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Seismicity re-evaluation of the northern Red Sea

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SUMMARY

The Aqaba subnetwork of five vertical short-period stations of the seismological observatory of King Saud University was installed in late 1986 along the eastern side of the Gulf of Aqaba, northern Red Sea. During the first six years (1986 August to 1992 July) of the subnetwork operation, 400 microearthquakes were detected. Of these, 93 events were recorded by most of the subnet stations and were located. Their epicentres lie in the northern part of the Red Sea between latitudes 25.5 °N and 27.5 °N and longitudes 33.5 °E and 36 °E along the axial depression of the Red Sea where the large intrusions (deeps) are located. Magnitudes of the locatable events ranged from 2.1 to 4.8. Two intensive swarms of about 200 microearthquakes occurred in February and June of 1992. The February swarm is the first intensive sequence observed in the surveying area since the establishment of the KSU network. Frequency–magnitude analysis of the recorded events for the period 1986–1992 yielded 3.543 for *a* and 0.658 for *b*. These relatively higher *b* values (0.658) are a good indication of the crustal heterogeneity under the spreading zone of the northern Red Sea. USGS and KSU data together show 3.41 for *a* and 0.49 for *b*. This study, together with historical data, confirms that the area is very seismically active and that the activity is mainly of swarm type, and may be attributed to the subsurface magmatic activity and spreading centres that are usually associated with strike-slip and normal faulting, respectively.

Key words: earthquake, N Red Sea, seismicity.

INTRODUCTION

The physiography of the Red Sea is characterized by the presence of three structural features: the coastal shelves, a main trough and a deep axial trough with active seafloor spreading (Drake & Girdler 1964; McKenzie, Davis & Molnar 1970; Girdler & Styles 1974, 1978). The main trough covers the central part of the Red Sea, extends over a distance of about 1500 km and is generally shallower than 1 km. This trough is cut near its centre by the axial trough, whose width varies from about 30 km in the north to about 10 km in the south. Evidence of seismic activity in the Red Sea indicates that the axial trough is an area of active spreading with strike-slip movement along NE–SW-trending transform faults (Fairhead & Girdler 1970). The northern Red Sea is characterized by a wide main trough (Coleman 1974), currently at the stage of continental rifting, and beginning to undergo the transition to oceanic seafloor spreading. The rift can be divided into two distinct provinces within the main trough of the northern Red Sea north of latitude 26 °N, which have been identified by Martinez & Cochran (1988) as 'marginal areas' and an 'axial depression' (Fig. 1). The marginal areas form a series of bathymetric terraces that step down from the eastern and western shelves towards the central part of the Red Sea. Geophysical data obtained by Martinez & Cochran (1988) indicate that the marginal areas are underlain by faulted and tilted basement blocks. The lack of magnetic expression of the seafloor is attributed to the tectonic regime of diffuse extension (Mart & Hall 1984). Seismic reflection profiles of the evaporates and overlying sediments in the marginal areas show that they are affected by relatively widely spaced faulting and salt tectonics, which in many cases appears to have been activated by the faulting. Tectonic activity in the marginal areas continues to the present, as indicated by several small grabens that offset the most recent sediments (Martinez & Cochran 1988). However, from the historical seismicity data, Barazangi (1981) and Ambraseys & Melville (1989) suggested that much of the Red Sea activity is of swarm type and is related to volcanism (the 1256 earthquake of Al-Madina) and tectonics (the 1068 earthquake). Previous research (Ben-Menahem & Aboodi 1971; El-Isa & Al-Shanti 1989) indicated little seismic activity in the northern Red Sea area. Al-Amri (1995) stated that the northern part of the Red Sea could not be considered as a seismic gap. Most of this activity is concentrated in the vicinity of latitude 27.5 °N, where the Red Sea bifurcates into two gulfs, the Suez and the Aqaba. Many microearthquakes

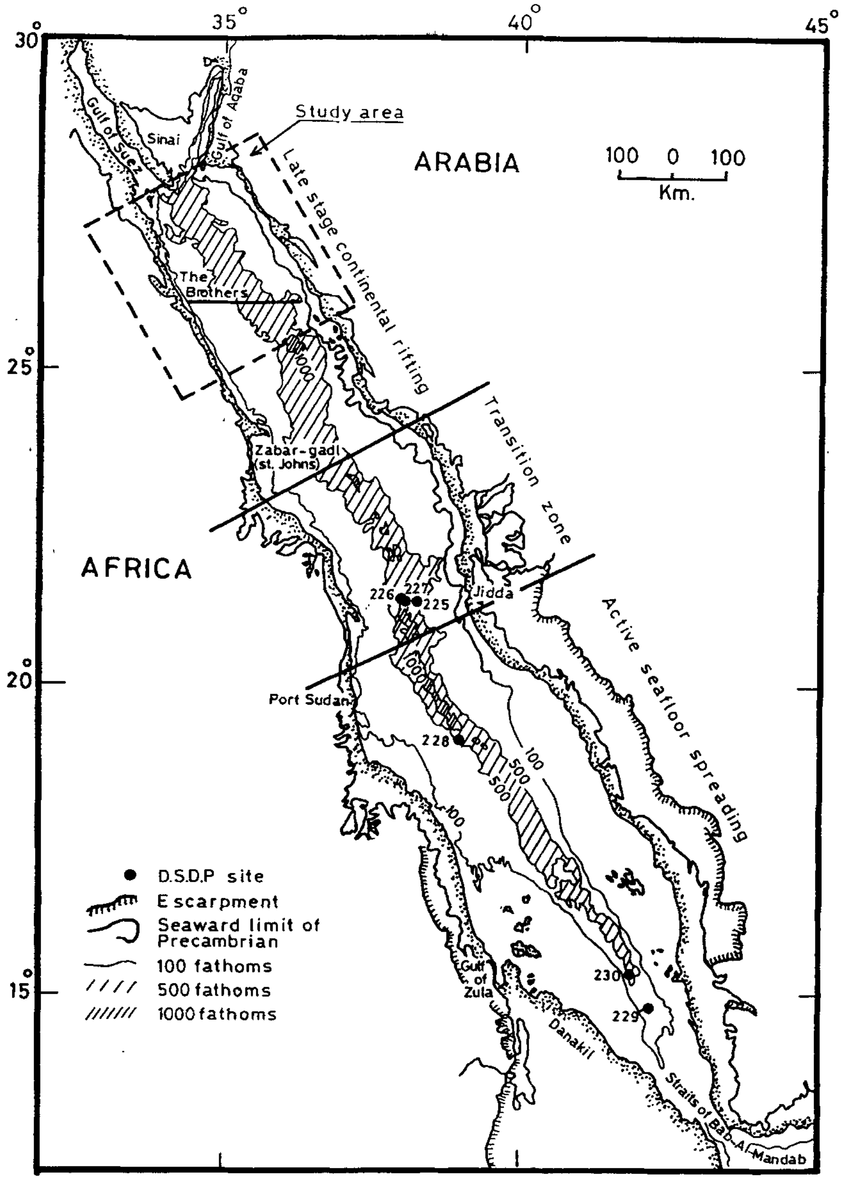

Figure 1. Map of the Red Sea showing division into three sections representing different stages in the development of the margin, where the northern section of the Red Sea is the last stage of the continental extension (after Martinez & Cochran 1988).

were also detected in the Red Sea coastal region near Yanbu in 1979 (Merghelani 1981). Recently, a few earthquake sequences occurred in the northern Red Sea and were recorded by the seismological stations in the Middle East region: October 1982, February 1983, February 1985, April 1986, February 1992 and June 1992. Some of those sequences were recorded by KSU stations; they will be discussed in this study. The epicentral locations of the activity are clustered in a small area with no significant single large events (main shock). This type of earthquake sequence, consisting of many relatively small events in a local area, is called an earthquake swarm (Mogi 1963). Earthquakes of this type are generally associated with magmatic, volcanic and man-made activities, such as impounding of dams, fluid injection and oil extraction. Seismic activity in the northern Red Sea south of the Gulf of Suez area is concentrated in the axial depression, and heat-flow profiles across the main trough show maximum values, which occur consistently over the axial depression (Martinez & Cochran 1988).

The purpose of this study is to investigate the characteristics of the seismicity mentioned above of the northern part of the Red Sea and to correlate, where possible, the seismicity of the region with the existing tectonics features.

GENERAL GEOLOGY AND TECTONICS

The history of the Red Sea has been much debated and is very controversial. Girdler & Styles (1974, 1978), Styles & Hall (1980) and Girdler (1985) believed, on the basis of their interpretations of magnetic, bathymetric and gravity profiles, that two stages of seafloor spreading were involved in the opening of the Red Sea. The first stage occurred between 23.5 and 16 Ma and was followed by a quiet period that witnessed the deposition of up to 5 km of evaporites in the main trough.

The second stage of spreading started from around 4.5 Ma and has continued to the present. In an alternative model, Bonatti (1985) and Cochran (1981, 1983) proposed that extension has been continuous since the Oligocene but that seafloor spreading has only been active during the past 5 Ma. It is generally considered that the Arabian plate separated from Africa in a northeasterly direction and that several transform faults trending NE–SW may have been formed (Hall, Andersen & Girdler 1976). Distributions of new and older oceanic crust for the northern Red Sea (zones 1 and 2) and continental crust (zone 3) are shown in Fig. 2. Diapirs are very abundant in the northern Red Sea from the Late Miocene. They are associated with the rifts and are encountered along the rifts' boundary faults. Mart & Hall (1984) suggested that the absence of linear magnetic anomalies on the one hand, and the presence of extensional rifts and diapirs on the other, indicate a tectonic regime of diffuse extension in which continental separation, rifting and crustal thinning occurred prior to the spreading of the seafloor and the evolution of the accreting plate boundary. The lack of magnetic expression of the seafloor in the northern Red Sea could be attributed to the presence of evaporites, which permit the seafloor to cool more slowly and thereby acquire a reduced thermoremanent magnetization (Hall 1979) due to a coarser grain size. This implies that the oceanic crust is intruded beneath the salt where the temperatures are high. The rifts in the northern Red Sea are commonly 25–50 km long and 7 km wide but they appear to be at the initial stage of evolution (Cochran 1983). In many places, rifts were found to change their structural patterns and become inactive, and their boundary faults did not offset the uppermost sedimentary strata (Mart & Hall 1984). However, the northern Red Sea is an intermediate stage between a continental rift valley and a young ocean basin and delineation of its structure and tectonics allows a model to be developed for the evolution of a rifted continental margin (Cochran & Martinez 1988). Cochran & Martinez (1988) suggested that extension at this stage is concentrated in an axial depression and begins to be partially accommodated by large intrusions that form deeps whose positions are controlled by the transfer zones established in the earliest stages of rifting. Rifting starts in a series of linked half-grabens 50–60 km long formed over detachment surfaces that probably penetrate no deeper than the mid- or lower crust. Gaulier *et al.* (1988) acquired seismic profiles along the Gulf of Suez and northern Red Sea and found a 4 km thick sedimentary section above a 9.25 km thick crust consisting of layers with seismic *P*-wave velocities of 5.8, 6.4–6.6 and 7 km s^{-1}. However, the crust near 27 °N shows low velocities and is thin, with a thickness typical of continental crust, while it shows higher velocities and is thicker near 26 °N. The difference in the crustal velocities determined for the northern (near latitude 27 °N) and southern (near latitude 26 °N) parts of the northern Red Sea has been interpreted by Gaulier *et al.* (1988) as being related to a fundamental change in the nature of the basement observed onshore.

The seismic activity in the axial trough of the Red Sea supports the interpretation of the magnetic data in terms of seafloor spreading. Earthquakes probably occur where new oceanic crust is being formed. Along the Red Sea, the seismic activity was higher in the southern part and in the two gulfs than in the northern part, while there was no significant earthquake activity in the middle part of the Red Sea between latitudes 22 and 25 °N.

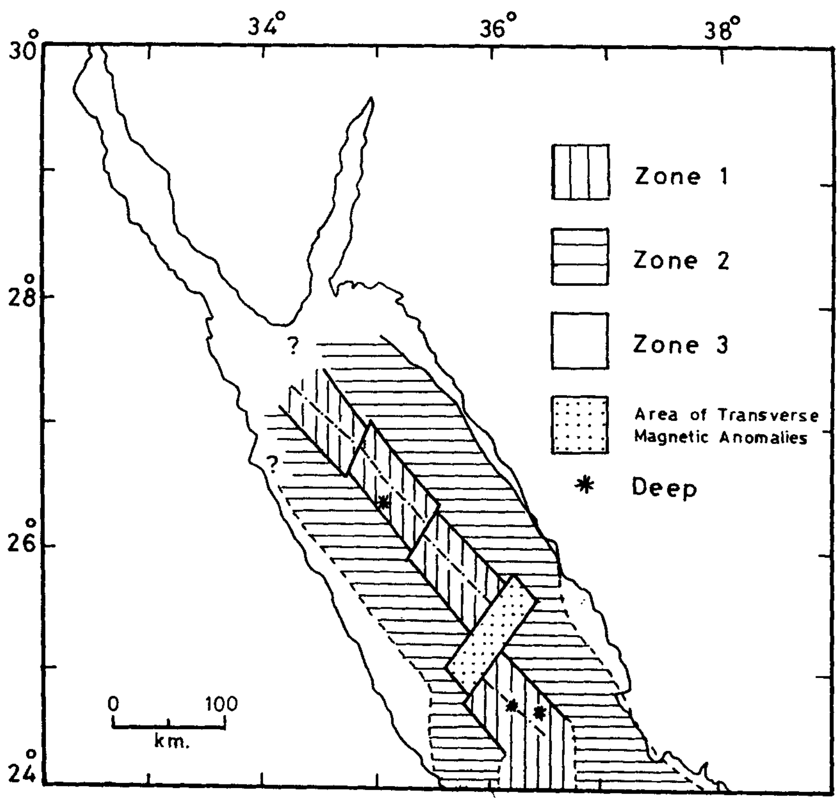

Figure 2. Crustal structure of the northern Red Sea. Zones 1 and 2 are underlain by oceanic crust and zone 3 is underlain by continental crust (Hall *et al.* 1976).

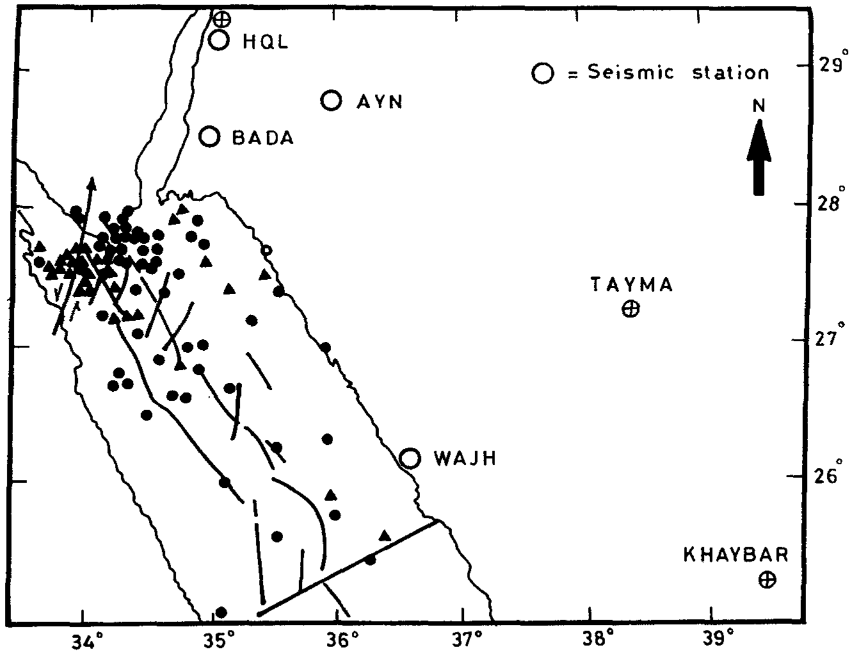

Figure 3. Tectonic map of the northern Red Sea showing previous seismicity, historical and instrumental data from 1952 to 1991, where circles with crosses indicate historical felt localities with intensity IX for the 1068 earthquake, solid triangles indicate USGS epicentres and solid circles indicate KSU epicentres.

PREVIOUS SEISMICITY

At least four historical earthquakes have occurred in the northern Red Sea region within the period AD 627–1588 (Ambraseys 1978; Ambraseys & Melville 1989). A historical earthquake in 1068 been reported as being located in the NW of Arabia close to the Red Sea centre (Poirier & Taher 1980) and was felt with VIII intensities (a tentative epicentre is shown in Fig. 3) at Khayber, Taym and Aqaba. The historic volcanic eruptions of Al-Madina in 1122 and 1256 were accompanied by an earthquake swarm that began a few days before the eruption. This volcanic eruption near Madina has not resulted in any significant earthquake activity in this century.

By searching the USGS data tapes for the events that have occurred in the region and that were recorded by stations in the neighbouring countries since 1952–1985, 40 earthquakes with magnitudes >4.0 (Table 2) were found in the northern Red Sea north of latitude 25 °N (Fig. 3). 27 of them were located in the mouth of the Gulf of Suez, mainly beneath Shadwan Island (Maamoun 1976; Dagget *et al.* 1982). Some of these events are associated with transverse structure (e.g. 1955 November 12, $M = 6.0$), while a few earthquakes occurred within the trough zone (e.g. 1972 October 14, $M = 4.8$, Maamoun 1976). The fault-plane solutions for the 1969 Shadwan activity are normal dip-slip along northwest-striking nodal planes (Dagget *et al.* 1982). However, the high 1969 Shadwan activity is classified as foreshock, main-shock ($m_b = 6.9$) and aftershock type (Maamoun & El Khashab 1978), which is different from the other northern Red Sea activity.

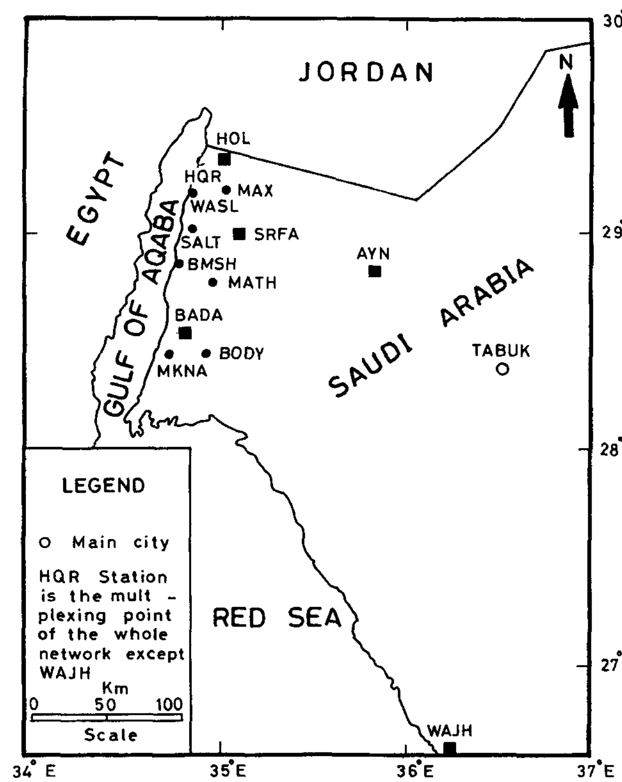

Figure 4. Location map of the Aqaba and NW Saudi Arabia subnet stations, where solid squares show stations installed in 1986 and solid circles show stations installed in 1993.

RECENT SEISMICITY (KSU DATA)

All the data after 1986 used in this study were obtained from the records of the Aqaba subnetwork of the KSU observatory. A location map of the stations is shown in Fig. 4. Typical seismograms from the station WAJH are shown in Figs 5 and 6. The analogue seismograms were read for P arrival times and polarities, S times and coda duration. The accuracy of the readings was ± 0.07 s for P (P_g and P_n) and ± 0.1 s for S (S_g

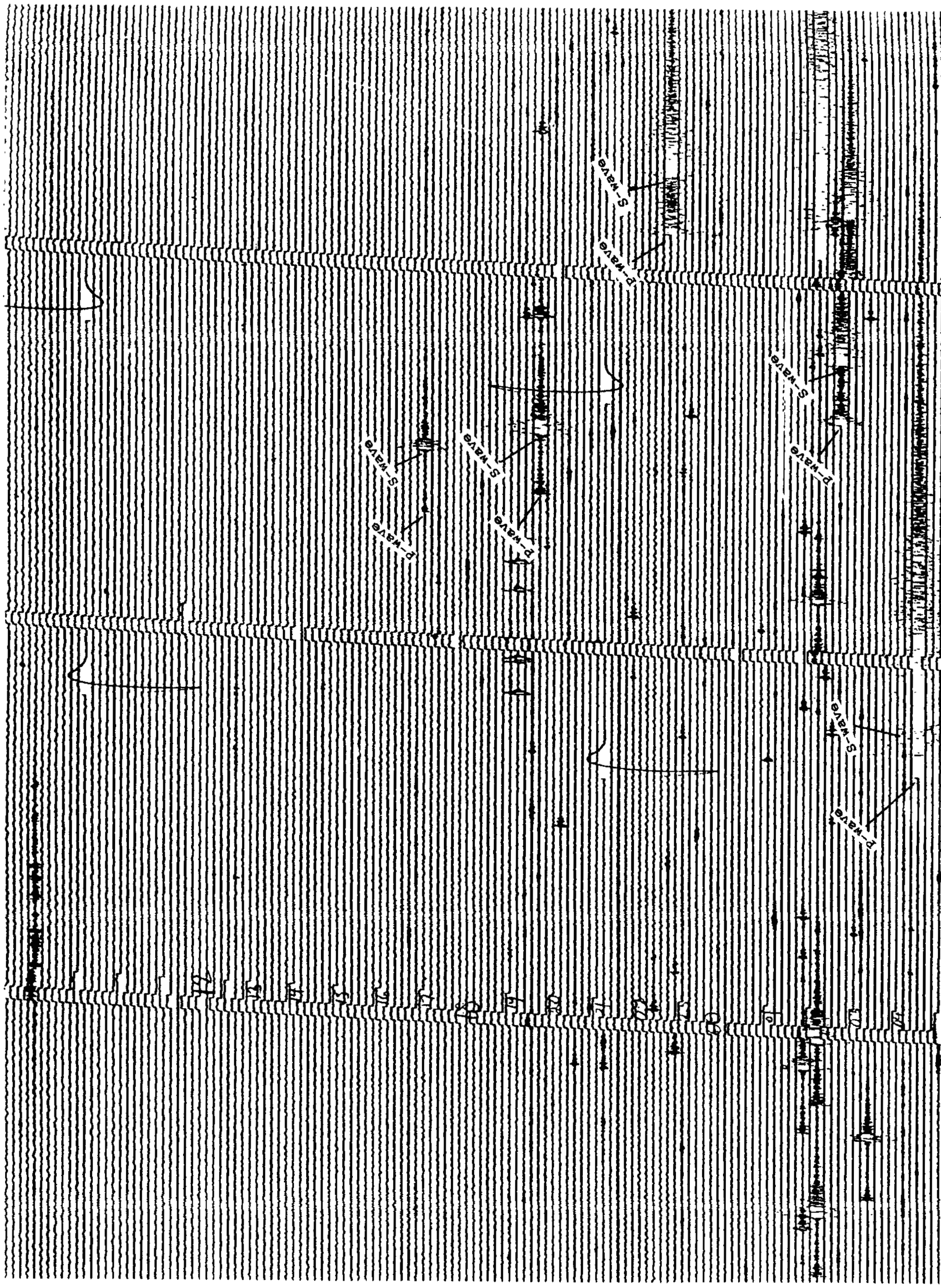

Figure 5. Typical seismogram of the first 24 hours of the 1992 February 18–19 swarm recorded by the WAJH short-period station.

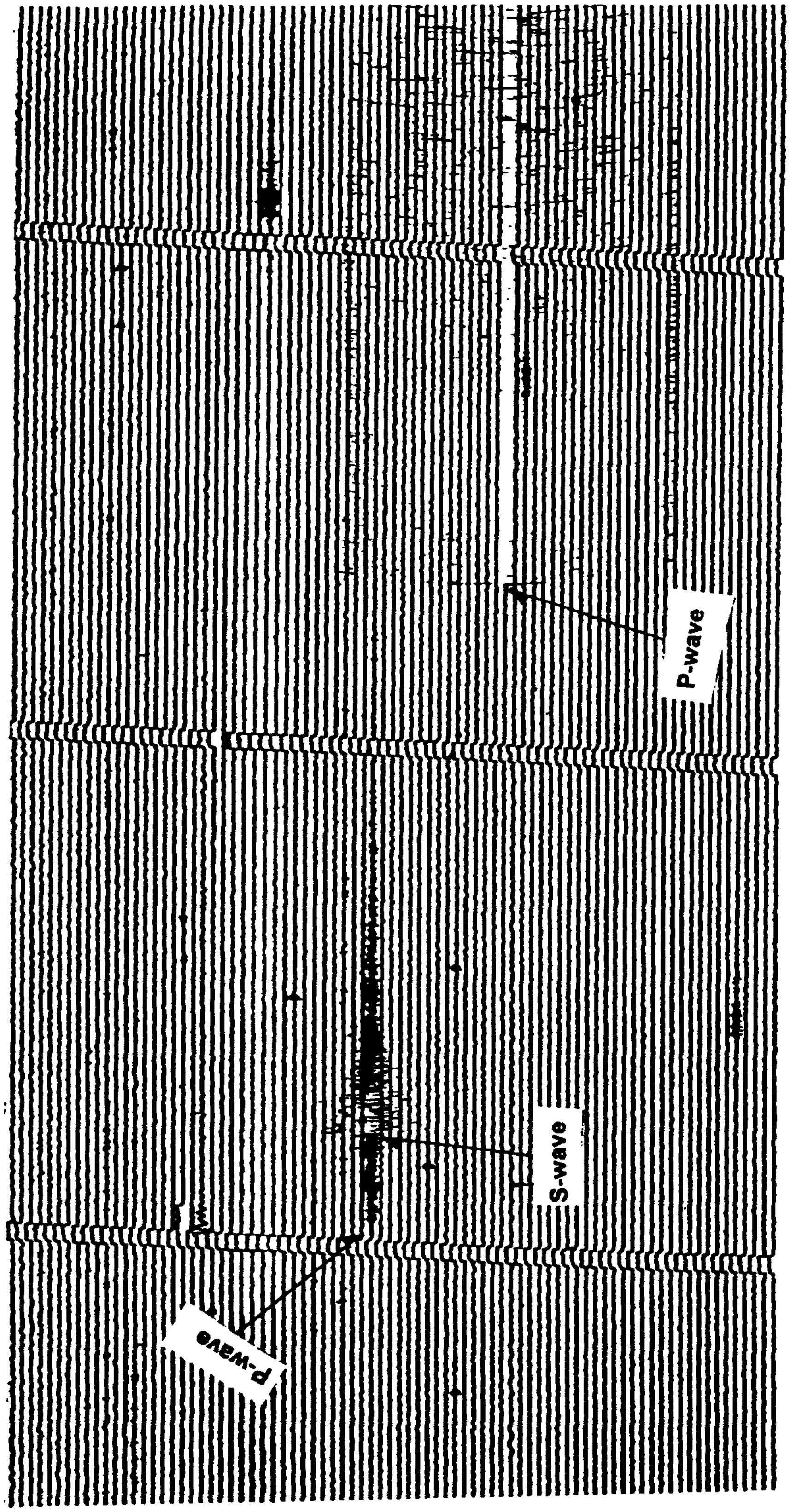

Figure 6. Typical seismogram of the 1992 June 2 swarm recorded by the WAJH short-period station.

Table 1. Crustal structure model for the Aqaba region assuming $V_p/V_s=1.73$ (after El-Isa *et al.* 1987).

V_p (km sec^{-1})	Depth (km)
3.50	0.0
6.05	1.5
6.50	18.0
6.65	20.0
7.38	28.5
8.10	33.5

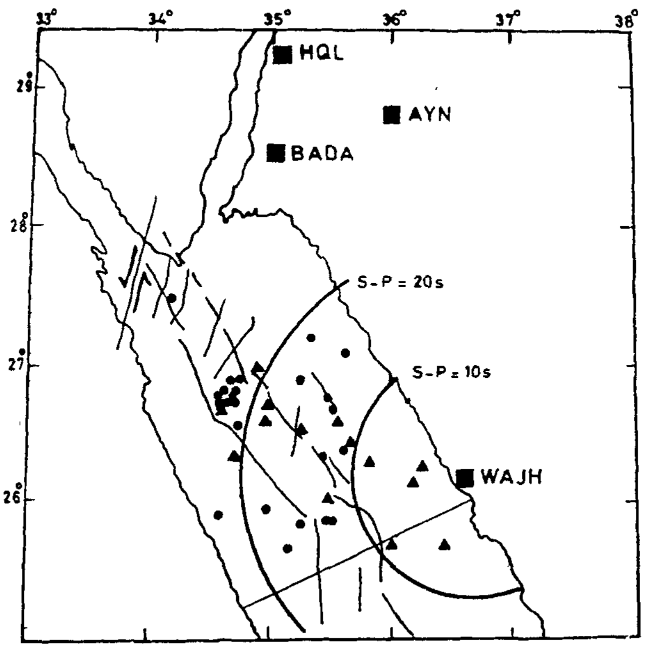

Figure 7. Epicentral distribution of the 1992 February and June swarms, which are represented by solid circles and triangles, respectively.

and S_n). First, the crustal model of the northern Red Sea proposed by Rihm, Makris & Moller (1991) was used for epicentre calculations, but this gave a larger root-mean-square error than the structure for the Aqaba region (El-Isa *et al.* 1987); the latter (given in Table 1) was then used to estimate epicentres. The hypocentres that were recorded well by at least three stations (both *P* and *S*) were calculated using the modified version of the computer program by D. Evans and D. Steeples of the Kansas Geological Survey, Lawrence, KS.

The magnitudes were calculated from the coda duration at the WAJH station using the observatory calibrated local formula (Gharib, Necioglu & Al-Amri 1994)

$$M_D = 2.48 \log \tau - 2.1 + 0.00035H + 0.0004\Delta,$$

where τ is the total duration in seconds, H is the focal depth in km and Δ is the epicentral distance in km.

The nominal errors in epicentral coordinates, given by the location algorithm, range from 0.1 km to over 20 km; epicentres with uncertainties of less than 20 km were considered further. The epicentral distances of events recorded only at station WAJH were estimated from *P*-to-*S* traveltime differences using a *P*-wave velocity of 6.5 km sec^{-1}, and a *P*-to-*S*-velocity ratio of 1.73, compatible with the velocity-gradient crustal model of the Gulf of Aqaba. The focal depth for a minority of the events ranged from 8 to 19 km; a clear maximum of activity was observed between 10 and 12 km.

During the period 1986 to December 1996, 610 events were recorded, mainly by station WAJH (the nearest station to the cluster area) and some other network stations. A list of the events located by KSU is shown in Table 2. 55 of those shocks were large enough to be recorded clearly by stations BAD, SRFA, HQL and AYN. All the events are located north of the Red Sea between latitudes 26.5 and 27.9 °N and longitudes 33.3 and 36.3 °E. The location of this activity is in the northern end of the Red Sea at the mouth of the Suez Gulf (Shadwan Island), as shown in Fig. 3.

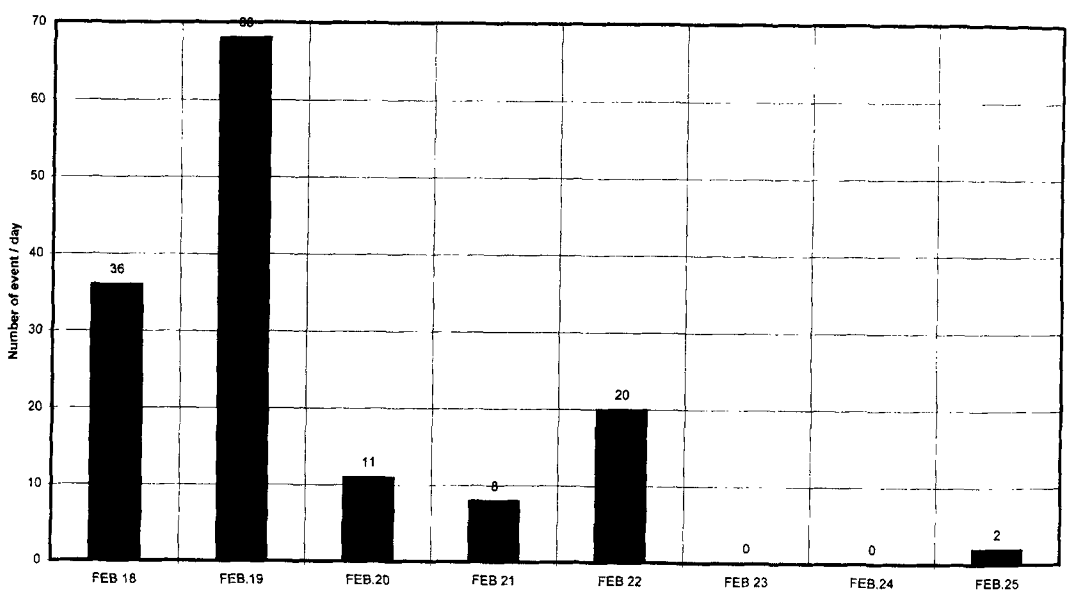

Figure 8. Histogram showing the number of events per day in the February 1992 earthquake swarm in the northern Red Sea.

Table 2. A list of the events located recorded by KSU stations.

Year	MO	Day	Hr	Min	O. T.	Lat. N	Long. E	Dep.	Mag	N. St.
1986	03	7	4	18	47.50	27.74	34.07	15	2.80	3
1986	03	20	16	42	28.60	27.02	35.21	14	3.00	3
1986	04	08	8	43	34.20	27.09	34.36	10	4.40	3
1986	10	16	3	3	40.74	27.57	34.55	22	0.58	3
1986	10	25	2	25	39.03	27.85	34.29	22	1.33	3
1986	11	2	15	42	17.58	27.79	34.43	24	1.73	3
1986	11	23	20	27	49.48	27.71	34.65	5	2.56	4
1986	11	27	9	32	22.82	27.77	34.32	23	1.40	3
1986	12	1	12	49	22.83	27.92	34.97	22	2.90	4
1987	1	15	2	56	12.82	27.36	34.69	3	2.20	3
1987	2	4	23	55	15.13	27.39	35.57	15	2.00	3
1987	3	3	3	36	4.77	27.68	34.34	9	1.25	3
1987	5	15	0	31	2.36	27.72	35.00	3	2.30	3
1987	5	22	22	17	31.37	27.69	34.55	16	1.49	3
1987	7	23	7	15	0.34	27.76	34.46	5	1.93	3
1987	10	3	23	57	28.92	27.80	34.34	15	1.59	3
1987	11	10	12	4	51.87	26.68	34.43	22	1.30	3
1987	11	13	11	59	24.59	26.74	34.36	20	1.60	3
1987	12	9	23	10	35.81	27.80	34.35	19	1.09	3
1987	12	12	4	37	15.24	27.78	34.37	22	1.45	3
1988	1	21	21	3	47.65	27.61	34.43	21	1.93	4
1988	2	18	18	15	13.38	27.60	35.13	3	1.11	3
1988	3	26	8	52	34.80	27.67	34.40	20	1.32	3
1988	3	26	8	43	56.84	27.37	34.51	18	1.85	4
1988	4	24	22	20	31.27	27.04	36.30	20	1.67	3
1988	6	8	3	43	5.34	27.58	33.67	12	1.50	3
1988	7	20	3	33	19.29	27.73	35.67	12	1.50	4
1988	7	24	19	15	20.24	27.82	34.37	12	2.35	3
1988	8	8	11	11	19.67	26.76	34.35	12	2.10	3
1988	8	14	3	14	6.13	27.80	34.39	12	2.92	4
1988	9	28	4	5	6.95	27.76	34.39	12	2.66	4
1988	10	10	16	21	55.70	27.87	34.51	12	2.80	3
1988	10	22	1	27	43.26	27.80	34.62	12	1.98	5
1988	11	14	0	19	34.04	26.61	34.85	12	1.80	5
1988	11	19	19	28	37.76	27.57	34.38	12	1.90	4
1988	12	30	4	34	47.97	27.32	34.15	12	1.41	4
1989	1	6	20	28	43.20	27.84	34.59	12	3.97	5
1989	1	12	22	18	50.90	27.62	34.43	12	1.10	4
1989	1	13	11	48	52.70	27.99	34.05	12	1.10	2
1989	1	18	2	23	45.31	27.56	34.29	12	1.71	4
1989	1	19	16	10	16.40	27.96	33.96	12	3.75	4
1989	1	19	22	27	4.20	27.78	34.29	12	3.75	4
1989	1	21	7	55	26.70	27.22	34.22	12	3.74	4
1989	1	25	20	47	15.20	27.74	34.15	12	3.46	4
1989	1	26	10	10	21.64	27.96	33.95	12	2.28	4
1989	1	31	22	49	31.00	26.49	34.61	12	3.55	5
1989	2	9	13	10	1.75	27.77	34.65	14	1.67	4
1989	2	15	17	52	40.84	27.58	34.61	12	2.73	5
1989	2	24	0	28	11.43	27.59	34.59	12	2.40	5
1989	6	10	9	48	18.90	27.41	34.30	15	3.20	
1989	6	14	5	39	55.90	27.34	33.38	10	3.50	
1989	6	25	12	52	3.60	27.05	33.85	20	2.80	
1989	8	20	3	34	19.50	27.24	34.10	20	2.10	
1989	9	7	0	53	13.00	27.10	33.65	10	3.50	
1989	10	4	21	25	9.40	27.53	33.56	20	3.30	
1989	12	8	14	5	56.50	27.02	33.96	20	3.80	
1990	1	16	5	57	3.43	26.56	34.77	12	2.34	4
1990	2	17	20	34	43.80	27.70	34.08	8	2.00	
1990	2	23	4	58	30.50	27.79	33.62	7	2.90	
1990	3	31	22	9	10.30	27.70	34.11	8	3.40	
1990	6	19	9	14	27.83	26.64	34.92	12	2.18	4
1990	6	23	11	11	30.46	25.46	36.31	12	2.55	4
1990	7	2	0	6	42.52	27.51	34.78	12	2.23	4
1990	7	13	17	51	19.50	27.78	34.11	8	3.00	
1990	7	26	21	1	11.40	27.31	35.03	5	3.30	

Table 2. *(Continued.)*

Year	MO	Day	Hr	Min	O. T.	Lat. N	Long. E	Dep.	Mag	N. St.
1990	7	31	4	3	7.00	27.80	34.44	5	3.20	
1990	8	1	21	28	38.92	26.68	35.19	12	1.50	3
1990	9	14	18	7	14.40	27.70	33.95	9	2.90	
1990	11	3	18	49	5.40	27.67	34.44	5	3.40	
1991	1	21	00	47	6.80	27.76	35.75	9	2.20	
1991	1	27	11	6	27.60	27.76	33.64	20	2.40	
1991	1	28	11	18	57.10	27.49	33.33	20	2.10	
1991	4	15	13	19	9.50	27.58	33.58	16	2.90	
1991	6	14	7	43	14.80	27.33	33.65	16	2.40	
1991	9	6	00	38	37.90	27.68	33.90	17	4.00	
1991	11	2	2	25	22.40	27.80	34.89	6	4.00	
1991	11	8	19	34	42.40	27.90	34.47	13	2.40	
1991	12	22	13	43	46.06	27.61	35.58	12	1.70	3
1991	12	29	3	5	0.43	26.75	35.09	12	1.82	3
1991	12	29	13	21	3.28	26.10	35.61	12	2.78	4
1992	1	14	3	57	1.70	25.99	35.66	12	1.50	4
1992	1	24	3	56	46.65	24.86	35.23	12	2.05	4
1992	1	24	7	20	22.46	25.64	35.61	12	2.14	4
1992	1	29	4	30	6.18	27.12	34.49	12	1.88	4
1992	2	19	19	1	45.14	25.83	35.24	20	2.27	4
1992	2	20	5	34	17.40	29.48	34.91	22	1.67	3
1992	2	20	23	44	58.50	26.37	35.57	15	2.07	4
1992	2	22	2	34	35.58	26.84	34.70	15	3.43	4
1992	2	22	2	40	16.50	26.83	34.71	14	1.39	3
1992	2	22	3	47	11.10	27.19	35.33	13	1.30	3
1992	2	22	4	19	55.26	26.77	34.56	17	1.58	3
1992	2	22	5	5	42.65	26.82	34.68	17	1.66	3
1992	2	22	5	5	43.25	26.80	34.62	15	1.66	3
1992	2	22	8	53	5.73	26.80	34.70	15	2.28	4
1992	2	22	8	56	22.76	26.85	34.73	20	1.51	3
1992	2	22	14	33	36.34	26.94	34.80	15	1.32	3
1992	2	22	15	53	32.32	26.95	34.90	15	1.45	3
1992	3	6	0	10	1.53	26.89	35.19	12	2.42	4
1992	4	17	13	33	46.17	6.74	35.51	12	1.38	3
1992	4	18	9	27	50.75	27.09	35.62	12	1.40	4
1992	5	4	23	22	46.59	26.68	34.77	12	1.77	4
1992	6	1	23	53	9.90	25.65	36.09	12	4.54	3
1992	6	1	23	59	11.69	26.55	36.65	13	2.45	3
1992	6	2	20	12	45.20	26.41	36.50	12	4.80	3
1992	6	3	0	53	43.81	25.65	37.30	12	3.89	3
1992	6	3	15	4	45.64	26.67	35.01	12	3.77	3
1992	6	10	14	20	18.50	26.68	35.54	12	3.59	3
1992	6	17	22	51	10.56	26.25	35.85	12	3.36	3
1992	6	19	9	29	17.36	26.69	35.01	12	3.29	3
1992	6	20	9	42	6.52	26.31	34.74	12	3.42	3
1992	6	27	21	58	12.55	26.51	35.40	13	2.27	3
1992	6	30	1	36	20.16	26.01	35.38	12	2.08	3
1992	6	30	23	2	28.27	26.90	33.82	12	1.60	4
1992	8	8	1	26	32.42	27.03	34.89	12	2.10	3
1992	10	19	17	11	14.80	27.29	34.47	16	3.10	
1992	10	29	3	25	12.00	27.38	34.10	7	3.60	
1992	11	4	11	30	9.20	27.08	34.64	14	3.30	
1992	11	20	9	4	4.00	27.24	33.23	18	3.30	
1993	2	23	17	58	24.80	27.17	34.06	14	3.50	
1993	2	24	15	5	43.80	27.18	35.50	10	3.70	
1993	4	3	6	55	47.10	27.70	34.26	14	2.80	
1993	4	3	13	49	59.80	27.55	33.17	9	3.50	
1993	4	25	10	55	5.20	27.57	34.30	10	3.10	
1993	7	19	8	53	52.20	27.53	34.38	16	4.20	
1993	8	7	21	50	38.50	27.47	35.02	6	2.70	
1993	8	23	13	27	52.40	27.43	34.99	8	3.20	
1993	11	6	15	4	48.10	27.43	34.93	17	3.40	
1994	5	2	15	2	45.00	27.80	33.77	15	2.50	
1995	1	6	9	17	46.87	26.75	34.64	14	2.80	
1995	1	17	6	1	13.87	26.88	34.62	18	2.70	
1995	1	17	12	4	3.90	26.93	35.39	13	2.50	

Table 2. (*Continued.*)

Year	MO	Day	Hr	Min	O. T.	Lat. N	Long. E	Dep.	Mag	N. St.
1995	1	19	10	35	13.48	26.49	34.62	12	2.50	
1995	1	22	2	28	3.57	26.05	35.75	13	2.60	
1995	2	1	10	32	18.97	27.47	33.98	12	2.50	
1995	2	8	8	8	17.45	26.85	34.74	17	2.70	
1995	2	9	15	20	22.59	27.41	33.79	12	2.80	
1995	3	15	9	20	22.59	26.91	33.03	19	2.80	
1995	6	18	23	22	9.51	27.39	34.38	15	2.90	
1995	8	9	13	2	19.50	27.20	34.08	12	2.50	
1995	10	3	19	33	26.28	27.53	34.40	16	2.60	
1996	5	1	5	20	14.45	27.84	34.30	15	2.50	
1996	5	5	00	26	8.95	27.83	34.35	14	2.60	

FEBRUARY 1992 SWARM

An earthquake swarm occurred in the northern Red Sea 1992 February 18–21 and was detected by the Aqaba subnetwork stations. There were more than 180 events in the magnitude range (M_D) 0.8–3.6. This swarm occurred between 1992 17 H 01 M UTC February 18 and 21 H 06 M February 22 in the northern Red Sea, between 25.94 and 27.52 °N and 34.47 and 35.64 °E (Fig. 7). The temporal variations between the number of events at different magnitude ranges recorded are shown in the histograms of Fig. 8, while Fig. 9 shows the number of shocks per day. Fig. 8 shows a gradual decrease in number with time and also indicates an event clustering where the peak of activity seems to have occurred on February 18 and 19. On February 18, a peak of activity occurred where 30 shocks were detected within 6 hr. During a second peak, which was the highest, 60 shocks were recorded in the early hours of February 19. During the following days, February 20, 21 and 22, the activity slowed down in magnitude and number of shocks. It is likely that most, if not all, of this activity has a magnitude lower than 4. The largest magnitude was 3.43 and was recorded by four stations of the subnet and very few of the nearby KSU stations. The lack of a clear onset (only four stations in one side of the cluster area) did not permit us to obtain a fault-plane solution. The depths of the located events are in the range 10–20 km, suggesting that the seismic activity was mainly intracrustal. Two circle arcs with radii equal to 80 and 160 km were plotted for values of t_s–t_p equal to 10 and 20 s, respectively, with their centres at station WAJH (Fig. 10). The calculations of hypocentral parameters indicate that the epicentres migrated northwards by about 75 km in 5 days, where t_s–t_p started at 9–10 (80 km from WAJH) as the predominant traveltime delay on February 18 and 19, while a value of 18–20 (160 km from WAJH) for t_s–t_p was reported

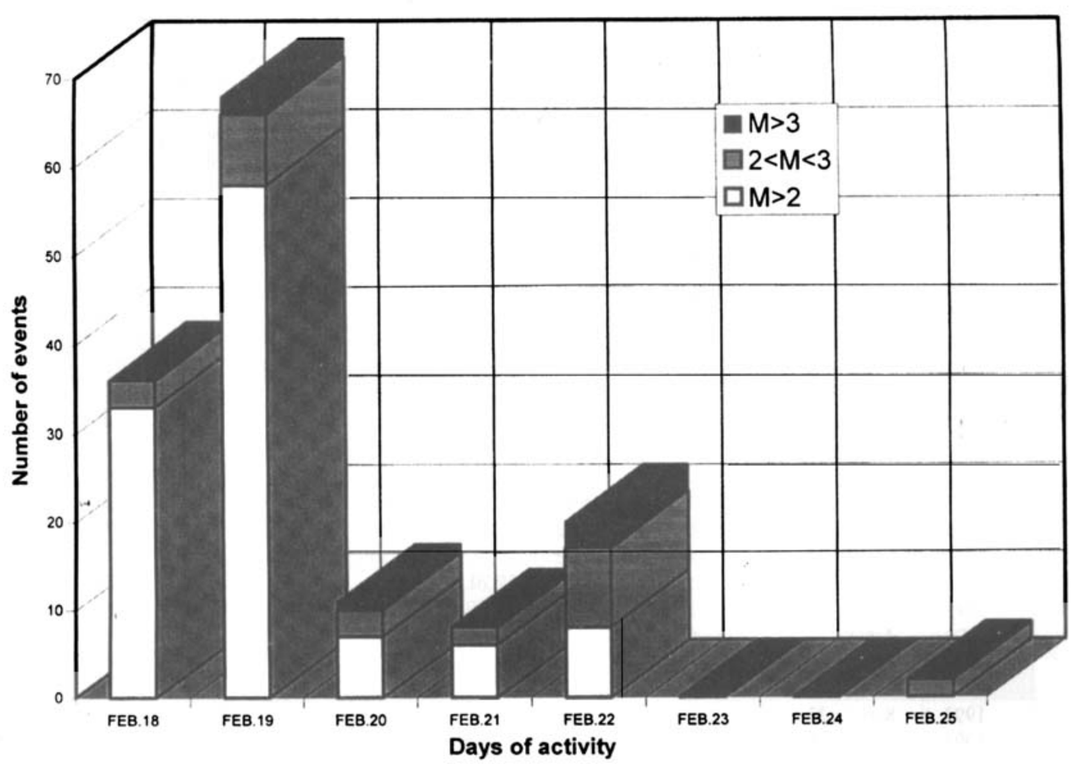

Figure 9. Histogram showing the number of events per day at certain magnitude ranges for the 1992 February earthquake swarm in the northern Red Sea.

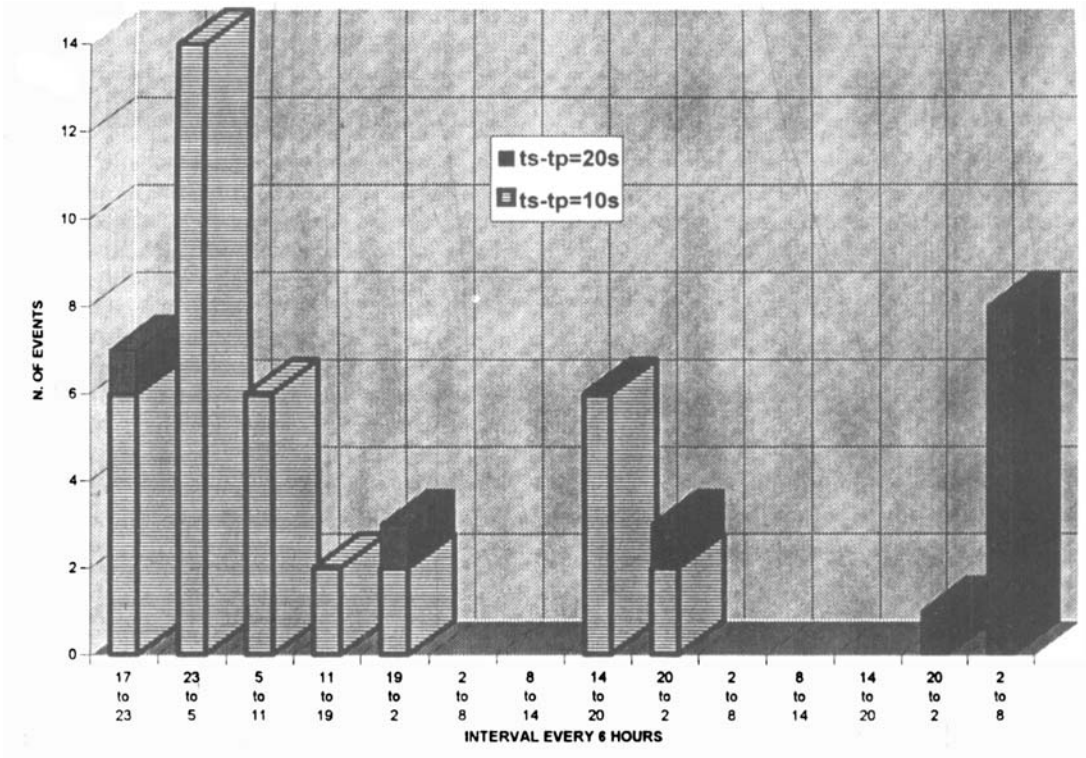

Figure 10. T_s–T_p time distribution every six hours for the 1992 February 18–22 swarm.

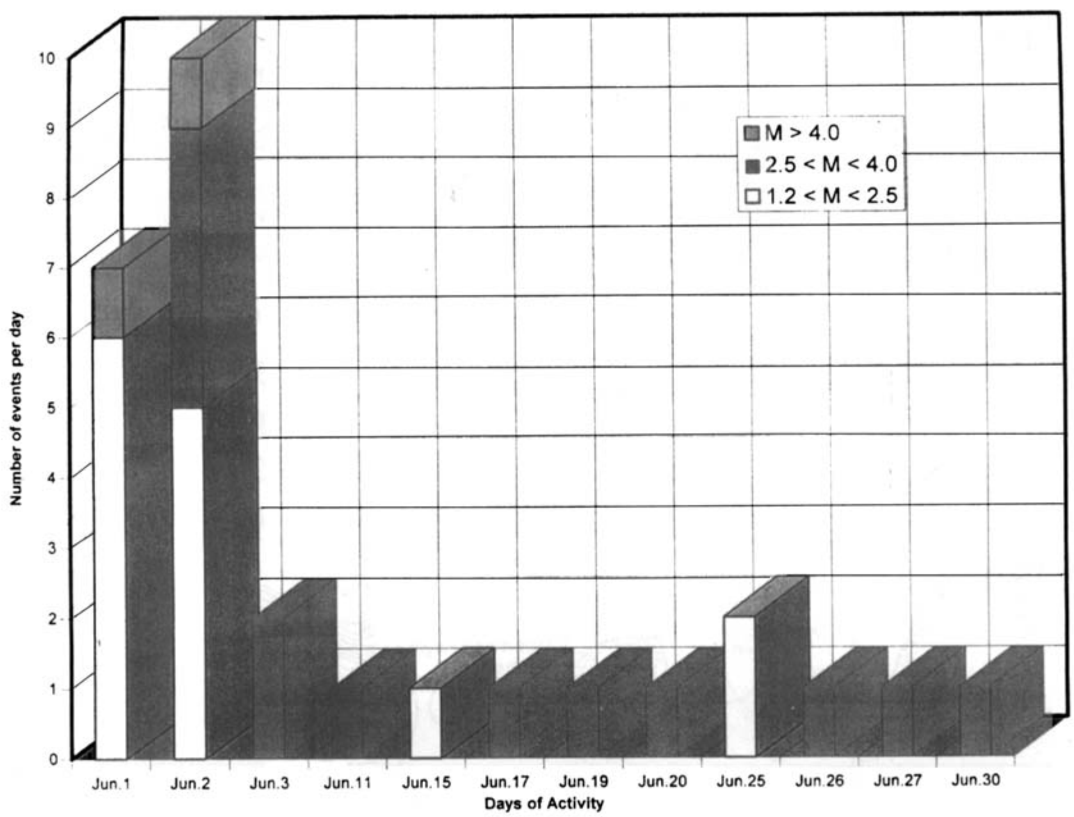

Figure 11. Histogram showing the number of events per day at certain magnitude ranges for the 1992 June earthquake swarm in the northern Red Sea.

for most of the later activity (February 21 and 22), as illustrated in Figs 7 and 10.

JUNE 1992 SWARM

Another swarm occurred in the same area and started on the first of June 1992. This swarm lasted for 5 days and was characterized by a smaller number of events and larger magnitudes. The histogram in Fig. 11 shows the daily activity of the June 1992 swarm. There were four shocks with magnitudes greater than 4, three of them having a magnitude of 4.6. Those three events have been located using our readings and nearby Jordanian stations around latitude 26.13 °N and longitude 36.26 °E, as shown in Fig. 7. Only one event has been reported in the PDE of the NEIC on 1992 June 2 (OT 201217.3); its location was 25.905 °N, 37.52 °E, with $m_b = 4.8$. This epicentre is located on land, 30 km east of Al-Wajh city, which is implausible because there were no reports of a felt earthquake. Most of the shocks have a focal depth of 12 km. Also, following this swarm, at the end of December of the same year there were some events that were detected from the study area with a magnitude range of 1.7–3.35.

FREQUENCY—MAGNITUDE ANALYSIS

Local-duration magnitude scale (Gharib *et al.* 1994) was used to estimate *a* and *b* values for the northern part of the Red Sea ($\log N = a - bM$, Gutenberg & Richter 1954). The constant *a* is the intercept of the curve, which depends on the period of observation, the size of the area investigated and the level of seismic activity, while the constant *b* is the slope, and depends on the ratio of the number of earthquakes in the low- to high-magnitude groups. It varies from region to region with focal depth. Mostly, the February 1992 swarm had an epicentre around latitude 27 °N and longitude 34.5 °E, with values of 2.821 and 0.887 for *a* and *b*, respectively. The June 1992 swarm had an epicentre around latitude 26.5 °N and longitude 36.5 °E. The crust is thicker with lower velocities, with values of 2.272 and 0.428 for *a* and *b*, respectively. The values of *a* and *b* for the period 1952 to 1986 (USGS data) are estimated to be 3.97

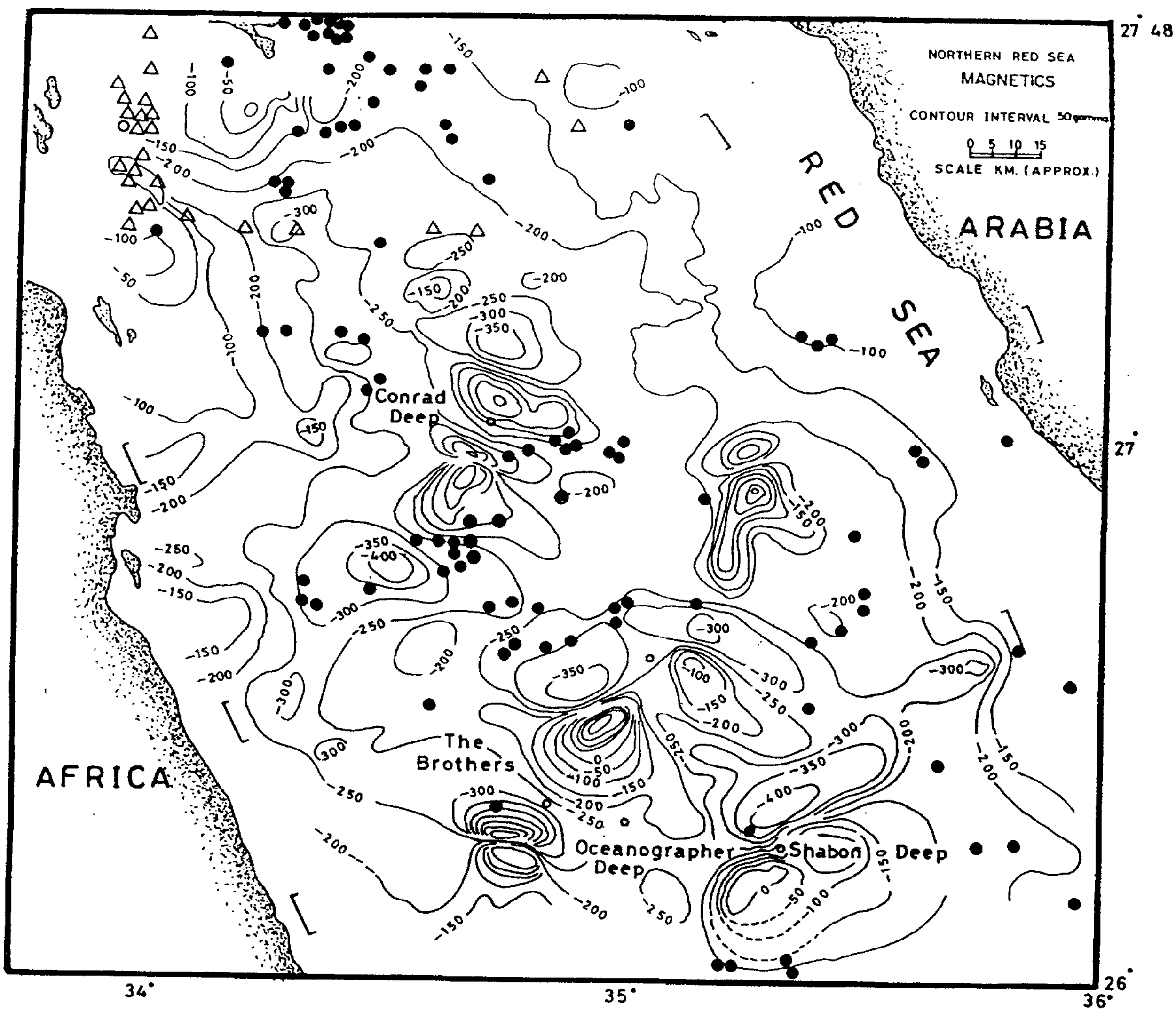

Figure 12. Map of the northern Red Sea showing the intensity magnetic anomalies (after Martinez & Cochran 1988) with the seismicity. Open triangles represent USGS epicentres; solid circles represent KSU epicentres.

and 0.603 (Table 3) for the region located around Shadwan Island (close to the mouth of the Gulf of Suez), where the crust is thinner with lower velocities. Only instrumental data for the period from 1986 to 1992 were used in this calculation. The data are categorized into two localities: above latitude 27 °N and between latitudes 25 and 27 °N, respectively. The KSU data for the period 1986 to 1992 indicated values of 3.543 for a and 0.658 for b, indicating the epicentre of the spreading zone, south of latitude 27 °N. Combining USGS and KSU data for the period 1952–1992 for the northern part of the Red Sea, values of 3.41 for a and 0.49 for b were obtained. These are slightly different from those given by El-Isa & Al-Shanti (1989) and Al-Amri (1995) for the northern Red Sea excluding the two Gulfs. We believe that our results are more accurate because of a larger database and a longer period of observation.

Table 3. a and b values obtained from different data sources for the northern Red Sea.

Data sources	a	error	b	error
El-Isa & Shanti 1989	2.10	0.380		
USGS (this study)	3.97	0.147	0.60	0.027
KSU (this study)	3.54	0.140	0.66	0.049
USGS + KSU (this study)	3.41	0.060	0.49	0.015

DISCUSSION AND CONCLUSIONS

From the geological and tectonic information, the seismic activity is attributed to subsurface magmatic activities (Fig. 12) and resulting isostatic adjustments in the Gulf of Aqaba region. The extensional stresses responsible for Red Sea rifting have resulted in movements and magmatic activity along Tertiary–Quaternary and older tectonic lineaments. The locations of most of the events are distributed along several bathymetric escarpments (Fig. 13). The a and b values showed that the three swarms (March 1969, February 1992 and June 1992) of the northern Red Sea were generated by three different tectonic units: Shadwan Island (first unit), around latitude 27 °N and longitude 34.5 °E (second unit) and around latitude 27 °N and 36.5 °E (third unit). This means that the general distribution

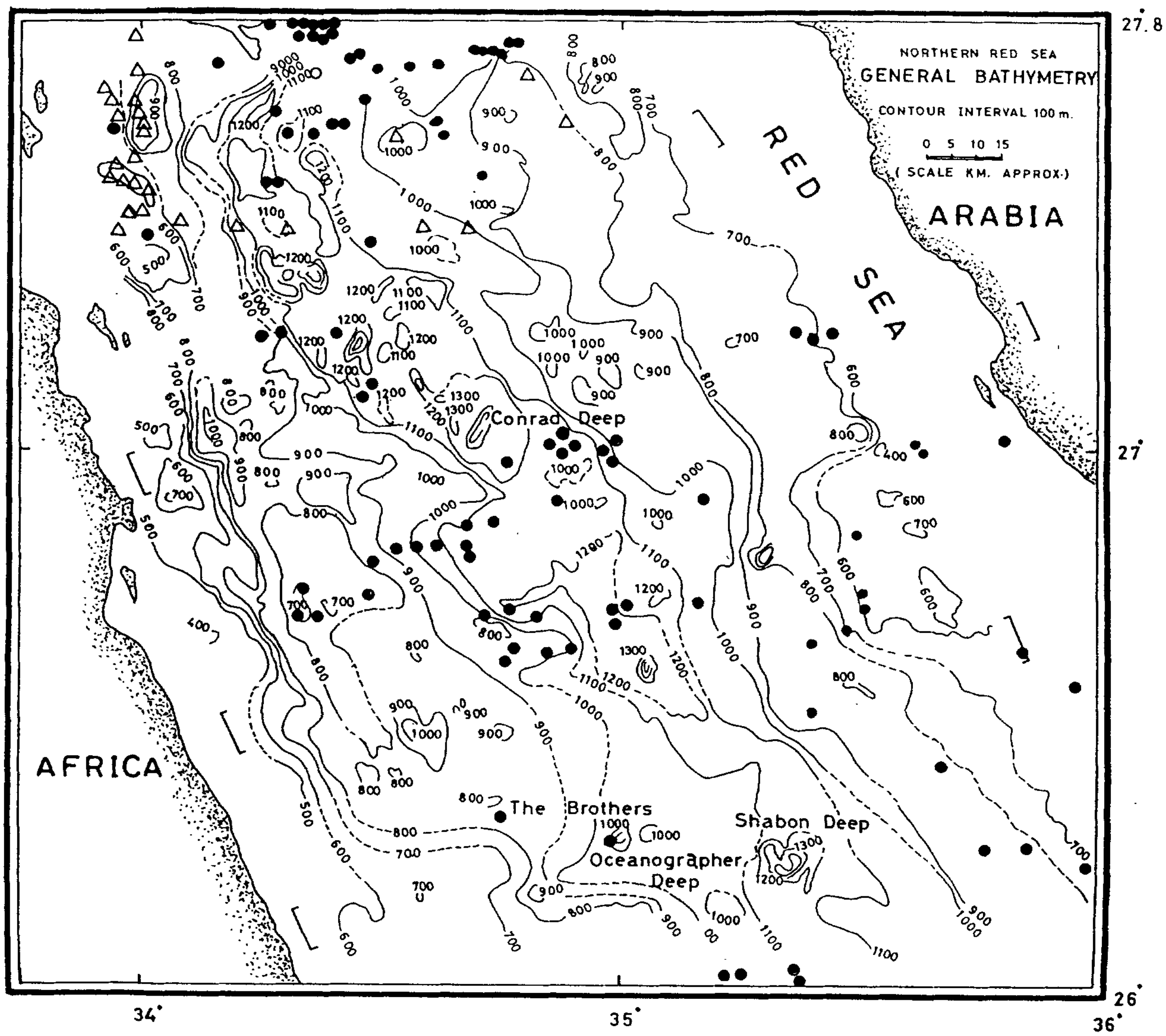

Figure 13. Map of the northern Red Sea showing bathymetric contours of the northern Red Sea (after Martinez & Cochran 1988) and the seismicity. Open triangles represent USGS epicentres; solid circles represent KSU epicentres.

of epicentres correlates well with the major structures of the region (Figs 3 and 7).

Tatham & Savino (1974) and Sykes (1967) believe that earthquake swarms are produced by major strike-slip faulting on transform faults. Therefore, the February and June 1992 swarms would be related to strike-slip motion due to spreading and opening of the Red Sea as well as shallow magmatic activity in the region. It can be concluded that the northern Red Sea region has a relatively high level of seismicity. Because of the lack of seismic stations close to the northern Red Sea before 1986, however, seismic activity with smaller magnitudes was not recorded. Therefore, we suggest the following:

(1) the region should be monitored closely by a dense network of seismograph stations;

(2) there is a need for stations on the Egyptian side of the Red Sea;

(3) a crustal structure model of the northern Red Sea for a better determination of epicentres.

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