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The Deep Structure of the Red Sea

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The deep structure of the Red Sea

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The results of an intensive seismic survey in the Red Sea are presented. Analysis of twenty seismic refraction lines leaves no doubt that much more than just the central trough of the Red Sea is underlain by material with a seismic velocity which is characteristic of oceans. In addition, up to 5 km of what we interpret as evaporites were regularly found. The suggestion that the Red Sea crust could be oceanic in character over the major part of its width is examined in conjunction with magnetic and gravity data. We conclude that there is no evidence against sea floor spreading on a substantial scale in the Miocene. The implications of this in terms of neighbouring features is briefly discussed.

1. Introduction

The purpose of this paper is to outline the results, conclusions and conjectures that arise from a recent seismic survey conducted in the Red Sea. A full discussion of the work has already been published (Tramontini & Davies 1969) and we do not propose to repeat any of the detail. However, some of the more important information from that paper bears repetition and brief discussion in the light of its relevance to questions of evolution of the Red Sea, relationships with adjacent features and plate tectonics. These questions have become crucial in the problem of placing the Red Sea in its correct global perspective in relation to the ocean ridge system and its role in continental drift.

It has been customary to represent the ocean ridge system as continuous from the Carlsberg Ridge in the Indian Ocean into the Red Sea via the Gulf of Aden. A major transform fault, the Owen Fracture Zone (Matthews 1963), displaces the Ridge off the Gulf of Aden and several well-mapped transform faults in the Gulf itself (Laughton 1966) displace the ridge to a lesser degree. The seafloor spreading evidence in favour of the Gulf of Aden being a junior ocean is compelling. The major problem remaining in this picture was the respective positions of the East African rift system and the Red Sea in the scheme of things. The ground rules of plate tectonics (McKenzie & Parker 1967; Morgan 1968) formalized the intuitive idea that the Gulf of Aden spreading had to be intimately associated with Red Sea spreading or with some combination of movements in the Red Sea and the East African rift system. McKenzie, Molnar & Davies (in press) explain in detail the consequences of preserving the structural integrity of large blocks, in particular Saudi Arabia and the African blocks. Since the Gulf of Aden evidence is not only convincing for present-day spreading but also strongly suggests that spreading was initiated in the Miocene, it is of added importance to attempt to reconstruct the Red Sea during Miocene times.

2. The seismic survey

Previous seismic refraction work in the Red Sea was limited to a survey conducted in 1958 by RV. *Vema* and RV. *Atlantis*. The results were reported by Drake & Girdler (1964). We shall consider their results north of 18° N only, because those south of this latitude may be associated with the complex structure in the Afar region and its seaward continuation. Drake & Girdler

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found evidence for intrusive basaltic rocks down the central valley of the Red Sea on the basis of high seismic velocities for the bottom layer of the crust, but on the flanks where the water depth, in coral free regions, is in the 500 to 1000 m range, the results were not unequivocally in favour of either a continental or an oceanic crust. This seismic work had been aimed at a broad coverage of the area; we decided in view of the clear unity of the Red Sea that concentration on a small area of the Red Sea was the next logical step as all the indications from magnetic and bathymetric data were that the Red Sea was basically a two-dimensional feature and could be sampled anywhere along its length. True, the magnetic anomaly and central valley become vestigial at the north end and practically no seismicity is reported (Sykes & Landisman 1964) but seafloor spreading rates could be so small that well developed features would not be expected. Left lateral movement along the Dead Sea rift (Freund, this volume, p. 107) and the recent occurrence of a sequence of earthquakes at the centre of the north end of the Red Sea (U.S.C.G.S. 1969) reinforce our confidence that the Red Sea is structurally two-dimensional.

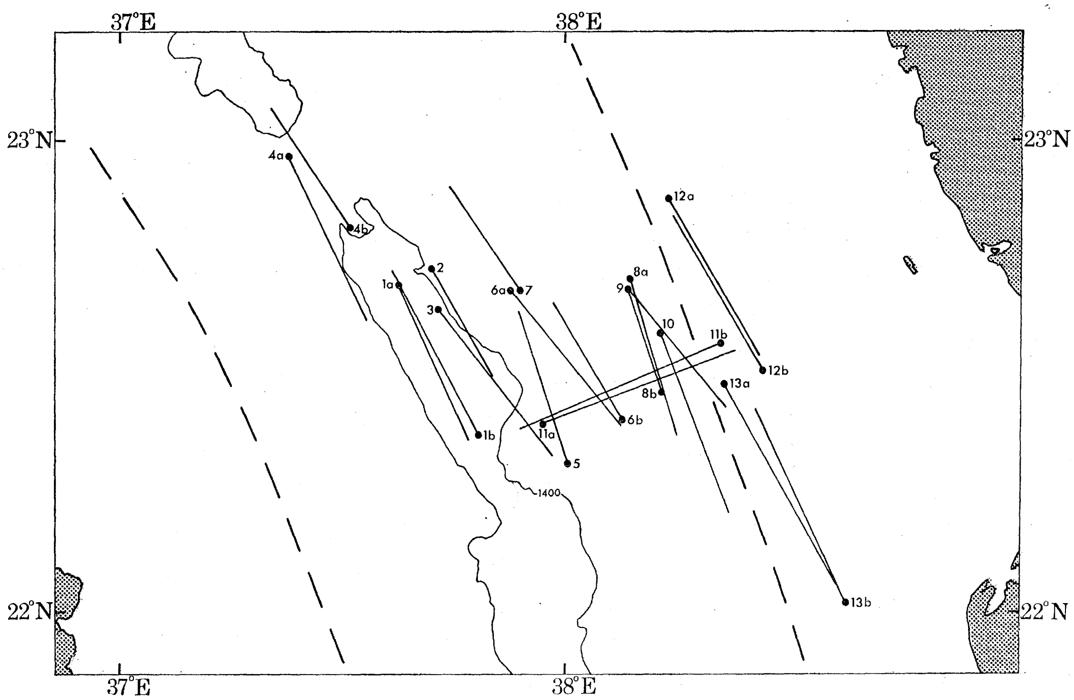

FIGURE 1. The area of the seismic survey. The 1400 m contour is shown, as is the boundary between the marginal and axial zones of the main trough (dashed line). The location and number of each seismic refraction station is given, and the large black dots indicate the positions at which the first sonobuoys were laid for each line.

The area shown in figure 1 which we chose for the survey is a one degree square centred on 22° 30′ N, 38° 00′ E. It includes a portion of the central trough and a large proportion of the so-called main trough flanking the central trough. Further work would have been attempted nearer the shoreline were it not for strong currents (0.5 to 1.0 m s^{-1}) and the consequent difficulties in navigation in a poorly charted region.

An Ethiopian cargo vessel, M.V. *Assab* (gross tonnage 97) was chartered for the purpose of the work and 13 Mg of explosive were used in the firing of 20 refraction lines. The Hill (1963) sonobuoy technique was used, and as far as possible we attempted to fire the lines as reversed pairs. A slow ship (2.8 m s^{-1}) and the unpredictable currents often prevented the reversal from being satisfactory but the treatment of the data, described below, avoided the need for thinking entirely in terms of reversed pairs.

Table 1 shows in summary our results. It is compacted from table 1 of Tramontini & Davies (1969). At this stage we have retained where possible the concept of reversed pairs and interpreted the data accordingly. We have also divided the region into four—the central trough, an inter-trough zone, 'axial zone' of the main trough and 'marginal zone' of the main trough. The distinction between axial and marginal zones (each occupying about half the area of the main trough) is that given by Knott, Bunce & Chase (1966). They distinguish this on the basis

Table 1

	station	mean water depth km	thickness of unconsolidated sediment (assumed velocity 2.0 km s⁻¹) km	upper layer velocity km s⁻¹	apparent lower layer velocity km s⁻¹	'dipping plane' velocity for lower layer km s⁻¹
axial trough	1*a*	2.08	0.29 (?)	4.48 (?)	6.20	6.38
	1*b*	2.26	0.10 (?)	4.52 (?)	6.57	
	2	1.95	—	—	6.57	—
	3	2.06	—	—	5.72	—
inter-trough zone	4*a*	1.67	0.39	4.25	7.33	6.86
	4*b*	1.82	0.06	4.01	6.45	
axial zone of main trough	5	1.37	—	—	7.13	—
	6*a*	1.21	0.20	4.23	6.07	6.78
	6*b*	1.12	0.12	4.09	7.65	
	7	1.19	0.16	4.12	7.51	—
	8*a*	1.06	0.21	4.55	8.64	6.92
	8*b*	1.00	0.23	4.40	5.77	
	9	0.97	0.22	4.27	—	—
	10	0.88	0.28	4.31	5.96	—
	11*a*	1.25	0.31	4.51	7.18	6.62
	11*b*	0.97	0.19	4.41	6.14	
marginal zone of main trough	12*a*	0.72	0.25	4.31	5.94	6.11
	12*b*	0.75	0.27	4.22	6.30	
	13*a*	0.80	0.13	4.20	6.47	6.83
	13*b*	0.84	0.33	3.99	7.22	

of the bottom topography and the topography of the seismic reflexion found at a depth of about 500 m. In both cases, there is a marked transition as the coast is approached from the central trough. In the axial zone of the main trough the topography is more rugged than in the marginal zone. Whether this distinction is based on the superficial layers is a manifestation of any deeper boundaries is open to question. The categories are convenient for our purpose as it turns out that the axial zone results are a fairly homogeneous set, whereas what work was done in the marginal zone did not reveal the same homogeneity.

In no case did we obtain any first refracted arrivals from unconsolidated sediments presumed to lie immediately below the ocean bottom and to have a seismic velocity of about 2.0 km s^{-1}. Accordingly, we have calculated the maximum thickness which such sediments could have and still be undetected by our observations. The table shows that about 200 m of such material could exist over most of the region studied and this figure may be compared with the values of up to 500 m of Knott *et al.* (1966) and Phillips & Ross (this volume, p. 143) for depths to a strong reflector.

Except in the central trough where the indications are poor, the next deeper layer has a seismic velocity close to 4.3 km s^{-1}. This is in good agreement with Drake & Girdler's (1964) findings and the velocity is close to that associated with evaporites. It is more than a standard deviation lower than the characteristic oceanic 'layer 2' velocity of 5.07 ± 0.63 km s^{-1} (Phillips 1967) widely believed to be associated with lava flows. The presence of extensive Miocene evaporite sequences in many wells on the margins of the Red Sea increases our confidence that evaporites have been deposited right out from the shore to the flanks of the central trough.

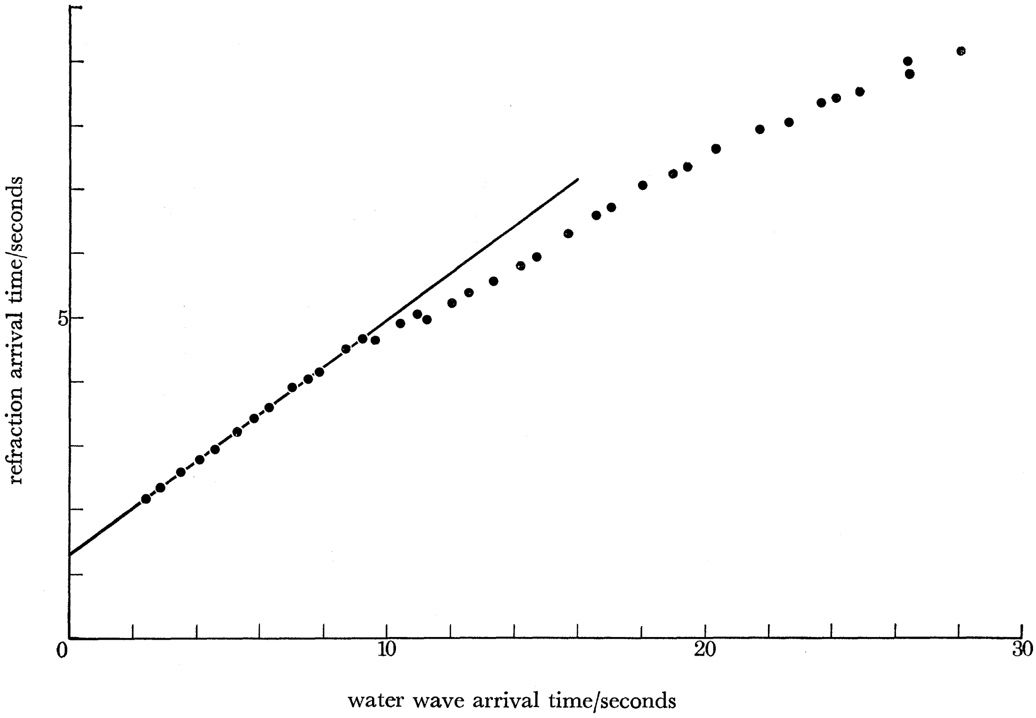

FIGURE 2. A typical travel-time plot (line 6*a*). The upper layer is well defined, with a seismic velocity of 4.23 km s^{-1}.

TABLE 2

no. of points included	6	8	10	12	14	16	18	20	22	24
apparent velocity / km s^{-1}	6.84	6.30	5.63	5.36	5.37	5.45	5.65	5.80	5.94	6.07

The next seismic discontinuity encountered (and the final one, since isostatic considerations place the Mohorovičić discontinuity at too great a depth to be observed by seismic lines at most 45 km long) is much less well defined on a first analysis. Although the lines in the travel-time plots have on average 15 points on them the velocities in two reversed directions do not match well at all as may be seen in table 1. A simple dipping layer analysis assuming plane boundaries yields in all instances seismologically reasonable velocities but it is clear from the travel-time plots themselves that a plane layer assumption is quite unreasonable. Figure 2 shows such a plot and the large-scale structure in the refracting layer is obvious. The major problem that such structure poses is when to finish firing. The apparent velocity represented by a least squares fit can fluctuate greatly as each successive shot is fired. Table 2 shows the variations in apparent velocity as more points are included from figure 2.

Under these circumstances we abandoned the plane layer approach and took a set of data which appeared homogeneous. The refraction lines fired in the axial zone of the main trough were taken *en bloc*. There was good evidence (which is discussed in Tramontini & Davies 1969) that this could be justified purely on seismic travel-time information. After appropriate corrections to allow for the varying depth of water, all first-arrival data points which had been assigned to the deepest refractor in the plane layer analysis were merged in one travel-time plot (figure 3). There is nothing in this figure to indicate other than that a layer of constant velocity over the area in question is contributing all the first arrivals and that such scatter as there is about a least squares fit is caused by topographic variations at the top of this layer. We thus conclude with confidence that the axial zone of the main trough is underlain by a material with seismic velocity 6.63 ± 0.16 km s^{-1}. We can also from this line obtain a mean depth to this layer of 4.6 km. This implies a mean thickness of the postulated evaporite layer of about 3.6 km, but the scatter of individual points in figure 3 indicates that locally the layer is from 2 to 5 km thick.

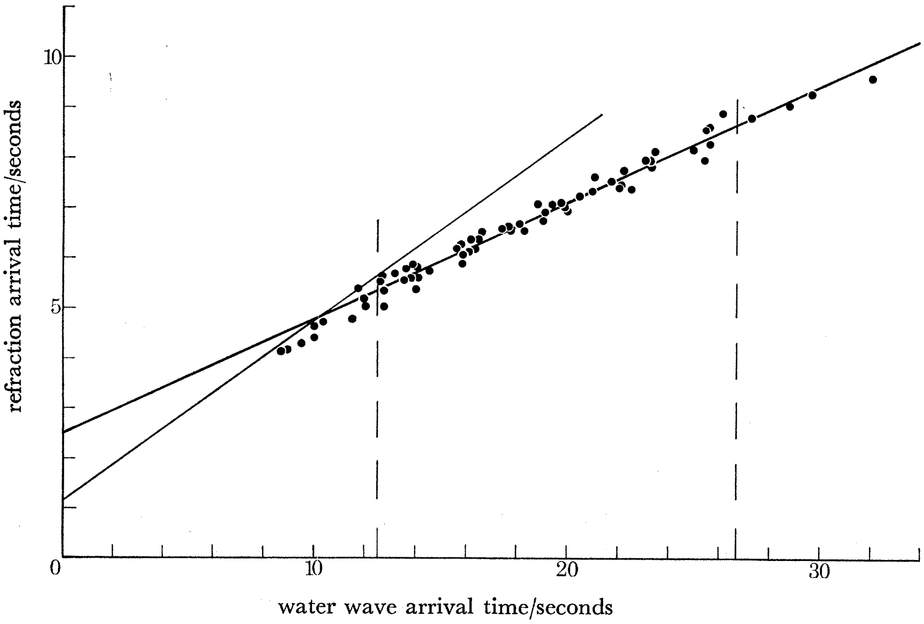

FIGURE 3. A composite travel-time plot for the axial zone of the main trough. A typical 'upper' layer line is drawn, and a least squares line has been fitted to all the points between the two vertical broken lines.

It is important to appreciate that a layer with velocity intermediate between 4.3 km s^{-1} and 6.6 km s^{-1} could certainly exist between the two layers and not be detected by seismic refraction techniques. A reduced thickness of evaporite and up to a kilometre of material with a seismic velocity of 5.0 km s^{-1} (a typical 'layer 2' velocity) would be an equally valid solution to the data. If the velocity of a 'hidden layer' were as low as 4.6 km s^{-1}, rather more than 2 km of such a layer could exist, but under these circumstances we would expect the layer to manifest itself through first arrivals on at least one line.

Having placed strictures on the interpretation of the lowest layer by dipping plane techniques we are unwilling to read too much into our data from the other regions which is not extensive enough to allow such comprehensive treatment. However, the refraction lines fired in the central trough do show distinctly different features. The layer with seismic velocity 4.3 km s^{-1} is difficult to identify as the underlying layer is shallower and the water depth greater. A similar analysis to that described above for the velocity of the lower layer (figure 4) yielded a value of 6.31 ± 0.10 km s^{-1}. Again we note that a substantial thickness of 5.0 km s^{-1} material could pass unnoticed.

One reversed line was fired along the axis of the central trough but in a region where bathymetric and magnetic data indicated that the trough was poorly defined or absent (the 'inter-trough zone'). Similarity with the axial zone of the main trough rather than the central trough itself was noted.

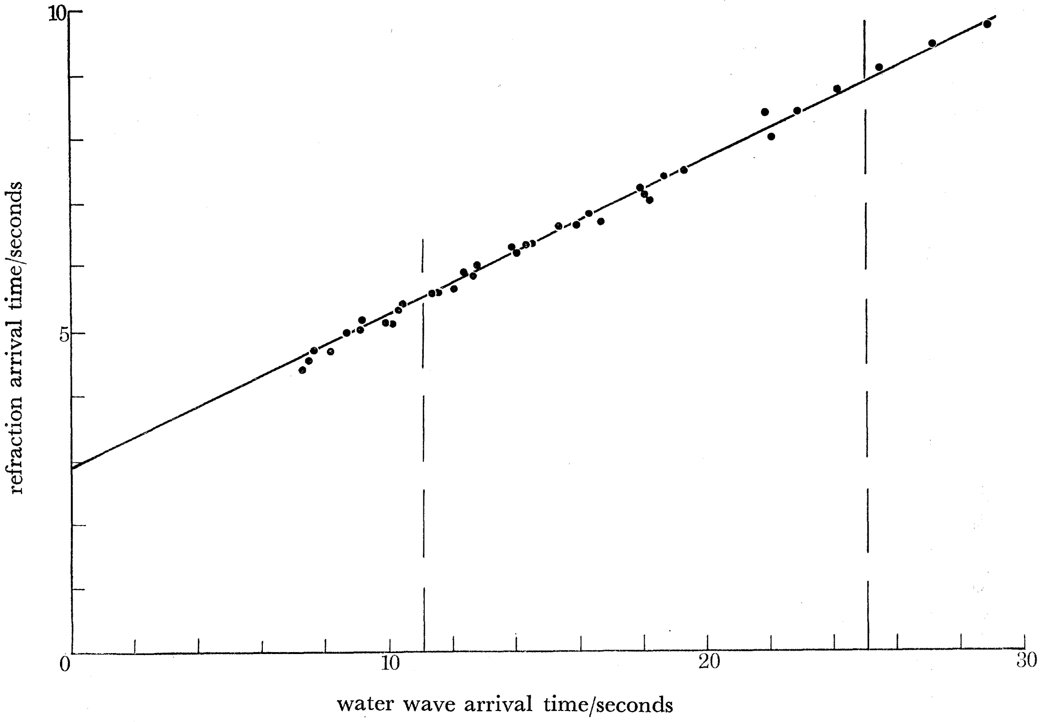

Figure 4. A composite travel-time plot for the central trough; again only points within the vertical broken lines are used to produce a least squares line.

The results from the two reversed lines in the marginal zone are not conclusive and allow of more than one interpretation. In neither case could the quality of the data nor the adequacy of the coverage be questioned, yet it is seen from table 1 that 'dipping plane layer velocities' do not lead to any obvious pairing of the lines together. Lines 13*a* and *b* could belong to the axial zone set but with an increase in thickness of the overlying layer by about 2 km. Lines 12*a* and *b* would be difficult to fit into this context and for this reason we are loath to do more than report the results.

3. Geophysical interpretation

By far the most important result to emerge from this work is the clear indication that much of the main trough of the Red Sea is underlain by rocks whose seismic velocity is higher than the vast majority of velocities reported from continents. The velocity is in good agreement however with the oceanic average of 6.69 km s^{-1} (Phillips 1967) and we believe there is little doubt that the eastern side of the Red Sea for a distance of about 60 km from its axis has an

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oceanic crust. We see no reason to believe that a similar structure does not exist on the western side. From there to the shoreline we are not prepared to generalize except to note that there is, apart from a superficial change in sediment reflexion characteristics, no reason to suppose that the structure changes. Certainly other geophysical evidence would not support the idea of a boundary.

We must, however, consider the implications of our assertion in the light of other geophysical evidence—magnetic and gravitational. The comprehensive survey by Allan (this volume, p. 153) acts as a basis for discussion. Allan found a large central magnetic anomaly down much of the Red Sea and interpreted this in terms of Plio-Pleistocene spreading of the seafloor. Away from the centre the amplitude of the anomalies is substantially smaller but not negligible. Kabbani (this volume, p. 89) has presented a detailed survey of the magnetic field in the main trough close to the region of our study, and this too shows smaller flanking anomalies. We are probably dealing in the main trough with anomalies whose amplitudes do not exceed ± 50 nT (gammas) and this is worth considering in the light of our assertions of oceanic crust underlying much of the region. Laughton *et al.* (this volume, p. 227) reports anomalies of ± 100 nT in the Gulf of Aden. Although anomalies are small compared with most oceanic magnetic anomalies two factors have to be taken into consideration.

First, we have no notion of the actual spreading rate when the Red Sea main trough was being formed. Results from the northwest Indian Ocean may be irrelevant as there is good evidence that the Carlsberg Ridge is not (at least at present) entirely 'coupled' to the Gulf of Aden and Red Sea. Earthquakes along the extension of the Owen Fracture Zone north-eastwards towards India imply that the Carlsberg Ridge and Gulf of Aden spreading are not proceeding at the same rate. Banghar & Sykes (1969) are cautious about the nature of the relative movements as they have only one fault plane solution for such an earthquake. Accordingly it is not possible to assign rates to spreading in earlier times with much confidence. If the seafloor creation were rapid there need only be one or two recognizable magnetic features—if it were slow (say less than $\frac{1}{2}$ cm per flank per year) the 'wavelength' of the magnetized bodies would be such that the anomaly, upward continued to the sea surface would be at most ± 50 nT.

Secondly, we believe that layer 2, if it exists beneath the evaporite, is probably less than 1 km in thickness. This leads to a corresponding diminution in the surface magnetic anomaly, which is further reduced if the magnetized bodies lie approximately north–south. Figure 5 shows an example computed by Tramontini (1969) under the assumptions of slow spreading.

We are thus convinced that magnetic data in no way runs counter to our seismic conclusions.

In considering the gravity data we note that a Bouguer anomaly profile can only reasonably be obtained if we take note of the low density evaporites. It is necessary to remove them before filling up the Red Sea with granite, and this explains why many Bouguer profiles of the Red Sea have shown a peak over the central trough, which disappears on taking account of the evaporite. We have computed a specimen profile (Tramontini & Davies 1969) which is consistent with the gravity and is based on the seismic evidence. Although it is not a unique solution it does indicate that the great thickness of evaporites must be underlain by a compensating body (i.e. layer 3) of width at least 100 km. In fact boreholes very near the shores have revealed evaporite columns thick enough to make it likely that layer 3 extends even further towards the shore.

On the basis of this discussion we propose that the geophysical evidence for a large part of the Red Sea being oceanic in character is substantial. How the Red Sea evolved is not a subject we wish to speculate on more than just to raise some points which appear important.

The case for an early Miocene episode is strong, based on Laughton's work in the Gulf of Aden and Freund's Dead Sea rift work, with the proviso that Freund is not able to time the left lateral shear (which is the correct sense) of 60 km better than between Cretaceous and Miocene. The extensive occurrence of Oligocene–Miocene igneous rocks in the region, including hypabyssal intrusions on the margins itself dated at 21 Ma, and basalt dated from 32 to 25 Ma (Brown, this volume, p. 75) in flows such as one might expect from igneous extrusions uninhibited by overlying sea water all point to a large-scale igneous event in early Miocene.

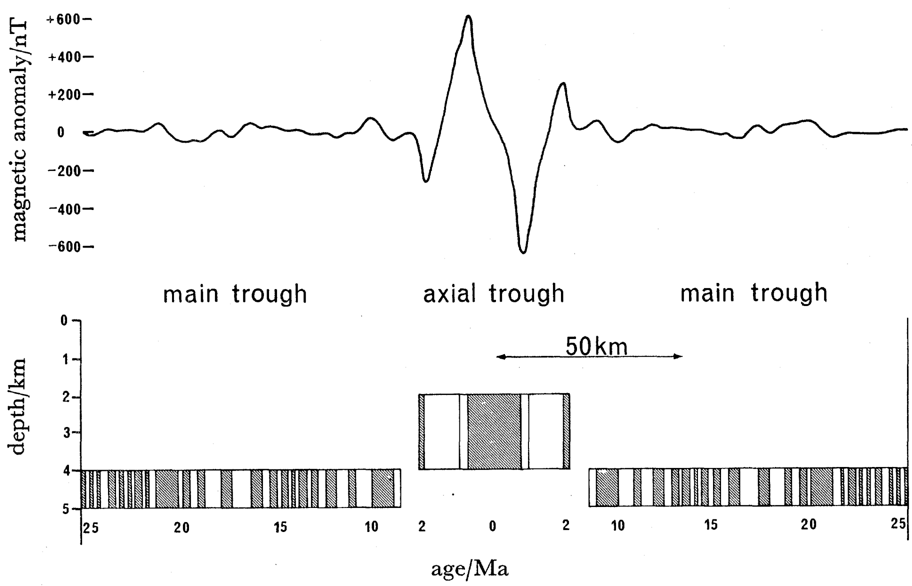

FIGURE 5. The synthetic magnetic anomaly from a *possible* structure beneath the Red Sea (1 nT = 1 gamma). Slow spreading (0.5 cm a^{-1} per flank) is assumed for the main trough and the model shows the reversal pattern. Susceptibilities of 0.01 e.m.u. are assumed.

If this is correct, and we accept that the activity terminated later in the Miocene only to be revived perhaps 2 to 3 Ma ago, the evaporite column must have been generated in the space of 10 to 15 Ma. It is believed that the Red Sea was cut off from the Indian Ocean during this time but open to the Mediterranean via the Suez Isthmus (Heybroek 1965). The formation of 4 km of evaporites must have proceeded during this time when the Red Sea was an inland sea. The numerous reports of hot salty holes in the central trough may indicate that present-day vulcanism is dissolving this evaporite—this mechanism would certainly account for the unusual bathymetric profile of the Red Sea which has no parallels elsewhere.

We thank the crew of M.V. *Assab* for their cheerful assistance at all hours. We are particularly grateful to M. E. Tramontini who took effective command of the ship and saved us from many catastrophes. M. Mason and T. Vertue helped us greatly by their efficiency in keeping the equipment in good order under extremely unpleasant conditions. Sir Edward Bullard, S. B. Frazier (Gulf Oil Co. of Ethiopia) and Dr R. W. Girdler all supported our work actively. It was financed by a grant from the Natural Environment Research Council.

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