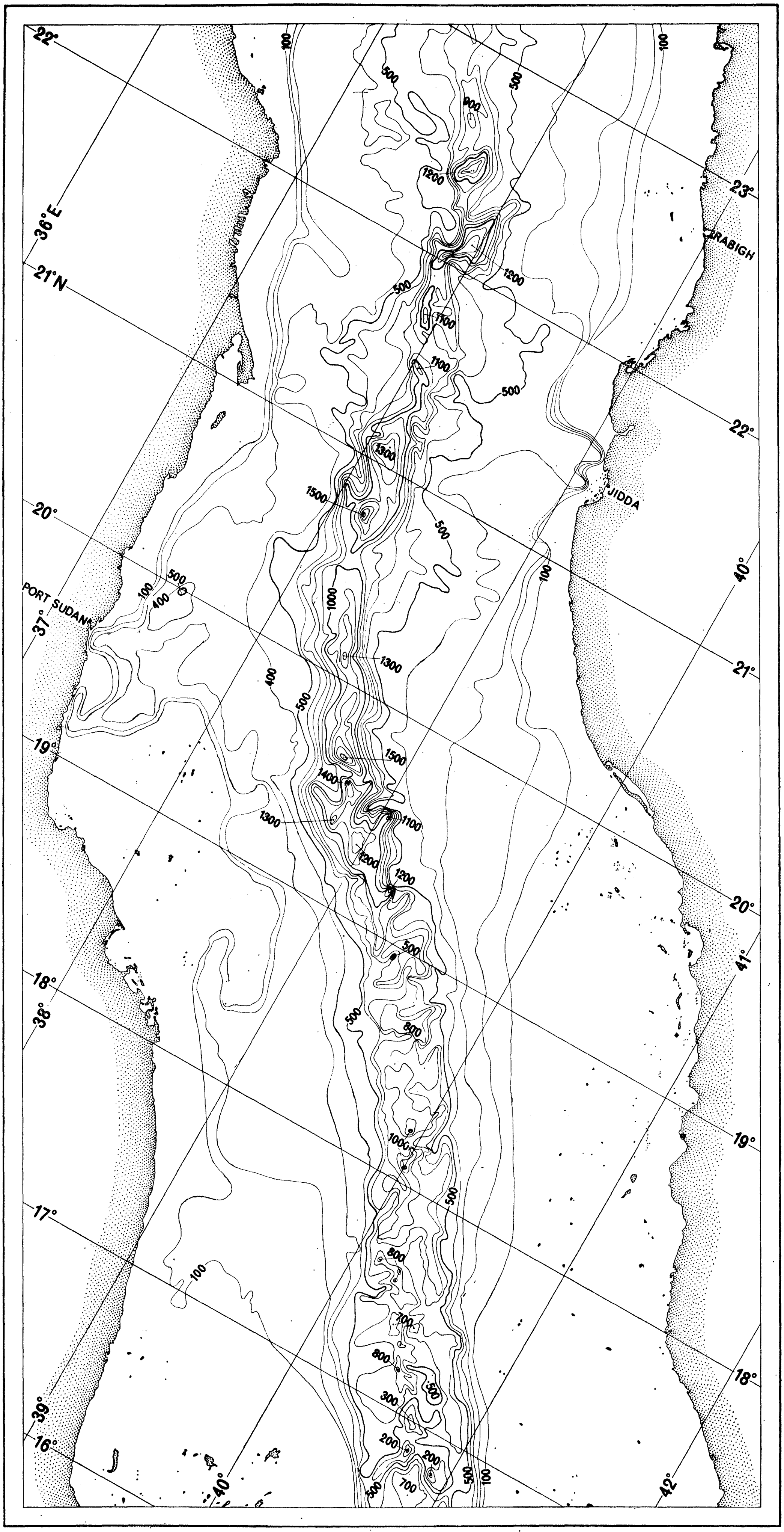

FIGURE 3. Detail of bathymetric chart over the central part of the Sea. Contour interval 100 fathoms. Soundings corrected.

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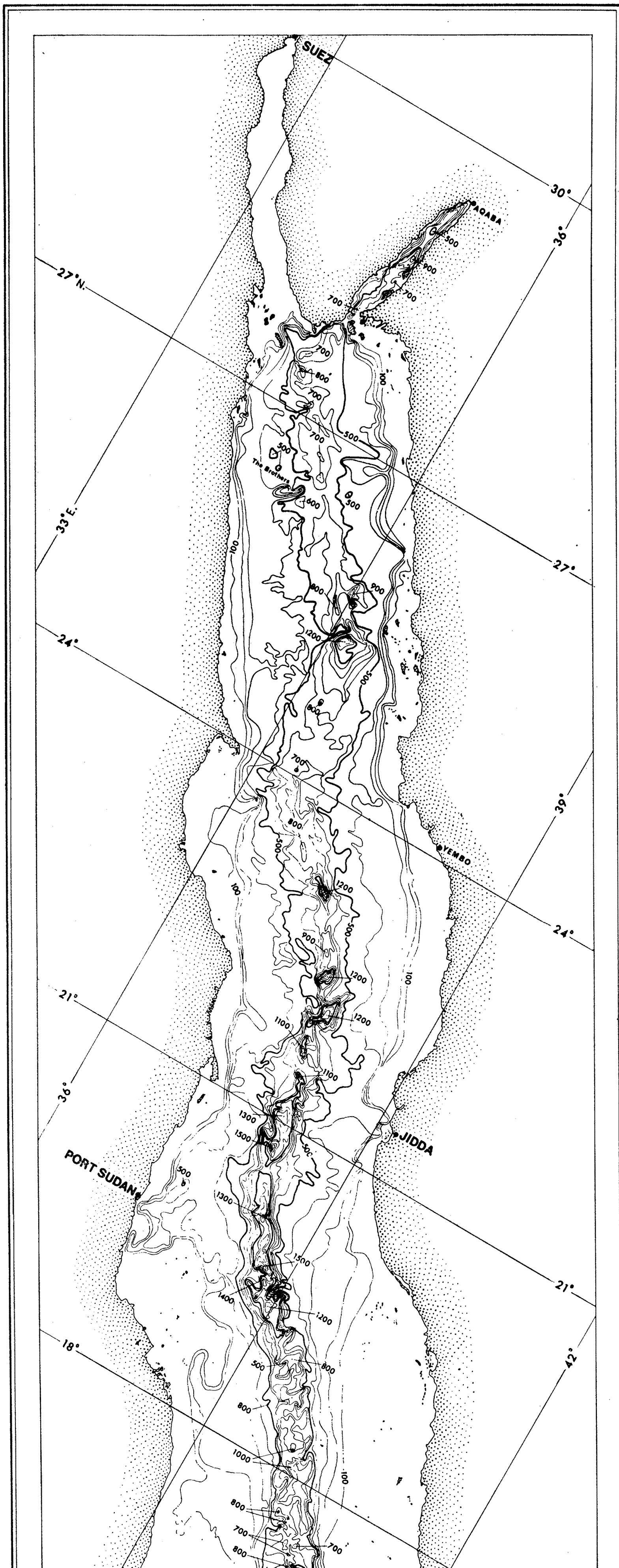

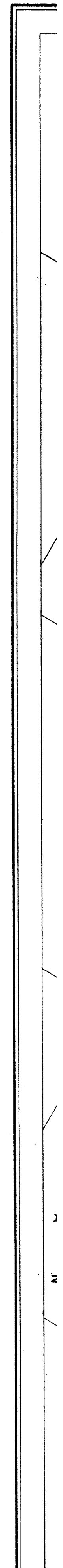

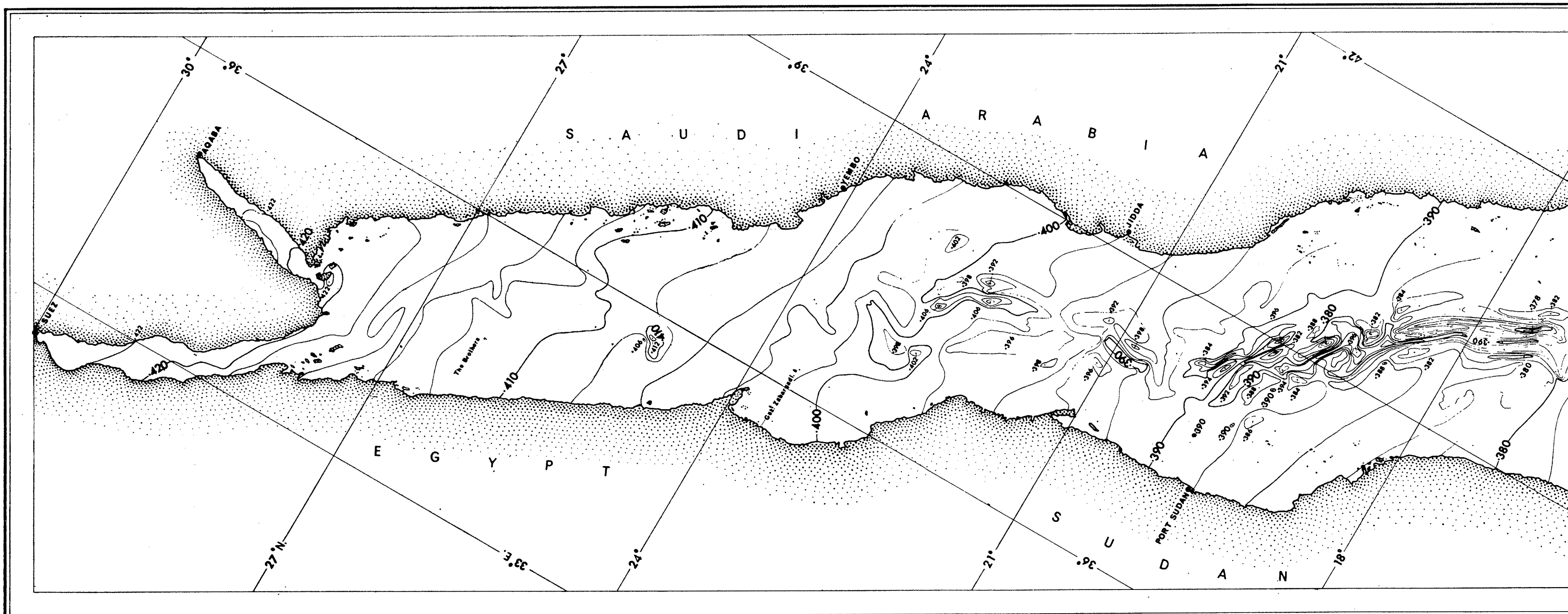

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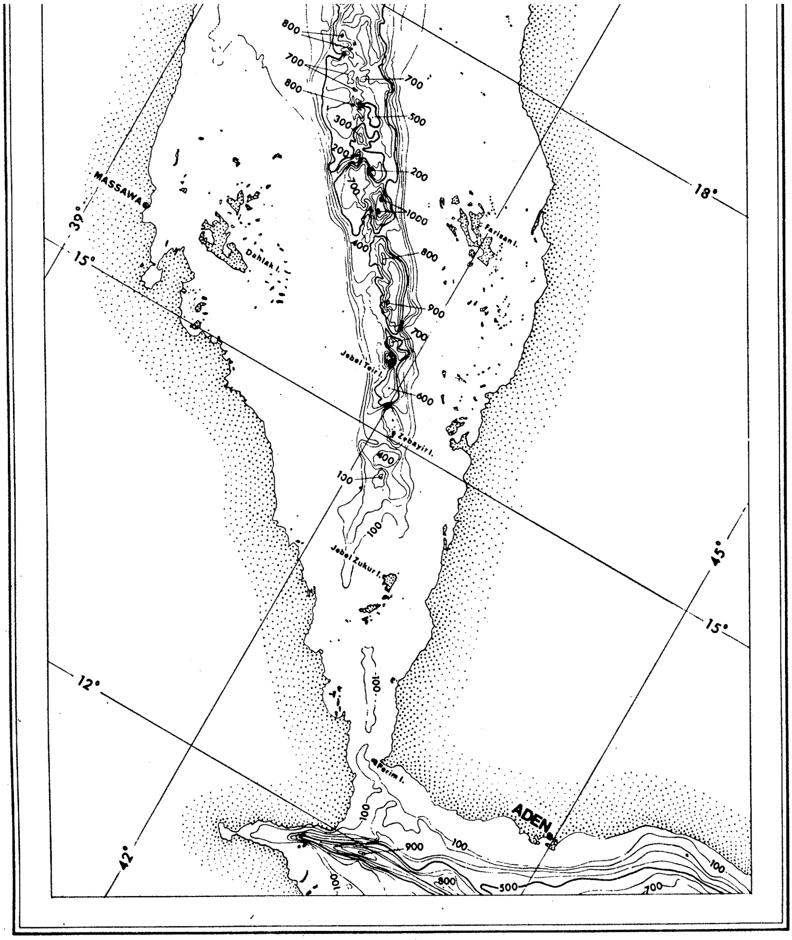

FIGURE 2. Bathymetric chart with 100 fathom (183 m) contour interval. (All soundings corrected for velocity of sound in sea water according to Matthews' Tables, H.D. 282.)

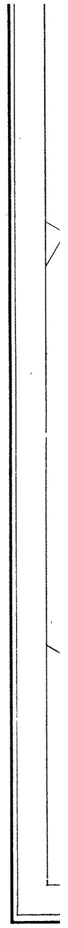

FIGURE 5. Ch

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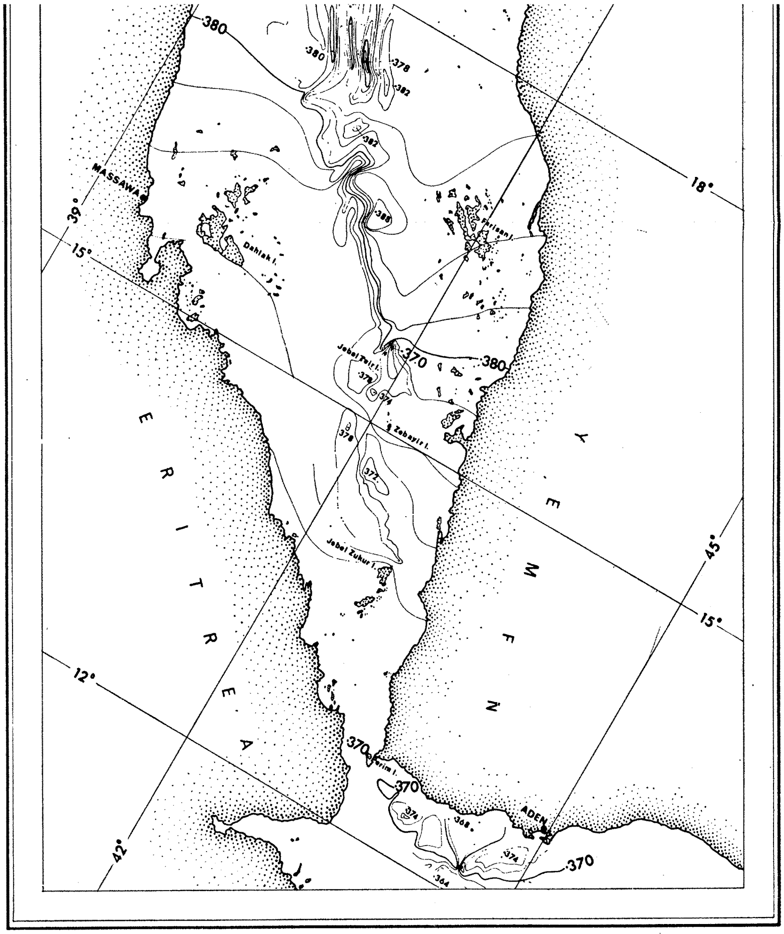
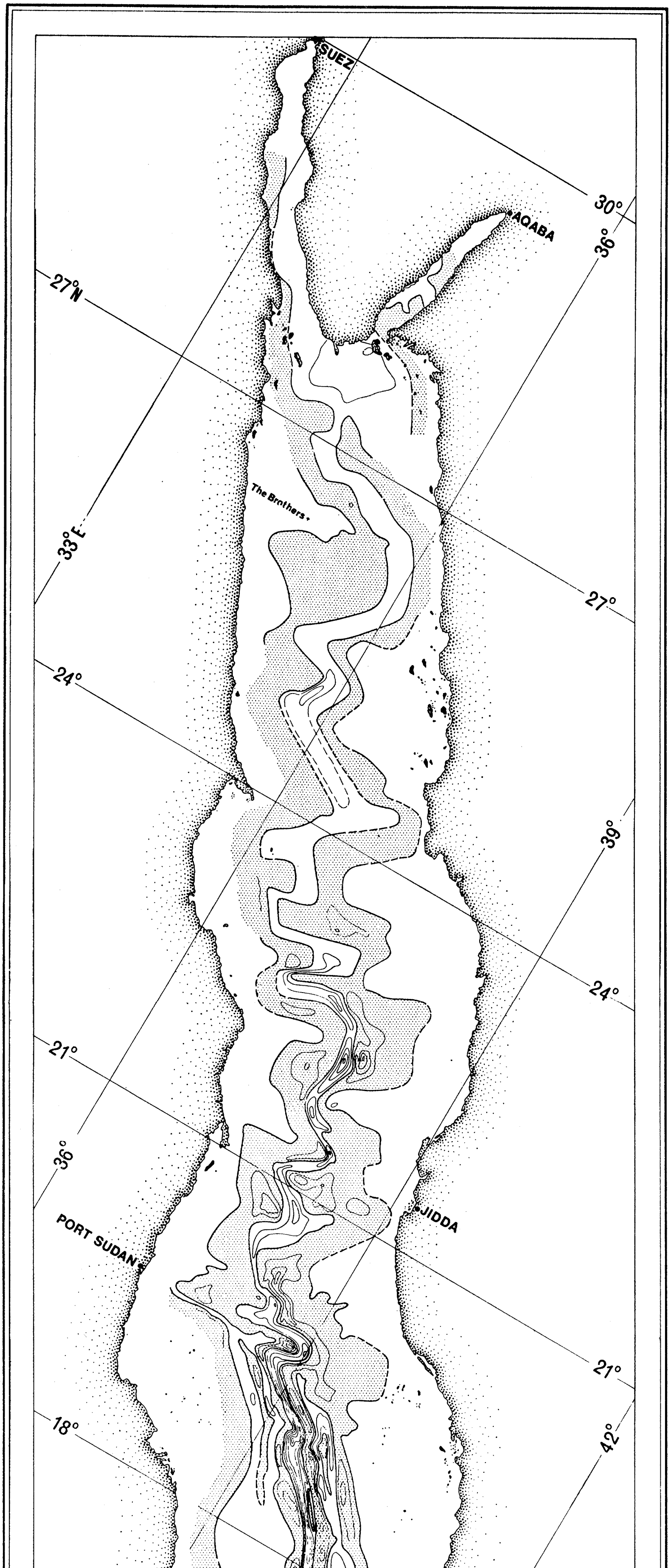
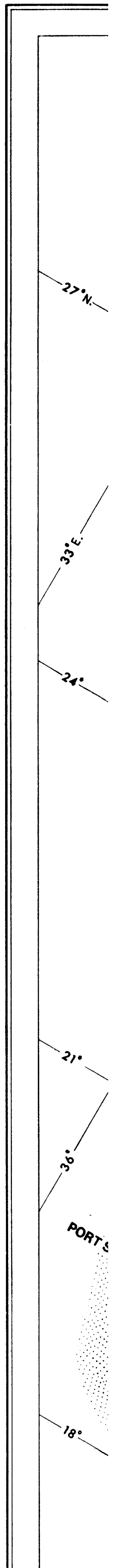


URE 5. Chart of total magnetic field for epoch 1961. Contour interval 200 nT (gammas)





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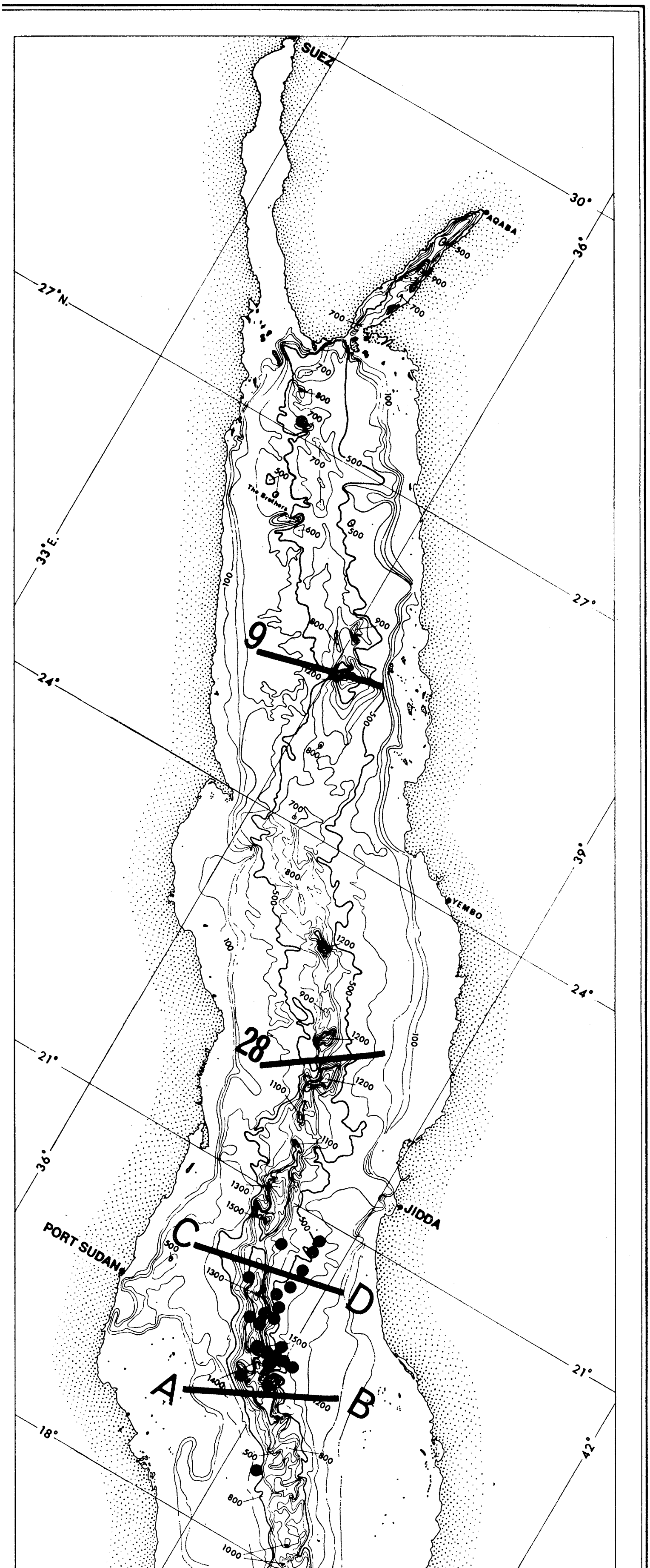

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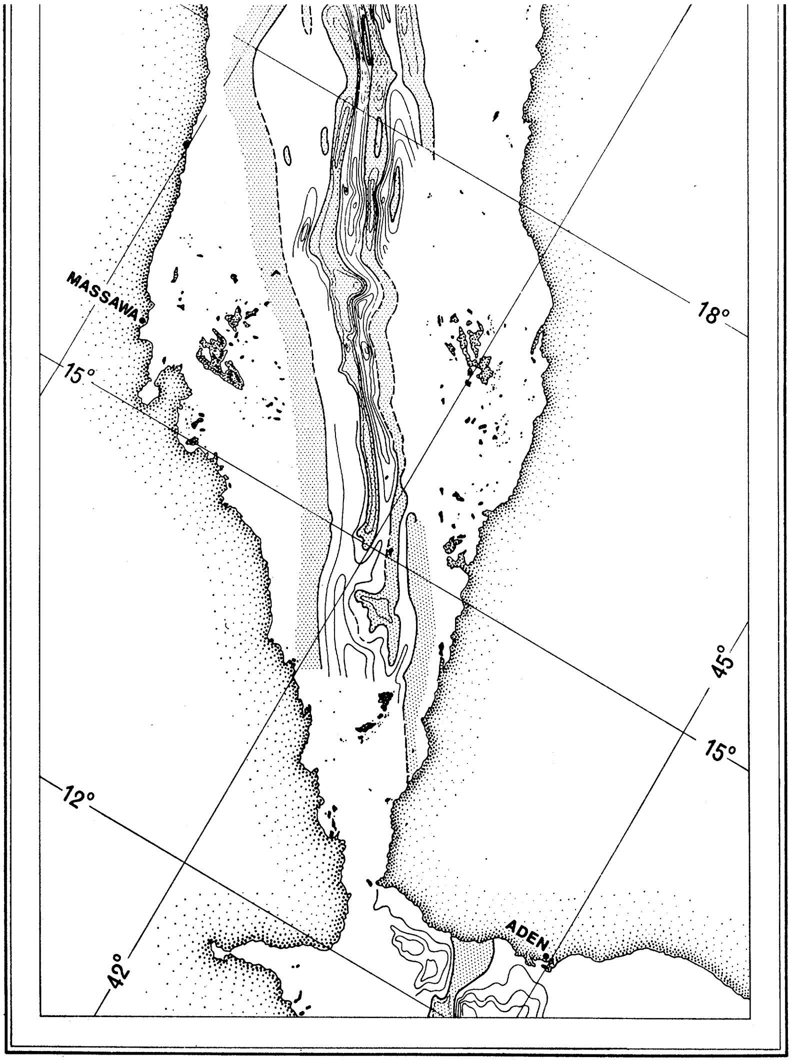

Figure 6. Chart of magnetic anomaly constructed by subtracting a regional field from the observed values. Contour interval 200 nT. Negative anomalies are shaded.

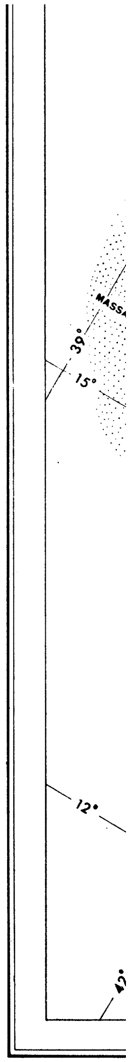

Figure 18. Location of
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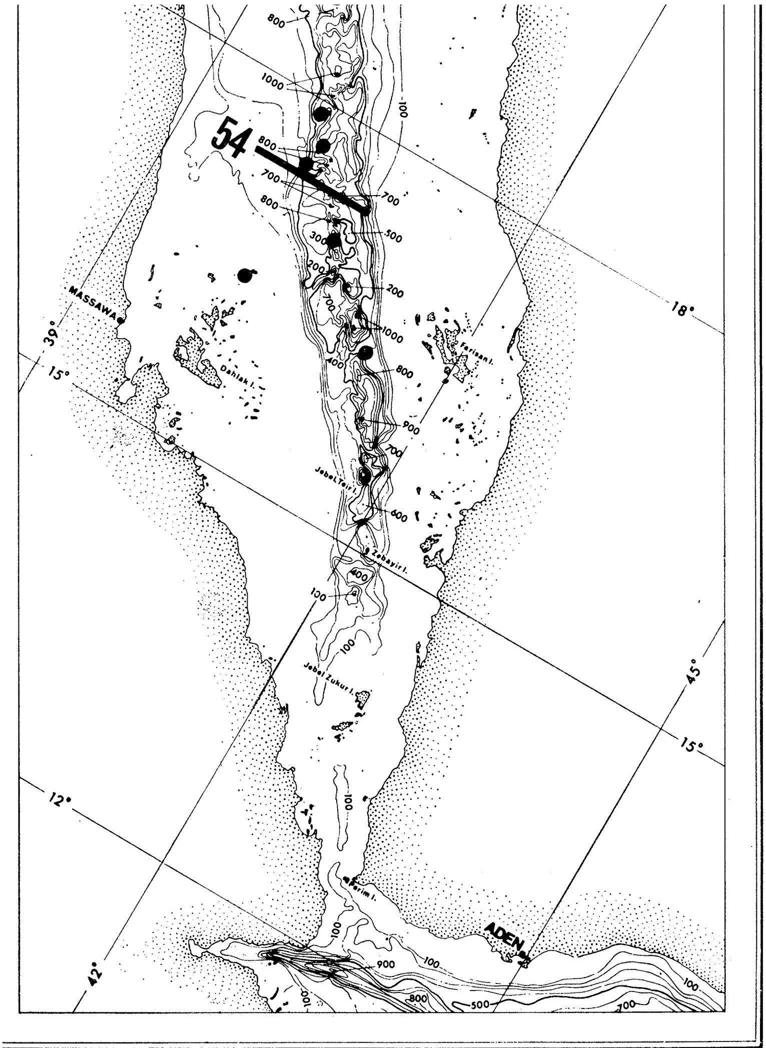

ɔcation of gravity profiles for which an interpretation is shown in figure 19. Also shown hquake epicentres for the whole Sea. Note the lack of seismic activity in the north.

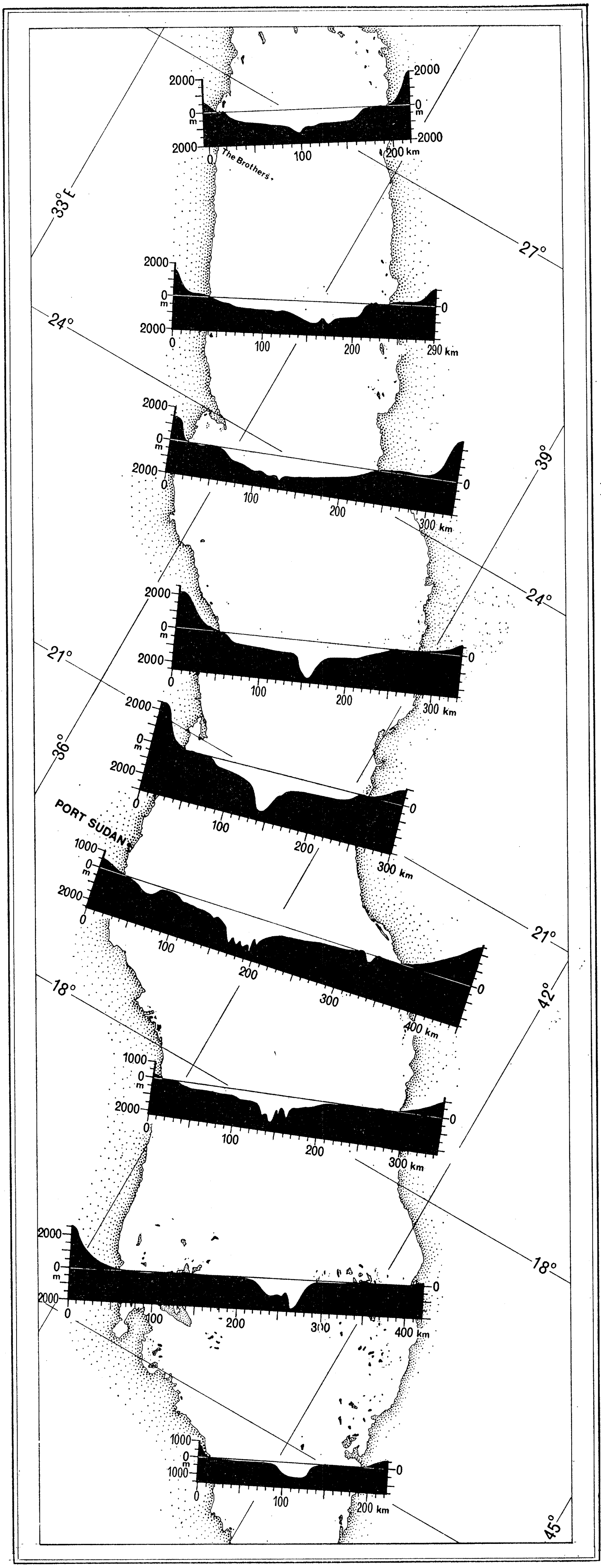

FIGURE 4. Selected topographic sections illustrating the main trough in the north and the development of the axial trough to the south.

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latitudes 21 and 19° N, their width being more or less confined to the width of the axial trough. Because the shapes of the anomaly curves show considerable variation, correlation of features from one profile to another is hazardous with the profile spacing used. In general a positive peak is recorded to the west of a negative trough but on some profiles the order is reversed and on others only the negative is recorded. A cut-out model of the profiles is shown in figure 9, plate 15. South of 19° N the anomalies are closely related to the axial trough and correlation of peaks between successive profiles can be made with fair confidence as far south as $16\frac{1}{2}$° N where the navigation channel begins to narrow to an extent that makes long profiles impossible.

Interpretation

The axial trough in the Red Sea appears to be similar in many respects to the rift valleys found at the centre of many of the Earth's mid-ocean ridges. The theory, proposed by Vine & Matthews (1963), that over mid-ocean ridges a spreading ocean floor together with periodic reversals in the Earth's dipole field should cause magnetic lineations symmetrical about the ridge axis, has now been confirmed over many parts of mid-ocean ridges where magnetic data are available. Vine (1966) applied the theory to two profiles in the central and southern Red Sea reported by Allan *et al.* (1964) and Drake & Girdler (1964). He found a spreading rate of 1 cm a^{-1} on each limb, with model blocks truncated to fit only the axial trough.

The profiles shown in figure 9 allow a more detailed assessment to be made. Five successive magnetic profiles which cross the axial trough south of 19° N are shown in figure 10, together with a single spreading model and its calculated anomaly. The assumed intensity of magnetization of the blocks is 0.008 except for the central block which has twice this value (following Vine & Matthews). The blocks are assumed to lie between 3.6 and 7.2 km below the sea surface, to extend to infinity on either side of the profile and to strike in the same direction as the Red Sea, that is, N 27° W. Although several details of the individual profiles are not reproduced in the calculated curve the main features match reasonably well. The total width of the model is 75 km giving an average spreading rate of 1.1 cm a^{-1}.

North of about $19\frac{1}{2}$° N the linear magnetic pattern breaks up and the shapes of the anomaly curves begin to change. On profile 49 the positive peak still lies to the west of the negative trough as in the five profiles to the south but by profile 44 (approximately 80 km to the north of profile 49) the order has changed with the positive lying to the east of the negative. Such a change-over can be explained by a rotation of the disturbing bodies from the original Red Sea strike of approximately N 30° W to a strike of N 30° E. Anomaly curves were calculated for model blocks striking at 10° intervals in the range N 30° W to N 30° E. They show not only a change in the relative positions of positive and negative peaks but also a change of amplitude that is quite well reproduced in the observed profiles. The comparison between observed and theoretical anomalies computed for bodies of varying strike is shown in figure 11. Only profile 43, which has a rather non-descript form, fails to give good agreement with the computed curves. On profile 47 the observed peak-to-trough amplitude is 1700 nT and a reasonable fit can be made with a model striking N 30° W and with an intensity of magnetization of 0.011; on adjacent profile 46 the peak-to-trough amplitude drops to 750 nT and a reasonable fit can be made with essentially the same block striking N 10° W. The intensity of magnetization for all calculated models lies in the range 0.008 to 0.011 (always with the exception of the central block which is twice as high).

The computed positions of the central block (the Brunhes) for each profile between $17\frac{1}{2}$ and

FIGURE 9. Cut-out model of observed magnetic anomaly profiles over the central and southern parts of the Sea.

(*Facing p.* 158)

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20° N are shown in figure 12 where the assumed strike of the disturbing block is indicated by its inclination on the profile. Also shown are the positions of the earthquake epicentres for the period 1958 to 1967 (kindly supplied by the International Seismological Centre, Edinburgh). From this reconstruction it can be seen that not only do the blocks appear to have rotated but there are two major displacements in the position of the blocks between profiles 45 and 44 and profiles 44 and 43. The remarkable coincidence of the epicentres with the postulated displacements, especially that between profiles 44 and 43, is convincing proof of the existence of a transform fault in this region. The faulting is also reflected in the bathymetry. In figure 13 the trend of the axial trough is shown by a line following the greatest depths. Between $19\frac{1}{2}°$ and $19\frac{3}{4}°$ the contours become complicated and if an attempt is made to join the axial trend in the south to the trend in the north then displacements must be inferred as shown.

It is rather curious (and at variance with the form of many transform faults plotted across mid-ocean ridges) that there appear to be two displacements in opposite senses so that the pattern reverts to the original Red Sea trend. The horizontal displacements are approximately 40 km but the profile spacing does not allow an accurate assessment of the strike of the faults and further detailed surveys in this area are called for.

An interesting observation is the apparent rotation of the disturbing body in the area leading up to the transform fault that would seem to indicate a twisting of the block in the direction of the shear before fracture.

In the area of strong magnetic anomalies to the north (22 to 23° N) an attempt can also be made to fit a spreading model to the observed anomalies. The results are less satisfactory—partly because only two profiles can be used (see figure 9) and partly because the shapes of the profiles are more ambiguous. With these reservations, it does appear that a theoretical model (considered to be of more limited lateral extent than that to the south because of the narrower axial trough) gives the best agreement to the observed curves for a spreading rate of 1.5 cm a^{-1}. It is difficult to reconcile this higher rate of spreading to the north with any simple and constant rotation of Africa from Arabia about a pole position north of the central latitude of the Sea and because of the lack of unambiguous evidence this figure should be treated with some caution.

The magnetic contour charts in figures 6 and 8 show evidence of other offsets in the magnetic pattern together with some supporting evidence of offsets in the bathymetric trend (figure 13). However, the earthquake data supply no supporting evidence of movement along these displacements. They may represent fracture zones which, with further spreading, will become active transform faults. More detailed surveys are required to remove the present uncertainty.

4. Gravity

Charts of the free-air and Bouguer gravity anomalies constructed from the *Aragonese* profiles are shown in figures 14 and 15 (whole sea) and figures 16 and 17 (detail). In the computation of the Bouguer anomaly, terrain corrections were applied and the density assumed for the rock replacing the water column was 2.67 g cm^{-3}. It is believed now that this value may be too high in view of the large thickness of low-density evaporites that is believed to underlie parts of the Red Sea depression.

The whole of the Red Sea from the entrance to the Gulf of Aqaba to the Bab-el-Mandeb Strait is characterized by a positive Bouguer anomaly. The +100 mgal† contour follows very

† 1 mgal = 10^{-3} cm s^{-2} = 10^{-5} m s^{-2}.

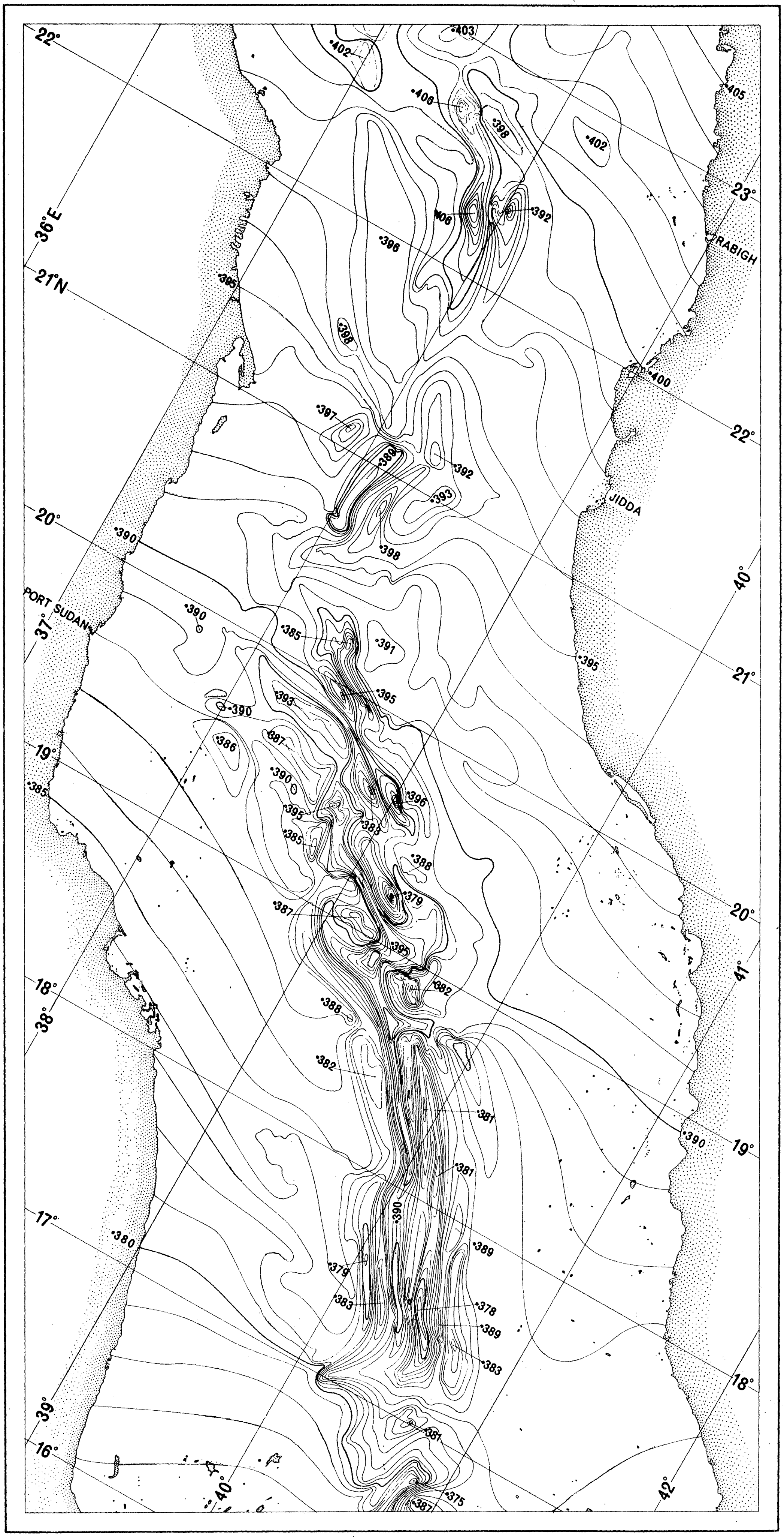

FIGURE 7. Detail of total magnetic field (epoch 1961). Contour interval 100 nT.

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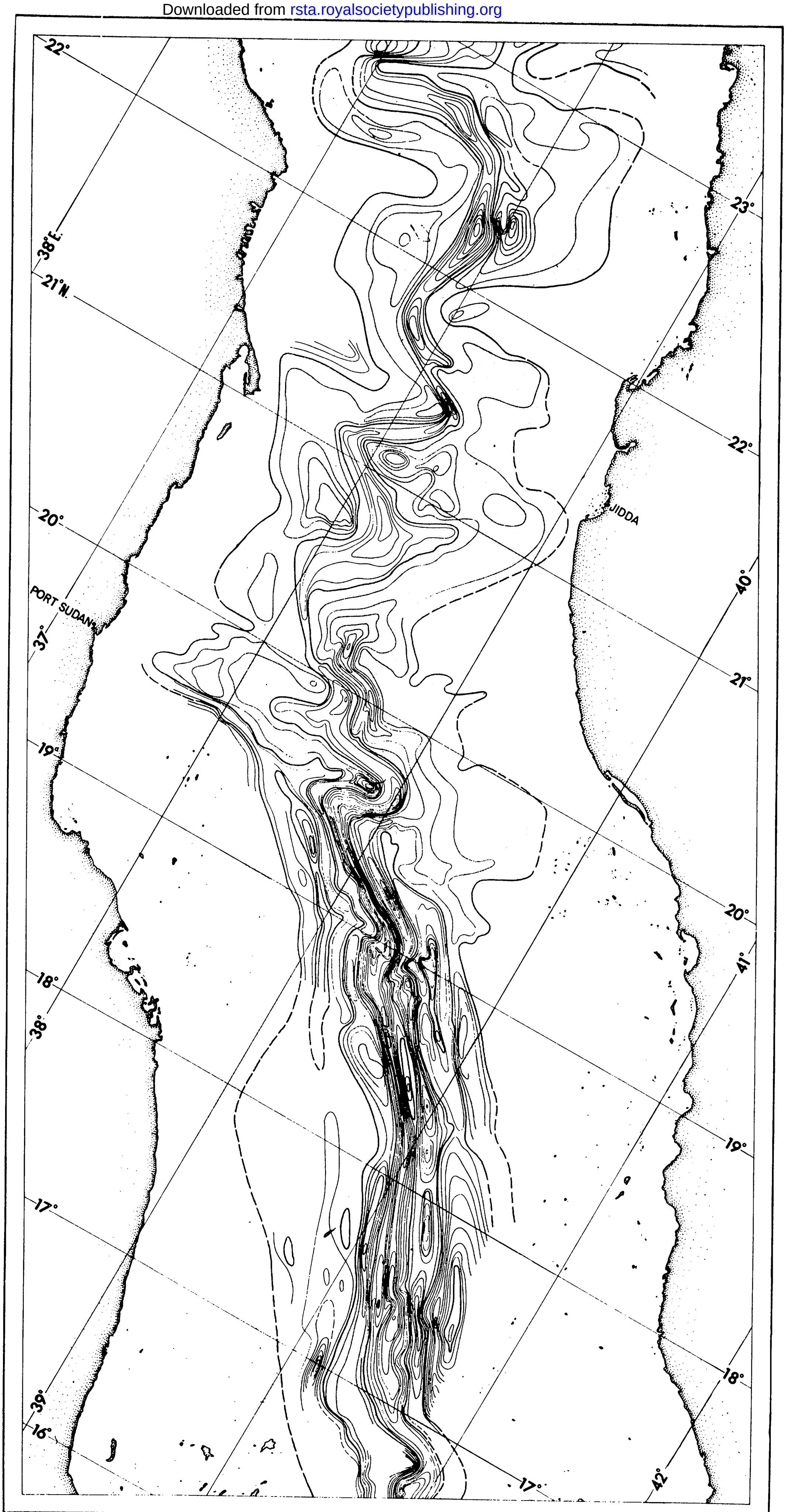

FIGURE 8. Detail of anomalous magnetic field. Contour interval 100 nT. Negative anomalies are shaded.

closely the boundary of the axial trough with maximum values in the range 120 to 150 mgal recorded over the centre. North of latitude 23° N, where both the magnetic anomalies and the axial trough start to die out, the gravity anomaly diminishes in amplitude but remains positive up to the northern margin of the Sea with an average maximum of approximately +80 mgal. A possible explanation of this behaviour is that whereas the magnetic anomalies are caused by a relatively thin and shallow block, the gravity anomaly is produced by a combination of this

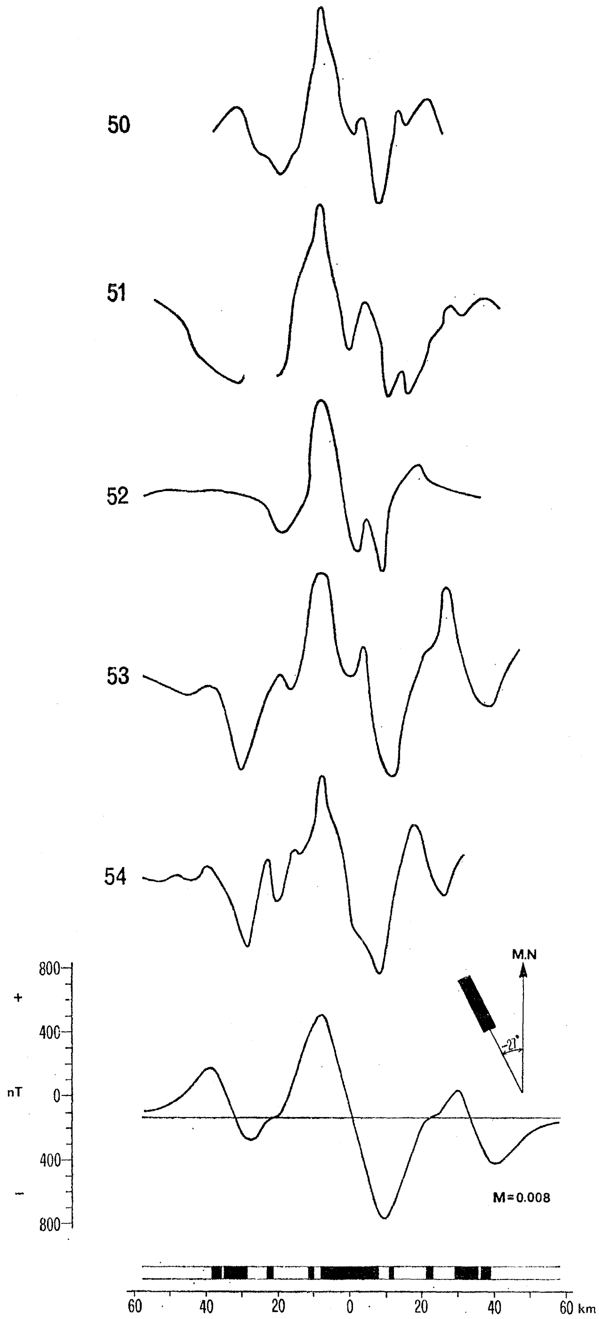

FIGURE 10. Five consecutive magnetic profiles south of 19° N compared with the calculated anomaly (bottom curve) for the spreading model with a spreading rate of 1.1 cm a^{-1}.

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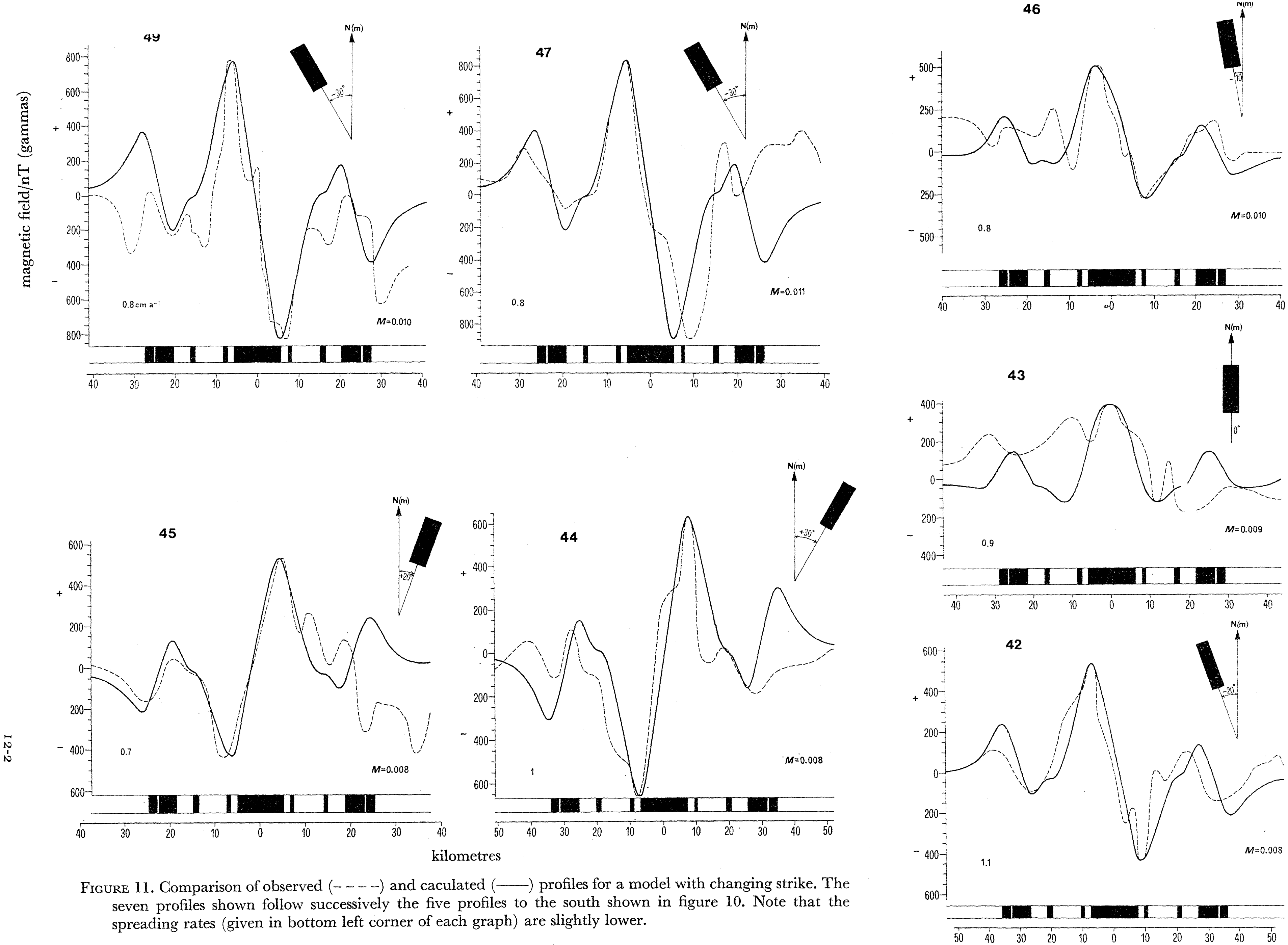

FIGURE 11. Comparison of observed (– – – –) and caculated (——) profiles for a model with changing strike. The seven profiles shown follow successively the five profiles to the south shown in figure 10. Note that the spreading rates (given in bottom left corner of each graph) are slightly lower.

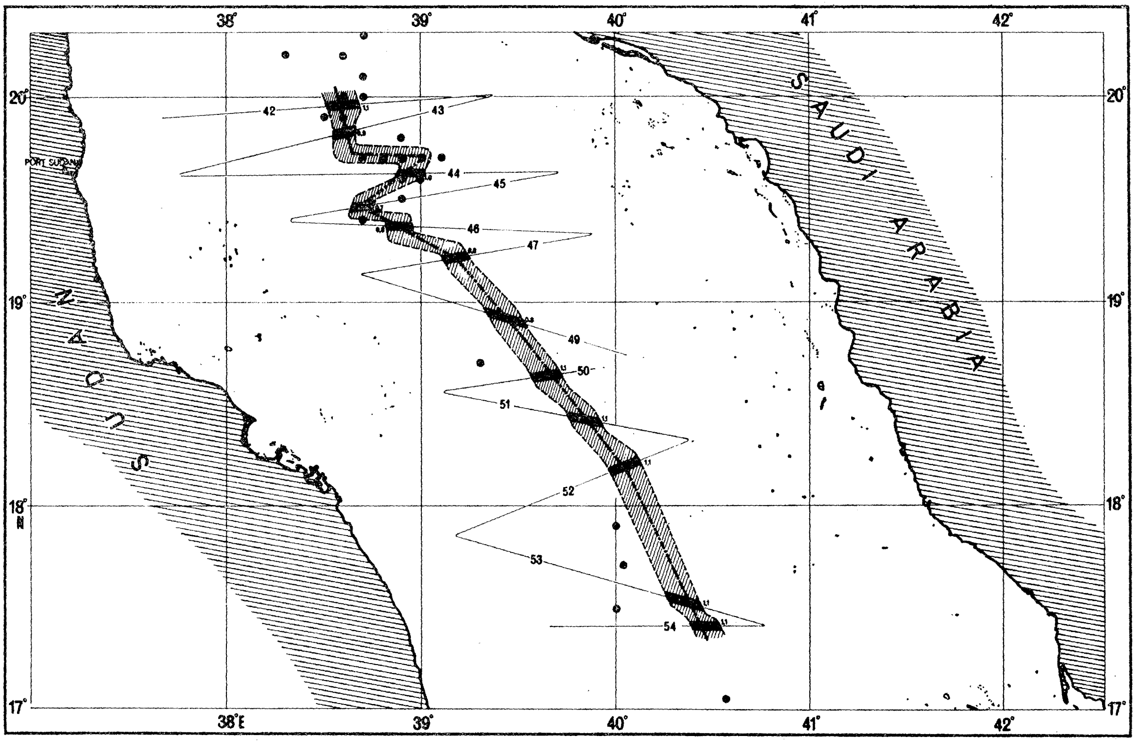

Figure 12. The trend of the model blocks for the profiles shown in figures 10 and 11. The assumed strike of the models is shown by the inclination of the central block (Bruhnes) on the profile. Earthquake epicentres for the period 1958–1967 (International Seismological Centre) are also shown.

block and an elevated mantle—the greatest effect being produced by the latter. Not only are the anomalies too wide and their gradients too small to be produced by shallow bodies of limited vertical extent but the amplitudes are such that a very high density contrast would have to be assumed between an intrusive shallow body and the surrounding shield rocks.

An interpretation has been attempted on the assumption that the material which causes the magnetic anomalies is underlain by a block which is generally wider, twice as thick and with a density contrast twice that of the magnetic material. Although these assumptions may appear rather arbitrary the intention is to see if a universal basic model can reproduce the main features of the anomaly rather than attempt a perfect fit for each profile by adjusting the shape of the disturbing body. The observed curves are not symmetrical and therefore a perfect fit is not possible using bodies of rectangular cross section; nevertheless, the duplication of the main features is fair. The location of the selected profiles is shown in figure 18. Profiles AB and CD were reconstructed from the contour chart while the others are observed profiles. Where no magnetic anomaly was recorded only the deeper block was assumed and where a magnetic interpretation had been made with a spreading model then the same model dimensions were used for the gravity interpretation together with the deeper block.

The results are shown in figure 19. The density contrast for the shallow block averages 0.18 g cm^{-3} and for the deeper, non-magnetic block, 0.36 g cm^{-3}. Such an interpretation implies that the gravity anomalies in the northern part of the sea are caused by a rising mantle. To the south rifting has occurred to an extent that has caused the injection of magnetic dykes forming a veneer between the bottom of the rift and the top of the mantle. The implications of this interpretation are discussed in § 7.

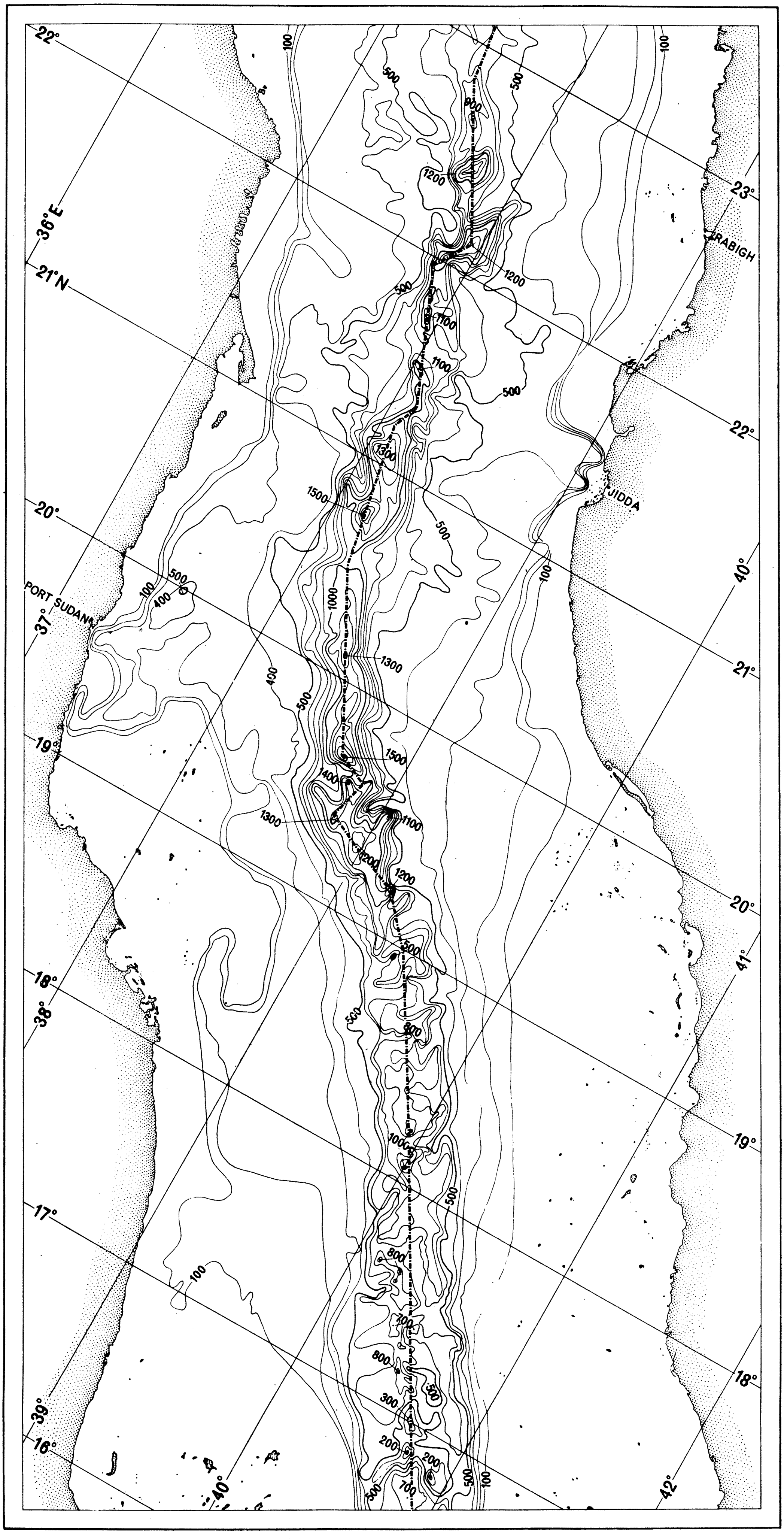

FIGURE 13. The trend of the deepest part of the axial trough. Note the apparent offsets.

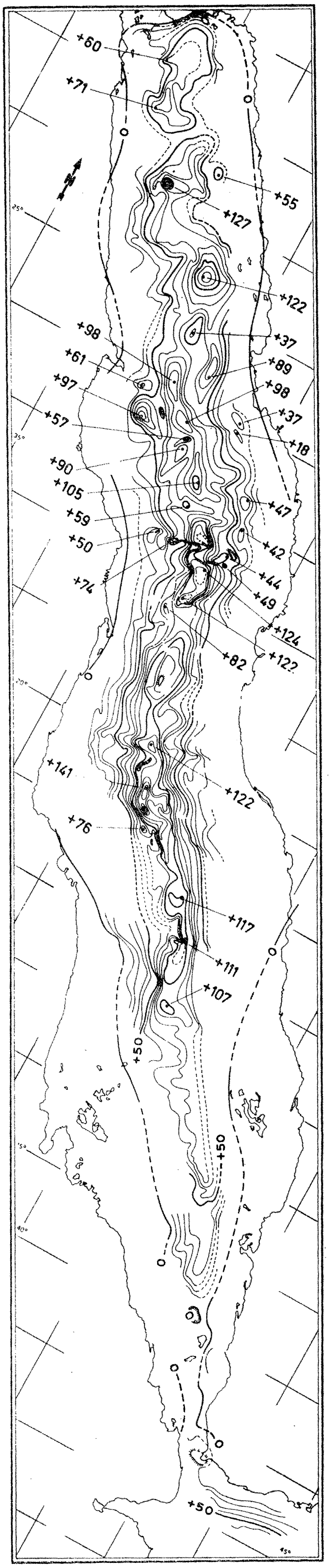

FIGURE 14. Free-air gravity map over the whole Sea. Contour interval 10 mgal.

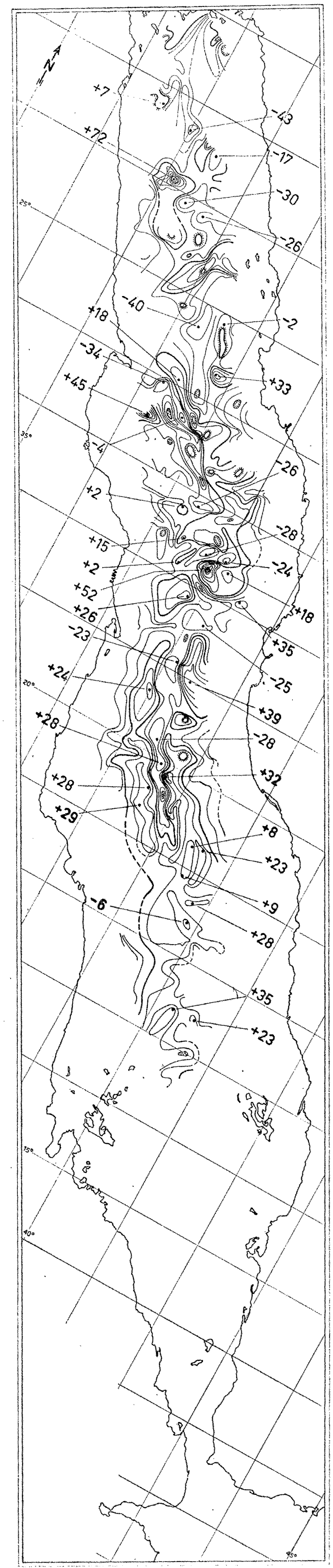

FIGURE 15. Bouguer gravity anomaly over the whole Sea. The water column is assumed to be replaced by rock of density 2.67 g cm^{-3}. Contour interval 10 mgal.

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6. The Gulf of Aqaba

A one-day survey of the Gulf of Aqaba, extending two-thirds of the way up to the Gulf, was made by *Aragonese* at the conclusion of the Red Sea survey. Contour charts of bathymetry, magnetic field and free-air gravity are shown in figures 20 to 22.

In contrast to the Gulf of Suez, the Gulf of Aqaba reaches a remarkably great depth with respect to its width. The magnetic field is featureless while the free-air gravity anomaly falls from zero at the entrance of the Gulf to −190 mgal over the deepest part.

There is ample geological evidence for a shear along the Gulf of Aqaba and Jordan Valley (Quennel 1958; Freund 1965 and this volume, p. 107) which caused a two-stage horizontal displacement of the Arabian block with respect to the Sinai block. The first stage dates from Lower Miocene and resulted in a southerly displacement of 62 km of the Sinai block. After a period of quiescence a second stage movement caused a further 45 km displacement in the same direction.

The geophysical measurements in the Gulf of Aqaba support the geological evidence for a shear movement. The large negative gravity anomaly and the absence of any significant magnetic anomaly are in marked contrast to the central and southern Red Sea although the depth of water is comparable.

7. The drift of Africa and Arabia

The success of the seafloor spreading theories, the subsequent development of plate tectonics by Morgan (1968), Le Pichon (1968) and others and independent paleomagnetic and geological evidence have so firmly established the concept of continental drift that there is no longer any serious doubts on whether or not Africa and Arabia have drifted apart but only on the manner and extent of separation.

The axial zone of the Red Sea is similar in many respects to the rift valleys at the crests of mid-ocean ridges. The few heat flow measurements that have been made in the Red Sea (Sclater 1966; Birch & Halunen 1966; Langseth & Taylor 1967) have an average value three times higher than the world's average. Seismic refraction profiles reported by Drake & Girdler (1964) and Tramontini & Davies (1969) show the axial trough to be underlain by material with an acoustic velocity in the range 6.4 to 7.3 km s^{-1}. Where the trough is well developed this material reaches to 4 km below the sea surface (2 km below the sea floor) while in the north, under the main trough, the depth increases to 7 km below the sea surface.

Seismic reflexion profiles reported by Knott, Bunce & Chase (1965) show a sequence of mildly deformed sedimentary rocks reaching a thickness of 1.8 km under the marginal zones of the main trough. No such sequence exists under the axial trough where the subbottom was found to be intensely deformed.

Before the heat flow and seismic measurements, the results of four gravity stations in the southern Red Sea (Girdler & Harrison 1957) and the *Dalrymple* magnetic profiles (Allan 1960) were already being interpreted in terms of a rifting and intrusion of basic rock along the axial trough. Girdler (1962) has been particularly active in relating the formation of the Red Sea to continental drift.

Any postulated movement of blocks to form the Red Sea must take account of: (i) the horizontal displacements known to have occurred along the Dead Sea–Aqaba rift (Quennel

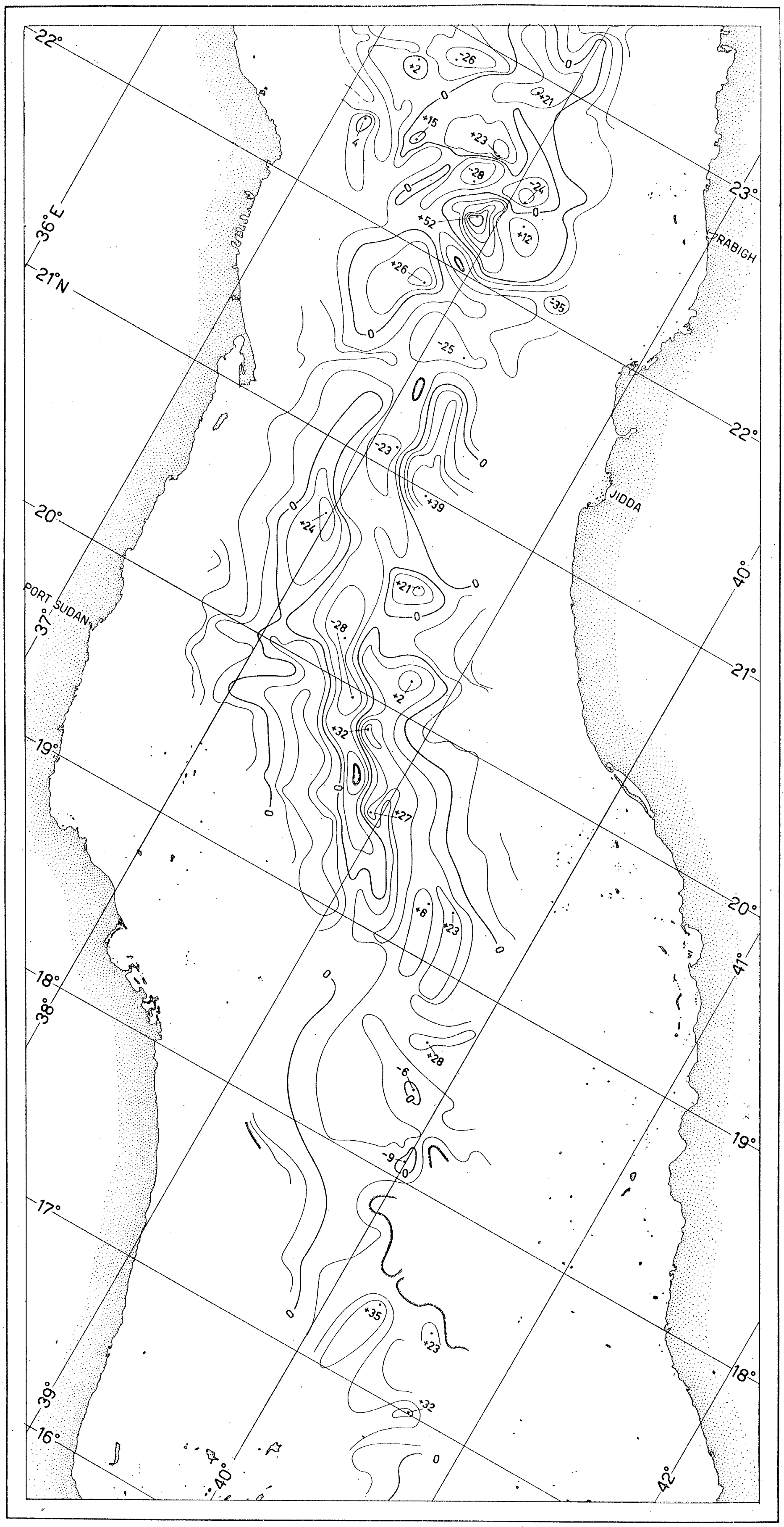

FIGURE 16. Detail of free-air gravity anomaly over the central part of the Sea. Contour interval 10 mgal.

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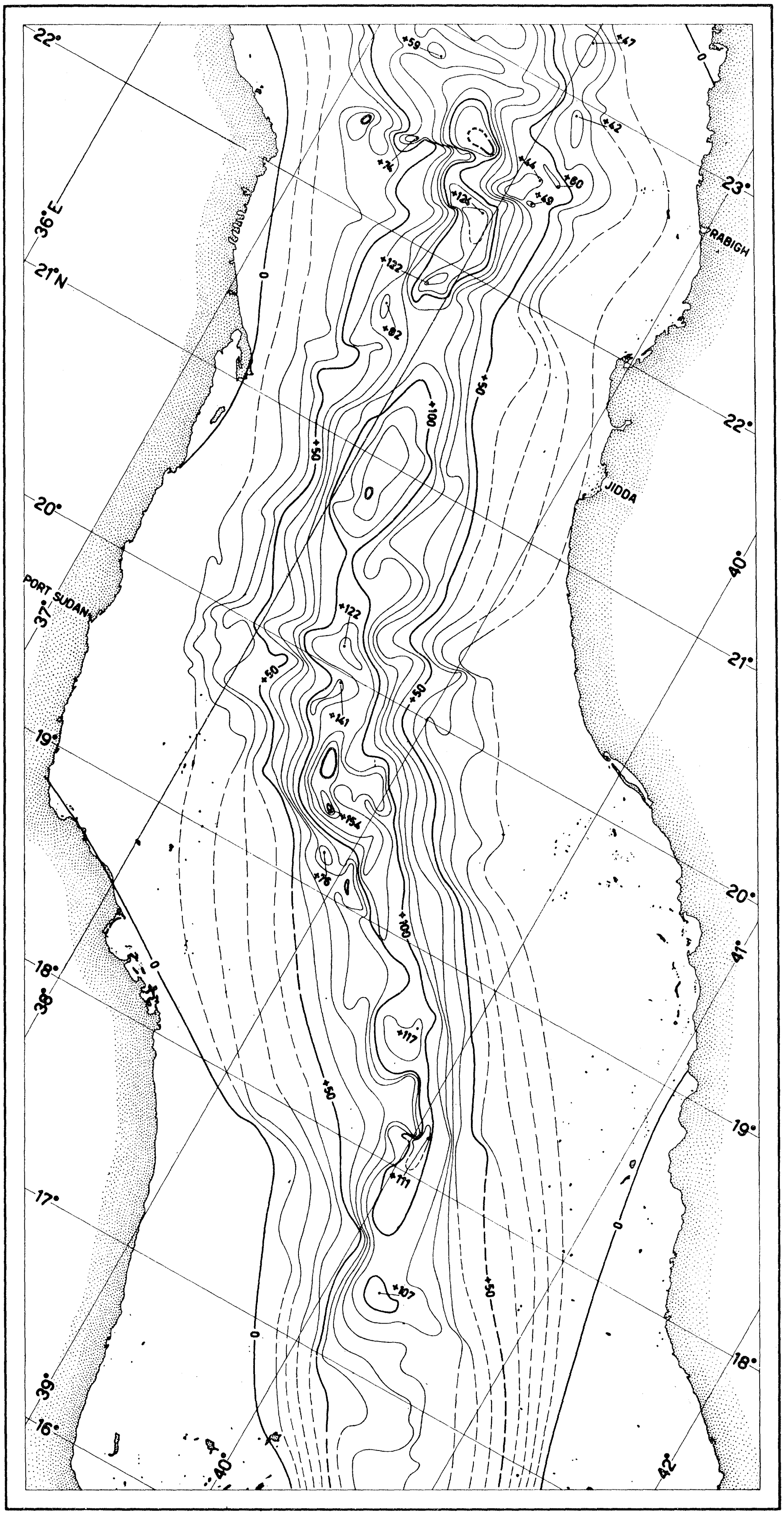

Figure 17. Detail of Bouguer gravity anomaly over the central part of the Sea. Contour intervals 10 mgal.

1958; Freund 1965, this volume, p. 107), and (ii) the mode of formation of the Gulf of Aden.

Laughton (1966) considered the Gulf of Aden to have opened in two stages. The first stage which started in Lower Miocene, carried the Arabian block north–northeast and rotated it anticlockwise. Block faulting gave rise to the Gulf of Aden fault scarps of Somalia and Southern

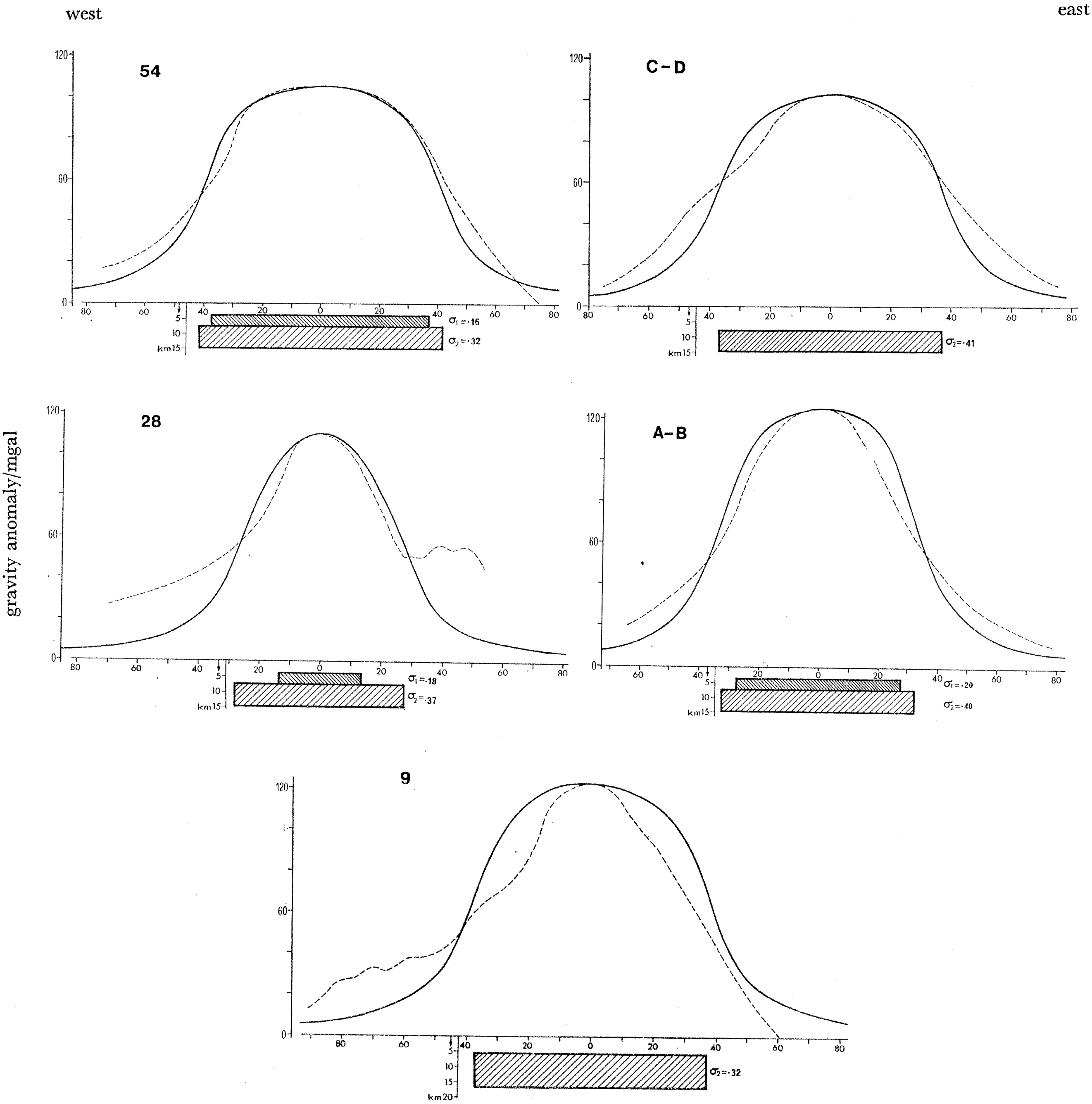

Figure 19. Comparison of observed and calculated Bouguer anomalies for five selected profiles. The upper block, where present, corresponds to the model assumed in the magnetic interpretation.

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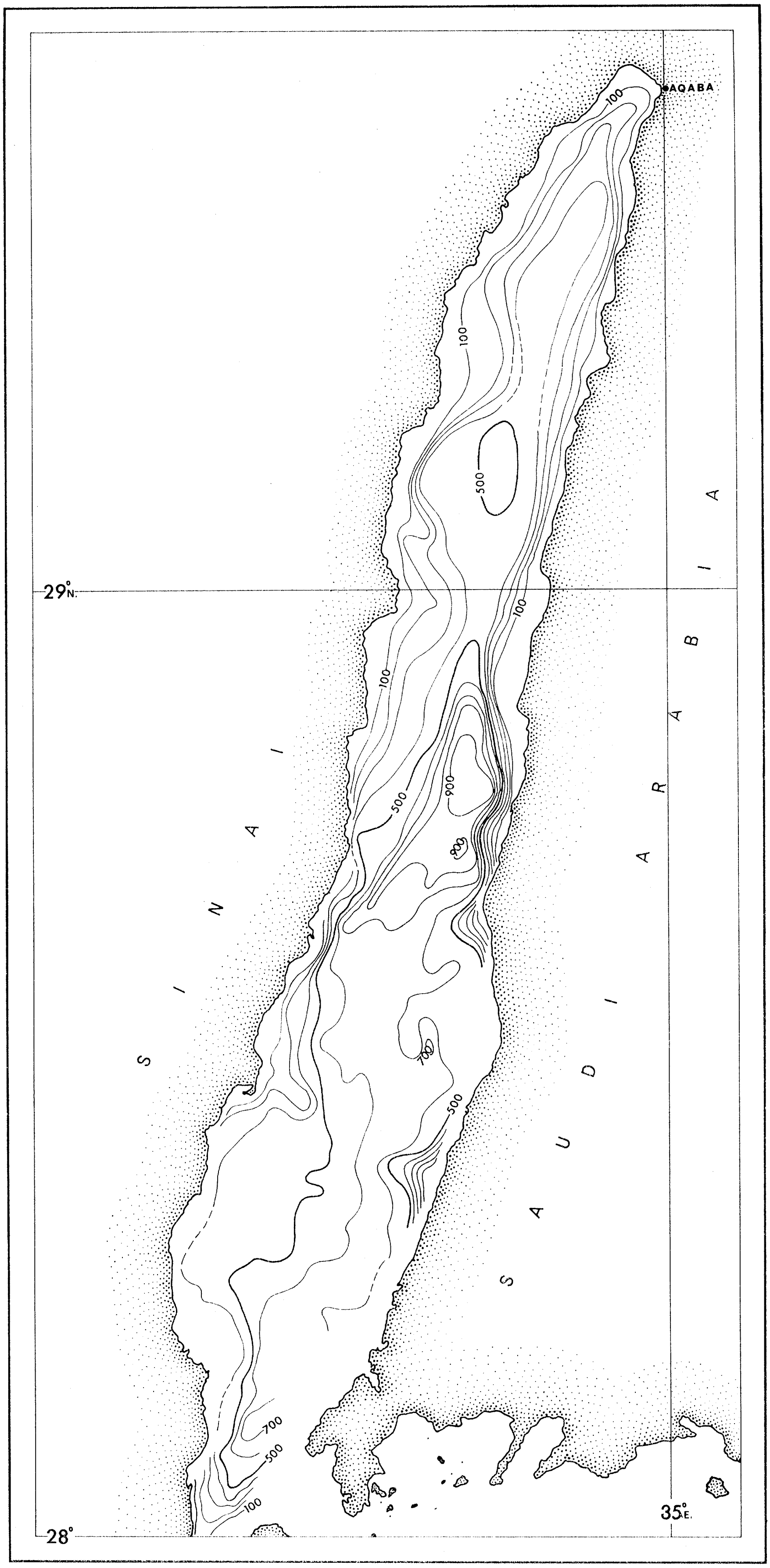

FIGURE 20. Bathymetry of Gulf of Aqaba. Contour interval 100 fathoms. Soundings corrected.

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Arabia and the graben formed is now found as the coastal plains and continental shelves of the Gulf. Subcrustal movements formed new crustal material by stretching, fracturing and thinning of the continental crust and by the intrusion of basaltic dykes. There was then a period of little or no movement during which the main trough accumulated 0.5 to 1.5 km of sediment. The second phase of movement followed the pattern of the first. New crustal material of predominantly basic rocks now forms the central rough zone of the Gulf.

Drake & Girdler (1964) considered the opening of the Red Sea to be limited to the area of the axial trough with down-faulted continental blocks forming the main trough. Their argument was based on the limited extent of the strong magnetic anomalies which they considered to delineate the intrusion of new oceanic crust. Such a reconstruction was not easily reconciled with that postulated by Laughton for the Gulf of Aden nor with the observed displacements along the Aqaba–Dead Sea rift. Girdler (1965) subsequently modified the reconstruction by assuming a northward movement of Arabia by 100 km and a rotation of 7°. Paleomagnetic evidence in support of a rotation of this order had been reported by Irving & Tarling (1961). To take account of the fact that the revised estimate of separation was no longer reflected by the extent of the magnetic anomalies, Girdler assumed the anomalies to be caused not only by the high acoustic velocity material (layer 3) but by volcanic material overlying it. The difficulty in this approach is the ambiguity in the interpretation of the seismic data; for it is necessary to assume that, where magnetic anomalies are present, the low velocity material (3.0 to 5.0 km s^{-1}) overlying layer 3 is volcanic, but, where the anomalies are absent, material of about the same acoustic velocity is evaporite. From bore holes on land (Heybroek 1965) it is known that very large thicknesses of evaporites do occur and it is somewhat unfortunate that the seismic refraction profiles cannot readily distinguish this material from volcanics.

Girdler's revised construction went part of the way to reconciling the displacements along the Aqaba–Dead Sea rift and the rifting of the Gulf of Aden with the Red Sea opening. It did, however, invoke translational as well as rotational movements. A different reconstruction can be made using only rotational movements provided the four blocks postulated by Swartz and Arden are used, that is, Sinai, North-East Africa, Arabia and the Horn of Africa.

From the pattern of seafloor spreading magnetic anomalies in the Indian Ocean and from the direction of transform faults on the Carlsberg Ridge and in the Gulf of Aden, Le Pichon & Heirtzler (1968) estimated that Africa had rotated clockwise about a pole position in Libya (26° N, 21° E). By assuming a total movement of rotation of 7° about this pole at a constant rate since early Miocene (20 Ma), good agreement was found in the Gulf of Aden and the Carlsberg Ridge between calculated and measured rate of spreading and between calculated and measured strike of the ridge (if it is assumed that movement of the crust was perpendicular to the ridge crest). It is significant, however, that poor agreement was found for the Red Sea where the calculated spreading rate (at latitude 19° N) was 0.6 cm a^{-1} as opposed to the measured value in the range 0.8 to 1.1 cm a^{-1}. There is reason then to reconsider the mode of formation of the Red Sea with respect to the more recent data.

At present it is difficult to establish an accurate direction of rotation from either the strike of transform faults or from first motion studies of the earthquake data. By trial and error, it is found that an African pole of rotation located in Southern Italy gives a reasonably good fit for the opposite shorelines of the Red Sea and at the same time provides the necessary shear displacement along the Dead Sea–Aqaba rift if the Sinai peninsula is considered as a separate block. The suggested two phases of movement are shown in figure 23. During the first phase a

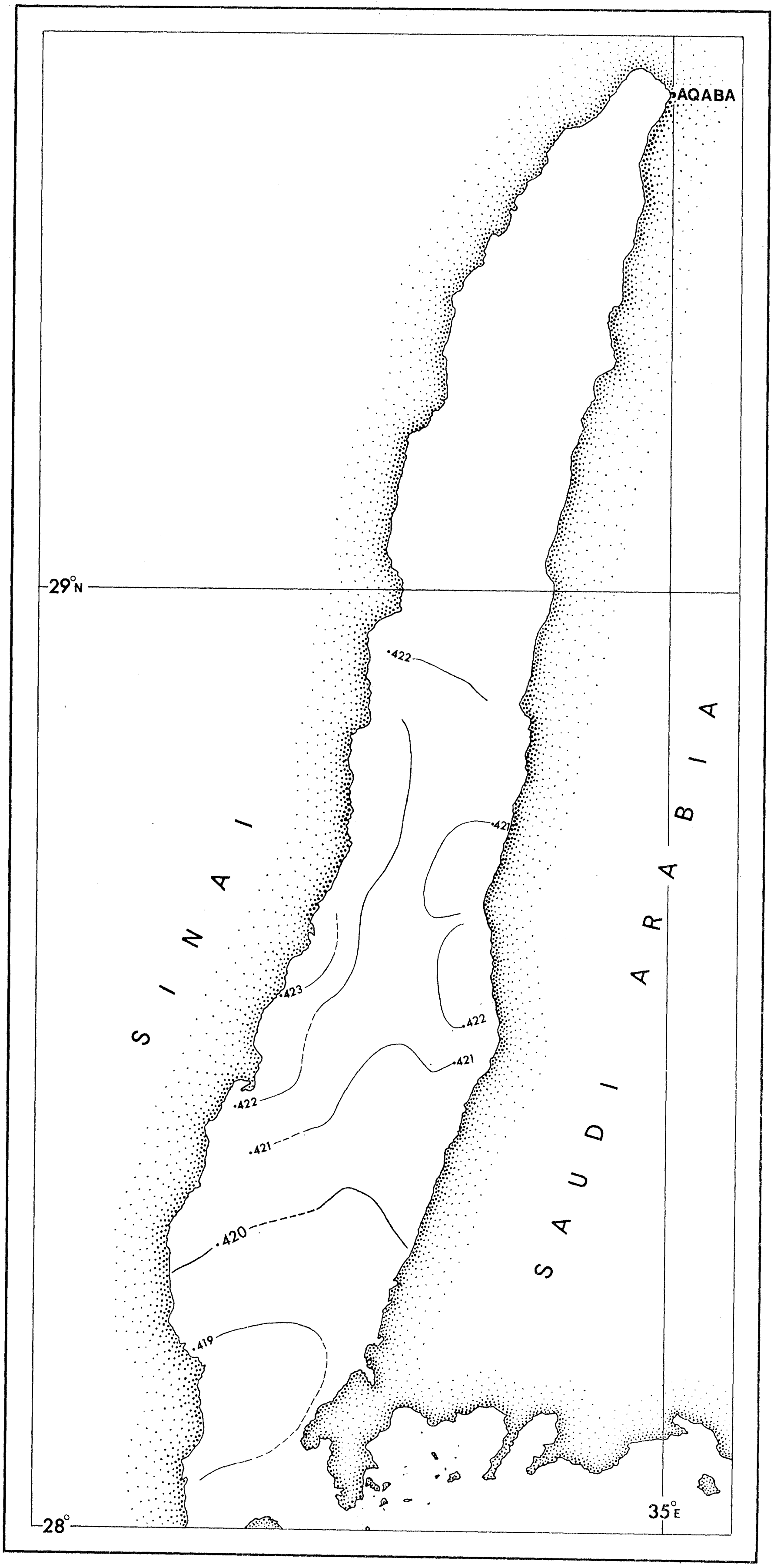

FIGURE 21. Total magnetic field over the Gulf of Aqaba. Contour interval 100 nT.

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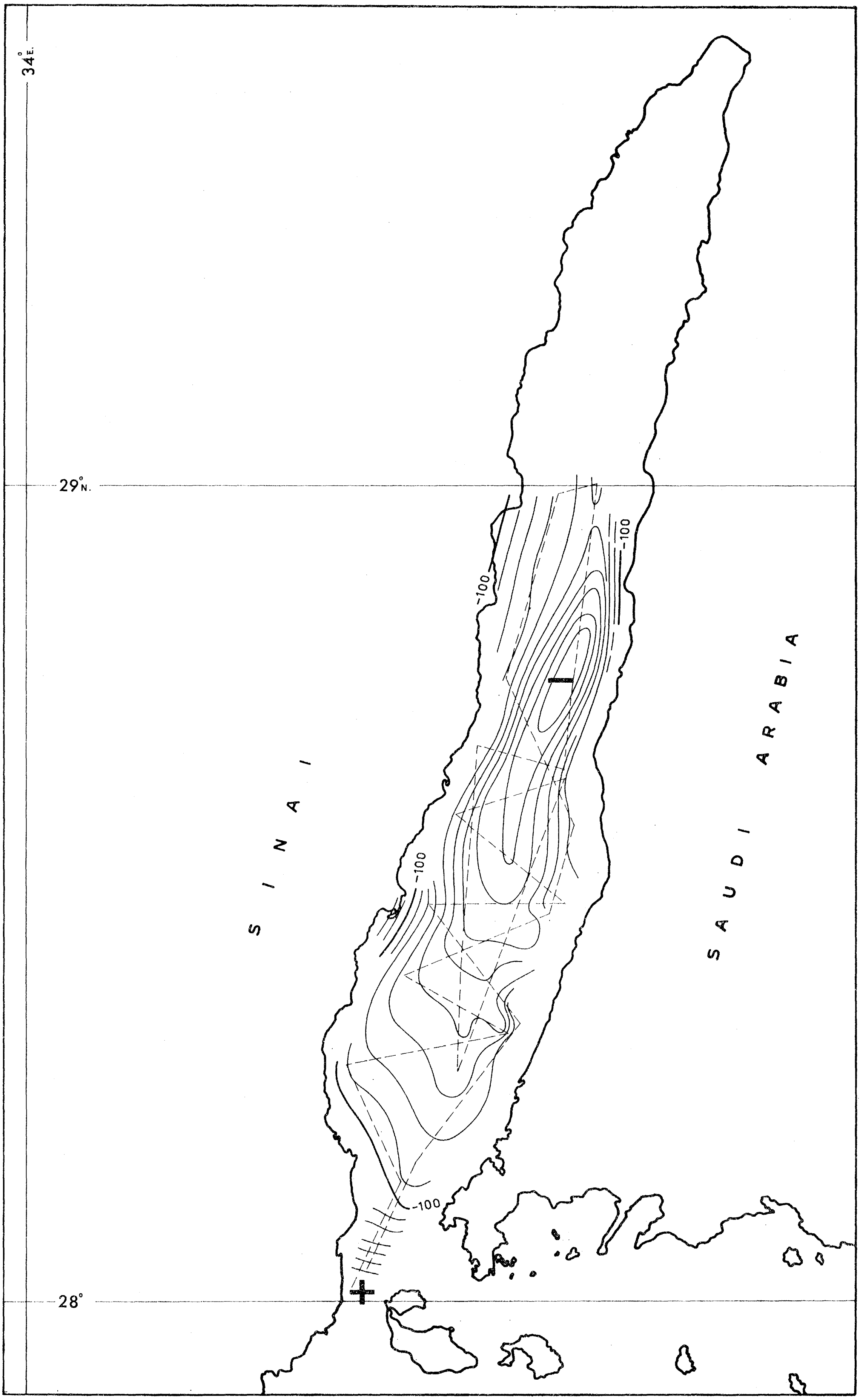

FIGURE 22. Free-air gravity anomaly in the Gulf of Aqaba. Contour interval 10 mgal; – – –, track of profiles.

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horizontal displacement of 60 km is assumed along the Dead Sea–Aqaba rift and during the second phase 45 km is assumed. Local compression between Sinai and Arabia would explain the high physiographic relief of the area and the observed negative gravity anomalies in the Gulf of Aqaba. The axial trough of the Red Sea is considered to have been formed during the second stage.

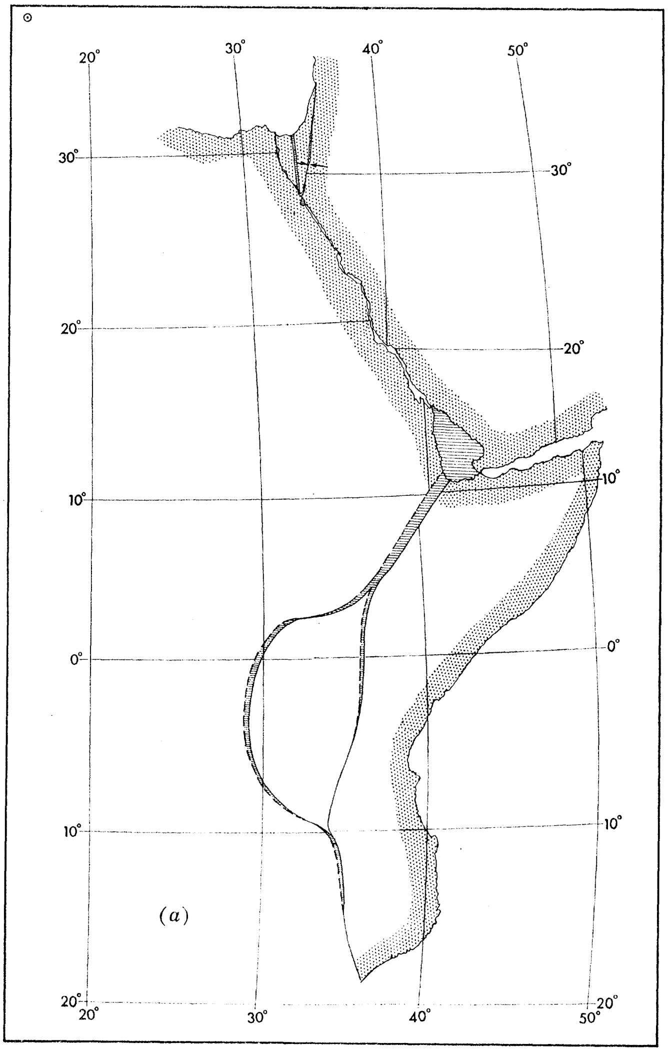

Figure 23 *a–c*. Reconstruction of the rotations between the four blocks—North Africa, Sinai, Arabia and the Horn of Africa.

(*a*) Positions at the Lower Eocene. The hatched areas represent overlap. Note the juxtaposition of the arrows along the Aqaba–Dead Sea rift.

The simple rotation cannot, however, supply the amount of opening required to form the Gulf of Aden but if the Horn of Africa forms a separate block as suggested by Swartz and Arden, then a rotation of this block as shown in figure 23*b*, increasing the opening in the Gulf of Aden at the expense of movement along the present East African rift system, provides most of the additional movement required. It is evident that such a reconstruction requires that the Yemen once overlapped the Afar triangle.

The negative gravity anomalies and general absence of magnetic anomalies over the Gulf of Aqaba and the East African rift valleys may be considered as expressions of the complementary compressional forces which accompanied the tensional forces opening the Red Sea and Gulf of Aden.

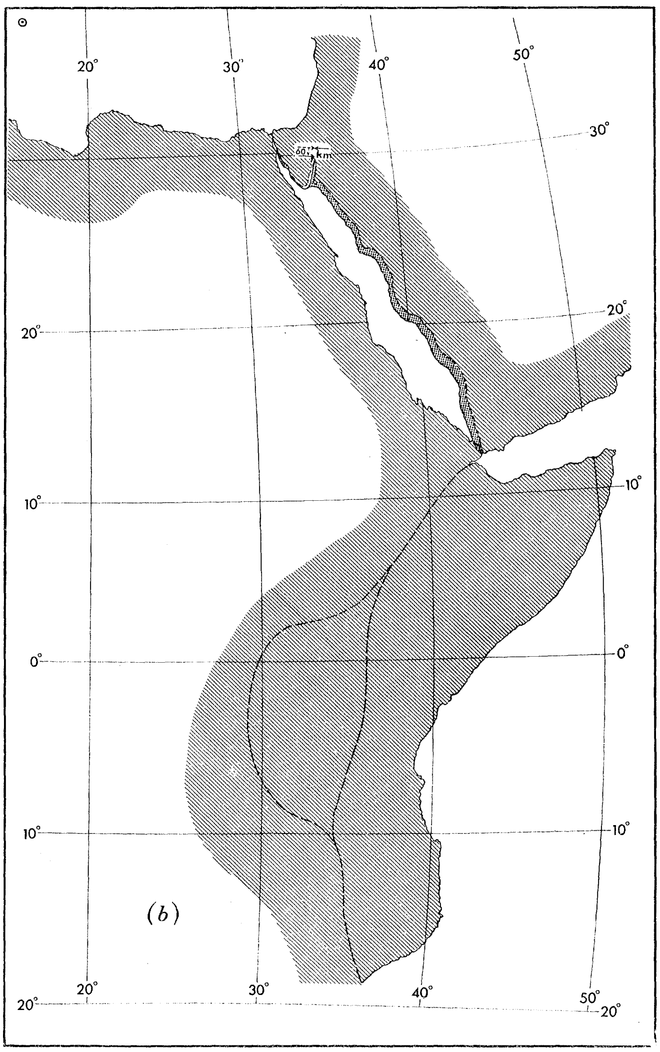

Figure 23 (*b*). Positions approximately 4 Ma ago. The North African block has been rotated clockwise about the pole position shown in the top left-hand corner. This rotation has caused the Sinai block to move 60 km to the south. The Horn of Africa has rotated clockwise about a pole position in South Africa. The dotted strip along the eastern coast of the Red Sea represents the difference between the present coastlines and those 4 Ma ago. The width of the strip approximately equals the present axial trough.

It has been shown that the magnetic anomaly pattern over the central and southern Red Sea indicates a spreading rate of about 1 cm a^{-1} over the last 3–4 Ma. This rifting, which present earthquake activity indicates is still going on, represents the second stage of opening. Between the first and the second stage there was, apparently, a period of quiescence borne out by the large thickness of sediment observed on the flanks of the trough by Knott *et al.* (1965). Likewise, Laughton (1966) attributes observed sediment thicknesses of 0.5 to 1.5 km in the Gulf of Aden to a period of quiescence between two active periods of rifting.

The first stage of separation was started in the Lower Miocene (Swartz & Arden 1960). Compressional forces occurred in the northern part of the Red Sea while tensional forces developed in the south. The gradual separation of the African and Arabian blocks continued throughout the Eocene and Oligocene while the Horn of Africa started to rotate during the Lower Miocene. If such a two-stage separation is correct, then an explanation must be found for the fact that the strong magnetic anomalies in the Red Sea occur only over the axial trough and not over the wider main trough. It was this observation that originally led Drake & Girdler to assume that the separation in the Red Sea was limited to the width of the axial trough.

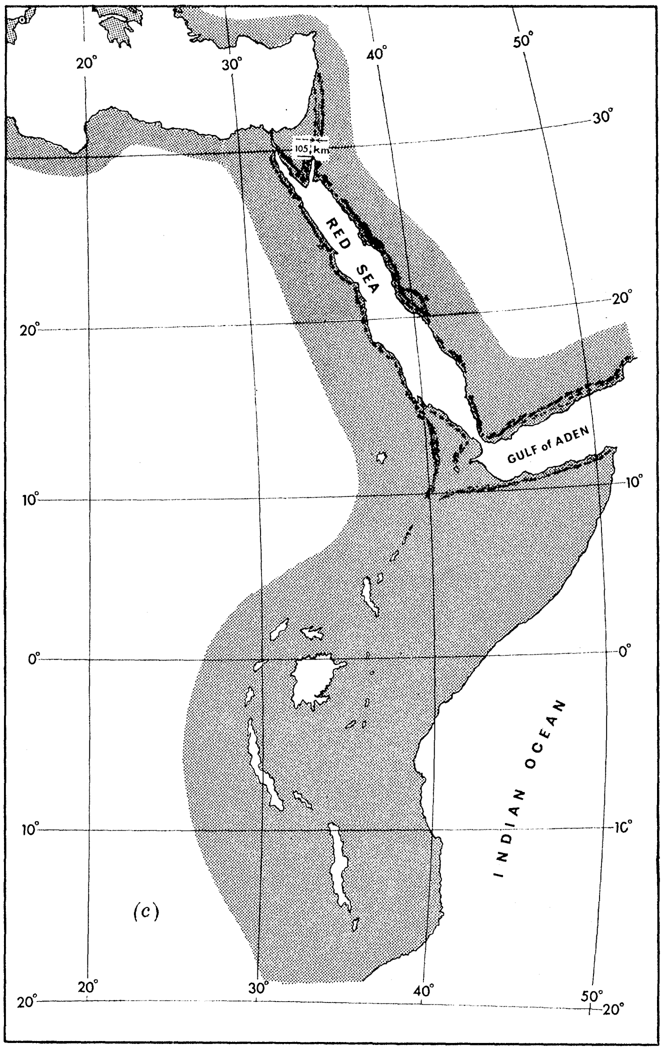

FIGURE 23 (c). The Red Sea area at present. A further rotation of the North African block about the same pole position has caused a further 45 km displacement of the Sinai block. This most recent rotation has opened the axial trough of the Red Sea.

When the African–Arabian blocks first came under tension it is highly unlikely that there would be an immediate rupture with injection of new oceanic crust into the crack. The first result would be a thinning and necking of the continental crust rather in the manner of a bar

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of caramel being pulled apart. The mantle would rise, the two blocks would move apart but fracture would not necessarily occur. Also, since the separation may have continued throughout the Eocene and Oligocene the rate of separation could have been comparatively slow. These two factors could explain the lack of magnetic expression of the first stage of separation.

If this is the true explanation for the observed magnetic pattern one would nevertheless expect an elevated mantle under the whole of the Red Sea and the fact that the Bouguer anomalies are everywhere positive (being approximately zero along opposite coastlines) appears to support this view. In the northern Red Sea there is no axial trough and no strong magnetic anomaly pattern but the gravity anomalies are positive. This would indicate that the tensional forces of the second stage of opening have not yet been sufficiently great to cause rupture and injection of magnetic material although the mantle has been elevated under the main trough. By contrast the shear movement between the Sinai block and the Arabian block is largely the result of compressional forces which is reflected in the Gulf of Aqaba by a negative gravity anomaly and the absence of magnetic anomaly.

There remains some uncertainty about the nature of the material causing the magnetic anomalies. In the calculation of spreading rates, the anomalies were associated with layer 3 material, considered to lie between 3.6 and 7.2 km below the sea surface. It is quite possible, however, that a major part of the anomaly is produced by a volcanic layer overlying layer 3 and with an acoustic velocity similar to that of evaporites. Under the axis of the main trough in the northern part of the sea, layer 3 was detected at a depth of approximately 7 km below the sea surface (station 183 of Drake & Girdler 1964). A magnetic profile passes close to this station and calculations were made on the anomaly that would be produced by model blocks lying between 7 to 11 km and 7 to 8 km. The intensity of magnetization was taken to be equal to the lower limit (0.008) of the range calculated for the axial trough anomalies. Even the thinner of the two models produces a peak-to-trough amplitude of 200 nT which was not observed on the profile. It appears that layer 3 material may not be the basic cause of the anomalies, although at a depth of 6 km below the sea floor it is possible that the increase in temperature is high enough to raise the material above its Curie point. Thus the test is not conclusive and it is probable that the anomalies are produced by a combination of layer 2 (volcanics) and layer 3 where it reaches close to the sea floor.

8. Conclusions

An attempt has been made to show how the magnetic, gravity and bathymetric results in the Red Sea may be reconciled with a two-stage separation of Africa and Arabia.

The axial trough and the associated magnetic anomalies are expressions of the second stage which has lasted 3 to 4 Ma at an average spreading rate of approximately 1 cm a^{-1}. The northern part of the sea, which shows no magnetic patterns and is seismically inactive, has not yet suffered from this second-stage rupture. In the south the earthquake epicentres provide striking corroborative evidence for a transform fault at $19\frac{1}{2}°$ N which was first detected by the offset in the magnetic pattern.

The first stage of the Red Sea separation started in Lower Eocene and caused the largest separation but due to thinning and necking of the continental crust, and possibly also due to a slow spreading rate, there is no pattern of magnetic lineations. The upwelling of the mantle during this first stage is reflected in the positive Bouguer gravity anomaly which extends over the whole sea.

The negative gravity anomalies and lack of magnetic anomaly in the Gulf of Aqaba plus the high physiographic relief of the Sinai peninsula are considered to reflect shear movement between the Sinai block and the Arabian block during the clockwise rotation of the main African block.

The opening of the Gulf of Aden was caused by two separate effects—the rotation of Africa from Arabia which opened the Red Sea plus the rotation of the Horn of Africa from Arabia. Some shear movement probably occurred along the East African rifts which, like the Gulf of Aqaba, are characterized by negative gravity anomalies.

The pole of rotation of the African block which best fits this reconstruction lies in the toe of southern Italy, while, for the Horn of Africa, the pole of rotation lies in South Africa, but lacking sufficient knowledge of the direction of transform faults in the Red Sea, these determinations are approximate, based on a trial and error fitting of the blocks.

I am grateful to Professor C. Morelli for providing the gravity data. Mr G. Tognarini had the painstaking job of drawing the bathymetric and magnetic contour charts. The Director of the Centre, I. M. W. van Batenburg, kindly allowed me time from other duties to complete the manuscript.

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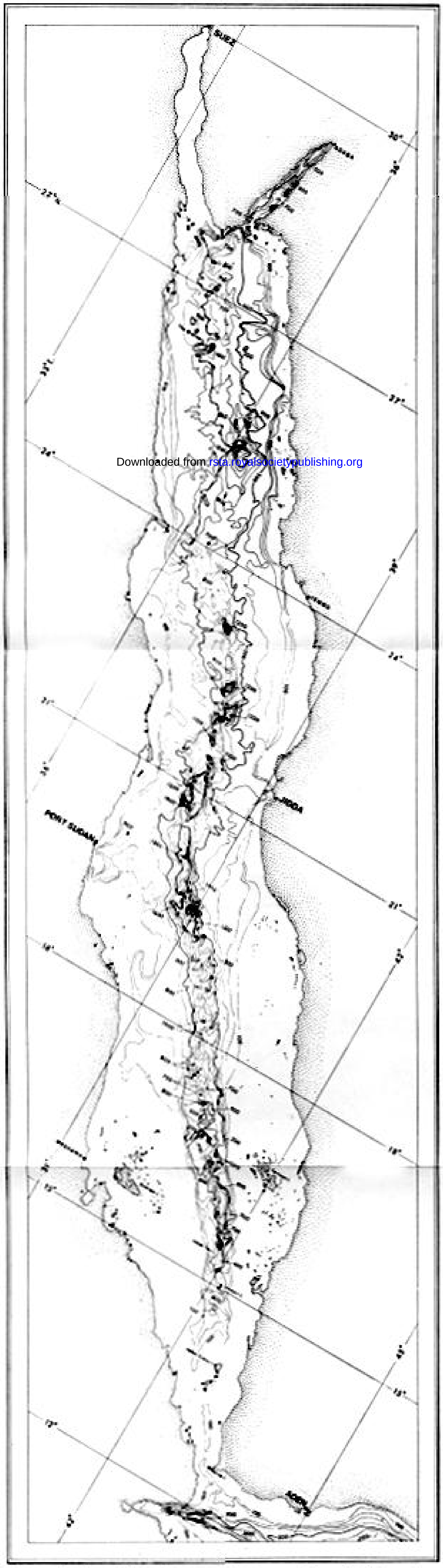

Figure 2. Bathymetric chart with 100 fathom (183 m) contour interval. (All soundings corrected for velocity of sound in sea water according to Matthews' Tables, H.D. 282.)

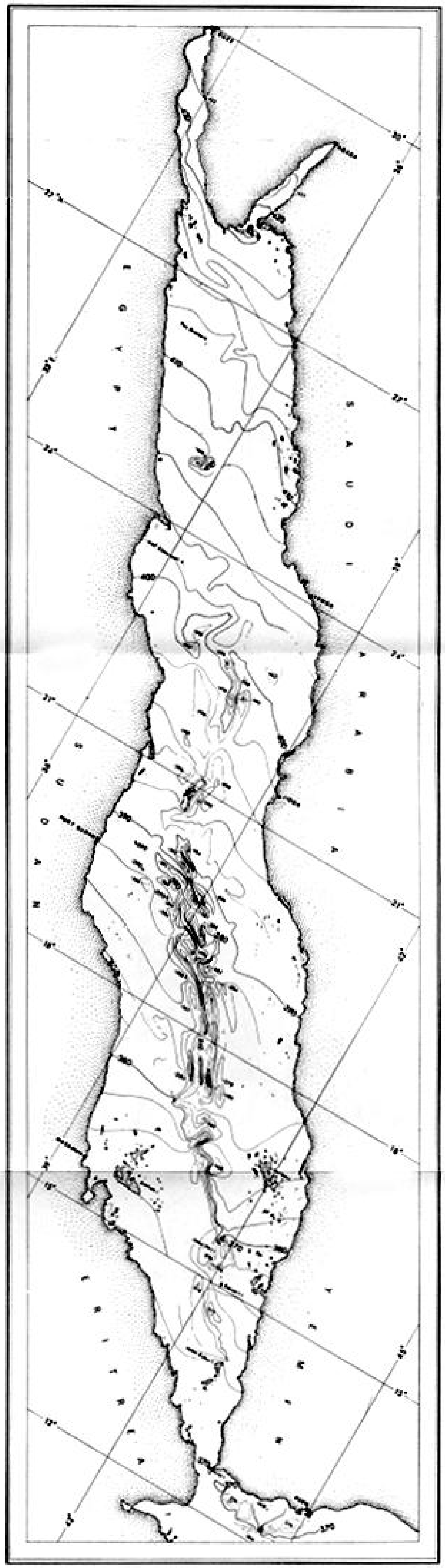

Figure 5. Chart of total magnetic field for epoch 1961. Contour interval 200 nT (gammas).

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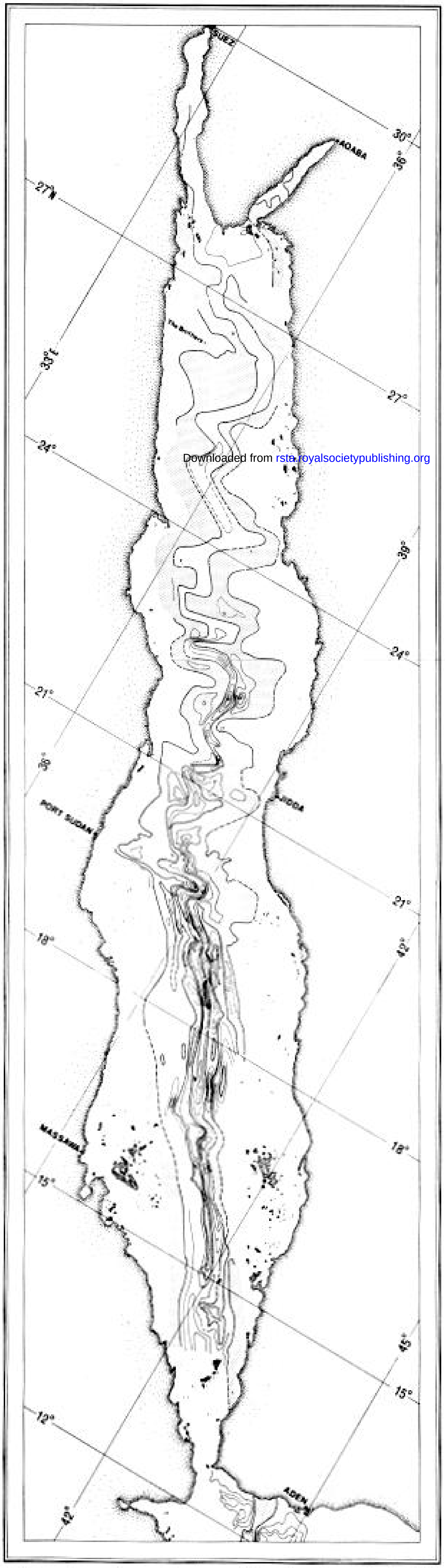

URE 6. Chart of magnetic anomaly constructed by subtracting a regional field from the observed values. Contour interval 200 nT. Negative anomalies are shaded.

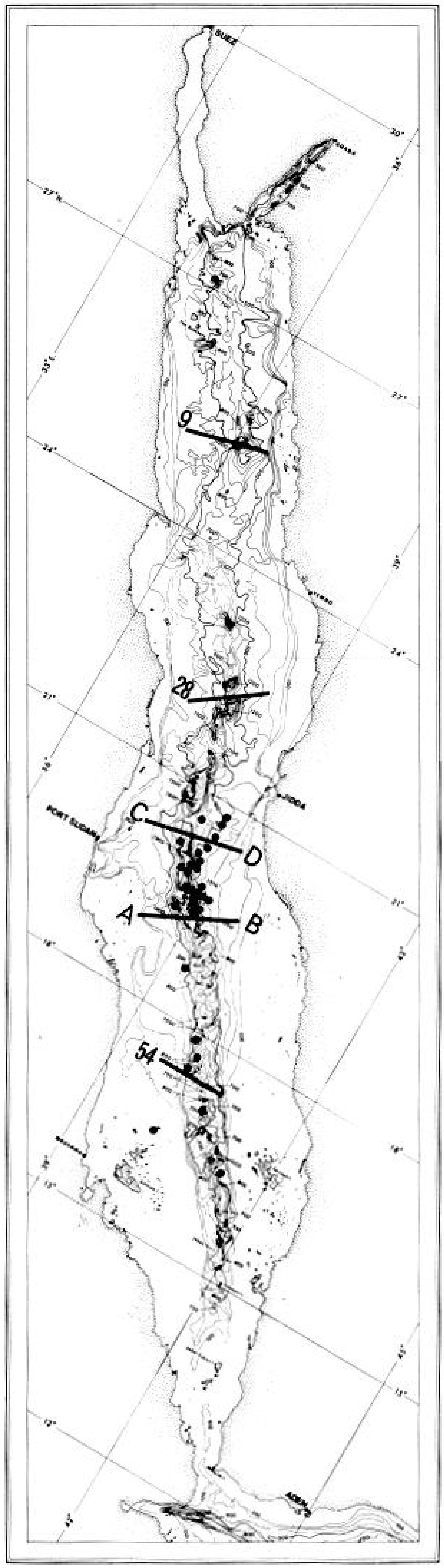

FIGURE 18. Location of gravity profiles for which an interpretation is shown in figure 19. Also shown are the earthquake epicentres for the whole Sea. Note the lack of seismic activity in the north.

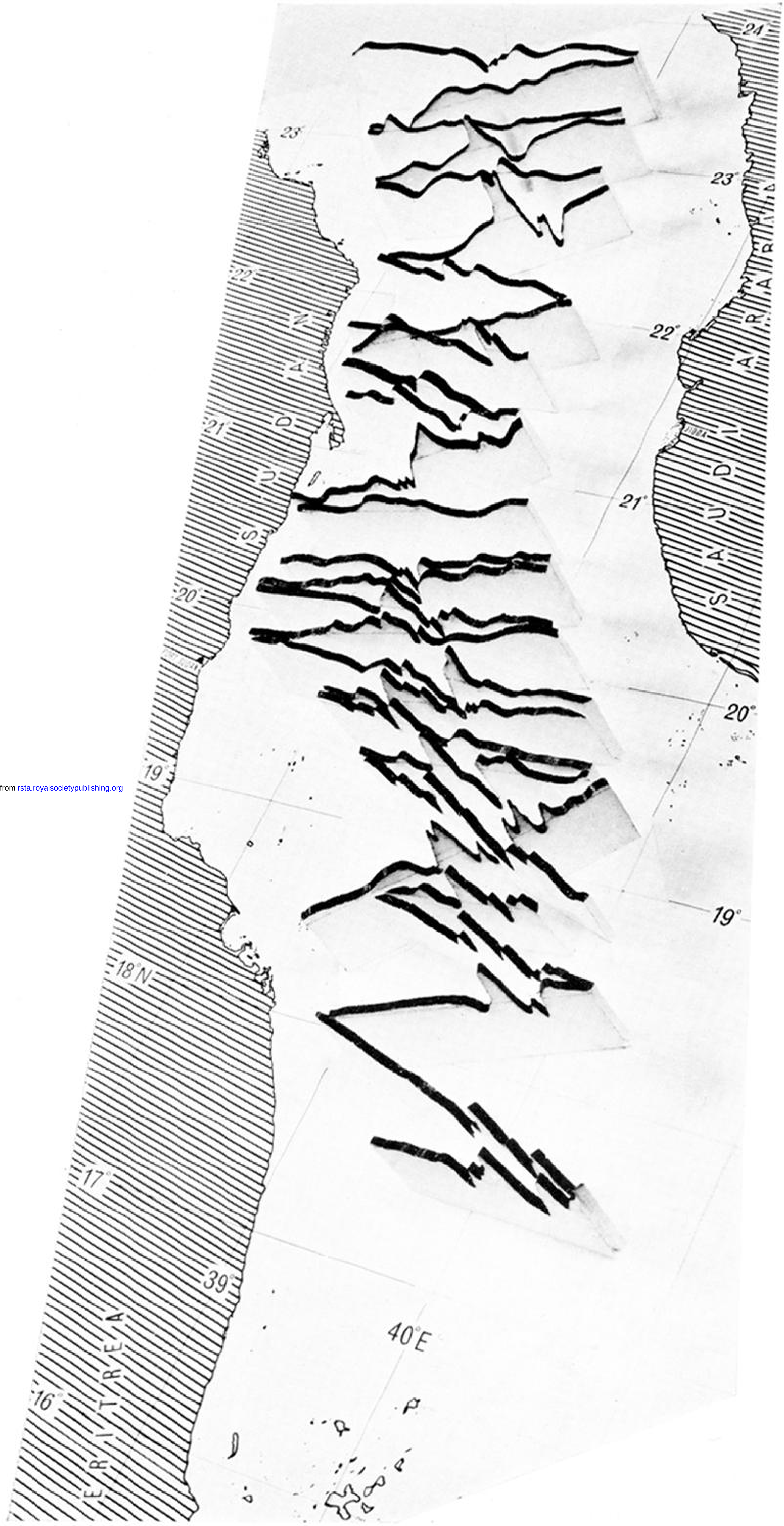

FIGURE 9. Cut-out model of observed magnetic anomaly profiles over the central and southern parts of the Sea.

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