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The evolution of the Gulf of Aden

By A. S. LAUGHTON, R. B. WHITMARSH and M. T. JONES
National Institute of Oceanography, Wormley, Surrey

[Plates 17 and 18; three charts in accompanying wallet]

Marine geological and geophysical data from the International Indian Ocean Expedition, especially from cruise 16 of R.R.S. *Discovery*, have made it possible to prepare new charts of the bathymetry and the magnetic anomaly field which, together with other data, enable the evolutionary history of the Gulf of Aden to be worked out. Over the past 10 Ma the theory of seafloor spreading can account satisfactorily for the features of the Sheba Ridge and provides evidence of spreading rates in the direction of the fracture zones varying from 0.9 cm a^{-1} per limb in the west to 1.1 cm a^{-1} per limb in the east. Between the initial creation of the Gulf and 10 Ma ago, the evolution is less certain, although the geophysical evidence indicates that the crustal structure of the Gulf outside the Sheba Ridge is oceanic.

Introduction

During the past ten years, the body of bathymetric and geophysical data in the Gulf of Aden has increased considerably as a result both of research cruises in the Gulf and of the passage of research ships taking part in the International Indian Ocean Expedition. Most of these ships carried precision echo sounders, many had proton magnetometers and shipborne gravimeters and many stopped for station work. With the closure of the Suez Canal in 1967 and the ending of the I.I.O.E., the rate of data accumulation has considerably decreased, and it is therefore an opportune time to summarize and interpret the data in terms of the theory of seafloor spreading and plate tectonics.

The Gulf of Aden links the East African rift valley system and the Red Sea with the Carlsberg ridge in the NW Indian Ocean, which in turn is part of the world mid-ocean ridge system. The axis of the Carlsberg ridge is offset 310 km right laterally along the Owen Fracture Zone (Matthews 1966) at about 10° N 57° E and continues into the Gulf of Aden as the Sheba Ridge (Matthews, Williams & Laughton 1967). Although in geographical terms, the Gulf of Aden lies westward of the line joining Cape Guardafui to Ras Fartak (approximately 52° E), the bathymetry shows that the continental margin extends, on the south side east of Socotra, to 55° E, and on the north side east of the Kuria Muria Islands to 58° E. In geological terms, the Gulf therefore also extends to these limits. In this paper, the Gulf of Aden will be considered to extend beyond these limits to the junction of the Sheba Ridge with the Owen Fracture Zone since this forms the natural eastern limit of the features associated with the Gulf structure.

The broad outlines of the structures of the Gulf of Aden were discussed by Laughton (1966*a*), interpreting geophysical data that were available up to 1965, mainly as a result of passage work by research and survey ships. At this stage the Sheba Ridge (originally called the central rough zone) was recognized as part of the mid-ocean ridge system and tentative suggestions made about the existence of a median valley, associated with a negative magnetic anomaly, cutting

Note: The units used in this paper conform with the International System of Units (SI). The units of magnetic field used are the nanotesla (nT) equal to 1 γ and the microtesla (μT) equal to $10^3\,\gamma$. a = year; ka = 10^3 years; Ma = 10^6 years.

across the NE–SW ridges and valleys. The median valley, and indeed the entire ridge, was found to be offset by a series of fracture zones (transform faults) the largest of which was the Alula–Fartak trench. Earthquake epicentres correlated with the median valley, and in particular the fracture zones. High heat flow was found over the whole Gulf, the highest values being in the centre. The conclusion was drawn from the geophysical evidence that the Sheba Ridge was an extension westwards of the Carlsberg Ridge.

The sediment-filled troughs either side of the Sheba Ridge showed magnetic anomalies that suggested that they too were underlain by an oceanic crust and this theory was supported by the available seismic refraction data.

It thus appeared that the Gulf of Aden was a young ocean arising from the separation of two continents forced apart by the same mechanism that gave rise to the mid-ocean ridge system. It was suggested that the edges of the broken continent corresponded approximately to the 500-fathom (914 m) line (except in the western end) and that separation had occurred since the Miocene at a rate of about 2 cm a^{-1}.

At the time of writing the above paper, much of the interpretation was speculative and considerably more and better data were needed to substantiate the hypothesis of continental rifting and separation. Rocks were needed from the seabed, crustal structure sections were needed in critical places, the nature of the transform faulting and its effect on the median valley and its associated magnetic anomaly needed investigation, and much more comprehensive mapping was necessary to determine topographic and magnetic trends, especially of the E. Sheba Ridge between the Alula–Fartak trench and Owen Fracture Zone.

Cruise 16 of R.R.S. *Discovery* in 1967 was planned to fill in many of these gaps and several weeks were spent on trans-Gulf sections, on detailed studies of small areas typical of the different physiographic regions, and on long-range seismic refraction stations. The results of some aspects of this cruise have already been published or are in press (Matthews *et al.* 1967; Roberts & Whitmarsh 1969; Laughton & Tramontini 1970) and some will be dealt with in detail in later papers. In this paper, we present a new bathymetric chart, together with the results of some detailed surveys, and a new magnetic anomaly chart, which, together with magnetic profiles of the Sheba Ridge, is interpreted in terms of a seafloor spreading model.

Detailed surveys

Gulf of Tadjura

The Tadjura Trench between 43 and 45° E (figure 1) is associated with a strong negative magnetic anomaly (Girdler & Peter 1960). Westward it continues into the Gulf of Tadjura where two independent coast to coast zig-zag surveys were made by R.R.S. *Discovery* and R.V. *Oceanographer* in 1967. The data from these surveys were combined and published by Roberts & Whitmarsh (1969). The bathymetry (figure 2) showed that north of Djibouti and the shallow shelf around the Musha Islands, the Tadjura Trench shoaled from over 1463 m (800 fathoms) to 667 m (370 fathoms) but deepened westward to 883 m (483 fathoms). Roberts and Whitmarsh concluded that a NE–SW transform fault crossed the Gulf at 43° 10′ E displacing the axis of the median valley left laterally and substantially reducing the amplitude of the magnetic anomalies in the vicinity of the fault. West of the fault the trend of the shorter wavelength magnetic anomalies changed to NW–SE, parallel to the structural trend lines on land. However, the marine survey was unable to determine the trend of the anomalies of longer wavelength since these wavelengths are of the same order as the width of the Gulf. The aeromagnetic survey of the Afar Depression (Girdler 1970) covered this area and showed that the longer wavelength anomalies continued the E–W trend found further east.

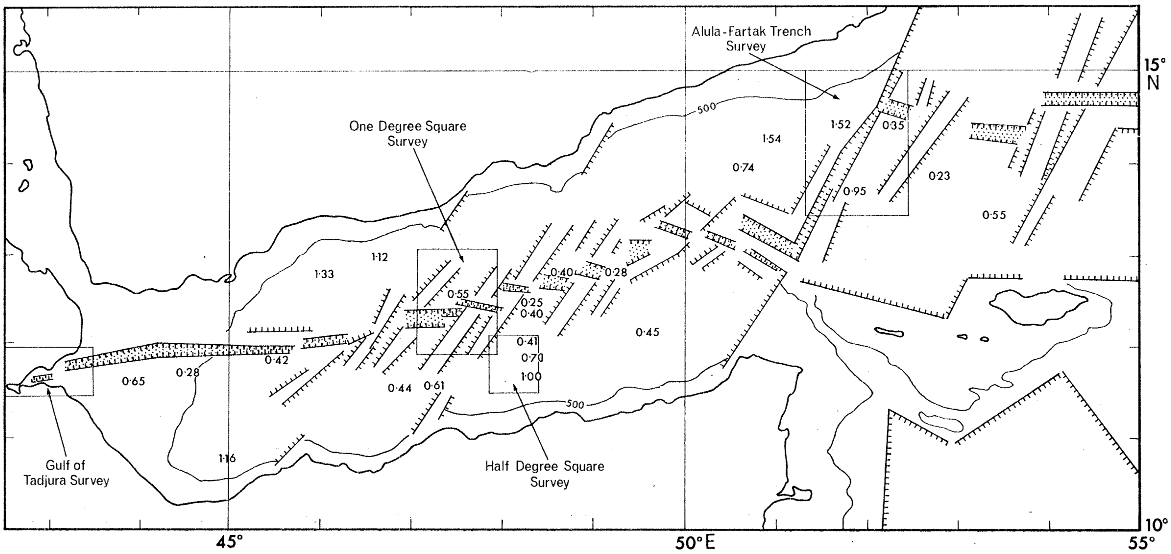


Figure 1. Generalized structural features of the Gulf of Aden showing the 500 fathom (914 m) contour, principal scarps and the median valley (stippled). Areas of detailed surveys are indicated, and thicknesses of sediment above layer 2 derived from seismic reflexion and refraction studies are given in kilometres.

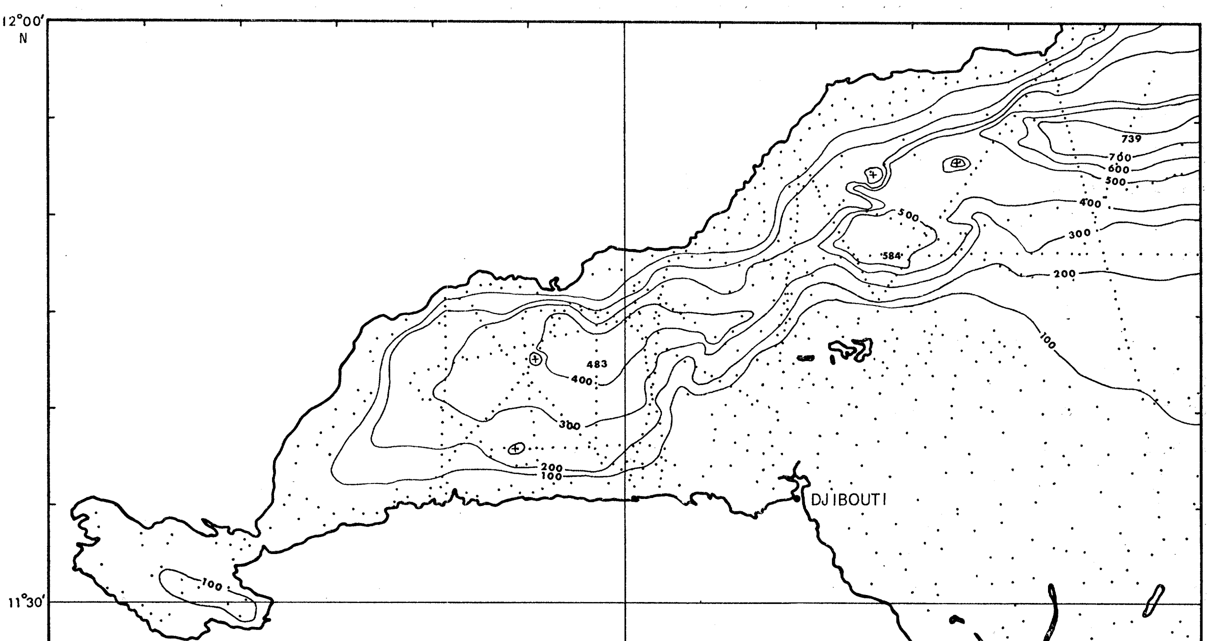


Figure 2. Bathymetric chart of the Gulf of Tadjura prepared from data obtained from R.R.S. *Discovery* and R.V. *Oceanographer* in 1967 and from Admiralty chart 253. Depths are in fathoms (corrected) and the contour interval is 100 fathoms. Sounding control is shown by dots.

One Degree Square

An area approximately 1° square between 12 and 13° N, and 47 and 48° E was chosen for detailed survey as being representative of the central part of the West Sheba Ridge with the complexity of NE–SW trending ridges and valleys crossed by the E–W median valley. Four anchored dan buoys with radar transponders provided navigational control for the greater part of the survey, comprising ten N–S tracks spaced about 9 km (5 n. miles†) apart (figure 3). A more detailed survey was made of the median valley at 12° 35′ N, 47° 35′ E, and numerous cross-tracks have been used to link the survey lines. Additional bathymetric and magnetic data have been obtained from other ships' tracks crossing the area, and these data have been integrated with the survey by adjusting track positions to give the best bathymetric fit at cross over points.

The resulting bathymetric chart (figure 4) shows parts of three major NE–SW ridges which dominate the topography. These are separated by sediment-filled valleys. The NE end of the northernmost ridge disappears gently beneath a cover of sediment. These ridges are usually asymmetrical (figure 5), the steeper side facing in to the median valley, and are broader and more block like than the ridges associated with and parallel to the median valley in other less fractured parts of the Sheba Ridge (see figure 14*e*).

At 12° 30′ N, 47° 45′ E, one ridge is interrupted by a valley joining two deeps. Similarly, at 12° 20′ N, 47° 05′ E, the westernmost ridge is also interrupted. In between these ridges, there are local deeps (depths greater than 2377 m (1300 fathoms) are shown shaded in figure 4) which are bounded north and south by other smaller ridges trending approximately E–W. These deeps are believed to be the median valley, and in terms of seafloor spreading, to be the line of generation of new ocean crust. The association of the deeps with a large negative magnetic anomaly supports this view, and the dislocation of the magnetic pattern (discussed later) between the NE–SW ridges indicates that the survey covered the zone of a transform fault.

The youthfulness of the median valley is indicated by the absence of a flat sediment floor in it, in spite of the fact that at one place on its northern side (at 12° 36′ N, 47° 36′ E) the abyssal plain fed from the north joins the valley without any barrier. A seismic reflexion profile (figure 6*a*, plate 17) across this junction shows flat-bedded sediments outcropping on the cliff. In the valley, fresh ropy basalts and pillow lavas were dredged (Cann 1969). However, out of 100 bottom photographs at two stations in the valley, only two showed rock outcrops, lightly covered by sediments (figure 7, plate 18), the remainder showing sediment only. The rate of sedimentation in this area must be fairly high since the area is surrounded by land (one photograph showed a beer can that could not be older than 10 a, covered by a millimetre or more of sediment indicating a minimum sedimentation rate of 10 cm ka^{-1}) so that the photographic evidence of bottom sediments is not inconsistent with geological youthfulness.

The pattern of bathymetry, then, is one in which a relatively youthful median valley, associated with parallel ridges extending 28 km (15 n. miles) either side, has been superimposed on an older system of NE–SW ridges. Between these two tectonic episodes, it is suggested that there was a quiet period 0.5 Ma ago during which sediment filled the valleys and covered the rough topography associated with earlier stages of seafloor spreading for which the evidence comes from the magnetic patterns (see figure 18) preserved on the ridges themselves.

The inward facing steep cliffs of the ridges parallel to the median valley indicate that the

† Throughout this paper 'n. miles' refers to 'nautical miles'.

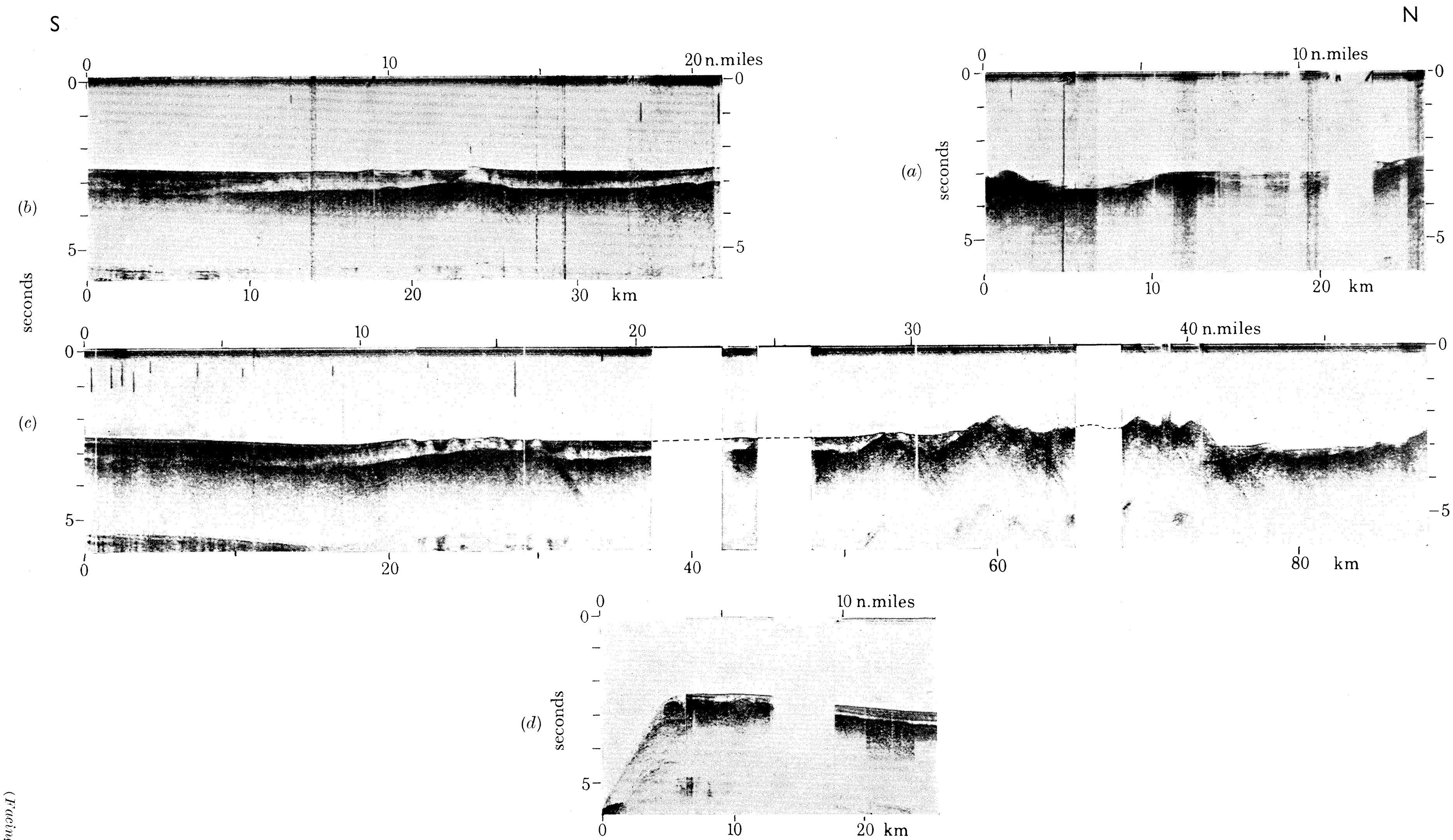


FIGURE 6. Seismic reflexion profiles obtained by air gun (cf. figure 15): (*a*) across median valley in One Degree Square (figure 4); (*b*) and (*c*), across south main trough in Half Degree Square (figure 9); (*d*), across east side of Alula–Fartak Trench.

(*Facing p.* 230)

FIGURE 7. Bottom photograph in median valley showing sediment cover on young basaltic rocks similar to those dredged in vicinity. (Photo 6246.18, depth 2290 m (1250 fathoms); width of picture 2 m; 12° 35′ N, 37° 30′ E.)

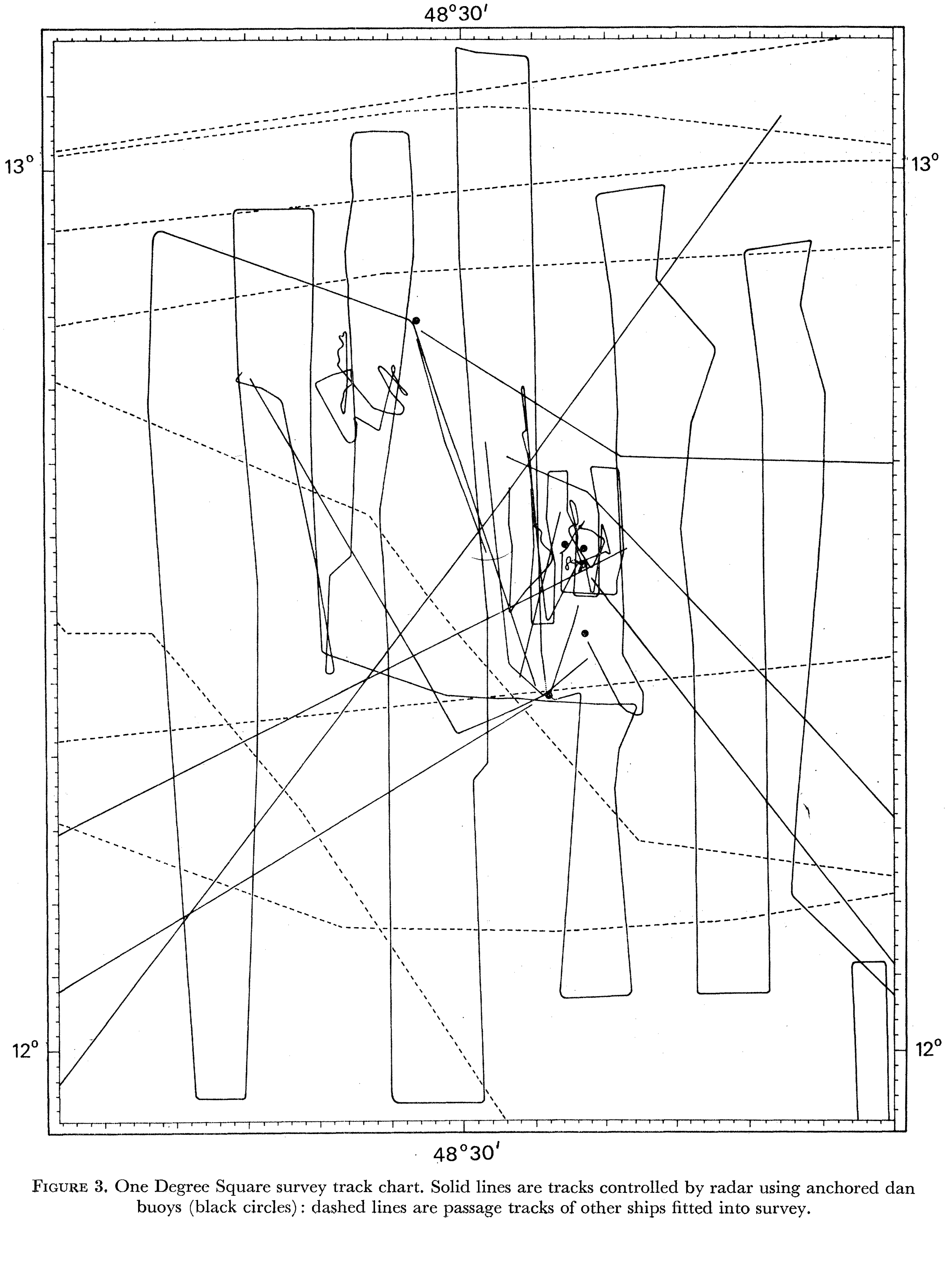


Figure 3. One Degree Square survey track chart. Solid lines are tracks controlled by radar using anchored dan buoys (black circles): dashed lines are passage tracks of other ships fitted into survey.

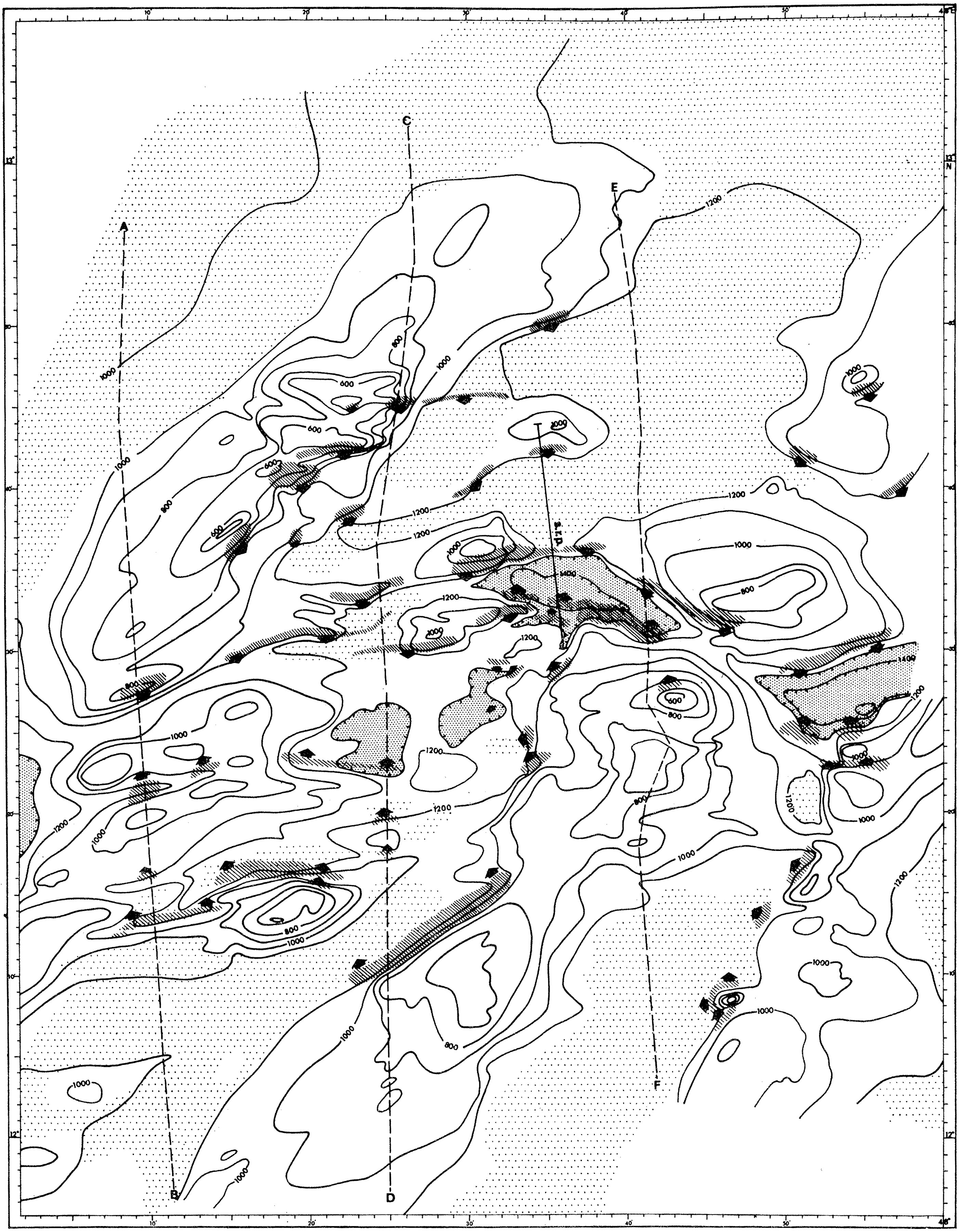


FIGURE 4. One Degree Square bathymetric chart. Contour interval 100 fathoms (uncorrected: calculated from 1 s ≡ 800 fathoms (1460 m)). Coarse stipple: areas of sediment accumulation. Fine stipple: median valley deeper than 1300 fathoms (2380 m). Diagonal shading and arrows: steep scarps and the direction in which they face. Bathymetric profiles (dashed) are illustrated in figure 5. Seismic reflexion profile (s.r.p.) is illustrated in figure 6*a*, plate 17.

mechanism of emplacement of new ocean crust is associated with uplift and block faulting, as has been reported in the Pacific by Atwater & Mudie (1968) and in the Atlantic by van Andel & Bowin (1968). It is not clear, however, whether the steep inward facing cliffs of the NE–SW ridges are due to the fact that these ridges are comprised of an uplifted mass of E–W ridges, or

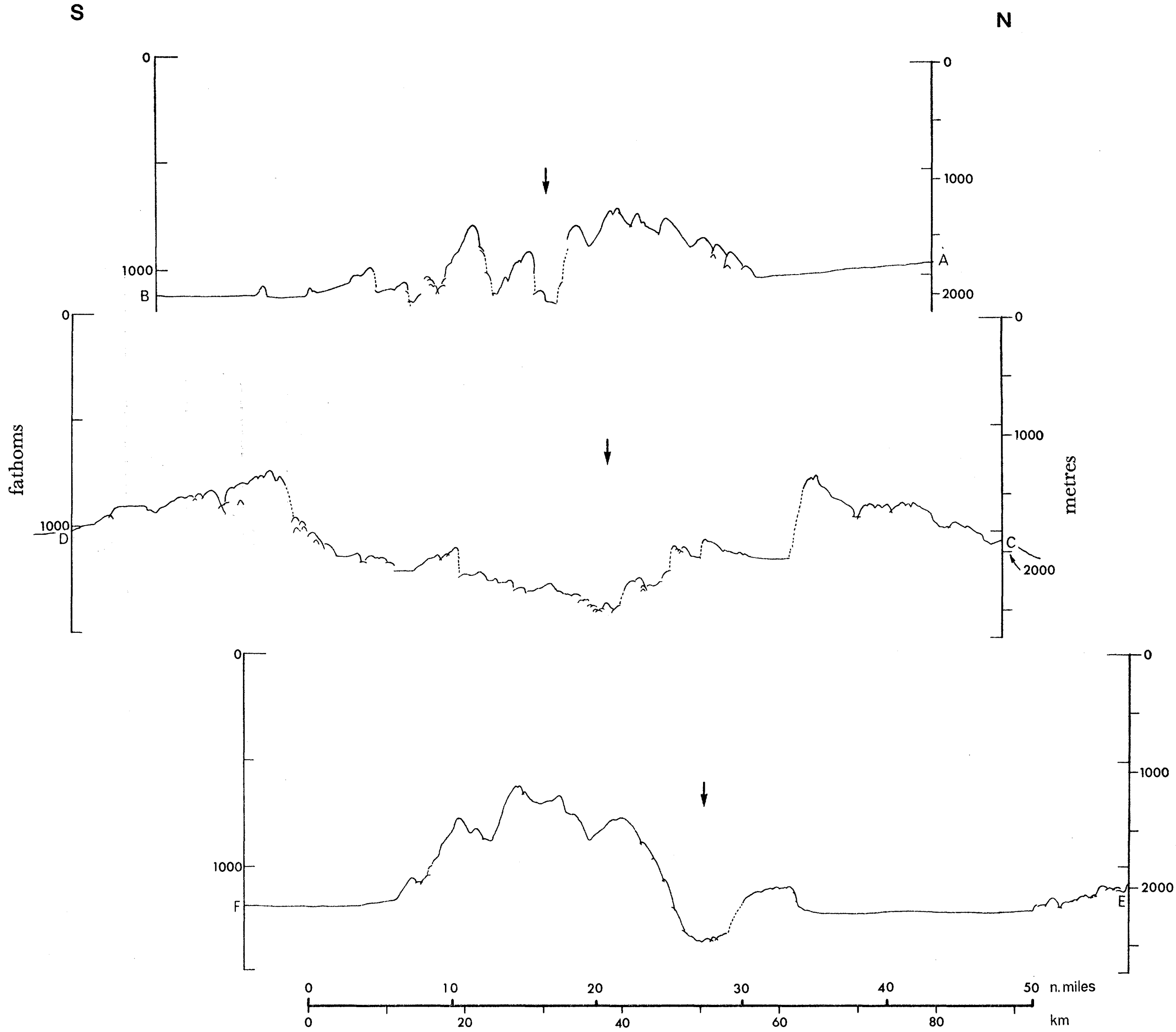


Figure 5. Bathymetric profiles across One Degree Square (figure 4). Depths are in uncorrected fathoms (1 s ≡ 800 fathoms) and metres, vertical exaggeration approx. 12:1. The arrows indicate position of median valley. Note inward facing cliffs in profile DC.

whether they arise from an asymmetry of the NE–SW ridges themselves. At 12° 45′ N, 47° 20′ E, a small area of a NE–SW ridge was surveyed and found to consist of at least two E–W structures. Rocks dredged from these ridges were weathered basalts and dolerites with as much as 3 cm of manganese encrustation indicating that they are old compared to the basalts of the median valley (Cann 1969).

Half degree square

An area for survey was chosen in the sediment-filled south main trough well clear of the underwater spur running out from the coast at 47° 20′ E, but near to the One Degree Square survey. The aim was to establish the trend of the magnetic anomalies in the main trough and to see if there was any evidence for a SW extension of the NE–SW ridges of the Sheba Ridge.

Fifteen N–S tracks (figure 8), separated by 4 km (2 n. miles), were controlled by a single dan buoy and radar transponder anchored in the centre of the area which was bounded by 11° 36′ and 12° 06′ N, and 47° 57′ and 48° 28′ E.

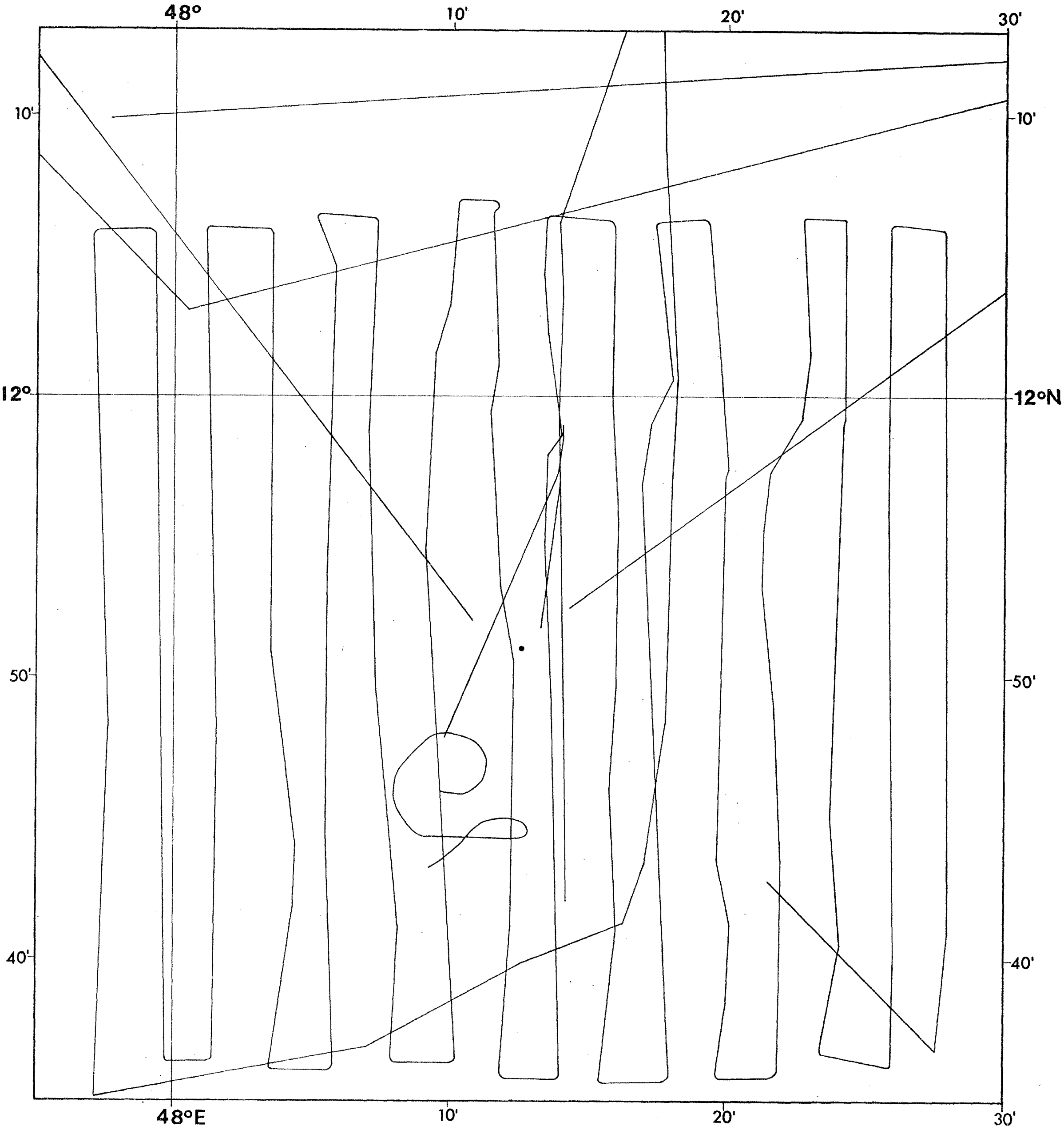


FIGURE 8. Half Degree Square survey track chart, controlled by radar on an anchored dan buoy (black circle).

The bathymetry (figure 9) shows two rough zones, where the relative relief is of the order of 180 m (100 fathoms) or less, which are extensions of the more pronounced NE–SW ridges to the NE. Separating these areas is an abyssal plain fed from the south. In the south of the survey area the continental rise grades steadily into the slope.

Two seismic reflexion profiles cross the survey area, one of which runs northward to the Sheba Ridge (figure 6). Both show a strong reflector at a 'depth' of approximately 0.5 s which

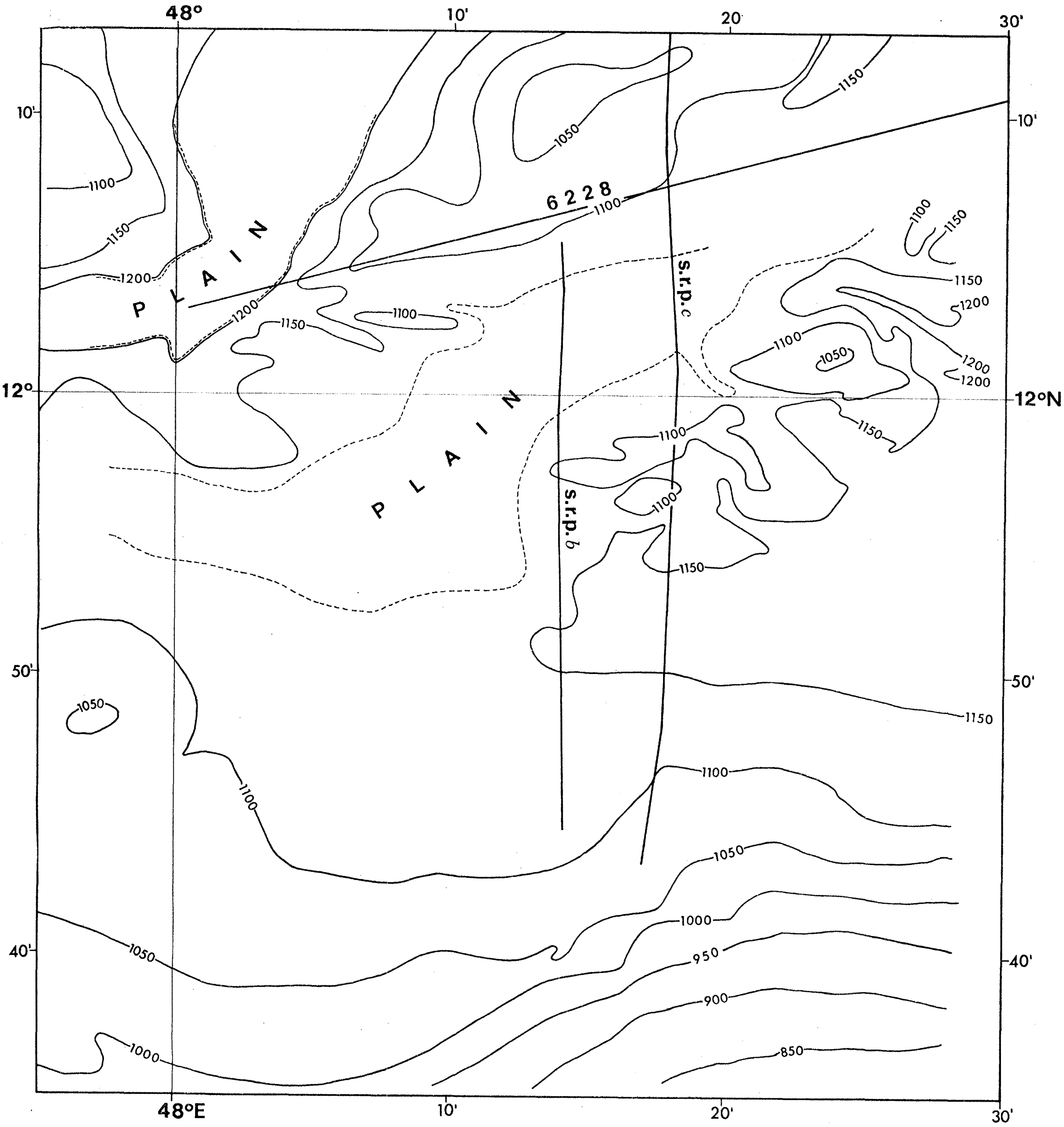


FIGURE 9. Half Degree Square bathymetric chart. Depths in uncorrected fathoms (1 s ≡ 800 fathoms); contour interval 50 fathoms; dashed line, edge of abyssal plain; Seismic reflexion profiles (s.r.p.) illustrated in figure 6*b* and *c*.

corresponds with the top of layer 2 (velocity 5.22 km s^{-1}) found on seismic station 6228 which crosses the profiles (Laughton & Tramontini 1970). The rough zone in the NE part of the survey lies above a rise in layer 2 (figure 6*c*), the northern edge of this rise consisting of a steep scarp similar to inward-facing cliffs in the One Degree Square. Similarly, in figure 6*b*, the surface topography reflects a rise in layer 2.

In both profiles, lying above layer 2 is a transparent layer, the top of which is highly irregular under the rough zone and has been infilled and nearly completely smoothed by layered turbidites clearly derived from the continental margin to the south.

The nature of layer 2 and the transparent layer above it give rise to some speculation. On the cliffs of the Alula–Fartak Trench, a similar strong reflector, also identified by seismic refraction measurements as layer 2, was found to outcrop and basalts were dredged in the area at this depth. Similarly, basalts were dredged in the median valley in the One Degree Square. However, the top of layer 2 seems remarkably flat compared with the basaltic mountains comprising the Sheba Ridge farther north. Perhaps in the earlier stages of evolution of the Gulf of Aden, the magma was more fluid and formed flood basalts. On the other hand, in the extreme west of the Gulf of Aden, layer 2 velocities are found very close to 4 km s^{-1}, a value which has been shown in the Red Sea to correspond to a thick evaporite sequence. Against this view is the observation of diapiric salt structures in the Gulf of Mexico (Worzel, Leyden & Ewing 1968) and in the Mediterranean (Glangeaud, Alinat, Polveche, Guillaume & Leenhardt 1966) where they have appeared on seismic reflexion profiles as 'transparent' layers or as diapirs, suggesting that evaporite sequences do not give the strong reflexion observed here. The most plausible identification of layer 2 is that here it consists of flood basalts probably interbedded with some sediments.

The transparent layer above layer 2 could be evaporite, or a uniform pelagic or airborne sediment. Some fine structure can be seen in it but it contrasts with the strongly stratified layers above it. The transparent layer has a maximum thickness in the region of 11° 55′ N suggesting that this may have been the axis of a sediment basin. The broken nature of the top of the transparent layer is interpreted as due to submarine canyons cut down the axis of the basin at the start of a new sedimentary régime when turbidity currents became the dominant influence. As these increased, so the basin became filled and in time the canyons themselves were filled. In the final stage of evolution, it is suggested that the axis of the basin in this region was upfaulted and tilted by the tectonic activity along the NE–SW fracture zone of the Sheba Ridge, distorting the turbidity deposits upwards and raising the region of rough topography seen in this survey area.

An alternative explanation of the irregular top to the transparent layer could be fracturing, distorting and gravity sliding resulting from the first stages of uplift, or possibly diapiric movement if the transparent layer is primarily evaporitic. However, if there are salt diapirs it is hard to see where the source of the salt is in view of the continuous nature of the strong reflector underneath.

Farther north on the long profile (at 59 km (32 n. miles), figure 6*c*) the strong reflector merges into the mountains of the Sheba Ridge which are downfaulted towards the median valley. The evidence points once again to a general uplift of the central area of the Gulf of Aden accompanied by block faulting and tilting.

Alula–Fartak Trench

A bathymetric chart of the Alula–Fartak Trench, cutting right across the Gulf of Aden, was presented by Laughton (1966*a*). It contains the greatest depth (5360 m, 2931 fathoms) found in the Gulf of Aden (figure 10). Subsequent bathymetric data have shown that the trench is joined at both its north and south ends (14° 40′ N and 13° 10′ N) by well-defined sections of

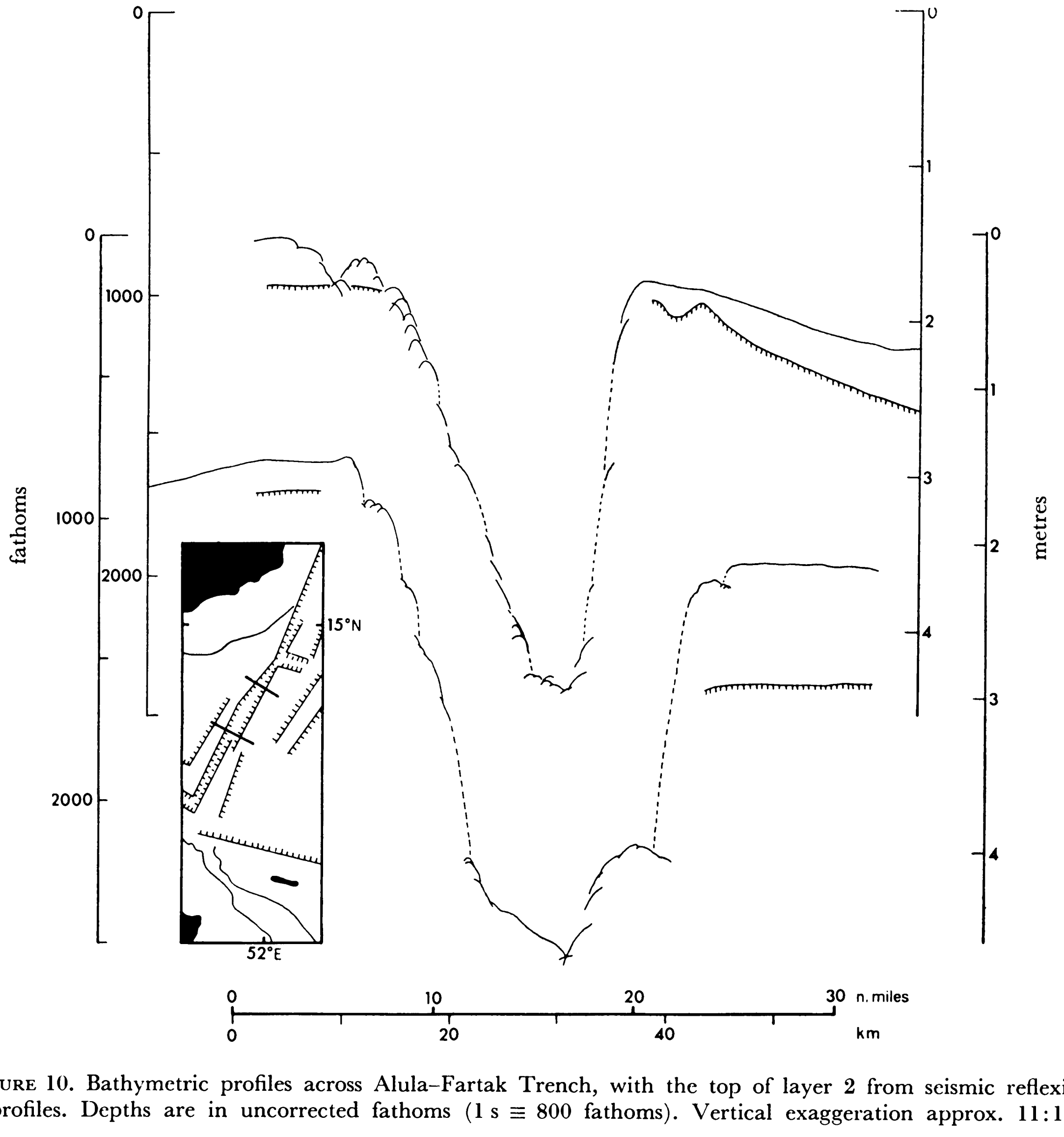


FIGURE 10. Bathymetric profiles across Alula–Fartak Trench, with the top of layer 2 from seismic reflexion profiles. Depths are in uncorrected fathoms (1 s ≡ 800 fathoms). Vertical exaggeration approx. 11:1.

the median valley and that these are approximately perpendicular to the axis of the trench (figure 11, see accompanying wallet). Over these sections of the median valley, displaced by 212 km (115 n. miles), are negative magnetic anomalies of approximately 400 nT (gammas) and the anomaly pattern either side can be identified with the magnetic reversal sequence out to anomaly 3 or 5 (cf. later discussion). The cluster of earthquake epicentres on the trench (see figure 16) and the analysis of first motion of one of them (Sykes 1968) confirm the view that the Alula–Fartak Trench is a well-defined example of a transform fault.

Gravity data obtained by H.M.S. *Owen* (Admiralty 1966) in 1963 across the trench indicated that high density rocks (2.6 to 2.9 g cm^{-3}) must outcrop on the cliffs of the trench and therefore in 1967 seismic refraction measurements were made on both sides of the trench parallel to its axis and reflexion records obtained to link these to possible dredging sites on the cliffs. A number of dredge hauls were made on two sections across the trench. A full discussion of the structure and development of the Alula–Fartak Trench will appear in a later publication, although some aspects have already been published (Laughton & Tramontini 1970; Ramsay & Funnell 1969). The general conclusions from these studies are that (*a*) the trench may contain a considerable thickness (1.5 km) of low density sediments implying the extension of the marginal faults to about 6 km depth, (*b*) parallel to the trench 30 km (16 n. miles) to the west is another fault, layer 2 of the intervening horst rising to near the seabed, (*c*) the ages of the oldest rocks dredged from the cliffs at the various sites are consistent with the rates of spreading from the ridge axis deduced from the magnetic reversal time scale, (*d*) the distribution and character of sedimentary rocks in the area suggest that at one time the trench may have been filled with sediments during a tectonically inactive period, and that subsequently it may have been rejuvenated.

Bathymetry of the Gulf of Aden

The detailed surveys discussed above have given an insight into the nature of the topography in various typical areas of the Gulf of Aden and have served as a guide in the preparation of the bathymetric chart of the whole of the Gulf from all available data (figure 11). The sounding control is indicated on the chart as one dot for each sounding used at the compilation scale of 1:1 000 000 (23 000 soundings have been used). The contour interval of 100 fathoms (183 m) has been continued onto the land to indicate comparative relief.

At this contour interval, many of the smaller features of the bathymetry, such as submarine canyons, abyssal plains, areas of rough topography with relief less than 100 fathoms, do not show up. Therefore a physiographic diagram was prepared (figure 12) to help illustrate these features. This diagram differs from those produced by Heezen and Tharp (Heezen, Tharp & Ewing 1959) in that it makes no attempt to reproduce the actual profiles of bathymetric traverses. Instead a visual symbolism has been used to indicate the continental shelf break and slope, undulating sediment covered areas (swale topography), abyssal plains, canyons (in the vicinity of where they have been crossed), mountainous regions (with some indication of where the bigger mountains are) and the valleys and trenches. The diagram was prepared from examination of the echosounding records that were available.

An alternative technique for visualizing the three-dimensional aspects of the topography is illustrated in figure 13 (see accompanying wallet). The stereoscopic effect of an anaglyph is obtained by using red and green filters to separate left and right eye viewing respectively, and the red and green contours are displaced left or right in proportion to the depth below or the height above sea level. The cartography for the anaglyph was produced automatically from the contours of figure 11, and digitized and processed by the Experimental Cartography Unit using a Geagraph cartographic plotting table (Bickmore 1968).

The topography of the East Sheba Ridge was established by a series of traverses separated by 40 to 70 km (20 to 40 n. miles). These showed that the median valley intersected the Owen Fracture Zone at Wheatley Deep (Matthews *et al.* 1967) approximately perpendicular to the fracture zone. Between here and 150 km (80 n. miles) northwest of Wheatley Deep, the valley

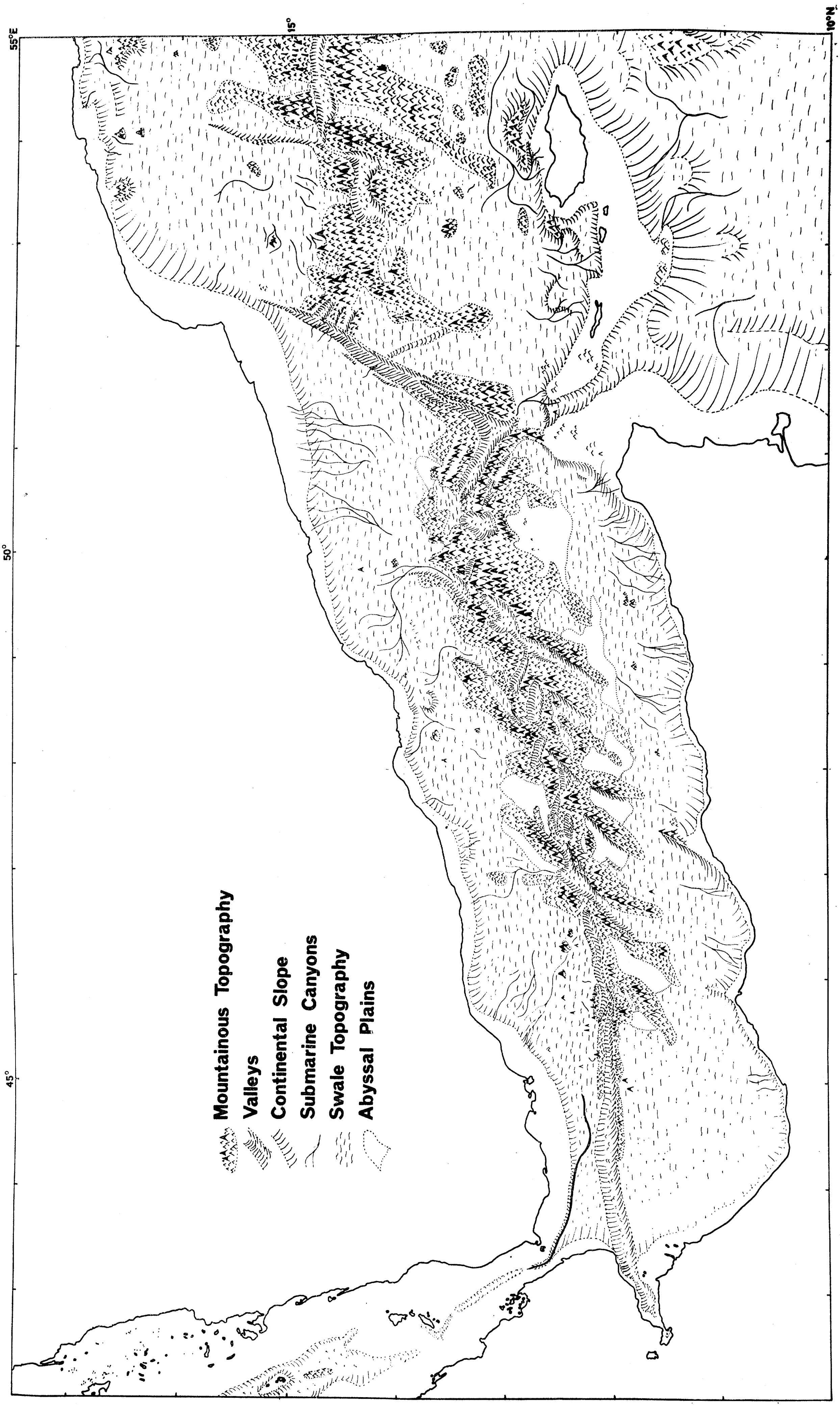


FIGURE 12. Physiographic diagram showing the distribution of mountainous areas, valleys, swale topography, abyssal plains and canyons.

cuts through the ridges of the Owen Fracture Zone, clearly post-dating them. The lack of sediment in Wheatley Deep which is contiguous to an abyssal plain, suggests that the valley is post-Pleistocene.

West of 57° E, the valley appears to change its orientation from NW–SE to E–W. The contouring in this area is not tightly controlled owing to the spacing of the data, so it is possible that this apparent change of trend could be explained by a series of transform faults offsetting short sections of a NW–SE valley. Indeed the cluster of earthquakes and some anomalously deep soundings in the vicinity of 14° 30′ N, 56° 30′ E suggest that there may be an undetected transform fault linking the eastern margins of Socotra and the shelf east of the Kuria Muria Islands. It is of some interest to determine whether this change of trend is real, since in general mid-ocean ridges tend to be perpendicular to transform faults. Menard & Atwater (1968) suggest that this is an intrinsic property of ridges and transform faults, and that where it is not the case, it implies a recent change of spreading direction. In the Gulf of Aden, however, the E–W trend, possibly between 54 and 56° E and certainly between 44 and 46° E, cannot be accounted for by a change of spreading direction since the transform faults link the two continental blocks. In this area, the initial relative orientation between ridge and transform fault must have been determined by the initial lines of weakness along which splitting took place, and subsequent adjustment towards perpendicularity made in those shorter sections of ridge between close transform faults.

Between 54 and 46° E all sections of median valley are nearly perpendicular to the fracture zones, although frequently offset. The WNW–ESE trend is seen most clearly where the valley joins the Alula–Fartak Trench, and in the One Degree Square survey.

The size and shape of the median valley does not differ greatly from one end of the Sheba Ridge to the other (figure 14). However, the rough topography of the Sheba Ridge as a whole decreases in width westward from 300 km (160 n. miles) to almost zero. To understand this, it is necessary to separate the topography due to ridges parallel to the median valley from that arising from transform faults, and also to estimate the effect of the increased sedimentation at the western end. Furthermore, the regional uplift of the Sheba Ridge extends farther from the axis than the rugged parallel ridges. These ridges are extremely steep sided, giving filled-in hyperbolae on the echosounding records, and often sit on top of broad blocks tilted away from the median valley and downfaulted in the central region (figure 14). They contrast strongly with the wider less rugged NE–SW ridges of the fracture zones. The fracture zone ridges are very variable in length, they often show an asymmetry of shape with steep cliffs facing the median valley and sometimes show evidence of tectonic activity that considerably postdates the age of the ocean crust of which they are formed, as was shown in the Half Degree Square.

Sediment distribution

Data on unlithified sediment thickness come from seismic refraction measurements shown in figure 15 from Laughton & Tramontini (1970) and from some seismic reflexion profiles taken on R.R.S. *Discovery* in 1967. The correlation of the top of layer 2 with the strong sub-bottom reflector found throughout the area enables these two sets of data to be combined.

The distribution of sediment thickness (figure 1) shows an increase towards the margins, especially in the region south of the Wadi Hadramaut at 15° N 51° E, and a slight tendency to increase westwards near the axis of the Sheba Ridge. Clearly the criteria used by Ewing &

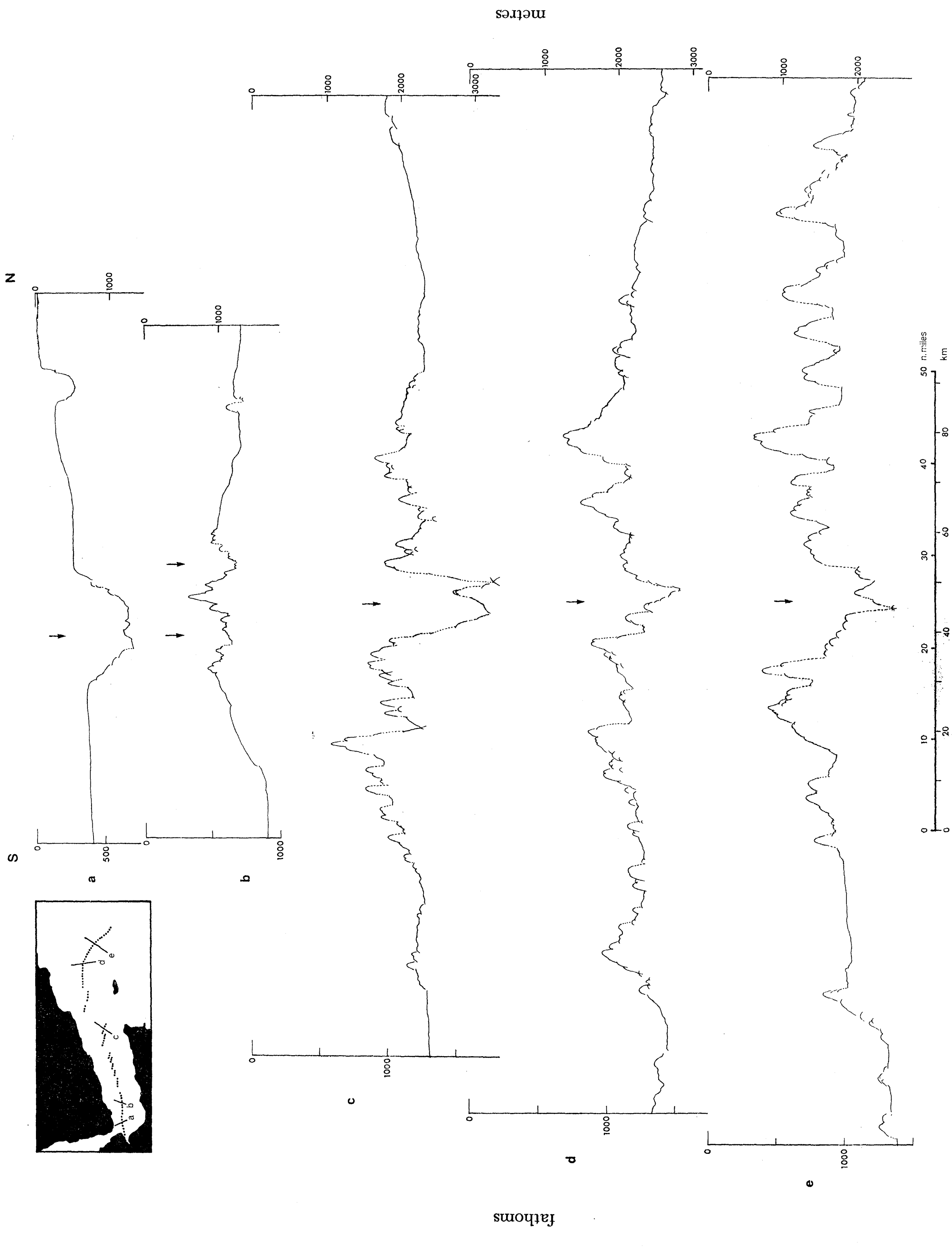


FIGURE 14. Bathymetric profiles across the Sheba Ridge. Depths are in uncorrected fathoms (1 s ≡ 800 fathoms). Vertical exaggeration approx. 12:1. Arrows indicate position of median valley.

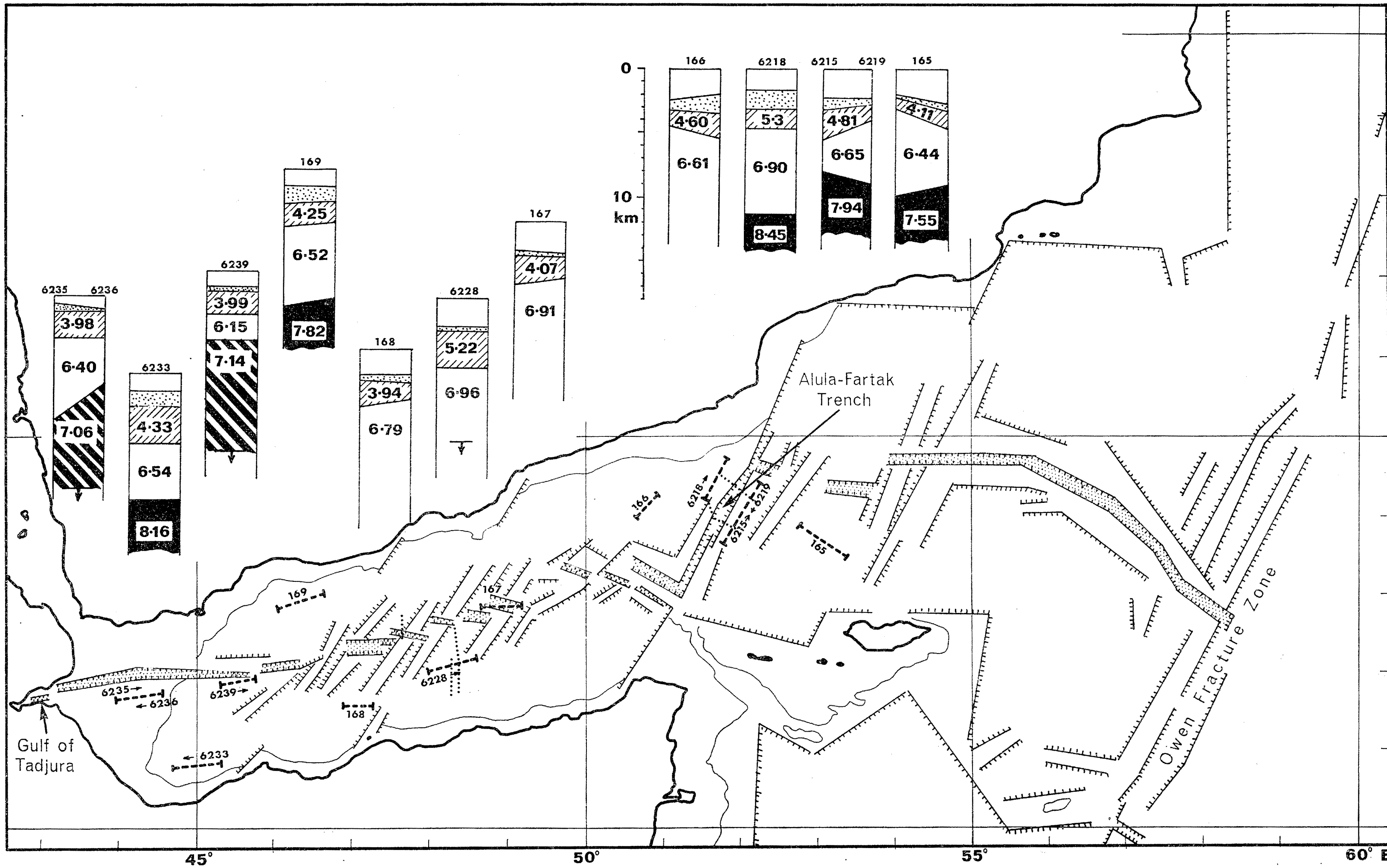


FIGURE 15. Crustal structure sections derived from seismic refraction stations of R.R.S. *Discovery* in 1967, and R.V. *Vema* and R.V. *Atlantis* in 1958. Position of refraction stations indicated by dashed lines; position of reflexion profiles indicated by dotted lines (after Laughton & Tramontini 1970).

Ewing (1967) to deduce a hiatus in seafloor spreading on mdi-ocean ridges are not applicable here since the rate of sediment supply is not uniform over the area. The profiles shown in figure 6 show sedimentation by turbidites from the continental margin, and this has not been uniform with time. The pelagic or airborne contribution discussed above has not uniformly covered the mountains although there are some indications of transparent sediments on mountain tops at the north end of profile *c* (figure 6).

The evidence from sediment distribution for a hiatus in spreading comes from the existence of valleys in the central zone of the ridge which are accessible to turbidity currents but which are not sediment filled. Such valleys are the Tadjura Trench, the median valley in the One Degree Square, the north end of the Alula–Fartak Trench and Wheatley Deep, as well as other less well-surveyed valleys between 48 and 50° E. This hiatus must have occurred just before the most recent phase of spreading in the last million years and may not have been long enough to be detected in the magnetic anomaly pattern.

The existence of an earlier hiatus in tectonic activity is suggested by the relatively thick blankets of sediment which lie on the outer flanks of the updomed Sheba Ridge, and by the relict submarine canyons found there. North of the median valley at 46° E and north of the ridge at 53° E (figure 12) canyons were found on the side of the sediment basin away from the continental margin. Such canyons might be due to turbidity currents from the uplifted mountains of the Sheba Ridge, or more likely they might be uplifted relict canyons of an earlier topographic phase when the central area was a basin and before the mountains of the Sheba Ridge were formed. At this time the Alula–Fartak Trench may have been filled allowing the considerable sediment east of the present trench to have accumulated from the Wadi Hadramaut region. This hiatus in spreading might correspond to the worldwide hiatus of 10 Ma ago suggested by Ewing & Ewing (1967).

The concentration of canyons between 50° E and 51° 30′ E at 14° 30′ N indicates that sediment is being supplied from the Wadi Hadramaut to the north main trough. Another major canyon leads from the shelf at 14° N 49° E into the Sheba Ridge. Many minor canyons are found along the southern margin, and many more doubtless exist in sections of the margin not yet visited. No canyons were found at the western end of the Gulf, except the well known, but not well explained, canyon emerging from the straits of Bab-el-Mandeb (figure 14, profile *a*), which is probably related to the exchange of water between the Red Sea and the Gulf of Aden. It does not appear to contribute significantly to the sediment distribution.

Crustal structure

The details of seismic refraction studies of the crustal structure are reported elsewhere (Laughton & Tramontini 1970) and so only the results will be summarized here. In eleven separate profiles, the velocities could be grouped into:

(*a*) Unconsolidated sediments (1.83 to 3.08 km s^{-1}).

(*b*) Layer 2 (3.94 to 5.3 km s^{-1}).

(*c*) Layer 3 (6.15 to 6.96 km s^{-1}).

(*d*) Upper mantle (7.55 to 8.45 km s^{-1}).

(*e*) Anomalously low velocity upper mantle found on the western end of axis of Sheba Ridge (7.06 to 7.14 km s^{-1}).

Apart from (*e*), the velocities and the layer thicknesses which are indicated in the crustal sections in figure 15 are all typically oceanic and strongly support the hypothesis that the Gulf of Aden has formed by the horizontal separation of Arabia and Somalia. The oceanic sections found at stations 6233 and 169 within 55 km (30 n. miles) of the north and south coasts indicates a minimum separation here of 260 km (140 n. miles).

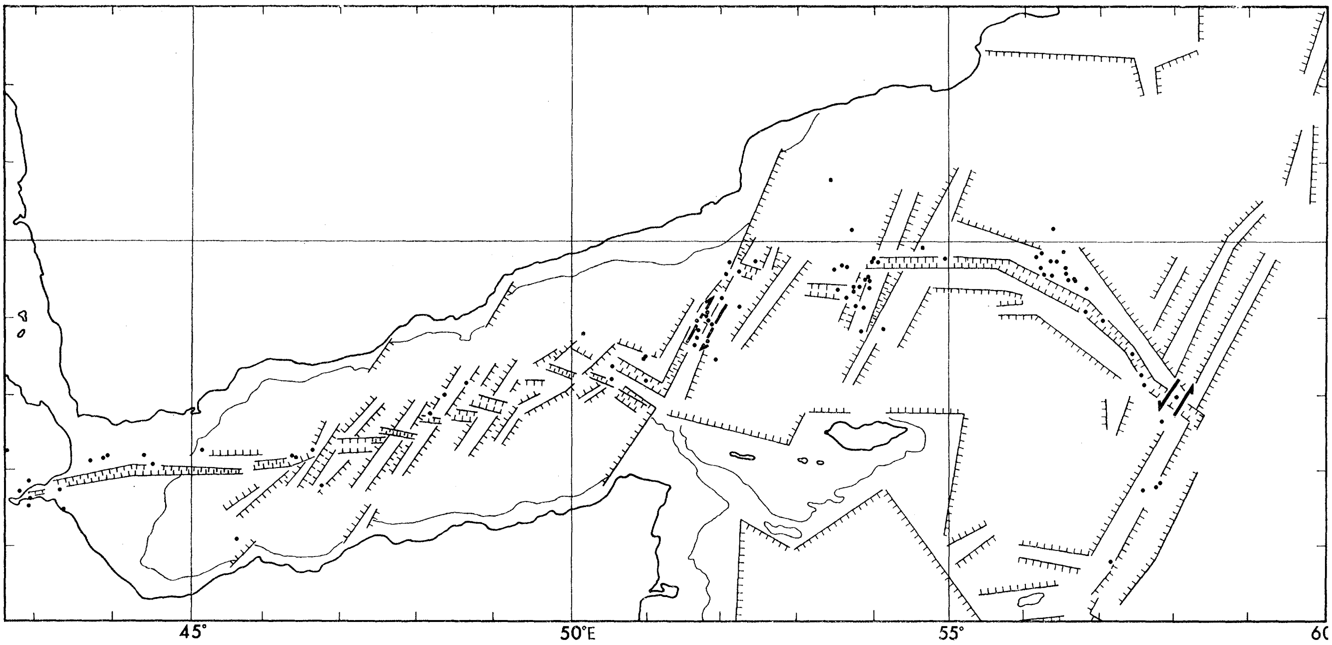


FIGURE 16. Earthquake epicentres for period 1955–68. Sheba Ridge and Gulf of Aden: relocated by Fairhead (1968). Owen Fracture Zone and Carlsberg Ridge: from Sykes & Landisman (1964) 1955–64, and from U.K. Atomic Energy Establishment, 1963–8. Fault plane solutions by Sykes (1968).

EARTHQUAKE EPICENTRES

The epicentres of earthquakes occurring in the Gulf of Aden between 1955 and 1968 are plotted in figure 16. The position of those lying on the Sheba Ridge and on the fracture zones in the Gulf have been relocated by Fairhead (1968) and Fairhead & Girdler (1969) using the method of joint epicentre determination. Fairhead estimates the positional accuracy of the relocated epicentres to be ± 2 km (± 1 n. mile) relative to master locations used, which in turn are considered to have an absolute accuracy of ± 10 km (± 5 n. miles).

The epicentral zone coincides in general with the axis of the Sheba Ridge and with the major transform faults. Clusters of earthquakes are found near the Alula–Fartak Trench and at the transform fault at 14° 30′ N, 54° E. Away from transform faults the epicentres do not lie along the median valley within the accuracy of determination but lie scattered about it by some tens of kilometres. This may be due to tectonic adjustment of the ridge either side of the locus of generation of new oceanic crust, as has been indicated by the faulting observed in the topographic sections. Alternatively the earthquakes may lie on smaller and as yet undetected transform faults crossing the median valley, such as that suggested previously at 14° 30′ N, 56° 30′ E. To distinguish between these two possibilities fault plane solutions are necessary.

Along the transform faults, some earthquakes lie outside the limits of the offset median valley, implying that tectonic readjustment takes place far from the spreading axis. By simple transform fault theory, no such earthquakes should occur. However, some stress release by normal faulting undoubtedly occurs. Evidence for tectonic readjustment of this sort was discussed in relation to the Half Degree Square survey.

Two earthquakes have been analysed for fault plane solutions by Sykes (1968). One on the Alula–Fartak Trench (figure 16) shows strike-slip motion in the correct sense for a transform fault explanation of the trench. The other lies very close to, but 11 km (6 n. miles) north of, the median valley where it crosses the Owen Fracture Zone. The strike-slip solution is not consistent with its position outside the offset of the median valley (contrary to Sykes's conclusion which was before the location of the median valley). However, the combination of navigation errors in determining the bathymetry, and epicentral position errors could combine to place it south of the valley. In such a complex intersection of median valley and transform fault, a strike-slip motion is quite possible.

Geomagnetic field

The general features of the geomagnetic field in the Gulf of Aden have already been described by Laughton (1966*a*) and by Laughton & Tramontini (1970). Since 1966 considerably more magnetic data have become available which have enabled us to produce a contoured magnetic anomaly chart of the whole Gulf of Aden.

The contrast between the geomagnetic field over the Gulf of Aden and over the adjacent continents can be illustrated by the aeromagnetic profiles obtained during Project Magnet (figure 17). Also illustrated is one profile from a more recent aeromagnetic survey carried out in Ethiopia and Afars and Isaas (Girdler 1970). The profiles have three characteristic components. Over dry land and the continental shelves the magnetic field appears to be flattest except on track T 205 where the ground rose to 1280 m (4200 ft) above sea level as the aeroplane traversed the Somalian Plateau at 2740 m (9000 ft). The anomalies over the continent along track QP are due to local sources probably associated with volcanism. Track 501 crosses the edge of the continental shelf six times. The anomalies seen on this profile lie over the continental slope and the quiet parts of the profile lie over the shelf. Seaward of the continental shelf edge the anomalies increase in amplitude to the crestal region of the Sheba Ridge. Here a large negative anomaly, characteristic of the median valley at this latitude, is often observed. The general trend of the median valley anomaly along the length of the Gulf of Aden is evident from the narrowness of this feature on T 205 and its broadness on 544, with tracks 531 and 503 showing intermediate stages.

One Degree Square

The contoured magnetic anomaly chart of the One Degree Square (figure 18; see figures 3 to 5 for bathymetry) was drawn after correcting the anomalies for daily variation (for the method see Whitmarsh & Jones 1969). A correction was applied derived from the observed variation of the horizontal component of the geomagnetic field, H, at Addis Ababa, Ethiopia during the survey. Figure 18 demonstrates that a large negative anomaly of -400 to -600 nT exists over the discontinuous deep valley which can be followed from the eastern to the western margin of the survey area. It has been suggested already from bathymetric evidence that this valley is the median valley of the Sheba Ridge and the magnetic evidence supports this. In fact

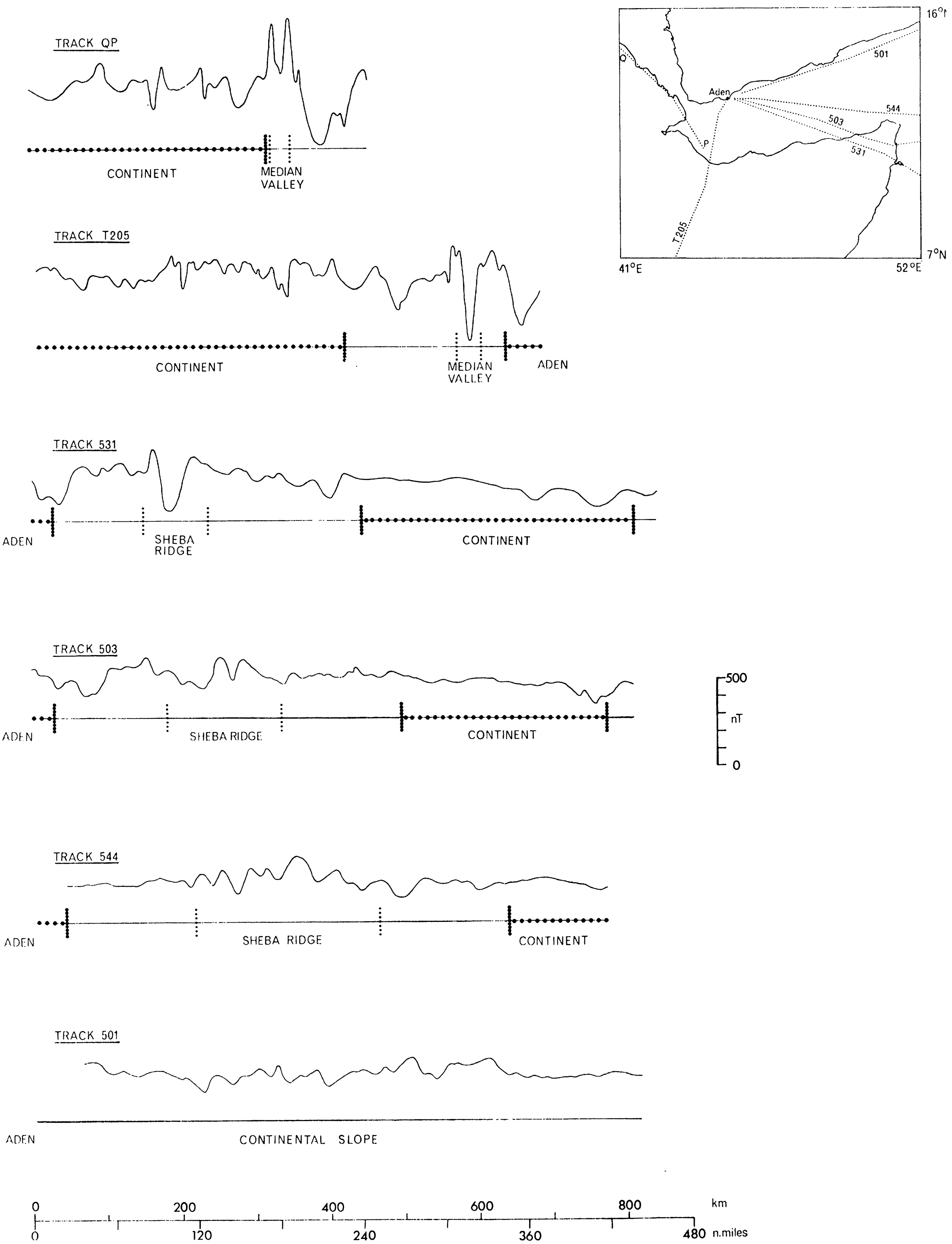


FIGURE 17. Aeromagnetic profiles radiating from Aden flown as part of Project Magnet (by courtesy of U.S.N.O.O.). Range of flight height from 2100 m (7000 ft) to 3000 m (10 000 ft). Profile QP from Airborne Geophysical Survey of Ethiopia (Girdler 1970) at flight height of 1800 m (6000 ft). 1 nT ≡ 1γ.

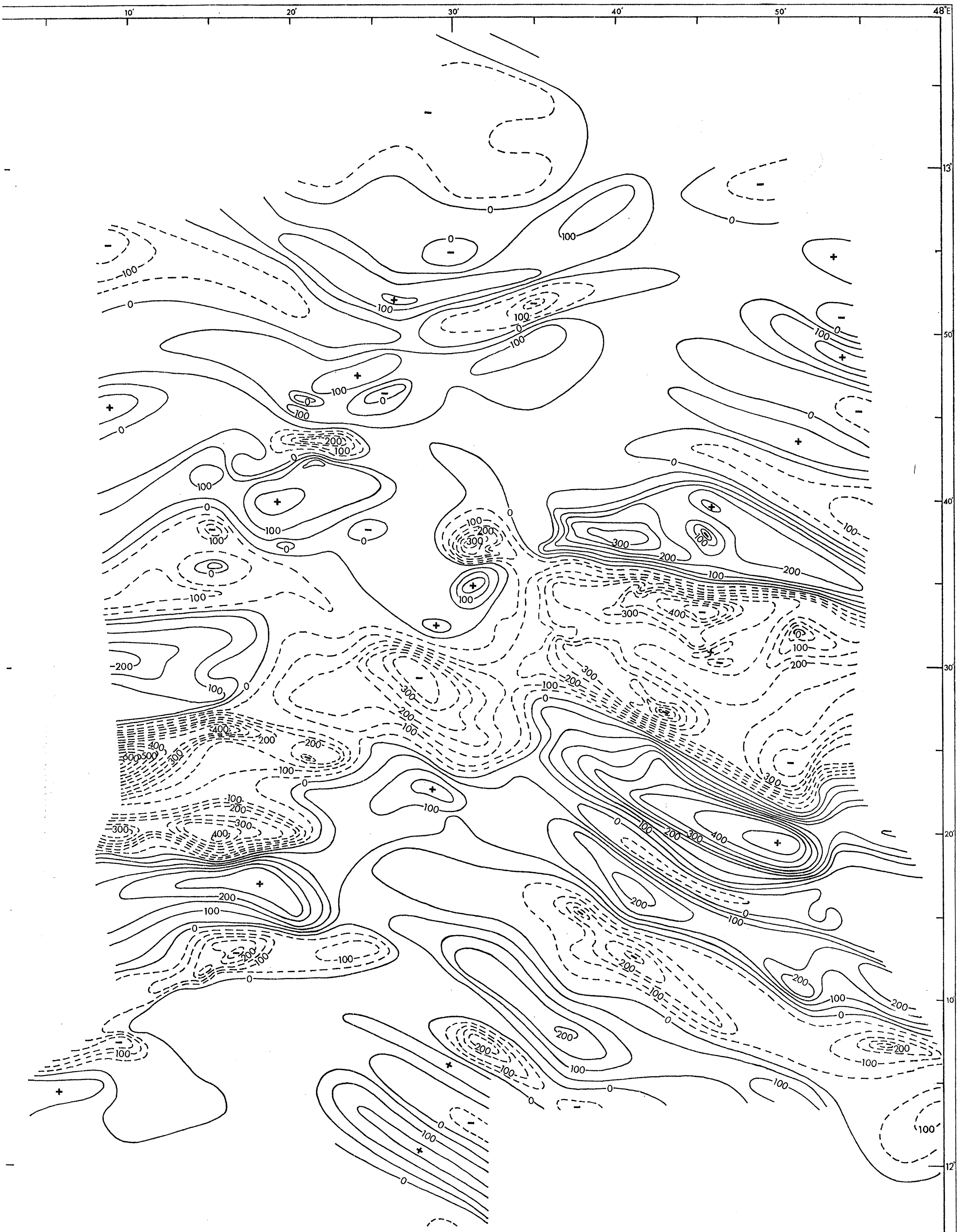


FIGURE 18. Magnetic anomaly chart of One Degree Square. Contour interval, 50 nT (gammas); solid lines, zero and positive contours; dashed lines, negative contours. Regional field used is the third order polynomial derived from H.M.S. *Owen* data (The Admiralty 1963). A daily variation correction has been made (cf. text).

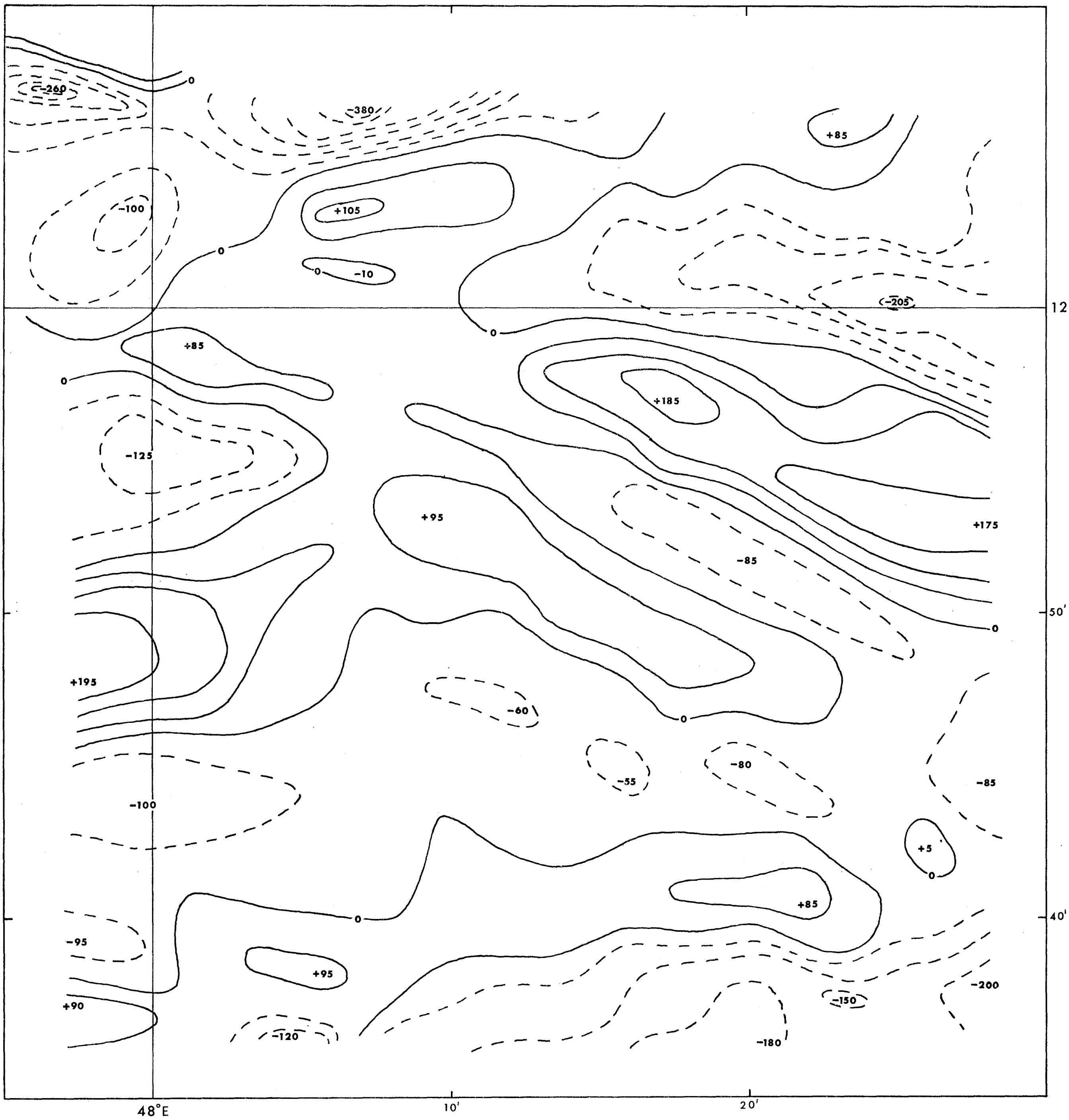


FIGURE 19. Magnetic anomaly chart of Half Degree Square survey. Contour interval, 50 nT (gammas); solid lines, zero and positive contours; dashed lines, negative contours; regional field as in figure 18. Daily variation correction has been made.

a profile oriented at about 020° across the eastern part of the anomaly chart fits the computed curve from the model of Heirtzler, Dickson, Herron, Pitman & Le Pichon (1968), with the axial anomaly lying over the median valley. The axial anomaly is not continuous in the central region of the chart, but is displaced left laterally. In this region both eastern and western portions of this anomaly run into positive anomalies while a rather flatter negative region trending roughly NE–SW joins the two ends of the axial anomaly.

The other anomalies on the chart display linear trends which are E–W in the western half of the survey area and ESE–WNW in the eastern part. The zone of offset of the axial anomaly appears to extend NNE–SSW and separates the two areas of different trend. It is marked by a belt of reduced magnetic relief and this is a characteristic of transform faults where they cross mid-ocean ridges and has been noted elsewhere (see, for example, Matthews, Vine & Cann 1965; Roberts & Whitmarsh 1969).

The zone of displacement of the linear magnetic anomalies lies in the centre of the valley between the NE and SW ridges, whereas on the ridges and across their bounding scarps the linear pattern is preserved. This strongly suggests that the scarps are the results of vertical movements only whereas the transform faulting occurs in a region now buried by sediments.

Half Degree Square

The contoured magnetic anomaly chart (figure 19; for bathymetry see figures 8 and 9) was produced in the same way as that for the One Degree Square.

In many ways figure 19 resembles figure 18 except for the absence of the large negative anomaly marking the median valley. Elongated linear anomalies with peak to trough amplitudes of 150 to 350 nT extend WNW–ESE to E–W. These anomalies appear to be displaced along a NNE–SWW zone which shows similar characteristics to that seen in the One Degree Square. It is suggested that here again there is a fracture zone. The bathymetry discussed earlier supports this interpretation.

The regular pattern of alternating elongated linear anomalies, seen over most of the survey area, seems to be much weaker along the southern boundary where the trend is approximately EW. This effect may be related to the foot of the continental slope which lies at about latitude 11° 40′ N at a depth of 2000 m (1100 fathoms).

Method of data reduction

The distribution of all ships' tracks along which measurements of the total geomagnetic field are known to have been made in the area of the Gulf of Aden, are shown in figure 20. Flight lines from Project Magnet and from a recent aeromagnetic survey over the Afar triangle (Girdler 1970) are also shown in the figure. The ship data were obtained during cruises of British ships of the Hydrographic Department and the National Institute of Oceanography, from American ships of the Scripps Institution of Oceanography, Woods Hole Oceanographic Institution, Lamont–Doherty Geological Observatory, and the Earth Sciences Services Administration, and from R.V. *Meteor* of the Deutsches Hydrographisches Institut, over a period of ten years between 1959 and 1968.

The Gulf of Aden lies within the zone influenced by the equatorial electrojet. The electrojet is a relatively narrow daytime current flowing at an altitude of about 100 km which produces an increase of up to 100 % in the range of daily variation observed on the Earth's surface within about 6° of latitude (Onwumechilli 1967). At the longitude of the Gulf of Aden the axis of the equatorial electrojet lies approximately at 9° N latitude and passes close to the Addis Ababa Geophysical Observatory where daily variation ranges of 200 nT have been observed. Because of this large range of daily variation it was decided to correct the data to be used in the construction of the magnetic anomaly chart for the effects of daily variation. Also, since the data were collected over a period of ten years and the secular variation was believed to be about 20 nT a^{-1}, it was considered necessary to correct for secular variation too.

A method was devised for correcting observations in the Gulf of Aden for daily variation using magnetograms from the Addis Ababa Geophysical Observatory. An empirically determined latitude dependent scaling factor was used to estimate the daily variation in the Gulf of Aden from the Addis Ababa results. The method has been described in detail by Whitmarsh & Jones (1969). The secular variation in the Gulf of Aden was also determined by these authors and found to be -10.6 ± 3.1 nT a^{-1}.

The magnetic data obtained by the ships were reduced by a Fortran V computer program. The input data consist of 5 min readings of the total magnetic field, a list of geographic positions and times to define the ship's track, a list of 24 mean hourly means of H at Addis Ababa for each month covered by the magnetic data, and a list of field coefficients used to define the regional field. The applied daily variation correction depended on both the latitude and longitude of the ship because of the latitude dependent scaling factor and because a time correction was applied equal to the difference in local solar time between the ship and Addis Ababa. The scaling factor and time correction were re-computed after every 6 h of magnetic data since they vary only slowly with changes in a ship's position. The recently adopted International Geomagnetic Reference Field (Zmuda 1969; I.A.G.A. 1969) was used as the regional field in the anomaly calculations. The field was calculated at each 5 min magnetic observation and subtracted from the corrected observed value. The output from the programme consists of the time (in G.M.T.), the magnetic anomaly, the corrected total field value, and the latitude and longitude of each 5 min reading.

The magnetic anomaly chart

Before the contouring of the magnetic anomaly chart was begun a number of tracks had to be adjusted because of systematic discrepancies between tracks, so that the cross-over errors were minimized. By this means the cross-over error could usually be reduced to less than 50 nT. Since all the ships which provided magnetic data navigated only by dead reckoning and celestial fixes (except one which used a satellite navigator) it is likely that many tracks are in error by several kilometres. Whitmarsh & Jones (1969) have estimated the mean error of such tracks in the Gulf of Aden to be ± 6.4 km (± 3.5 n. miles).

The contouring of the anomaly chart (figure 20, see accompanying wallet) was done with constant reference to the analogue profiles of the ship data and to the positions of peaks and troughs of the aeromagnetic profiles. The termination of magnetic anomalies at fracture zones, as shown by the two detailed surveys discussed above, was allowed for when contouring along such zones of offset. These zones could often be traced in detail across the seabed from the more extensive coverage of bathymetric data. The contouring is thought to be subjective only to the extent that, since long narrow linear anomalies are believed to be common over mid-ocean ridges (Raff & Mason 1961; Heirtzler, Le Pichon & Baron 1966), wherever the data did not forbid it, correlations between tracks of suitably placed ridges and troughs in the anomaly field were made. It should be noted that the mean value of the anomaly field lies closer to -100 nT than to zero indicating a systematic difference between the observed total field and the International Geomagnetic Reference Field in the whole of this area.

The anomaly chart covers an area of approximately 1800 by 370 km (1000 by 200 n. miles). A quick glance at the chart shows that many of the anomalies can be followed continuously along the Gulf of Aden for more than 370 km (200 n. miles). There is a regular stripey pattern formed by alternating positive and negative anomalies trending along the length of the Gulf. This pattern appears to be continued in the southern half of Girdler's aeromagnetic chart of the Afar triangle. West of the Gulf of Tadjura the pair of positive anomalies, which flank the axial anomaly, can be followed to the SW through a series of left lateral offsets.

In the Gulf of Aden the median valley is invariably accompanied by an axial magnetic anomaly. In some places, however, there is an axial anomaly but no median valley. Generally the peak to trough amplitude of the axial anomaly varies inversely with the local density of fracture zones.

In the extreme western end of the Gulf of Aden the axial anomaly has a peak to trough amplitude of 500 nT. Eastwards, however, it rapidly increases in amplitude to 2300 nT at 45° E, which is the maximum value seen on the chart. In this portion of the Gulf it is only slightly sinuous and if there are any transform faults their offsets must be less than 10 km (5 n. miles). The axial anomaly is considerably north of the median line between the coasts, but it does lie midway between the coasts along lines that are small circles about the pole of rotation of Arabia relative to Somalia. The −400 nT negative E–W anomaly just south of Aden mainly lies over the continental shelf. However, it appears to be a Vine–Matthews anomaly since it parallels the axial anomaly and east of Aden it strikes away from the coast and persists into deeper water.

In the region of 46° 40′ E, however, there is a swing to the north in the axial anomaly and from here until 54° E there is a series of left lateral transform faults of varying offset and spacing. One such fault has already been identified within the One Degree Square but east of this area there are at least five more offsets of the axial anomaly corresponding to transform faults. The biggest displacement among these faults is shown by the Alula–Fartak Trench at 51° 45′ E. A track along the axis of this fracture zone showed low magnetic relief of less than 50 nT. In the region of 47° E the axial anomaly apparently changes direction through 60°. This is not a normal feature of seafloor spreading and requires further investigation. East of this area the ESE trend continues to 54° E.

Beyond 54° E the axial anomaly appears to continue with no major offset as far as the Owen Fracture Zone in the extreme SE corner of the chart. On meeting this fracture zone the linear anomalies are abruptly terminated and do not continue on its SE side. It should be noted that the density of tracks is considerably less in this region of the chart, making it difficult to detect small offsets of the axial anomaly. The apparent curvature of the axial anomaly might be the result of a series of such offsets although the track control over a flanking anomaly is such as to indicate that this curvature is real. Thus here again the axial anomaly, which usually is found to be a straight feature, is behaving atypically.

The foregoing remarks about the axial anomaly are equally applicable, with only slightly less certainty, to those flanking anomalies out to that numbered 5 in the Heirtzler system. Landward of anomaly 5 the track control is often poor. Hence here it is difficult to be certain which way, if any, the anomalies trend. On the whole the anomalies are broader in this region and are certainly of lower amplitude. Of especial interest is an area between 50° 30′ E and

52° 30′ E which extends about 110 km (60 miles) from the north coast. Along tracks in this region the anomaly values only fluctuate by a few tens of nanoteslas. The continental shelf is broader in this area probably as a result of sediment deposition from the Wadi Hadramaut which meets the coast at 51° 05′ E. Seismic refraction data show that the sediments are at least 1.5 km thick (figure 1). It is tempting to suppose that there is a causal connexion between the sediment pile and the lack of magnetic anomalies which involves some decay of the original magnetization of the source bodies of the magnetic anomalies.

Interpretation of magnetic anomalies

Magnetics and seafloor spreading

The magnetic contours in the Gulf of Aden are characterized by an elongation of magnetic anomalies parallel to the direction of the median valley and by the bilateral symmetry of these lineations about the median valley itself. These characteristics suggest that an interpretation of the anomaly chart of figure 20 should be sought in terms of the seafloor spreading model proposed by Vine & Matthews (1963), and applied extensively to the worldwide network of mid-ocean ridge spreading centres (Vine 1966; Pitman, Herron & Heirtzler 1968; Dickson, Pitman & Heirtzler 1968; Le Pichon & Heirtzler 1968). According to this model the reversal history of the earth's magnetic field is recorded in the oceanic crust as bands of normally and reversely magnetized blocks striking parallel to the ridge axis.

The main oceanic layer, according to the Hess model, consists of about 5 km of serpentinite (layer 3) overlain by about 1 to 2 km of basalts contained in layer 2 (Vine & Hess 1970). As the remanent magnetization for basalts is of the order of 50 times greater than that for serpentinites, and as the ratio of remanent to induced magnetization exceeds 10 in basalts but is usually less than 1 for serpentinites (Pitman *et al.* 1968), it can thus be argued that the source of magnetic anomalies lies in the basalt layer (Vine 1968). An effective susceptibility (= total intensity of magnetization (remanent and induced)/present total magnetic field intensity) of ± 0.01 may be considered typical for this material. From the analysis of observed magnetic profiles across mid-ocean ridges, Heirtzler *et al.* (1968) have produced a time scale (hereafter called the Heirtzler time scale) for the reversals of the Earth's magnetic field over the past 76 Ma based on the assumption that spreading in the South Atlantic has been uniform during this period. Any spreading rates determined using this time scale must thus be considered as being relative to the South Atlantic rate.

Most analyses of magnetic anomaly patterns assume that the bands of normally and reversely magnetized blocks lie between parallel surfaces of layer 2. However, because of the relatively shallow depth of the ridge in the Gulf of Aden, some estimate is required of the possible effect of variations in depth to the top of layer 2. This can be obtained by fitting the prisms of the Vine–Matthews model to a typical bathymetric profile across the East Sheba Ridge. A computed magnetic profile is shown in figure 21, where the base of the magnetic layer was taken to be at 4 km below sea level and the top of the layer to follow the surface topography provided by a track just west of the Alula–Fartak Trench (track *YZ* of figure 22). Vertically sided normally and reversely magnetized prisms were fitted within these boundaries according to the Heirtzler time scale with a spreading rate of 1.0 cm a^{-1} per limb. For comparison a profile derived from a topography free model of magnetic prisms contained within a 2 km thick

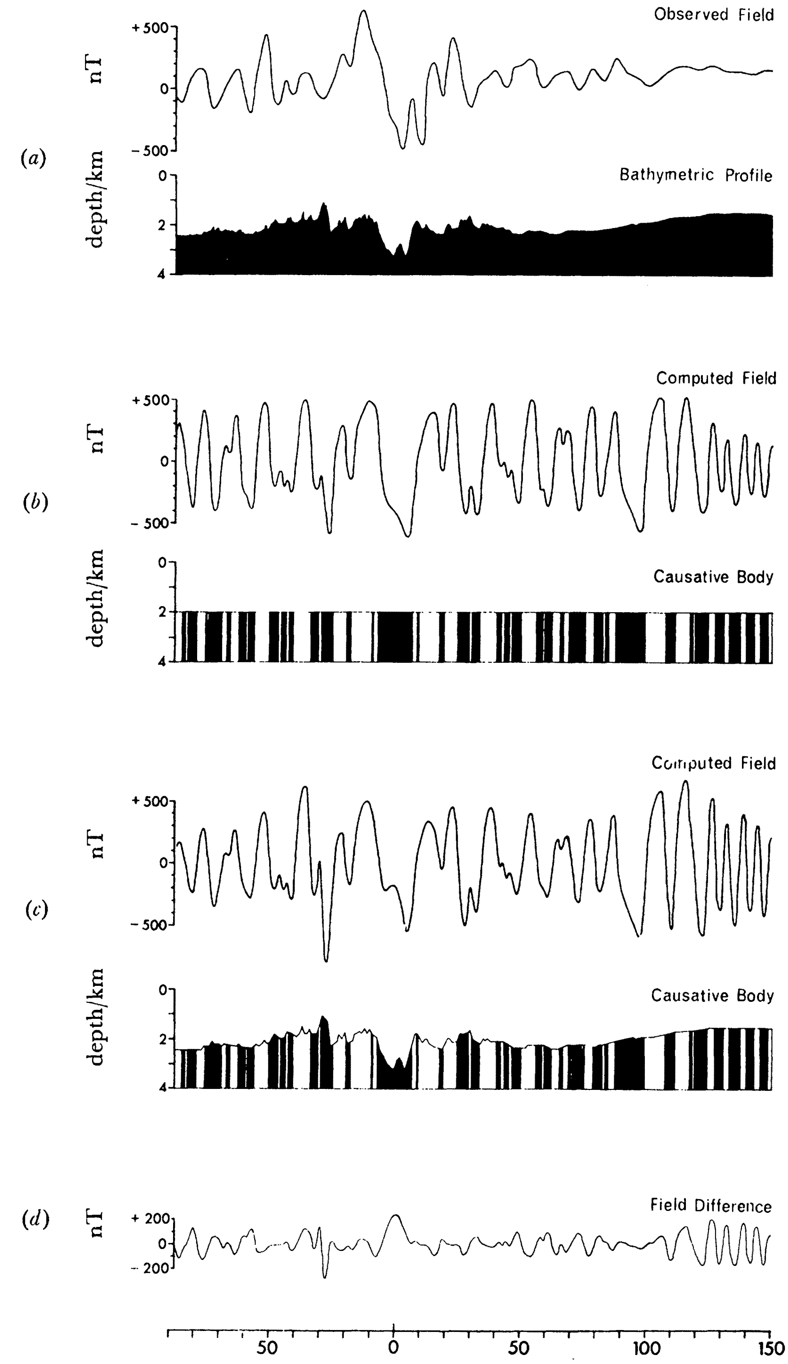


FIGURE 21. Topographic effect on computed magnetic profiles. (*a*) Observed magnetic and topographic profiles along track YZ (figure 22) projected onto direction 037°; (*b*) computed profile from a horizontal magnetic layer of uniform thickness; (*c*) computed profile from a horizontal magnetic layer whose top surface follows the topography of (*a*); (*d*) difference in field between computed models (*b*) and (*c*). (Orientation of profiles 037°. Models computed with normally (black) and reversely (white) magnetized blocks fitted to Heirtzler time scale with a spreading rate of 1.0 cm a^{-1} per limb. Assumed ridge strike, 297°; effective susceptibility, ± 0.01; intensity and dip of Earth's field, 38 μT and $+12°$ respectively.) 1 nT $\equiv$ 1 γ.

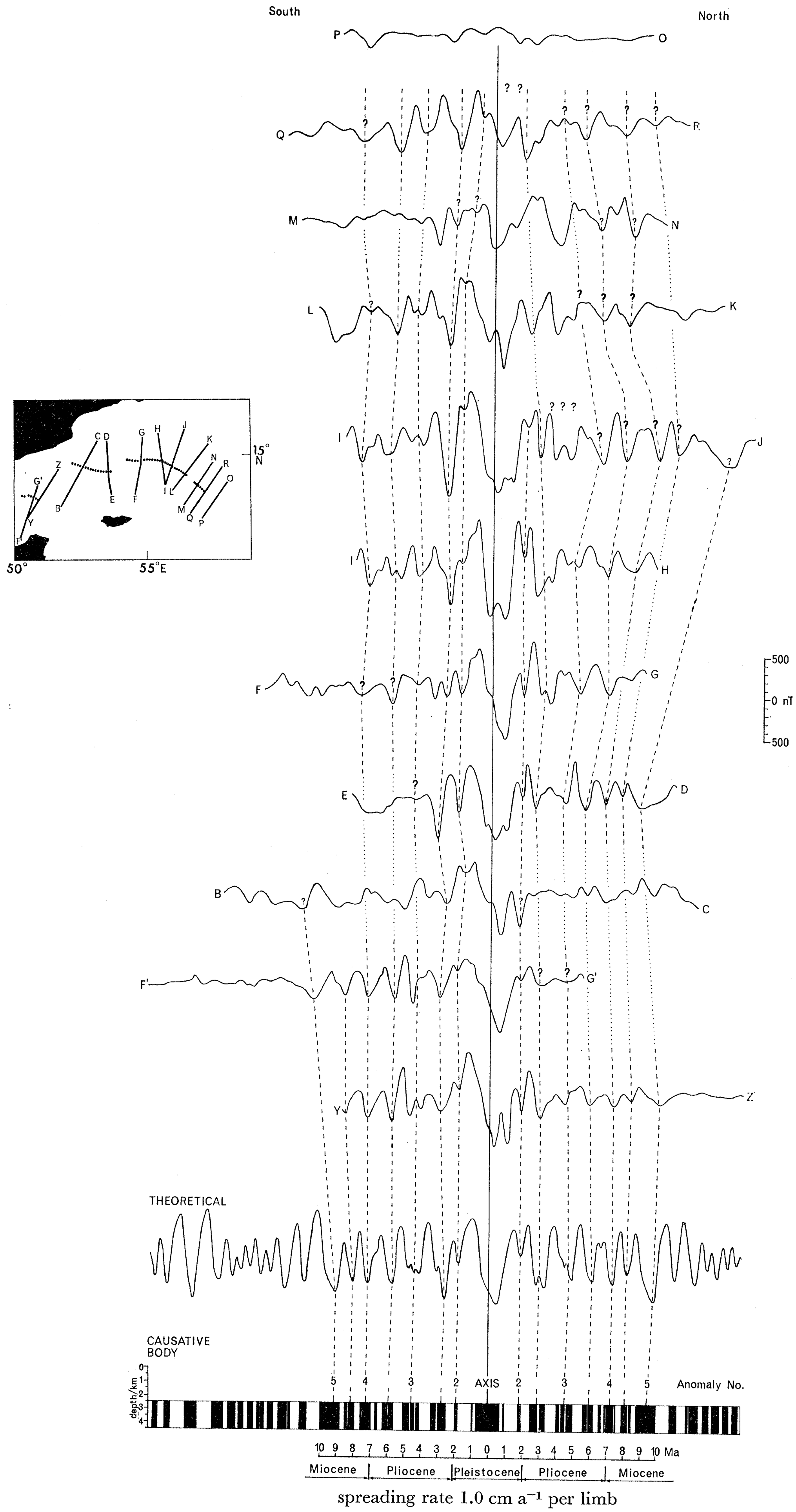
horizontal layer at a depth of 2 km below sea level is also shown in figure 21 together with a profile representing the total field difference between the two models. It will be noted that, although the introduction of a topography term produces a second-order influence on the amplitude and the shape of the computed magnetic anomalies, it does not affect the relative positions of the maxima and minima in the computed profile. The computed positions of the anomalies agree well with those of the magnetic profile observed for the particular track studied, although the computed profiles do not simulate accurately the exact form of the observed profile.

In nature, dyke injection is likely to be scattered about the median line of a mid-ocean ridge. Computations by Matthews & Bath (1967) and Harrison (1968) suggest that the standard deviation of this scatter should be of the order of 3 to 5 km or less. If this is so then all magnetic blocks except the central one will at some time have been injected with oppositely magnetized material. However, from observations of magnetic anomalies near the bottom, Larson & Spiess (1969) conclude that the width of the dyke injection zone may be as small as 140 m. Palaeomagnetic measurements by Cox (1969) suggest that the intensity of the earth's field may vary by as much as 60 to 80 % with a typical period of 10 ka, but in relation to the spreading rates in the Gulf of Aden this period is too short to influence magnetic profiles obtained a few kilometres above the sea bottom. The observed magnetic field would however be influenced by any components of these oscillations that had periods of the order of 0.1 Ma or greater, and also by any decay in the remanent magnetization of the basaltic rocks of layer 2. From measurements on dredged rocks, it has been suggested that the magnetization is lower on the flanks of mid-ocean ridges than on the crests (Godby, Hood & Bower 1968). The observed field may also be influenced by any horizontal component of flow of the basaltic material injected at the ridge centre, and by the presence of any volcanic cones in regions away from the central axis. Local faulting may well distort the shape of the normally and reversely magnetized blocks. In particular the sequence of blocks along any cross-section of a mid-ocean ridge could be upset by transform fault offsets, in which case magnetic anomalies would either appear to be missing in the sequence or else additional anomalies would be introduced. It is clear therefore that a model of vertically sided normally and reversely magnetized blocks contained in a horizontal layer is too simple to simulate the exact form of an observed profile. However, it may be used effectively as a means of correlating magnetic anomalies with reversals in the Earth's magnetic field and as such can be applied to the Gulf of Aden to derive an isochron map for the Gulf's evolution and to determine the rate of drift of Arabia from Somalia.

For the purpose of analysing magnetic profiles, the Gulf of Aden is divided into two sections —a region east of longitude 50° E where the ridge axis is assumed for the analysis to strike at right angles to the fracture zones, and a region west of longitude 47° E where, in contrast to the fracture zone trend of 035°, the normal to the median valley axis strikes approximately N–S.

Identification of magnetic anomalies

In order to interpret the magnetic anomalies in terms of seafloor spreading, magnetic profiles are required at orientations not far removed from the normal to the axis of spreading and along tracks that cross the median valley and are continuous for distances in excess of 100 km. Eleven such traverses across the East Sheba Ridge east of longitude 50° E were obtained during cruise 16 of R.R.S. *Discovery* in 1967 (figure 22). These profiles were derived from the original records after removing regional trends using the third order-polynomial regional field



spreading rate 1.0 cm a^{-1} per limb

FIGURE 22. The identification of magnetic anomalies east of 50° E. Observed magnetic anomaly profiles projected onto direction 037°, perpendicular to assumed orientation of spreading axis. Computed anomaly profile from normally (black) and reversely (white) magnetized blocks according to Heirtzler time scale. Assumed ridge strike, 297°; effective susceptibility ± 0.01; intensity and dip of Earth's field 39 μT and + 15° respectively.

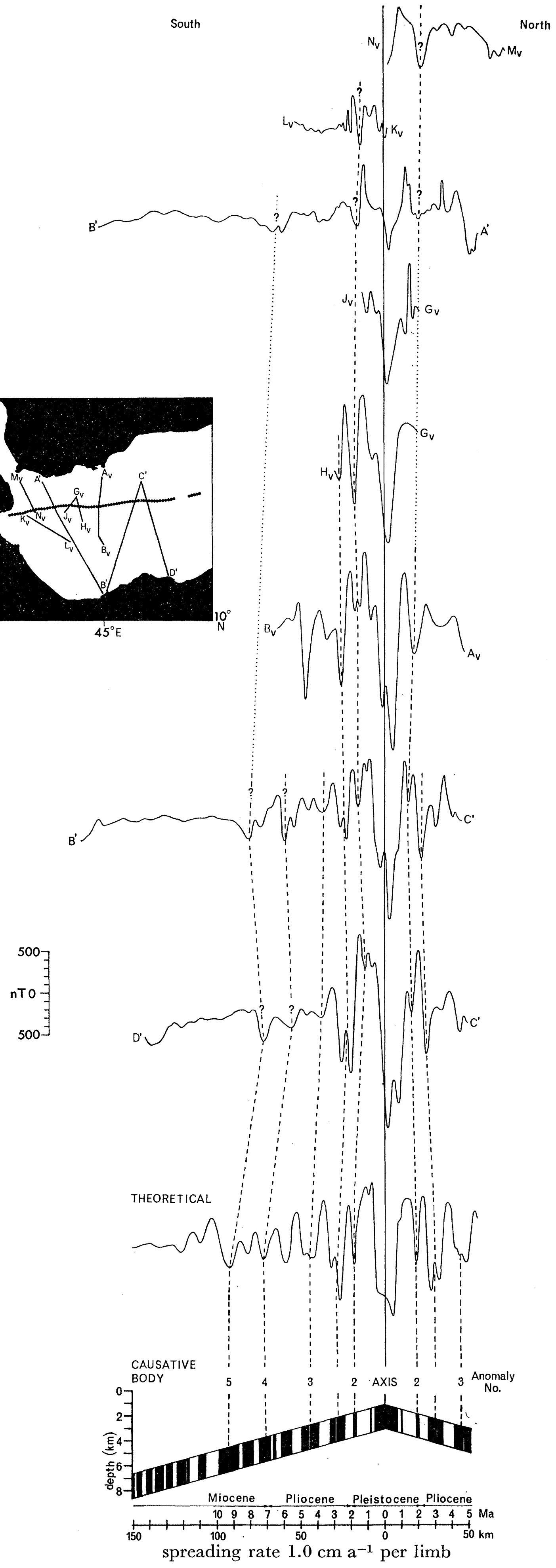
derived from H.M.S. *Owen* data (Admiralty 1963). No corrections have been made for daily variation since, at normal cruising speeds, these appear with wavelengths much larger than those of the crustal anomalies. All the profiles of figure 22 are resolved along a direction 027° (the mean strike of the Owen Fracture Zone and the Alula–Fartak Trench). For comparison a profile was computed for a sequence of normally and reversely magnetized prisms striking perpendicular to the fracture zone and contained in a 2 km thick layer the top of which is $2\frac{1}{2}$ km below sea level (the $2\frac{1}{2}$ km level is determined by the mean depth along the eleven selected tracks).

Because of the factors discussed earlier, the correlation of observed and computed profiles must to a certain extent be subjective. However, in many cases, anomalies 1, 2, $2\frac{1}{2}$, 3 and 5 can be reliably identified because of their characteristic shape. Once some of these distinctive anomalies have been identified the others may be identified in sequence from the positions of the maxima and minima in the observed profile.

Except for the eastern tracks OP, QR and MN, all the profiles of figure 22 exhibit a striking negative anomaly associated with the median valley together with, in most cases, a neighbouring pair of maxima enclosing anomaly 2. Many correlations are possible beyond this, although in some cases the identified sequence of anomalies is terminated by fracture zones when the anomalies become greatly subdued or distorted. No significant anomalies are present along profile OP taken close to the edge of a fracture zone graben. It is, however, possible to correlate out to anomaly 5 on both sides of the central ridge axis just west of the Alula–Fartak Trench, but beyond this the anomalies are greatly subdued. Although a possible identification of anomaly 5 is obtained on profiles ED and IJ, no continuous tracks are available east of the Alula–Fartak Trench for studying the anomaly pattern beyond anomaly 5. Sufficiently long sequences of identified anomalies are however obtained for an evaluation of the seafloor spreading associated with East Sheba Ridge during the past 10 Ma. It is interesting to note that beyond anomaly $2\frac{1}{2}$ on the northern side of profile IJ the anomaly correlation is confused, although anomalies 3 to 5 may be identified in positions displaced by 20 km relative to the computed profile. A confused zone is also noted in a similar position on profiled LK. This zone of confusion is associated with a concentration of earthquake epicentres (figure 16) and appears in a region where, according to the bathymetric and magnetic contour charts, the East Sheba Ridge starts to curve westwards. The possibility of unmapped transform faults here has already been discussed.

A similar interpretation of magnetic profiles was also attempted for the data available west of longitude 47° E. In figure 23 the magnetic anomaly profiles obtained from *Vema* cruise 14 and *Discovery* cruise 16 data are shown plotted normal to the E–W trend of the median valley in this region. Although they all exhibit a strong central anomaly there appears to be a much steeper fall off in anomaly amplitude away from the spreading centre than is the case on the East Sheba Ridge. Evidence presented by Laughton & Tramontini (1970) reveals that along tracks A′B′ and B′C′ the top of seismic layer 2 deepens from about 1.3 km at 25 km from the median axis to 2.5 km at a distance of 130 km, while its thickness in this interval increases from 1.8 to 2.9 km. If the magnetic layer can be identified with the seismic layer 2 the evidence suggests that the magnetic anomalies should be simulated by a dipping layer model. Using the

FIGURE 23. The identification of magnetic anomalies west of 47° E. Observed magnetic anomaly profiles from tracks of *Vema* cruise 14 (lettered with suffix 'v') and *Discovery* cruise 16 (inset), projected onto direction 000°. Computed anomaly profile from normal (black) and reversely (white) magnetized blocks according to Heirtzler time scale. Assumed ridge strike, 090°; effective susceptibility, ± 0.01; intensity and dip of Earth's field, 37 μT and +8° respectively. 1 nT ≡ 1 γ.



spreading rate 1.0 cm a^{-1} per limb

For legend see facing page.

Heirtzler time scale and a spreading rate of 1.0 cm a^{-1} per limb, a magnetic profile was computed from a sequence of normally and reversely magnetized blocks contained within a 2 km thick layer dipping from a depth of 1 km at the centre of the median valley to 7 km at a distance of 160 km (figure 23). Although the dip is some three times greater than that suggested by the seismic evidence, this profile simulates well up to anomaly 5 the fall off in anomaly amplitude away from the median valley as observed along tracks B′C′ and C′D′. It is possible that the seismic layer 2 is not entirely composed of magnetized basalt, and that the magnetized layer as well as dipping also thins away from the central axis of the median valley. An alternative explanation is that the remanent magnetization of basaltic rocks decays with time (Vine 1968).

The large central negative anomaly is easily identified on all the profiles west of longitude 47° E, although it decreases in amplitude to the west. Where the length of profile permits it is also possible to identify anomaly 2. However, west of longitude 45° E no further correlations are possible and the general form of the profiles does not seem to correspond to that required by the simple sea floor spreading model. On the other hand, east of 45° E the computed profile simulates fairly closely both profiles B′C′ and C′D′ between anomaly 2 on the northern side of the median valley and anomaly 3 to the south. Outside this range the correlation of anomalies is less certain although there are indications that it might be possible to identify the most southerly prominent negative anomaly on each profile as anomaly 5. The anomaly pattern is greatly subdued beyond this in a manner similar to that observed beyond anomaly 5 on the East Sheba Ridge profiles. A possible explanation of this effect may be that before anomaly 5 (about 10 Ma ago) the igneous material injected at the axis of spreading was more fluid and flowed away from the active centre to provide horizontal beds of flood basalts. Such a process would then reduce the amplitude of the observed anomalies. This agrees with the nature of layer 2 in the Half Degree Square.

On five of the profiles studied in the Gulf of Aden (B′C′, C′D′, LK, FG and IH) it is interesting to note the presence of a small positive anomaly corresponding in position to the Mammoth reversed event (about 3 Ma ago) found by Vine (1966) in the Gauss normal epoch. If the random dyke injection computations of Harrison (1968) are valid, this would suggest that the standard deviation of the positional scatter of dyke injection about the central axis of the median valley of the Gulf of Aden should be less than 3 km.

The drift of Arabia from Somalia

The magnetic anomaly correlations of the previous section enable an isochron map to be constructed to illustrate the increasing age of the ocean crust away from the spreading axis. The present-day axis of spreading is located at the large central negative anomaly of the magnetic contour chart and at the position of the median valley. By using the anomaly correlations as a control for isochron identification the magnetic anomaly chart may then be used for determining the positions and trends of the other isochrons. An isochron chart for the Gulf of Aden is shown in figure 24. Stippled zones of confusion define regions where the identification of isochrons is not possible. In most cases these zones locate the positions of transform faults. At these faults the continuity of the isochrons is broken and the whole isochron sequence is offset by a finite amount. Only two of the zones of confusion fail to relate to known transform faults, namely a region just east of the Alula–Fartak Trench and a band around 14° 30′ N, 56° 30′ E that runs almost parallel to the median valley for about 100 km but is displaced northwards from it by approximately 30 km.

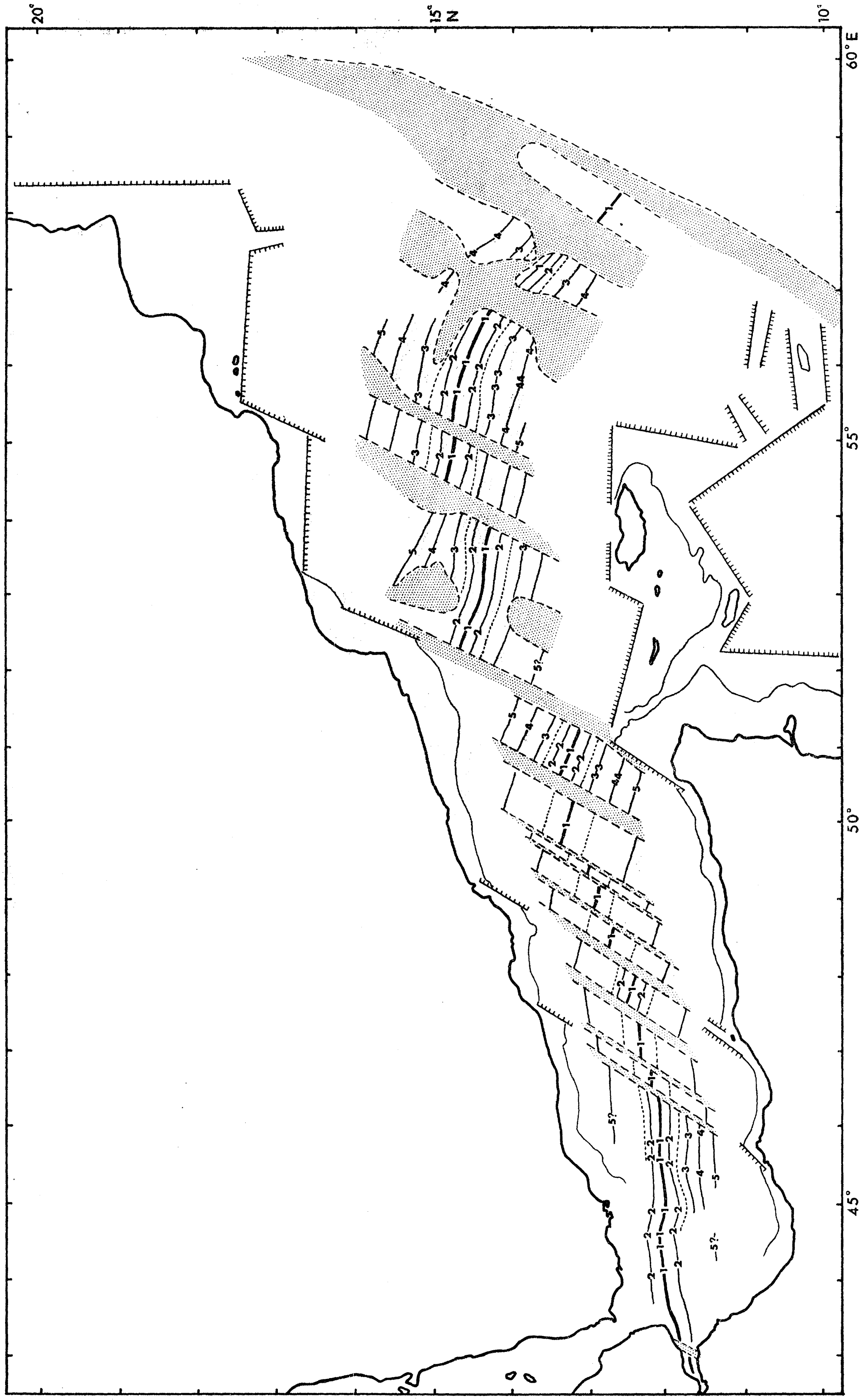


FIGURE 24. Isochron chart of the Gulf of Aden derived from the interpretation of magnetic anomalies, in terms of anomaly numbers. Solid lines represent the trends of the prominent anomalies out to anomaly 5 (about 10 Ma ago); dashed lines show trend of anomaly $2\frac{1}{2}$ (about 3 Ma ago). Zones of confusion are shown stippled.

The isochrons for anomalies $2\frac{1}{2}$ and 5, corresponding to approximately 3 and 10 Ma ago respectively, can be traced from just west of the Owen Fracture Zone right through into the western end of the Gulf of Aden, although the position of the anomaly 5 isochron is somewhat uncertain west of longitude 45° E. On the East Sheba Ridge the position of the anomaly 5 isochron lies close to the edge of the zone comprising ridges parallel to the median valley, and as suggested earlier this isochron may delineate the boundary between simple dyke injection at the axis of spreading and dyke injection accompanied by horizontal flows. Ewing & Ewing (1967) suggest that this anomaly corresponds in age to the end of a worldwide hiatus in spreading at about 10 Ma ago which is consistent with evidence from sediment distribution in the Gulf of Aden. The prominent negative anomaly close to South Yemen may be identified with either anomaly 4 or 5. If it is anomaly 5, then the South Yemen coast was at the spreading axis 10 Ma ago.

TABLE 1. SPREADING RATES DERIVED FROM THE ANALYSIS OF MAGNETIC ANOMALIES

track	position of spreading axis °E	position of spreading axis °N	angular distance from Le Pichon (1968) pole deg	anomaly range used (no. of max. and min.)†	mean spreading rate normal to spreading axis cm a^{-1} per limb	spreading rate along fracture zone strike cm a^{-1} per limb
QR	57.3	13.7	36.2	{2S–3½S (11); 2½N–4N (10)}	1.11 ± 0.05	1.11
LK	56.5	14.3	35.2	{4S–3S (7); 3S–2S (9)}	1.10 ± 0.05	1.10
IJ	56.0	14.6	34.6	4S–2S (14)	1.13 ± 0.10	1.13 (1.16*)
IH	55.6	14.7	34.2	2N–3½N (13)	1.10 ± 0.10	1.10 (1.38*)
FG	54.8	14.8	33.5	3S–3½N (18)	1.06 ± 0.10	1.06 (1.17*)
ED	53.6	14.4	32.6	{3S–2½N (14); 3N–5N (12)}	1.03 ± 0.05	1.03 (1.18*)
YZ	50.9	13.2	30.8	4½S–5N (30)	1.00 ± 0.05	1.00
F′G′	50.7	13.4	30.6	4½S–3N (21)	0.98 ± 0.05	0.98
C′D′	45.8	12.1	27.2	5S–2S (8)	0.78 ± 0.10	0.95
B′C′	45.6	12.0	27.0	2½S–2N (20)	0.79 ± 0.10	0.96
Carlsberg Ridge	63.8	3.7	46.7	5S–5N (26)	1.43 ± 0.05	1.43
	61.7	5.3	44.0	{4½S–2½N (8); 2½N–5N (10)}	1.35 ± 0.10	1.35

* Computed for curved spreading axis (see text).

† Refers to the range of numbered anomalies within which an undisturbed linear sequence of points was obtained from the quoted number of identified maxima and minima.

According to Morgan (1968) and McKenzie & Parker (1967) the active separation of two crustal plates can be described in terms of a finite rotation about a given pole. Transform faults across the axis of separation of the plates describe small circles about this pole and define the direction of motion. Although there is a tendency for the axis of a mid-ocean ridge to aline itself normal to the transforms, this is not a strict requirement of the rotation. Indeed, in the western Gulf of Aden the median valley runs almost E–W whereas the transform fault strike is about 035°. Spreading rates thus have to be determined along a direction normal to the ridge axis and then resolved in the direction of the transform faults to provide values representative of the rotational rate of separation.

The average spreading rate along an observed magnetic profile can be derived from a plot of the positions of the observed anomalies against their identified positions on the computed profile. So as to eliminate the effects of transform offsets, the spreading rate is then determined from the slope of the longest undisturbed linear sequence of points. A summary of the spreading rates obtained for the Gulf of Aden is given in table 1 as determined normal to the median valley strike and also projected parallel to the strike of the transform faults. East of 50° E it was assumed that the strike of the median valley was normal to the transform fault strike. As the magnetic and bathymetric contour charts show the East Sheba Ridge to be curved the spreading rates were also determined for profiles IJ, IH, FG and ED assuming a curved spreading axis. These rates are shown asterisked in table 1. It was possible to obtain an uninterrupted sequence of identified anomalies out to anomaly 5 on both profiles YZ and F′G′ such that no identified anomaly departed by more than 2 km from the best straight line fitted to plots of the observed positions of anomalies against their computed positions. This indicates that the drift of Arabia from Somalia has proceeded at a uniform rate during the past 10 Ma relative to the South Atlantic rate.

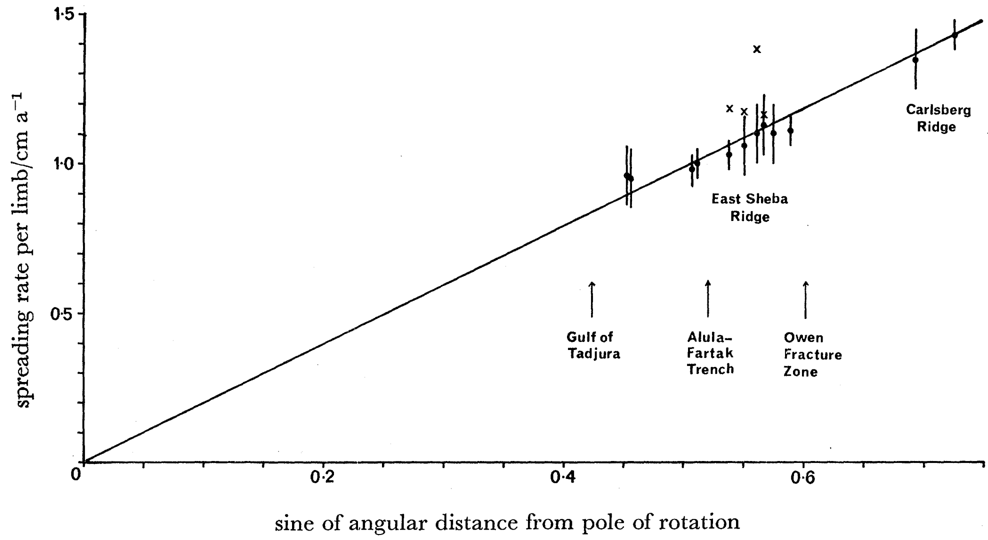


FIGURE 25. Spreading rates of Carlsberg and Sheba Ridges along small circles as a function of the angular distance from the Le Pichon (1968) pole of rotation. Crosses denote spreading rates derived assuming East Sheba Ridge to be curved.

From an analysis of the strike of the fracture zones in the Gulf of Aden, Le Pichon (1968) located the pole of rotation for the drift of Arabia from Somalia at 26° N, 21° E. In agreement with plate theory the spreading rates derived in the Gulf of Aden along the small circles about this pole of rotation are proportional to the sine of the angular distance from this pole (figure 25). Spreading rates derived using the curved ridge assumption (shown as crosses on figure 25) give a greater scatter of values than do the rates determined on the assumption that the East Sheba Ridge always strikes normal to the transform faults. This suggests that the ridge is not curved. However, the available information is not conclusive on this point. The ten points plotted on figure 25 for magnetic profiles analysed west of the Owen Fracture Zone provide a mean angular rate of rotation of Arabia relative to Somalia during the past 10 Ma of 3.5×10^{-7} deg a^{-1}, or a spreading rate at the equator of rotation of 1.96 cm a^{-1} per limb.

Spreading rates were also determined from two magnetic profiles taken by H.M.S. *Owen* across the Carlsberg Ridge at 3° 40′ N and 5° 20′ N (table 1). In deriving these rates it was assumed that the ridge axis was oriented normal to a fracture zone strike of 035°. As shown in figure 25 these values are consistent with the pole position and rotation rate derived for the drift of Arabia from Somalia. This would indicate that there is little differential movement along the Owen Fracture Zone and that the Owen Fracture Zone represents an active transform fault between the East Sheba Ridge and the Carlsberg Ridge. The Plio-Pleistocene drift of Arabia from Somalia must therefore be considered as only part of a much larger system of drifting plates that involve the separation of an East African–Somali Basin plate from a plate containing the Arabian Peninsular, the Arabian Sea and possibly India.

Conclusions

The new data on the Gulf of Aden have enabled us to confirm and elaborate on the hypothesis that at least during the last 10 Ma new oceanic crust has been forming in the central region as a result of the drifting apart of Arabia and Somalia. The Sheba Ridge shows many of the topographic and structural characteristics of a mid-ocean ridge linked to the world system and the detailed surveys have revealed some of the complex processes that occur where an expanding ridge is crossed by many transform faults. Ocean floor generation may be episodic at least on the time scale of a few hundred thousand years as evidenced by the latest phase of spreading which has created a median valley cutting through Pleistocene sediments; episodic spreading on this time scale in its earlier history is likely but would hardly be detectable on the magnetic anomaly record owing to the slow spreading rate as well as to subsequent disturbing factors.

Associated with a phase of spreading, there is evidently uplift of a broad central region of the ridge, many times wider than the median valley itself, and subsequent downfaulting of central crustal blocks which results in the steep inward facing cliffs of the ridges parallel to the median valley. These ridges may have been formed by this process, or more likely they may be the product of earlier phases of spreading thrown into greater relief and asymmetry by the upheaval of the current phase. Such a wide zone of tectonic activity agrees with the scatter of earthquake epicentres beyond the limits of the median valley.

The ridges associated with the NE–SW transform faults also appear to be affected by the spreading phase in the median valley. Normal faulting has been seen on one of these, and at least some of the earthquake epicentres on transform faults lie well beyond the zone between the median valleys.

However in spite of the wide zone of tectonic activity associated with spreading, the detailed correlation of magnetic anomalies with the magnetic reversal time scale shows that the intrusive zone is very narrow and well confined to the median valley itself. It is pertinent to ask therefore why intrusive material is not found along the other contemporaneous faults outside the median valley and what differentiates the nature of faulting inside from that outside. The answer appears to be that the faults outside the valley have no dilatational component to allow intrusions, and are probably under some compression whereas inside the valley in the centre few kilometres dilatation exists and intrusion can take place. This rapid change in the stress field in the crust over a few kilometres can only be caused by a narrow divergent zone of upper mantle flow dragging on the underside of the thin oceanic crust, such as might result from convective currents.

The linear magnetic anomaly pattern over the Sheba Ridge has been interpreted in terms of the Heirtzler magnetic reversal time scale out to anomaly 5 equivalent to about 10 Ma ago. Within this period isochrons can be drawn with reasonable confidence (due account being taken for the disturbance by fracture zones), and hence the Plio-Pleistocene movements can be deduced. Relative to the spreading rate in the South Atlantic and discounting episodic spreading on a time scale of less than a few hundred thousand years, the growth rate of the Gulf of Aden in this period has been constant. A palaeogeographic reconstruction (figure 26) has been drawn by removing all crust younger than anomaly 5 and closing Arabia and Somalia along the small circles of the transform faults. It is interesting to note that the northern edge of the

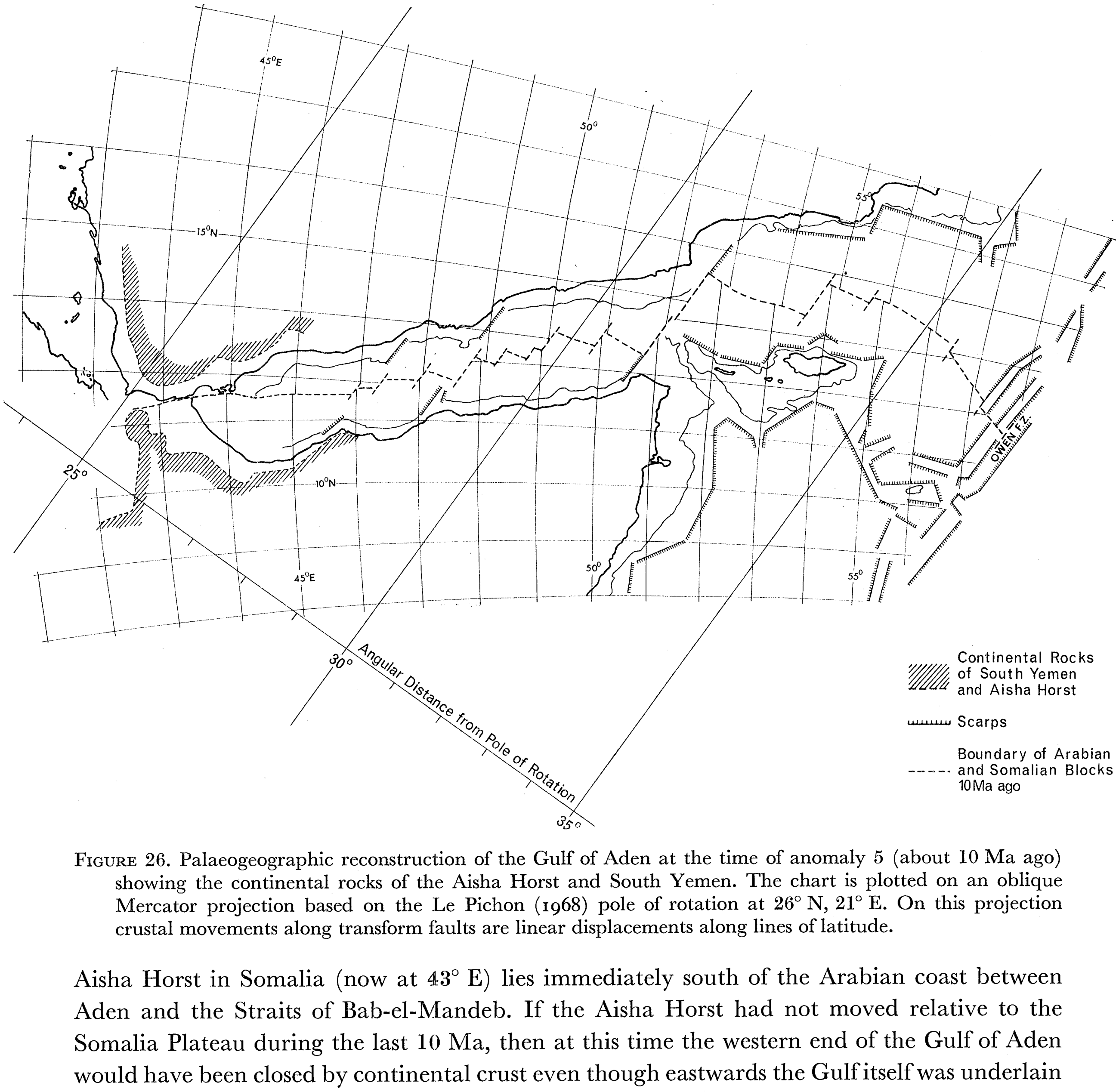


FIGURE 26. Palaeogeographic reconstruction of the Gulf of Aden at the time of anomaly 5 (about 10 Ma ago) showing the continental rocks of the Aisha Horst and South Yemen. The chart is plotted on an oblique Mercator projection based on the Le Pichon (1968) pole of rotation at 26° N, 21° E. On this projection crustal movements along transform faults are linear displacements along lines of latitude.

Aisha Horst in Somalia (now at 43° E) lies immediately south of the Arabian coast between Aden and the Straits of Bab-el-Mandeb. If the Aisha Horst had not moved relative to the Somalia Plateau during the last 10 Ma, then at this time the western end of the Gulf of Aden would have been closed by continental crust even though eastwards the Gulf itself was underlain by oceanic crust.

The geological development of the Gulf of Aden before 10 Ma ago is very much more difficult to determine. There is little doubt from the topography and structure that some of the crust outside anomaly 5 is oceanic, but the anomalies cannot be identified with the Heirtzler reversal time scale. There are indications of a hiatus in spreading at this time which allowed sediment to fill the Gulf, and the nature of the anomalies and of layer 2 suggest that the crustal material was more extrusive than intrusive before the hiatus which may have been the result of faster spreading. If the initiation of horizontal movement between Arabia and Somalia was 20 Ma ago as suggested by Laughton (1966*a*), then any appreciable duration of a hiatus requires an initial spreading rate to be faster than that observed during the last 10 Ma. However, it is not possible for the quiet period to be as long as that suggested by Ewing & Ewing (1967) who postulated that it started in Late Mesozoic or early Cenozoic.

An alternative explanation of the region of the Gulf outside anomaly 5 might be given in terms of crustal thinning. The initial stage of the separation of the Arabia and Somalia crustal blocks was probably associated with complex normal and transcurrent faulting resulting in a stretching and thinning of the continental crust. In some places intrusion of the new oceanic crust might have occurred along these faults in a somewhat random pattern resulting in a patchwork of non-magnetic continental fragments and magnetic intrusions. As separation proceeded the proportion of oceanic to continental crust increased and about 10 Ma ago, the weakest zone in the centre became the sole spreading centre for the generation of new crust. On this model, the oceanic structure found close to the continental margins (stations 169 and 6233 in figure 15) would not be representative of the whole of the region outside anomaly 5. Furthermore, it is difficult to see why the pattern of the median valley should so closely reflect the lines of the continental edges.

A problem of geometry arises at the western end of the Gulf for seafloor spreading before 10 Ma due to the juxtaposition of the Aisha Horst with South Yemen. Too little is known of the geological limits of the continental crust of the horst or of the magnetic anomaly field around it to resolve this problem completely. The aeromagnetic survey of Afar (Girdler 1970) clearly indicates that oceanic type anomalies continue westward of the horst, probably beyond anomaly 5, leaving the Aisha Horst as a promontory on the Somalia crustal block. The E–W anomalies here appear to be offset left laterally suggesting that there are several transform faults in the Afar depression. It is possible, therefore, that the Aisha Horst may be bounded by transform and transcurrent faults and that it may have moved relative to the Somalia block as a continental fragment, as has been suggested for the Danakil Horst (Laughton 1966*b*).

A complete reconstruction of the continents before fragmentation in the junction area must await a detailed interpretation of the recent geophysical and geological data acquired there. A test of the geological fit of the two sides of the Gulf of Aden has been made by Beydoun (1970) who concludes that while a comparison of detailed geology does not add substantial argument in favour of the proposed pre-drift reconstruction, in no way does it argue against it.

In conclusion, therefore, the geological and geophysical data from the Gulf of Aden and its surrounding continents require the drifting apart of Somalia and Arabia at a mean rate of about 2 cm a^{-1} about a pole at 26° N, 21° E for the last 10 Ma. This phase of drift was probably separated from the initial perhaps faster phase by a period of quiescence.

This paper has used data that have been made available from a wide variety of countries and organizations taking part in the International Indian Ocean Expedition. The authors are particularly grateful to Dr Matthews and his colleagues of the Department of Geodesy and Geophysics, Cambridge, both for their participation in the work and the data supplied, to Imperial College, London, and to the Hydrographic Department of the Ministry of Defence.

Magnetic and bathymetric data have also been provided by the Lamont-Doherty Geological Observatory, New York, the Woods Hole Oceanographic Institution, Massachusetts, the Scripps Institution of Oceanography, California, the Earth Sciences Services Administration, Washington, and the Deutsches Hydrographisches Institut, Kiel. We would also like to acknowledge the work of Mrs Judith Dixon of this Institute in the early collection and preparation of magnetic data. We thank Mrs S. Jupp for providing a program to calculate the International Geomagnetic Reference Field, and the Data Processing Group of this Institute for their patient assistance in handling the magnetic data. Finally, none of the expedition work would have been possible without the willing cooperation of the Master, Officers and crew of R.R.S. *Discovery*.

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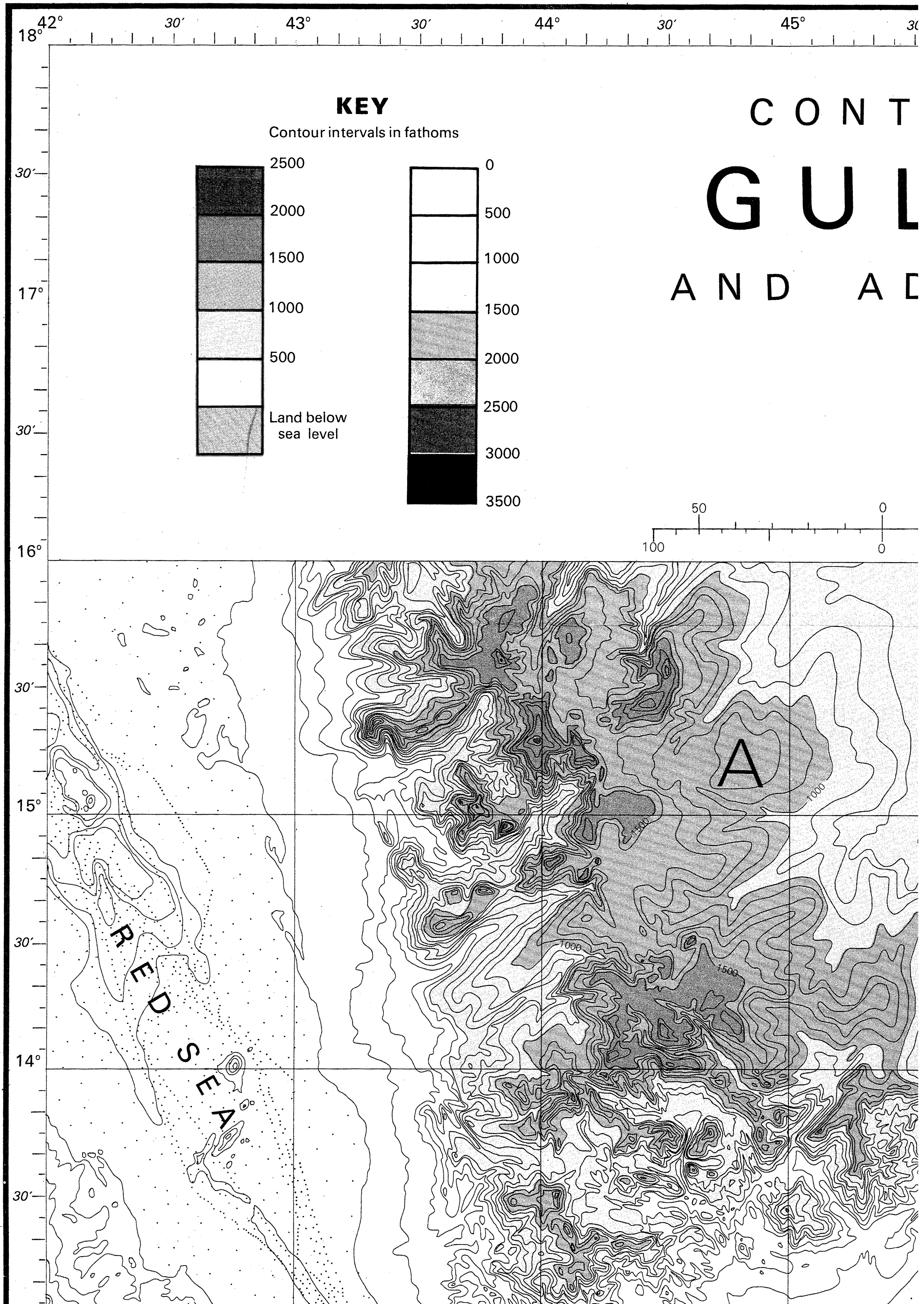
Discussion

J. K. A. Habicht (*B.I.P.M., The Hague*). The A.G.I.P. detailed 1:500000 geological map of Somalia shows a fault system, which runs subparallel to the individual segments of Laughton's Sheba ridge. The age of these faults, according to the map, is post-Eocene/pre-Late Miocene. A similar pattern of faults occurs also north of the Gulf of Aden.

The subparallelism of these faults and of the segments of the Sheba ridge would suggest that the initial opening of the Gulf of Aden 'made use' of this fault system. The break may have occurred along a zigzag track consisting of legs along the faults and intervening legs at a high angle to the faults: the latter developed into transform faults as separation was increasing, the former determined the direction of the segments of the Sheba ridge.

If the Sheba ridge system originated in this way, the opening of the Gulf of Aden could not have started before the fault system had been formed. It would appear therefore that the Gulf of Aden could not have started to form before the Oligocene.


KEY
Contour intervals in fathoms
2500
2000
1500
1000
500
Land below sea level
0
500
1000
1500
2000
2500
3000
3500
CONT
GUL
AND AD
50
0
100
0
42°
30′
43°
30′
44°
30′
45°
18°
30′
17°
30′
16°
30′
15°
30′
14°
30′
A
1000
1500
RED SEA

30′ 46° 30′ 47° 30′ 48° 30′ 49°

NTOUR CHART OF THE

LF OF ADEN

ADJACENT CONTINENTS

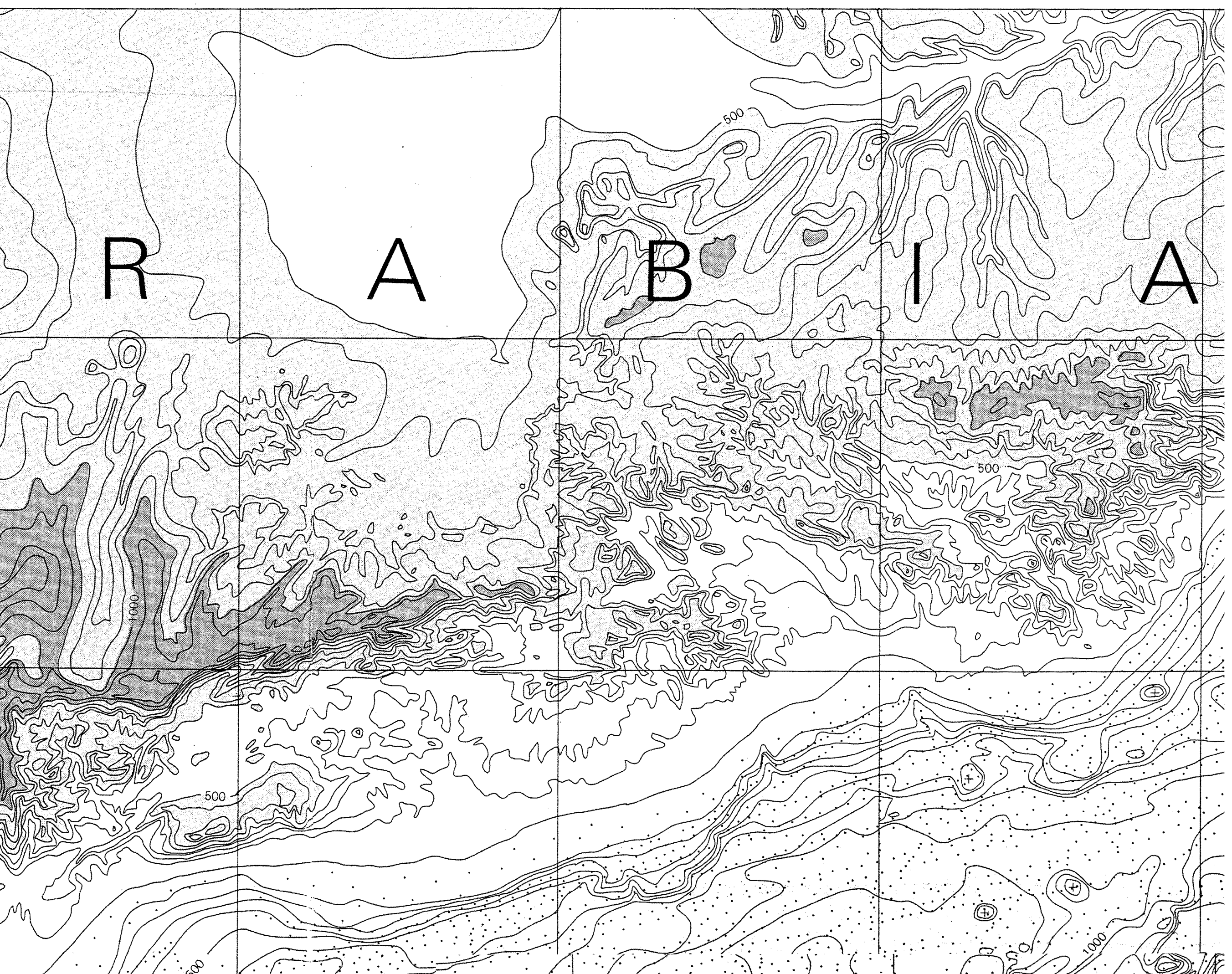
By A. S. LAUGHTON

National Institute of Oceanography
Great Britain

SCALE 1: 2,000,000 at 33° N

0 50 100 150 200 Statute Miles at 13° N

0 100 200 300 KM

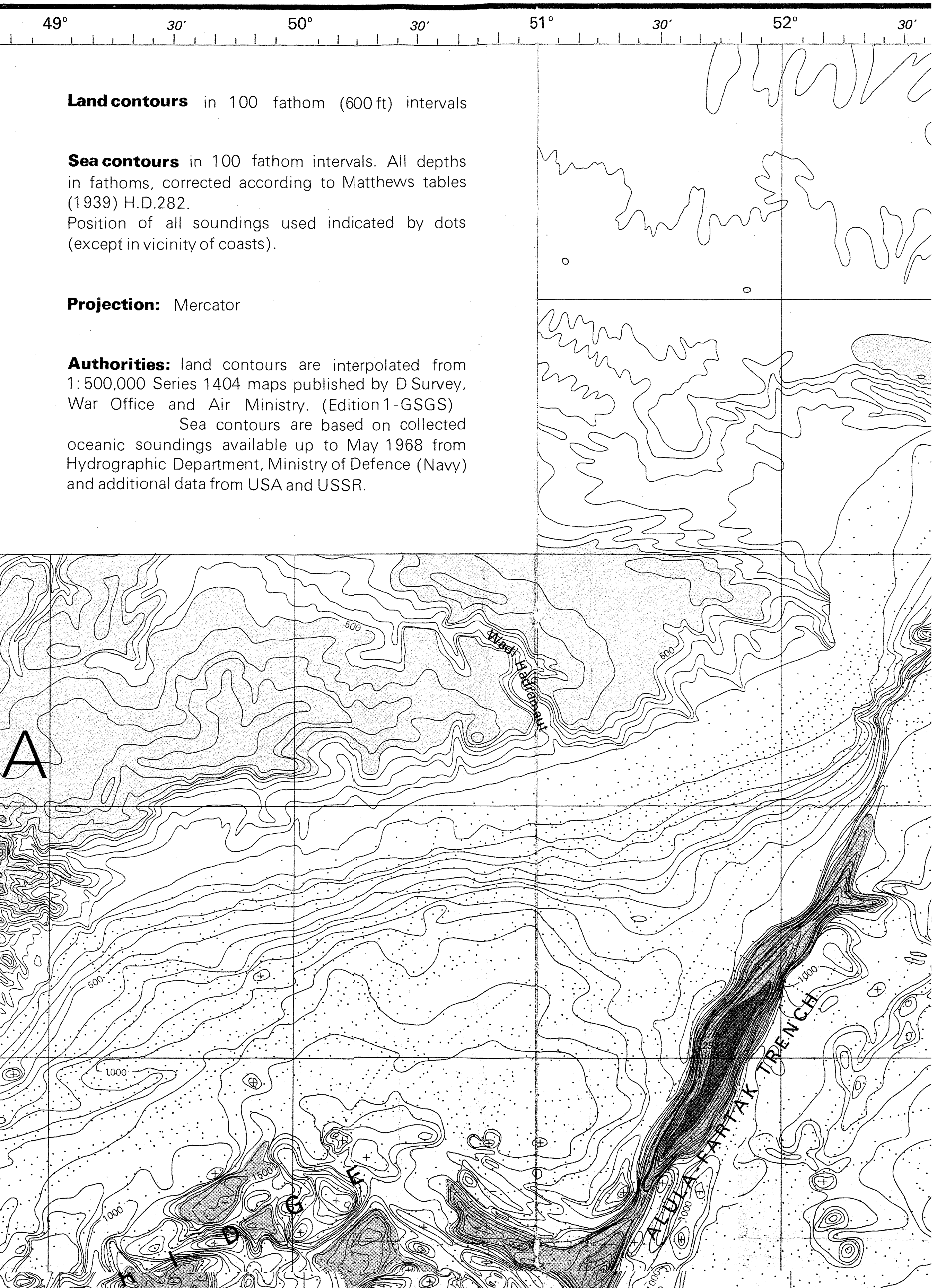


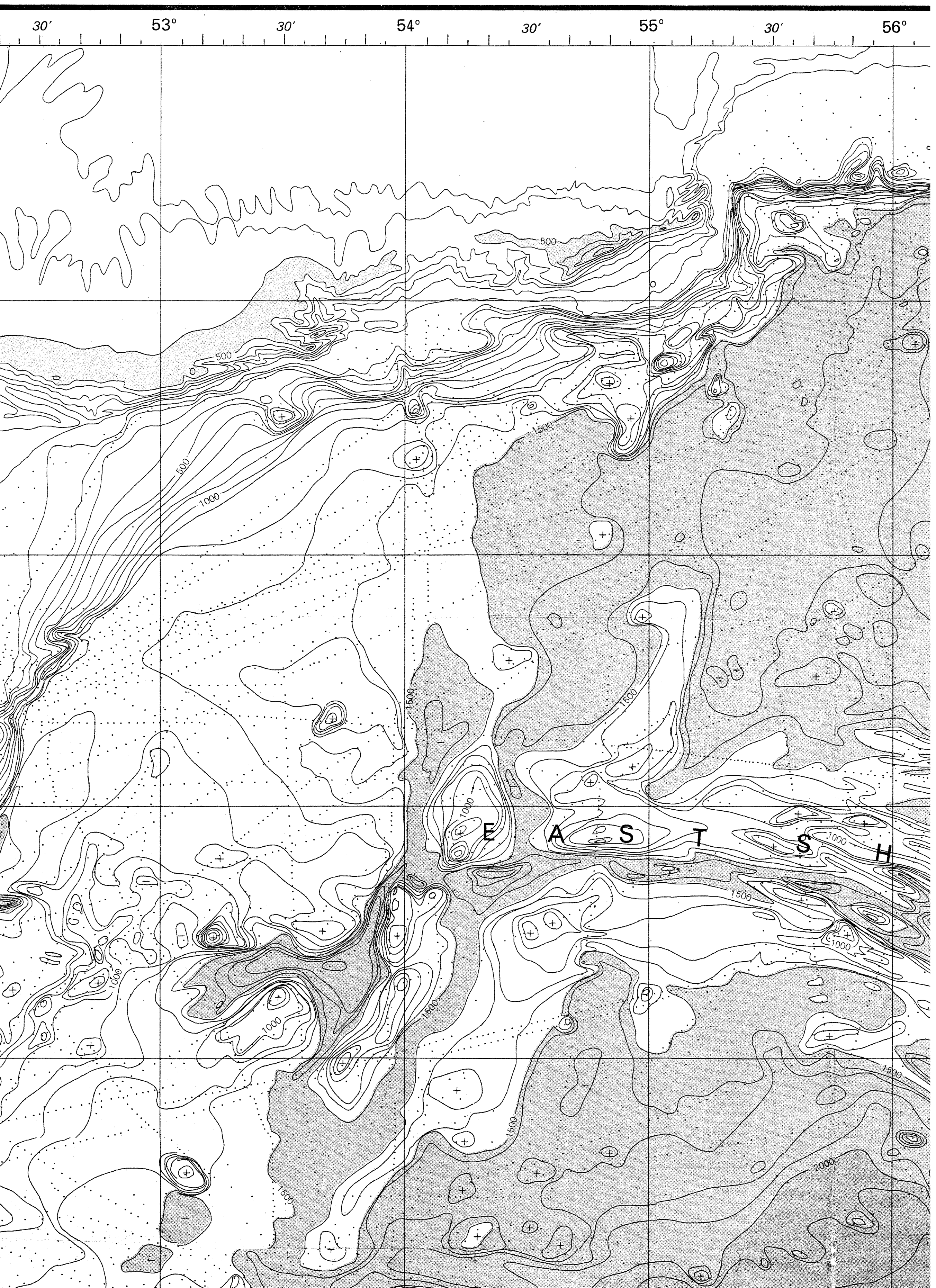
Land contours in 100 fathom (600 ft) intervals

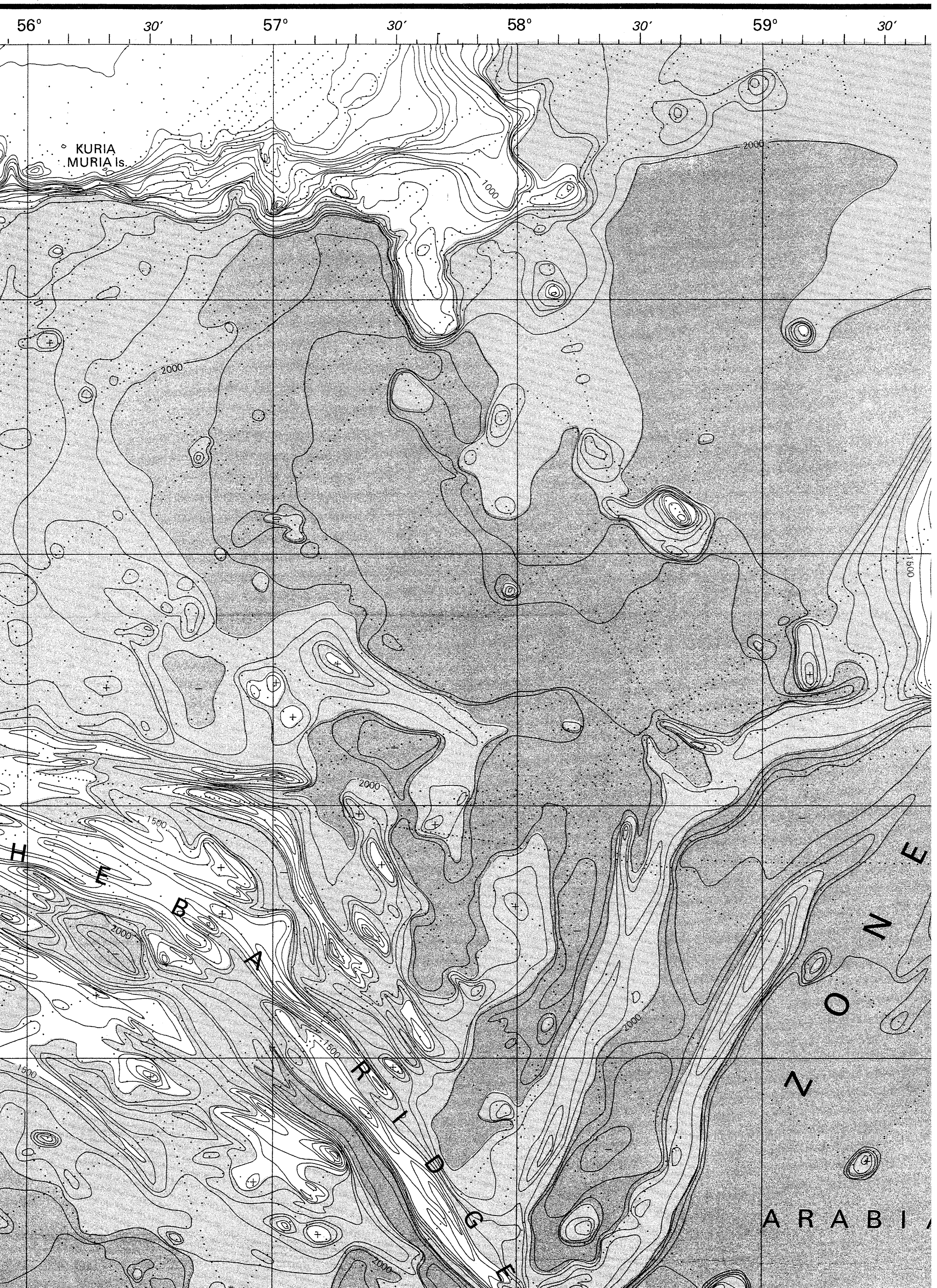
Sea contours in 100 fathom intervals. All depths in fathoms, corrected according to Matthews tables (1939) H.D.282.
Position of all soundings used indicated by dots (except in vicinity of coasts).

Projection: Mercator

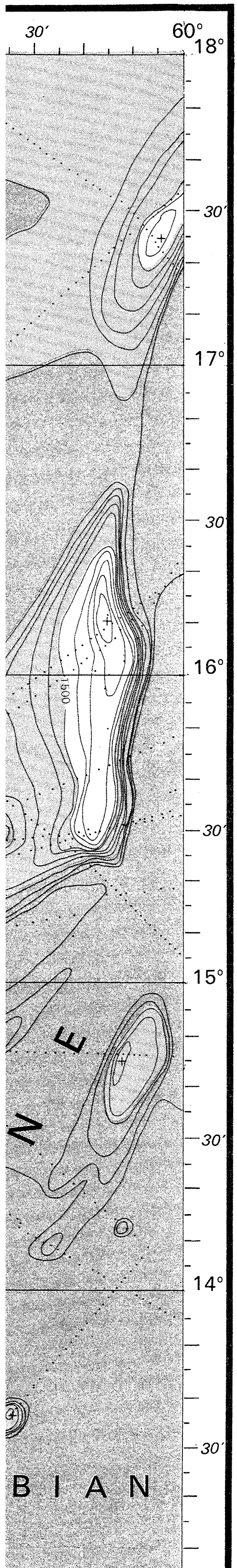
Authorities: land contours are interpolated from 1:500,000 Series 1404 maps published by D Survey, War Office and Air Ministry. (Edition 1-GSGS)
Sea contours are based on collected oceanic soundings available up to May 1968 from Hydrographic Department, Ministry of Defence (Navy) and additional data from USA and USSR.



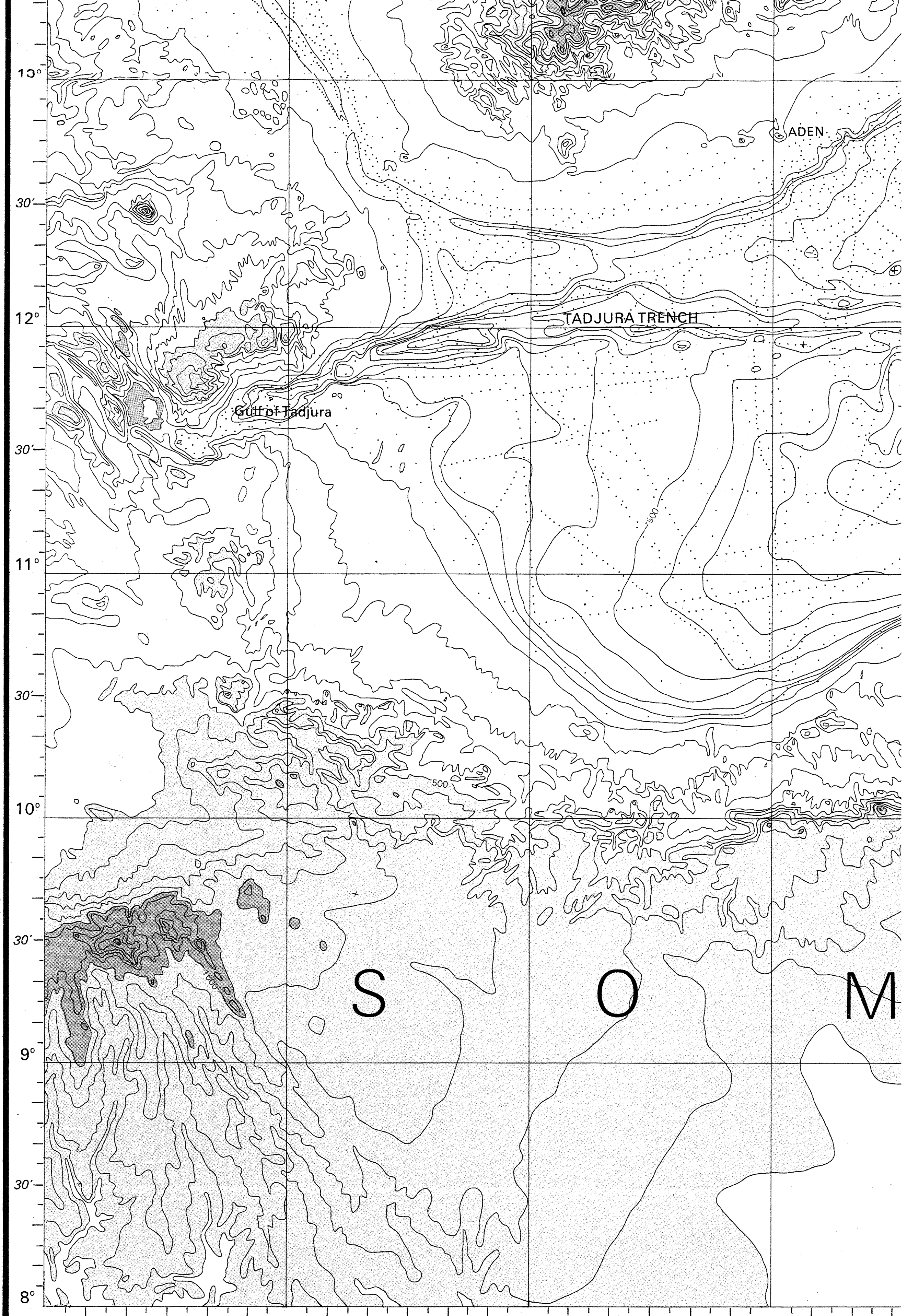

30′
53°
30′
54°
30′
55°
30′
56°
500
500
500
1000
1500
1500
1500
1000
E A S T S H
1000
1500
1000
1000
1500
1000
1500
1500
2000
1500



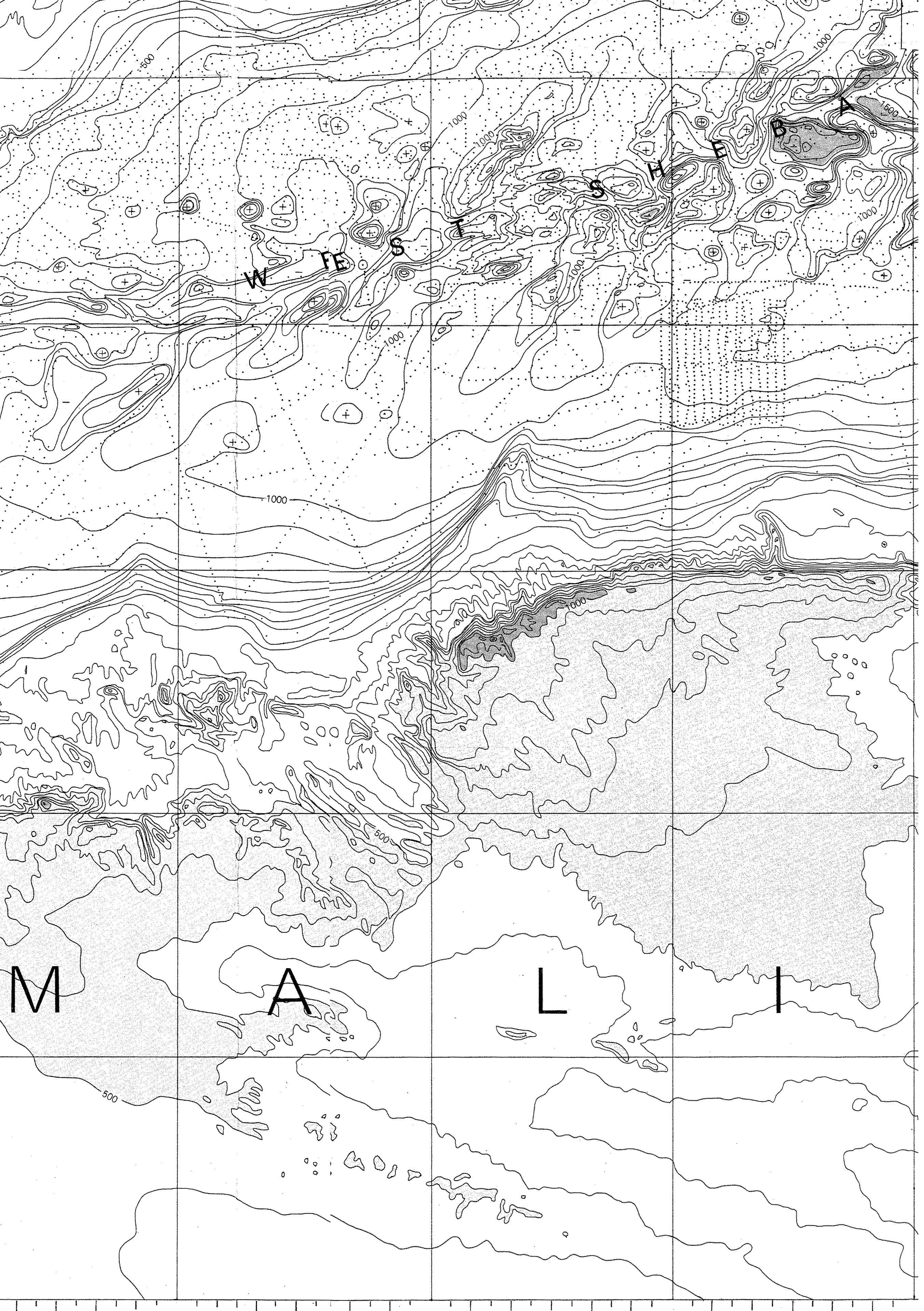
56°
30′
57°
30′
58°
30′
59°
30′
KURIA
MURIA Is.
1000
2000
1500
H E B A R I D G E
Z O N E
A R A B I A



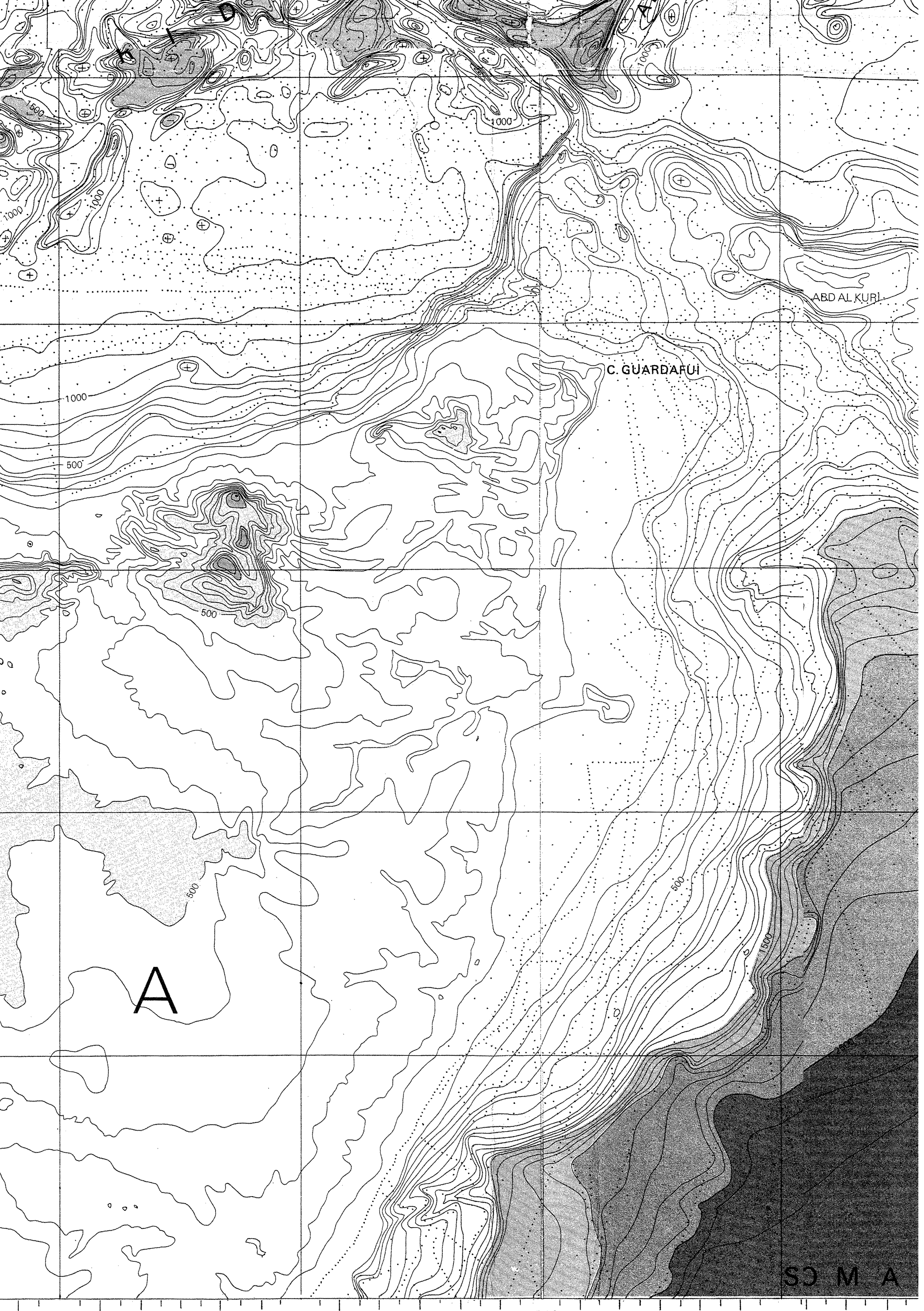
30′
60°
18°
30′
17°
30′
16°
1500
30′
15°
E
N
30′
14°
30′
B I A N



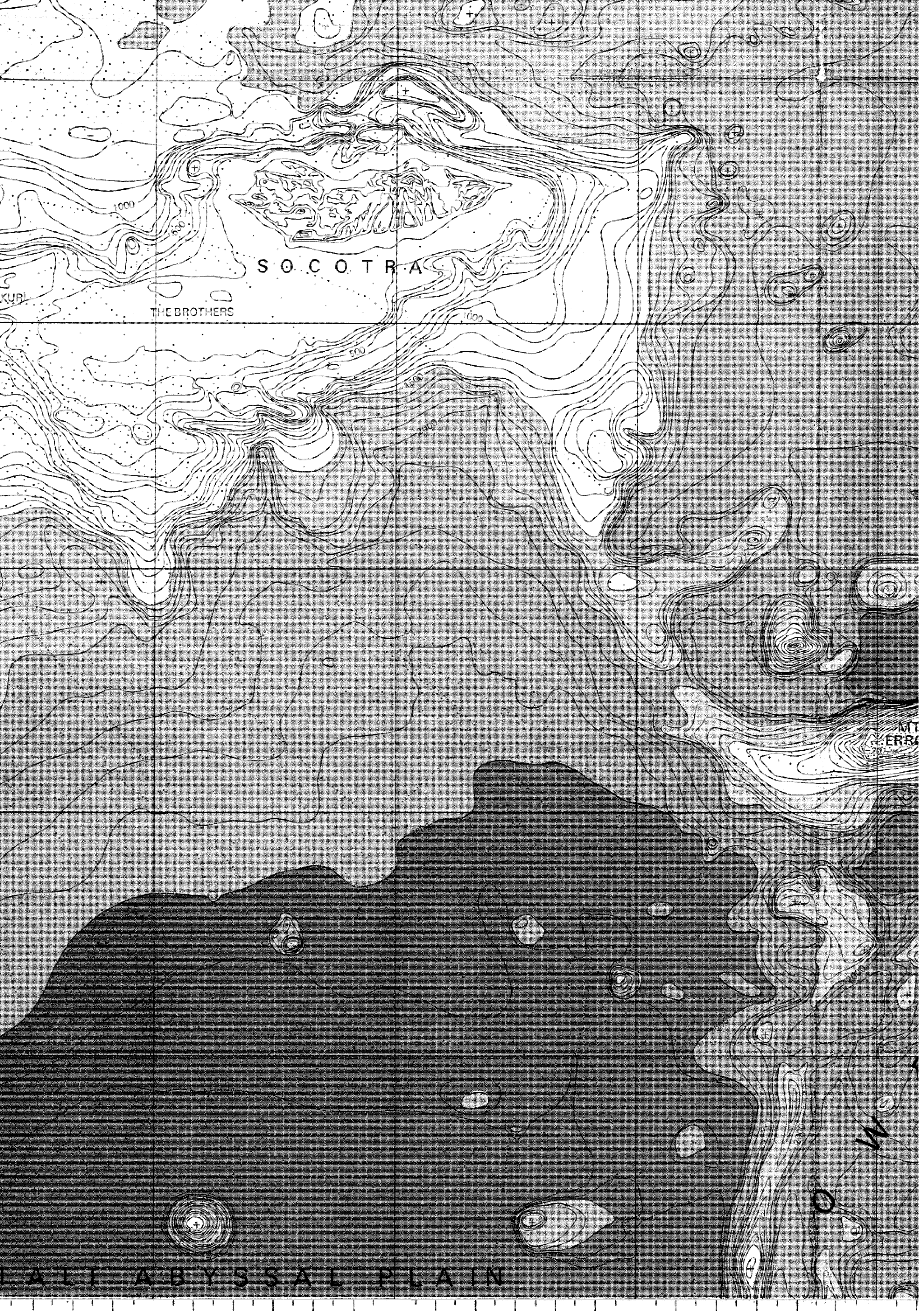
13°
ADEN
30'
12°
TADJURA TRENCH
Gulf of Tadjura
30'
500
11°
30'
500
10°
30'
1000
S
O
M
9°
30'
8°



W E S T S H E B A
M A L I
500
1000
1500

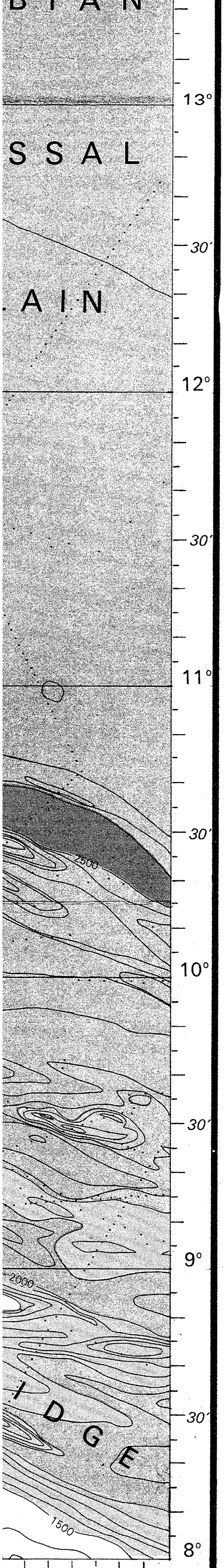


1500
1000
ABD AL KURI
C. GUARDAFUI
1000
500
500
500
500
1500
A

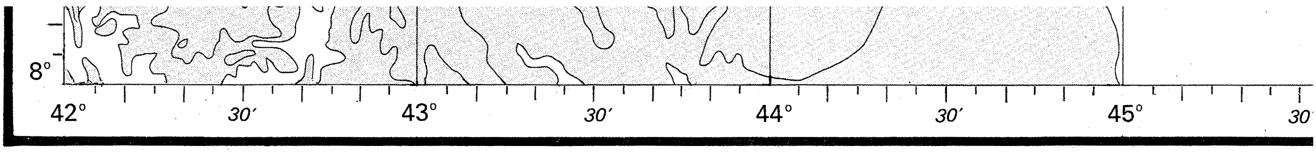


SOCOTRA
THE BROTHERS
1000
500
1500
2000

ABYSSA
PLAI
WHEATLEY
DEEP
FRACTURE
OWEN
MT.
ERROR
CARLSBERG RID
2000
1500



13°
S S A L
30′
A I N
12°
30′
11°
30′
2500
10°
30′
9°
2000
I D G E
30′
1500
8°



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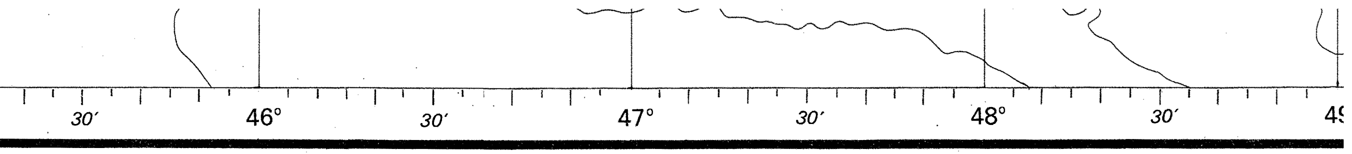
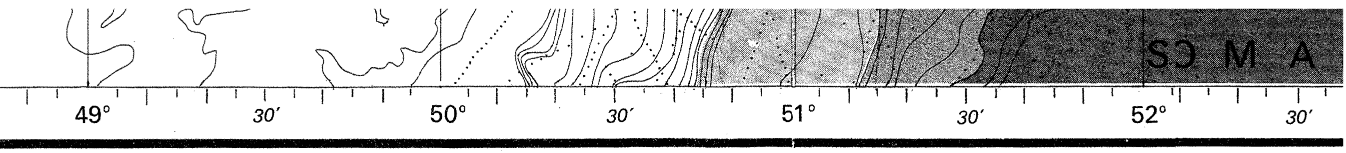
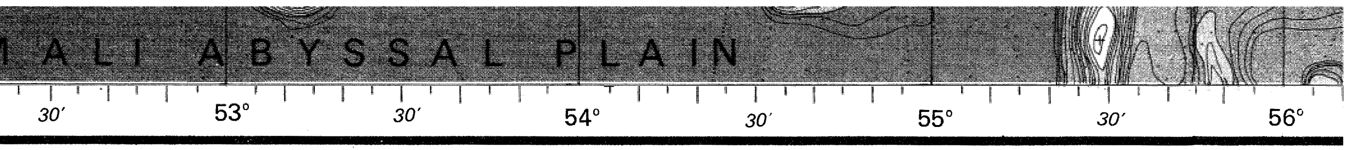
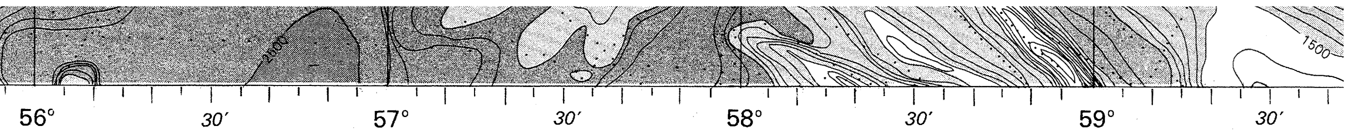
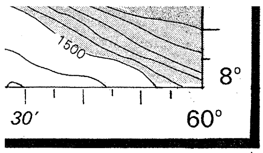

30′
46°
30′
47°
30′
48°
30′


49°
30′
50°
30′
51°
30′
52°
30′

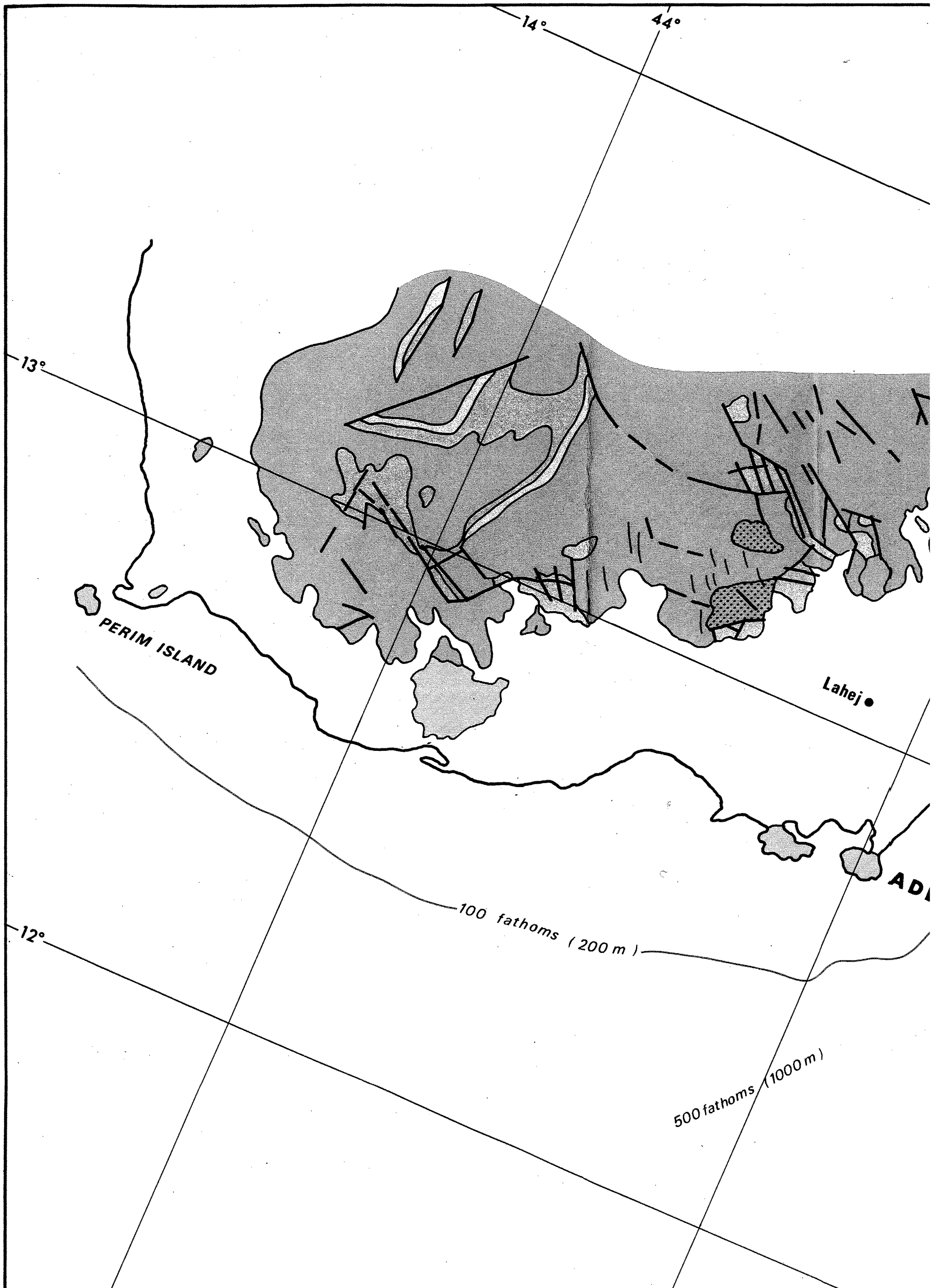

ALI ABYSSAL PLAIN
30′
53°
30′
54°
30′
55°
30′
56°



Automatic Cartography by the Royal College of Art, London E.C.U: m



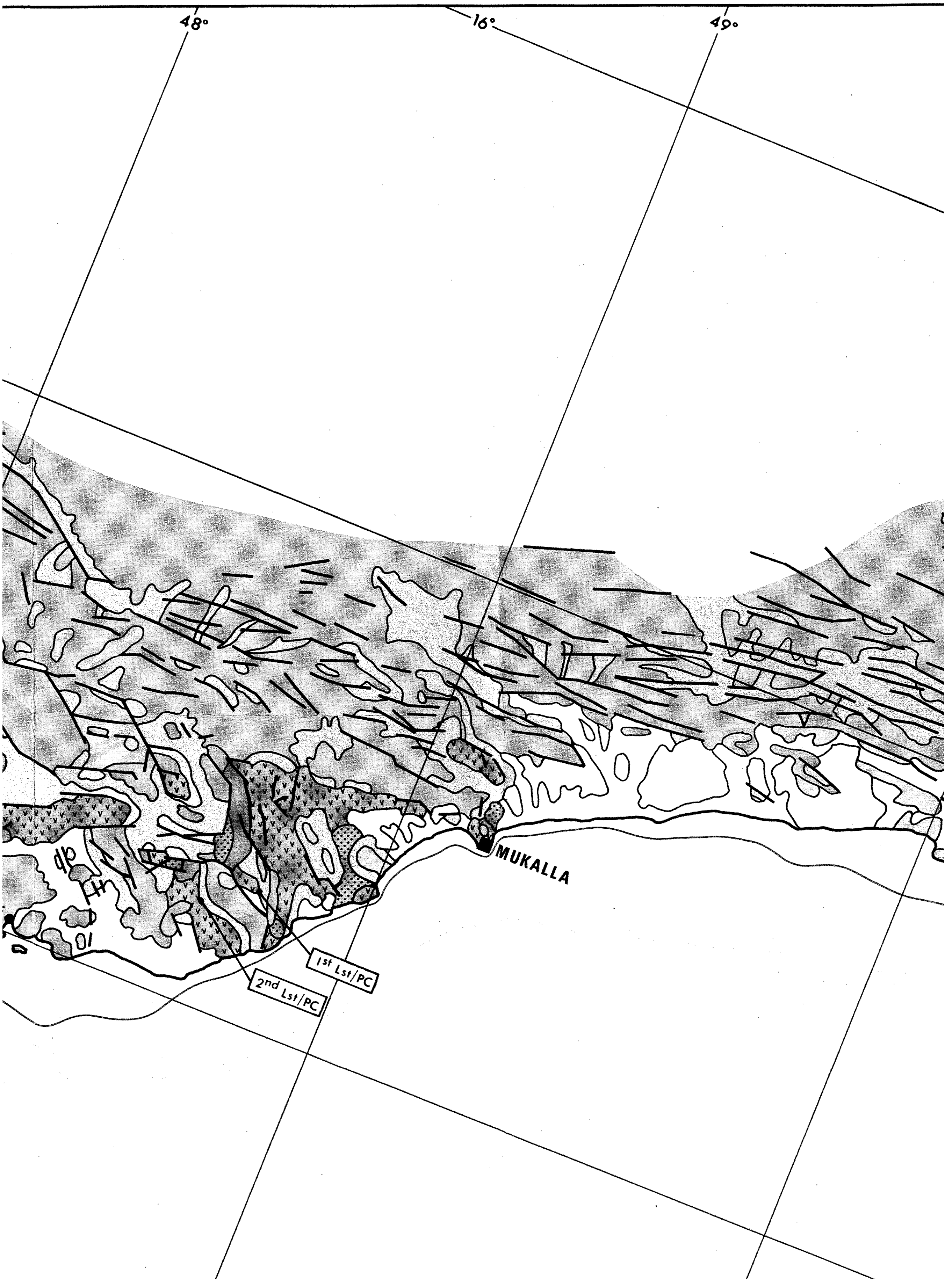
E.C.U. map ref. no. 2



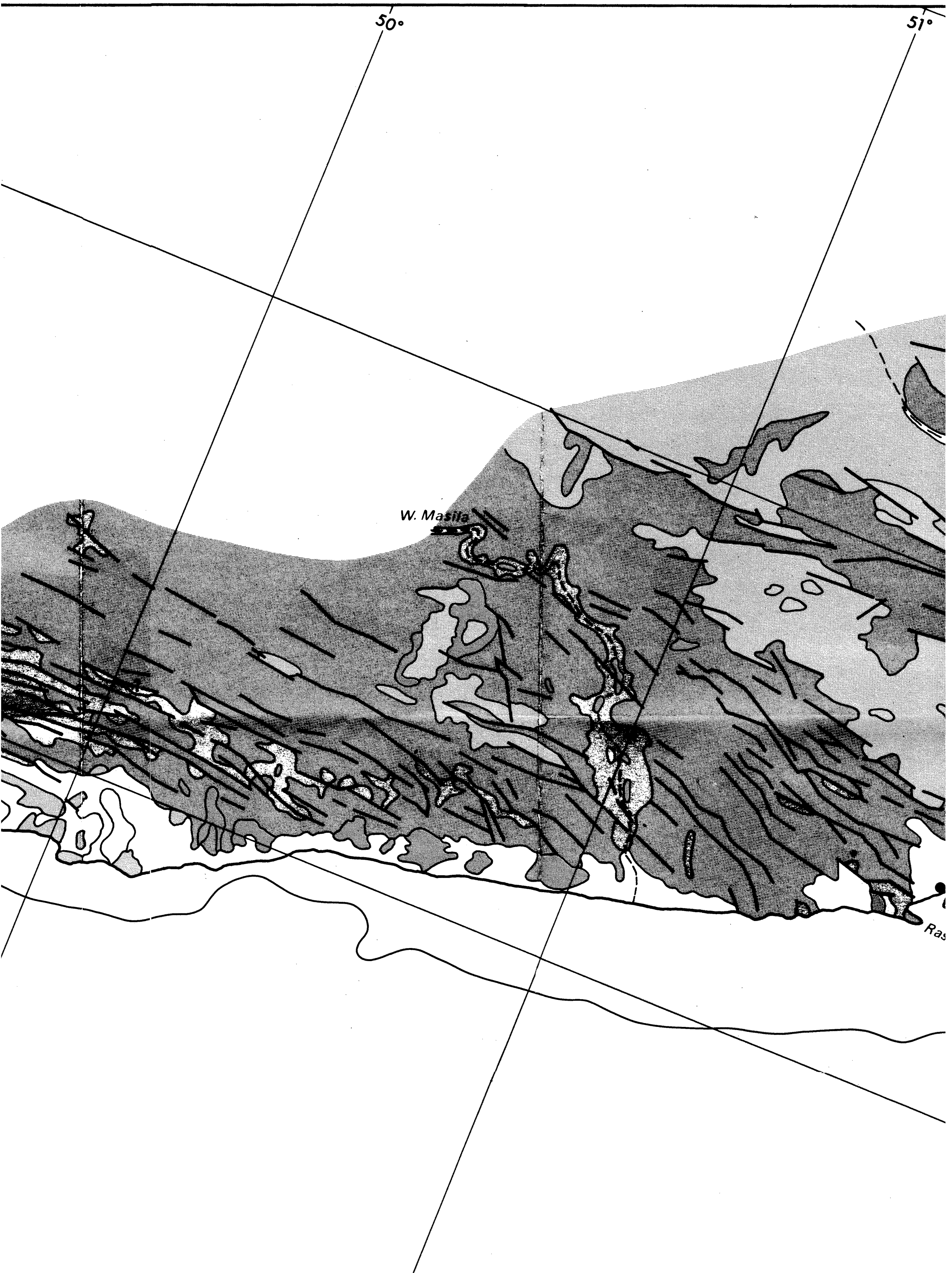
14°
44°
13°
12°
PERIM ISLAND
Lahej
ADE
100 fathoms (200 m)
500 fathoms (1000 m)

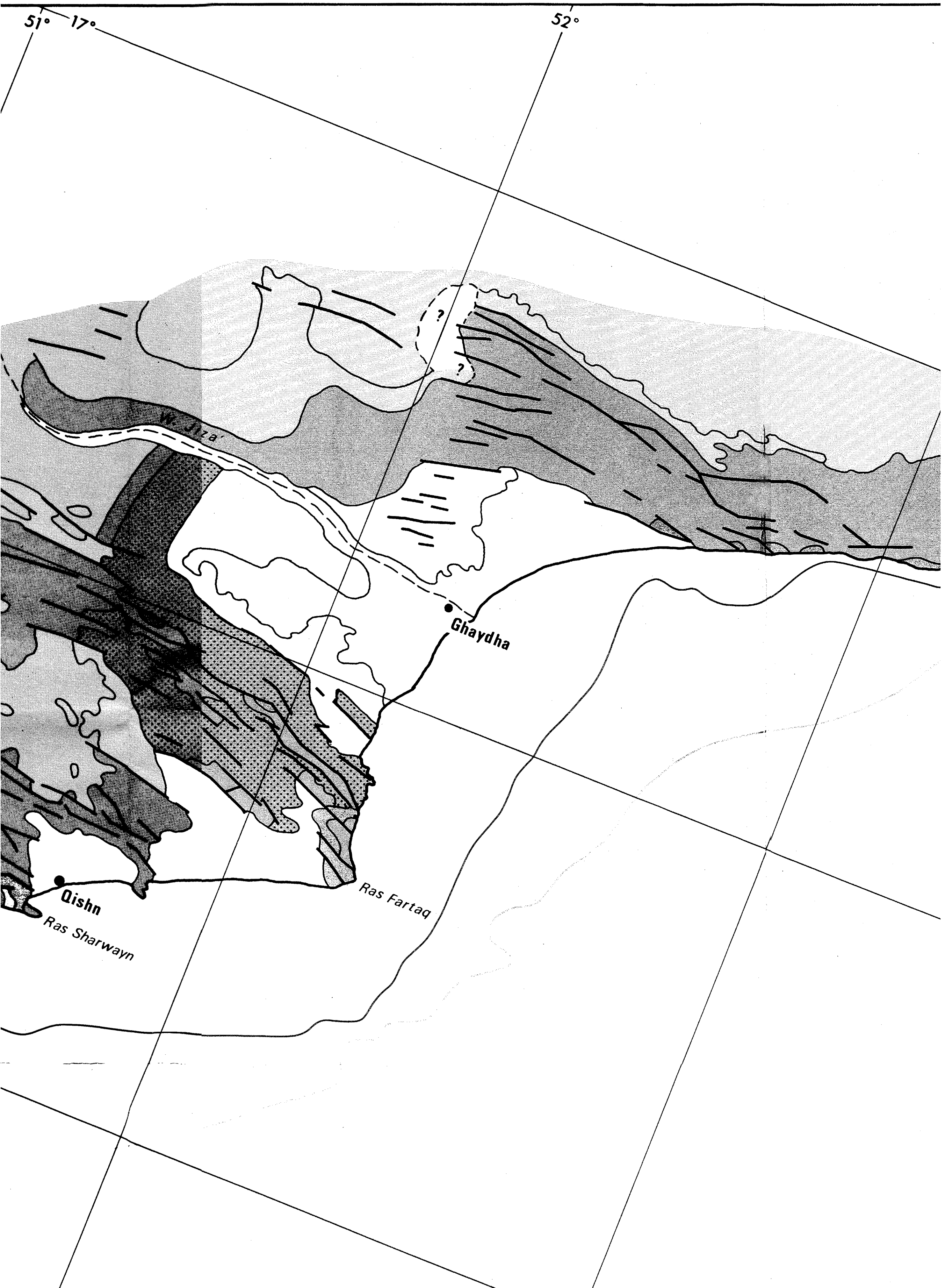

45°
46° 15°
Shuqra
Ahwa
ADEN

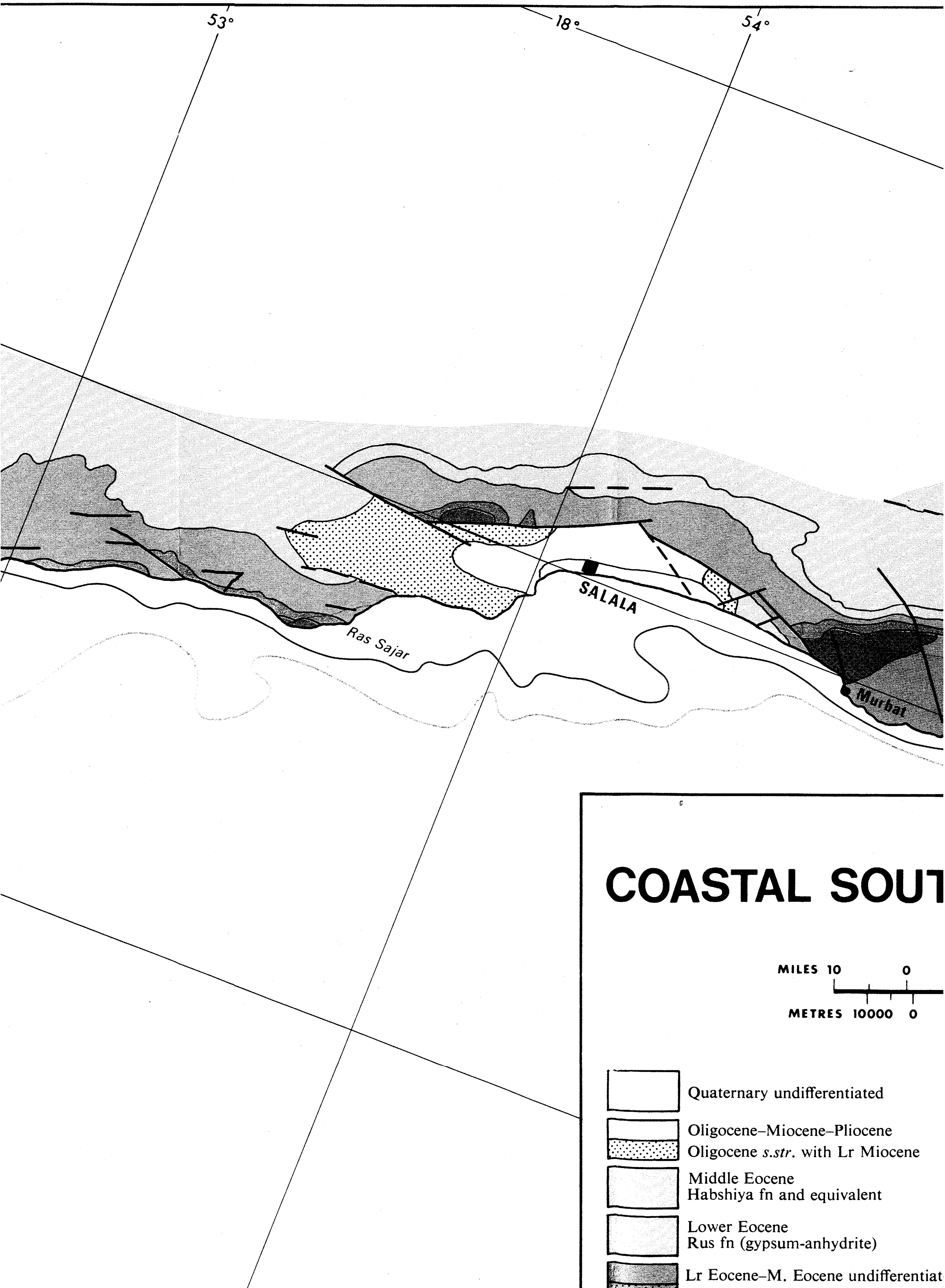
46° 15°
47°
Azzan
Ahwar
Bir Ali

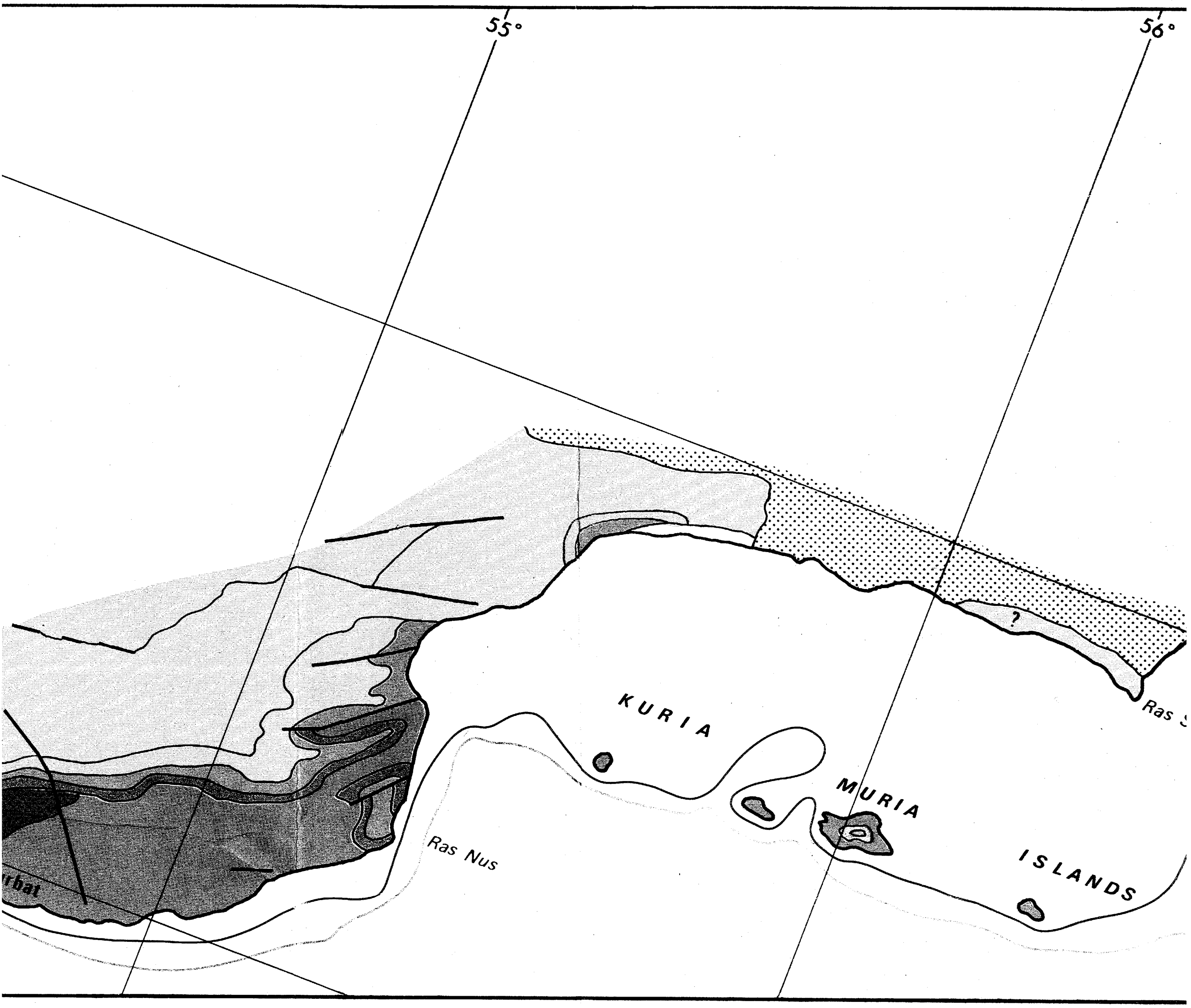


48°
16°
49°
MUKALLA
1st Lst/PC
2nd Lst/PC


50°
51°
W. Masila

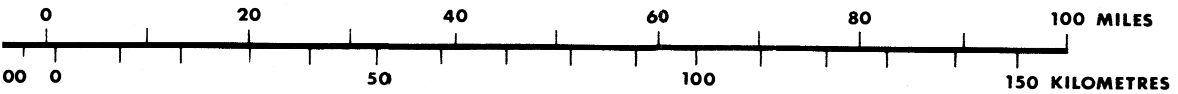

51°
17°
52°
W. Jiza'
?
?
Ghaydha
Qishn
Ras Sharwayn
Ras Fartaq


53°
18°
54°
SALALA
Ras Sajar
Murbat
COASTAL SOUT
MILES 10
0
METRES 10000
0
Quaternary undifferentiated
Oligocene–Miocene–Pliocene
Oligocene s.str. with Lr Miocene
Middle Eocene
Habshiya fn and equivalent
Lower Eocene
Rus fn (gypsum-anhydrite)
Lr Eocene–M. Eocene undifferentiat



GEOLOGICAL MAP
)UTH YEMEN AND DHUFAR, GULF OF ADE

Compiled by Z.R. BEYDOUN (see Figure 1 for sources)



Lambert Conical Orthomorphic Projection

d

ne
iocene

t

ifferentiated

Cretaceous undifferentiated

Jurassic undifferentiated

Cambro–Ordovician Murbat fn
Precambrian metasediments

Precambrian undifferentiated

Precambrian volcanics

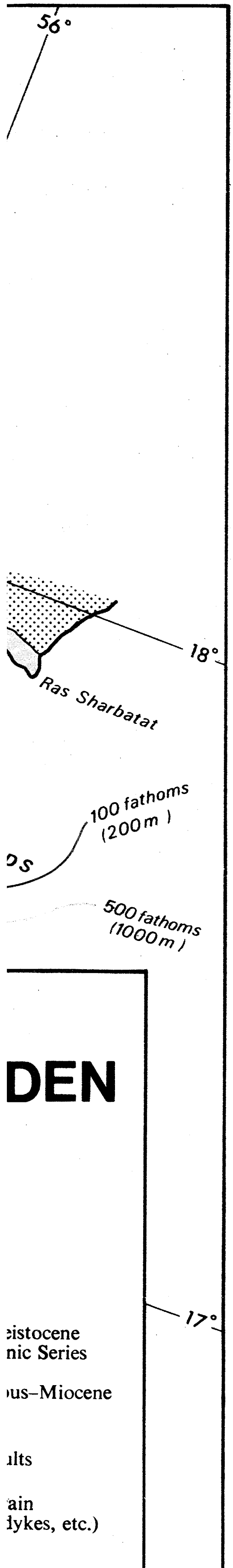
Pliocene–Pleistocene
Aden Volcanic Serie

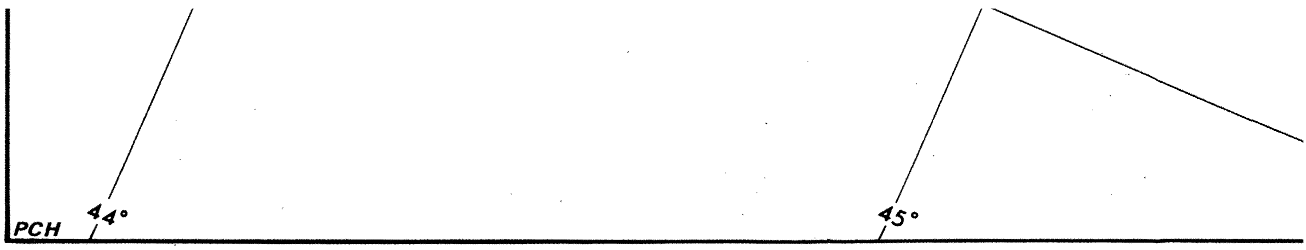
Ur Cretaceous–Mioc
Trap Series

principal faults

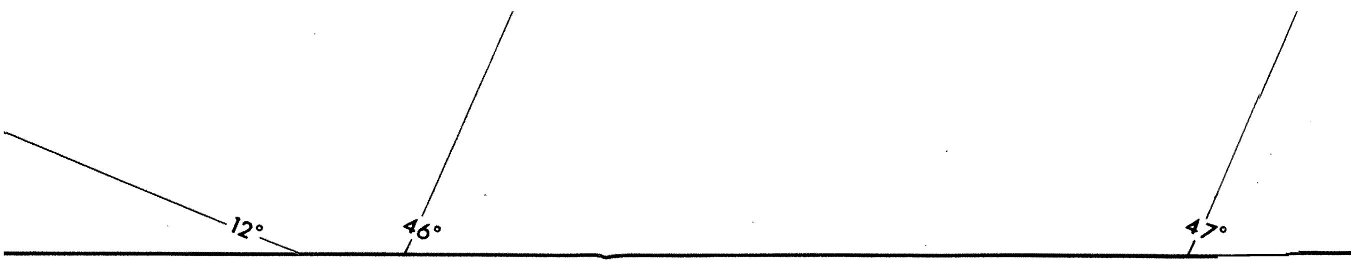
Basement grain
(foliation, dykes, etc

-100-

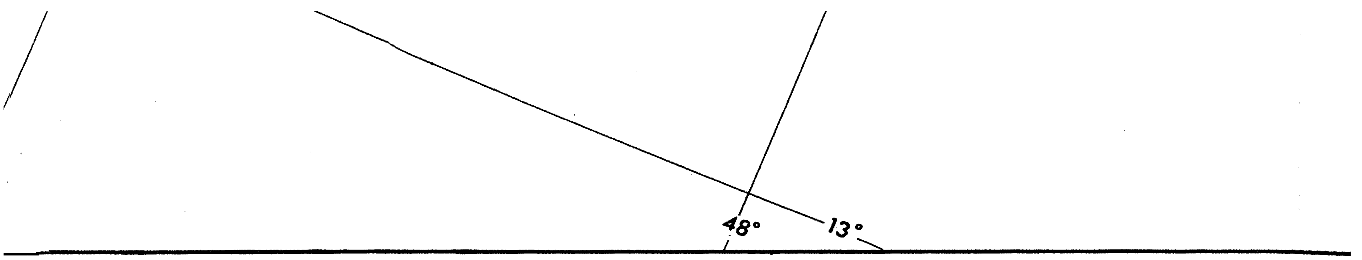

56°
18°
Ras Sharbatat
100 fathoms
(200 m)
500 fathoms
(1000 m)
DEN
17°
eistocene
nic Series
ous–Miocene
ults
ain
dykes, etc.)

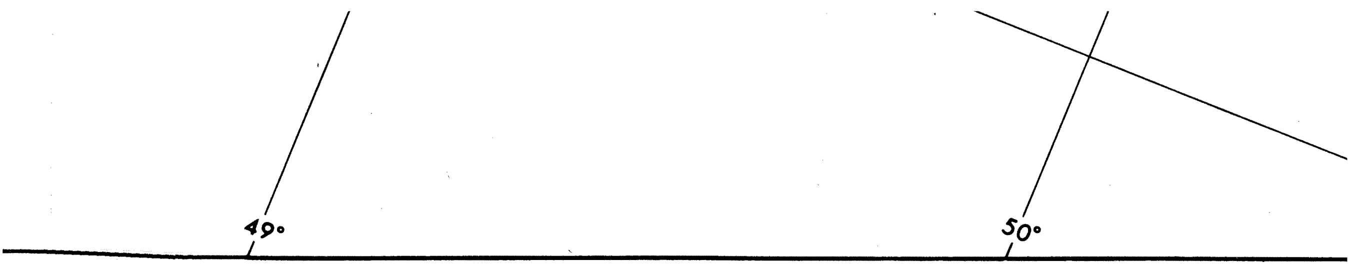


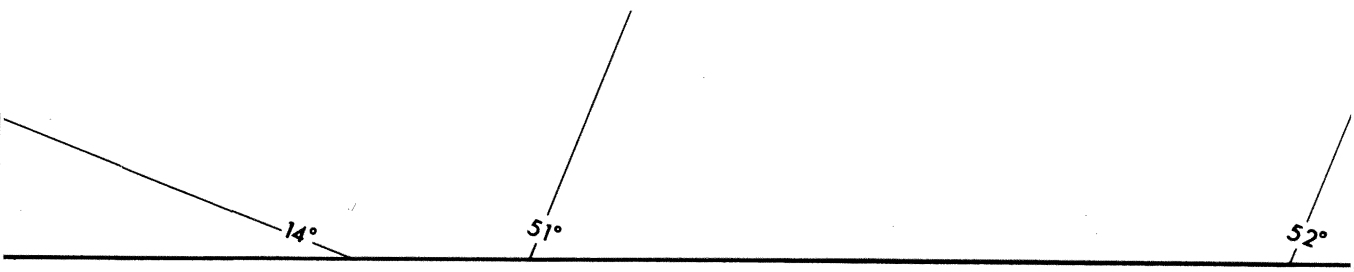
PCH
44°
45°

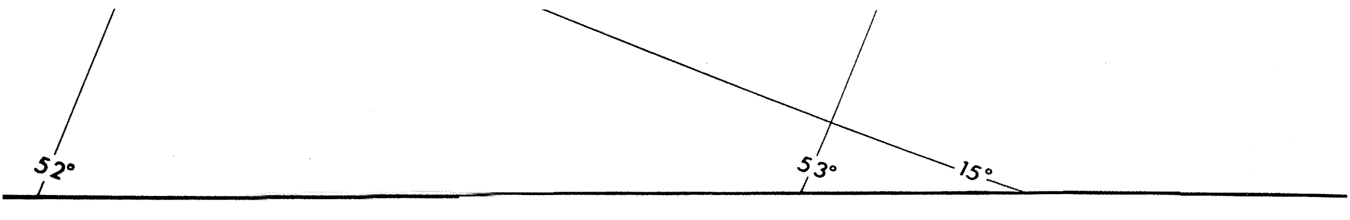


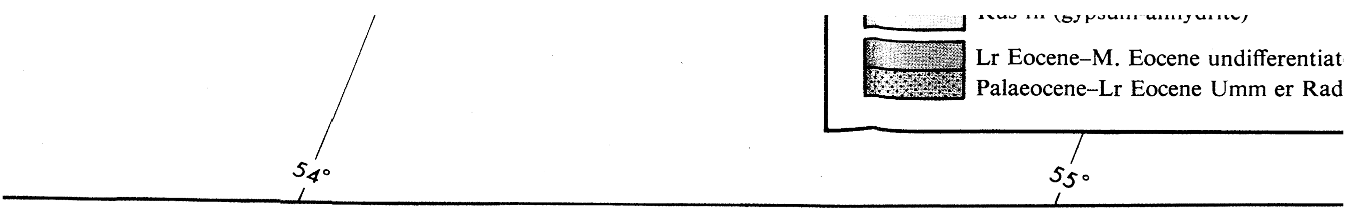
12°
46°
47°


48°
13°


49°
50°


14°
51°
52°


52°
53°
15°


Lr Eocene–M. Eocene undifferentiat
Palaeocene–Lr Eocene Umm er Rad
54°
55°

(foliation, dykes, etc

fferentiated

Precambrian volcanics

-100

m er Radhuma fn

Precambrian and Lr Palaeozoic granites

500 isobaths (in fathoms)

16°

56°

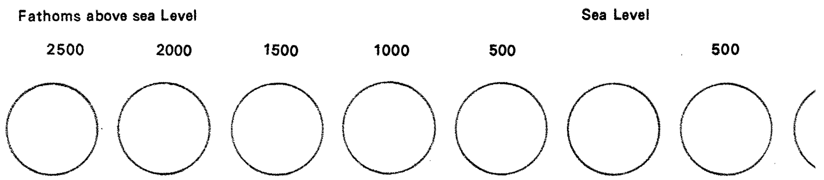
Figur

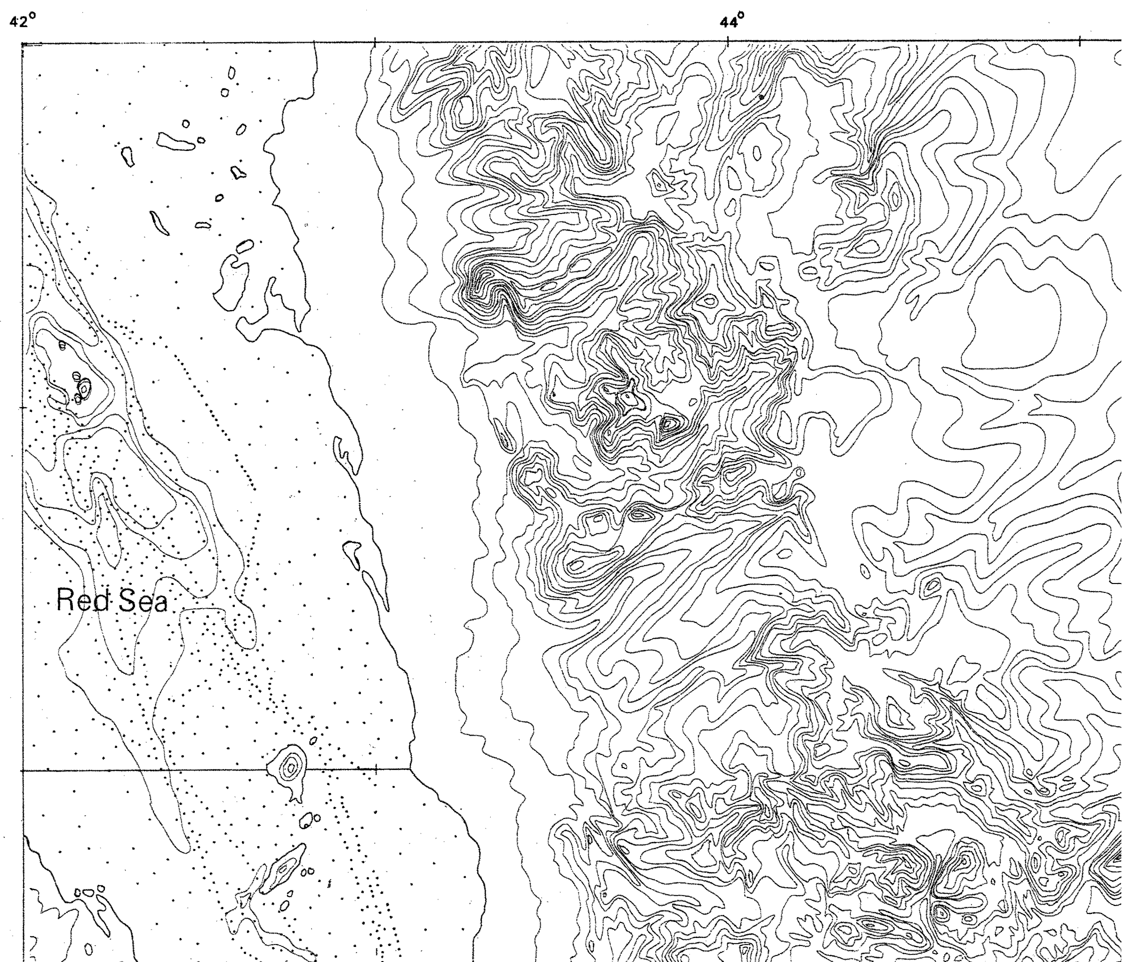
ıykes, etc.)

fathoms)

Figure 4

Anagly


Fathoms above sea Level
Sea Level
2500
2000
1500
1000
500
500


42°
44°
Red Sea

glyph map

Based on a conto

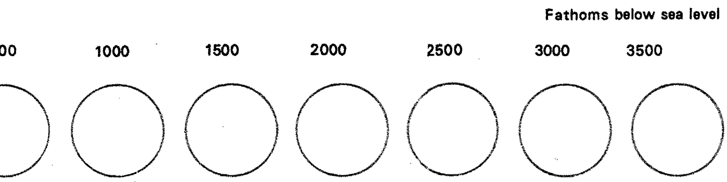
by A.S.Laughtor

Automatic Carto

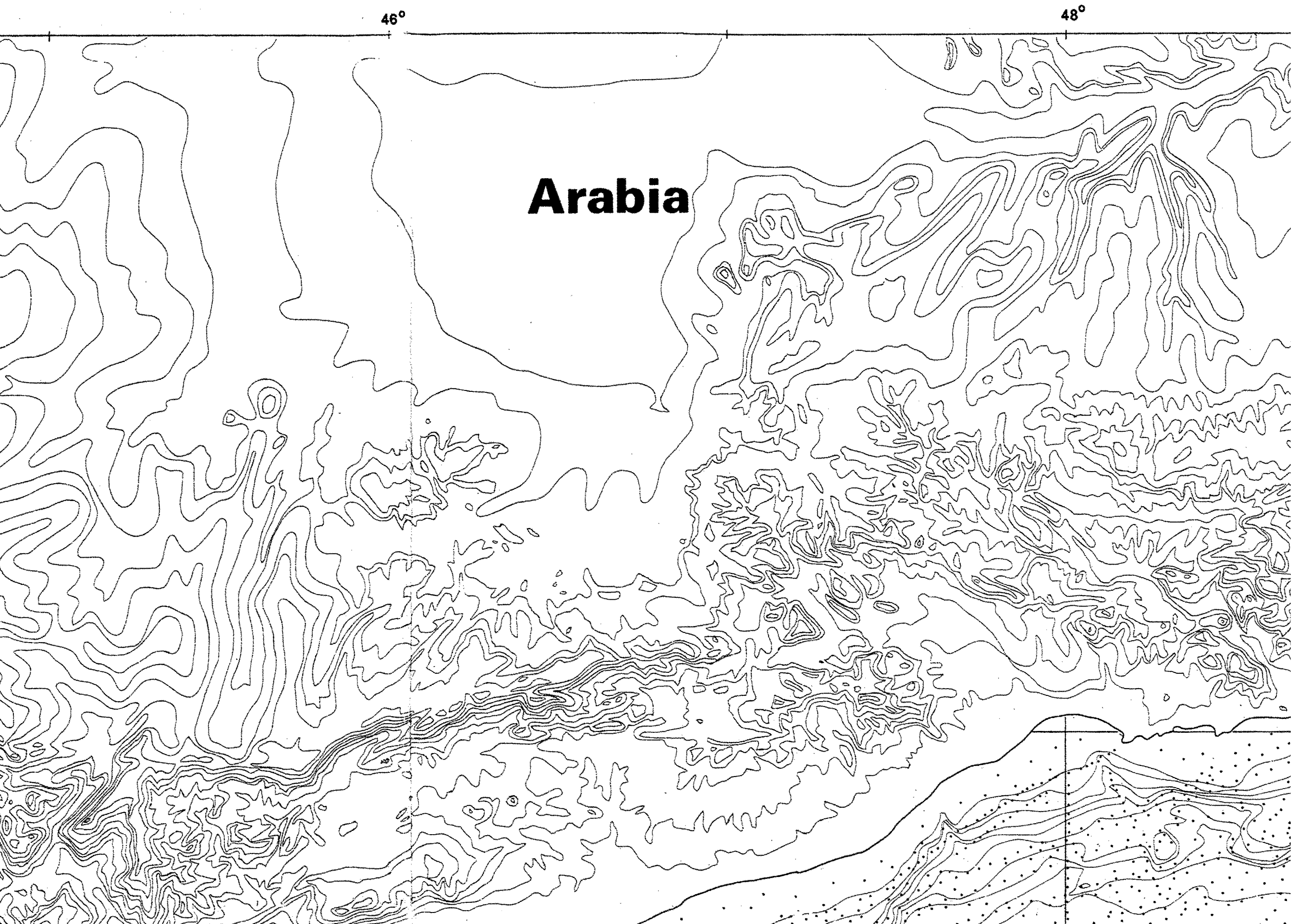
All contours in 1

Soundings are sh

Scale 1:2,000,00



To be viewed thr



no. 3 Printed by Cook, Hammond & Kell, Ltd., London.

a contour chart of the Gulf of Aden

ughton, National Institute of Oceanography, Great Britain

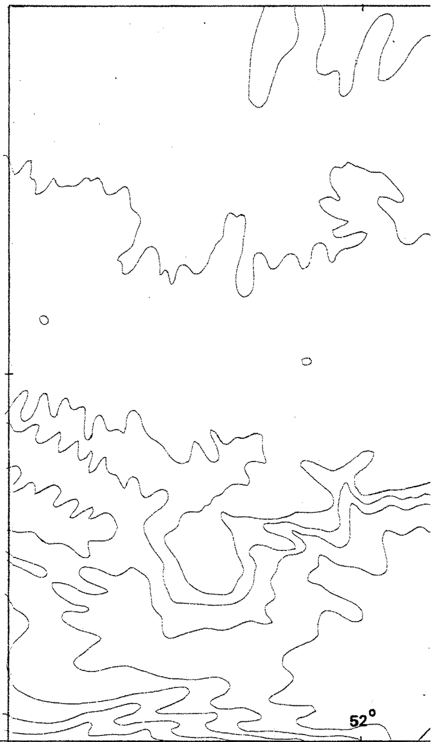
c Cartography by the Royal College of Art, London

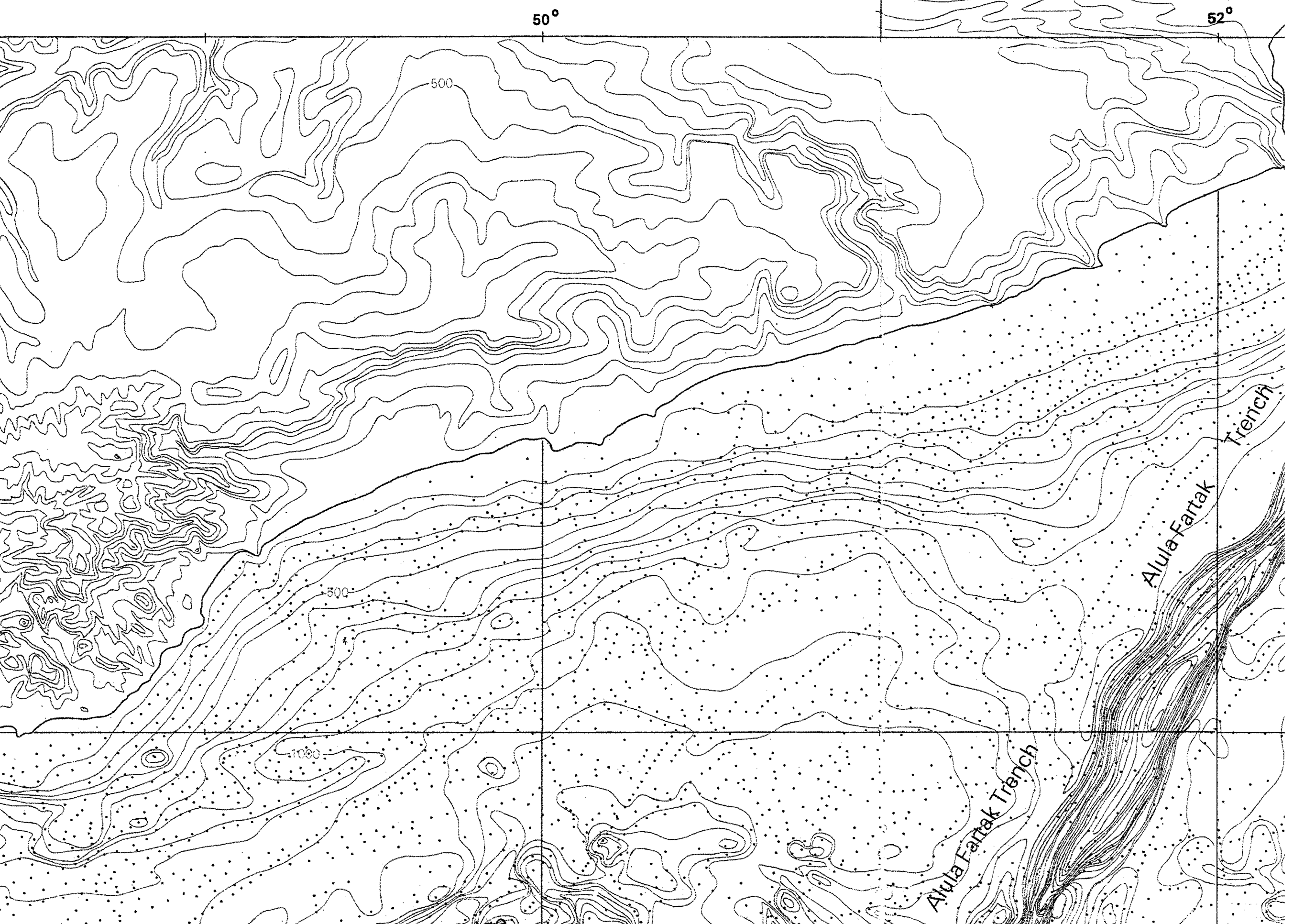
urs in 100 fathom intervals

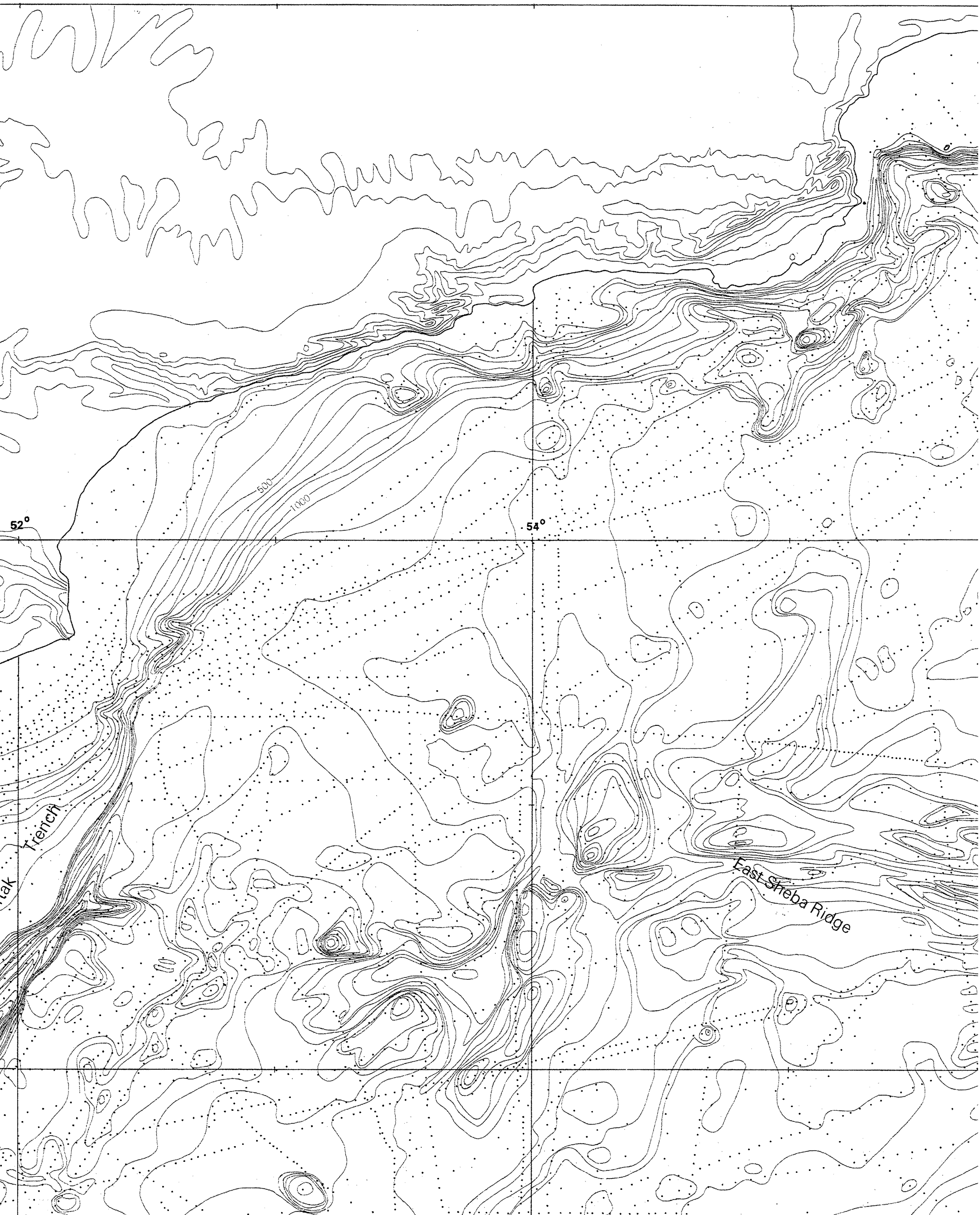
js are shown by black dots

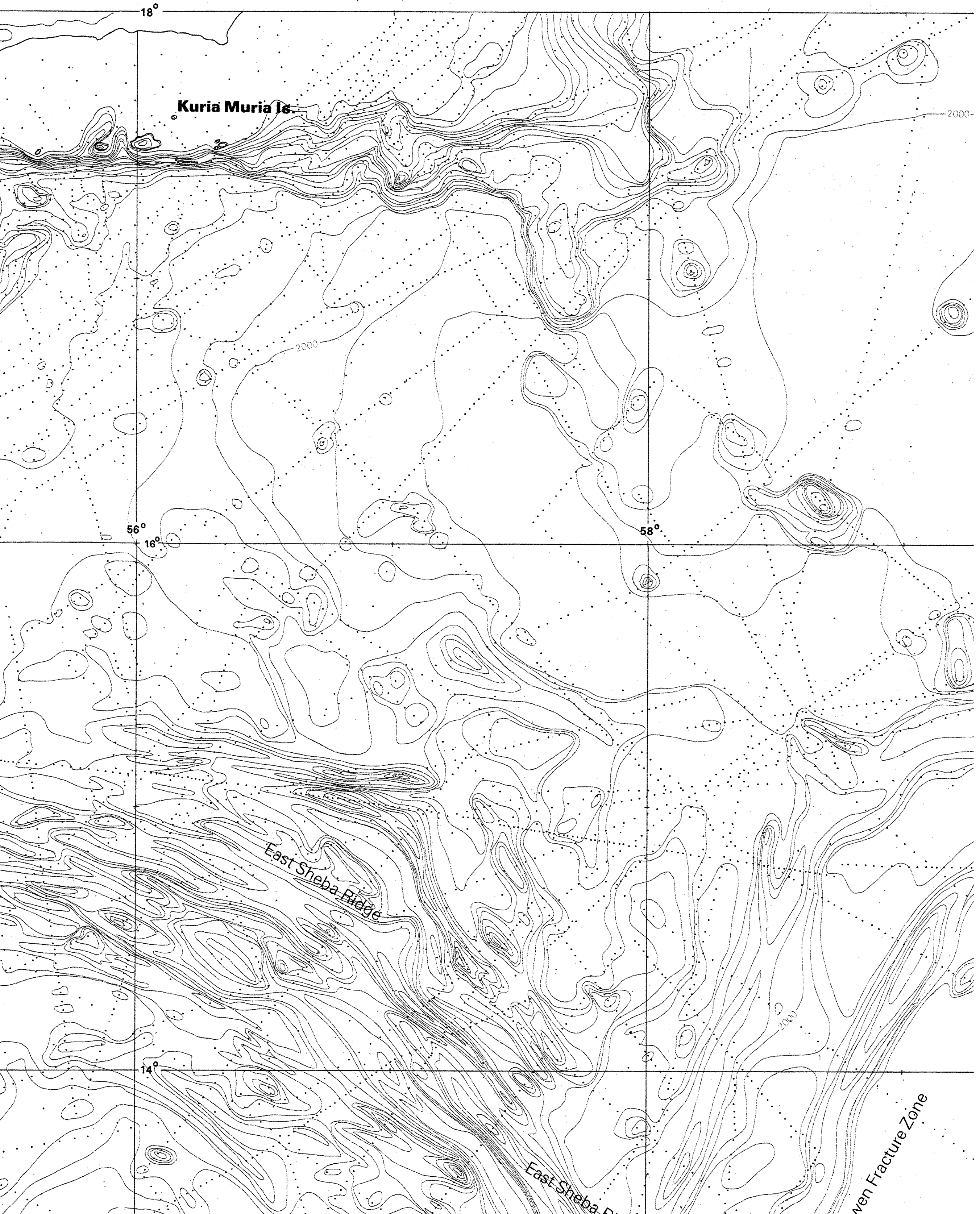
,000,000 at 33°N.

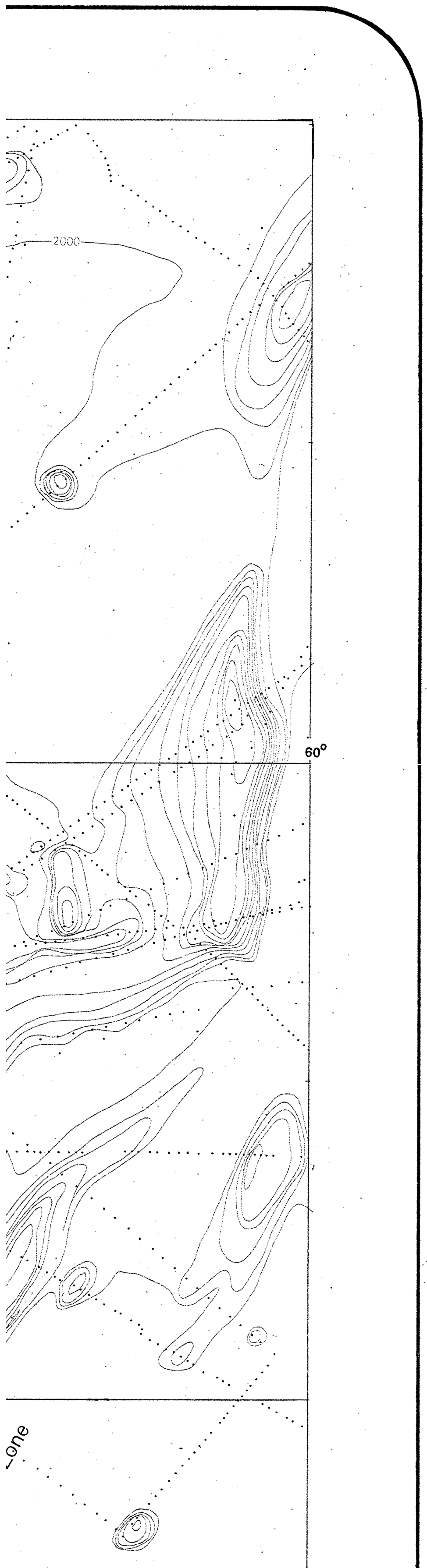
wed through red and green glasses



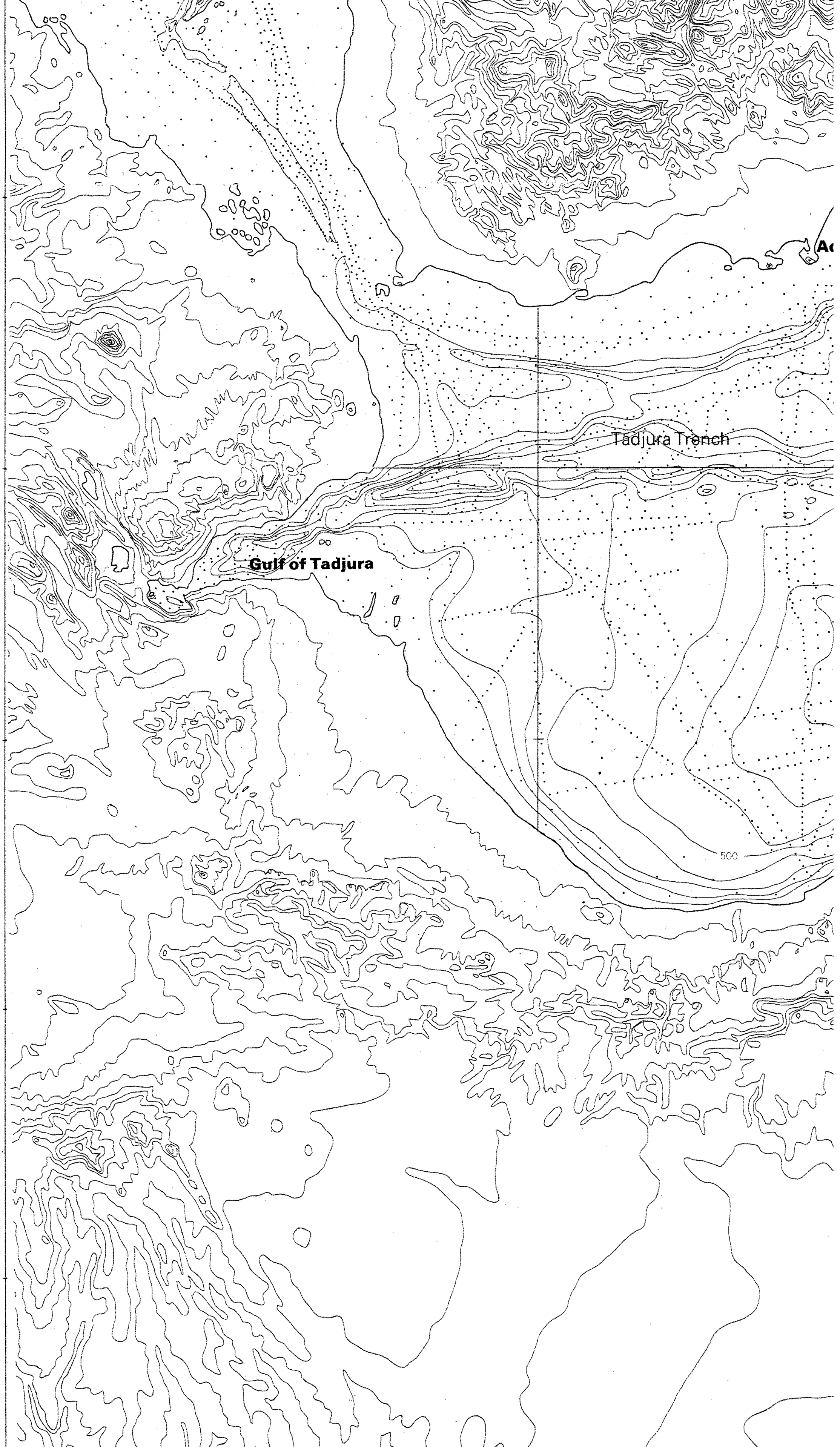


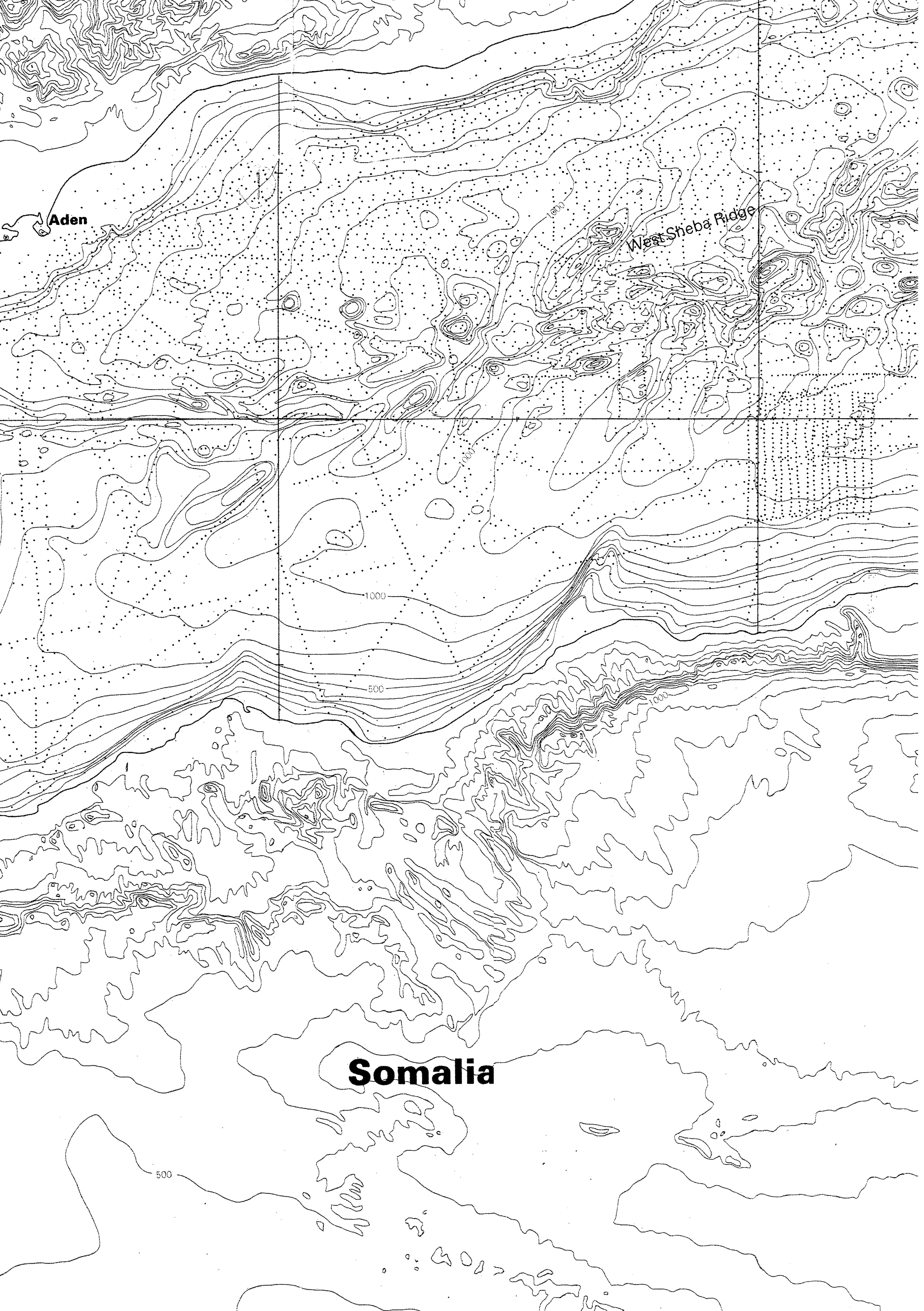

52°
54°
500
1000
Trench
East Sheba Ridge

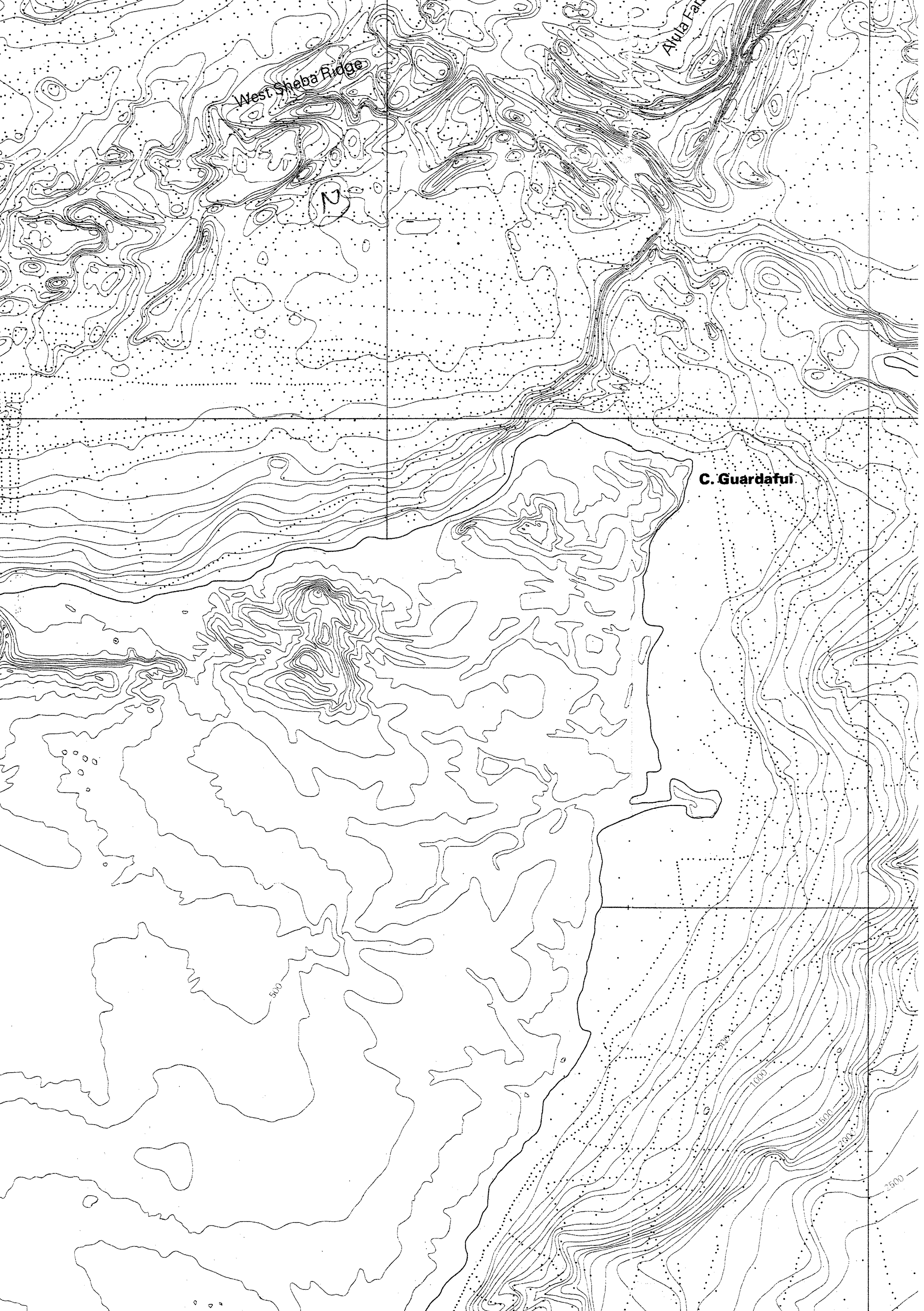

18°
Kuria Muria Is.
2000
2000
56°
16°
58°
East Sheba Ridge
2000
14°
East Sheba R
wen Fracture Zone

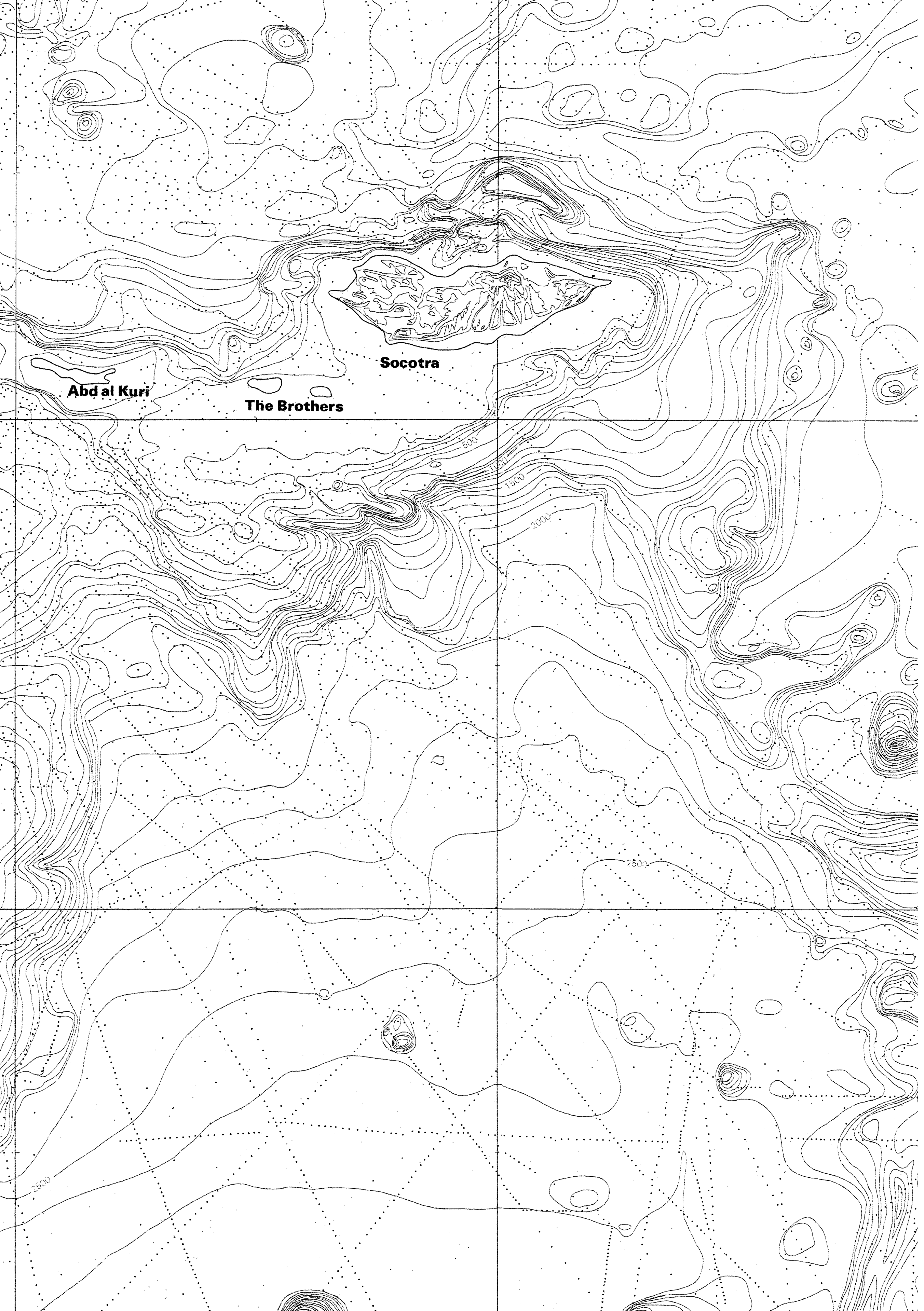


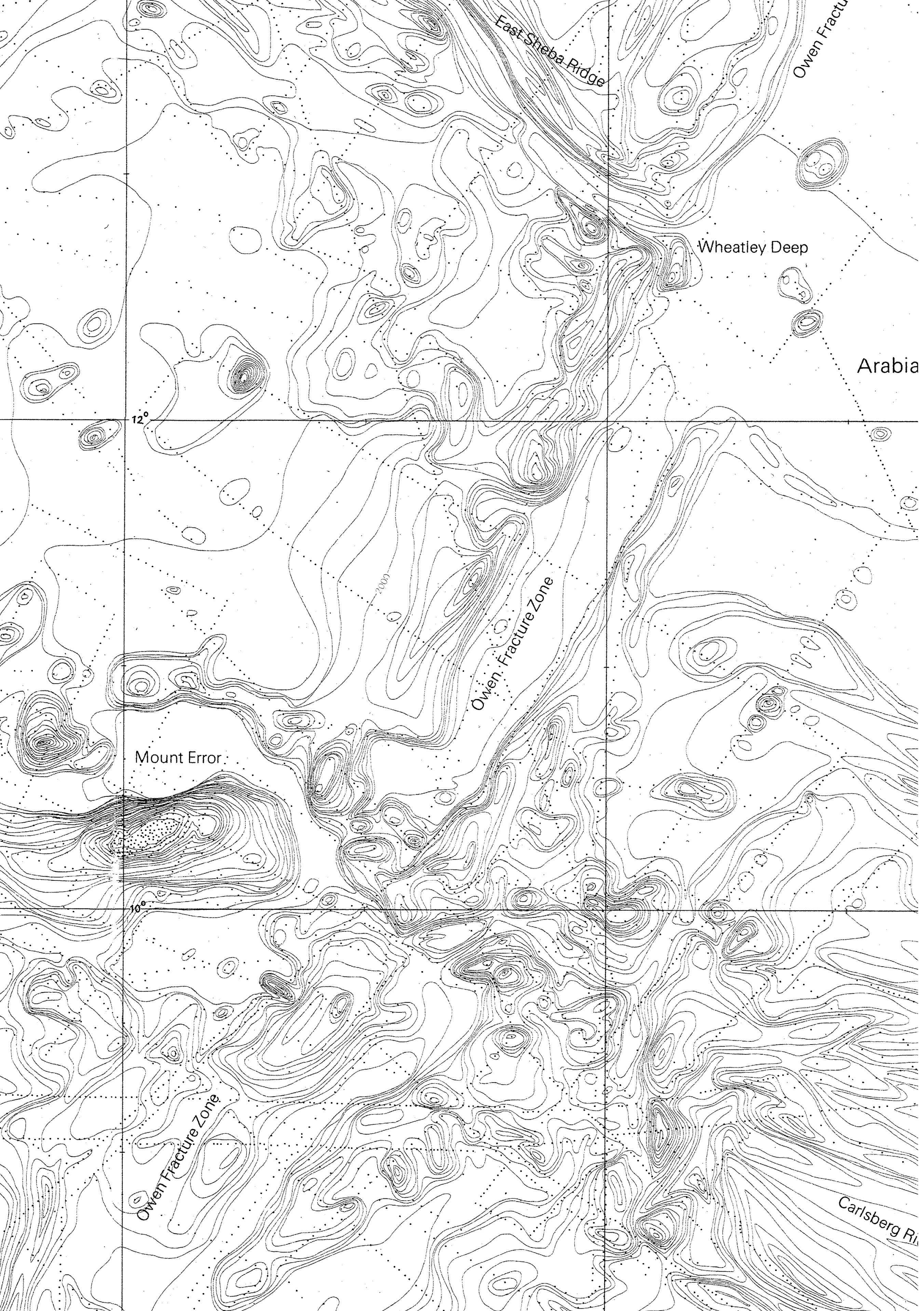
2000
60°
-one

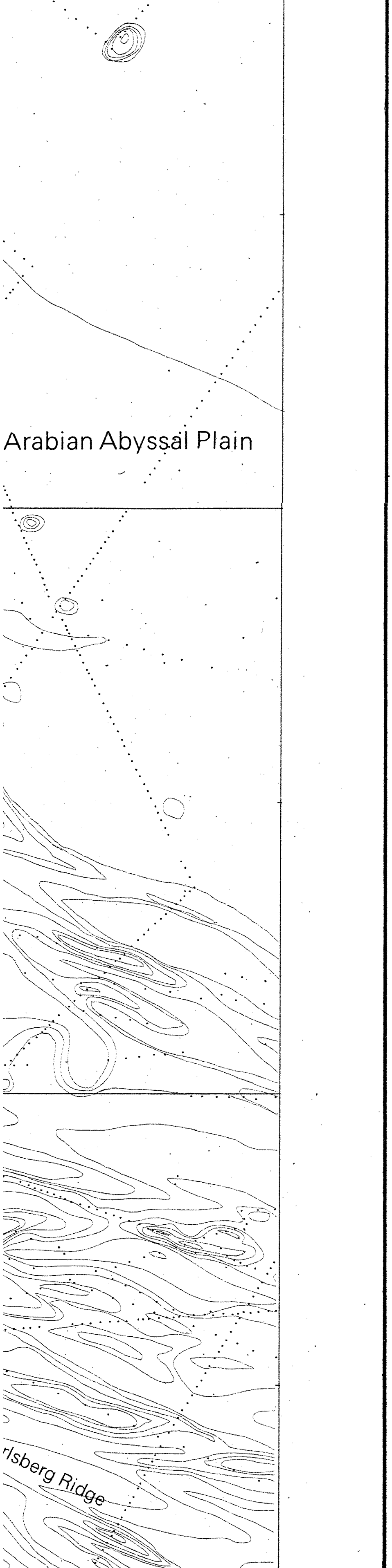

Ad
Tadjura Trench
Gulf of Tadjura
500


Aden
West Sheba Ridge
1000
1000
1000
500
1000
Somalia
500

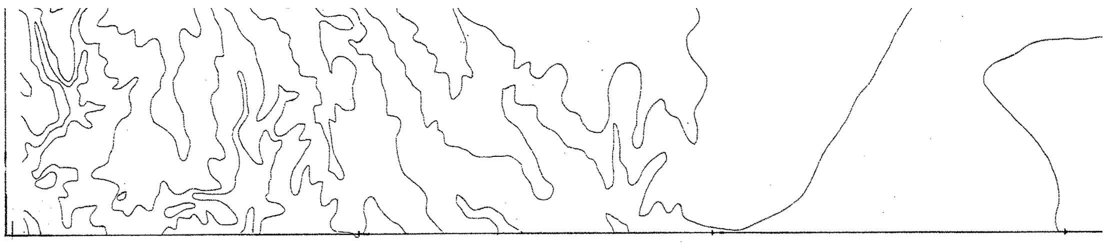

West Sheba Ridge
C. Guardafui
500
1000
1500
2000
2500

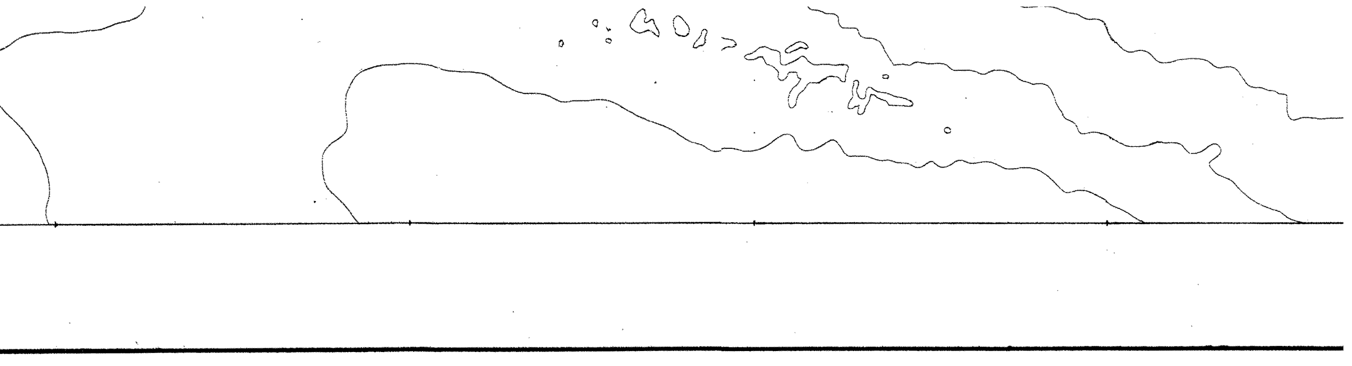

Socotra
Abd al Kuri
The Brothers
500
1000
1500
2000
2500
2500

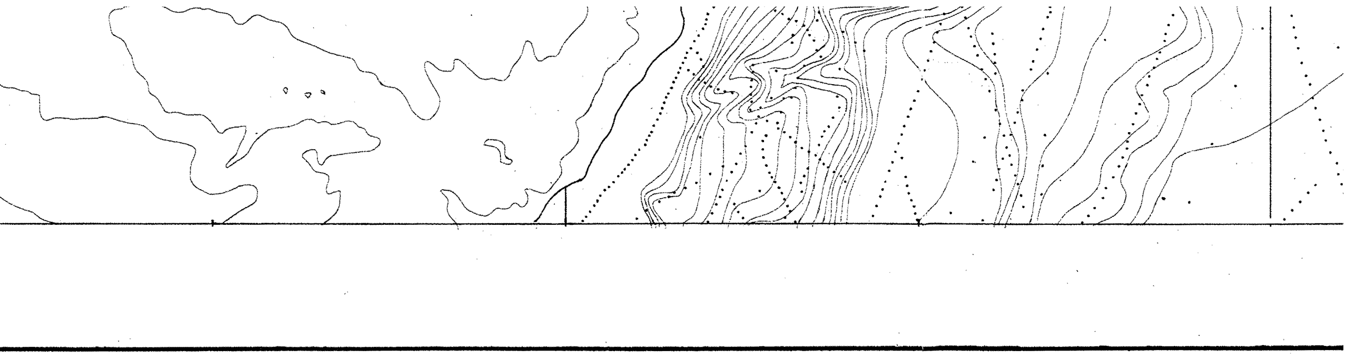

East Sheba Ridge
Owen Fractu
Wheatley Deep
Arabia
12°
2000
Owen Fracture Zone
Mount Error
10°
Owen Fracture Zone
Carlsberg Ri

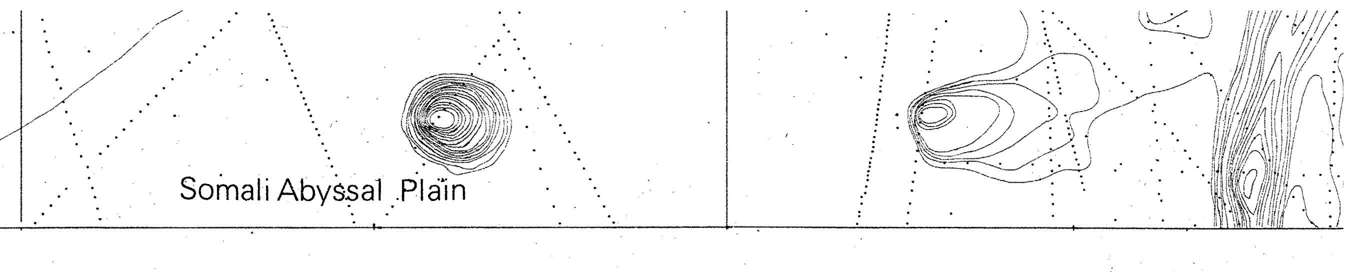


Arabian Abyssal Plain
rlsberg Ridge








Somali Abyssal Plain


8°

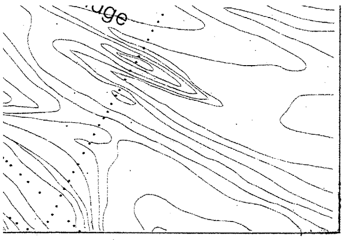


FIGURE 6. Seismic reflexion profiles obtained by air gun (cf. figure 15): (*a*) across median valley in One Degree Square (figure 4); (*b*) and (*c*), across south main trough in Half Degree Square (figure 9); (*d*), across east side of Alula–Fartak Trench.

FIGURE 7. Bottom photograph in median valley showing sediment cover on young basaltic rocks similar to those dredged in vicinity. (Photo 6246.18, depth 2290 m (1250 fathoms); width of picture 2 m; 12° 35′ N, 37° 30′ E.)

Laughton-Whitmarsh-Jones   Red Sea Discussion, Phil. Trans. Roy. Soc. A Fig. 11

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Automatic Cartography by the Royal College of Art, London   E.C.U. map ref. no. 2


KEY
Contour intervals in fathoms
2500
2000
1500
1000
500
Land below sea level
0
500
1000
1500
2000
2500
3000
3500
CONT
GUL
AND AD
50
0
100
0
RED SEA
A
1000
1500
1000
1500
42°
30′
43°
30′
44°
30′
45°
18°
30′
17°
30′
16°
30′
15°
30′
14°
30′
13°

30′ 46° 30′ 47° 30′ 48° 30′ 49°

NTOUR CHART OF THE ULF OF ADEN ADJACENT CONTINENTS

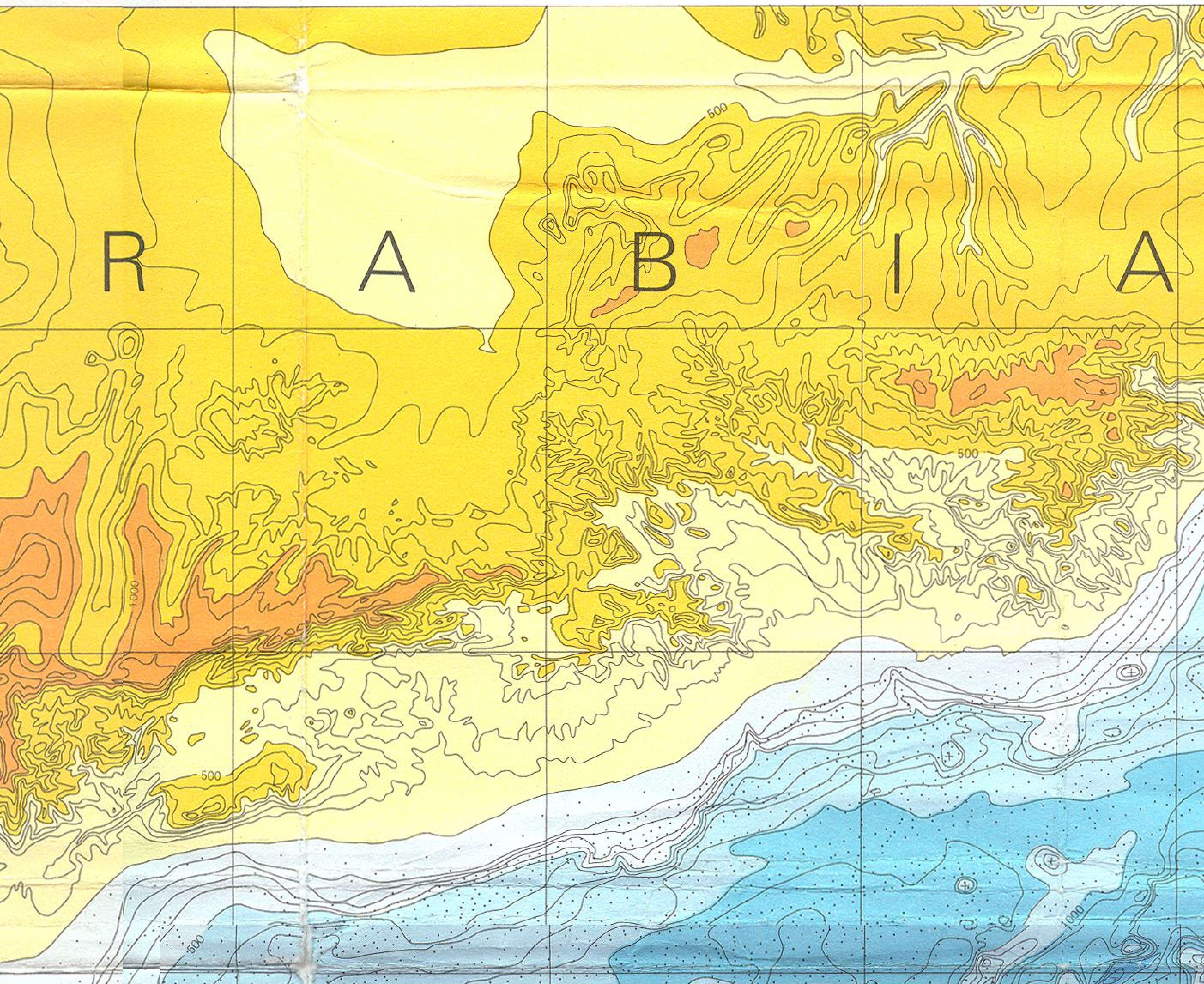
By A. S. LAUGHTON

National Institute of Oceanography
Great Britain

SCALE 1: 2,000,000 at 33° N

0 50 100 150 200 Statute Miles at 13° N

0 100 200 300 KM



Land contours in 100 fathom (600 ft) intervals

Sea contours in 100 fathom intervals. All depths in fathoms, corrected according to Matthews tables (1939) H.D.282.
Position of all soundings used indicated by dots (except in vicinity of coasts).

Projection: Mercator

Authorities: land contours are interpolated from 1:500,000 Series 1404 maps published by D Survey, War Office and Air Ministry. (Edition 1-GSGS)
Sea contours are based on collected oceanic soundings available up to May 1968 from Hydrographic Department, Ministry of Defence (Navy) and additional data from USA and USSR.

30′
53°
30′
54°
30′
55°
30′
56°
E A S T S H
500
1000
1500
2000


56°
30′
57°
30′
58°
30′
59°
30′
KURIA
MURIA Is.
1000
2000
1500
H E B A
R I D G E
Z O N E
A R A B I


30′
60°
18°
30′
17°
30′
16°
1500
30′
15°
E
N
30′
14°
30′
B I A N
13°

13°
30′
12°
30′
11°
30′
10°
30′
9°
30′
8°
42°
30′
43°
30′
44°
30′
45°
30′
ADEN
TADJURA TRENCH
Gulf of Tadjura
500
1000
S O M

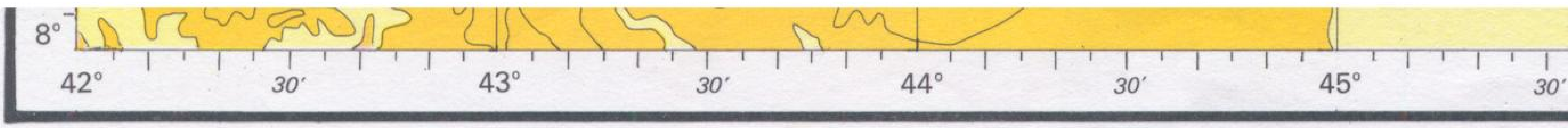

W E S T   S H E B A
M   A   L   I
500
1000
1500
30′
46°
30′
47°
30′
48°
30′
49°

ABD AL KURI
C. GUARDAFUI
1000
500
1500
2500
A
SOMA
49°
30′
50°
30′
51°
30′
52°
30′


SOCOTRA
THE BROTHERS
KURI
1000
500
1500
2000
2500
MT
ERRO
MALI ABYSSAL PLAIN
O W
30′
53°
54°
55°
56°


ABYSSA
PLAI
WHEATLEY
DEEP
E
R
U
T
C
A
R
F
MT.
ERROR
CARLSBERG RIDG
N
E
W
2000
2500
1500
56°
30′
57°
30′
58°
30′
59°
30′

S S A L
A I N
2500
2000
I D G E
1500
13°
30′
12°
30′
11°
30′
10°
30′
9°
30′
8°
30′
60°



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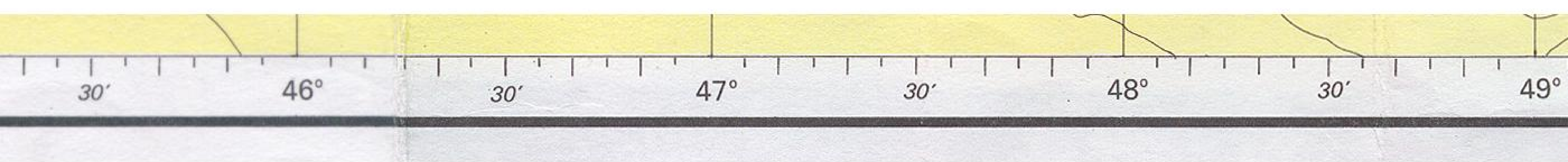
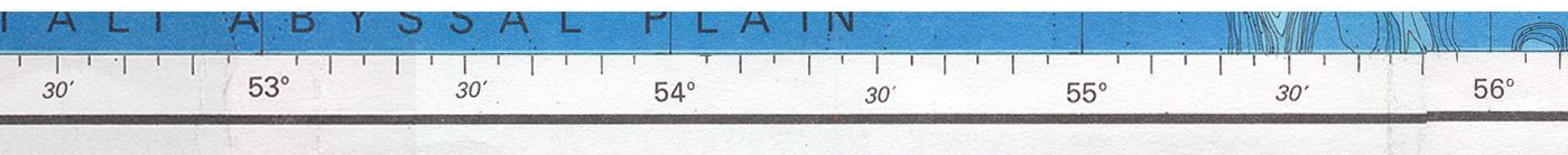
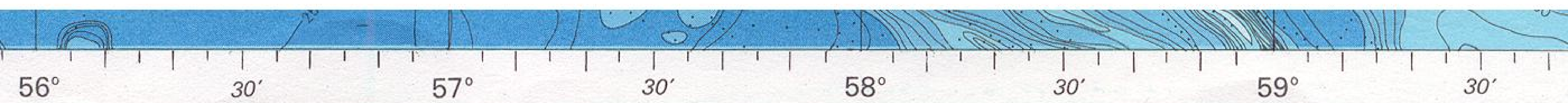
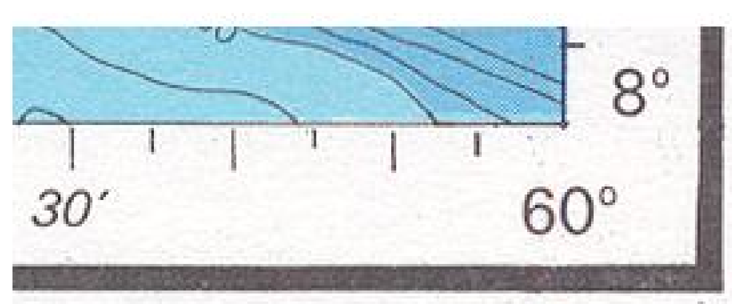

30′
46°
30′
47°
30′
48°
30′
49°

S O M A
49°
30′
50°
30′
51°
30′
52°
30′


ABYSSAL PLAIN
30′
53°
30′
54°
30′
55°
30′
56°



Automatic Cartography by the Royal College of Art, London E.C.U. m



E.C.U. map ref. no. 2


GEOLOGICAL MAP
COASTAL SOUTH YEMEN AND DHUFAR, GULF OF ADEN
Compiled by Z. R. BEYDOUN (see Figure 1 for sources)
MILES 10 0 20 40 60 80 100 MILES
METRES 10000 0 50 100 150 KILOMETRES
Lambert Conical Orthomorphic Projection
Quaternary undifferentiated
Oligocene–Miocene–Pliocene
Oligocene s.str. with Lr Miocene
Middle Eocene
Habshiya fn and equivalent
Lower Eocene
Rus fn (gypsum-anhydrite)
Lr Eocene–M. Eocene undifferentiated
Palaeocene–Lr Eocene Umm er Radhuma fn
Cretaceous undifferentiated
Jurassic undifferentiated
Cambro-Ordovician Murbat fn
Precambrian metasediments
Precambrian undifferentiated
Precambrian volcanics
Precambrian and Lr Palaeozoic granites
Pliocene–Pleistocene
Aden Volcanic Series
Ur Cretaceous–Miocene
Trap Series
principal faults
Basement grain
(foliation, dykes, etc.)
isobaths (in fathoms)
PERIM ISLAND
Lahej
ADEN
Shuqra
Ahwar
Azzan
Bir Ali
MUKALLA
W. Masila
Qishn
Ras Sharwayn
Ras Fartak
Ghayda
SALALA
Mirbat
KURIA MURIA ISLANDS
Ras Sharbatat
100 fathoms (200 m)
500 fathoms (1000 m)

Figure 4


14°
44°
13°
12°
PERIM ISLAND
Lahej
AD
100 fathoms (200 m)
500 fathoms (1000 m)


45°
46° 15°
Shuqra
Ahwa
ADEN

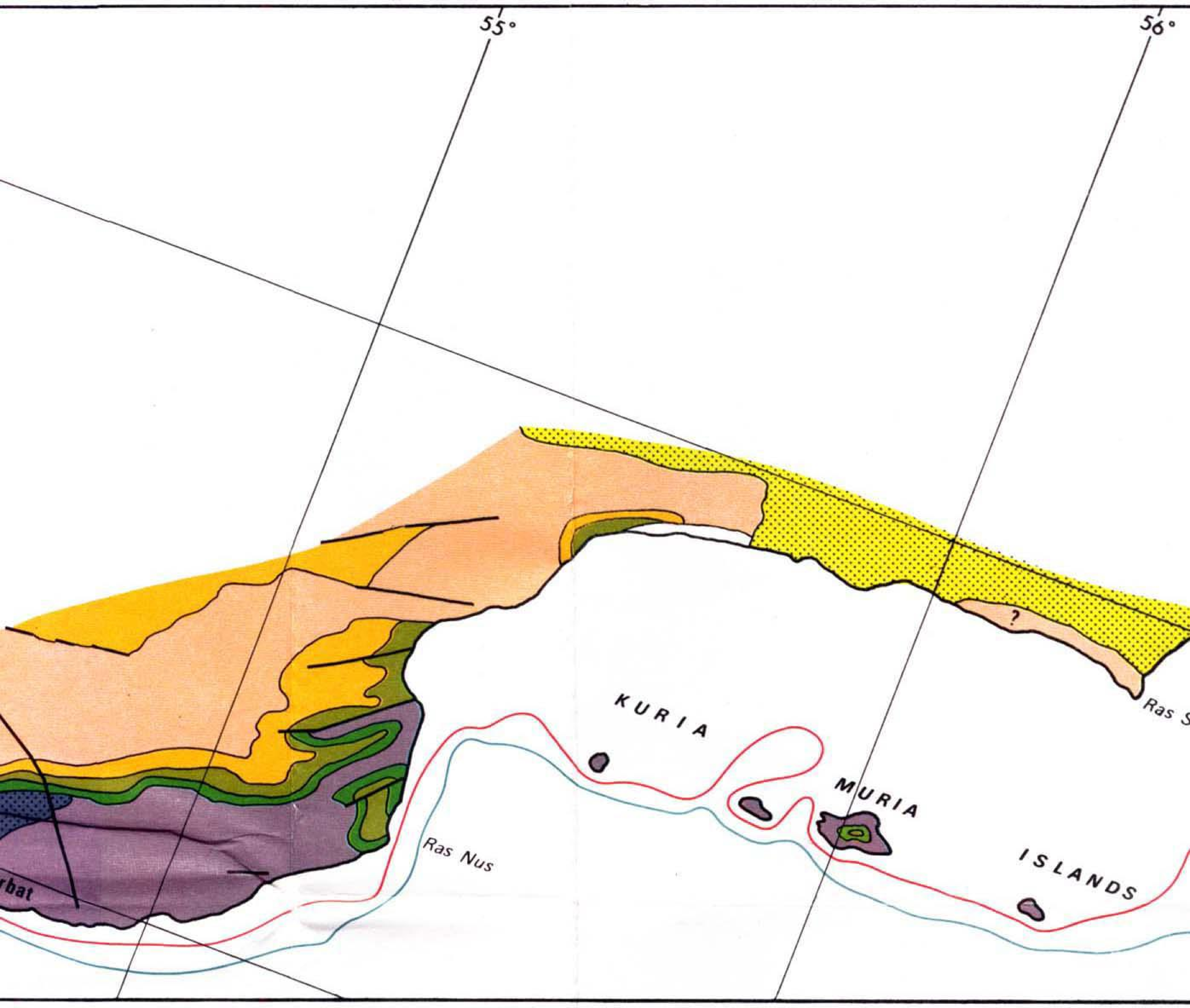
46° 15°
47°
Azzan
Ahwar
Bir Ali

48°
16°
49°
MUKALLA
1st Lst/PC
2nd Lst/PC


50°
51°
W. Masila
Ras

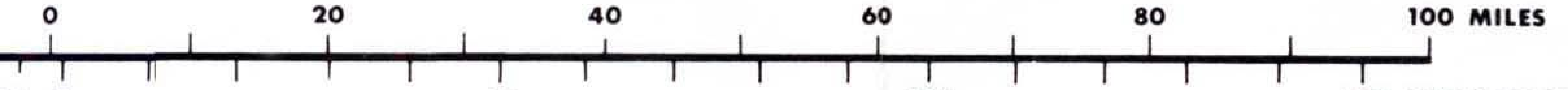
51°
17°
52°
W. Jiza'
?
?
Ghaydha
Qishn
Ras Sharwayn
Ras Fartaq


53°
18°
54°
SALALA
Ras Sajar
Murbat
COASTAL SOUT
MILES 10
0
METRES 10000
0
Quaternary undifferentiated
Oligocene–Miocene–Pliocene
Oligocene s.str. with Lr Miocene
Middle Eocene
Habshiya fn and equivalent
Lower Eocene
Rus fn (gypsum-anhydrite)
Lr Eocene–M. Eocene undifferentiat



GEOLOGICAL MAP
OUTH YEMEN AND DHUFAR, GULF OF ADE

Compiled by Z.R. BEYDOUN (see Figure 1 for sources)



Lambert Conical Orthomorphic Projection

l

ne
ocene

fferentiated

Cretaceous undifferentiated

Jurassic undifferentiated

Cambro–Ordovician Murbat fn

Precambrian metasediments

Precambrian undifferentiated

Precambrian volcanics

Pliocene–Pleistocene
Aden Volcanic Series

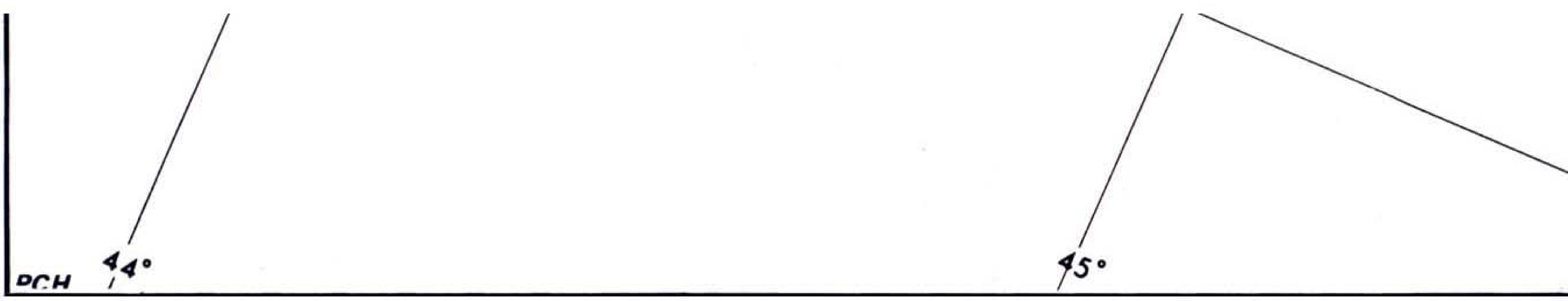
Ur Cretaceous–Mioc
Trap Series

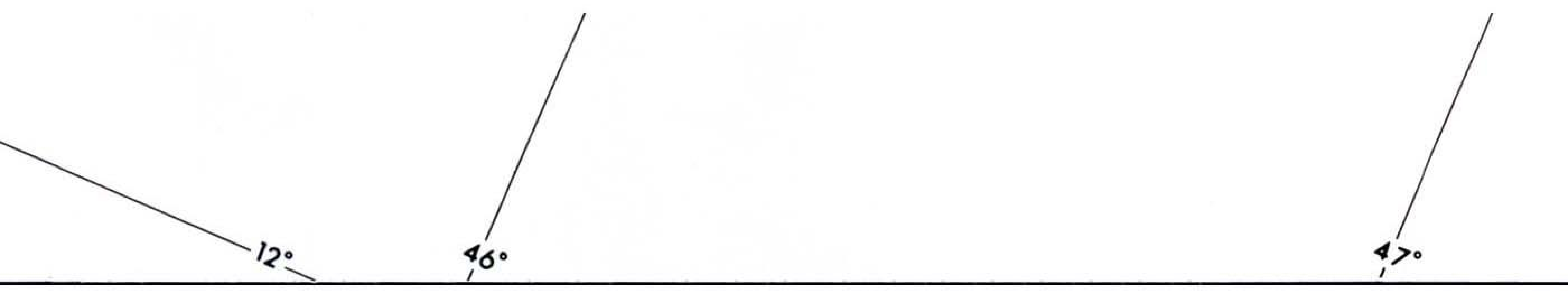
principal faults

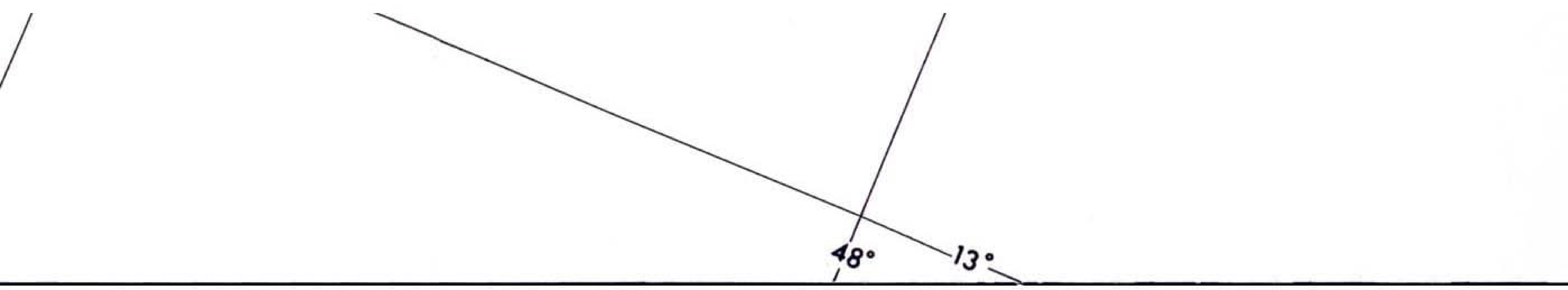
Basement grain
(foliation, dykes, etc

-100-


56°
18°
Ras Sharbatat
100 fathoms (200 m)
500 fathoms (1000 m)
DEN
17°
eistocene
nic Series
ous–Miocene
ults
ain
dykes, etc.)

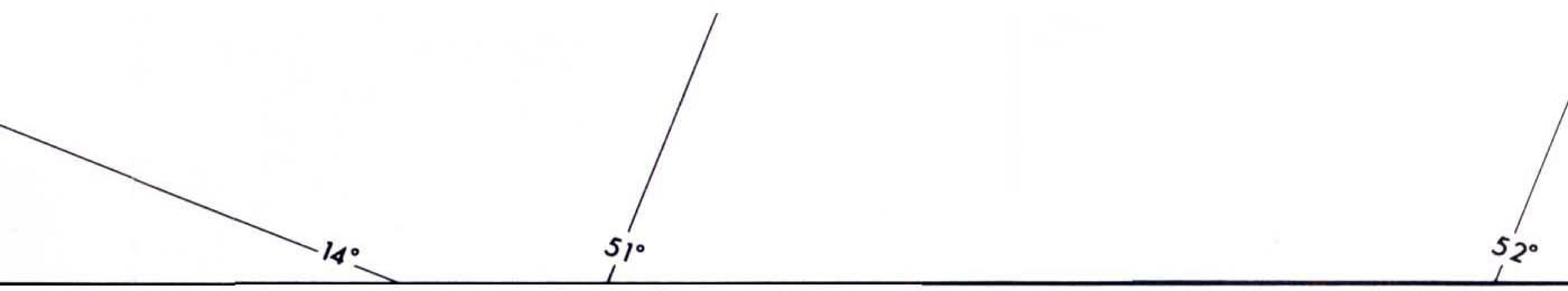

44°
45°

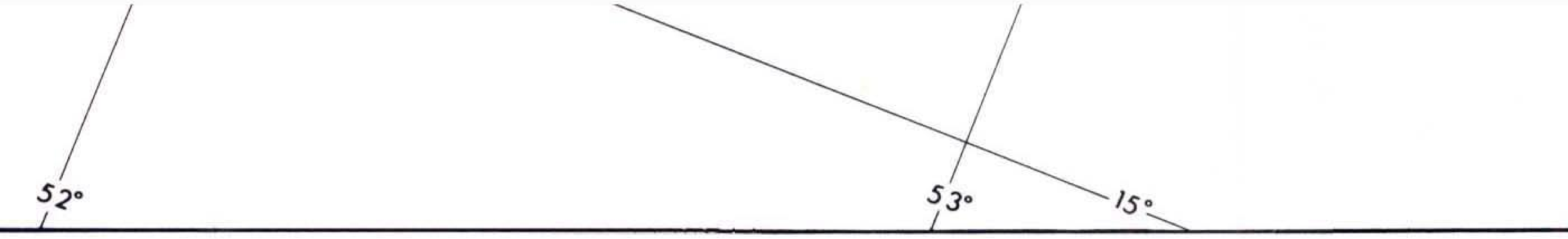

12°
46°
47°

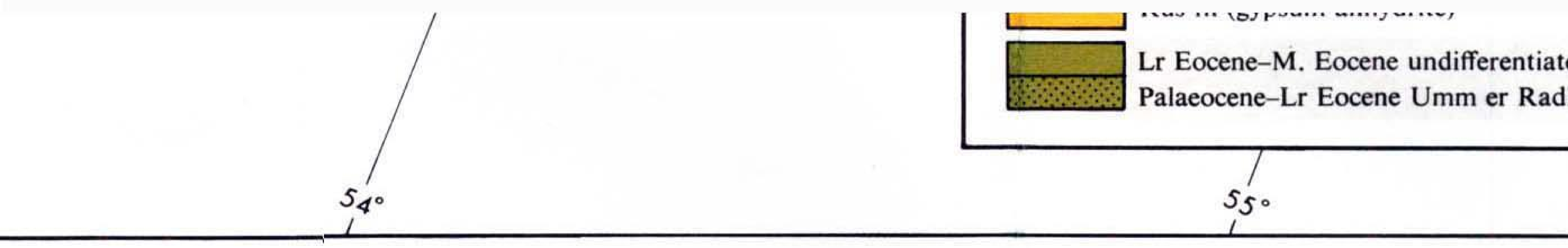


48°
13°

49°
50°


14°
51°
52°


52°
53°
15°



Lr Eocene–M. Eocene undifferentiat
Palaeocene–Lr Eocene Umm er Radi
54°
55°

(foliation, dykes, etc

ifferentiated

m er Radhuima fn

Precambrian volcanics

Precambrian and Lr Palaeozoic granites

100

500

isobaths (in fathoms)

16°

56°

Figur

dykes, etc.)

fathoms)

Figure 4

E C U mapref. no 3   Printed by Cook, Hammond & Kell, Ltd., London

Anaglyph map

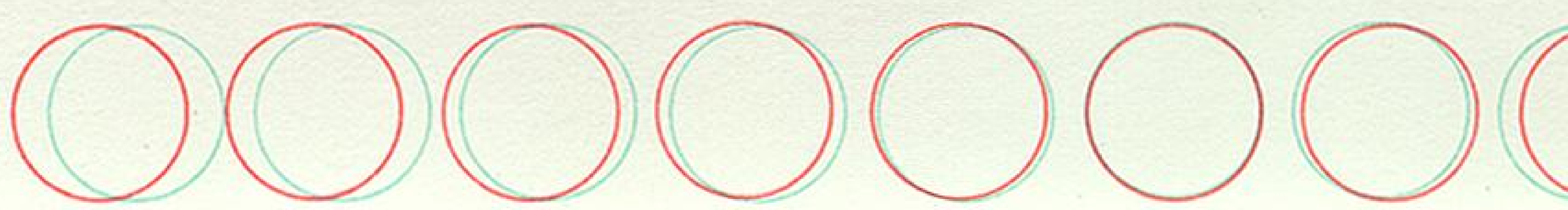
Based on a contour chart of the Gulf of Aden
by A.S.Laughton, National Institute of Oceanography, Great Britain

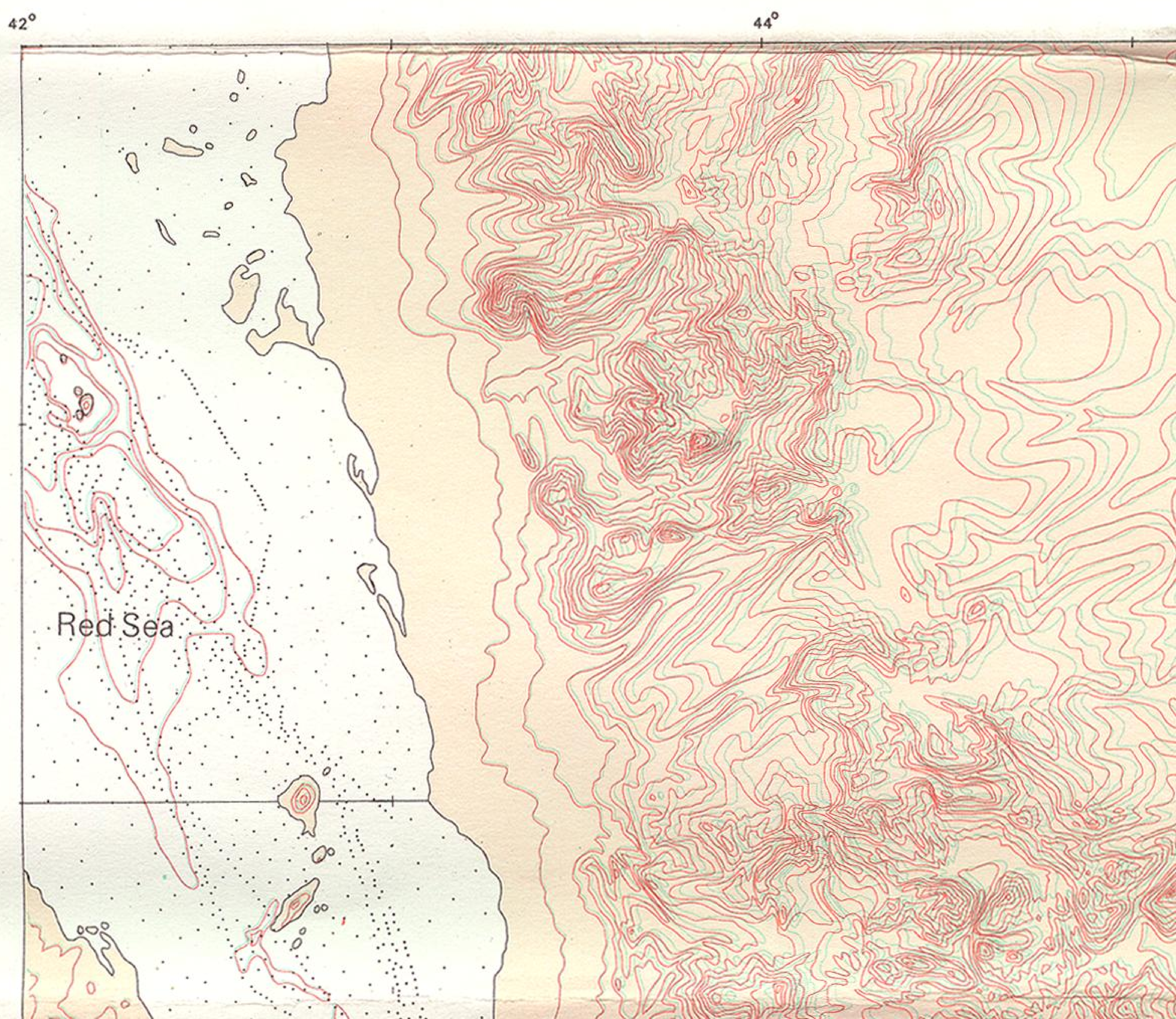
Automatic Cartography by the Royal College of Art, London

All contours in 100 fathom intervals
Soundings are shown by black dots
Scale 1:2,000,000 at 33°N

To be viewed through red and green glasses

Anagly


Fathoms above sea Level
Sea Level
2500
2000
1500
1000
500
500


42°
44°
Red Sea

E.C.U. map ref. no. 3

glyph map

Based on a conto

by A.S.Laughton

Automatic Carto

All contours in 1(

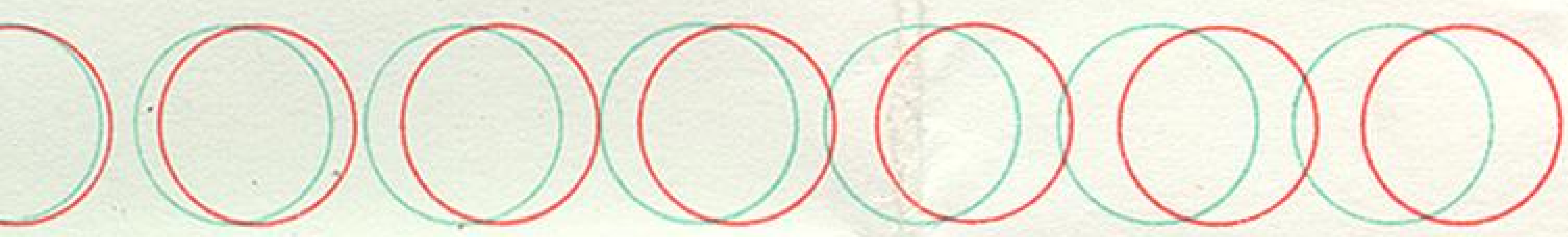
Soundings are sh

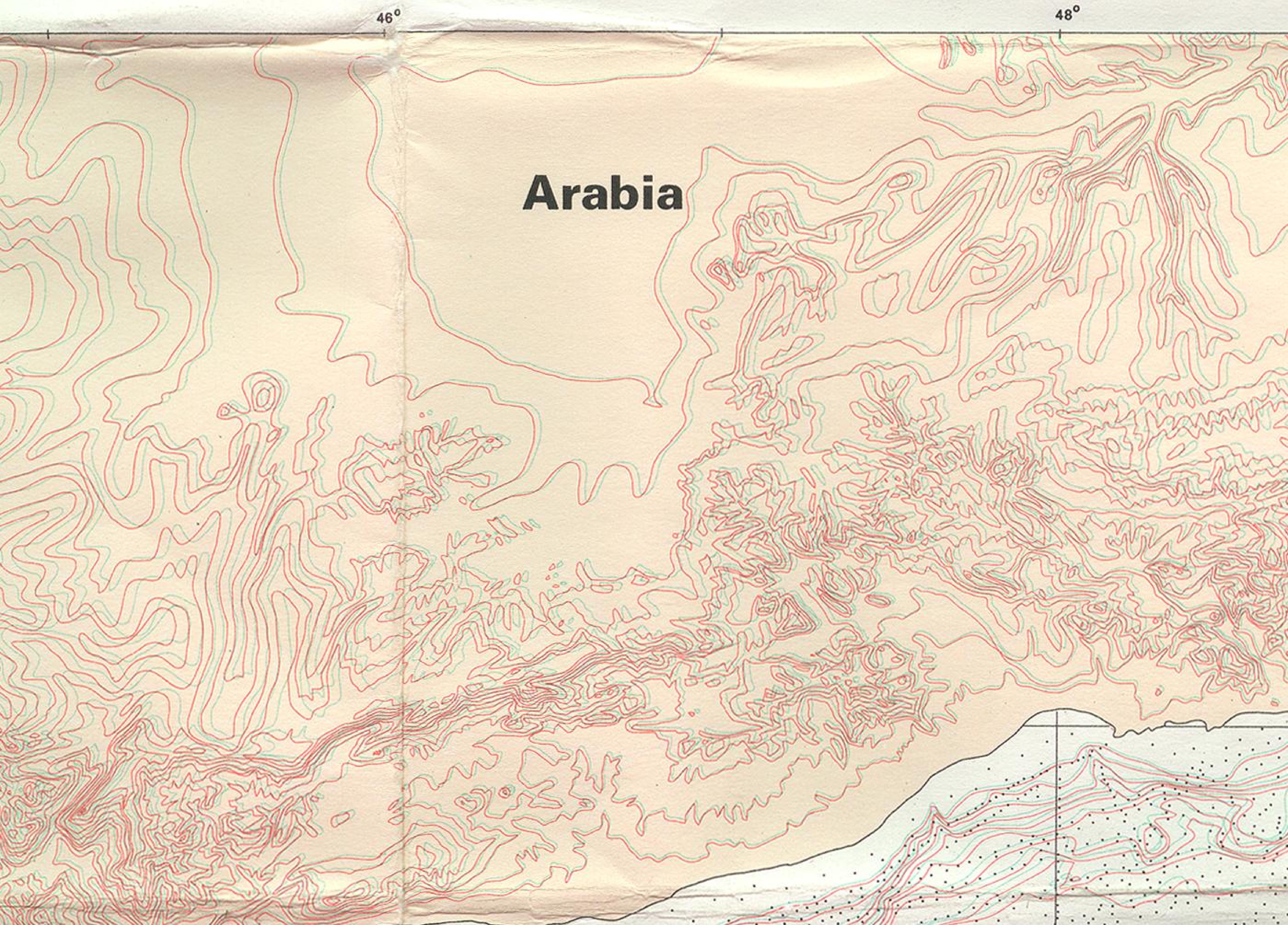
Scale 1:2,000,00

To be viewed thr

Fathoms below sea level

00 1000 1500 2000 2500 3000 3500





no. 3 Printed by Cook, Hammond & Kell, Ltd., London.

a contour chart of the Gulf of Aden

ughton, National Institute of Oceanography, Great Britain

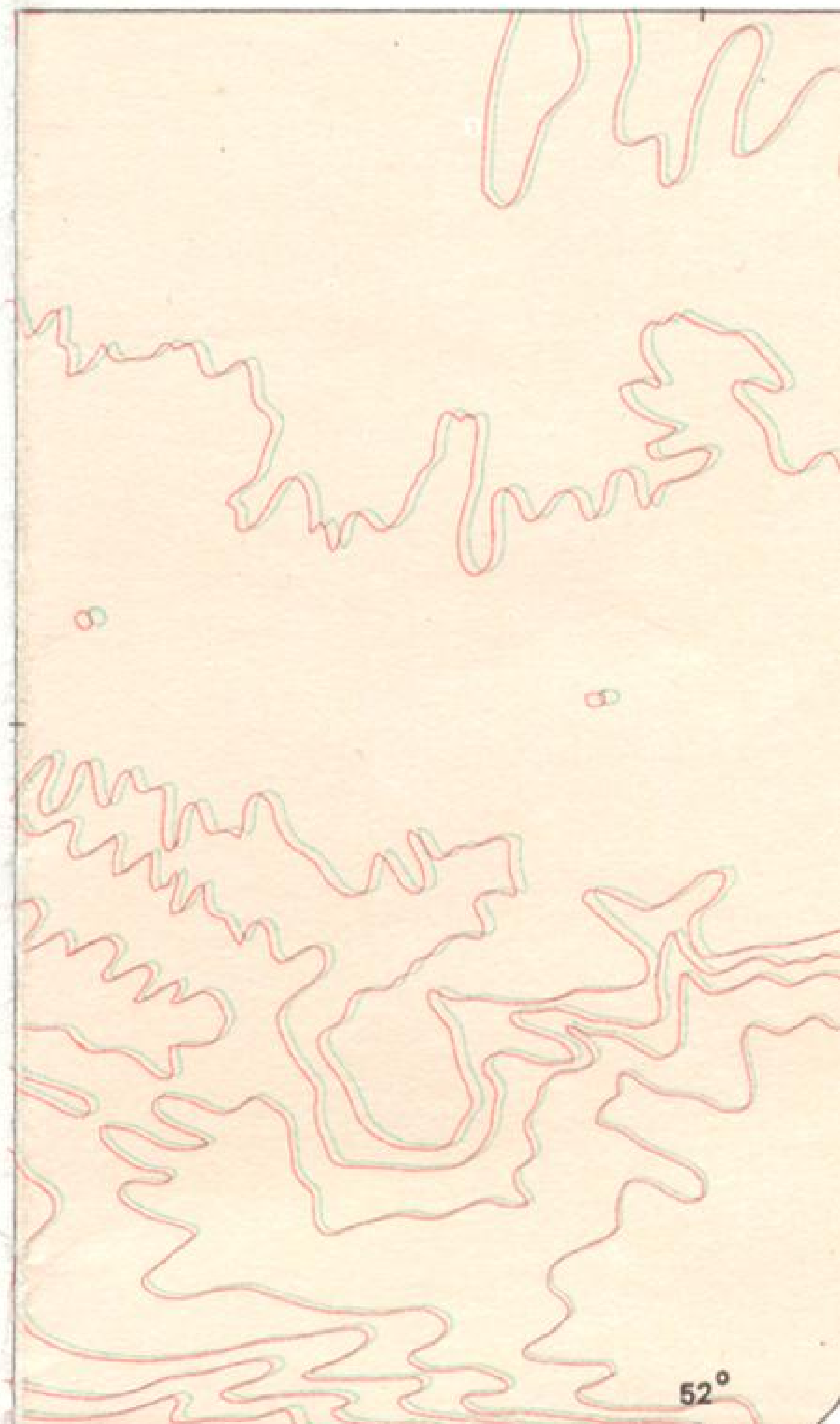
c Cartography by the Royal College of Art, London

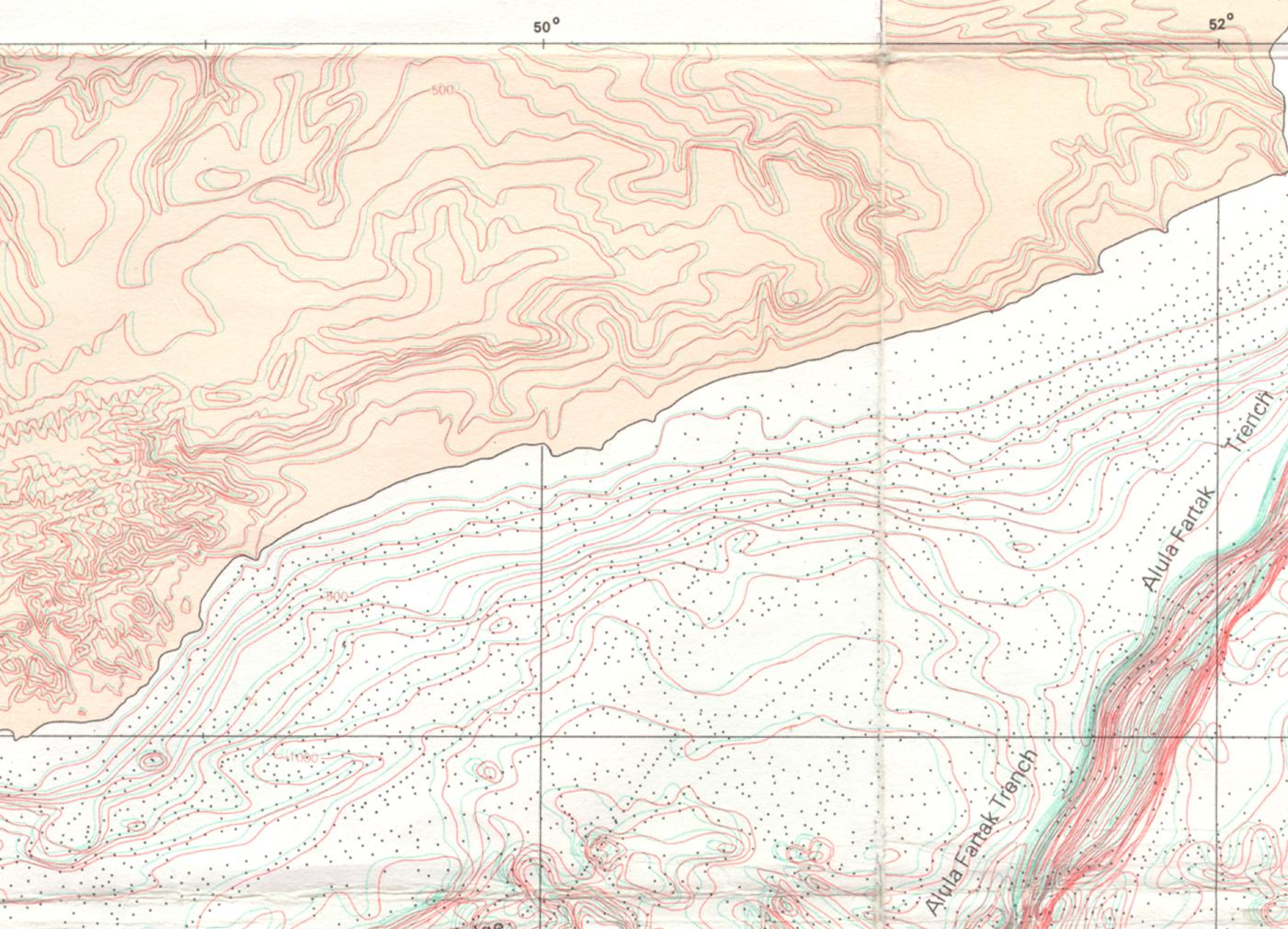
urs in 100 fathom intervals

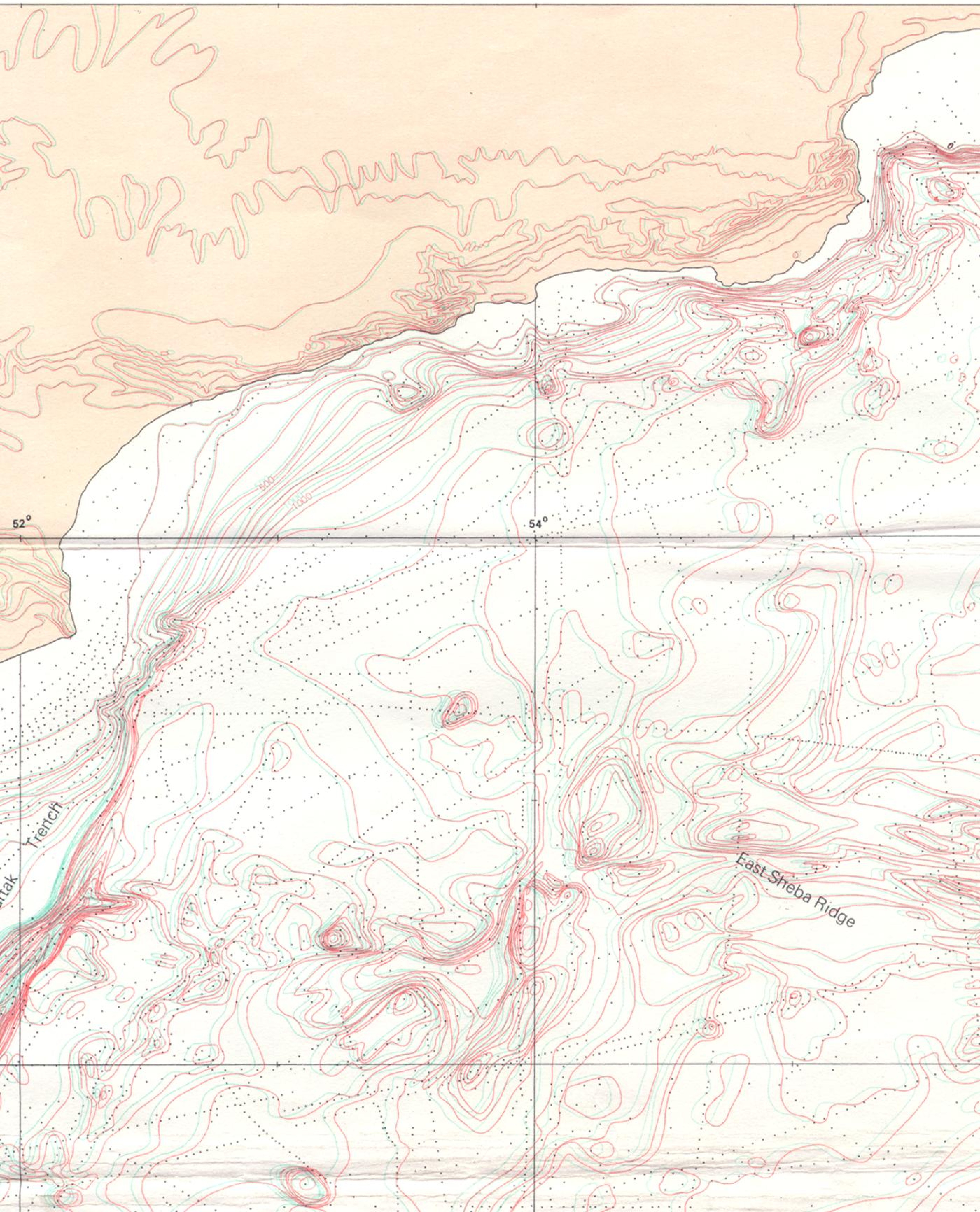
s are shown by black dots

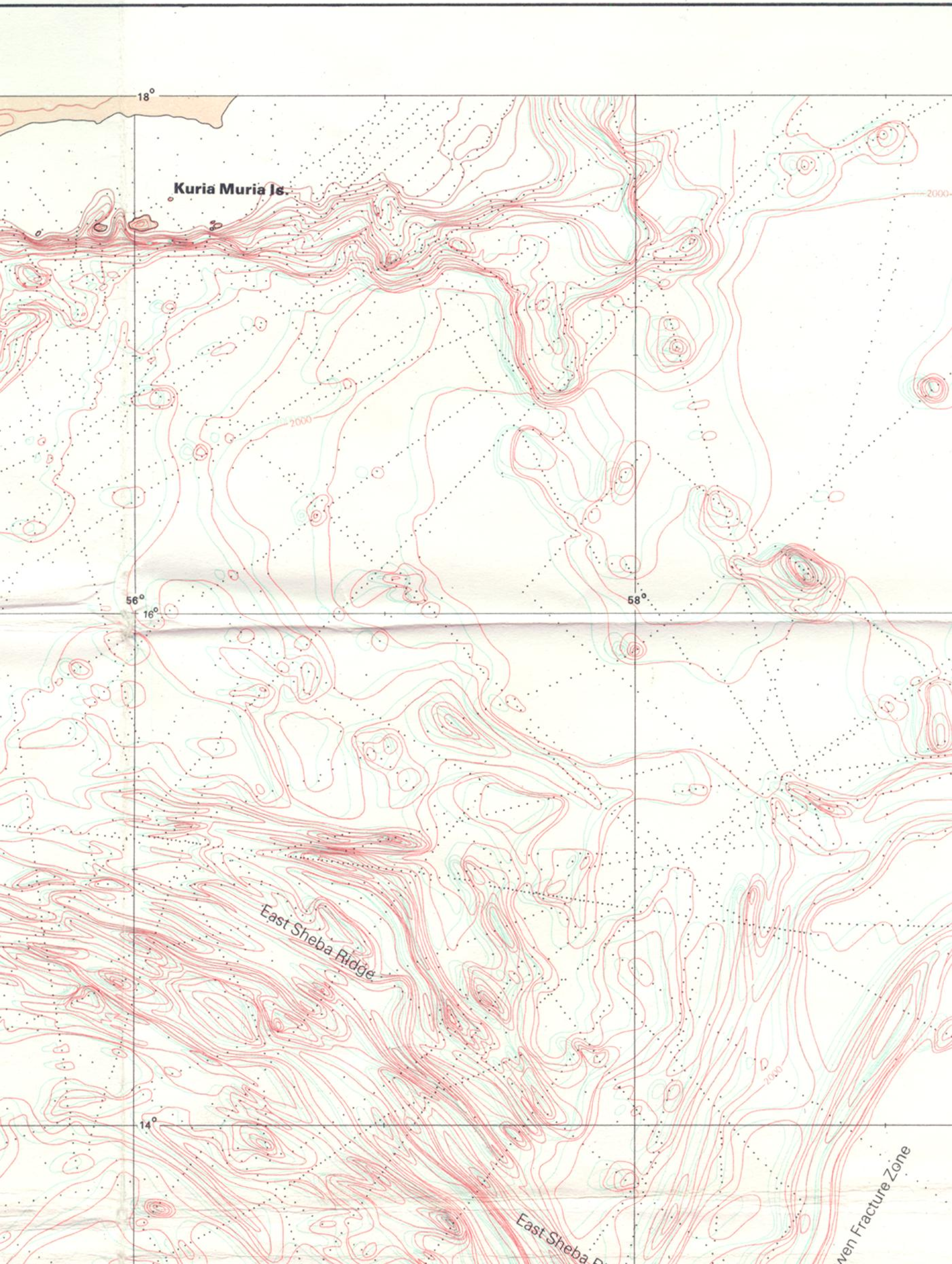
,000,000 at 33°N.

wed through red and green glasses

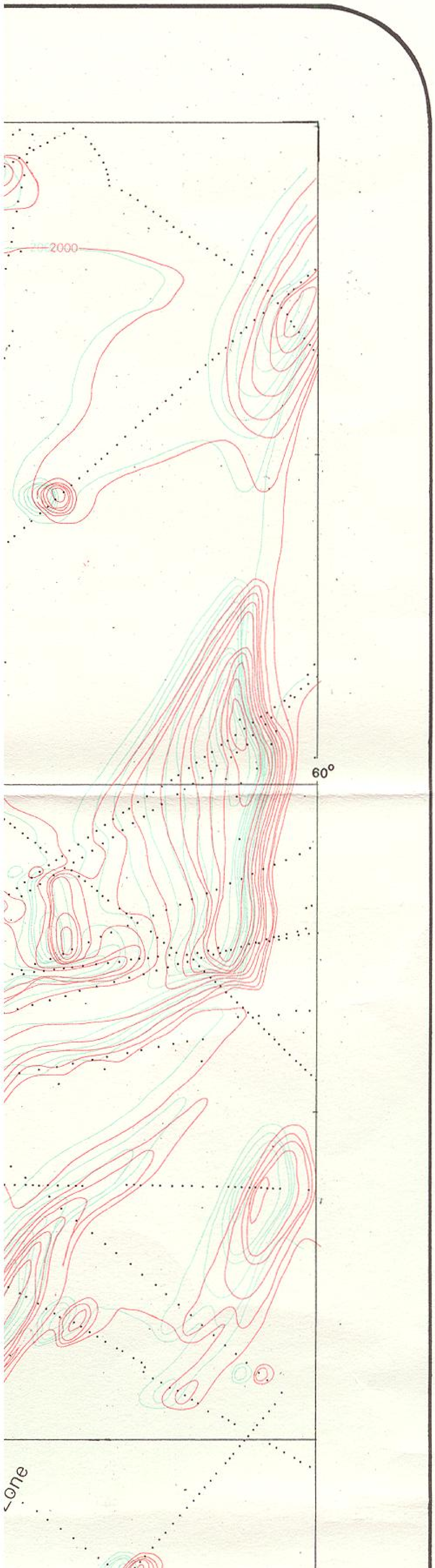





52°
54°
500
1000
Trench
East Sheba Ridge



18°
Kuria Muria Is.
2000
2000
56°
16°
58°
East Sheba Ridge
2000
14°



2000
60°
_one

Tadjura Trench
Gulf of Tadjura
500

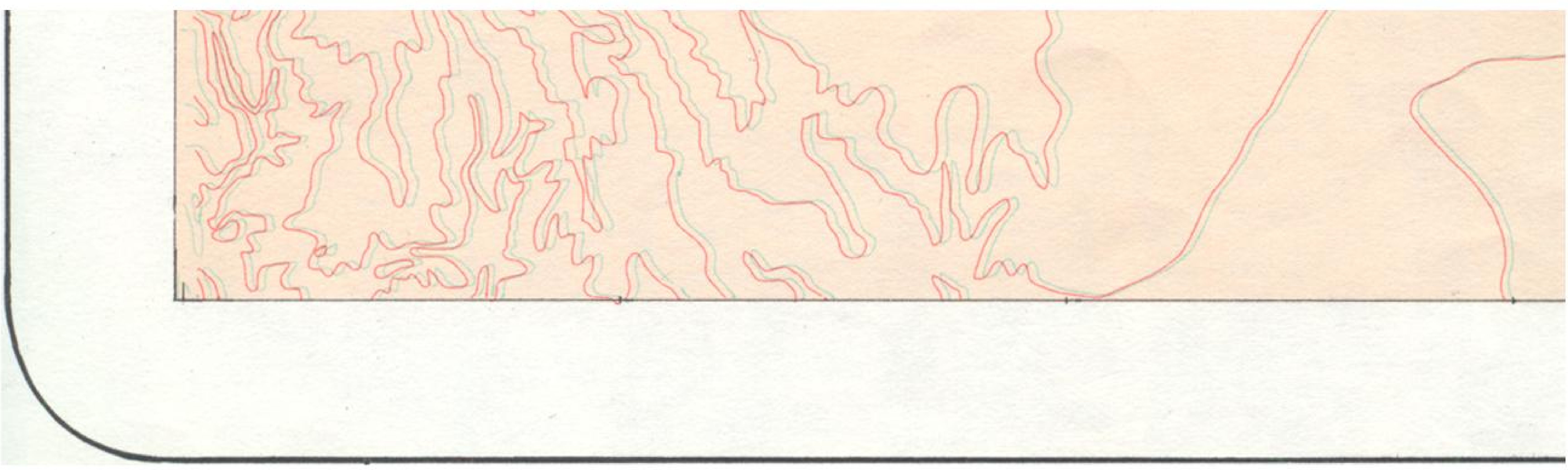

Aden
West Sheba Ridge
1000
500
Somalia
500

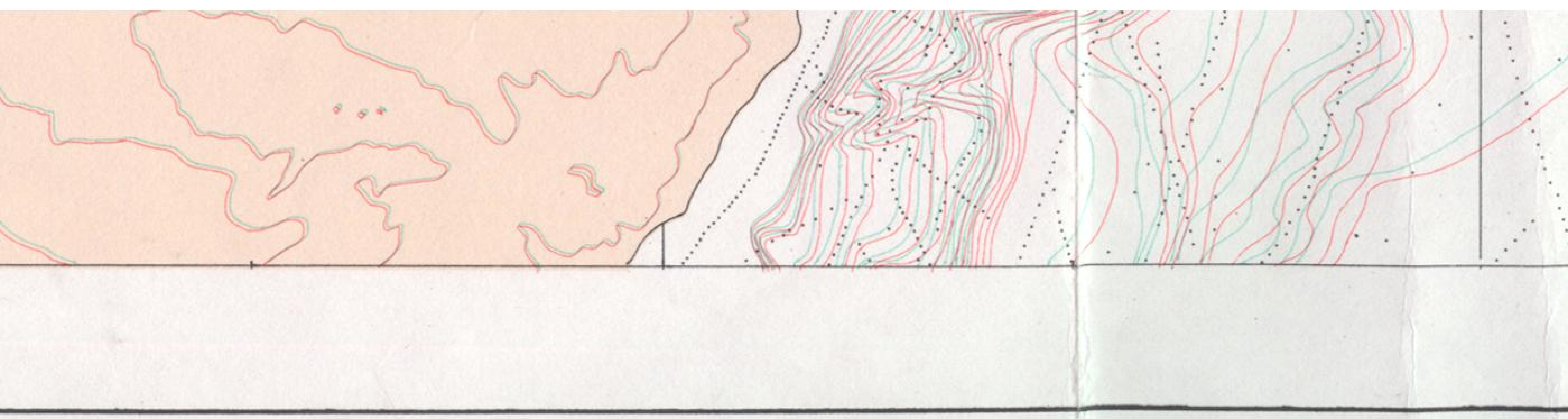

West Sheba Ridge
C. Guardafui

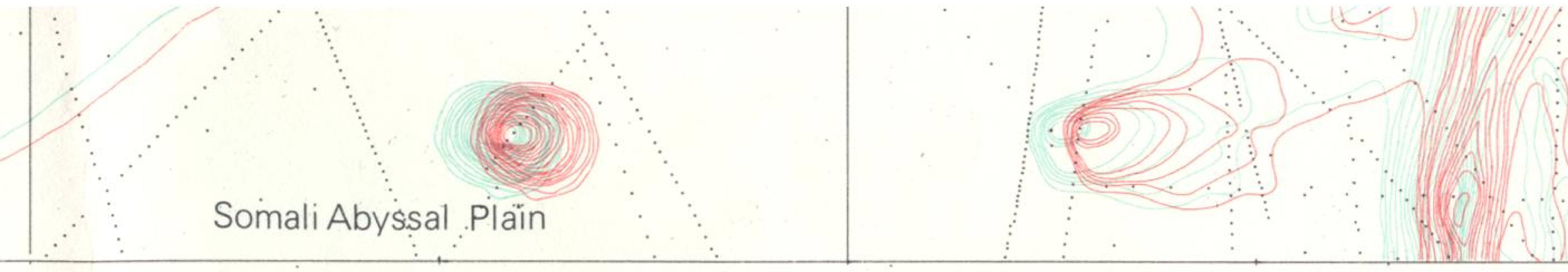

Socotra
Abd al Kuri
The Brothers

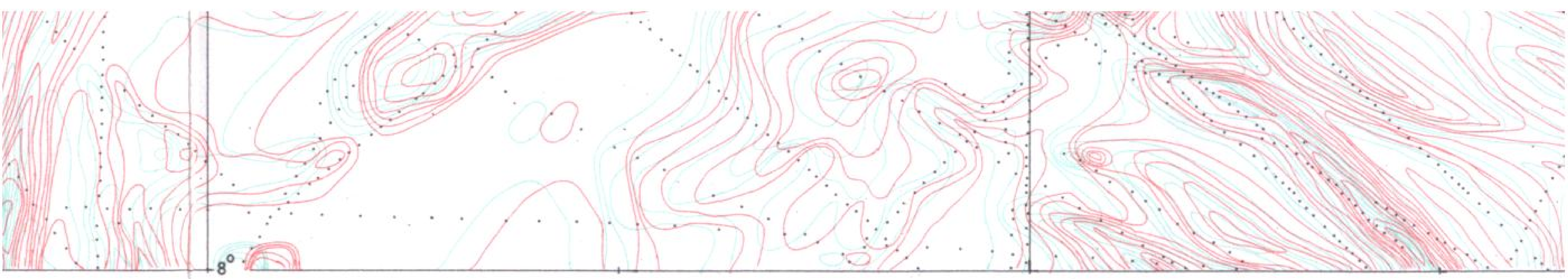

East Sheba Ridge
Owen Fractu
Wheatley Deep
Arabia
12°
Owen Fracture Zone
2000
Mount Error
10°
Owen Fracture Zone
Carlsberg Ri


Arabian Abyssal Plain
rlsberg Ridge






Somali Abyssal Plain


8°