Pergamon

Journal of African Earth Sciences, Vol. 19, No. 1/2, pp. 17–25, 1994

0899–5362/94 $7.00 + 0.00

0899–5362(95)00004–6

Seismicity of the south-western region of the Arabian Shield and southern Red Sea

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(Received 3 March 1994 : accepted 24 October 1994)

Abstract - Historical and instrumental seismicity in the southern Red Sea region has been examined in relation to tectonics and structures indicated by geologic and magnetic data. One hundred and seventy earthquakes recorded during the period 1913-1994 had body-wave magnitudes of between 3.0 and 6.6.

The majority of seismic activity is clustered on or near the transform faults of the deep axial trough in the southern Red Sea. The seismically active area between latitude 16.3° N and 17.4° N. is believed to extend north-eastwards to the Arabian Shield. The apparent low level of seismicity in the shield area might be due to the lack of detection of small events.

The frequency-magnitude analysis indicates that events above body-wave magnitude 4.2 are reliably determined in the southern Red Sea region. Estimation of constants a and b in the Richter relation of occurrence yielded 6.22 and -0.91, respectively.

This study and the historical data support the mechanism of sea-floor spreading and indicate that the seismic activity in the shield area and the southern Red Sea may be attributed to stresses resulting from subsurface magmatic activity and the spreading centres.

Résumé - La séismicité historique aussi bien qu'instrumentale de la Mer Rouge et environs a été étudiée en relation avec les structures tectoniques fournies par les observations géologiques et magnétiques. Cent septante tremblements de terre ont été enregistrés dans la période 1913-1994 et dont les magnitudes d'amplitude sont comprises entre 3.0 et 6.6. La majorité de l'activité sismique est concentrée sur ou près des failles transformantes du profond fossé axial de la Mer Rouge méridionale. La région séismiquement active entre les latitudes 16,3° et 17,4° N s'étend probablement vers le NE dans le bouclier arabe. Le niveau apparemment bas de l'activité sismique du bouclier pourrait être dû à la non-détection de petits séismes. L'analyse fréquence-magnitude indique que les séismes au-dessus d'une magnitude d'amplitude supérieure à 4,2 sont déterminés d'une manière fiable dans la zone de la Mer Rouge méridionale. L'estimation des constantes a et b de la relation de Richter sur leur occurrence est de 6,22 et -0,91, respectivement. Cette étude ainsi que les données historiques sont en accord avec le mécanisme d'expansion du fond de la Mer Rouge et elle indique que l'activité sismique du bouclier et de la Mer Rouge méridionale peut être attribuée aux contraintes (stress) résultant de l'activité magmatique de subsurface et aux centres d'expansion océanique.

INTRODUCTION

The area of interest for this investigation is defined by the latitudes 15° to 20° N and longitudes 37° to 45° E. This area incorporates the south-western part of the Arabian Shield and southern Red Sea (Fig. 1).

The regional distribution of the seismicity throughout the Red Sea has changed little since the early investigations of Drake and Girdler (1964), Gutenberg and Richter (1954), and Sykes and Landisman (1964).

A further improvement in the determination of epicentres has resulted from the establishment of the Worldwide Standard Seismograph Network (WWSSN) in 1963. Fairhead and Girdler (1970) used the method of Joint Epicentral Determination to relocate some epicentres in the Red Sea to an accuracy of 10-20 km. They indicated that epicentral locations were in error by less than 0.35° in latitude or longitude.

Previous research on the seismicity of Africa and Arabia indicates the presence of intermediate to shallow focus earthquakes which are restricted to plate boundaries. Thus, the Red Sea was recognized early in

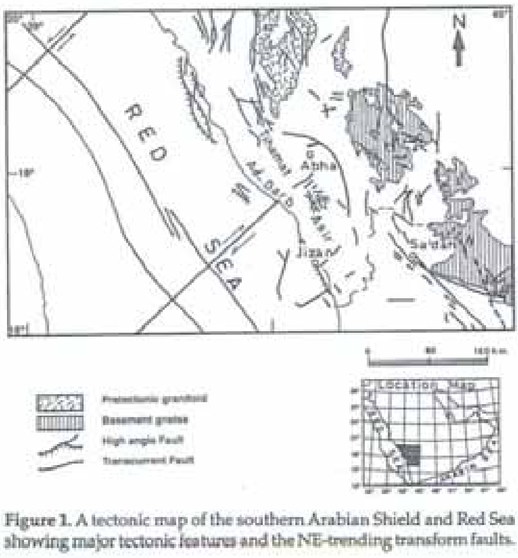

Figure 1. A tectonic map of the southern Arabian Shield and Red Sea showing major tectonic features and the NE-trending transform faults.

the development of the global plate tectonic theory as part of the worldwide rift system (Barazangi 1981; Sykes 1967).

Evidence of seismic activity in the southern Red Sea and western Arabia is found in diverse sources indicating its occurrence from historical time to the present (Ambraseys 1988; Ambraseys and Melville 1983; El-Isa and Al-Shanti 1989; Poirier and Taher 1980). The occurrence of the January 11, 1941 earthquake (surface wave magnitue M_s=5.9, Ambraseys and Melville 1983) with an aftershock on February 4, 1941 (M_s=5.2, Ambraseys 1988), the earthquake of October 17, 1955 (M_s=4.8) and the 1982 Yemen earthquake of magnitude 6.0 (Langer *et al.*, 1987) highlighted the hazards that may result from nearby seismic sources and demonstrated the vulnerability of northern Yemen to moderate-magnitude and larger earthquakes. Consequently, more studies started on local seismicity and seismic hazard assessment (Barazangi 1981, 1983; Merghelani 1979; Al-Haddad *et al.*, 1994; Thenhaus *et al.*, 1986). Analysis of land and marine magnetic anomalies (Hall 1979) indicates that some transform faults may extend north-eastwards from the Red Sea into the Arabian Shield. If these faults are active, then seismic risk in western Arabia may be significant.

More recently, microearthquake studies in the Tihamat Asir region (Merghelani and Gallanthine 1980) show a higher level of seismicity. They located ten events that ranged in magnitude from 2.0 to 2.5. Six of these events were epicentred near the Ad-Darb fault.

The seven telemetered remote seismographic stations of the King Saud University were established in the southern Arabian Shield during the period 1988-1991. Each station is equipped with a short period, single component seismometer and used as the primary source for local and microearthquake information.

Due to the aforementioned considerable seismic risk in a heavy populated area and the lack of local seismicity studies, the main objective of this study is to investigate the tectonics of the southern Red Sea and its relation to the southern Arabian Shield by comparing the interpreted structural directions from geology and magnetics with the distribution of historical and instrumental seismicity.

SEISMOTECTONIC SETTING

The Arabian plate is a relatively small lithospheric plate whose boundaries are representative of the different types of plate boundaries. The opening of the Red Sea has resulted in the development of tensional tectonics along the western margin of the Arabian plate, including its south-western portion.

The southern part of the Arabian Shield consists predominantly of Precambrian metamorphic and plutonic rocks (Greenwood *et al.*, 1977). To the east, the shield is bounded by the Phanerozoic sedimentary rocks of the Arabian Platform, which dip gently eastward and north-eastward. To the west, the Shield abuts the Tertiary rocks at the eastern edge of the Red Sea sea-floor spreading system. This tectonic boundary is characterized by complex faulting, Tertiary dyke injections and volcanism.

Both Precambrian rocks and the younger covering rocks of the shield margin at the eastern edge of the Tihamat Asir have been invaded by closely spaced diabase dykes. The number of dykes increases from east to west across the shield margin. Masses of gabbro and granophyre intrude into the dyke complex (Greenwood *et al.*, 1977). Blank (1977) considered the exposed western edge of the shield to mark the oceanic-continental crustal boundary and interpreted lateral offsets of the dyke swarm as Tertiary transform faults.

According to Hall (1979), two major Tertiary tectonic north-east trending faults were identified in the southern Red Sea region from the offsets of magnetic anomalies. These faults could be considered as newly formed transverse faults related to the opening and rifting of the Red Sea.

All of the volcanic activity is associated with fault zones and most of these occur on the crystalline shield plateau. South of Ad-Darb a line of volcanic cinder cones lies directly over the main fault zone. The largest of the Pleistocene-Recent flood basalts on the Red Sea coast is found in the Tihamat Asir and covers the coastal plain for 165 km (Skipwith 1973).

Recent volcanism within the epicentral area confirms the existence of magmatic activity in conjunction with the rifting process. The 1982 Yemen earthquake occurred in an area of active extensional tectonism characterized by a horst and graben structure and Holocene basaltic volcanism (Thenhaus *et al.*, 1986).

The majority of earthquakes and tectonic activities are concentrated along the belt which extends from the central Red Sea region south to Afar and then east through the Gulf of Aden. This belt indicates active sea-floor spreading along the deep axial trough (Hall 1979; Girdler and Styles 1978; Le Pichon and Francheteau 1978). The distribution of the shallow focus earthquakes (Fairhead and Girdler 1970) indicates that the axial trough is an area of active spreading and the earthquakes probably occur where new oceanic crust is being formed.

Based on earthquake catalogues for the southern Red Sea and on mapped fault geometry, general geotectonic information and epicentre distribution during this century, two seismogenic zones have been identified: the Northern zone (north of latitude 18° N) and the Southern zone (south of latitude 18° N). For each zone estimates of the parameters of the frequency-magnitude relationships, describing the regional seismicity level, are calculated.

EARTHQUAKE DATA TREATMENT

Nearly all earthquake catalogues document temporal changes in the rate of activity with particular magnitude ranges. Frohlich and Davis (1993) attribute this to changes in global network coverage and seismographic station practice, which can systematically affect magnitudes.

In order to construct a consistent and reliable earthquake data set, the catalogue of the Saudi Arabian Earthquake Database (SAED) has been compiled from different sources and serves as the primary source for the instrumental seismicity (1913-1994) in the southern Red Sea region. Entries in SAED were cross-checked and additions were made from various sources of earthquake records to ensure that repetitions are not included in this analysis.

Searches were made in a number of seismological catalogues and bulletins including those of the International Seismological Centre (ISC), Preliminary Determination of Epicentres (PDE) and related publications, with special interest in the work of Ambraseys (1988), Ambraseys and Melville (1983) and Poirier and Taher (1980). Local earthquake data for the period 1988-1994 was acquired from the Seismological Observatory, King Saud University, Riyadh.

For the period 1913-1964, the SAED catalogue relies heavily on Ambraseys (1988), Gutenburg and Richter (1954), Poirier and Taher (1980) and, from 1965 onwards, on the PDE, ISC and Ambraseys (1988). Since the above sources contained events that were repeated more than once, it was necessary to eliminate the repetitions. The events were considered duplicate if they had a time-origin difference of 15 seconds or less and a space-origin difference of 50 km or less. In a given set of duplicate events, an event which had a magnitude and PDE-source was retained as the record of the event. However, in the case of a set of repetitive records, in which neither had a magnitude reported, the one which was derived from a PDE- source was retained. Measures of earthquake size appear in the SAED catalogue as body-wave magnitude (m_b) and surface-wave magnitude (M_s).

For the statistical analysis of earthquake recurrence frequencies, the various measures of earthquake size were converted to surface-wave magnitude. A least-squares regression fit to the catalogue data for the southern Red Sea gives the equation :

$$M_s = 1.07\ m_b - 0.476$$

A major problem in the evaluation of the frequency-magnitude relationship is the incompleteness of the catalogues. The common approach for treatment of this incompleteness is to employ earthquake detection and reporting probabilities (Stepp 1973; Al-Haddad *et al.*, 1994). These probabilities are allowed to vary in time-span and with the size of the earthquake. The number of events for a specific magnitude range are adjusted to reflect the probability of detection and reporting. The rate of occurrence of the magnitude is then evaluated based on the time-span over which it is observed to occur.

The SAED catalogue for the period 1913-1994 has, in this way, been made as homogeneous and complete as possible. Consequently, epicentral locations and seismicity parameters were determined based on the date reported in the aforementioned refined catalogue (Table 1).

RESULTS AND DATA ANALYSIS

Instrumental Seismicity (1913-1994)

Historical earthquake data was incorporated into this study as evidence for defining seismotectonic provinces and extrapolating the short instrumental record to longer periods.

Historically, about 10 earthquakes have occurred during the period 1913-1994 with surface-wave magnitudes (M_s) between 5.2 and 6.1. The assigned epicentres of these earthquakes are indicated in Figs. 2 and 3. Some of these events were associated with earthquake swarms, long sequences of shocks and aftershocks (the earthquakes of 1941, 1955, 1967 and 1993). The inconsistency of locations between different compilations is of the order ±30 km.

Ambraseys (1988) relocated the mainshock and aftershock of the largest land earthquake (M_s=5.9) of Feb. 4, 1941. The relocation gives 16.75° N, 43.33° E for the mainshock and 16.9° N, 43.90° E for the aftershock (Fig. 2).

Instrumental seismicity of the southern Red Sea shows that 170 earthquakes ($3.0<m_b<6.6$) are reported to have occurred in the period 1965-1994. About 52% (88 events) of the seismic activity occurred in the axial trough of the Red Sea north of latitude 18° N. and the other 48% (82 events) also occurred in the axial trough but south of latitude 18° N . An epicentral concentration can be seen where the spreading zone is bisected by the north-east trending transform faults. This is clear in the vicinity of latitudes 16.8° and 19.7° N. The largest marine earthquake (m_b=6.9) occurred on March 12, 1967. The earthquake activity of this event near latitude 19.9° N took the form of a swarm that lasted for a few months during which 29 earthquakes occurred with $4.4<m_b<5.8$. There is an apparently lower rate of activity

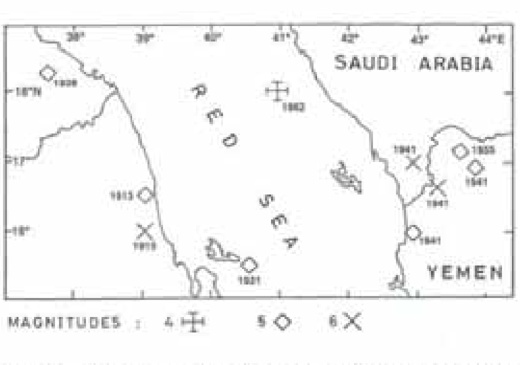

Figure 2. Historical seismicity of the southern Red Sea region for the period 1913-1964 A.D.

Table 1. A list of the historical and instrumental seismicity data for the southern Red Sea region from the period 1913-1994 A.D.

DATE Yr	Mo	Da	ORIGIN TIME	LAT.	LONG.	DEPTH (km)	m_b	Ms
1913	03	27	0313	16.500	39.000			5.7
1915	09	23	081448	16.000	39.000			5.8
1921	08	14	131528	15.500	40.500			5.9
1938	05	12	2132	15.300	37.600			5.8
1941	01	11	0831	16.640	43.310		6.5	5.9
1941	01	11	083156	17.000	43.000			
1941	02	04	0917	16.900	43.900			5.2
1955	01	17	2008	17.175	43.700		5.7	4.8
1962	08	25	005417	18.000	41.000			4.7
1965	12	30	085413.5	18.700	39.300	33	4.1	
1967	03	11	193348.2	19.570	38.978	33	4.9	
1967	03	11	193821.5	19.495	38.767	33	5.2	
1967	03	12	100149	19.827	38.933	33	5.8	
1967	03	12	100153	19.670	38.800	65	4.8	
1967	03	12	185522.4	19.441	38.845	33	6.1	
1967	03	12	214433.3	19.620	38.682	33	6.1	
1967	03	13	7280.9	19.613	38.691	33	5.8	
1967	03	13	81054.8	19.551	38.612	15	5.0	
1967	03	13	114829.6	19.568	38.776	33	5.0	
1967	03	13	192219.5	19.673	38.745	31	5.7	
1967	03	14	213207.8	19.625	38.775	33	5.6	
1967	03	16	24138.3	19.662	39.019	33	5.1	
1967	03	16	24142	16.550	38.960	63	5.0	
1967	03	16	31159.3	19.434	38.754	33	5.4	
1967	03	16	31203	19.520	38.720	59	4.9	
1967	03	16	144512.8	19.693	38.785	33	5.1	
1967	03	16	160013.9	19.473	38.729	33	6.2	
1967	03	16	160016.8	19.610	38.720	33	4.7	
1967	03	21	233923.9	19.701	39.233	33	6.1	
1967	03	21	233924.2	19.700	38.900	33	4.8	
1967	03	22	225950.5	19.600	38.600	33	5.6	
1967	03	24	63808.5	19.936	38.474	33	5.5	
1967	03	27	195344	19.980	38.460	30	4.9	
1967	03	28	24133.5	19.858	38.705	27	6.7	
1967	03	31	31823.6	19.963	38.407	33	4.9	
1967	04	03	73828	20.000	38.400	23	5.0	
1967	05	17	175039.2	19.683	38.681	33	5.4	
1967	07	14	31128.2	19.800	38.900	33	4.7	
1967	07	14	31132	19.550	38.750	71	4.4	
1967	09	18	20259.8	15.700	39.000	33	4.8	
1967	09	21	182626.1	17.900	40.000	16	4.4	
1967	11	16	22203.1	15.100	39.800	33	5.1	
1967	11	16	22205.2	15.190	39.490	33	5.0	
1969	09	26	45435.7	16.428	40.983	25	5.1	4.5
1974	04	17	182733.7	17.255	40.365	33	5.0	5.1
1974	04	26	180816.9	17.141	40.380	33	4.8	
1974	06	30	132624.7	16.013	39.631	33	4.4	
1975	06	29	130115.49	18.771	39.484	33	4.8	
1975	06	29	130116.1	19.050	39.460	33	4.8	
1975	06	29	214558.93	18.569	39.780	33	4.8	
1975	06	29	214559.3	18.743	39.773	33	4.8	
1975	06	30	42051.95	17.983	40.164	33	4.6	
1975	08	07	224313.5	15.288	40.407	37	4.6	
1976	01	31	23609.1	18.800	39.387	16	4.2	
1976	01	31	23610.2	18.971	39.225	16	4.3	
1976	03	18	173940.4	19.233	39.036	33	4.4	
1976	03	19	4957.9	19.174	39.042	33	4.3	
1976	04	22	162916.2	19.915	38.571	33	4.0	
1976	11	07	55307.6	15.820	41.423	34	4.8	
1976	11	07	202147.4	15.973	41.474	33	4.7	
1976	11	16	125333.7	15.905	41.915	33	4.9	3.9
1976	11	16	125334.21	15.861	41.781	33	4.6	
1976	12	01	50338.7	15.866	41.681	33	4.8	
1976	12	01	50341.3	15.769	41.850	36	4.8	
1977	05	15	41800.94	17.759	37.309	33	4.3	
1977	06	27	141320.2	16.154	40.013	33	4.3	
1977	12	28	24536.7	16.659	40.278	33	5.9	6.6

DATE Yr	Mo	Da	ORIGIN TIME	LAT.	LONG.	DEPTH (km)	m_b	Ms
1978	01	04	50443.01	16.554	40.932	33	4.4	
1978	01	04	50443.01	16.689	40.848	33	4.5	
1978	01	17	150027.4	16.521	40.263	10	5.2	5.0
1978	02	21	220442.24	16.316	40.452	33	4.7	
1978	02	21	220442.3	16.462	40.392	33	4.7	
1978	03	25	25504.2	16.530	40.259	10	5.0	
1979	05	13	204800.3	18.759	39.295	10	4.8	
1979	05	13	205540.3	18.864	39.190	10	4.5	
1979	05	13	205548.05	19.624	39.154	30	4.5	4.8
1979	07	17	170657.7	17.425	40.112	10	5.2	4.4
1979	07	17	170704.53	17.657	40.127	31	5.1	4.5
1979	07	22	185157.94	17.404	39.959	33	4.1	
1979	08	13	161750	15.267	42.032	10	4.4	
1979	08	15	22.42.33	15.308	41.8912	10	4.7	
1979	08	15	22043.2	15.393	41.699	10	4.7	
1980	01	14	41054	16.518	40.268	10	5.3	5.7
1980	01	14	42149.2	16.551	40.083	10	4.5	
1980	01	14	122822.6	16.453	40.232	10	5.3	5.1
1980	01	14	125715.4	6.323	40.173	10	4.7	
1980	01	14	125716.86	16.544	40.254	10	4.7	
1980	01	26	61530.4	16.372	40.137	10	4.6	
1980	01	26	61531.08	16.462	10.318	10	4.5	
1980	03	05	31205.2	16.610	40.239	10	4.9	
1980	04	07	164537.9	17.577	40.183	33	4.8	
1980	07	12	125904.5	17.193	40.266	10	4.3	
1980	07	16	231456.7	17.245	40.435	10	4.8	
1980	07	17	819.1	16.633	40.465	10	4.6	
1980	07	17	821.58	17.176	40.413	0	4.6	
1980	07	17	1246.0	17.142	40.743	10	4.3	
1980	07	17	1250.9	17.411	39.963	10	4.3	
1983	08	07	104218.35	16.449	41.326	10	4.5	
1985	06	13	81445.35	16.112	39.627	10	4.7	
1985	07	22	142726.33	19.052	39.194	33	4.6	
1986	08	02	16532.13	15.963	39.677	10	4.7	
1987	09	11	4816.45	16.992	40.341	10	4.8	
1988	03	30	65351.62	16.404	41.059	10	4.8	
1988	04	06	31122.64	16.371	41.166	10	4.8	
1988	04	08	223237.8	16.345	41.121	10	4.6	
1988	11	01	190648.27	16.602	40.846	10	4.5	
1988	11	01	191945.53	16.271	40.958	10	4.8	4.5
1988	11	01	191947.13	16.541	40.997	10	4.7	
1988	11	01	235104.95	16.791	40.614	10	4.2	
1988	11	02	3713.69	16.627	40.763	10	4.6	
1988	11	02	143636.14	16.482	40.967	10	4.4	
1988	11	03	11937.58	16.751	40.982	10	4.5	
1988	11	03	75509.48	16.490	41.019	10	4.7	
1988	11	03	192722.43	16.467	41.020	10	4.6	
1988	11	03	195058.59	16.539	41.076	10	4.8	
1988	11	04	10256.43	16.630	40.938	10	4.4	
1988	11	06	150008.16	16.580	41.150	10	4.6	
1988	12	10	173319.97	16.321	41.102	10	5.2	5.4
1990	06	07	214600.41	17.657	39.931	10	4.2	
1990	06	07	222824.33	17.609	40.466	10	4.5	
1990	06	08	31702.07	17.529	40.972	10	4.5	4.4
1990	06	08	31706.22	17.573	40.155	10	4.8	4.4
1991	03	31	231926.98	19.514	38.731	10	4.6	
1991	08	07	165835.78	17.807	40.004	10	4.2	
1993	03	04	191018.93	19.815	38.697	10	4.6	
1993	03	09	125935.64	19.783	38.704	10	4.7	4.4
1993	03	09	204330.92	19.608	38.662	10	4.8	4.8
1993	03	10	2914.30	19.729	38.706	10	4.6	4.1
1993	03	11	1853.60	19.764	38.655	10	4.3	
1993	03	1	81946.14	19.547	38.675	15	5.0	4.9
1993	03	11	142114.45	19.704	38.736	10	4.8	4.4
1993	03	11	215822.12	19.706	38.690	10	4.5	
1993	03	11	225806.78	19.826	38.750	10	4.5	4.4
1993	03	12	1917.29	19.678	38.700	10	4.6	

Table 1. Continued

DATE Yr	 Mo	 Da	ORIGIN TIME	LAT.	LONG.	DEPTH (km)	m_b	Ms
1993	03	12	34716.34	19.742	38.746	10	4.3	
1933	03	12	42419.33	19.576	38.743	10	5.1	5.2
1993	03	12	51202.67	19.516	38.711	15	4.6	4.3
1993	03	12	192201.34	19.864	38.754	10	4.3	4.5
1993	03	12	233246.49	19.633	38.647	10	4.7	4.7
1993	03	13	34044.33	19.619	38.709	10	4.7	4.5
1993	03	13	135959.16	19.400	38.778	10	4.9	5.1
1993	03	13	171226.2	19.626	38.799	10	5.7	5.4
1993	03	13	191531.02	19.923	38.935	10	4.0	
1993	03	14	81213.25	19.602	38.774	10	4.9	4.6
1993	03	14	144918.07	19.564	38.648	10	4.7	4.4
1993	03	15	13813.33	16.491	38.738	10	5.0	
1993	03	15	45733.09	19.438	38.762	10	4.7	4.3
1993	03	15	85755.45	19.434	38.708	13	4.9	4.7
1993	03	15	233345.07	19.677	38.860	10	4.2	
1993	03	16	65905.94	19.422	38.718	10	4.7	4.6
1993	03	16	115926.46	19.516	38.768	10	5.4	4.8
1993	03	17	10340.5	19.478	38.754	10	4.3	
1993	03	17	172302.33	19.712	38.974	10	4.2	
1993	03	17	211929.21	19.033	38.702	10	4.2	
1993	03	19	2047.59	19.615	38.752	10	4.6	
1993	03	19	10135.01	19.956	39.252	10	4.1	
1993	03	20	54935.36	19.593	38.777	10	4.9	4.6
1993	03	30	60502.99	19.567	38.814	10	4.7	5.0
1993	03	22	205137.64	19.498	38.734	10	4.9	4.8
1993	03	23	5932.78	19.590	38.693	10	5.2	5.0
1993	03	23	40522.09	19.533	38.704	10	4.8	4.7
1993	03	23	213511.41	19.480	38.871	10	4.4	
1993	03	24	183710.77	19.752	38.618	10	4.5	
1993	03	26	185051.66	18.385	44.358	10	5.9	
1993	05	04	22318.19	16.443	39.675	10	4.3	
1993	05	04	64734.13	15.191	39.900	10	4.1	
1993	05	07	35818.13	15.908	42.626	10	4.4	
1993	06	16	111014.68	17.294	39.951	10	4.7	4.6
1993	07	03	13717.53	17.865	39.982	10	4.9	4.5
1994	03	14	194100.52	19.578	38.908	10	4.6	

in the shield area and the coastal plains of the Red Sea. Since 1988 there apparently have been about eleven earthquakes in the southern Arabian Shield with magnitudes $2.7<M_L<4.5$, where M_L is the magnitude to log10. The largest two recent land earthquakes are reported to have occurred on Jan. 9, 1993 at 17° N and 43.9° E (M_L=4.5) and on Oct. 24, 1993 at 16.2° N and 44.3° E (M_L=4.3). These events are indicated by open circles in Fig. 3. Microearthquake studies in the Tihamat Asir region (Merghelani 1979) show a higher level of seismicity. He located ten events that ranged in magnitude from 2.0 to 2.5. Six of these events were located near to the Ad-Darb fault. These events are shown as closed circles in Fig. 3.

The earthquake location programme HYPO71 (Lee and Lahr 1975) was used to determine local seismicity with a velocity model based on the deep seismic refraction model (Mooney *et al.*, 1985). This model assumes that 6.3 km s^{-1} is the dominant crustal P-wave velocity to the Moho. The sub-Moho (at 38 km depth) P-wave velocity is 8.2 km s^{-1}. A Wadati plot of S and P wave travel times from local events was used to determine an average V_p/V_s of 1.73.

Focal depths in the range 10 - 30 km have been reported for the 170 events. These depths are not reliable and have been judged unstable because of the lack of dense station coverage. Therefore, some of these depths were fixed at 10 km, which is the average free depth solution.

Frequency-Magnitude Relationship

A major problem in determining the frequency-magnitude relationship for the southern shield area is the considerable scatter in the distribution of earthquake epicentres. This is due partially to location errors.

The mislocation problem is even more severe for early historical earthquakes (Pre-1900 A.D). Although the documented seismic history of the region dates back to 200 B.C. (Ambraseys 1988), the inaccuracies in determining locations and magnitudes of historical events (Pre-1900 A.D.) are such that, with the exception of a few cases, they cannot be associated with particular zones. Consequently, the frequency-magnitude relationships estimated here are based on earthquakes which occurred during the present century (1913-1994). However, the historical information has been used to validate the results .

To find the magnitude thresholds above which the catalogues are consistent, the frequency versus magnitude relationship was derived utilizing the Gutenberg and Richter (1954) equation:

$$\text{Log } N = a - bM$$

where N is the number of earthquakes per unit time of magnitude equal to or greater than M and a and b are constants depending on tectonic factors such as the nature of faulting associated with the earthquakes. Clearly, b is a statistic measuring the proportions of large and small earthquakes in the group. When b is large, small earthquakes are relatively common, whereas when b is small, small earthquakes are relatively rare.

Because the seismicity of the southern Red Sea is generally moderate, and research has shown that significant errors in the computed b-value occur when the total number of earthquakes are less than about 40 (Bender 1982), b-values for regional collections of the two source zones having a total number of earthquakes in each zone from 82 to 88 were thus computed. Thenhaus *et al.* (1986) estimated b-values from maximum likelihood fits (Weichert 1980) to the combined data for the Red Sea and western Saudi Arabia to be between -0.89 and -1.11.

Figure 4 shows the plot of cumulative frequency (Log N) of 170 events versus the magnitude for the period 1913-1994. The least-squares estimates fit well to the whole southern Red Sea area for body-wave magnitude equal to or greater than 4.2, although for the northern

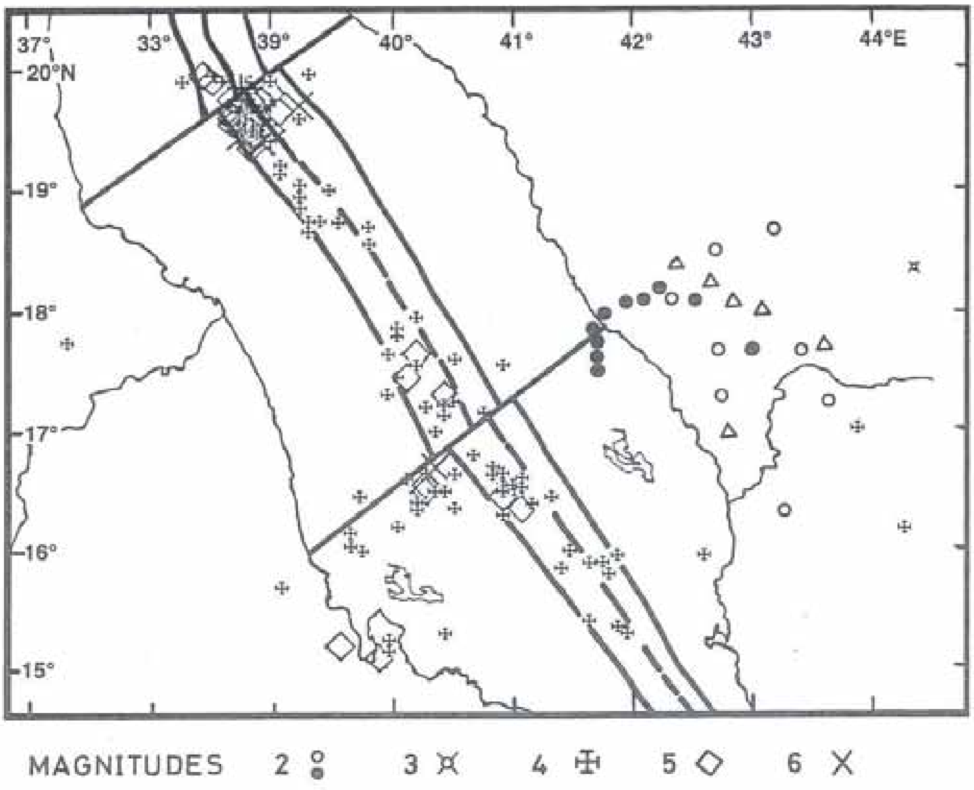

Figure 3. A seismicity map for the period 1965-1994 superimposed on oceanic transform faults. Open circles denote epicentres inferred by this study whereas closed circles denote epicentres located by Merghelani (1979). The triangles represent seismographic stations.

and southern zones taken independently, the least-square estimates fit well for body-wave magnitudes equal to or greater than 4.4.

Previous studies by Al-Haddad *et al.* (1994) and by El-Isa and Al-Shanti (1989) show that the b-values for the whole southern Red Sea are in the range -0.50 to -0.8. This study has found that a and b values for the whole southern Red Sea are 6.22 and -0.91 respectively. The standard error in calculating the b-value is 0.03. More specifically, for the northern zone of the southern Red Sea area, a and b values are 5.41 and -0.80 respectively. They are 6.24 and -1.0 for the southern zone of the southern Red Sea area.

DISCUSSION AND INTERPRETATION

The regional and local seismicity shows that the major transform faults of the southern Red Sea are a considerable seismic risk and the relative level of ground motion is moderate.

The seismicity map of Fig. 3 indicates a concentration of activity near latitudes 16.5° and 19.6° N along the transform faults in the deep axial trough of the southern Red Sea. Blank (1977) showed that the distribution of epicentres seems to be confined to narrow linear belts coinciding with the axial trough and north-east trending fracture zones.

Examination of the total-intensity magnetic anomaly map of the Red Sea (Hall *et al.*, 1977) shows that some magnetic anomalies are offset in a north-easterly direction and others are normal to the axial trough lineations. This could be due to the magnetic expression of transform faults which cause the disturbance of the magnetic anomalies. These faults trend in a north-easterly direction, but because of the short distance across the Red Sea it is not possible to ascertain their azimuths accurately from the magnetic anomalies. Hall (1979) mapped large-amplitude, long-wavelength, linear magnetic anomalies along the shelves of the southern Red Sea and interpreted them as the expression of oceanic crustal strips of alternating remanent polarization that were emplaced during Tertiary seafloor spreading and subsequently buried by Miocene sedimentary deposits. These anomalies extend onto the coastal plain and inland as far as the exposed margin of the shield, where they are associated with the diabase dyke swarm (Kellogg and Blank 1982).

In order to investigate the relation between the epicentral distribution and the tectonic features of the study area, the locations of the faults inferred from the offset of magnetic anomalies (Hall *et al.*, 1977) were superimposed upon the seismicity map (Fig. 3). The alignment of epicentres and the north-east trending faults near latitudes 16.5° N could indicate that this fault extends north-eastward on land to at least 42° E. Focal mechanism solutions for two earthquakes located near latitudes 17.2° and 19.8° N indicate nearly pure strike-slip movement on north-east trending planes and suggest seismic activity on rift transform faults (Fairhead and Girdler 1970).

The proposed extension of the north-east fault has not been field checked and traced in the Tihamat Asir (coastal plains), because of the presence of thick deposits of unconsolidated sediments. Evidence for the fault zone, which is concealed beneath the pediment area of the Tihamat Asir, is seen in the straight fronts of the shield edge, in the uplifted escarpments and in a line of volcanic cones in the Tihamat Asir (Skipwith 1973). Several earthquakes occurred on land near the extension of the inferred fault. The 1962 earthquake (M_s=4.7) that occurred in the vicinity of latitude 18° N (Fig. 2) to the west of Ad-Darb town, is reported to be associated with a strike-slip mechanism (Fairhead and Girdler 1970). Merghelani and Gallanthine (1980) located six events in the neighbourhood of the north-east Ad-Darb fault, south-west of the town of Abha. More recently, in 1988, a moderate size earthquake (M_s=4.5) was located near Ad-Darb at 18.3° N and 41.9° E.

The scatter of some epicentres in the shield area is due to the complexity of the rift faulting, the temporal operation of seismic stations and inaccuracies involved in the calculation of the epicentres because of the poor azimuthal coverage of the existing stations (Fig. 3). The low level of seismicity in the coastal plains is caused by the fact that some deep faults exist without surface traces. Marine epicentres (1921 and 1967) are considered of less risk than land earthquakes (1941, 1955 and 1993) or seaquakes close to the shore (1962 and 1988) because of the high attenuation of seismic waves travelling through the rather soft and hot upper mantle material beneath the sea.

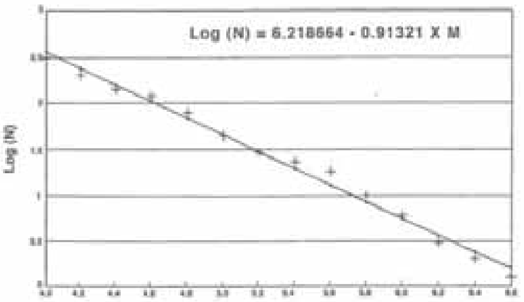

Figure 4. A magnitude-frequency relation for the period 1913-1994 (Magnitude vs. Log of a cumulative number of events) showing the limit of uncertainties.

The results of the frequency-magnitude relationship show that the least square estimates fit well for the northern and southern zones for the same data set only when m_b is equal to or greater than 4.4. This suggests that the SAED catalogue is complete for all instrumentally recorded earthquakes having body-wave magnitude equal to or greater than 4.4.

This study also indicates that the b-values gradually increase southwards to attain a value of -1.0. The high average b-value in the southern zone (south of latitude 18° N) compared to the northern zone (north of latitude 18° N) could be due to the heterogeneity in the lithosphere, the applied stress not being uniform, or both. The predominant stress field is the more recent Red Sea rifting, of which the primary principal compressional stress acts roughly perpendicular to the spreading axis of the Red Sea.

Udias (1977) correlated the low b-value with heterogeneous physical conditions in the corresponding crustal source region. Wyss (1973) pointed out that the b-value increases as the degree of crustal heterogeneity increases and as the degree of symmetry of the applied stress decreases.

Different b values for the same data set may vary according to different assumptions, such as maximum magnitude and different techniques of treating magnitude interval size. For different global catalogues, Frohlich and Davis (1993) find values of b ranging from 0.79 to 1.25. Since the frequency-magnitude relation is not linear, the b-value varies by 15% or more, even for individual catalogues, depending on the exact range of magnitude used for its determination.

SUMMARY AND CONCLUSIONS

Analysis of the seismicity data from the southern Red Sea region in conjunction with other available magnetic and geologic information enable the following conclusions to be drawn:

i) the frequency-magnitude analysis indicates that earthquakes with a body-wave magnitude equal to or greater than 4.2 have been well determined for the southern Red Sea region

ii) the seismicity is shallow and mainly associated with the deep axial trough zone in the central Red Sea

iii) the correlation of the offshore epicentral distribution with the major tectonic features is, in general, quite good. However, the low level of seismicity in the shield area and a poor correlation with the tectonics might be due to the complexity of faulting, lack of detection of small events and poor or inaccurate azimuthal coverage of stations.

iv) structural patterns inferred from magnetic data and earthquake locations (offshore and onland) provide evidence for the continuation of the faulting regime from the southern Red Sea north-eastward into the Arabian Shield

v) most of the seismicity of this region is of the swarm-type and is volcanic-related. Results of seismicity parameters suggest that a higher b-value for the southern Red Sea means that a smaller fraction of the total earthquakes occurs at the higher magnitudes and that the area of highest seismic risk is the spreading centre of the southern Red Sea.

Acknowledgments

The author wishes to thank the Seismological-Geophysical Observatory of the King Saud University for providing local earthquake data. Special thanks are extended to Dr. William Spence and Glen Reagor for providing historical and instrumental data. The author also acknowledges Dr. Kevin Kelly for his critical review and helpful suggestions for the improvement of this manuscript.

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