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The Seismicity of the Red Sea, Gulf of Aden and Afar Triangle

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The seismicity of the Red Sea, Gulf of Aden and Afar triangle

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The seismicity of the Red Sea, Gulf of Aden and Afar triangle has been studied for the period January 1953 through December 1968. Epicentres have been relocated using the method of Joint Epicentral Determination (Douglas 1967) and some fault plane solutions have been attempted. Magnitude–frequency studies indicate that with the present distribution of teleseismic stations, earthquakes with body wave magnitude $m_b \geqslant 4.8$ are well determined in this region.

The study confirms that there is surprisingly little major earthquake activity in the northern part of the Red Sea. Between 19.5 and 21.0° N, there is a concentration of epicentres and some of these might be associated with an active NNE transform fault. In the southern part of the Red Sea, most of the epicentres are associated with the deep, axial trough, although some are associated with the western margin, especially in the neighbourhood of the Gulf of Zula (15° N).

Earthquake activity is confined to the centre of the Gulf of Aden with concentrations of epicentres occurring on or near to NNE transform faults. The seismically active zone continues westwards through the Gulf of Tadjoura and across the Afar depression to the western boundary scarp. There are no teleseismically recorded epicentres between latitudes 12.2 and 14.2° N.

In general, most of the seismic activity occurs along the centres of the Red Sea and Gulf of Aden and this supports a sea-floor spreading mechanism for their origin. The number of plates involved is discussed.

1. Introduction

Since the pioneering work of Gutenberg & Richter (1949, 1954), the seismicity of the Red Sea area has been studied by Rothé (1954), Girdler (1964*a*), Drake & Girdler (1964) and Sykes & Landisman (1964).

In a remarkable paper, Rothé reported that the zone of shallow seismicity associated with the East African rift system continues through the floor of the Indian Ocean around southern Africa and joins with the mid-Atlantic rift. This paved the way to the recognition of the Red Sea and Gulf of Aden as part of the world rift system. Rothé's map was updated by Girdler (1964*a*) using I.S.S., U.S.C.G.S. and B.C.I.S. data while the more detailed seismicity and structure of the Red Sea were discussed by Drake & Girdler (1964).

Sykes & Landisman (1964) recomputed the epicentres for the Red Sea area for the period January 1955 through March 1964 using the high-speed computer technique of Bolt (1960) which minimizes the residuals of the P and PKP times. This improves the epicentral location by up to a factor of ten and enables correlations to be made of epicentres with major tectonic features.

A further improvement in the determination of epicentres is due to the increased number of seismic recording stations, especially the introduction of the Worldwide Standard Seismograph Net (W.W.S.S.N.) in 1963. Figure 1 shows the distribution of these high-quality W.W.S.S.N. stations on a projection centred on Africa at 5° N, 20° E, and figure 2 shows the distribution of all seismic stations regularly reporting to the seismological centres.

Since 1961 the U.S.C.G.S. have been using computer techniques giving their preliminary determination of epicentres an accuracy of about 10 km. For the hemisphere centred on Africa, epicentres for the period January 1963 through December 1968 are shown in figure 3. Girdler

(1964*b*, 1965) emphasized the value of plotting deep focus earthquakes separately from shallow focus earthquakes. The deep focus earthquakes are associated with island arcs, deep sea trenches, fold mountains and thrusts while the regions where *only* shallow earthquakes occur are regions of rifting and translational movement. Figure 4 shows the distribution of deep focus earthquakes (depth $h \geqslant 100$ km) for the hemisphere centred on Africa. Figure 3 shows very clearly how the Red Sea and Gulf of Aden are related to the Indian Ocean and mid-Atlantic rifts while figure 4 shows there are no deep focus earthquakes in Africa, the nearest being in the Mediterranean and Himalayan regions.

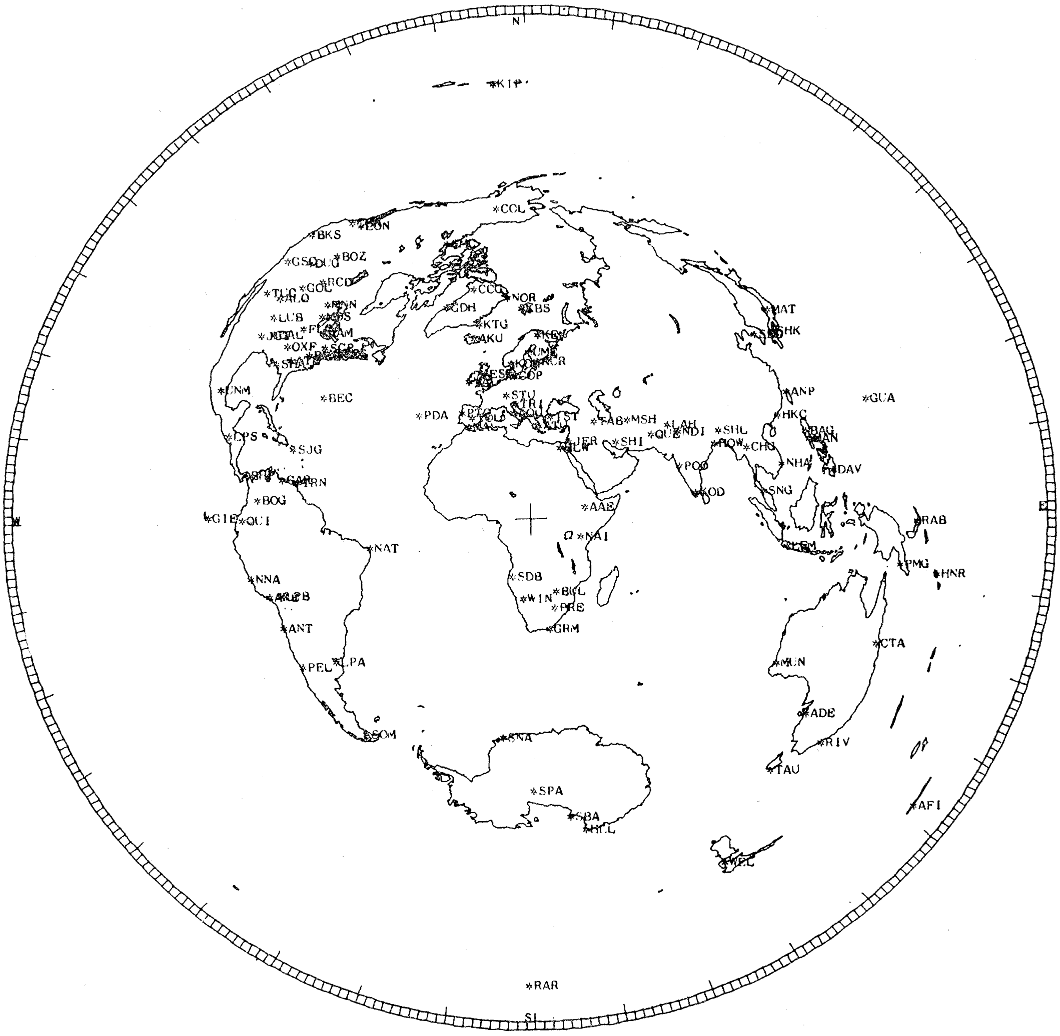

FIGURE 1. The distribution of W.W.S.S.N. stations. Azimuthal great circle projection centred on Africa at 5° N, 20° E (distances and angles are correct from centre).

Following McKenzie & Parker (1967), Morgan (1968) and Le Pichon (1968), figures 3 and 4 are now interpreted in terms of plate tectonics. The epicentres demarcate the boundaries of rigid plates. The shallow focus earthquakes occur where the plate boundaries are opening or where there is shear between plates. The deep focus earthquakes occur where the plates are bending down (Oliver & Isacks 1967) and being devoured by the mantle. The plate boundaries for Africa are seen in figure 3, the Red Sea and Gulf of Aden being regions of plate separation.

The scatter of epicentres in East Africa is due to the complexity of the rift faulting through the continental crust. The absence of deep focus earthquakes throughout Africa and south of Africa and their presence through the Mediterranean, Turkey and Iran suggest that the Afro-Arabian plate is moving north and being bent down beneath these regions. The northward movement has also been inferred from the palaeomagnetic data (Girdler 1968).

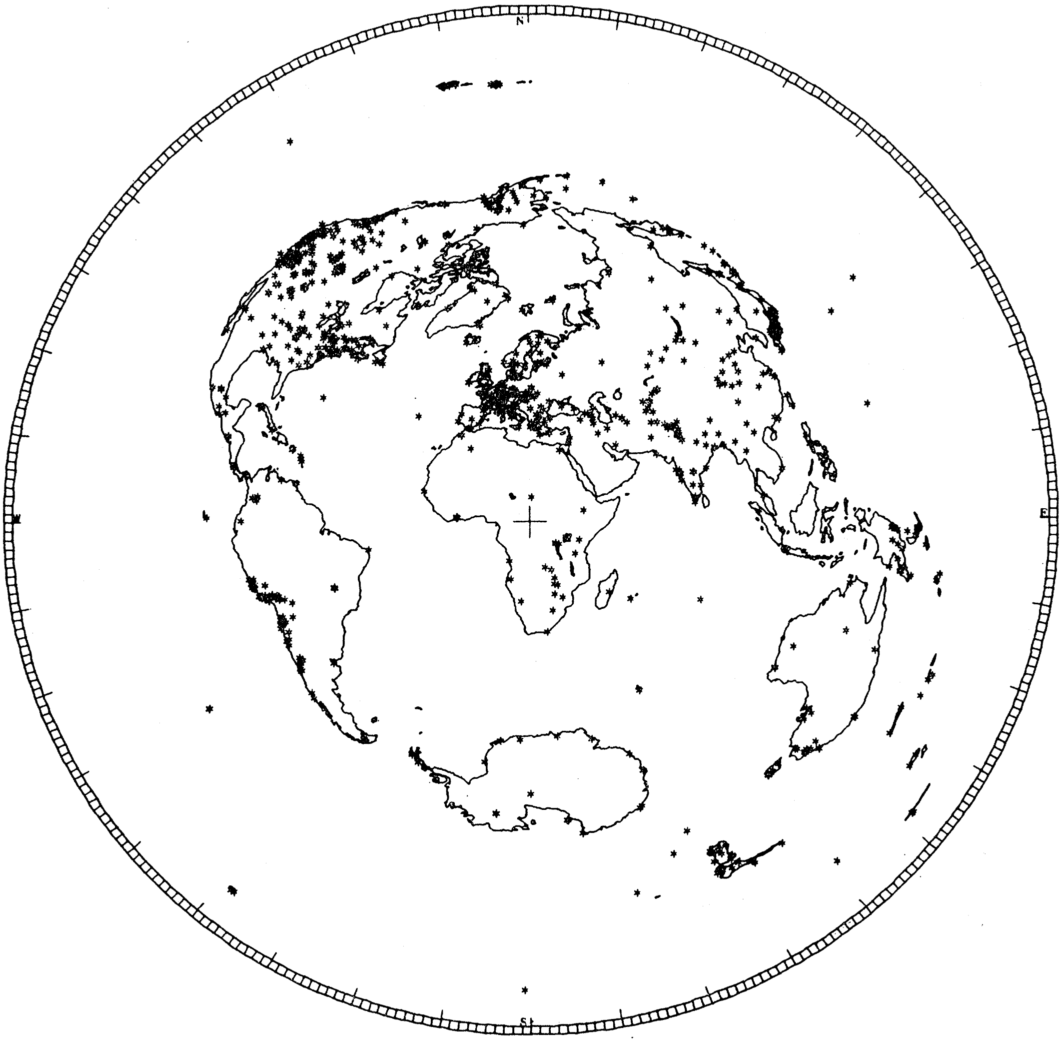

FIGURE 2. The distribution of all seismic recording stations (829). Azimuthal great circle projection centred on Africa at 5° N, 20° E (distances and angles correct from centre).

The main object of this paper is to study in more detail the break up of the Afro-Arabian plate along the Red Sea and Gulf of Aden. Five years have now passed since the introduction of W.W.S.S.N. and the publication of the last papers on the seismicity of this region. It was therefore decided to extend the seismicity study through to 1968 (Fairhead 1968) and to use the further refinement in the computation and location of epicentres due to Douglas (1967). For completeness, the epicentres (Gutenberg & Richter 1954) for the period 1913 through 1952 are shown in figure 5. These events are poorly located due to the small number of recording stations and may be in error by 200 to 500 km (B. Gutenberg, private discussion). Even so, from this early work, it is possible to infer that the axis of the Gulf of Aden is seismically active. It is of interest

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that for this 40-year period, 31 earthquakes were recorded, whereas for the 6-year period January 1963 through December 1968, 95 events were recorded for the same region. It is likely that this is almost entirely due to the improvement in the number and quality of recording stations.

2. Earthquake detection levels for the Red Sea and Gulf of Aden

Gutenberg & Richter (1949, 1954) noted that the location of earthquakes in these regions was difficult due to the small number of recording stations; because of this the earthquakes shown in figure 5 are large earthquakes mostly with body wave magnitude $m_b \geqslant 6$. Since 1953,

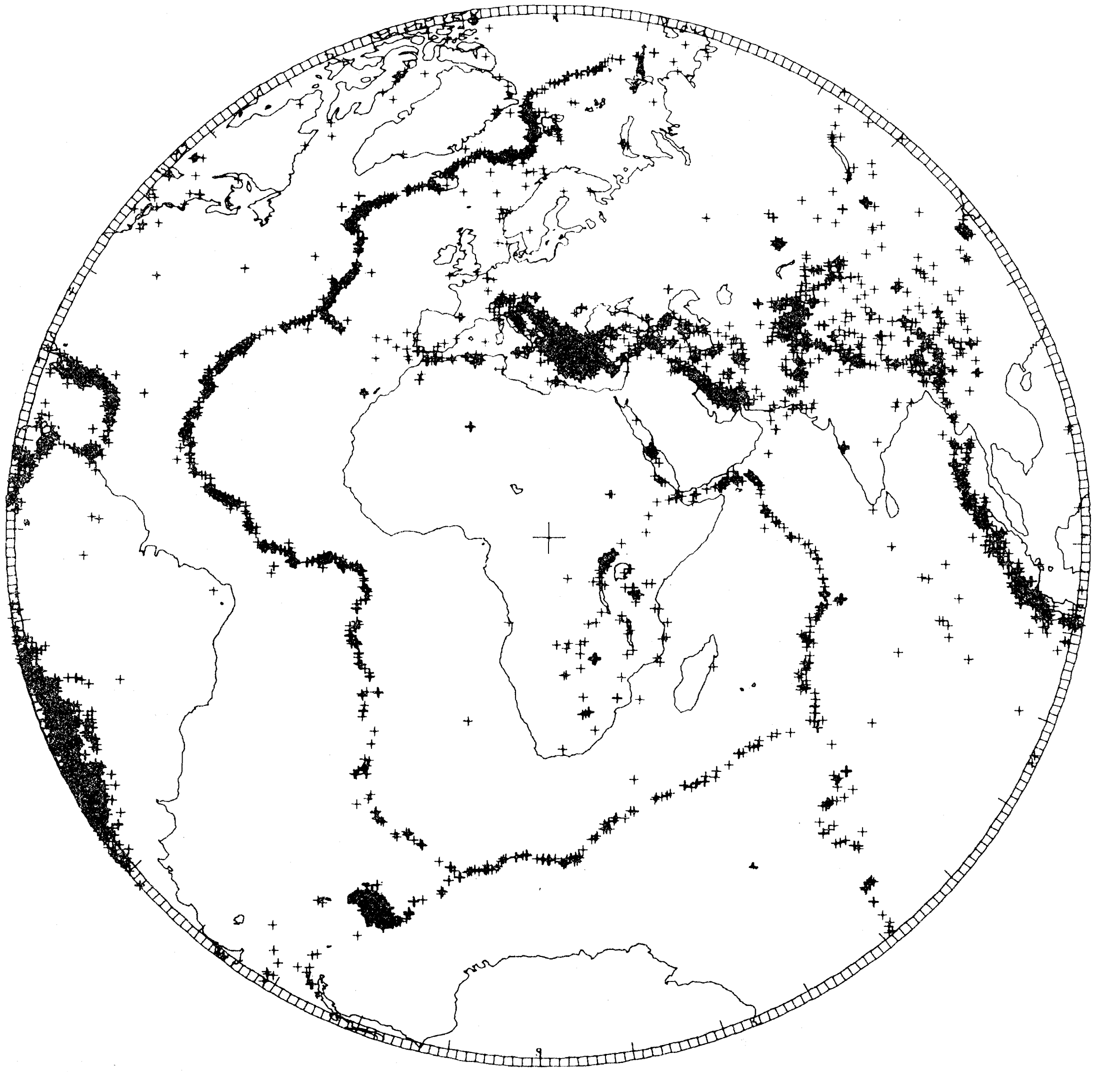

Figure 3. Shallow focus earthquakes ($h \leqslant 100$ km) for the period January 1963 through December 1968. Azimuthal great circle projection centred on Africa at 5° N, 20° E (distances and angles are correct from centre).

the number and distribution of recording stations have improved considerably. An idea of the present teleseismic detection levels can be obtained from magnitude–frequency plots. It is found that the frequency of earthquakes is related to their magnitude by the relation

$$\lg N = a - bM,$$

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where N is the number of events of magnitude M or greater and a and b are constants probably depending on tectonic factors such as the nature of the faulting associated with the earthquakes. In figures 6 and 7, the cumulative number N is plotted on a logarithmic scale against the body wave magnitude m_b. Figure 6 is for the before and after shocks of the large Red Sea earthquake of 13 March 1967 and figure 7 is for Gulf of Aden earthquakes for the period January 1963 through June 1968. For the Red Sea the straight-line relation holds for $m_b \geqslant 5.0$ and for the Gulf of Aden for $m_b \geqslant 4.8$. It is concluded that earthquakes with body wave magnitude $m_b \geqslant 5.0$ are being well determined for the Red Sea, and for the Gulf of Aden the detection level is a little better with earthquakes with $m_b \geqslant 4.8$ being well determined.

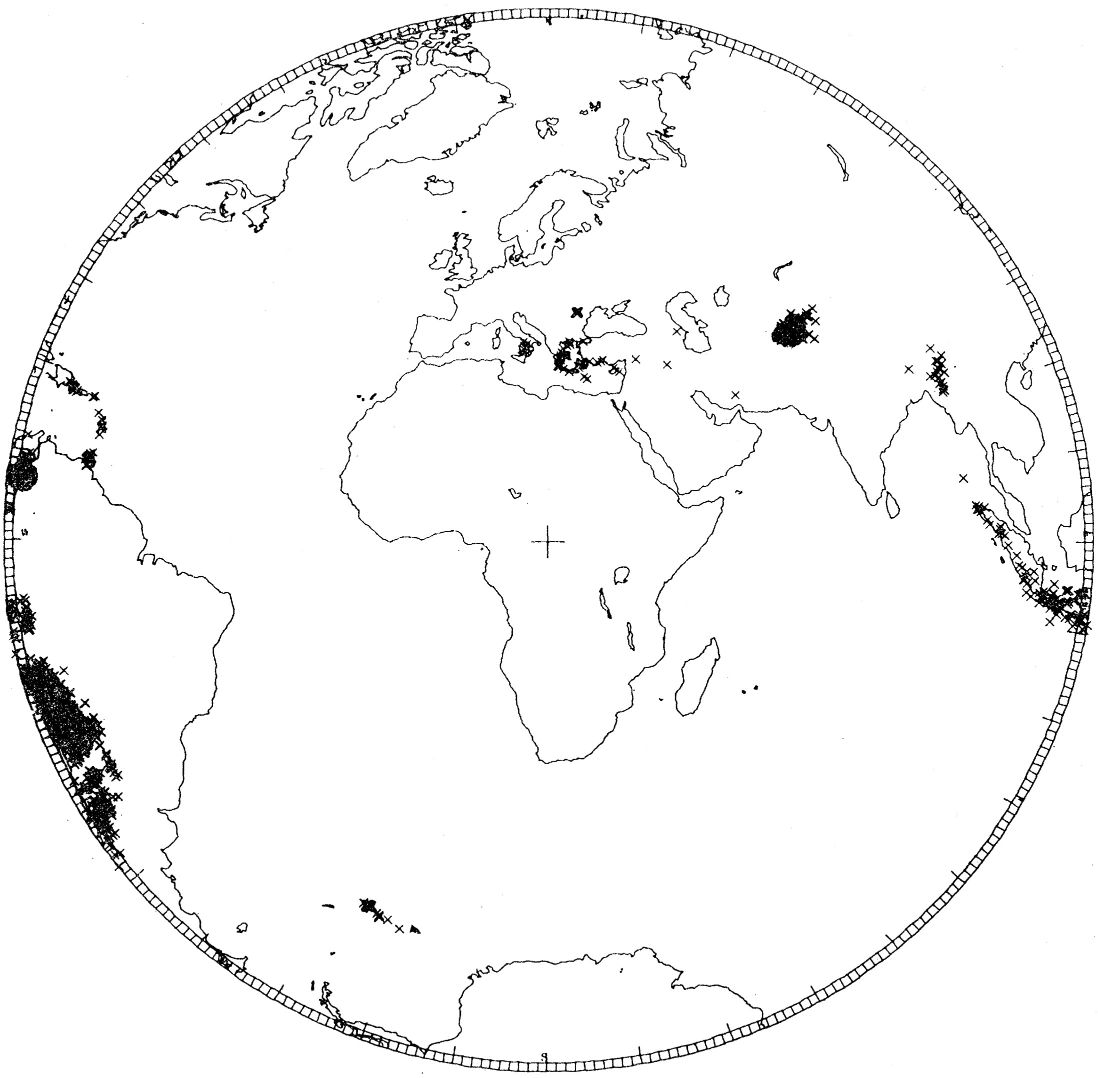

FIGURE 4. Deep focus earthquakes ($h \geqslant 100$ km) for the period January 1963 through December 1968. Azimuthal great circle projection centred on Africa at 5° N, 20 E (distances and angles are correct from centre).

It is noted that although the detection level is much improved, the azimuthal distribution of stations (figures 1 and 2) still leave much to be desired. Most of the recording stations are to the north and northwest of the region and it is unfortunate that Chad (to the west) is not a W.W.S.S.N. station and there is no station at Mahé in the Indian Ocean (to the southeast).

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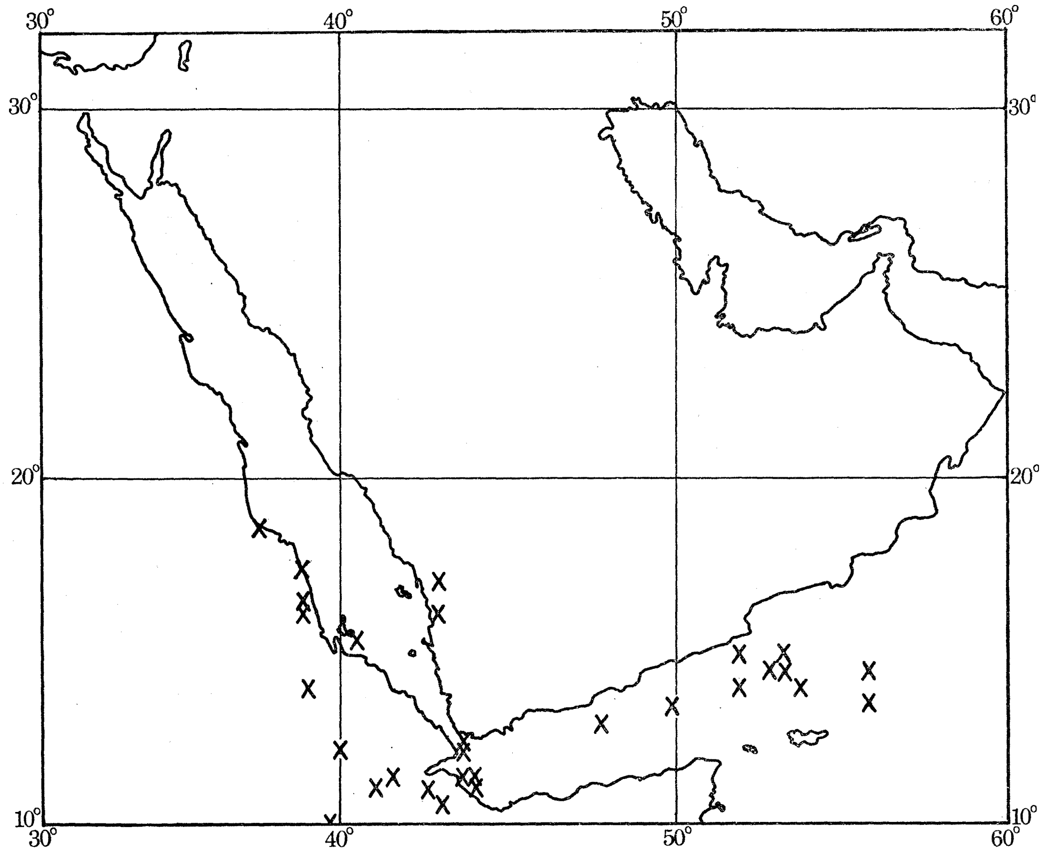
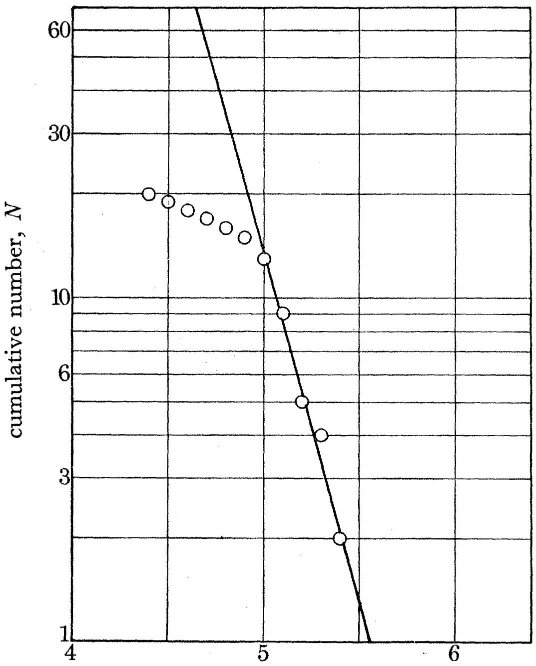
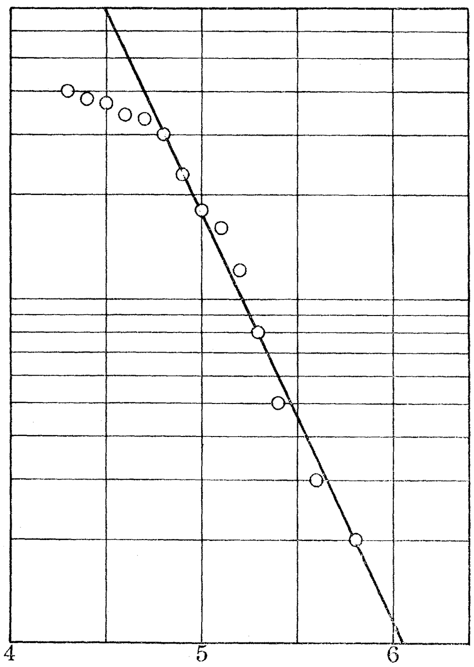


FIGURE 5. Seismicity of the Red Sea and Gulf of Aden (as far as the Owen fracture zone) for the period 1913 through 1952 (after Gutenberg & Richter 1954).





magnitude, m_b

FIGURE 6. Cumulative plot (giving $\lg N = 11.3-2.03m_b$) for the before and aftershocks of the central Red Sea earthquake of 13 March 1967.

FIGURE 7. Cumulative plot (giving $\lg N = 7.1-1.18m_b$) for forty Gulf of Aden earthquakes for the period January 1963 through June 1968.

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3. Method used for relocating epicentres

(a) *Joint epicentre determination*

The method used for refining the location of epicentres is due to Douglas (1967). It involves selecting and fixing a master event and then relocating large and small nearby events with reference to the fixed master. The technique known as joint epicentre determination (j.e.d.) takes into account station corrections, source bias and local variations in the travel time curves. The relative positions with reference to the restrained master event have a much better accuracy. This is especially true of the smaller events. From checks against nuclear explosion data (Blamey & Gibbs 1968), the locations relative to the master event can be as good as ±2 km. The absolute accuracy depends on the fixed master but is usually about ±10 km. The good relative accuracy makes the method particularly valuable for studying the relation between earthquake epicentres and gelogical features.

(b) *Master and submaster events*

The earthquake selected for the master event occurred southwest of Lake Manyara in Tanzania on 7 May 1964. The choice was governed by the following criteria. First, the event must be post-1963, i.e. since the introduction of W.W.S.S.N. Secondly, the event must be recorded by sixty or more teleseismic stations. Thirdly, the stations should have good azimuthal

Table 1. Data for master and submaster events

origin time					latitude	longitude	N	m_b	source
					master event				
	day	h	min	s					
1964 May	07	05	45	31.9 ± 0.11	03.88 ± 0.031° S	35.06 ± 0.036° E	63	6.4	I.S.C.
					submaster events				
Red Sea and northern Afar									
1967 Mar	13	19	22	15.4	19.70° N	38.85° E	60	5.8	U.S.C.G.S.
		19	22	16.3	19.79	38.82			j.e.d.
Western Gulf of Aden and eastern Ethiopia									
1966 Apr	18	08	14	18.8	12.92° N	48.31° E	34	5.4	U.S.C.G.S.
		08	14	19.9	13.00	48.35			j.e.d.
Eastern Gulf of Aden and Arabian Sea									
1968 Feb	08	12	28	21.0	14.63° N	54.04° E	74	5.4	U.S.C.G.S.
		12	28	22.1	14.72	54.07			j.e.d.

distribution. Lastly, the epicentre should check with local data reports. The 7 May 1964 event had a body wave magnitude of 6.4 and its location by the International Seismological Centre, Edinburgh (which used the greatest amount of data), is close to the area of greatest damage and near a NE–SW fault about 60 km southwest of Lake Manyara. This was therefore considered as the best determined epicentre to use as a master event for j.e.d. studies of the seismicity of the East African rift system at the time this work was done. Details of the earthquake are given in table 1.

For reasons of computer storage, the East African rift system was divided into seven regions. The 27 largest post-1963 earthquakes throughout these regions were relocated with reference to the master event. For convenience, these are called submasters. Of these, seven are in the Red Sea, nine in the Gulf of Aden and one in the Gulf of Tadjoura. Three of these submaster events

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(table 1) were restrained and used to relocate the remaining events in the Red Sea and the western and eastern parts of the Gulf of Aden respectively. In addition, the remaining submasters were included and relocated with reference to the three restrained submasters of table 1 as a check on the consistency of the data.

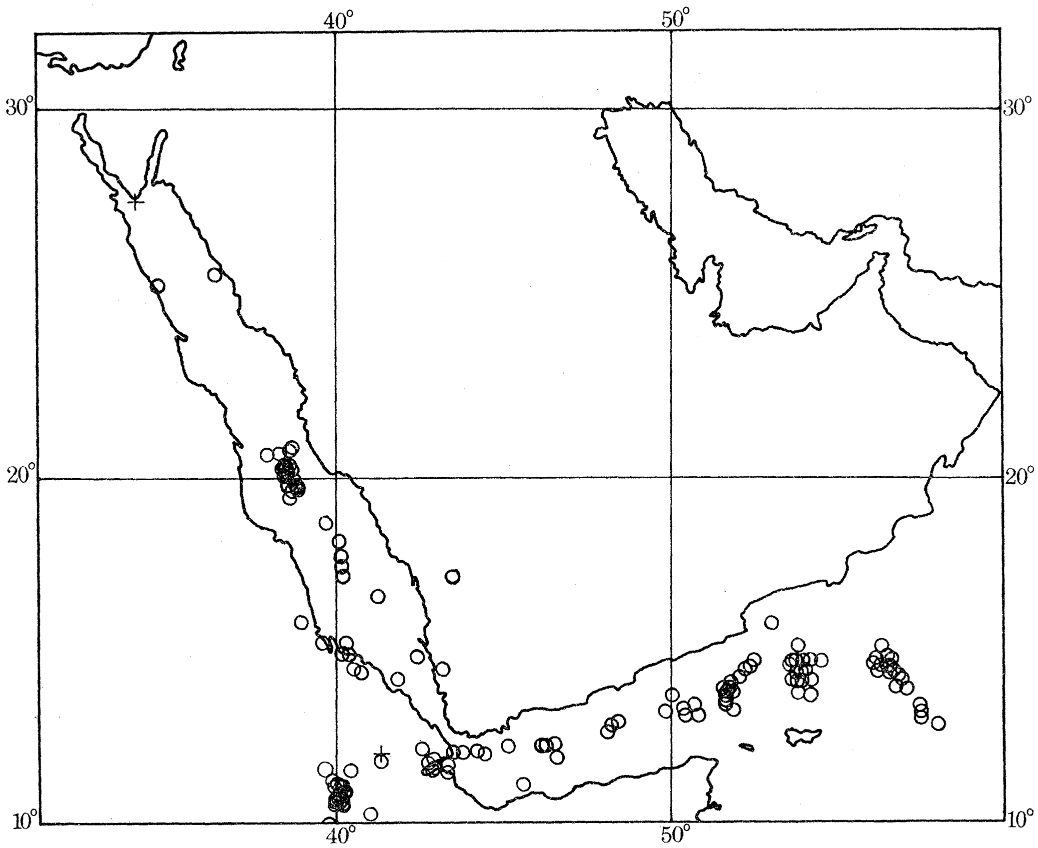

FIGURE 8. Epicentres for the Red Sea, Gulf of Aden (as far as the Owen fracture zone) and Afar depression for the period January 1953 through December 1968.

4. Epicentral locations

(a) *General features*

Epicentres for the period January 1953 through December 1968 for the Red Sea, Gulf of Aden and Afar triangle of Ethiopia are plotted in figure 8. Where there is sufficient data, j.e.d. redeterminations have been carried out. It is interesting to compare figure 8 with figure 5. Figure 8 shows that the axes of both the Red Sea and Gulf of Aden are seismically active, whereas this was not apparent from the earlier work (figure 5). The seismic activity along the axis of the Red Sea supports the interpretation of the magnetic anomalies by Vine (1966) in terms of sea-floor spreading. The earthquakes occur where new oceanic crust is being formed as a consequence of the separation of Africa and Arabia. A similar explanation holds for the Gulf of Aden.

Other features of general interest include the fact that the seismically active zone along the centre of the Gulf of Aden continues westward through the Gulf of Tadjoura and across the Afar triangle maintaining the same direction (N 075°) right up to the western rift scarp of

Ethiopia. The southernmost part of the Red Sea is relatively quiet and at about 15° N, the seismicity is associated with the coastal regions and marginal faults. The seismic activity near the Gulf of Zula found in the early work of Gutenberg and Richter seems to be genuine (cf. figures 5 and 8).

The seismicity of various parts of the Red Sea and Gulf of Aden is now considered in detail.

(b) *The Red Sea*

(i) *Northern part* (*north of* 25° N)

This region which includes the Gulf of Suez, the Gulf of Aqaba and its northern extension through the Dead Sea–Jordan rift has had remarkably few earthquakes for the period of study (figure 8 and table 2). Of the two earthquakes listed, one is located on the western marginal scarp of the Red Sea and the 9 February 1964 event was found on relocation to be close to the shelf edge on the eastern side of the Red Sea.

Table 2. Northern Red Sea (25 to 33° N, 30 to 42° E). Seismic data for period January 1953 through December 1968

	U.S.C.G.S. and B.C.I.S.			j.e.d.				
date	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1955 Nov. 12	05 32 14.5	25.29° N	34.58° E				95	6.0
1964 Feb. 09	06 07 30.0	25.6	36.4	06 07 30.2	25.67° N	36.48° E	06	—

Just before the start of the Red Sea discussion meeting (27 to 29 March 1969) a locality near the mouth of the Gulf of Suez became seismically active, the first event being on 24 March with $m_b = 5.2$. On 31 March, a large earthquake ($m_b = 6$ to 7) shook Cairo with aftershocks continuing through April. The centre of activity (preliminary determination) was at 27.7° N, 34.0° E and is shown by a cross in figure 8. A fuller discussion is given in Appendix 1.

The S.I.P.R.I. report (1968) suggests that earthquakes with $m_b \geqslant 4.5$ should now be capable of detection in this region. Shocks are frequently felt along the Dead Sea–Jordan rift and the few epicentres for this region (figure 8) is surprising. This would be a most interesting region to monitor smaller earthquakes by setting up local stations.

(ii) *Central Red Sea* (17 *to* 25° N)

This region was especially active during 1967 when twenty-nine events were recorded. The largest event of 13 March 1967 ($m_b = 5.8$) was restrained and the smaller events, many of them aftershocks, were relocated with reference to it. The relocated epicentres are shown in figure 8 and on a detailed bathymetric chart in figure 9. Data for the earthquakes are given in table 3.

Unlike farther north, the earthquakes are confined to the deep, axial trough. Further it appears from figure 9 that the seismicity is mainly associated with the eastern wall of the deep axial trough, although this could be due to error in the location of the submaster. Groups of earthquakes are often associated with transform faults (e.g. in the Gulf of Aden) and it is tempting to speculate on the possibility of a NNE transform fault between 20 and 21° N in line with the bathymetric feature at 21.3° N 38.9° E. It is noted from the earthquake origin times that there was a general northward migration in the positions of the aftershocks.

(iii) *Southern Red Sea and northern Ethiopia* (13 *to* 17° N)

The epicentres for this region (figure 8 and table 4) show that the seismic activity associated with the deep axial trough continues south to about latitude 14° N. In addition, there is seismic activity to the south and west of the Gulf of Zula in northern Ethiopia. This is discussed in § 4*d*.

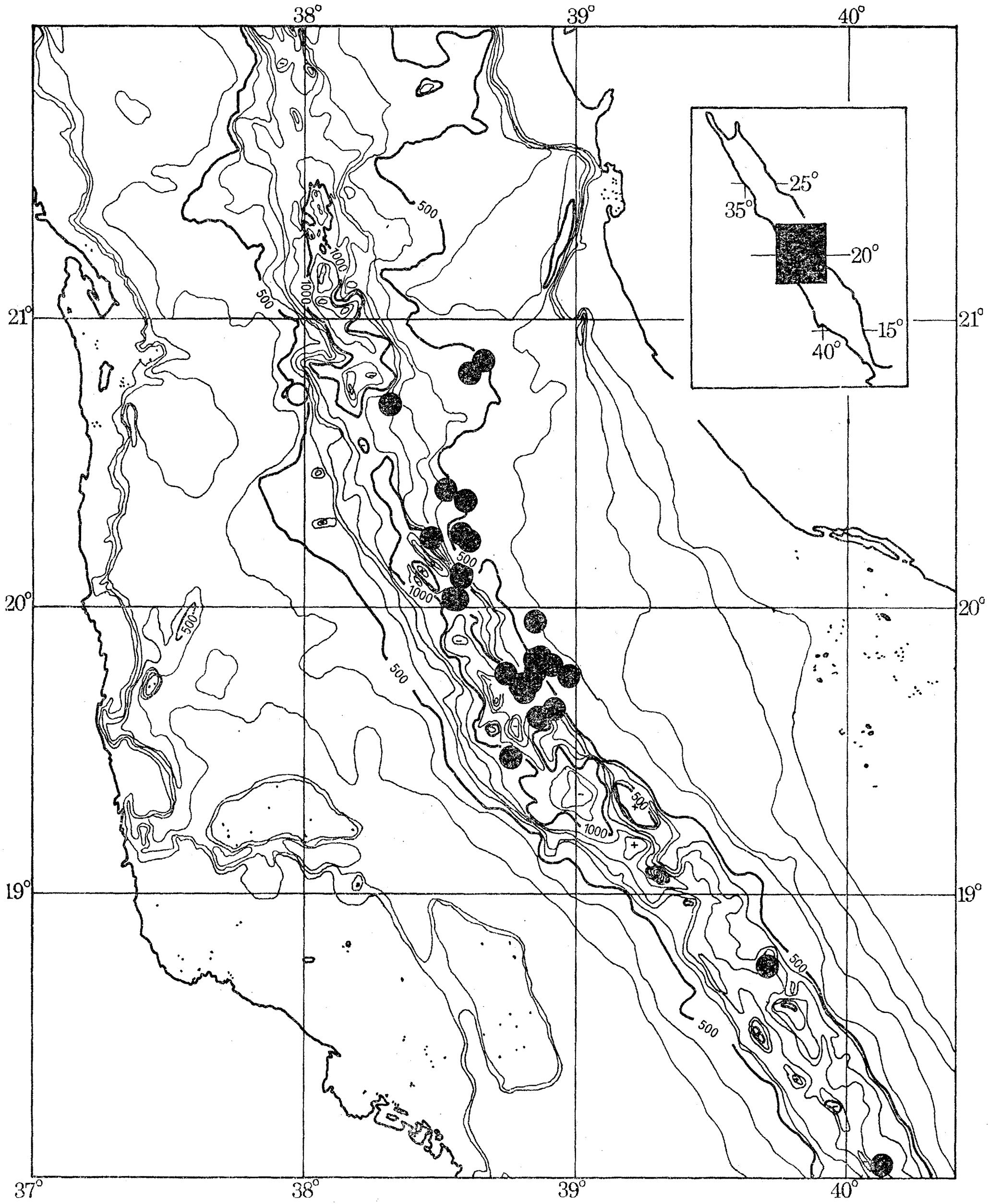

FIGURE 9. Seismicity and bathymetry of the central Red Sea. ○, epicentres for January 1953 through December 1962; ●, epicentres for January 1963 through December 1968. Contours (in corrected fathoms) by A. S. Laughton, 1968.

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Table 3. Central Red Sea (17 to 25° N, 32 to 44° E). Seismic data for period January 1953 through December 1968

	U.S.C.G.S. and B.C.I.S.			j.e.d.				
date	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1955 Oct. 17	20 08 53.1	17.16° N	43.65° E	—	—	—	12	—
1956 June 25	20 10 18.5	20.31	37.95	20 10 26.9	20.73° N	37.98° E	12	—
1958 Jan. 09	07 56 27.2	17.71	40.12	—	—	—	7	—
1960 Oct. 23	19 21 07.7	17.50	40.07	—	—	—	8	—
1962 Nov. 11	15 15 28.0	17.05	40.58	15 15 33.9	17.22	40.58	95	5.6
1965 Dec. 30	08 54 13.5	18.75	39.49	08 54 14.5	18.87	39.71	5	4.1
1967 Mar. 11	19 33 48.1	19.55	38.97	19 33 49.6	19.65	38.92	6	4.9
1967 Mar. 11	19 38 21.5	19.65	38.86	19 38 22.3	19.73	38.80	12	5.2
1967 Mar. 12	10 01 49.0	19.83	38.93	10 01 50.7	19.90	38.88	6	—
1967 Mar. 12	21 44 32.8	19.71	38.89	21 44 34.2	19.82	38.86	11	—
1967 Mar. 13	07 28 05.7	19.66	38.82	07 28 06.3	19.74	38.82	14	5.3
1967 Mar. 13	08 10 56.3	19.63	38.88	08 10 57.4	19.70	38.81	13	5.0
1967 Mar. 13	11 46 28.5	19.67	39.05	11 46 29.9	19.77	38.98	11	5.0
1967 Mar. 13	19 22 15.4	19.70	38.85	19 22 16.3	19.79	38.82	60	5.8
1967 Mar. 14	21 52 05.3	19.37	38.67	21 52 06.6	19.49	38.76	11	4.6
1967 Mar. 16	03 11 59.0	19.50	38.88	03 12 00.3	19.61	38.87	12	5.4
1967 Mar. 16	11 41 28.9	19.71	39.03	11 41 29.8	19.80	38.91	6	—
1967 Mar. 16	14 45 12.6	19.73	38.88	14 45 13.6	19.83	38.87	12	5.1
1967 Mar. 16	16 00 16.0	19.79	38.90	16 00 17.9	19.96	38.85	11	5.0
1967 Mar. 22	02 54 22.6	20.30	38.69	02 54 23.6	20.38	38.60	8	—
1967 Mar. 22	22 59 49.8	19.73	38.79	22 59 51.7	19.77	38.74	7	—
1967 Mar. 24	01 57 49.0	20.21	38.32	01 57 49.2	20.25	38.46	18	5.0
1967 Mar. 24	06 38 08.8	20.02	38.66	06 38 10.3	20.11	38.59	14	5.1
1967 Mar. 24	10 00 31.0	20.12	38.70	10 00 32.1	20.23	38.61	5	—
1967 Mar. 24	12 34 35.5	20.83	38.72	12 34 37.3	20.86	38.66	6	—
1967 Mar. 27	19 53 40.6	20.02	38.60	19 53 42.6	20.10	38.59	34	5.1
1967 Mar. 28	02 41 33.5	19.87	38.61	02 41 34.7	20.03	38.55	6	—
1967 Mar. 31	03 18 24.2	20.22	38.64	03 18 25.3	20.26	38.59	19	4.8
1967 Apr. 03	07 38 28.4	19.91	38.46	07 38 29.5	20.03	38.56	30	5.1
1967 Apr. 15	16 59 07.3	20.75	38.73	16 59 08.7	20.81	38.61	5	4.9
1967 May 17	17 50 39.6	19.74	38.72	17 50 39.6	19.78	38.84	28	5.3
1967 June 19	14 35 20.2	20.65	38.39	14 35 21.0	20.70	38.31	28	4.5
1967 July 14	03 11 28.2	19.81	38.93	03 11 28.3	19.80	38.91	18	4.7
1967 Sept. 11	19 58 23.2	20.33	38.67	19 58 24.8	20.41	38.51	7	—
1967 Sept. 21	18 36 26.0	17.94	39.97	18 36 27.0	18.05	40.13	7	4.4

Table 4. Southern Red Sea and northern Ethiopia (13 to 17° N, 38 to 44° E). Seismic data for period January 1953 through December 1968

	U.S.C.G.S. and B.C.I.S.			j.e.d.				
date	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1955 Mar. 03	00 43 40.2	16.46° N	41.29° E	00 43 44.8	16.54° N	41.25° E	4	—
1957 Mar. 14	00 11 33.0	14.80	40.22	00 11 38.5	14.97	40.19	13	—
1958 Feb. 13	10 23 33.7	14.34	42.00	10 23 36.5	14.26	41.92	20	—
1959 Aug. 16	13 31 10.4	14.54	43.14	13 31 15.1	14.52	43.21	9	—
1960 Aug. 13	22 28 13.6	14.70	40.16	22 28 19.4	15.11	40.15	5	—
1960 Dec. 16	16 49 15.0	14.65	42.57	16 49 20.5	14.81	42.48	28	—
1962 Aug. 25	00 54 08.0	16.49	40.12	00 54 17.5	17.12	40.14	11	4.8
1966 Apr. 09	19 11 10.5	14.37	40.79	19 11 12.0	14.46	40.74	6	4.7
1967 May 19	15 52 34.2	14.53	40.26	15 52 40.5	14.87	40.14	26	5.1
1967 Sept. 18	02 02 59.8	15.69	39.03	02 03 01.8	15.80	38.93	14	4.8
1967 Nov. 16	02 22 03.1	15.09	39.82	02 22 06.2	15.17	39.53	7	5.1
1968 May 23	23 36 06.4	14.75	40.22	—	—	—	13	4.8

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(c) *The Gulf of Aden*

The seismicity of the Gulf of Aden is considered from east to west in two parts, i.e. east and west of the Alula–Fartak trench (longitude 51° E). The Owen fracture zone is taken as marking the boundary of the Gulf of Aden with the Indian Ocean.

(i) *Gulf of Aden east of* 51° E

This region (figure 10) extends west from the Owen fracture zone and includes the Alula–Fartak trench. The bathymetric features have been described by Laughton (1966*a*, *b*) and Matthews, Williams & Laughton (1967). The main feature between the Owen fracture zone and the Alula–Fartak trench is the Sheba Ridge.

Because of the large number of earthquakes in this region and for reasons of computer storage, joint epicentre determinations were done in two groups, pre- and post-1 January 1963. Both groups are restrained to the same sub-master, the event of 8 February 1968 with body wave magnitude 5.4. The relocated epicentres are shown in figure 10 and details are given in table 5. Because of the larger number of recording stations, the post-January 1963 events (solid circles) are likely to be better located than the pre-January 1963 events (open circles).

The relocations show there is a good correlation between seismicity and topography. For the Sheba Ridge between longitudes 56 and 58° E the epicentres lie closely along the axis and these are presumably associated with the opening of the axial rift.

A second group of earthquakes in the region of 14.5° N, 53.8° E show no simple pattern but here the bathymetry is also very complicated. It is possible there maybe a minor NNE transform fault in this region and the earthquakes maybe associated with this. Alternatively, the earthquakes maybe associated with submarine volcanism.

A third group of earthquakes is associated with the Alula–Fartak trench and here the alinement of the post-January 1963 epicentres with the trench is most impressive.

(ii) *Gulf of Aden west of* 51° E

For this region, the submaster event of 18 April 1966 ($m_b = 5.4$) was restrained. This is the largest post-1963 event and fortunately is near the centre of the region (figure 11). The j.e.d. relocated epicentres are shown in figure 11 and details are given in table 6.

This part of the Gulf of Aden maybe divided into three physiographic provinces, the continental margins, the main trough and the central rough zone (Laughton 1966*a*). All but one of the earthquakes are associated with the central rough zone. The one outside the rough zone is the event of 16 May 1965 near the Somali shore which is near a possible southward extension of one of the many NNE transform faults.

Two features are noted. First, the zone of seismicity does not exactly bisect the Gulf of Aden but tends to be consistently to the north of the central axis (including the Gulf of Tadjoura). Secondly, there is a tendency for some of the epicentres to concentrate near the intersections with NNE transform faults.

(d) *The Afar depression*

This is the region at the junction of the Red Sea and Gulf of Aden (figure 12). Seismic activity seems to be associated with three areas: the westward extension of the axial rift zone of the Gulf of Aden, the western margin rift scarp and northern Afar.

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

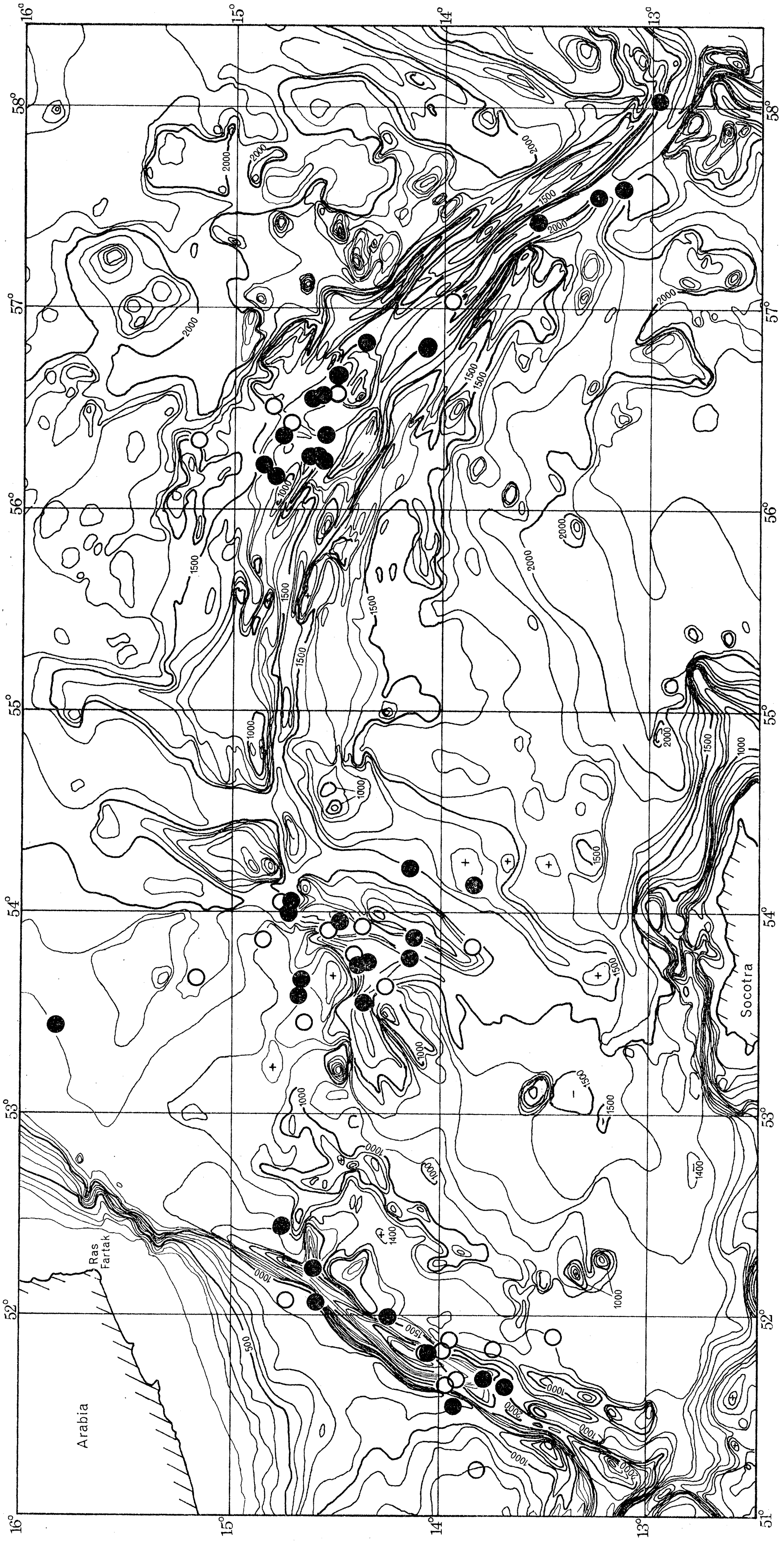

Figure 10. Seismicity and bathymetry of the Gulf of Aden east of 51° E including the Sheba Ridge and Alula–Fartak trench. ○, epicentres for January 1953 through December 1962; ●, epicentres for January 1963 through December 1968. Contours (in corrected fathoms) by A. S. Laughton, 1968.

Table 5. Eastern Gulf of Aden and Arabian Sea (9 to 17° N, 51 to 58° E). Seismic data for the period January 1953 through December 1968

	U.S.C.G.S. and B.C.I.S.			j.e.d.				
date	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1954 Jan. 11	22 45 06.0	13.75° N	51.25° E	—	—	—	—	—
1955 Apr. 26	01 37 19.9	14.59	56.34	01 37 21.1	14.51° N	56.59° E	7	—
1957 Dec. 19	15 56 32.0	14.36	53.44	15 56 37.2	14.62	53.50	11	—
1958 Nov. 04	05 06 11.6	14.08	53.58	05 06 16.8	14.41	53.83	9	—
1958 Nov. 13	23 19 22.2	14.97	53.81	23 19 25.2	15.15	53.72	13	—
1958 Nov. 13	23 26 37.5	13.29	53.74	23 26 43.3	13.83	53.86	6	—
1958 Dec. 04	10 25 48.3	13.84	51.70	10 25 51.8	14.07	51.81	23	—
1959 Jan. 05	08 17 14.6	13.72	51.61	08 17 18.6	13.71	51.82	25	—
1959 Jan. 21	13 57 29.9	13.60	51.76	13 57 33.6	13.92	51.88	29	—
1959 Apr. 14	01 23 08.2	14.86	56.50	01 23 10.2	14.86	56.51	6	—
1959 Apr. 14	01 39 52.6	15.34	56.21	01 39 53.9	15.17	56.38	5	—
1959 June 07	09 03 44.0	14.55	53.70	09 03 46.8	14.51	53.90	13	—
1959 Dec. 21	11 19 15.1	13.98	51.71	11 19 18.7	13.98	51.82	136	6.7
1959 Dec. 22	00 09 39.8	13.95	51.40	00 09 42.2	13.87	51.70	53	—
1960 May 31	00 23 49.5	14.87	54.56	00 23 53.7	14.92	54.67	32	—
1960 June 07	15 34 48.9	13.74	56.97	15 34 53.7	13.97	57.03	44	4.8
1961 Feb. 07	02 57 53.4	14.65	53.90	02 57 57.1	14.77	54.10	24	—
1961 Apr. 06	21 23 45.7	14.28	54.11	21 23 49.6	14.39	53.96	17	—
1961 July 18	21 26 28.0	13.88	56.80	21 26 33.4	14.08	56.81	43	—
1961 Aug. 03	00 41 30.7	14.48	52.16	00 41 35.9	14.73	52.10	29	5.5
1961 Oct. 25	16 24 12.4	14.21	56.44	16 24 07.9	14.51	56.67	61	5.0
1961 Nov. 10	13 52 33.4	13.24	51.69	13 52 36.7	13.47	51.93	14	—
1962 June 16	21 42 07.3	14.3	53.6	21 42 09.6	14.53	53.94	8	—
1962 July 15	21 52 20.1	14.11	53.51	21 52 24.3	14.26	53.67	37	4.5
1962 Aug. 15	13 08 36.5	14.51	56.49	13 08 42.5	14.74	56.44	38	5.0
1962 Nov. 29	02 20 29.4	14.70	54.86	02 20 33.3	14.79	54.94	10	—
1962 Dec. 21	17 47 25.6	13.87	51.63	17 47 29.9	13.96	51.68	44	5.3
1963 Feb. 07	16 44 45.3	14.4	53.3	16 44 45.4	14.37	53.55	7	—
1963 Feb. 13	01 34 40.4	13.0	57.9	01 34 40.0	12.97	58.04	13	4.7
1963 Feb. 13	19 55 36.0	11.6	57.7	19 55 38.2	11.84	57.81	6	—
1963 July 21	06 01 57.1	14.8	56.1	06 01 55.8	14.64	56.56	10	4.8
1963 Sept. 29	19 31 22.7	13.5	57.5	19 31 23.6	13.54	57.43	7	—
1963 Nov. 01	07 02 41.7	14.6	53.6	07 02 43.1	14.67	53.67	7	5.1
1964 Mar. 19	08 06 19.8	14.4	56.8	—	—	—	20	—
1964 Mar. 19	09 42 34.9	14.7	56.3	09 42 35.2	14.57	56.38	13	5.8
1964 May 23	00 11 56.0	14.77	56.01	00 11 56.2	14.80	56.17	5	—
1964 May 23	00 17 07.5	14.6	56.3	00 17 08.9	14.64	56.28	15	5.3
1964 July 20	13 31 13.9	14.42	53.53	13 31 16.6	14.69	53.59	7	—
1964 Sept. 07	11 27 14.7	15.72	53.32	11 27 15.9	15.82	53.44	19	4.6
1964 Oct. 14	20 39 42.3	13.86	54.57	20 39 49.4	14.15	52.23	10	—
1965 June 15	16 41 12.5	13.92	51.69	16 41 13.5	14.05	51.81	25	5.2
1965 Aug. 02	04 49 58.6	13.79	53.96	04 49 59.8	13.84	54.14	5	4.3
1965 Aug. 02	04 56 19.3	14.43	53.92	04 56 20.2	14.49	53.96	12	4.8
1966 Mar. 27	01 40 59.4	14.54	56.68	01 40 58.8	14.38	56.83	12	—
1966 July 01	17 26 13.9	14.03	56.87	17 26 14.9	14.08	56.82	6	4.9
1966 July 18	09 59 10.0	13.10	57.60	09 59 11.5	13.24	57.56	23	5.1
1966 Sept. 09	20 42 06.3	14.68	52.29	20 42 07.8	14.76	52.45	30	4.9
1966 Sept. 18	11 58 28.5	13.03	57.60	11 58 29.9	13.12	57.60	8	—
1966 Dec. 25	05 41 57.6	14.17	53.83	05 41 58.3	14.14	53.88	6	5.0
1966 Dec. 25	05 42 44.5	14.14	53.79	05 42 46.0	14.35	53.76	12	5.2
1966 Dec. 25	05 49 47.7	14.23	53.58	05 49 49.1	14.16	53.78	7	4.8
1967 Apr. 12	19 28 55.3	14.38	56.72	19 28 56.8	14.50	56.68	10	4.7
1967 Apr. 13	21 43 12.4	14.47	56.52	21 43 15.6	14.58	56.25	7	4.1
1967 Apr. 14	18 58 20.3	14.55	56.48	18 58 21.9	14.58	56.57	8	4.8
1967 Oct. 15	06 36 39.7	14.71	56.40	06 36 41.8	14.76	56.37	12	5.1

TABLE 5 (*cont.*)

date	U.S.C.G.S. and B.C.I.S. h m s	lat.	long.	j.e.d. h m s	lat.	long.	N	m_b
1967 Nov. 23	08 35 49.5	14.53	52.07	08 35 55.1	14.58	52.06	63	5.8
1967 Nov. 25	16 01 46.1	14.59	52.06	16 01 46.6	14.60	52.23	9	4.8
1967 Nov. 27	13 04 16.0	14.10	52.01	13 04 17.5	14.25	52.00	15	5.1
1967 Dec. 11	19 05 01.9	14.86	55.97	19 05 02.3	14.85	56.22	8	4.5
1967 Dec. 11	19 48 43.3	13.69	51.59	19 48 44.4	13.76	51.69	25	5.2
1967 Dec. 11	22 30 18.3	13.62	51.60	22 30 18.9	13.66	51.65	31	5.6
1967 Dec. 14	02 20 27.9	14.30	53.65	02 20 28.3	14.40	53.74	26	4.9
1968 Feb. 08	10 58 22.1	14.62	53.94	10 58 23.0	14.73	54.00	46	5.2
1968 Feb. 08	12 28 21.0	14.63	54.04	12 28 22.1	14.72	54.07	74	5.4
1968 Aug. 06	08 34 42.3	13.93	51.54	—	—	—	27	4.9
1968 Aug. 30	22 02 19.8	14.62	56.25	—	—	—	22	5.2
1968 Nov. 04	09 02 31.9	12.21	58.00	—	—	—	18	5.1

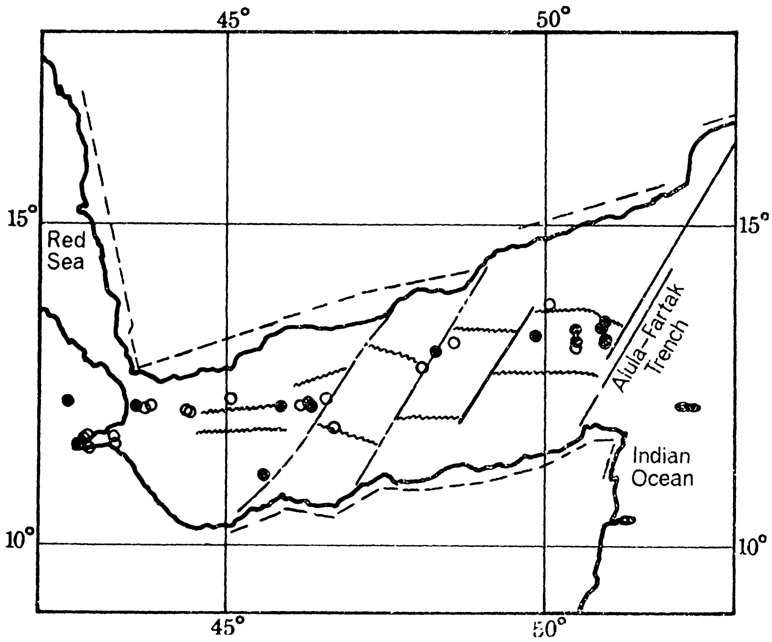

FIGURE 11. Seismicity and general features of the Gulf of Aden. ○, epicentres for January 1953 through December 1962; ●, epicentres for January 1963 through December 1968. The main NNE transform faults are shown together with the location of the central rough zone.

(i) *Southern Afar*

The epicentres for this region are shown in figures 8 and 12 and details are given in tables 6 and 7. As previously noted (figure 8) the way in which the seismically active zone of the Gulf of Aden continues west through the Gulf of Tadjoura and across Afar is impressive. This result and the absence of teleseismic epicentres between 12.2 and 14.2° N was surprising. However, the fact that the magnetic anomalies (described in a succeeding paper) also maintain a west–east trend across the whole of this region gives confidence to the view that the main active rift zone continues westward to intersect the western fault-scarp of Afar.

During the third morning (29 March) of the meeting when this region was the subject of lively discussion, a large earthquake (m_b = 5.8) occurred. The Ethiopian village of Sardo was unhappily destroyed with more than 160 casualties. Another large shock (m_b = 6.2) occurred on 5 April and there have been several aftershocks. The centre of activity (preliminary determination) was at 12.0° N, 41.3° E and has been added to figures 8 and 12. This active centre is also associated with the westward extension of the Gulf of Aden trend. A fuller discussion of these events is given in Appendix 2.

Table 6. Gulf of Aden and eastern Afar (10 to 15° N, 41 to 51° E). Seismic data for the period January 1953 through December 1968

	U.S.C.G.S. and B.C.I.S.			j.e.d				
date	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1953 Sept. 25	23 03 00.0	13.0° N	50.5° E	—	—	—	—	—
1955 Jan. 17	15 35 13.2	12.23	46.02	—	—	—	5	—
1957 Apr. 12	15 58 43.5	11.54	43.05	15 58 47.3	11.47° N	43.30° E	12	5.0
1958 May 24	22 25 32.6	12.17	43.58	—	—	—	9	—
1958 May 24	23 53 38.0	12.14	43.59	23 53 42.7	12.13	43.82	44	5.5
1958 May 25	02 53 48.4	12.13	43.69	02 53 53.1	12.16	43.88	37	5.0
1958 June 28	17 05 16.2	11.94	45.44	17 05 24.5	12.26	45.13	9	—
1960 Jan. 04	06 07 55.1	11.50	42.87	06 08 00.7	11.83	42.84	8	—
1960 Jan. 04	06 16 30.9	11.55	42.77	06 16 35.3	11.51	42.84	22	—
1960 Mar. 25	09 45 40.4	12.12	46.62	09 45 46.0	12.26	46.61	21	—
1960 Aug. 08	12 28 07.7	12.06	44.49	12 28 12.4	12.06	44.49	41	5.4
1960 Sept. 12	03 13 43.7	11.78	46.61	03 13 48.0	11.80	46.72	6	—
1961 Mar. 11	08 41 03.6	11.65	42.95	08 41 07.9	11.71	43.25	85	5.9
1961 June 20	03 21 29.5	12.23	44.34	03 21 28.8	12.17	44.37	77	6.1
1961 Dec. 08	10 40 36.7	13.45	50.22	10 40 44.6	13.78	50.13	13	—
1962 June 24	15 08 18.6	13.0	48.6	15 08 20.0	13.13	48.66	—	—
1962 Sept. 01	00 38 12.8	12.69	48.10	00 38 17.2	12.76	48.17	23	5.0
1963 Oct. 05	14 57 47.4	11.6	42.8	14 57 47.8	11.60	42.85	21	5.3
1963 Oct. 05	17 18 25.0	11.7	42.6	17 18 25.6	11.70	42.71	7	—
1965 Mar. 07	07 32 38.1	12.06	46.26	07 39 39.4	12.19	46.34	19	4.9
1965 Mar. 07	07 42 31.2	12.06	46.34	07 42 32.2	12.17	46.38	26	5.3
1965 May 16	00 45 56.8	10.93	45.52	00 45 58.0	11.07	45.61	7	—
1965 May 18	10 27 13.4	13.23	49.75	10 27 41.1	13.27	49.91	7	4.5
1965 June 07	13 43 57.2	11.43	41.48	13 43 59.0	11.63	41.38	8	—
1965 June 20	16 31 19.5	13.29	50.35	16 31 20.0	13.35	50.55	16	5.0
1965 July 19	15 49 35.8	12.12	42.58	15 49 37.0	12.22	42.56	5	—
1966 Jan. 21	12 39 43.1	12.00	43.77	12 39 44.9	12.11	43.64	6	4.7
1966 Apr. 18	08 14 18.8	12.92	48.31	08 14 19.9	13.00	48.35	34	5.4
1966 Sept. 02	10 41 12.4	12.93	50.95	10 41 23.4	13.16	50.99	12	4.8
1966 Oct. 15	06 54 20.2	13.00	50.30	06 54 21.5	13.19	50.53	13	4.7
1967 July 06	18 58 39.7	13.40	50.77	18 58 40.3	13.45	50.96	26	4.9
1967 July 06	22 02 33.9	13.51	50.75	22 02 33.7	13.16	50.99	12	4.5
1967 July 07	01 09 59.0	13.46	50.77	01 05 59.0	13.48	50.98	18	4.8
1968 Dec. 12	17 30 30.2	12.09	45.87	—	—	—	15	4.6

(ii) *Western scarp of Afar*

It will be noticed that the majority of shocks listed in table 7 occurred between 29 May 1961 and 24 June 1961. All of these are located on or near the western marginal rift scarp at latitudes 10 to 11° N. longitude 40° E. There were two large earthquakes, the first (m_b = 6.4) was on 1 June 1961 and recorded by 147 stations and the second (m_b = 6.2) was on 2 June 1961 and recorded by 142 stations. The remaining events (more than 30) were presumably foreshocks and aftershocks of these two large events. A local j.e. determination was performed on these events using the 1 June 1961 earthquake (previous located with reference to the Gulf of Aden submaster) as an extra submaster. These relocated events are shown in figure 13. The grouping of the events is considerably improved (Fairhead 1968) and the quakes were clearly associated with the rift scarp.

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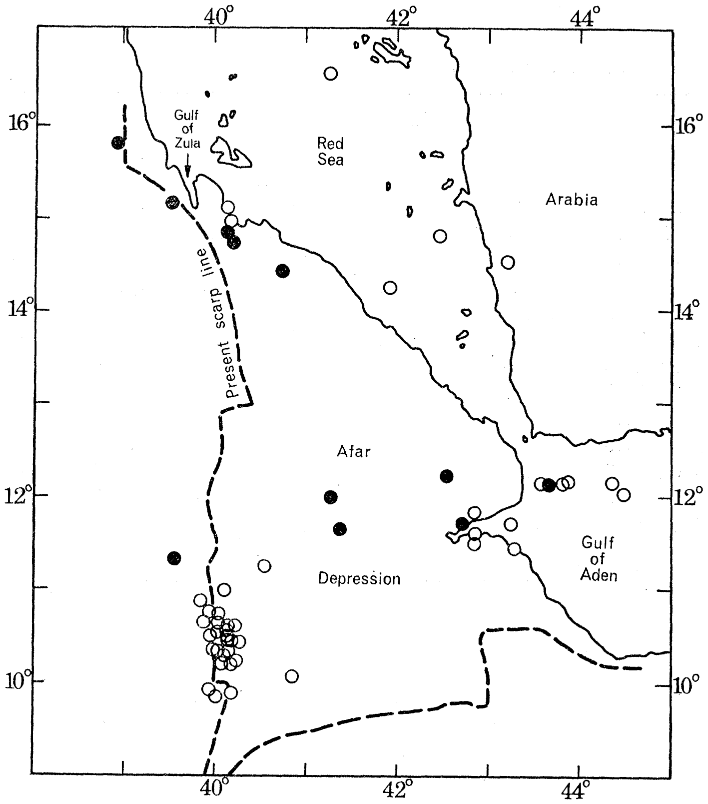

FIGURE 12. Seismicity of the junction area of the Red Sea and Gulf of Aden. ○, epicentres for January 1953 through December 1962; ●, epicentres for January 1963 through December 1968.

TABLE 7. CENTRAL ETHIOPIA (7 TO 13° N, 38 TO 41° E).
SEISMIC DATA FOR THE PERIOD JANUARY 1953 THROUGH DECEMBER 1968

	U.S.C.G.S. and B.C.I.S.			j.e.d.				
date	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1960 July 14	18 39 35.8	07.17° N	38.46° E	18 39 49.1	07.18° N	38.82° E	38	6.3
1961 May 29	04 59 38.9	10.50	39.74	04 59 42.1	10.43	40.03	21	5.0
1961 May 29	10 51 59.5	10.39	39.81	10 51 49.4	10.43	40.16	55	5.5
1961 May 29	11 39 47.5	10.17	40.12	11 39 56.2	10.62	40.03	11	—
1961 May 29	19 24 01.3	10.50	39.84	19 23 53.9	10.46	40.18	46	5.0
1961 May 29	19 40 24.4	10.43	39.77	19 40 29.0	10.46	40.16	22	—
1961 May 30	13 11 16.9	10.72	39.79	13 11 19.4	10.58	40.12	16	—
1961 June 01	21 07 18.5	10.92	39.57	21 07 21.7	10.75	39.94	11	—
1961 June 01	23 29 18.8	10.63	39.81	23 29 21.7	10.53	40.17	147	6.4
1961 June 01	23 56 37.8	09.43	39.89	23 56 52.0	10.65	39.89	10	—
1961 June 02	00 01 42.8	10.46	39.63	00 01 47.3	10.49	39.96	32	—
1961 June 02	00 08 53.5	10.41	39.90	00 08 57.6	10.42	40.26	46	—
1961 June 02	00 21 18.9	10.41	39.70	00 21 19.4	09.84	40.01	13	—
1961 June 02	00 57 53.2	10.03	39.20	00 57 55.3	09.89	40.19	16	—
1961 June 02	02 35 33.9	10.88	40.51	02 35 41.6	11.27	40.54	17	—
1961 June 02	03 19 34.9	10.03	40.12	03 19 39.5	09.94	39.95	9	—
1961 June 02	03 49 04.0	09.71	40.69	03 49 11.1	10.06	40.84	11	—
1961 June 02	04 51 10.6	10.36	39.91	04 51 04.8	10.31	40.13	142	6.2
1961 June 02	05 22 28.5	10.30	40.05	05 22 19.1	10.20	40.08	72	—
1961 June 02	05 44 52.7	10.59	40.06	05 44 36.9	10.27	40.22	82	5.8
1961 June 02	06 17 10.7	10.54	39.82	06 17 15.8	10.67	40.07	26	—
1961 June 02	07 02 46.1	10.14	39.91	07 02 47.1	10.20	40.19	62	5.5

TABLE 7 (*cont.*)

	U.S.C.G.S. and B.C.I.S.			j.e.d.				
	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1961 June 02	07 21 43.7	10.50	39.74	07 21 49.8	10.73	40.04	26	—
1961 June 02	22 19 30.0	10.31	39.89	22 19 34.5	10.43	40.28	9	—
1961 June 02	23 32 34.6	10.42	39.95	23 32 39.7	10.52	40.15	34	—
1961 June 03	02 05 27.5	09.80	40.22	02 05 36.1	10.29	40.11	11	—
1961 June 03	15 20 22.4	10.17	39.97	15 20 28.7	10.43	40.16	33	—
1961 June 03	15 23 16.4	10.49	39.93	15 23 03.6	10.62	40.23	68	5.8
1961 June 03	16 25 51.8	10.61	40.01	16 25 56.0	10.59	40.13	15	—
1961 June 04	00 41 39.2	10.40	39.82	00 41 43.1	10.34	40.02	9	—
1961 June 06	17 46 42.8	11.08	39.19	17 46 43.4	10.88	39.86	8	—
1961 June 07	15 01 12.2	10.59	40.04	15 01 16.5	10.54	40.17	11	—
1961 June 14	20 32 17.8	10.62	39.80	20 32 10.1	10.55	40.05	89	5.7
1961 June 19	04 34 11.6	10.46	39.96	04 34 14.3	10.44	40.21	8	—
1961 June 24	15 04 31.3	10.69	39.89	15 04 34.2	10.65	40.14	5	—
1964 July 13	19 18 34.0	11.01	39.28	19 18 33.0	11.32	39.57	9	5.0
1968 Jan. 23	19 18 13.0	08.71	37.66	19 18 14.7	08.74	37.56	20	5.1

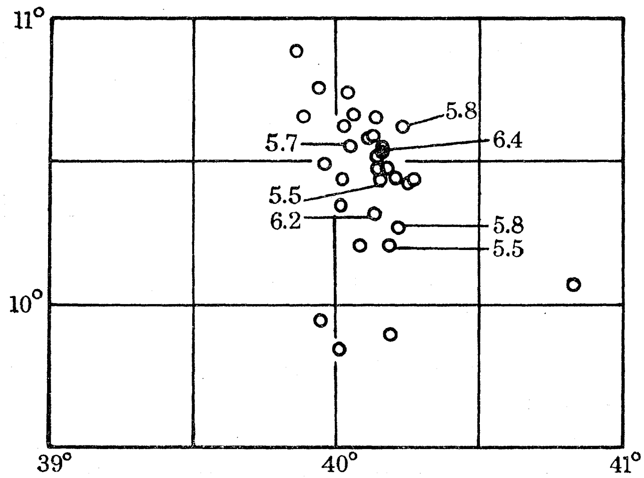

FIGURE 13. J.e.d. relocations for the foreshocks and aftershocks of the 1 June 1961 earthquake on the western scarp of Afar.

The rift scarp is most impressive in this region being more than 2 km high. It is possible the shocks were caused by step faulting along this fault line or were associated with transform movement, the fault scarp acting as a terminal transform fault to the Gulf of Aden spreading. Unfortunately, these events occurred before the introduction of W.W.S.S.N. and it has not been possible to do fault plane solutions which would be of the greatest interest.

(iii) *Northern Afar*

The epicentres for this region are shown in figure 12 and details are given in table 4. Figure 12 shows that some of the earthquakes are associated with the western marginal scarp and some are just to the north of the Danakil horst. The magnetic anomalies (succeeding paper) are somewhat confused in this region but the general trend is NW–SE.

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5. Earthquake mechanisms

To assist the understanding of the tectonics of the area, all the events listed were examined for the possibility of obtaining fault plane solutions. Only three solutions were possible, two in the Red Sea and one in the Gulf of Aden (Alula–Fartak trench). These are listed in table 8. Full details of the Red Sea solutions are given in Fairhead (1968) and the Gulf of Aden solution is by Sykes (1968). The data for the southern Red Sea event of 11 November 1962 was also worked by Sykes who obtained a similar solution.

Table 8. Fault plane solutions

	origin time		lat.	long.			
		h min s	°N	°E	m_b	strike	dip
Central Red Sea	1967 Mar. 13	19 22 16.3	19.79	38.82	5.8	N 53°	82° SE
Southern Red Sea	1962 Nov. 11	15 15 33.9	17.22	40.58	5.6	N 49°	78° SE
Alula–Fartak trench	1959 Dec. 21	11 19 18.7	13.98	51.82	6.7	N 33°	75° SE

For the 13 March 1967 event, first motions were obtained from W.W.S.S.N. long period records and all available bulletin data. More than 50 stations were used and only two of the seismograms read were inconsistent with the solution obtained. These were the Indian array station and New Delhi. The first has short-period data and the second lies close to the nodal plane of the solution. The solution shows clear strike-slip motion with nearly vertical fault and nodal planes. The two planes have strike N 053°, dip 82° SE and strike N 141°, dip 83° NE respectively. The first was chosen as the fault plane as it best fits what is known about the movement of Arabia, i.e. data from the Aqaba–Dead Sea rift and the transform faults of the Gulf of Aden. The fault plane movement is dextral.

By similar arguments, the southern Red Sea event of 11 November 1962 gave a fault plane with strike N 049°, dip 78° SE and nodal plane with strike N 141° and dip 81° SW. The fault plane movement is sinistral. It is emphasized that data for this solution are very poor, the event occurring before the introduction of W.W.S.S.N. There is a shortage of long period records and the azimuthal distribution of stations is bad. The solution is thus subject to large error.

The two solutions are illustrated on a simplified bathymetric map in figure 15. There seems to be no simple correlation between the motion associated with the 13 March 1967 event and the bathymetry. However, the overall seismicity and bathymetry of the region (figure 9 and § 4*b* (ii)) suggest the possible presence of a transform fault but the strike is nearer to N 020° than N 053°. For the 11 November 1962 event, there appears to be a relation with the bathymetry (figure 14) but this may not be structural, as to the south the bathymetry is complicated by the build up of evaporites and corals (Girdler 1968).

Assuming that both earthquakes occurred to the east of the axis of deepest water (this is by no means certain for the pre-1963 event) the simplest explanation of the fault movements is shown in figure 15. This invokes differential spreading on the eastern side of the Red Sea. The region of most recent spreading is probably approximately delineated by the 500 fathom (914 m) contour and is shown shaded. The agreement between the strikes (N 049° and N 053°) is thought to be fortuitous.

The 21 December 1959 event in the Gulf of Aden has been related to the bathymetry by Sykes (1968, figure 14). The motion was shown to be consistent with transform fault movement along the Alula–Fartak trench.

All three fault plane solutions are shown in figure 16 on an azimuthal great circle projection centred on 26° N, 21° E, the pole of rotation for Africa calculated by Le Pichon (1968). On this projection, distances and angles are correct from the centre. The small circles are at 5° intervals

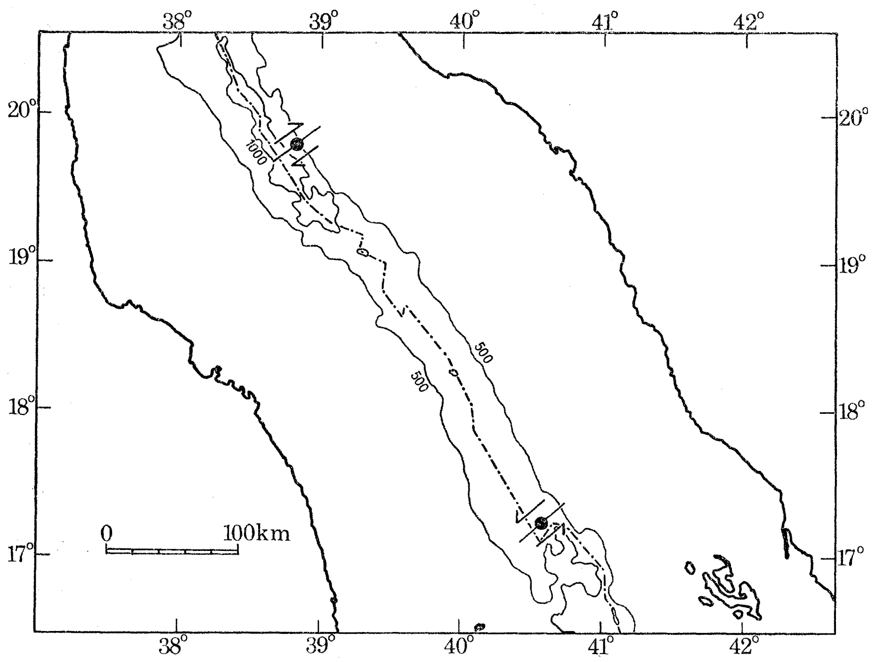

FIGURE 14. Fault-plane solutions for the Red Sea. The 500 fathom (914 m) and 1000 fathom (1829 m) contours are from the bathymetric chart of Laughton (1968). The dashed line marks the axis of deepest water.

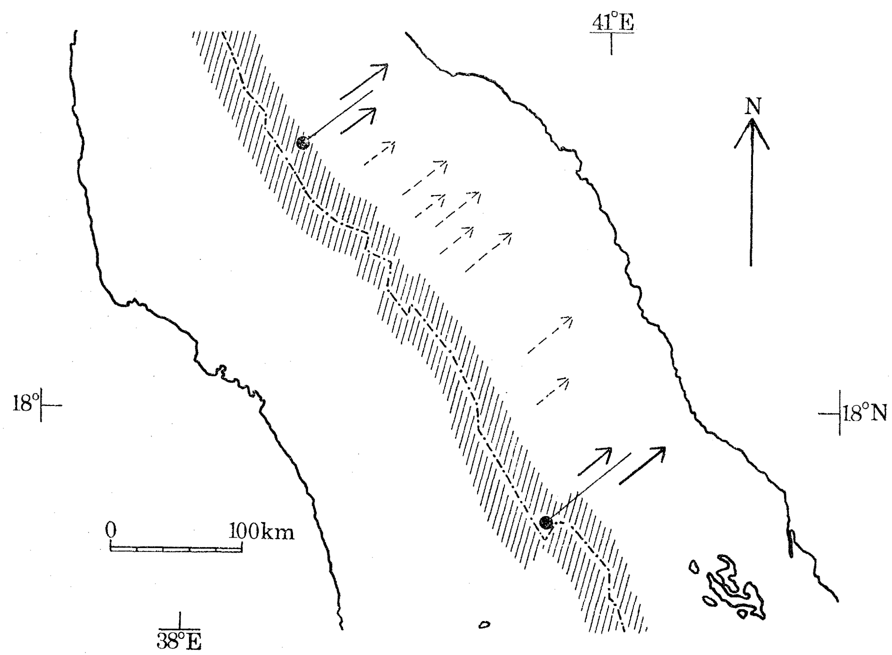

FIGURE 15. A possible interpretation of the fault-plane solutions of figure 14 in terms of differential spreading from the axis of the Red Sea.

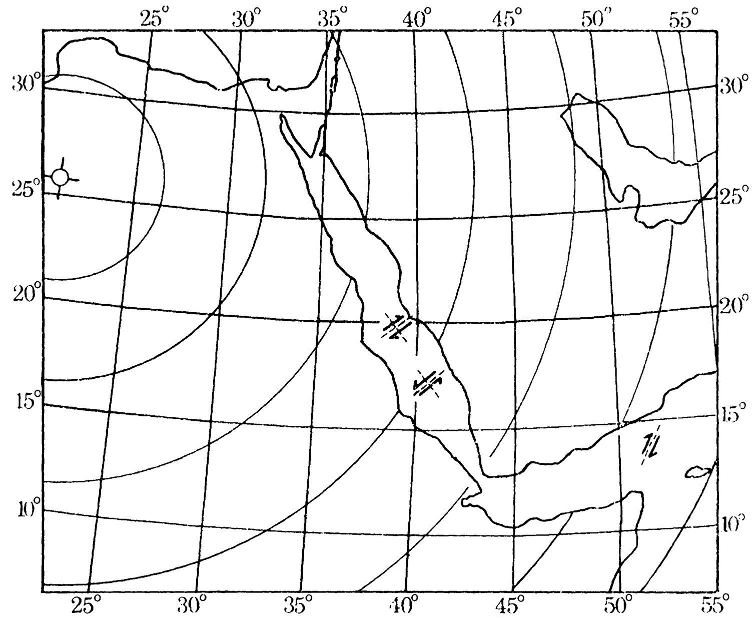

FIGURE 16. Fault-plane solutions for the Red Sea and Gulf of Aden plotted on an azimuthal great circle projection centred on the African (Arabia–Somalia) pole of rotation at 26° N, 21° E (Le Pichon 1968). Distances and angles are correct from the centre of rotation.

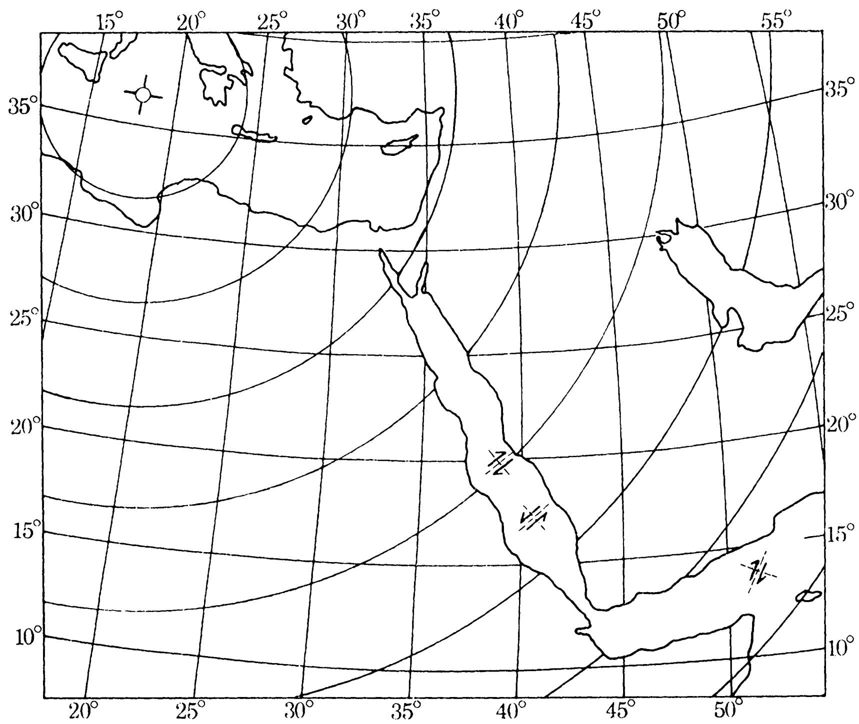

FIGURE 17. Fault-plane solutions for the Red Sea and Gulf of Aden plotted on an azimuthal great circle projection centred on the Arabia–Nubia pole of rotation at 36.5° N, 18.0° E. Distances and angles are correct from the centre of rotation.

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and the directions of movement should be parallel to these small circles. The pole was computed from Gulf of Aden, Owen fracture zone and Indian Ocean data. The Gulf of Aden fault plane solution may therefore be expected to be in agreement with this pole. It is seen that the Red Sea fault plane solutions are only in approximate agreement. This could be due to poor quality of the fault plane solutions as previously discussed and/or the possibility that there may be three independent plates (Nubia, Somalia and Arabia) instead of two (Africa and Arabia).

The second possibility can be checked. The shorelines of the Red Sea fit so well that it is easy to compute a pole of rotation for Arabia–Nubia. This pole is at 36.5° N, 18.0° E and is shown in figure 17. It is seen that the Red Sea fault plane solutions are in agreement with this pole. There is therefore some evidence for the existence of three plates.

6. Conclusions

Seismicity studies, both on a global and local scale, have aided the understanding of the tectonics and origin of the Red Sea and Gulf of Aden. From this study the following conclusions maybe drawn.

(*a*) The complete absence of deep earthquakes ($h \geqslant 100$ km) throughout and to the south of Africa support the view that the Afro-Arabian plate is moving generally in a northerly direction and is underthrusting the northern Mediterranean, Turkey and Iran.

(*b*) The axes of both the Red Sea and Gulf of Aden are regions of shallow seismicity, the earthquakes occurring where new crust is forming as the African and Arabian plates separate.

(*c*) The j.e.d. method of relocating epicentres is particularly successful for relating earthquake trends to structural trends.

(*d*) Surprisingly few earthquakes have been recorded teleseismically for the northern Red Sea. The seismicity of the central and southern Red Sea is mainly confined to the deep, axial trough with the possibility of a NNE transform fault between 20 and 21° N.

(*e*) The seismicity of the Gulf of Aden is mainly associated with the central rough zone and many earthquakes concentrate on or near the NNE transform faults. The way in which the epicentres follow the axial rift of the Sheba Ridge and the alinement of post-1963 epicentres along the Alula–Fartak trench are particularly impressive. It is noted that the seismically active zone lies slightly asymmetrically to the north of a line bisecting the Gulf of Aden.

(*f*) The Gulf of Aden seismic zone continues west through the Gulf of Tadjoura and across the Afar depression to intersect the western marginal scarp. The magnetic anomalies also follow this trend.

(*g*) All three fault plane solutions show strike-slip motion. The fault plane solution for the Gulf of Aden is consistent with the Arabia–Somalia pole of rotation and the solutions for the Red Sea are consistent with the Arabia–Nubia pole of rotation supporting the possibility of three independent plates.

(*h*) The seismicity of the junction area of the Red Sea, Gulf of Aden and Ethiopian rifts, especially the way in which the Gulf of Aden seismic zone continues west across Afar also support the suggestion of three independent rigid plates.

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References (Fairhead & Girdler)

Blamey, C. & Gibbs, P. G. 1968 The epicentres and origin times of some large explosions. *Geophys. J. R. astr. Soc.* **16**, 1–7.

Bolt, B. A. 1960 The revision of earthquake epicentres, focal depths and origin times using a high-speed computer. *Geophys. J. R. astr. Soc.* **3**, 433–440.

Douglas, A. 1967 Joint epicentre determination. *Nature, Lond.* **215**, 47–48.

Drake, C. L. & Girdler, R. W. 1964 A geophysical study of the Red Sea. *Geophys. J. R. astr. Soc.* **8**, 473–495.

Fairhead, J. D. 1968 The seismicity of the East African rift system 1955 to 1968. M.Sc. Dissertation, University of Newcastle upon Tyne.

Francis, T. J. G. 1968 The detailed seismicity of mid-oceanic ridges. *Earth & Plan. Sci. Lett.* **4**, 39–46.

Girdler, R. W. 1964*a* Geophysical studies of rift valleys. *Phys. Chem. Earth* **5**, 121–156.

Girdler, R. W. 1964*b* How genuine is the circum-Pacific belt? *Geophys. J. R. astr. Soc.* **8**, 537–540.

Girdler, R. W. 1965 The evolution of new oceanic crust. *Phil. Trans. Roy. Soc. Lond.* A **258**, 123–136.

Girdler, R. W. 1966 The role of translational and rotational movements in the formation of the Red Sea and Gulf of Aden. *Symp. World Rift System, Ottawa, Canada*, Sept. 1965, *Geol. Surv. Pap. Can.* **66**–14, 65–77.

Girdler, R. W. 1968 Drifting and rifting of Africa. *Nature, Lond.* **217**, 1102–1105.

Girdler, R. W. 1969 The Red Sea—a geophysical background. In *Hot brines and recent heavy metal deposits in the Red Sea* (Degens, E. T. and Ross, D. A., eds.), pp. 38–58. New York: Springer-Verlag.

Gutenberg, B. & Richter, C. F. 1949, 1954 *Seismicity of the Earth and associated phenomena*, 1st and 2nd editions. Princeton University Press.

Laughton, A. S. 1966*a* The Gulf of Aden. *Phil. Trans. Roy. Soc. Lond.* A **259**, 150–171.

Laughton, A. S. 1966*b* The Gulf of Aden in relation to the Red Sea and the Afar depression of Ethiopia. *Symp. World Rift System, Ottawa, Canada*, Sept. 1965, *Geol. Surv. Pap. Can.* **66–14**, 78–97.

Le Pichon, X. 1968 Sea-floor spreading and continental drift. *J. geophys. Res.* **73**, 3661–3697.

Lilwall, R. C. & Douglas, A. 1969 Quest for a P travel time standard. *Nature, Lond.* **222**, 975–977.

McKenzie, D. P. & Parker, R. L. 1967 The north Pacific: an example of tectonics on a sphere. *Nature, Lond.* **216**, 1276–1280.

Matthews, D. H., Williams, C. A. & Laughton, A. S. 1967 Mid-oceanic ridge in the mouth of the Gulf of Aden. *Nature, Lond.* **215**, 1052–1053.

Morgan, W. J. 1968 Rises, trenches, great faults and crustal blocks. *J. geophys. Res.* **73**, 1959–1982.

Oliver, J. & Isacks, B. 1967 Deep earthquake zones, anomalous structures in the Upper Mantle and the Lithosphere. *J. geophys. Res.* **72**, 4259–4275.

Rothé, J. P. 1954 La zone seismique médiane Indo-Atlantique. *Proc. Roy. Soc. Lond.* A **222**, 387–397.

S.I.P.R.I. 1968 *Seismic methods for monitoring underground explosions.* Rap. D. Davies. Stockholm: Int. Inst. Peace & Conflict Res.

Sykes, L. R. 1968 Seismological evidence for transform faults, sea-floor spreading and continental drift. In *History of the Earth's crust* (ed. Phinney, R. A.), Princeton University Press.

Sykes, L. R. & Landisman, M. 1964 The seismicity of East Africa, the Gulf of Aden and the Arabian and Red Seas. *Bull. seism. Soc. Am.* **54**, 1927–1940.

Vine, F. J. 1966 Spreading of the ocean floor: new evidence. *Science, N.Y.* **154**, 1405–1415.

Appendix 1. Gulf of Suez earthquakes, 24 March 1969 through 9 August 1969

A large earthquake (m_b = 6.0) occurred near the mouth of the Gulf of Suez on 31 March 1969. It was preceded by three foreshocks and followed by seventeen aftershocks. The main shock was located using U.S.C.G.S. bulletin data and the travel time curve of Lilwall & Douglas (1969) incorporating station time corrections. The foreshocks and aftershocks were relocated with respect to this event using j.e.d. The events are listed in table 9 and shown in figure 18.

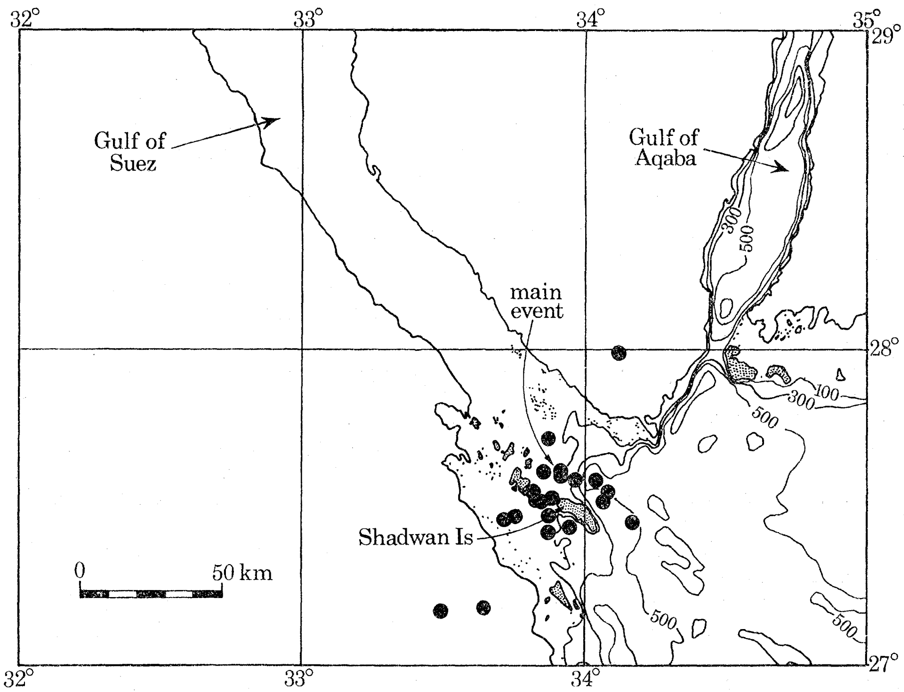

Figure 18. J.e.d. relocations of the foreshocks and aftershocks of the Gulf of Suez earthquake of 31 March 1969. Contours (in corrected fathoms) after A. S. Laughton (1968).

It is seen from figure 18 that most of the earthquakes occurred near the mouth of the Gulf of Suez in the neighbourhood of Shadwan island. The fault plane solution indicates normal faulting with northwesterly strike (A. Ben-Menahem, personal communication). This is consistent with the geology, the Gulf of Suez being a normal faulted structure. It is likely that these events were associated with block faulting in the neighbourhood of Shadwan island.

The magnitude–frequency graph for these events gives the relation

$$\lg N = 10.68 - 1.99 m_b.$$

The high value of b (1.99) is also consistent with normal faulting if the suggestion of Francis (1968) that rift zones have high values and fracture zones low values is correct.

The magnitude–frequency graph shows a divergence from the logarithmic relation for $m_b < 4.7$ indicating that events above magnitude 4.7 are reliably determined in the Gulf of Suez region.

TABLE 9. GULF OF SUEZ EARTHQUAKE SEQUENCE
24 MARCH 1969 THROUGH 9 AUGUST 1969

	U.S.C.G.S.			j.e d.				
date	h min s	lat.	long.	h min s	lat.	long.	N	m_b
1969 Mar. 24	11 54 15.5	27.53° N	33.83° E	11 54 16.2	27.52° N	33.84° E	40	5.2
1969 Mar. 24	12 50 50.5	27.57	33.78	12 50 51.6	27.55	33.81	35	4.8
1969 Mar. 27	06 15 29.9	27.53	33.94	06 15 31.6	27.53	33.88	23	4.7
†1969 Mar. 31	07 15 54.4	27.67	33.99	07 15 54.4	27.62	33.91	135	6.0
1969 Mar. 31	09 01 12.7	28.40	34.38	09 01 11.3	27.99	34.11	14	4.9
1969 Mar. 31	11 29 59.5	27.59	34.15	11 30 00.0	27.42	33.86	13	4.6
1969 Mar. 31	21 44 27.3	27.46	34.03	21 44 28.5	27.43	33.96	33	5.0
1969 Mar. 31	22 40 47.0	27.43	34.07	22 40 49.0	27.47	33.87	15	4.7
1969 Apr. 03	20 06 13.6	27.44	33.97	20 06 16.4	27.52	33.82	9	4.5
1969 Apr. 04	12 18 47.2	27.68	34.07	12 18 49.2	27.71	33.86	27	4.7
1969 Apr. 05	17 51 10.9	27.47	34.23	17 51 13.0	27.55	34.08	14	4.5
1969 Apr. 08	10 31 52.2	27.50	33.72	10 31 52.9	27.46	33.71	47	5.2
1969 Apr. 13	16 15 11.3	27.62	33.84	16 15 11.3	27.47	33.75	15	4.8
1969 Apr. 14	13 43 54.8	27.08	33.28	13 43 55.9	27.17	33.49	15	4.9
1969 Apr. 16	08 12 54.6	27.59	33.97	08 12 57.1	27.60	33.91	8	5.0
1969 Apr. 17	08 01 04.1	27.63	34.01	08 01 05.9	27.59	33.96	16	4.8
1969 Apr. 23	13 37 21.0	27.59	33.94	13 37 22.3	27.61	33.85	45	5.0
1969 May 10	09 27 57.0	27.50	34.18	09 27 58.9	27.51	34.07	36	4.8
1969 May 25	11 32 38.6	27.62	33.98	11 32 39.8	27.59	34.04	24	4.8
1969 Aug. 03	23 51 10.2	27.55	33.91	23 51 08.7	27.18	33.63	11	4.5
1969 Aug. 09	13 28 31.9	27.67	33.75	13 28 32.1	27.45	34.17	7	4.7

† Restrained master event.

APPENDIX 2. ETHIOPIAN EARTHQUAKES, 29 MARCH 1969 THROUGH 5 MAY 1969

A large earthquake ($m_b = 5.8$) occurred in Ethiopia on 29 March 1969 and was followed by eleven aftershocks, the first of these was less than 2 h after the main shock with magnitude $m_b = 5.6$. The main event was located using U.S.C.G.S. bulletin data and the Lilwall & Douglas (1969) travel time curve. The aftershocks were relocated with respect to the main

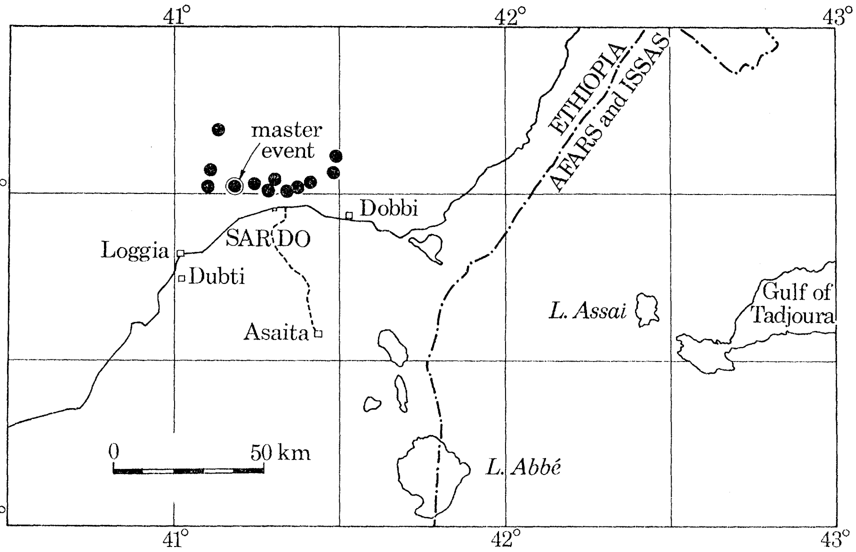

FIGURE 19. The Ethiopian (Sardo) earthquake of 29 March 1969 together with j.e.d. relocated aftershocks.

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event using j.e.d. Details of the events are given in table 10 and the epicentres are show in figure 19.

Figure 19 shows that the events follow the west–east Gulf of Aden trend and are close to the line of events (figure 8) extending westward from the Gulf of Tadjoura. The magnitude–frequency plot gives the relation

$$\lg N = 4.71 - 0.76 m_b,$$

the low value of b (0.76) shows that these events may be associated with shear motion (Francis 1968).

Table 10. Ethiopian earthquake sequence 29 March 1969 through 5 May 1969

date	U.S.C.G.S. h min s	U.S.C.G.S. lat.	U.S.C.G.S. long.	j.e.d. h min s	j.e.d. lat.	j.e.d. long.	N	m_b
†1969 Mar. 29	09 15 54.1	12.0° N	41.2° E	09 15 54.3	12.02° N	41.18° E	72	5.8
1969 Mar. 29	11 04 47.9	11.96	41.29	11 04 48.3	12.03	41.24	54	5.6
1969 Mar. 29	11 07 29.9	11.99	41.21	11 07 30.5	12.06	41.48	21	5.3
1969 Mar. 29	13 08 11.4	11.94	41.52	13 08 12.7	12.03	41.41	23	5.1
1969 Mar. 29	18 30 42.2	12.00	41.38	18 30 42.6	12.01	41.34	8	4.6
1969 Apr. 05	02 18 29.9	12.15	41.20	02 18 30.4	12.19	41.13	46	6.2
1969 Apr. 05	20 06 23.8	11.09	41.10	20 06 25.0	12.02	41.10	6	4.3
1969 Apr. 05	20 14 35.9	12.02	41.47	20 14 37.1	12.11	41.49	19	4.9
1969 Apr. 06	16 51 45.5	12.03	41.12	16 51 46.1	12.07	41.11	39	5.2
1969 Apr. 07	06 23 53.4	11.98	41.28	06 23 54.4	12.04	41.30	14	4.6
1969 Apr. 08	02 13 58.7	11.93	41.31	02 14 00.0	12.02	41.37	18	4.8
1969 May 05	02 45 38.9	11.94	41.26	02 45 40.2	12.01	41.28	20	5.2

† Restrained master event.

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