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RECENT SEISMIC ACTIVITY IN THE N®12T'HE N RED SEA

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Abstract-Recent seismicity and swarm activity in the northern Red Sea have been examined in relation to the tectonics and structures indicated by surface geology and marine magnetic anomalies. Seismicity appears to be low compared to the rest of the Red Sea. Sixty eight earthquakes recorded during the period 1964-1993 had body-wave magnitudes between 3.8 and 6. On 18 February 1992, a swarm of earthquakes began in the northern Red Sea and lasted for about 5 days. More than 180 local earthquakes were detected between 25.79 °-26.89 °N latitudes and 34.74°-35.57 °E longitudes, 12 of which were discernible enough on seismograms to establish epicenters and magnitudes. The majority of seismic activity of this swarm is clustered in the area located between lat. 26.7° and 27.3°. The most remarkable aspect of this earthquake swarm sequence is the migration of epicenters northward by about 100 km in 5 days with focal depths less than 20 km. This study and historical data confirm that the relatively low level of seismicity should not be used as an argument for minimizing the probability of seismic hazard. This swarm may release energy that can be accumulated to cause larger events in the future. This study, however, does not agree with the previous idea which states that the northern Red Sea is considered to be a seismic gap, where the faults are locked and do not generate earthquakes.

INTRODUCTION

The Red Sea, one of the world's youngest oceanic basins, separates the Arabian Shield from the Nubian Shield. The narrow, axial trough of the Red Sea is generally accepted as a divergent plate margin, the locus of sea floor spreading associated with the separation of Arabia from Africa (McKenzie et al., 1970; Girdler and Styles, 1974). Cochran (1983) suggested that the northern Red Sea is totally underlain by stretched and thinned continental crust.

The seismotectonic evolution of the northern Red Sea is of great importance in explaining the tectonic processes in the Red Sea. An understanding of marine seismicity will help in studying magma circulation at mid-oceanic ridges and locating active lineaments of the oceanic lithosphere. Makris and Rihm (1991) proposed a pull-apart model for the evolution of the Red Sea which is not in agreement with the above models. Their model explains the asymmetries of crustal types and shape of margins in the northern Red Sea in accordance with heat flow and gravity field.

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 and Girdler, 1970). Results of deep seismic soundings in the northern Red Sea (Rihm *et al.,* 1991) were reported to represent a thinned continental crust beneath the eastern flank and oceanic crust beneath the western flank (Egyptian side).

Previous research indicates little seismic activity in the northern Red Sea, and only three earthquakes have been recorded north of latitude 25 °N (Ben-Menahem and Aboodi, 1971). Historical data strongly suggest that much of the activity is of the swarm type and is related to volcanism of the 1256 earthquake of Al-Madinah and tectonism of the 1068 earthquake (Barazangi, 1981).

Recently, a significant number of microearthquakes were detected east and west of Al-Wajh (Kinkar *et* al., 1988) and north of Yanbu (Merghelani, 1981). The relatively recent earthquake swarm in February 1983, affecting the Gulf of Aqabah, has been described by El-Isa *et al.* (1984).

In 1992, an earthquake swarm occurred in the northern Red Sea between 18 and 22 February, during which more than 180 events ($1.2<MD<3.6$) were recorded by Wajh station at an epicentral distance of about 100 km.

The area of interest for this investigation extends from latitude 25 °N, to the southern tip of the Sinai peninsula at 27° 45'N and from longitude 33°, to the northwest portion of the Arabian Shield at 38 °E. The purpose of this study is to investigate the characteristics of the recent swarm activity. Correlating, where possible, the seismicity of the region with the pre-existing tectonic and active faulting to evaluate the most direct evidence relating to the potential seismic hazard in this segment of the Red Sea.

SEISMOTECTONIC SETTING

Precambrian crystalline basement is widely exposed throughout western Saudi Arabia, although large areas are covered by voluminous Tertiary basalt (Fig. 1). These flows are usually less than 50 m thick but are spread over vast areas and extend to about 150-200 km inland from the Red Sea coast.

It is generally considered that Arabia separated from Africa in the NE direction and several transform faults trending in that direction may have been formed. The locations of the faults were inferred from the offsets of the magnetic anomalies (Hall *et al.,* 1976). The lack of magnetic expression of the sea floor in the northern Red Sea is attributed to the presence of evaporites which permit the sea floor to cool more slowly and thereby acquire a reduced thermoremanent magnetization (Hall, 1979). Mart and Hall (1984) suggest 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 occur prior to the spreading of the sea floor and the evolution of the accreting plate boundary.

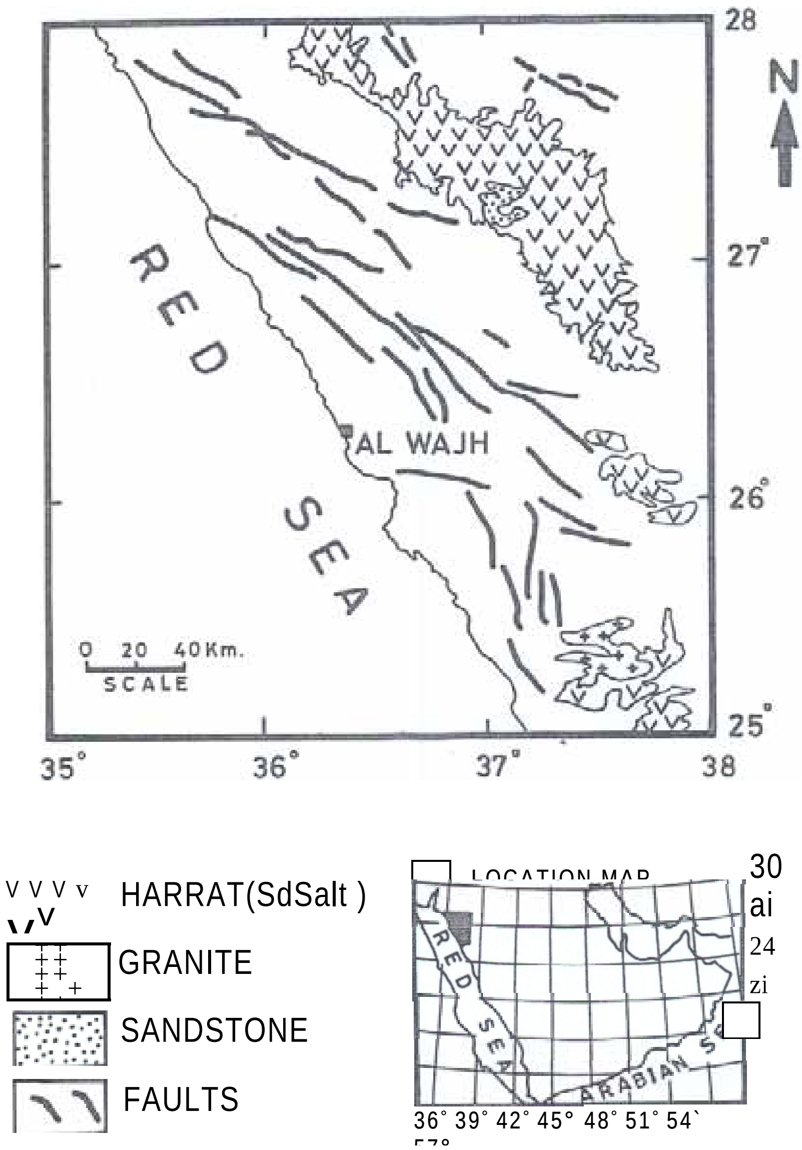

Fig. 1. Regional tectonics of the northern Red Sea area showing structural and lithological features (modified from Kinkar et al., 1988).

Bonatti (1985, 1987) and Cochran *et al.* (1986) propose that extension has been continuous since the Oligocene but that the sea floor spreading has only been active during the past 10 Ma. In other words, before the initiation of sea floor spreading, extension was marked by continental stretching and dike injection and resulted in the formation of the main trough.

The seismic activity in the axial trough of the Red Sea supports the interpretation of the magnetic anomalies in terms of sea floor spreading, and earthquakes probably occur where new oceanic crust is being formed. This activity is higher in the southern than in the northern Red Sea. Instrumental seismicity of the northern Red Sea shows that 68 earthquakes ($3.8<mb<6.0$) are reported to have occurred in the period 1964-1993. Fault-plane solutions of the 1969 earthquake at latitude 27.6°N (m_b = 6.9) indicate normal faulting (McKenzie *et* al., 1970). On spreading centers, earthquake swarms are generally associated with normal faulting (Sykes, 1967) and with major strike-slip faulting (Tatham and Savino, 1974).

The earthquake swarm of the Gulf of Aqabah in 1983 lasted for more than 4 months. This swarm indicates that the seismicity of the Dead Sea transform is characterized by both mainshock and aftershock as well as swarm types of activity (El-Isa et al., 1984). Geological and tectonic information attribute this swarm to subsurface magmatic activities and consequent isostatic adjustments in the Gulf of Aqaba region. Extensional stresses responsible for Red Sea rifting have resulted in movements and magmatic activities along Tertiary-Quaternary, and older, tectonic lineaments.

METHOD OF ANALYSIS

Earthquake catalogues

With the inception of the World Wide Seismographic Station Network (WWSSN) the location accuracy of the instrumental earthquakes has considerably improved since 1964. Thus, it can be stated that a reliable earthquake database for small magnitude events has only existed for the last three decades.

The earthquake data utilized for this study are based primarily on the King Saud University, Preliminary Determination of Epicenters (PDE) and International Seismological Center (ISC) catalogs, with entries cross-checked and additions made from other bulletins in the region (Ambrasseys, 1988; Poirier and Taher, 1980) covering the time period from 1964 to 1993.

Prior to 1984 no permanent seismic stations existed in Saudi Arabia. Thus, it is difficult to have seismic data which are complete. Most data sets lack historical and seismographic network data. The aforementioned database is treated against incompleteness, missing magnitudes, different reported magnitude scales and clusters.

The 12 epicenters of the 1992 earthquake swarm (as indicated by closed circles in Fig. 2) that generated discernible P and S waves were plotted using arrival time differences between S and P waves. This procedure is compared for accuracy using the HYPO-71 computer program (Lee and Lahr, 1975). The modified velocity crustal model used in these calculations was adopted from Rihm et al. (1991) based on wide angle reflection and refraction seismic surveys carried out at different sections of the northern Red Sea and adjacent land areas. In this model, the near-surface P-wave velocity is 6.0 km s^{-1} to the Moho at 15 km depth beneath the northern Red Sea and 30 km depth beneath the Precambrian basement. The sub-Moho P-wave velocity is 8.2 km s^{-1}. A Wadati plot of S and P wave travel times from these events was used to determine an average VWVS of 1.71. The duration magnitudes (M_D) for swarm shocks were estimated using the formula of Lee and Stewart (1981):

$$MD = 2.0 \log T - 0.87 + 0.0035\, D$$

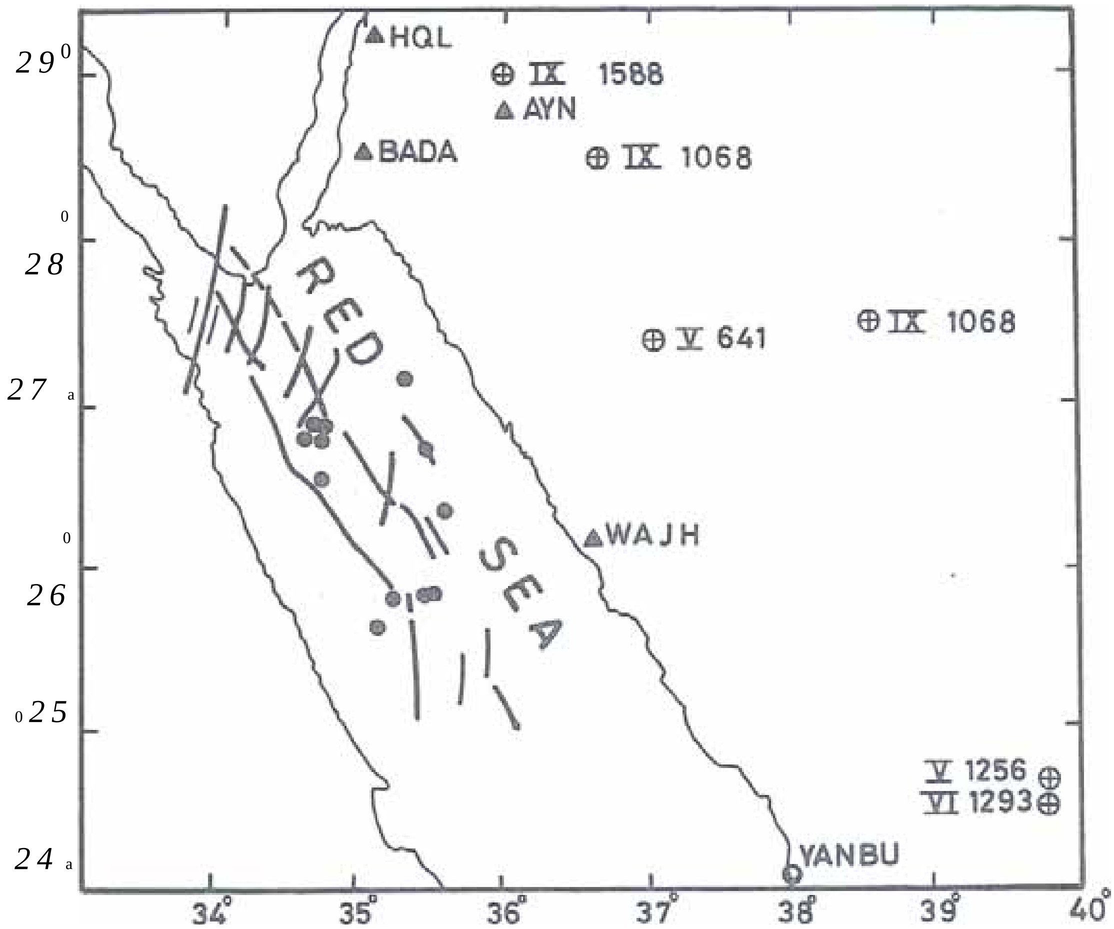

Fig. 2. Epicentral distribution of the swarm activity. ® and ® designate seismic stations and epicenters, respectively. Major historical earthquakes are denoted by their intensities.

where, T is signal duration in seconds, and D is epicentral distance in kilometers. The empirical recurrence relationship for earthquakes (Gutenberg and Richter, 1954) is:

$$Log N = a + b M$$

where, N is the number of earthquakes above the M magnitude in a given region and within a given period, and a and b are regression constants. The coefficient a is a constant that is dependent on the location and time of the sample used. The value of b is a measure of the relative abundance of large and small earthquakes. A large value for b indicates that small earthquakes occur frequently, and a small value for b indicates that small earthquakes are not so frequent and that large earthquakes are more likely to occur. The method of least squares is used to obtain the best fit of the data to a straight line. The least square estimates fit well for the northern Red Sea area only when body-wave magnitude is equal to or greater than 4.0. This study has found that a and b values for the 68 earthquakes (Fig. 3) are 6.174 and -1.0566 respectively. The standard error in calculating b-values is 0.098. The values of the seismicity parameters and the resulting

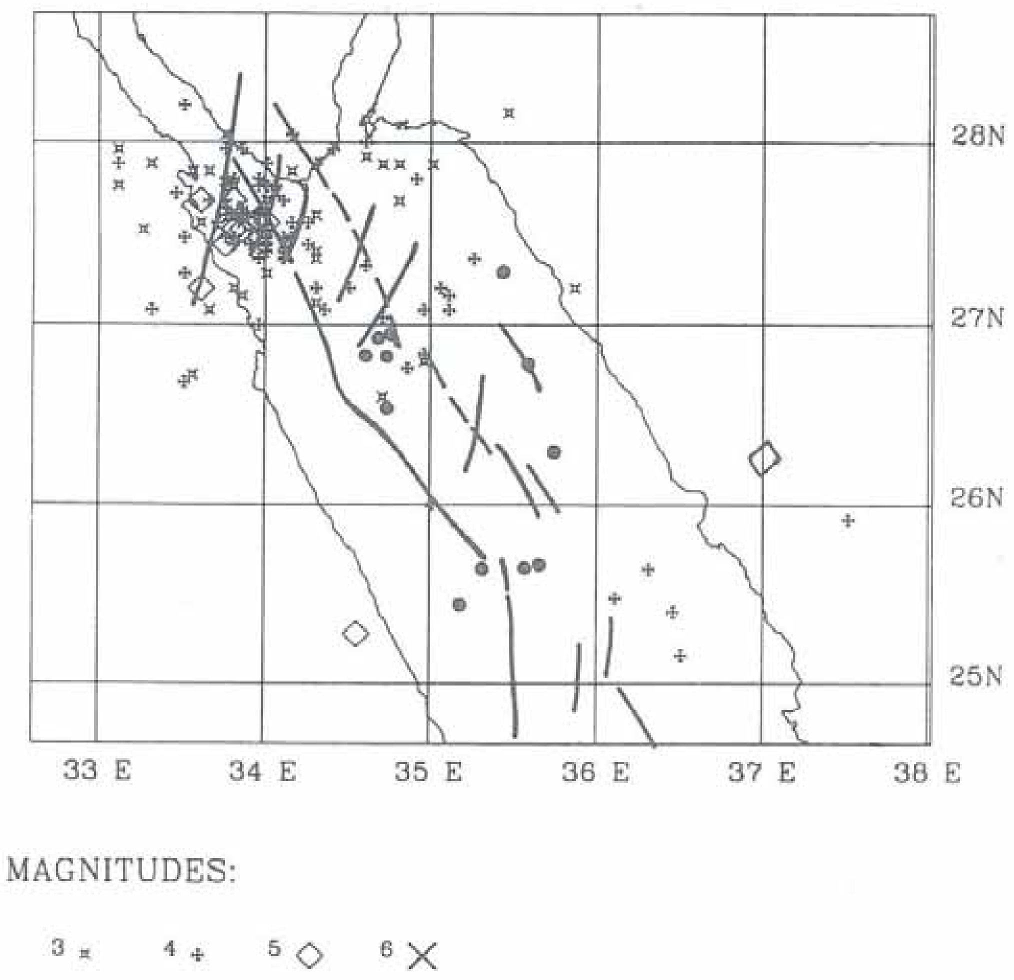

Fig. 3. Instrumental seismicity for the period 1964–1993 superimposed on major structural trends. Epicentral distribution of the swarm shocks are designated by ●.

recurrence relationships are shown in Fig. 4. The constants *a* and *b* for all swarm shocks are 2.703±0.083 and 0.596±0.036, respectively.

The determination of the maximum magnitude expected in this region is a difficult and quite subjective problem. Because the tectonics are very complex and it is not possible to single out a prominent fault, the maximum magnitude is estimated on the basis of the maximum historical earthquake. For short return periods, the ground motions are dominated by low-to-moderate magnitude events. In such a situation the choice for an upper bound is not a critical factor in determination of the ground motion levels (Al-Haddad *et al.*, 1994). In this study, the maximum value is taken to be the maximum magnitude generated by a source plus one half ($M_s=6.4$). Thenhaus *et al.* (1986) assigned a $M_s=6.5$ maximum magnitude to the Red Sea and Gulf of Aden area.

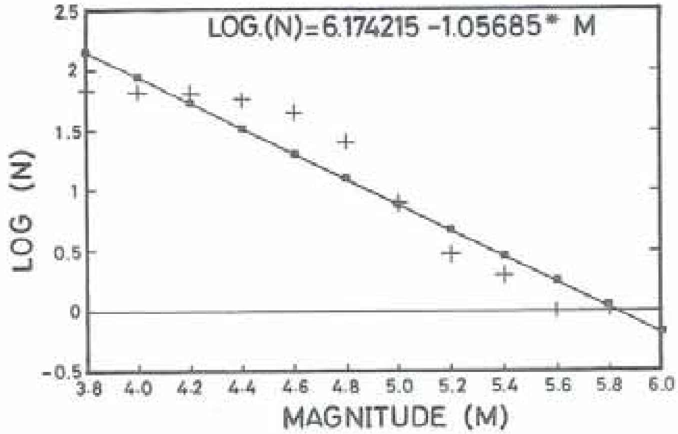

Fig. 4. Magnitude–frequency relation for the period 1964–1993 (magnitude vs. log cumulative no. of events). The solid line with dots is the best fit relationship for the data, whereas the crosses indicate the limit of uncertainties.

RESULTS AND DISCUSSION

Instrumental seismicity of the northern Red Sea shows that 68 earthquakes ($3.8<m_b<6.0$) are reported to have occurred in the period 1964–1993. About 77% of the activity occurred offshore and the other 23% occurred inland on both sides of the Red Sea. The epicentral map of Fig. 3 indicates a concentration of seismic activity in the area located between lat. 27.4° and 27.7° and long. 33.5° and 34.2° near Sinai triple junction. This high activity may be due to a northwest strike of the shear zone and the dextral sense of movement conjugate to the sinistral and northeast trending Gulf of Aqabah.

The correlation between marine seismicity and tectonics is not clear. Some epicenters lie on or close to at least one transform fault near latitude 27°, trending in the NE direction which was inferred from the offsets of the magnetic anomalies (Hall, 1979). El-Isa and Al-Shanti (1989) believe that northeast faults are known to cross the area southwest of Al-Wajh and may be considered as potential areas for future earthquakes.

All of the earthquake swarm data used in this research were obtained from the records of the Gulf of Aqabah subnetwork (HQL, BADA, AYN and WAJH stations as marked by solid triangles in Fig. 2). Most of the swarm events were only recorded by WAJH station. The analog seismograms were read for P arrival times and polarities, S times and coda durations. The accuracy of readings for P ($P_{g,n}$) was ± 0.07 s and for S ($S_{g,n}$) was ± 0.1 s. The smaller accuracy for the S reading is due to the fact that the seismic traces are already in motion. Unfortunately, there are no seismic stations in the west–northwest direction to minimize these errors. Some of the observed first motions of the swarm were not easily identified because of limited dynamic range in analog recording and all stations are equipped with short-period vertical seismometers. Consequently, it was difficult to obtain reliable fault plane solutions.

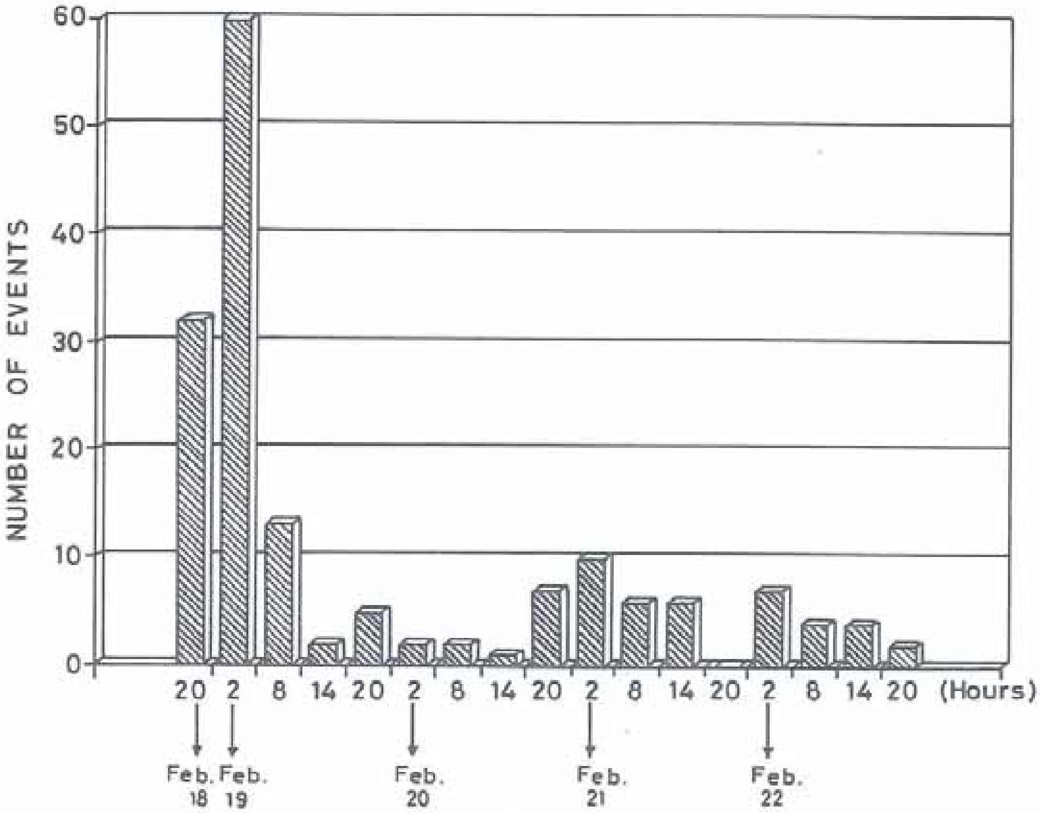

Fig. 5. A histogram showing the frequency of occurrence comprising 180 shocks every 6 h during the period 18–22 February 1992 with magnitude range 1.2–3.6.

The epicentral distances of the events were estimated from S–P arrival time differences. The largest 12 shocks are plotted in Fig. 2 as closed circles. Of these, 7 shocks have S–P times in the range 10–20 s. Three epicentral radii equal to 64, 80, and 160 km were determined for the values of S–P 8, 10, and 20 s, respectively with their centers at WAJH station. The calculations of hypocentral parameters indicate that the swarm epicenters migrated northwards by about 100 km in 5 days with focal depths less than 20 km.

The frequency of occurrence every 6 h during the period 18–22 February for 180 shocks ($1.2<M_D<3.6$) is shown in Fig. 5. It indicates a gradual decrease in number with time and also indicates that events of peak activity occurred on 18 and 19 February. On February 18, the first peak of activity occurred where 30 shocks were recorded within 6 h. A second peak, which is the highest with 60 shocks recorded, is observed in the early hours of 19 February. On the following days of 20, 21, and 22 February, the activity slowed down in magnitude and number.

The a-values for the northern Red Sea, including the Gulfs of Aqabah and Suez, are 3.93 while the b-values are 0.59. The latter constant (b) increases northwards to attain a value of 0.71 in the Gulfs (El-Isa and Shanti, 1989). Variations of a and b values are due to crustal heterogeneity which is believed to be caused by the presence of magmatic activity and diapiric structure. The epicenters were confined to a small focal area and probably shorter fault lengths which may indicate larger slip rates. The estimated seismic energy and moment for the largest shock of this swarm (M_D = 3.6) are 3.98 x 10^{13} and 1.66 x 10^{13} dyn.cm, respectively.

According to Richter (1958), earthquake swarms contain sequences of generally small-magnitude events with no large event predominating, and are usually small in aerial extent. Swarms have been classified by Mogi (1967) into three types, depending on whether or not they are associated with large earthquakes. Type 1 swarms contain mainshock-aftershock sequences; type 2 swarms contain foreshock-mainshock-aftershock sequences and type 3 swarms are not associated with any recognizable large events. The behavior of the three types of earthquake swarms has been explained by Aki (1984) in terms of the properties of the fault surface upon which the earthquake occurs. The swarm activity of this study fits type 3 of Mogi's (1967) classification, where the number and magnitude gradually increase with time and then decrease after a certain period with no single predominant principal earthquake. However, the largest marine earthquake (Mb= 6.9) occurred in 1969 near latitude 27.6 °N and longitude 33.9 °E and indicates normal faulting mechanism (McKenzie *et al.*, 1970). This activity took the form of a swarm and was classified as foreshock- mainshock-aftershock type (Maamoun and El Khashab, 1978). This activity may follow type 2 of Mogi's (1967) classification.

Generally speaking, it is believed that the low level of seismic activity in the northern Red Sea compared with the southern Red Sea and the Gulf of Aqabah could be due to one of the following reasons:

-Small-magnitude earthquakes occurring in the region do not give enough energy to be recorded on distant stations, and/or
-Lithospheric deformations in this region are occurring on the land.

The most direct evidence to support this assumption is the occurrence of some large historical earthquakes in 641, 1068, 1256, 1293, and 1588, which are reported to have been felt, causing ground cracking and widespread destruction. More recently, the occurrence of microseismicity in the volcanic fields, east of Al-Wajh (Kinkar *et al.*, 1988), north of Yanbu (Merghelani, 1981), and the earthquake of 23 April, 1988 which was located at latitude 26.28 °N and longitude 36.96°E (northeast of Al-Wajh) with NI_L=S, may also confirm this assumption. Thenhaus *et al.* (1986) assumed that any significant future seismic activities in the shield have to be related to the seismic reactivation of the Precambrian faults. Additionally, the absence of dense seismic stations on both sides of the northern Red Sea and lack of detection of small events is the main reason that no conclusive study has been carried out about the nature and level of the seismicity and the relationship between the uplift of continental crust and spreading of the Red Sea.

This study, however, based on the current available data, does not agree with the idea that the low level of seismicity in the northern Red Sea is attributed to seismic gap. The poor correlation between the epicentral locations of the historical and instrumental seismicity could be interpreted in terms of cyclic stress accumulation and release which may cause large events in the future. Identifying swarm characteristics, seisrnicity patterns, and relocation of major historical earthquakes will help to justify the above arguments. It should also be pointed out that installation of strong ground-motion instruments in this region will estimate the attenuation relationships and accelerations for better assessment of seismic hazard.

CONCLUSIONS

This work is a contribution to the better understanding of the northern Red Sea seismicity. It should be noted that this study does not agree with the previous idea which states that the northern Red Sea is considered to be a seismic gap, where the faults are locked and do not generate earthquakes. It is concluded that this region has a certain seismic potential which, however, is smaller than that of the Dead Sea transform and southern Red Sea.

The low level of seismicity in the shield and poor correlation of the offshore epicentral distribution with the tectonics might be due to the presence of magmatic activity and diapiric structure, lack of detection of small events, and the limited operational period of seismic stations. The swarm activity of this study fits type 3 of Mogi's (1967) classification, where the number and magnitude gradually increases with time and then decreases after a certain period, with no single predominant principal earthquake.

In terms of earthquake risk, this swarm may release energy that can accumulate to cause larger events in the future.

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