The Gulf of Aqabah Earthquake Sequence (Nov. 1995-Feb. 1996)

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SUMMARY – On November 22, 1995, a sequence of earthquakes began in the central part of the gulf of Aqabah at the Aragonese fault step zone. The largest event ($M_D = 5.9$) on Nov. 22 had an origin time of $04^h\ 15^m\ 12.3^s$ UTC, a latitude of 28.8° N and longitude 34.7° E. The event was followed by more than 7157 aftershocks ($1.5 < M_D < 5.9$) in the next 98 days.
The majority of seismic activity of this sequence is clustered in the area located between 28.6°-29.3° N. and 34.6°-34.9° E The most remarkable aspect of the earthquake sequence in the gulf is the spatial distribution overlapping of 1995 swarm with earthquake sequences in 1983,1985, 1991, and 1993 and the migration of the epicenters north and northeastward about 50 km in 98 days with focal depths less than 10 km confirming the continual recent crustal motion along the southern portion of Dead Sea transform system.
The structural picture revealed from five single focal mechanism solutions shows that main and aftershocks activities are generally characterized by strike-slip faulting. This mechanism is consistent with left-lateral strike-slip on N-NE trending faults of the Dead Sea transform system.
The results obtained from this study indicate that the seismic activity occurs in the form of mainshock-aftershock sequences. Surficial geology of the epicentral area, linear surface cracks observed in the field, and earthquake locations provide evidence for continuation of the strike-slip faulting regime from the gulf northeastward into the land beneath thick sediments, east of the gulf, suggesting that the northern portion of the gulf is subjected to more severe seismic hazard compared to the southern portion. The recent seismic activity indicates a cyclic pattern of events consisting of seismic minima which may represent episodes of accumulation of energy, and seismic maxima which represent the release of energy that can be accumulated to cause larger events in the future.

KEY WORDS: Gulf of Aqabah, Earthquake Sequence, Seismicity, Swarms.

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1. Introduction

In the 1980's and 1990's, the gulf of Aqabah has been considered as one of the most active seismic zones along the Dead Sea transform system. The internal structure of the gulf consists of three major segments. This geometry, combined with the left-lateral motion along the Arabian plate boundary, results in deeps at step zones, namely Elat deep in the north, Aragonese deep in the central part of the gulf and Dakar and Hume deeps in the south (Fig. 1).

The seismicity of the Dead Sea transform is characterized by both swarm and mainshock-aftershock types of earthquake activities. The instrumental and historical seismic records indicate a seismic slip rate of 0.15-0.35 cm/year during the last 1000-1500 years, while estimates of the average Pliocene-Pleistocene rate are 0.7-1.0 cm/year (Garfunkel, 1981).

Geological and tectonic information attribute this swarm to subsurface magmatic activities and consequent isostatic adjustments in the gulf of Aqabah region.

On spreading centers, earthquake swarms are generally associated with normal faulting (Sykes, 1967) and with major strike-slip faulting (Tatham and Savino, 1974). This variable mechanism indicates that volcanism is not itself the direct cause of the swarm but acts as a trigger and controlling factor.

Historical data strongly suggest that much of the activity is of the swarm-type and is related to volcanism for the 1256 earthquake of Al-Madinah, and to tectonism for the 1068 earthquake (Barazangi, 1981). Ben-Menahem (1979) indicated that about 26 major earthquakes ($6.1 < M_L < 7.3$) occurred in southern Dead Sea region between 2100 B.C. and 1900 A.D. Instrumental seismicity of the gulf of Aqabah shows that 750 earthquakes ($3.5 < M_L < 6.1$) are reported to have occurred in the period from 1965 to 1994.

Recently, the earthquake swarm of the gulf of Aqa-

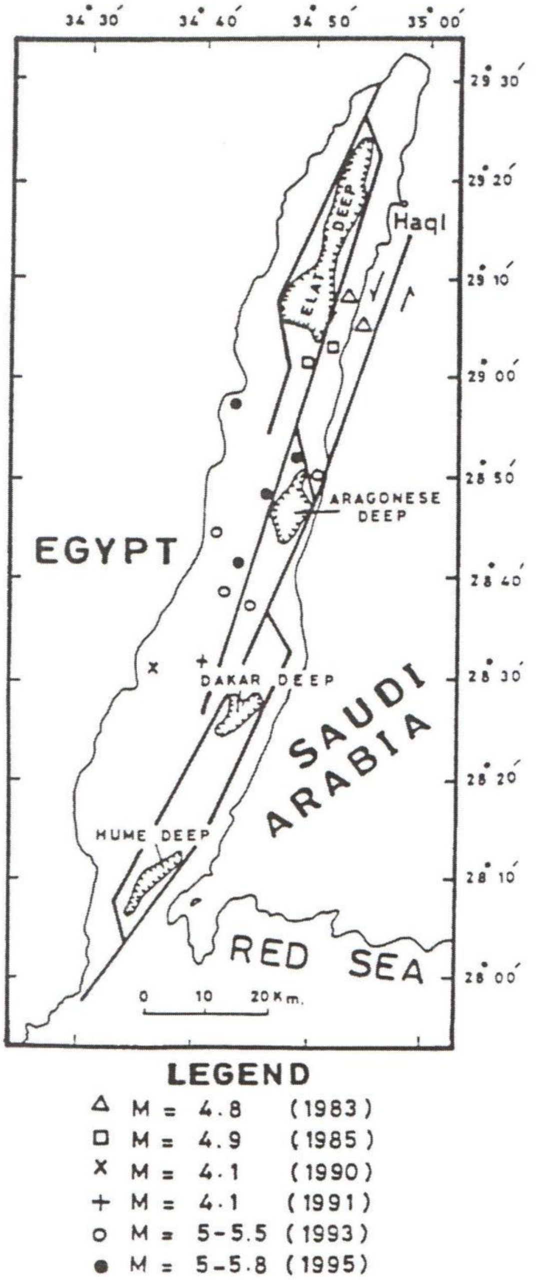

Fig.1 - Generalized structural model for the gulf of Aqabah. The deeps result from en echelon rhomb-shaped grabens (Ben-Avraham, 1985). The largest 14 events from 1983-1995 are superimposed on the structural model.

bah in 1983 lasted for more than four 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).

Two additional earthquake swarm sequences in April 1990 and in May 1991, had maximum magnitudes of 4.1. In July 1993, an earthquake swarm began in the gulf as a foreshock sequence and was followed by the mainshock of $M_D = 5.5$ on August 3. The mainshock was followed by nearly 15000 events with $M_D > 1.5$ in the next five months of 1993.

The most recent sequence activity began in November 22, 1995 in the central part of the gulf of Aqabah with a maximum magnitude of $M_D = 5.9$. More than 7157 aftershocks ($1.5 < M_D < 5.9$) were recorded in 98 days following the mainshock. Klinger *et al.* (1997) used 26 broadband teleseismic digital data for this swarm to perform a bodywave inversion and to estimate surface rupture observed on the coastal area of the gulf of Aqabah.

The purpose of this study is to understand the behavior of main and aftershock sequences of Nov. 22, 1995 earthquake from the data collected by portable seismographs and telemetred network of King Saud University (KSU) and King Abdulaziz City for Science and Technology (KACST) and to investigate the propagation characteristics, spatial distribution and overlapping of swarm activities from 1983-1995. Correlating the recent seismicity of the region with the pre-existing tectonic and active faulting is done to evaluate the evidence relating to the potential seismic hazard in the gulf of Aqabah.

2. Description of earthquake sequences

On Jan. 20, 1983 a swarm of earthquakes began around the Elat deep and lasted from January to April. The swarm was associated with a maximum magnitude of 4.8 followed by more than 500 event with $M_L < 3$. This activity indicates a cyclic pattern of events consisting of seismic minima which may represent episodes of accumulation of energy, and seismic maxima which represent the release of energy (Bazzari *et al.*, 1990).

The duration magnitudes (M_D) for the sequences were estimated using the calibrated formula of King Saud University:

$$M_D = 2.48 \log T - 2.1 + 0.0004\,E \quad \text{for } E < 500 \text{ km}$$

where T is signal duration in seconds and E is epicentral distance in kilometers.

The spatial distribution of 1983 epicenters 10-50 km south of Elat deep, overlaps with the 1985 sequences indicating that these events are representative of activity at the southern flank of the Elat deep. The largest 14 shocks from 1983 onward are plotted on Fig. 1. The largest 4 shocks in 1983 and 1985 have S-P times in the range 3-5 seconds from Haql station. Three epicentral distances equal to 20, 24, 30 and 40 km were determined for the values of S-P 3, 3.5, 4, and 5 seconds, respectively with their centers at Haql station (HQL). The farthest two shocks in 1990 and 1991 lie 10 km west of Dakar deep and their epicentral distance is about 80 km from Haql station. In 1990, 245 events

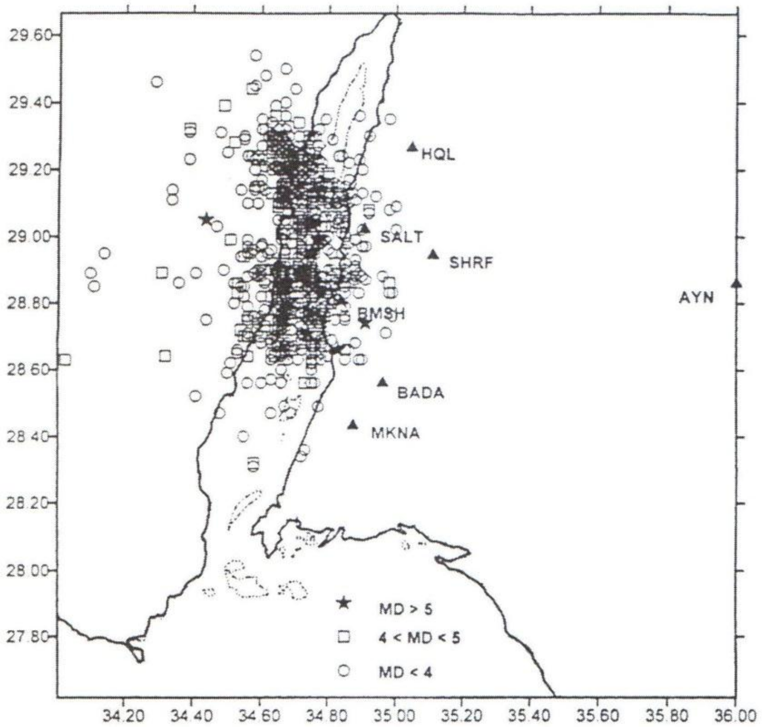

Fig. 2 – Seismicity map of the earthquake sequence from Nov. 22, 1995 to Feb. 28. More than 7157 events were recorded by KSU seismic stations with $1.5 < M_D < 5.9$.

with $M_L < 4.2$ are reported to have occurred and 113 events with $M_L < 4.1$ occurred in 1991 (Al-Arifi, 1996).

The sequence of 1993 began in July near Aragonese deep with a moderate increase in the frequency of background seismic activity followed by the mainshock on August 3 at 12:31 G.M.T with a magnitude 5.5 recorded by more than 120 local and regional stations. This swarm was characterized by a peak of activity followed by a quiescence and lasted until December 1993. Most of the activity concentrated 20 km SW of Aragonese deep with focal depths between 15-20 km, migrated southward in October and reoccurred in the Aragonese deep in November and December 1993.

More recently, a sequence of activity started during the period from Nov. 22, 1995 to Feb. 28, 1996. The largest event ($M_D = 5.9$) on Nov. 22 had an origin time of 04^h 15^m 12.3^s UTC, a latitude of 28.8° N and longitude 34.7° E. The event was followed by more than 7157 aftershocks ($1.5 < M_D < 5.9$) in the next 98 days in the central part of the gulf of Aqabah between Elat and Aragonese deeps (Fig. 2).

The frequency of occurrence of the activity every day for the first 40 days recorded at 14 stations is shown in Fig. 3. The total number is nearly 5000 events. One hundred and twenty three events are of $4 < M_D < 4.9$ and seven events of $M_D > 5$. The histogram shows that the level of activity fluctuated with time and also indicates events of peak activity occurred on Nov. 22 and Dec. 11. On Nov. 22, the first peak of activity occurred where 461 shocks were recorded within 20 hours. A second peak which is the second highest with 255 shocks was recorded in the next day. On the following days of Nov. 24-30, the recorded shocks reached 1147. On Dec. 30 and 31, the histogram shows another peak of activity with more than 490 shocks.

3. Discussion & Interpretation

The occurrence of swarm sequences in 1983, 1985, 1993 and 1995 in the gulf of Aqabah brought to attention the hazards that may result from offshore and onshore seismic sources. It could imply that the gulf of Aqabah is a region of moderate to high seismic hazard. The seismicity map (Fig. 1) of the largest 14 events is superimposed on a structural model of the gulf of Aqabah (Ben-Avraham, 1985). It indicates a concentration of seismic activity in the area located between lat. 28.5°-29.1° and long. 34.7°-34.9°. This high activity may be due to the thick sediments on the land beneath coastal area or to the deeps in the step zones which are sites of stress concentration, especially in the area between Elat and Aragonese deeps where some active normal and strike slip faults interact resulting in heterogeneous physical conditions within the crust.

The most remarkable aspect of the earthquake sequence in the gulf is the spatial distribution overlapping

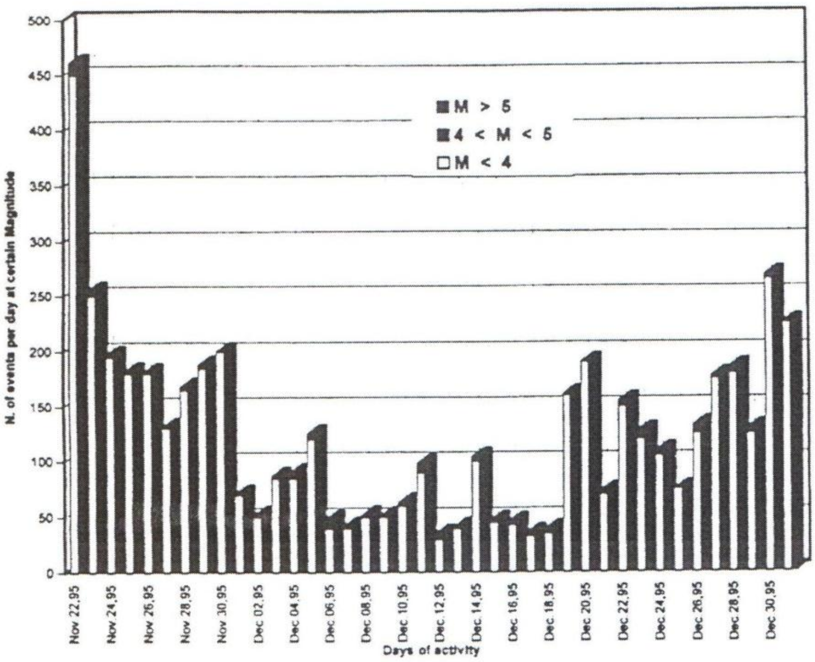

Fig. 3 – A histogram showing the frequency of occurrence for Nov. 22, 1995 earthquake sequence comprising nearly 5000 shocks during the period from Nov. 22, 1995 to Dec. 31, 1996 with magnitude range 1.5-5.9.

of 1995 sequence with earthquake sequences in 1983, 1985, 1991, and 1993 and the migration of the epicenters north and northeastward about 50 km in 98 days with focal depths less than 10 km confirming the continual recent crustal motion along the southern portion of Dead Sea transform system. The locations of the 1995 epicenters indicate a clear overlap with the 1993 sequence west of Aragonese deep, suggesting that one tectonic unit is located in the area between Elat and Aragonese deeps. The remaining excess strain energy after 1993 was released by the 1995 sequence. Al-Arifi (1996) indicates that local isostatic adjustments in the fault system in the gulf of Aqabah result in the uplifting of crustal rocks that disturbs the stress regime and causes a gradual stress release as in swarm-type activity.

Field geologic measurements indicate past faulting and confirm the activity on the land (Rowaihy, 1984). High-pass filtering was applied in image processing techniques to prove fault extension and fractures. Strong dominance of lineaments are in NE-SW directions which are in good agreement with the regional trend of the gulf of Aqabah. Comparison of observed lineaments with previously mapped features showed that many of them coincide with mapped faults.

In addition to local and portable seismic stations (20 stations) of KSU and KACST, some other stations in the west, northwest and north of the gulf were used to obtain a reliable first motion direction and fault plane solutions. Some of the observed first motions of the swarm were not easy to be 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.

However, a fault-plane solution was determined using the polarities of P arrivals recorded at more than forty stations within 300 km of the epicenter. A total of five single event focal mechanisms (Fig. 4) for main and aftershocks were carried out for the largest magnitudes ($4.7 < M_D < 5.9$). All events are located in the gulf of Aqabah. The mainshock of Nov. 22 of $M_D = 5.9$ indicates strike-slip faulting on planes striking N 9^0 W. The second event is an aftershock of Nov.23 ($M_D = 5.3$) showing strike-slip faulting (N 79^0 E) with a component of thrust faulting. Both events occurred in the Aragonese deep. The third and fourth event occurred around lat. 29^0 N between Elat and Aragonese deeps. They indicate strike-slip faulting on planes striking N15^0-48^0 E. The fifth event, an aftershock of Nov. 24 ($M_D = 4.8$), occurred in the southern flank of the Elat deep. It indicates nearly pure strike-slip faulting on planes striking N 3^0 E.

Generally, the results obtained from the above five fault-plane solutions indicate strike-slip faulting on planes striking N to NE and dipping 40^0-70^0 to the northwest and northeast.They are in good accordance with the three focal mechanism solutions of Nov. 22 earthquake obtained by Klinger *et al.* (1997). The bodywave inversion (Klinger *et al.*, 1997) and the location of the aftershocks demonstrates that Nov. 22 rupture is formed by the successive breaking of three segments oriented N-S. They suggest that the rupture is propagating toward the north, jumping to the left from one seg-

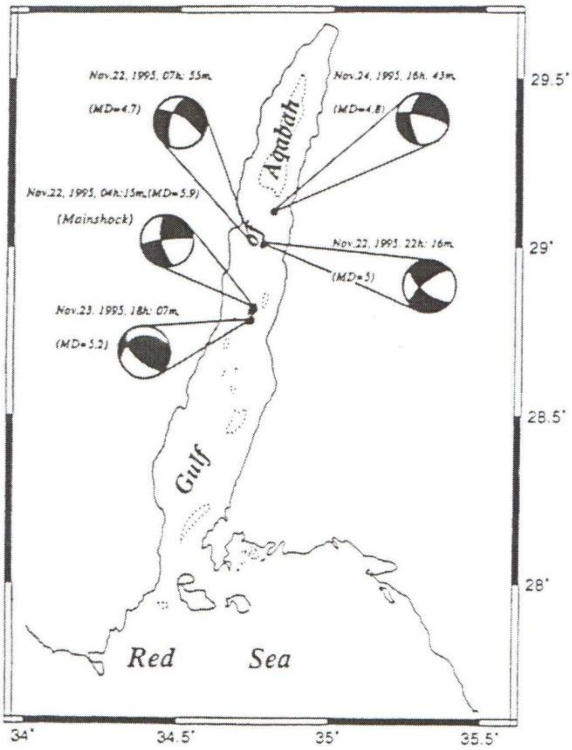

Fig. 4 - Location map of largest five events of sequence activity showing single event focal plane solutions (compressional quadrants are shaded).

ment to the next along E-W structures. This is in good agreement with the previous models (Ben-Avraham, 1985; Al-Amri *et al.*, 1991) of pull-apart basins for the gulf of Aqabah.

The a-value for the northern Red Sea, including the gulfs of Aqabah and Suez is 3.93 while the b-value is 0.59. The latter increases northwards to attain a value of 0.71 in the gulfs of Aqabah and Suez (El-Isa and Al-Shanti, 1989). Variations of a and b values are due to incomplete, insufficient, and heterogeneous database. The epicenters of the 1995 sequence were confined to a small focal area and the related events had probably shorter fault lengths, which may indicate larger slip rates.

The estimated seismic moment as indicated by the USGS focal mechanism solutions for the mainshock of this sequence ($M_D = 5.9$) is 3.1 * 10^{19} Joule. If we assume that the surface rupture length is 25 km (twice the largest observed surface rupture) and the width of rupture is 15 km, then the average calculated displacement is about 2.8 m. The largest shock of 1983 swarm ($M_L = 4.85$) had a seismic moment of 2.213 * 10^{23} dyne.cm (El-Isa *et al.*, 1984).

According to Richter (1959), earthquake swarms contain sequences of generally small- magnitude events with no large predominant event 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. Type1 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 activities of 1983 and 1993 fit type 2 of Mogi (1967) classification, whereas the activity of 1995 fits type 1.

It is believed that the low level of seismic activity south of latitude 28.5° compared with the northern segment of the gulf of Aqabah could be due to one of the following reasons: (1) small-magnitude earthquakes occurring in the region do not give enough energy to be recorded on distant stations; (2) the presence of magmatic activity and diapiric structure in Lisan basin to the east of Dakar deep; (3) lithospheric deformations in this region are occurring on land. The most direct evidence to support the third 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.

Thenhaus *et al.* (1986) assumed that any significant future seismic activities in the shield areas, east of the gulf of Aqabah has to be related to the seismic reactivation of the Precambrian faults. Additionally, the absence of dense seismic stations on the western side of the gulf and lack of detection of small events is the main reason that no conclusive study has been carried out on the orientation of the regional stress tensors and the relationship between the uplift of continental crust and spreading rate of the gulf of Aqabah.

Seismic hazard maps produced by Thenhaus *et al.* (1986) and Al-Haddad *et al.* (1994) give contours of accelerations (or velocities) having a 90 percent probability of not being exceeded in time periods of 50 and 100 years. The estimated peak ground acceleration for the gulf of Aqabah region do not exceed 0.30 g (Thenhaus *et al.*, 1986) and 0.2 g (Al-Haddad *et al.*, 1994).

4. Conclusions

It can be concluded from this study that the seismic activity along the gulf of Aqabah occurs in the form of sequences, each lasting up to several months, reaching peak magnitude up to 7.0 and covering a specific tectonic segment of the gulf. Places of interaction of normal and strike-slip faulting at the southern flank of the Elat deep could be the sites of sequence sources and stress accumulations in the 1980's and 1990's. A clustering of sequence activity in time may suggest an episodic source of strain or a constant source with repeated slip along the fault zone. Geologic field measurements observed after Nov. 22, 1995 earthquake and seismic data provide evidence for continuation of the faulting regime from the gulf NE and NW into the land causing significant seismic hazard.

The principal mode of faulting, as determined by the five single focal mechanism solutions of main and aftershocks was strike-slip faulting on planes striking NE and dipping 40°-70° to NW-NE. This result is what would be expected from the regional left-lateral slip movement of the Dead Sea transform system and from linear surface cracking observed in the affected areas.

The earthquake activity of the gulf fits types 1 and 2 of Mogi (1967) classification. In terms of earthquake risk, the temporal distribution of events within each sequence with a few days to two weeks of gradually increasing magnitudes, suggests that the detection of the beginning of the sequence is feasible and can lead to relatively successful short-term prediction in the gulf region. The recent sequence may release stress that can accumulate to cause larger events in the future.

It should also be pointed out that installation of strong ground-motion instruments in this region will lead to better estimates of the attenuation relationships and accelerations for seismic hazard assessment purposes.

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