PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A
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The Gulf of Aden

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THE GULF OF ADEN

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The details of topography outlined in a new contour chart of the sea floor are related to the geophysical studies made in the Gulf of Aden during the last decade. These studies include magnetic and gravity field, seismic refraction, heat flow and earthquake epicentre measurements. The Gulf is interpreted as a tensional feature involving the separation of the continental blocks of Arabia and Africa and the formation of new oceanic crust in between. The central rough zone is compared with mid-ocean ridges. The matching of pre-Miocene continental geology on either side is discussed in the light of this theory.

INTRODUCTION

During the past five years, a renewed interest in the Indian Ocean has taken many oceanographic research ships and survey ships through the Gulf of Aden. Most of these ships are equipped with deep-sea echosounders and the resulting accumulation of soundings has made it possible to prepare a new contour chart of the bathymetry of the Gulf and its eastern extension into the Arabian Sea.

Several of these ships also made measurements of the total intensity of the Earth's magnetic field, of the gravitational field, of heat flow and of the crustal structure in the Gulf of Aden, using seismic refraction techniques. The geophysical data can be examined together with the structural trends indicated by the bathymetry, to find out the geological history of the Gulf and its relation to current trends of thought on continental fracture and drift.

The account given here is the result of a preliminary examination of the data, many of which are still coming in, and some of which are still being collected. The publication of the bathymetric chart covering the Gulf of Aden will have to await the production of a fair copy, but examples of two parts of the chart are shown.

TOPOGRAPHY

The main features of the topography in the Gulf of Aden were outlined by Farquharson (1935), following the John Murray expedition and have been later discussed by Stocks (1941, 1944) and Cloos (1942). These authors recognized the northeast–southwest lineation of ridges and valleys in the centre of the Gulf and the similarities between the coastlines of Arabia and Somaliland. However, the mean spacing between echosounding lines available at this time was about 30 miles and much of the data used was derived from earlier spot soundings obtained by weight and wire.

Today much of the Gulf is covered with echosounding lines separated by less than 10 miles, and the improved quality of the records enables a new assessment of the topography to be made. Samples of the newly contoured chart showing the density of tracks are shown in figures 2 and 3.

A problem arises with the correlation of soundings taken in such a comparatively densely sounded area. The navigational accuracy away from the coast depends on the quality of the horizon for astronomical observations. During parts of the year dust storms, haze and variable refraction lead to errors in fixes that may be 10 miles or more, and horizontal shear in the surface currents can increase the errors in the interpolated track between fixes. Some sounding lines have had to be moved by up to 15 miles to present a consistent picture of the topography. When the navigational errors are comparable to the sounding line spacing, contouring can produce a spuriously complicated picture, which is not improved by additional data.

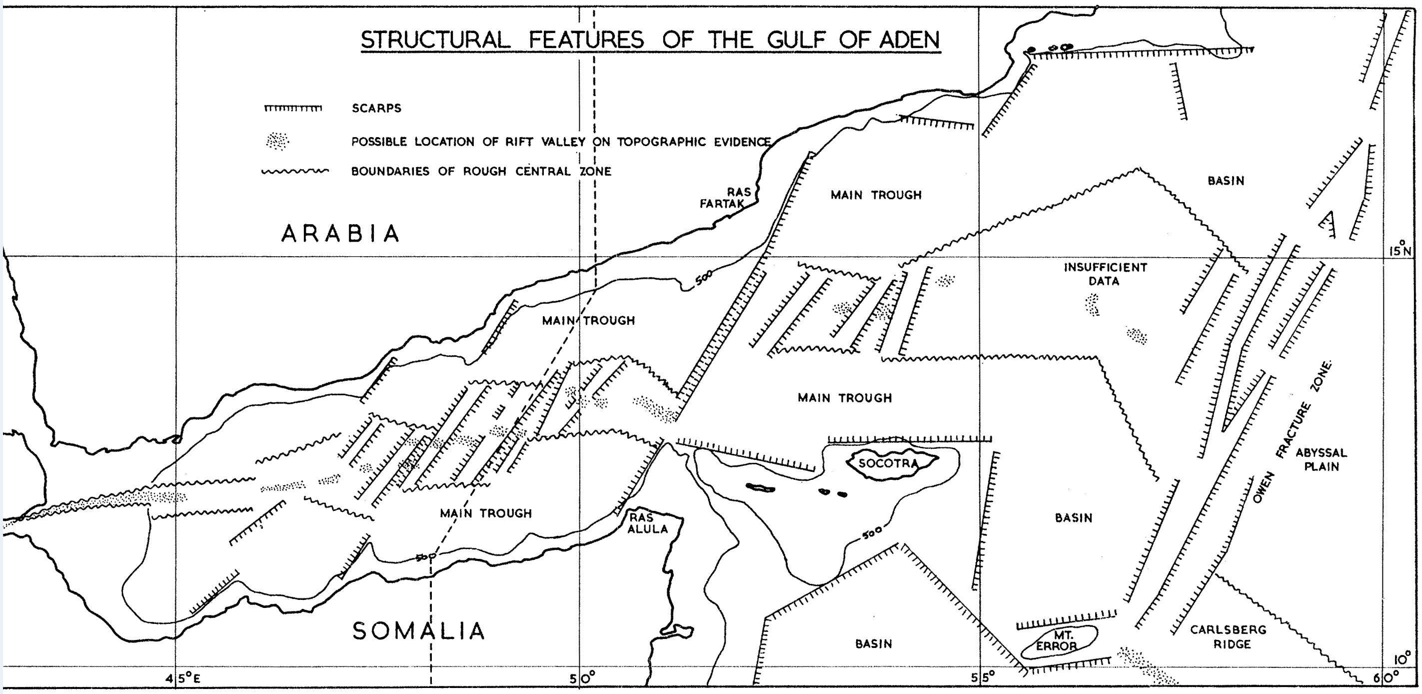

FIGURE 1. Structural features of the Gulf of Aden. (Dashed line shows position of profile shown in figure 2.)

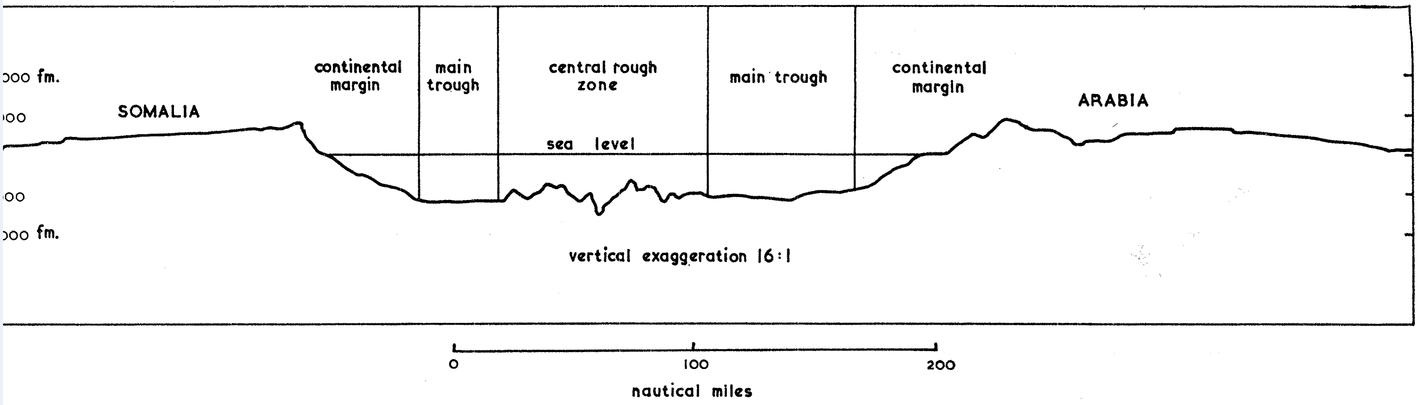

FIGURE 2. Typical topographical profile across the Gulf of Aden.

PHYSIOGRAPHIC ZONES

The main features of the Gulf of Aden deduced from the underwater topography are outlined in figure 1. Three physiographic zones can be recognized; a typical cross-section is shown in figure 2.

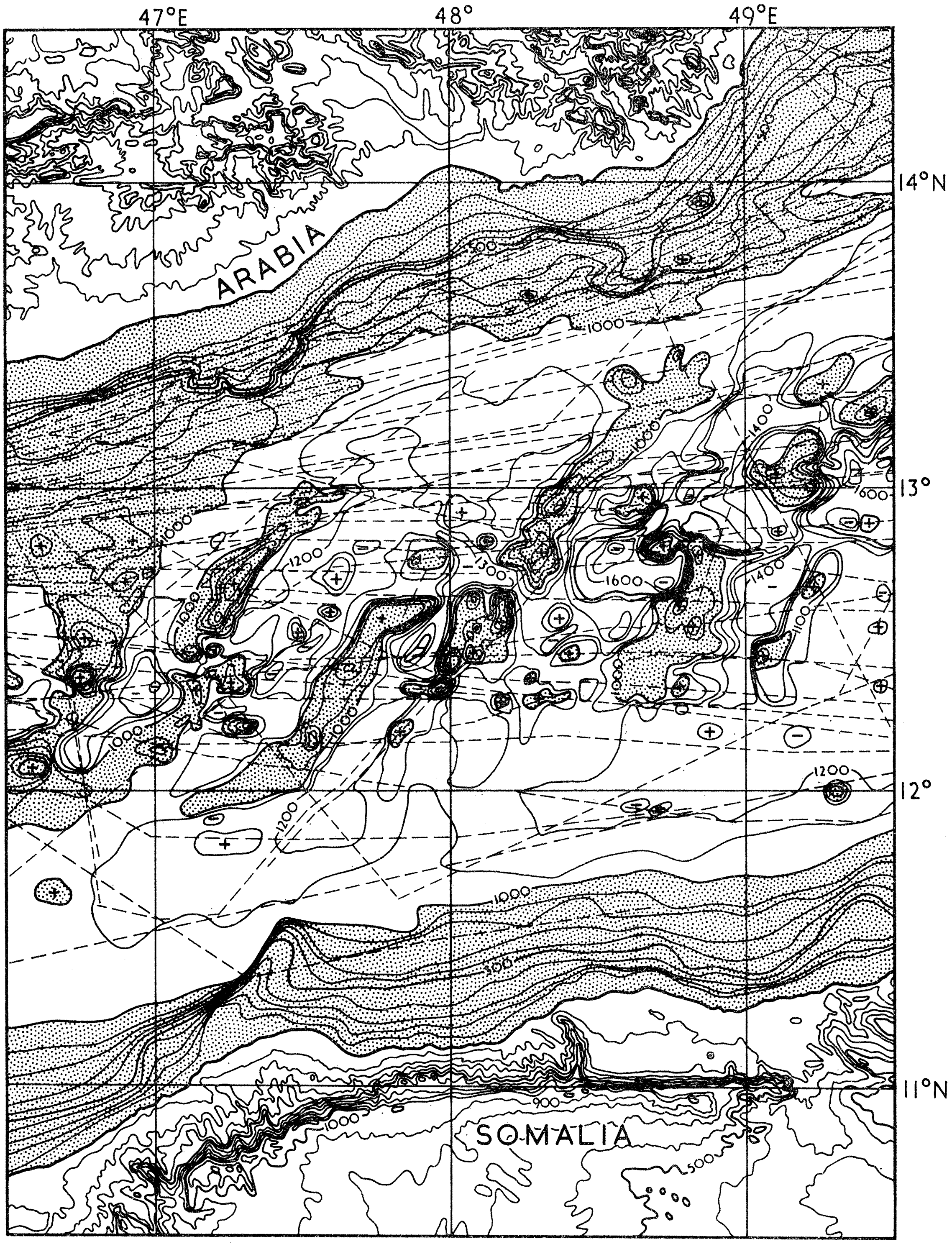

FIGURE 3. Detailed topography of part of the Gulf of Aden. Depths in corrected fathoms. Contour interval on land and sea 100 fm. Stippled area: 0 to 1000 fm. depth. Dashed lines: ship's tracks with sounding data.

Continental margins

The coastlines of Arabia and Somalia consist of a series of capes separated by broad shallow bays. These capes and bays can be correlated across the Gulf and have suggested to many geologists that they once fitted together. However, it is the continental shelf edges which have to be considered in this context.

The continental shelves west of 52° E are narrow and not well delineated by the soundings. The slopes are gentle (1 in 20) and lead smoothly into the sediment-filled basins at the bottom. In many places the slopes are cut with canyons and channels.

However, north and south (respectively) of the capes on the Somalia and Arabian coasts, the continental shelf extends some tens of miles farther out to sea and the slope itself is steepened into a scarp lying along a northeast–southwest axis. On the Somalia coast, the scarps face northwest and on the Arabian coast they face southeast. These linear scarps can be matched in pairs between the north and south coasts of the Gulf and are related to features in the centre of the Gulf.

East of 51° E off the African coast, the continental shelf is well developed and forms the platform out of which rise the islands of Abd Al Kuri, the Brothers and Socotra. The continental slope forming the northern boundary is steep (1 in 5) and has a strike east–west.

Off the Arabian coast between 56 and 58° E, the shelf is well developed, supporting the Kuria Muria Islands, and the south-facing slope is also steep (1 in 2 in places) and strikes east–west. North of the spur of the shelf at $17\frac{1}{2}$° N, 58° E, the continental slope resumes the north-easterly trend that is found off the east coast of Somalia.

The edge of the continental shelf is fairly well defined by the 500 fm. line, except in the western part of the Gulf where the depth of the main trough becomes less than 500 fm. In this region the shelf edge is better located by the 100 fm. line which runs roughly parallel with the coast line.

Main trough

Between the continental slopes on either side, there is the main trough of the Gulf of Aden in the centre of which is a zone of rough topography which forms the third physiographic division. In this paper, the main trough will refer to the fairly flat zone lying between the base of the continental slope and the well-defined edges of the central rough zone.

The depths in the main trough increase steadily from west to east. Between 44 and 46° E, the depth increases from 200 to 1000 fm. Between 46 and 56° E the increase is less rapid from 1000 to 2000 fm. By and large, the line joining equal depths either side of the central rough zone lies parallel to the main northeast–southwest lineations of the Gulf.

The floor of the main trough is sediment covered in most places, gently undulating and cut by occasional channels, but in places there are small abyssal plains.

Between Socotra and the Owen fracture zone, and also south of the spur at $17\frac{1}{2}$° N, 58° E, the main trough widens into flat-bottomed sediment-filled basins bounded to the east by the ridges of the Owen fracture zone. The northerly basin may have connexions with the Arabian abyssal plain through gaps in the ridges.

Central rough zone

Occupying the centre third of the Gulf of Aden is a zone of rough topography whose character changes progressively from west to east, developing from a single valley to a 100-mile wide range of mountains.

In the extreme west, i.e. west of 45° E, the zone is characterized by a single deep valley that runs slightly south of west right into the coast in the Gulf of Tadjura. This valley is in places 500 fm. deeper than the adjacent shelves.

From 45 to 46° E no continuous valley can be seen and the zone is characterized by isolated peaks and ridges.

The greater part of the rough central zone, between 46 and 54° E consists of parallel ridges and valleys trending 030–210°: the distance between crests of ridges is about 30 miles and their relief relative to the valleys is often about 1000 fm. The ridges terminate quite abruptly and the zone is well defined by a line joining these terminations, and enclosing most of the isolated hills.

An important fact regarding the valleys is that they are usually deeper than the adjacent main trough, although there is no barrier preventing them from being filled by sediment from the coast. Indeed one valley (at 13° 15′ N, 49° 00′ E) contains an abyssal plain fed by a canyon from the north. This suggests that the valleys (and hence the ridges) were formed after the greater part of the sediment in the main trough had been laid down.

East of the Alula–Fartak trench (cf. below) the lineation in the central rough zone is still present although less well defined. Between 54 and 57° E, the sounding data is too sparse to establish any lineations. But east of 57° E, the zone runs into the three major ridges forming the central part of the Owen fracture zone (Matthews 1966, this volume, p. 172). The most westerly ridge is terminated within the zone, but the other two form part of a ridge and trough system extending 1500 miles both north and south. The trend of the fracture zone is similar to that of the lineations farther into the Gulf.

The boundaries of the central rough zone indicate that it increases in width from 25 mi. at 44° E to 150 mi. at 57° E. The boundaries also show a series of offsets in a left lateral sense, and these correspond in direction and amplitude to the offsets on the edge of the continental shelves discussed above. Each offset block comprises two ridges and the direction of the offsets is parallel to the ridges.

The most spectacular offset is that at 52° E where the axis of the central rough zone is displaced by 100 mi. The offset is marked by a linear trench 150 mi. long and 10 mi. wide (figure 4). This runs between Ras Alula on the Somalia coast and Ras Fartak on the Arabian coast. It is suggested that the trench be called the Alula–Fartak trench. The maximum recorded depth is 2931 fm. (corrected) and depths greater than 2000 fm. are recorded over 120 mi. of its length. To the west of the trench is a ridge 400 to 500 fm. above the main trough level of 1200 fm. and this extends southward from a bulge in the continental slope. (The bulge is thought to be due to the deltaic accumulation of sediments from the mouth of the Wadi Hadramaut at 51° E, confined to the east by the ridge associated with the Alula–Fartak trench. It is cut with numerous canyons and channels emanating from the mouth of the Wadi.)

The section of the central rough zone between 54 and 57° E resembles in many ways

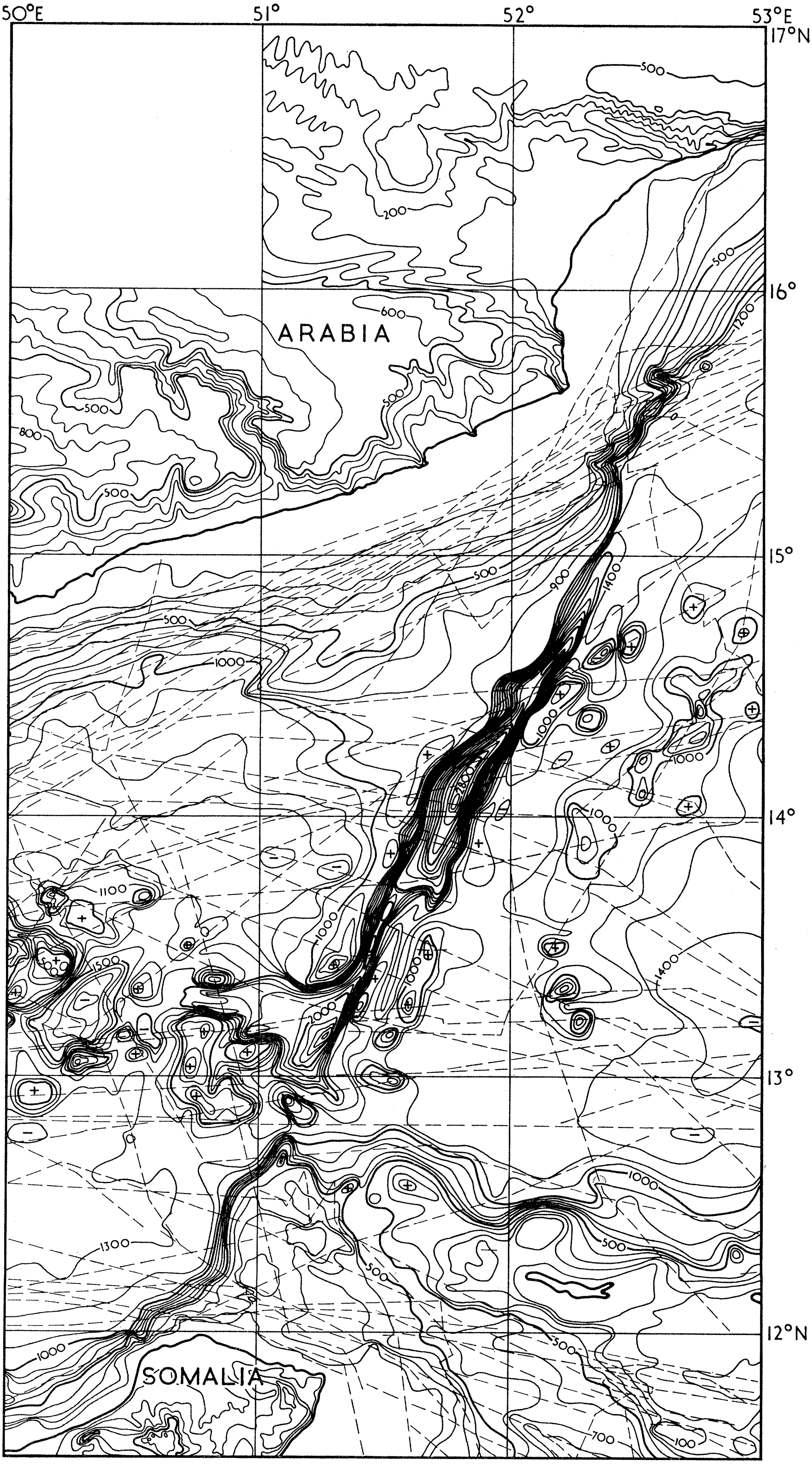

FIGURE 4. Detailed topography of Alula–Fartak trench. Depths in corrected fathoms. Contour interval on land and sea 100 fm.

the northwest end of the Carlsberg Ridge. The scale of the topography, the magnetic anomalies and epicentre belt suggest the Carlsberg Ridge to have been displaced southwestwards by the Owen fracture zone since its formation (Matthews 1963, 1966). It is therefore pertinent to look for a median valley in the central rough zone equivalent to that on the Carlsberg Ridge.

Any section at random across the zone will show one, or perhaps two, deep valleys but, as discussed above, these are alined northeast–southwest not east–west. A median valley is obvious in the extreme west. Between 46 and 55° E, an examination of the topography was made to see if the traces of a median valley could be found superimposed on the linear ridge and valley system. It was found that many ridges were interrupted along their length by a gap, or col, some 500 fm. below the ridge crest (e.g. 12° 40′ N, 48° 15′ E, cf. figure 3). Many of the valleys had an especially deep region (e.g. 12° 50′ N, 48° 35′ E). When connected together such regions show east–west lineations within each offset block and may represent the locus of new fractures (cf. dotted areas in figure 1).

In the eastern region deep soundings have been found on two crossings at 14° 20′ N, 56° 25′ E, but no linear trend has been established.

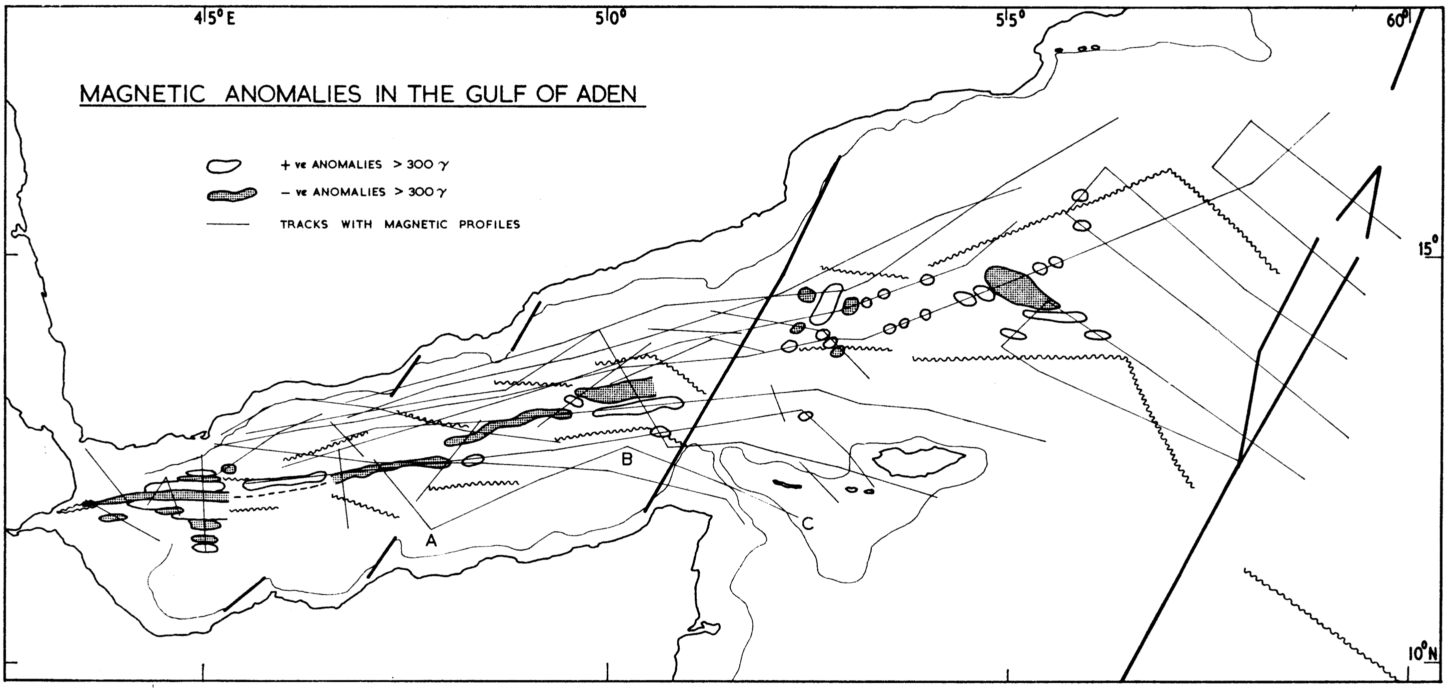

Figure 5. Magnetic anomalies.

Geophysical data

Magnetic field

The position of tracks along which measurements have been made of the total intensity of the earth's magnetic field are shown in figure 5. A regional gradient has been removed from the profiles using a third-order polynomial regional field derived from meaning the data over the northwest Indian Ocean (Admiralty 1963). The resultant anomalies have been plotted and, where the spacing of the data permits, they have been contoured.

The continental shelf, apart from the neighbourhood of Aden where there are extensive volcanics on land, is characterized by a flat magnetic field, anomalies seldom exceeding a few tens γ.

In contrast to this, the anomalies over the main trough are typically $\pm 100\,\gamma$ with wavelengths of the order of 10 mi. These anomalies are reminiscent of those found over the deep ocean basins and are indicative of a rough buried topography of volcanic rocks. A striking example of the contrast with the shelf anomalies is shown on the crossing of the shelf edge 30 mi. north of Ras Alula (figure 6).

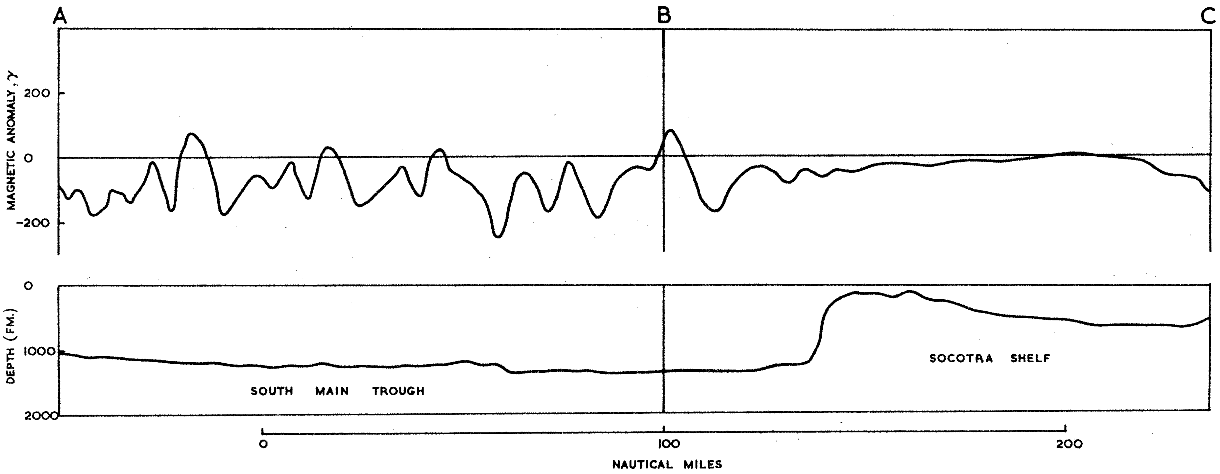

Figure 6. Comparison of magnetic anomalies over south main trough and Socotra shelf (position of profile shown in figure 5).

In the central rough zone the magnetic field is extremely disturbed and there are anomalies as high as $\pm 1000\,\gamma$. In figure 5 positive and negative anomalies $> 300\,\gamma$ are shown and it can be seen that these all lie within the central rough zone. (An exception is at the west end of the Gulf where the source of the anomalies is shallow and hence the anomalies are large.) Most crossings in the zone are characterized by a large negative anomaly whose trend can be fairly accurately determined to be east–west.

West of 45° E, the main magnetic anomalies have been interpreted by Girdler & Peter (1960). The large negative anomaly which lies over the rift valley can be accounted for by an intrusive dyke or dyke swarm 4·5 km wide reaching up to the bottom of the valley from about 15 km. The intensity of magnetization is $2{\cdot}5\times10^{-3}$ e.m.u./cm^3 and is alined with the present earth's field. Just north of the valley, a positive anomaly is ascribed to a reversely magnetized dyke or dyke swarm 1·2 km wide reaching the surface. The intensity of magnetization is $4{\cdot}0\times10^{-3}$ e.m.u./cm^3. The other strips of negative and positive anomalies north and south of the valley may also be attributed to normally and reversely magnetized dykes.

East of 45° E, the east–west lineation of the main negative anomaly can be followed as far as the Alula–Fartak trench, although it is offset with the blocks of the central rough zone. It appears to follow the line suggested by the topography for an incipient median valley. North and south of it there are positive anomalies with similar lineation, although not well defined.

East of the Alula–Fartak trench, the large anomalies are still found although the trends are difficult to establish. At $14\frac{1}{2}^\circ$ N $55\frac{1}{2}^\circ$ E an east–west trend is apparent from the difference of projected wavelength along two courses at right angles. The largest anomaly ($-710\,\gamma$) is found in the centre of the rough zone.

East of 56° E, the magnetic relief dies away rapidly and the Owen fracture zone ridges do not have a clear magnetic signature. However, because of the orientation of tracks, a median magnetic anomaly may exist undetected along the line of earthquake epicentres between 56 and 58° E.

Superimposed on the main median magnetic anomaly are smaller anomalies (of the order of $\pm 100\,\gamma$) that show a certain tendency to be alined with the northeast–southwest ridge and valley structure. These are found throughout the central rough zone and may perhaps be continuous with those found over the smoother main trough. There is, however, no magnetic anomaly associated with the Alula–Fartak trench. Indeed the field over the trench seems abnormally smooth. If the trench is a region of shear in the crust, brecciation, dislocation and low grade metamorphism may reduce the overall magnetic effect of the rocks, as has happened in the Carlsberg ridge (Matthews, Vine & Cann 1965).

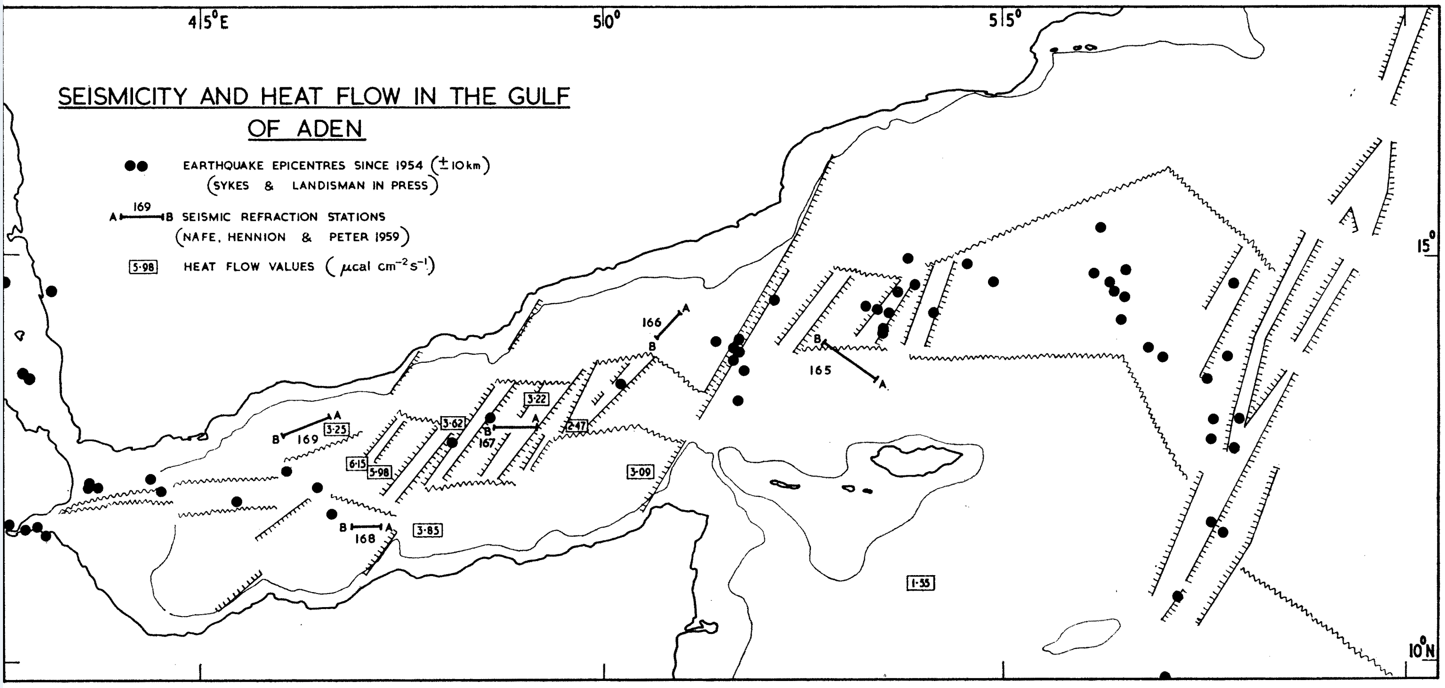

Figure 7. Seismicity, seismic refraction stations and heat flow data.

Seismicity and heat flow

A belt of shallow focus earthquakes has long been known to run into the Gulf of Aden. Sykes & Landisman (1964) have relocated epicentres of earthquakes since 1954 to an estimated accuracy of 10 km. These are shown in figure 7, where the size of the dots indicates the accuracy of location. Nearly all epicentres lie within the rough central zone excepting those that are concentrated on the Alula–Fartak trench and on the Owen fracture zone.

Heat-flow measurements made in the Gulf of Aden (figure 5) are all higher than normal ranging from 2·5 to 6·0 μcal cm^{-2} s^{-1} (Herzen 1963; Sclater, p. 271 below). Although the highest values lie within the central zone, the three stations in the main trough also show abnormally high values, suggesting that if the high values are associated with the upward limb of a mantle convection current, then it is wider than the earthquake belt.

Seismic refraction data

In 1958 R.V. *Vema* and R.V. *Atlantis* carried out five seismic refraction stations in the Gulf, two of which lay within the central rough zone and three in the main trough (figure 7). The results were discussed by Nafe, Hennion & Peter (1959), although details of the layering were not published. Table 1 and figure 8 present the data. The structure is essentially similar at all five stations although the high velocity (7·7 km/s) layer was observed only at stations 169 and 165. The main crustal layer (6·4 to 6·9 km/s) had a mean thickness of about 6 km, the bottom lying at a depth of 10 km below sea level. This velocity and thickness is comparable to the oceanic crustal layer attributed to basic igneous rocks.

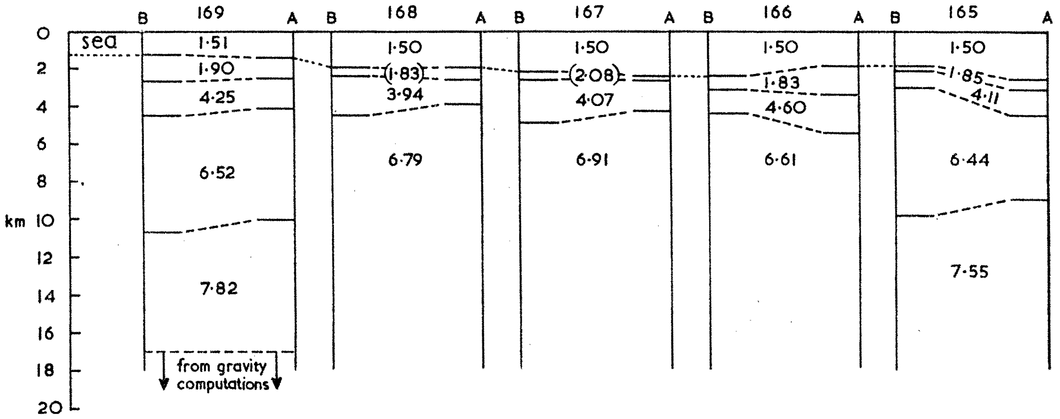

FIGURE 8. Crustal layering obtained by seismic refraction stations of *Vema* and *Atlantis* 1958 (by courtesy of Dr Nafe, Lamont Geological Observatory).

Above these rocks there is a layer with velocities ranging from 3·94 to 4·60 km/s. These fall within the range of velocities for Layer 2 (Raitt 1963), although they are lower than the mean value of 5·07 km/s for all oceans.

The superficial layer of sediments (1·85 km/s) varies in thickness from 1·5 km in the north main trough, to 0·5 km in the south main trough and even less in the central rough zone, as might be expected.

The low value of velocity in the sub-crustal rocks may be due to poor determinations of the velocity. However, if they are typical mantle rocks with appropriate densities, then gravity computations (Nafe *et al.* 1959) suggest a large positive anomaly which is not observed. The transition to mantle rocks could only take place below 17 km below sea level. The 7·7 km/s layer may be similar to the modified mantle rocks found beneath the mid-ocean ridges (Le Pichon *et al.* 1965).

A comparison of crustal structure can be made with that of the Red Sea (Drake & Girdler 1964) where an oceanic section was observed for the central valley, whereas under the shallower regions of the main trough, velocities of 5·8 km/s were attributed to continental shield rocks. The difference between the crustal structure of the main troughs in the Red Sea and the Gulf of Aden is critical to the interpretation of these features in relation to continental drift movements of Arabia relative to Africa.

TABLE 1. LAYER DETERMINATIONS IN GULF OF ADEN

Vema 14—Atlantis 242 1958 (by courtesy Dr J. E. Nafe, Lamont Geological Observatory).

station no.	station *B*	locations *A*	thickness at *B* (km)	velocity (km/s)	thickness at *A* (km)	comments
165	13° 54′ N,	13° 29′ N,	1·98	sea 1·50	2·67	high velocity weakly determined
	52° 45′ E	53° 23′ E	0·23	1·85	0·55	
			0·85	4·11	1·36	
			6·84	6·44	4·44	
				7·55		
166	13° 58′ N,	14° 17′ N,	2·48	sea 1·50	2·00	offset assumed 4·6 to 6·6 interface
	50° 36′ E	51° 00′ E	0·74	1·83	1·54	
			1·22	4·60	1·95	
				6·61		
167	—	12° 58′ N,	2·22	sea 1·50	2·45	( ) assumed velocity and consequent assumed thickness
		49° 47′ E	(0·40)	(2·08)	(0·28)	
			2·36	4·07	1·64	
				6·91		
168	11° 38′ N,	11° 38′ N,	1·97	sea 1·50	2·00	( ) assumed velocity and consequent assumed thickness
	46° 48′ E	47° 16′ E	(0·44)	(1·83)	(0·61)	
			2·13	3·94	1·53	
				6·79		
169	12° 47′ N,	13° 02′ N,	1·31	sea 1·51	1·48	high velocity weakly determined
	46° 01′ E	46° 35′ E	1·33	1·90	1·12	
			1·85	4·25	1·57	
			6·25	6·52	5·90	
				7·82		

Drake & Girdler allow relative movement of Arabia such that the axial rift represents the amount of new oceanic crust formed and the main trough consists of the down-faulted continental blocks resulting from the collapse of the up-arched Arabian–Nubian shield. Such an interpretation is not possible in the Gulf of Aden where the whole width of the main trough, including the rough central zone, has the characteristic velocities and thicknesses of an oceanic crust, and where the magnetic anomalies indicate extensive emplacement of basic rock. The concentration of earthquake epicentres, high heat flow and the existence of a median valley with associated large magnetic anomalies, in the rough central zone, suggests that this is the presently active region of the creation of new ocean crust whereas the main trough is older and no longer so active.

If this interpretation is accepted, then a reconstruction of the African–Arabian continent must involve the fitting of continental edges along the continental slope, which is fairly represented (except in the extreme west) by the 500 fm. line.

The validity of such a reconstruction rests on the matching of geological features that were formed prior to the relative movement of the continents.

Geological evidence for predrift reconstruction

Simplified geology

A simplified map of the geology of South Arabia and Somalia is shown in figure 9. On the Arabian peninsula the geological features have been taken from Wissman, Rathjens & Kossmat (1942), Beydoun (1960), Geological Map of Africa sheet 3 (U.N.E.S.C.O. 1963) and Geological Map of the Arabian Peninsula (U.S.G.S. and Aramco 1963). On the Somali coast data has been drawn from Dainelli (1943), Somaliland Oil Exploration Company (1954) and Geological Map of Africa sheet 6 (U.N.E.S.C.O. 1963).

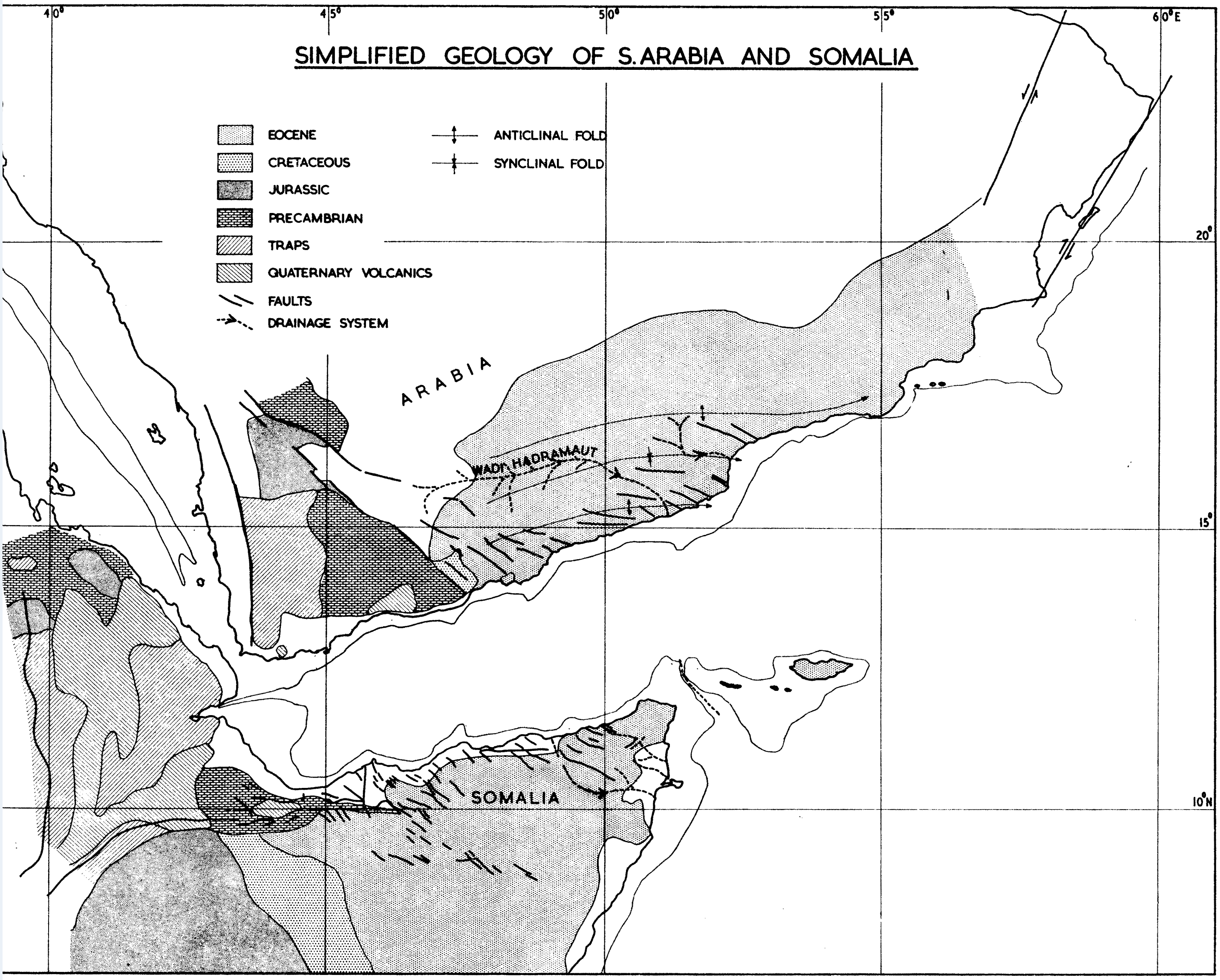

Figure 9. Simplified geology of south Arabia and Somalia.

East of 47° E in Arabia and east of 44° E in Somalia the geology is very similar. Middle to Upper Eocene strata occupy the top of the stratigraphic column underlain by Lower Eocene, Cretaceous and in most places Jurassic beds. These sit unconformably on Precambrian crystalline basement rocks. In Arabia, this sequence is gently folded along an east–west axis. The North and South Hadramaut arches (along 17 and 15° N) are separated by a synclinal depression which crosses the coast at Qamar Bay (16° 10′ N, 52° 30′ E). ‘The south flank of the south arch has collapsed in complex block-faulting in the western part and in more regular E–W and ENE–WSW step faulting to the east, where the blocks are generally tilted southwards’ (Beydoun 1960). Beydoun suggests that the Hadramaut arch attained its maximum development in the Upper Eocene after emergence. The folding is truncated obliquely by the coastline between 52 and 55° E.

The Eocene Sea was limited to the west by the uplifted zone now represented by the exposed Precambrian rocks of the Yemen (Wissman *et al.* p. 290, 1942). Along the north-east side of this zone an extensive fault system has been mapped (U.S.G.S. and Aramco 1963) running southeast from 17° N, 44° E, to the coast at 14° N, $47\frac{1}{2}$ °E.

In the North Somaliland Plateau the Mesozoic and Lower Tertiary succession is tilted gently upwards to the north but is severely down faulted along an east–west line to produce the Guban Sunklands lying between the coastal mountain range and the coast itself.

Three main trends of faulting have been demonstrated in Somalia (Som. Oil Ex. Co. 1954). ‘Red Sea trend’ faults are numerous but are concentrated mainly in the region between $45\frac{1}{2}$ and $47\frac{1}{2}$° E where the east–west mountain range is interrupted. A belt of these faults continues southeast across the Nogal region to $8\frac{1}{2}$° N, $48\frac{1}{2}$° E. The Red Sea trend faults are dated by stratigraphic disruptions to be Upper Eocene to Oligocene.

The east–west, or ‘Gulf of Aden trend’, faults responsible for the north boundary of the main mountain ranges (the Golis Scarp) in Somalia are dated with certainty to have been initiated in early Miocene times (Som. Oil Ex. Co. 1954, p. 35).

The third fault system, with north–south or ‘East African trend’ is developed only at $45\frac{1}{2}$° E and is thought to be pre-Jurassic, although rejuvenated in the Tertiary.

West of the Eocene plateau in Central Somalia, Cretaceous and Jurassic beds are exposed bounded farther west by the north end of the Rift Valley.

The Precambrian basement is exposed north of the Golis scarp between 43 and 45° E. The northern limit of this exposure is 10° 40′ N. On the Arabian side, Precambrian metamorphics form a large part of the exposed rock between the fault line running northwest–southeast through 15° N, 46° E, and the volcanic rocks of the Yemen.

The greater part of the rocks occupying the Afar triangle, forming the northern part of the African Rift Valley, are Oligocene-Miocene and Quaternary volcanics, although the Danakil mountains at 14° N, 41° E are Jurassic.

Evidence for the start of the tectonic movements that caused the Gulf of Aden come from the dating of the ‘Gulf of Aden trend’ faults that parallel the Gulf, which have been associated with the uparching and subsequent block faulting of the original graben. These are clearly post-Eocene as Eocene strata are faulted. In Somalia they have been found to be Miocene (Som. Oil Ex. Co. 1954). Girdler (1958) discusses the age of the Red Sea–Rift Valley system and suggests Eocene-Miocene for the main Rift subsidence. Beydoun (1960) recognizes an Oligocene-Miocene marine invasion of the Gulf of Aden trough giving sedimentary sequences which have been subsequently faulted and tilted.

Evidence for pre-drift geological connexions must therefore be sought in pre-Miocene geological features. The evidence can be discussed under three headings: stratigraphic, tectonic and erosional.

Stratigraphic continuity

Figure 10 shows Arabia shifted towards Africa to fit along the 500-fathom contours. This fit was discussed by Wissman *et al.* (1942), but eventually rejected in favour of mainly vertical movements. Such a shift does not overlap exposures of the Precambrian basement but brings them adjacent. The western limit of the Eocene sea is concordant between Africa and Arabia. The overlap of the Yemen and parts of Ethiopia imply that only parts of these areas can have a continental basement and that the remainder was formed as new crust after drift was initiated. It is suggested that a large part of the Afar triangle represents this new crust, whereas the volcanics of the Yemen were extruded through fractured continental crust which they now cover. The Danakil mountains are interpreted as a continental remnant.

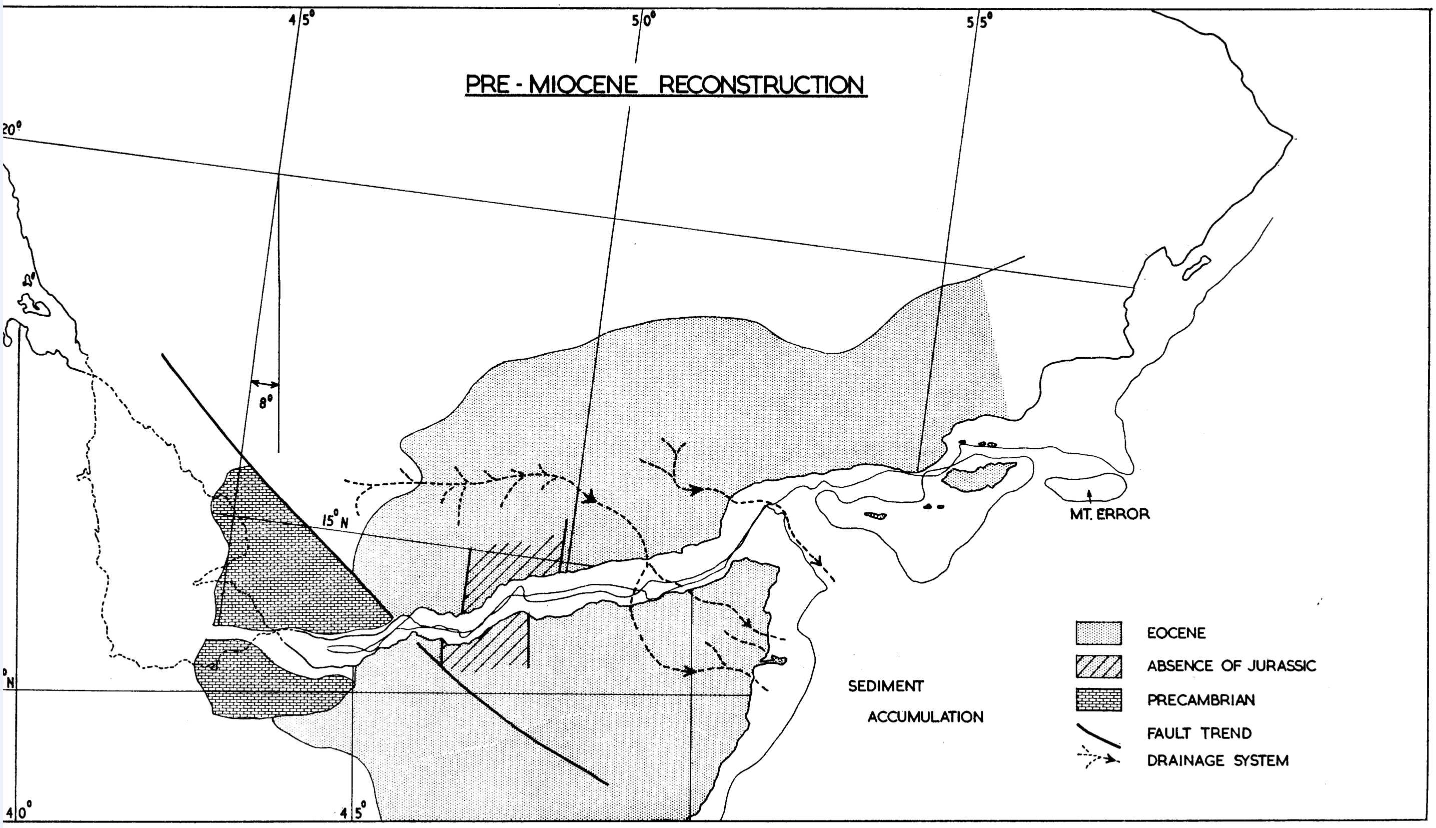

FIGURE 10. Pre-Miocene reconstruction of Gulf of Aden.

An interesting correlation can be made of the Jurassic strata (figure 11) underlying the Cretaceous and Eocene in Arabia and Somalia. Beydoun (1960) remarks on the block faulting following the Jurassic in Arabia 'resulting in variable elevation and erosion, and in the complete removal of the Jurassic from a broad, elevated feature extending south–north through Mukalla' (p. 144). The axis of this erosion lies along 49½° E. In Somalia a similar uplift and erosion has removed Jurassic strata between 46½ and 47½° E (Som. Oil Ex. Co. 1954) in the Guban. South of the plateau scarp Jurassic rocks are absent between 43 and 47° E. The reconstruction in figure 10 shows how the uplifted and eroded Jurassic beds form a continuous feature across the closed up Gulf.

The reconstruction brings the Socotra shelf with its islands close to the Arabian coast. To fit the steep continental slopes together requires an additional shift of the shelf north-eastwards relative to Africa. Socotra then becomes adjacent to the Kuria Muria Islands. A faulted south shore to the latter islands was suggested by Wiseman & Sewell (1937).

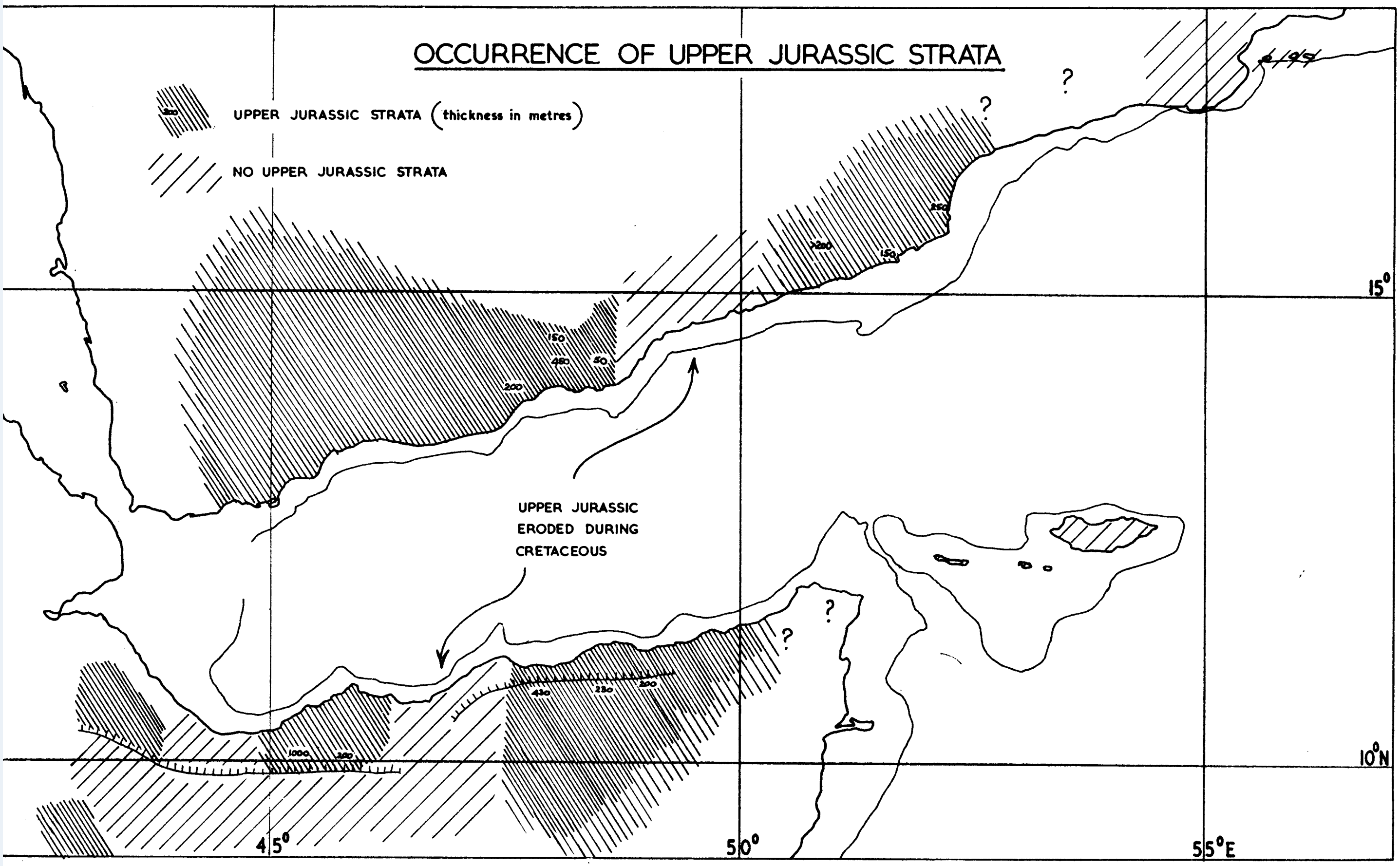

FIGURE 11. Occurrence of Upper Jurassic strata in South Arabia and Somalia.

Reed (1949) describes the islands on the Socotra shelf as fault blocks separated from the mainland in late Tertiary times. Both the Socotran Islands and the Kuria Muria Islands have a stratigraphy similar to that of the adjacent Arabian and Somalia mainland, and are similar to each other. An important aspect of their similarity is the absence of Jurassic rocks. In the case of Socotra, this places limitations on the position along the Arabian coastline where it might have originated.

Mount Error is a flat-topped non-magnetic seamount which is believed to be continental in origin and which now lies in position $10\frac{1}{4}°$ N, 56° E on the extension of the Carlsberg ridge (figure 1). It is discussed elsewhere in relation to the Owen fracture zone (Matthews 1966). Fine grained porcelaneous limestone has been dredged from the top. It is possible that Mount Error was originally part of the continent east of Socotra and fitted against the shelf now in position $17\frac{1}{2}°$ N, 57° E, and that the major tear fault, which displaced the Carlsberg ridge from the mouth of the Gulf of Aden and formed the Owen fracture zone, also moved Mount Error southwards.

Tectonic continuity

The major 'Red Sea trend' fault system in the Yemen and Somalia predates the opening up of the Gulf of Aden. It should therefore be recognizable on both sides. A continuous fault zone running from the Yemen to 8½° N, 48½° E can be recognized, although the data is inadequate to be certain about this. On the Arabian coast the faults are east–west at 50° E but turn to WNW–ESE at 52° E where the structures form the high cliffs of Ras Fartak. No detailed information has been found about the possible continuity of these trends across the Horn of Africa. Similarly, the lack of data has not allowed the South Hadramaut arch to be traced across the same region.

The pre-Jurassic north–south fault at 45½° E on the Somalia coast should be detectable on the Arabian coast at 47¾° E. Although no known fault is mapped there, it coincides with the truncation of the mountains west of the funnel of dune sands extending 30 mi. inland from the coast.

Continuity of erosion features

A major erosional feature such as a river valley formed prior to drift should be able to be traced between the land masses. The Wadi Hadramaut is the dominating erosion feature of the Arabian coast, adjacent to the Gulf. It has been described in detail and its method of formation discussed by Wissman *et al.* (1942). It consists of a narrow and steep-sided canyon some 250 mi. long cut through the almost flat Tertiary and Mesozoic strata of the Hadramaut. Its western end widens into the desert sands of Ramlat as Sab'atayn and to the east it curls south to the Gulf at 51° E. Over half its length it follows more or less along the syncline between the North and South Hadramaut arches but at its eastern end it cuts across the South arch. Since the synclinal folding reached its maximum during the Upper Eocene (Beydoun 1960), the river cutting the canyon must have originated between the emergence of the Middle Eocene strata and the Upper Eocene folding. Wissman describes how the Wadi Hadramaut developed continuously during the recession of the Eocene Sea 'when part of the Yemen was rising up as the lip of an older Red Sea graben but when the Gulf of Aden had not yet made inroads as a graben' (p. 315).

We can therefore look for evidence of the continuity of this feature at about 49¼° E on the Somalia coast. Aerosurvey maps (War Office & Air Ministry 1960) show a large drainage system running south from 10° 50′ N, 49° 15′ E (south of Bender Cassim) and curving towards the east into the Wadi Giahel which reaches the coast at Ras Hafun (10° 30′ N, 51° 00′ E). There is a break in the coastal mountain range near its highest point through which a connexion might be made. An alternative course of the river might have been from Candala (11° 30′ N, 49° 50′ E), eastwards to 50° 20′ E and thence to the coast near 11° N, 51° E along Wadi Giael (not to be confused with Wadi Giahel). The north coast sections of possible old river courses will, of course, have been subsequently reversed and possibly obscured by the faults of the Gulf of Aden formation.

A second drainage system of S. Arabia, Wadi al Jiz, runs into Al Qamar Bay at 16¼° N, 52¼° E. Before the drift, this would have crossed the shelf between Socotra and the Horn of Africa and may be related to the 500 fm. deep channel now found separating the two.

The contours of the North Somali Basin suggest that a large part of the sediment filling it has come from the north. Seismic reflexion profiling has indicated large thicknesses of sediment; with the present topography of the Gulf of Aden it is difficult to see where such large quantities of sediment have originated, since the Socotran shelf and the Horn of Africa do not seem adequate. Sediment from farther north would be trapped by the Gulf of Aden.

However, in the suggested reconstruction, Wadi Hadramaut and Wadi al Jiz could have carried sediment from a large part of South Arabia and deposited it in the north Somali basin. If this is so, then Tertiary sediments in the basin ought to be quite near to the surface.

Development of the Gulf of Aden

If the reconstruction described above is a true one for pre-Tertiary times, then it should be possible to outline the stage by stage development of the Gulf of Aden on the basis of current ideas about continental margins, continental drift and mid-ocean ridges. The following account is highly speculative and only the initial stages have been geologically dated.

As the Eocene sea receded eastwards and the sediments emerged, synclinal folding started in the Hadramaut reaching its maximum during the Upper Eocene (Beydoun 1960). The uplift of the northern edge of the Somali Plateau was possibly part of this same folding, the whole system being part of the uplifted arch or dome which characterizes the junction between the African Rift Valley, the Red Sea and the Gulf of Aden (Cloos 1942). The Red Sea trend fault system in Somalia developed during this period. The uplift may be associated with the rising limb of mantle convection.

Associated with the arching, either simultaneously as in the case of the African Rift valley, or later (Miocene in Somalia), block faulting took place along the axis of the embryo Gulf, giving rise to the Gulf of Aden fault scarps of Somalia, and the east–west faults of Southern Arabia (figure 12). The graben so formed would then collect sediments from the mountains either side: the river systems would be truncated and trapped, and possibly flow eastwards along the graben towards the sea. This graben is now found as the coastal plains and continental shelves.

At the western end of the Gulf at the junction with the Red Sea, the faulting might have resulted in the extensive lava flows that now cover much of the Yemen and Ethiopia.

The sub-crustal movements also produced forces that both carried the Arabian block north-northeast and rotated it anticlockwise. The down-faulted block yielded along two sets of fracture lines, one set being east–west parallel to the faults on land, the other being northeast–southwest parallel to the continental margin. The line of parting between the two continental blocks ran along both sets of these fractures in an echelon pattern passing between Socotra and the Kuria Muria Islands.

The first phase of the drift of Arabia relative to Africa opened up the main trough of the Gulf of Aden, the movement being shown in figure 13. New crustal material was formed in the Gulf by stretching, fracturing and thinning of the continental crust and by massive intrusion of basaltic dykes, giving it the magnetic properties and structure discussed above. The Aden volcanic rocks may belong to this development. In the Afar triangle, continental fragments remained, surrounded by basaltic material. The movement of the Socotra shelf towards Africa may have taken place at this time.

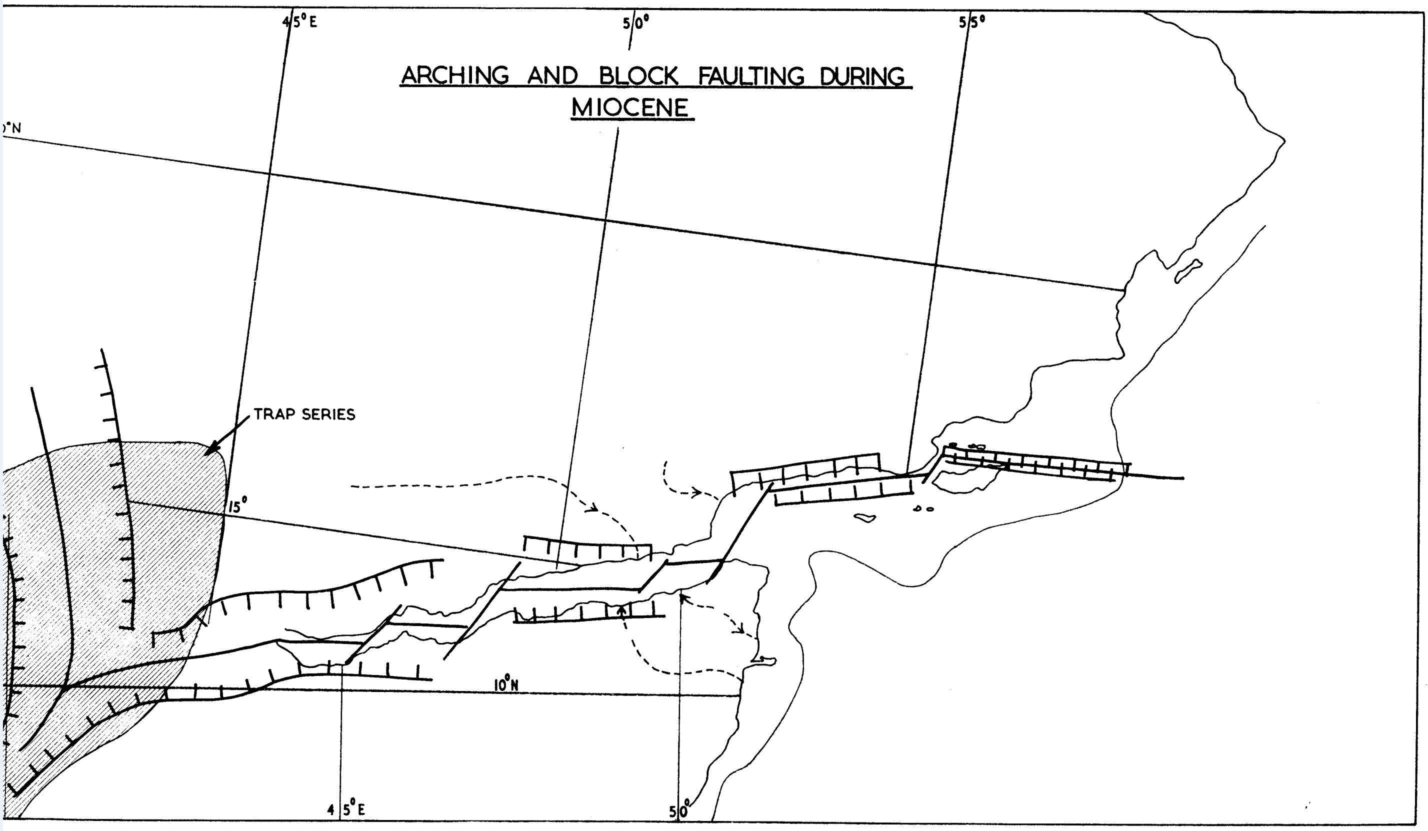

Figure 12. Arching and block faulting during Miocene.

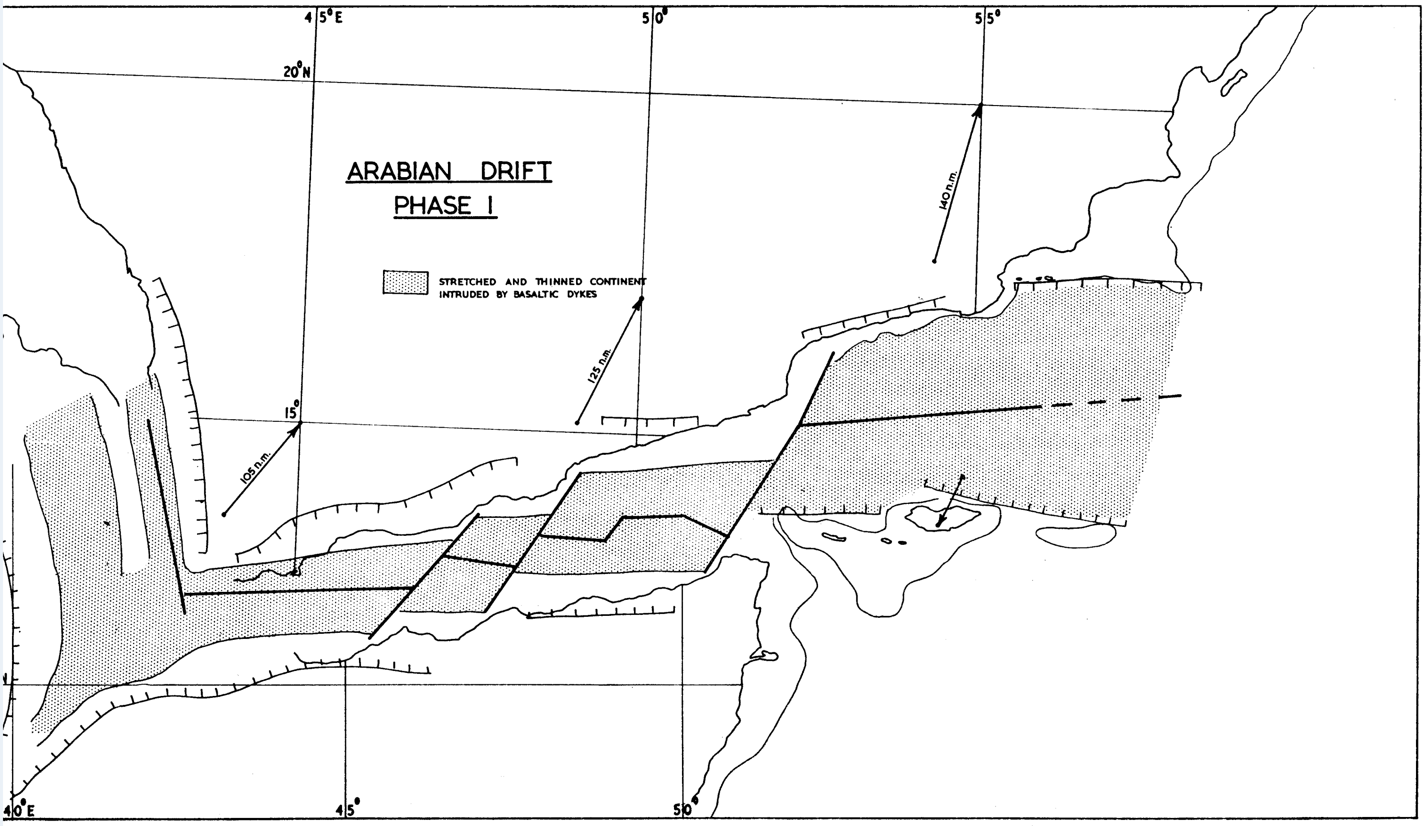

Figure 13. Arabian drift, phase 1.

After this first phase, there may have been a period of reduced movement during which the main trough accumulated the 0·5 to 1·5 km of sediment indicated by the seismic refraction data. This would obscure the rugged relief that one would expect from the formation of the new crust. It is unlikely that the sediment was deposited during the second active phase of drift since there are valleys in the central rough zone which have not been filled.

The second phase of the Arabian drift is shown in figure 14. A new line of parting follows the same two sets of preferred fracture lines running along the centre of the now inactive main trough. The movement is in the same direction as before and accompanied by rotation. The resulting new crustal material, perhaps consisting now of basic rocks alone without continental fragments, forms the central rough zone of the Gulf. The northeast–southwest linear features in the zone may be volcanic fissures along lines dictated by the fracture pattern combined with horst and graben structures. This zone extending out into the Arabian Sea develops into the Carlsberg ridge.

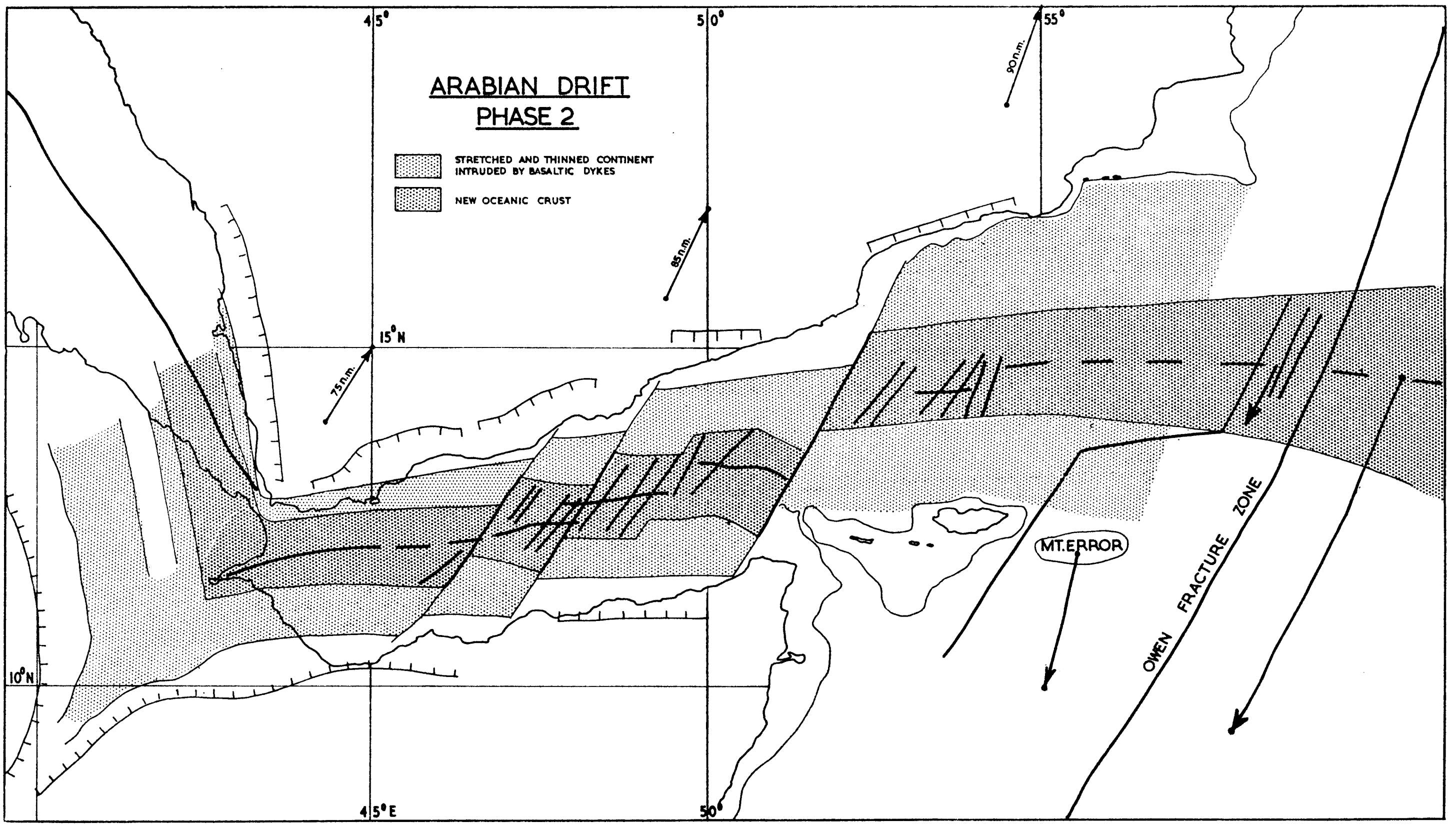

Figure 14. Arabian drift, phase 2.

The offsets of the blocks forming the central rough zone therefore represent the boundaries of the new crust resulting from the original stepped fracture line, in just the same way as the edges of the continental shelves are offset. The northeast–southwest lines joining these offsets, the biggest being the Alula–Fartak trench, are therefore not tear faults in the usual sense of the word since the surface area on either side is not conserved, although along parts of the line shearing has taken place. This accounts for the fact that no trace of these major lineations can be found on the adjacent continental blocks.

In the final phase, massive crustal movement has displaced the Arabian Sea end of the Carlsberg Ridge south-westwards resulting in the Owen fracture zone (Matthews 1963, 1966) and in the displacement of Mount Error.

Recent activity, indicated by high heat flow and earthquakes, is responsible for the formation of yet another fracture line running down the centre of the rough zone giving rise to the well developed Tadjura rift valley and the embryo median valley farther east. The central rift valley of the southern end of the Red Sea may also belong to this era.

Discussion

The formation of the Gulf of Aden by continental drift of Arabia away from Africa has been long postulated by Wegener (1929) and others in the general break up of Gondwanaland. Wiseman & Sewell (1937) associated the Carlsberg Ridge with the rift structures of Africa and the Red Sea. However, in the extensive German studies of the area, Wissman *et al.* (1942) and more strongly Cloos (1942) consider the drift theory and reject it in favour of a continental horst and graben development arising from extension in a NNW–SSE direction and compression in a NNE–SSW direction. 'The breaking-up of the floor of the Gulf is partly due, then, to the arched extension of the Nubian–Arabian Shield. The general pattern was dictated by the environment of the graben emerging from great depths, but the particular directions of fractures were a consequence of older environmental factors and more recent forces acting in the upper crust at this time' (p. 361). His objections to drift lay in the proximity of Arabia and Africa at the south end of the Red Sea and the continental character of the Danakil Alps. These objections are discussed above. The available geophysical data on the Gulf oppose the view of a continental crust.

The recent swing of opinion in favour of continental drift has revived interest in the relationship of Arabia to Africa. Swartz & Arden (1960) discuss the geological history of the Red Sea in terms of the continental geology of Arabia and Africa and favour a theory in which the Red Sea has been formed by the separation of the two crustal blocks starting in the Lower Eocene at the northern end and continuing through the Middle Eocene and Oligocene. In the Lower Miocene they suggest the breaking away of the Horn of Africa and the formation of the Gulf of Aden. Their reconstruction of the Arabian–African continental block requires the fitting together of the shelves of the two continents and the overlapping of the Yemen on Ethiopia. However, Drake & Girdler (1964) and Girdler (1964) consider geophysical data (seismic, magnetic and gravity) from the Red Sea and conclude that only the 60 km wide central rift valley is new oceanic crust and that the main trough is a down-faulted continental block. This cannot be easily reconciled with the development of the Gulf of Aden outlined above. The key to the problem lies in more detailed information about the crustal structure in the Afar triangle. Drake & Girdler present evidence, from the distribution of magnetic anomalies and of topographic features in the Red Sea and the Gulf of Aden, for the rotation of Arabia relative to Africa of 6 to 9° anticlockwise. Palaeomagnetic data from Aden volcanics (Irving & Tarling 1961) support this view. This is consistent with the rotation required for the theory presented above (8°). However, the two theories differ in the distance of movement of Arabia, i.e. in the choice of a fulcrum about which rotation has taken place. In such discussions, it is assumed that the continental blocks have moved bodily without change of shape, whereas such distortions are probable in the light of work on continental tectonics.

In east Arabia, the mountain ranges of the Oman have been folded and overthrust during the Miocene-Pliocene (Morton 1959). In the Zagros mountains of Iran, the geological picture is one of thrust from the southwest. These compression features bordering the Persian Gulf are consistent with a northeast movement of Arabia during the late Tertiary.

If it is assumed that the Arabian drift occurred at a uniform rate since the early Miocene, say 20 My ago, and that the mean displacement of the Hadramaut relative to Africa is 210 n.mi. (400 km), then the drift is 2 cm/y. However, if the movement was spasmodic, as has been suggested, higher drift speeds may have occurred for shorter periods.

The ideas outlined in this paper are based on the published data of the land geological history and on the recent geophysical work at sea, much of which has arisen from the International Indian Ocean Expedition. However, a great deal more detailed information on the land geology, in particular the deeper structure revealed by geophysical techniques, lies in the hands of the oil exploration companies. Data from the International Indian Ocean Expedition is still being collected and many critical regions might be examined in the light of the above ideas. Very little is known of the actual rocks of the central rough zone of the Gulf of Aden or of the Owen fracture zone and it is hoped that this paper will stimulate a greater collection of data.

Thanks are due to those laboratories which have allowed me to incorporate unpublished data in this paper. Much of the magnetic data has been obtained and assembled by the Department of Geodesy and Geophysics, Cambridge, from cruises of H.M.S. *Owen*, H.M.S. *Dalrymple* and R.R.S. *Discovery*. This department has also supplied new heat-flow data in the Gulf. Topography and magnetic data have been supplied by Imperial College, London, from H.M.S. *Dalrymple*, by Lamont Geological Observatory, New York, from R.V. *Vema* and Woods Hole Oceanographic Institution, Massachusetts, from R.V. *Chain*. Lamont have kindly supplied further details of seismic refraction stations. Soundings from many other ships have been made available on the collected sounding sheets of the Hydrographer of the Navy, Great Britain.

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