

Migration of local earthquakes in the Gulf of Aqaba, North Red Sea

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ABSTRACT

The Gulf of Aqabah has been considered one of the most seismically-active regions in the Middle East during the last 15 years; a catalogue of 1,415 earthquakes (duration magnitude $M_d \geq 2.8$) during 1985-1995, compiled by Al-Arifi (1996) and Al-Shaabi (1998), mainly based on data from King Saud University. Seismic Studies Center (SSC), Saudi Arabia, for 28°- 30°N and 30°-36°E, has been used for studying local aftershock migration. Aftershocks migrated northwards about 60 km for the 1993 sequence and about 70 km for the 1995 sequence and also to shallow focal depths (15 km focal depth for 1993 main-shock). Depths reduced as time elapsed until reaching 2 km for the last strong aftershock ($M_d=5.2$) which occurred during the late stage of the sequence. The 1993 main-shock caused a redistribution of stresses to the parallel faults' segment where the largest 1993 aftershock occurred triggering these faults' segment to become an area of stress nucleation and generated the 1995 main-shock.

Keywords: Gulf of Aqabah, Local earthquake Migration, seismicity, Red Sea.

RESUMEN

El Golfo de Aqabah ha sido considerada una de las regiones con más actividad sísmica del Medio Oriente durante los últimos 15 años. Un catálogo de 1415 terremotos (magnitud de duración $M_d \geq 2.8$) entre 1985-1995, compilado por Al-Arifi (1996) y Al-Shaabi (1998), basado principalmente en datos de la Universidad King Saud, Centro de Estudios Sísmicos (SSC), Arabia Saudita, para la zona ubicada entre 28°- 30°N y 30°-36°E, ha sido usado para estudiar la migración de réplicas locales. Las réplicas migraron unos 60 km al norte para la secuencia correspondiente al año 1993 y unos 70 km para la secuencia por el año 1995 y también hacia bajas profundidades focales (15km de profundidad focal para el evento principal en el año 1993). Las profundidades se redujeron con el tiempo hasta alcanzar 2 km para la última réplica fuerte ($M_d=5.2$) que ocurrió durante la última etapa de la secuencia. El principal evento del año 1993 causó una redistribución de los esfuerzos hacia el segmento de las fallas paralelas donde la mayor réplica en el año 1993 ocurrió, desencadenando el movimiento de estas fallas para llegar a ser un área de nucleación y generando el principal evento en el año 1995.

Palabras claves: Golfo de Aqabah, migración local terremotos, sismicidad, Mar Rojo .

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Manuscript received: 14/10/2011
Accepted for publications: 06/05/2012

Introduction

The 1,100 km long strike-slip Gulf of Aqaba-Dead Sea transform fault is a major active tectonic feature linking the southern Turkey-western Iran Taurus-Zagros area with the Red Sea rift. It has been suggested that its left-lateral strike-slip motion is a result of relative oblique left-hand movement between Arabia and Africa which opened up the Red Sea (Quennell 1959; Freund *et al.*, 1970).

Lyberis (1988) indicated that movement in the southern Dead Sea transform fault, representing the Gulf of Aqaba, started in late Miocene and was associated with a strike-slip stress pattern (40° extension associated with 130° compression). This movement produced the left lateral motion between the Arabian plate and Sinai Peninsula and faulting has been

the result of an E-W extension since the end of the Miocene, indicating a rotation of the regional stress pattern in the vicinity of the transform fault. Al-Arifi (1996) found the main maximum compressive stress (σ_1) direction to be 137° and the main minimum stress direction (σ_3) to be 222° using the focal mechanism solution for 53 recent earthquakes in the Gulf of Aqaba,

The Gulf's structure is dominated by en-echelon normal faults delimiting three elongated basins (Ben-Avraham *et al.*, 1979, Reiss and Hottinger 1984). The northern basin has a simple bathymetry and structure, dominated by the flat-bottomed Eilat deep (<900 m). The central basin consists of two deeps: Aragonese deep (<1,850m), and Arnona deep (<1,550m); the southern basin includes the Dakar (<1,400m) and Tiran (<1,300m) deeps (Figure 1).

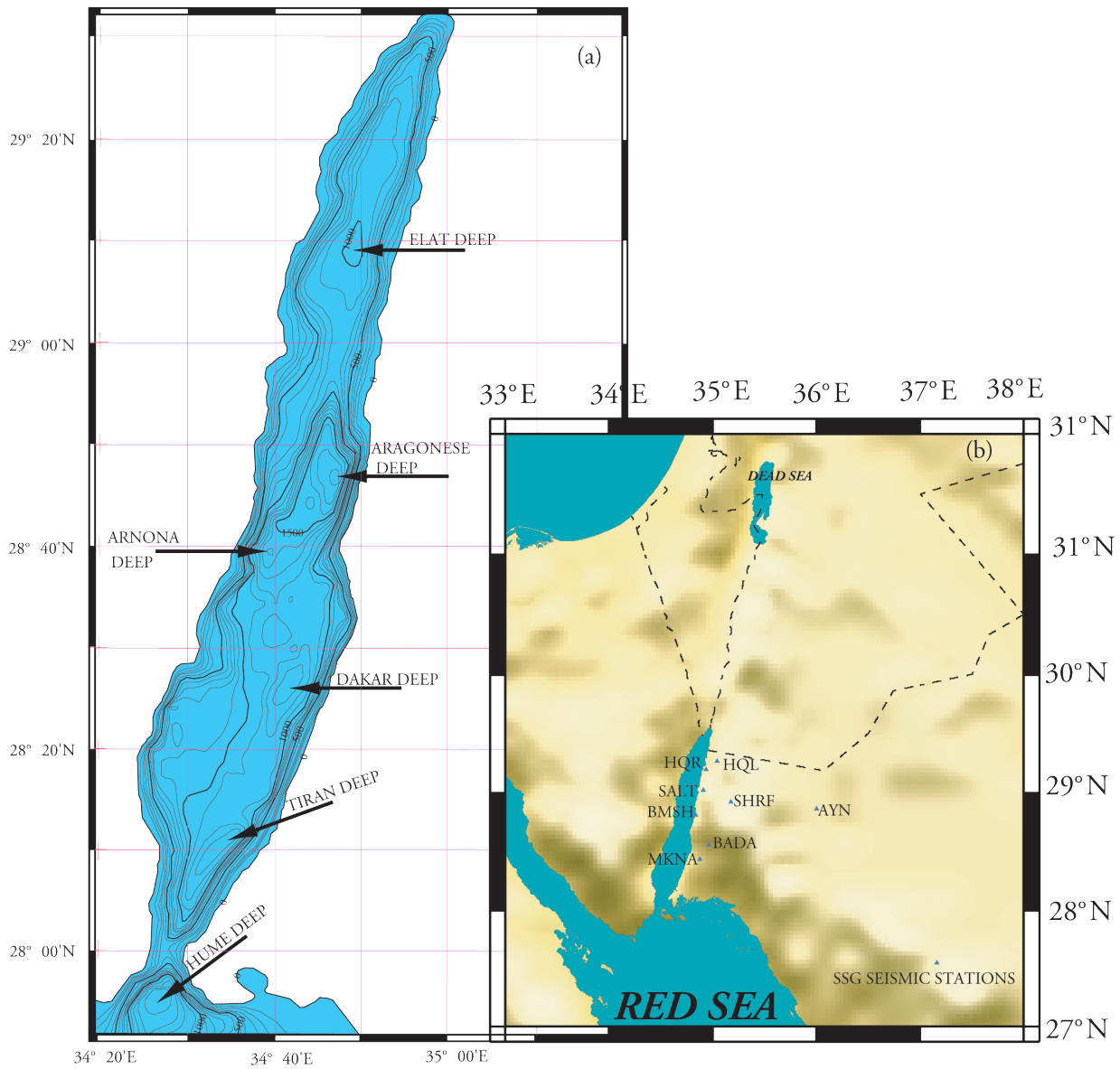


Figure 1. Index map showing the location of the study area in addition to a bathymetric chart of the Gulf of Aqaba (Bathymetric map after Hall and Ben-Avraham, 1978).

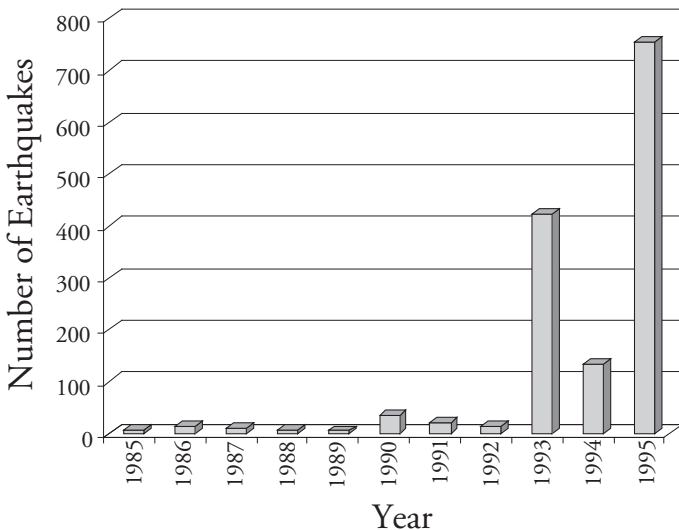


Figure 2. A histogram showing the frequency of occurrence (number of events/day) in the Gulf of Aqaba from 1985 to 1995.

This paper considers aftershocks' vertical and horizontal local migration for the most recent sequences (i.e. the 1993 and the 1995 sequence) in the Gulf of Aqaba and presents some observations regarding the stress migration which has caused large earthquakes in the Gulf.

Data

The Gulf of Aqaba has been considered one of the most seismically-active regions in the Middle East during the last 15 years. A catalogue of 1,415 earthquakes (duration magnitude ≥ 2.8 Md) for 1985-1995 has been compiled by Al-Arifi (1996) and Al-Shaabi (1998), based mainly on Seismic Studies Centre (SSC) data, King Saud University, Saudi Arabia, for 28°-30°N and 30°-36°E. Historical seismicity (1068-1964) has shown that the region has suffered at least 18 moderate to large earthquakes. Instrumental seismicity (1965-1984) has included 284 events, 244 of them related to the 1983 sequence and centred on the Eilat deep in the northern Gulf. Recent seismicity (1985-1995) has shown that seismicity in the Gulf of Aqaba has been episodic (Figure 2). An earthquake sequence in July 1993 began with foreshocks, followed by a mainshock (6.0 Md) on August 3rd 1993, and then 403 aftershocks ($M_d \geq 2.8$) during the next four months (M_d 5.6 for the larg-

est aftershock) (Figure 3); the region experienced a widely-felt earthquake on November 22nd 1995, located at 28.81°N, 34.75°E, having 12 km focal depth. The mainshock (Md=6.2) was followed by 733 aftershocks (Md≥2.8) over a 40-day period (Md 5.3 for the largest aftershock) (Figure 3).

The 1983 sequence was concentrated in the northern part of the Gulf of Aqaba (28.8°- 29.4°N and 34.3- 35.1°E). Most of this sequence was off-

shore and coincided with the Eilat deep. Although determining depth was difficult (due to a lack of stations before SSC stations were established), El-Isa *et al.*, (1984) observed that surface waves had been clearly reported in Jordan University seismic station records, suggesting a very shallow depth for the 1983 sequence. Their observation was supported by recent SSC recorded earthquakes located in the same area that suffered from the 1983 sequence; these earthquakes were located at a shallow depth not exceeding 10 km (A1-Shaabi 1998). The 1993 sequence was concentrated in the Dakar and Tiran deeps in the southern part of the Gulf having focal depths not exceeding 26 km. The 1995 sequence was distributed into two clusters, the more northerly of which was again concentrated in the Eilat deep, whereas the southern cluster was in the Aragonese and Arnona deeps in the central Gulf. The 1995 sequence depth was less than the 1993 sequence; this may have been due to the aftershock area location where the 1993 aftershock zone was concentrated in the southern part

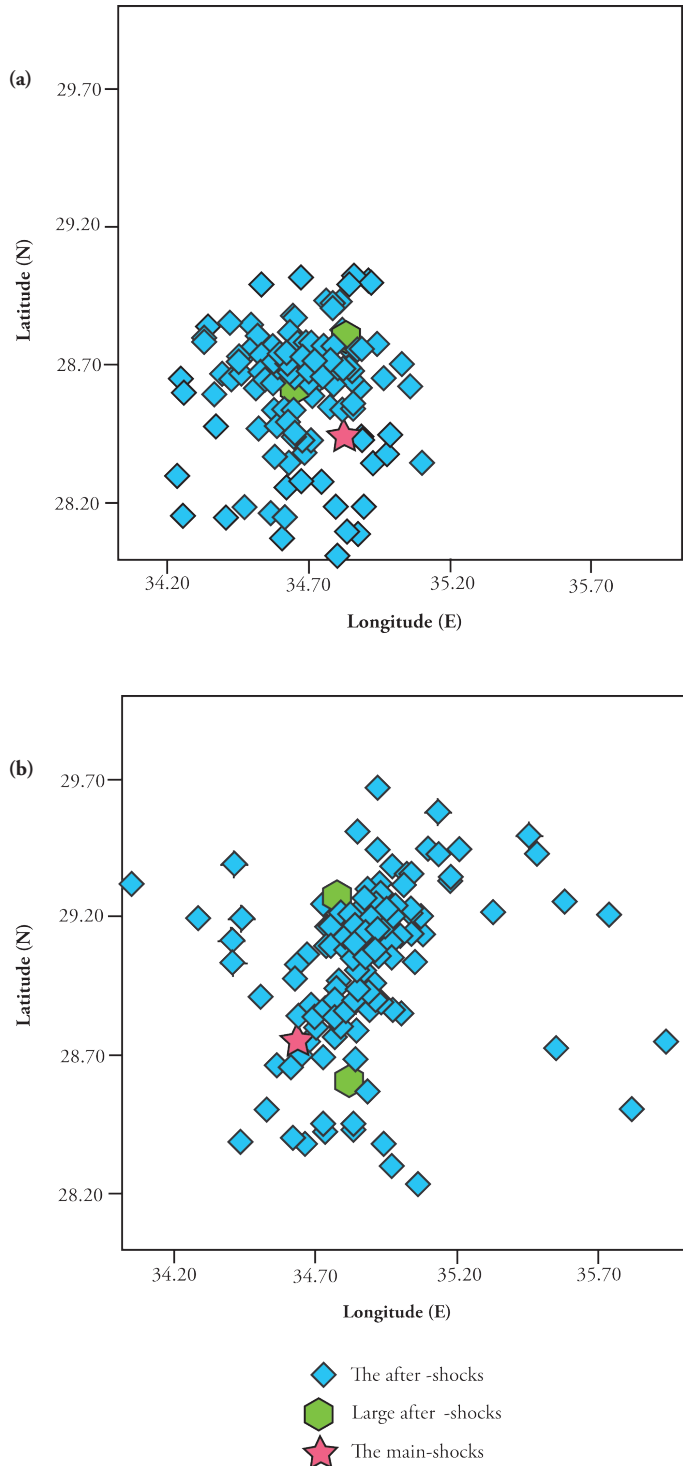


Figure 3. Epicentral distributions of earthquakes (MD>3.5) for two sequences. Where A is the 1993 sequence and B is the 1995 sequence. Small and large arrows indicate the direction of the minimum and maximum compressive stresses respectively, according to small scale structures study (Reches 1987), and focal mechanism study (Al-Arifi 1996).

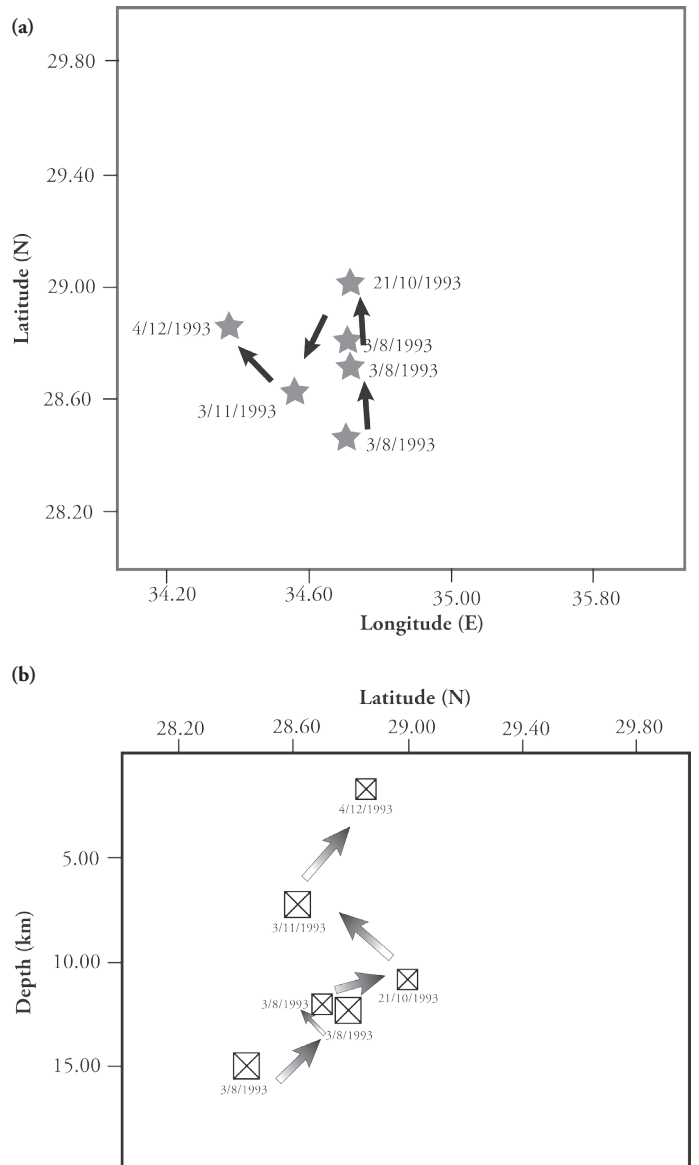


Figure 4. (a) Shows the local migration of strong aftershocks of the 1993 sequence in the Gulf of Aqaba. (b) Shows profiles for jumping of strong aftershocks of the 1993 Gulf of Aqaba sequence. The arrows indicate the direction of the local migration and jumping.

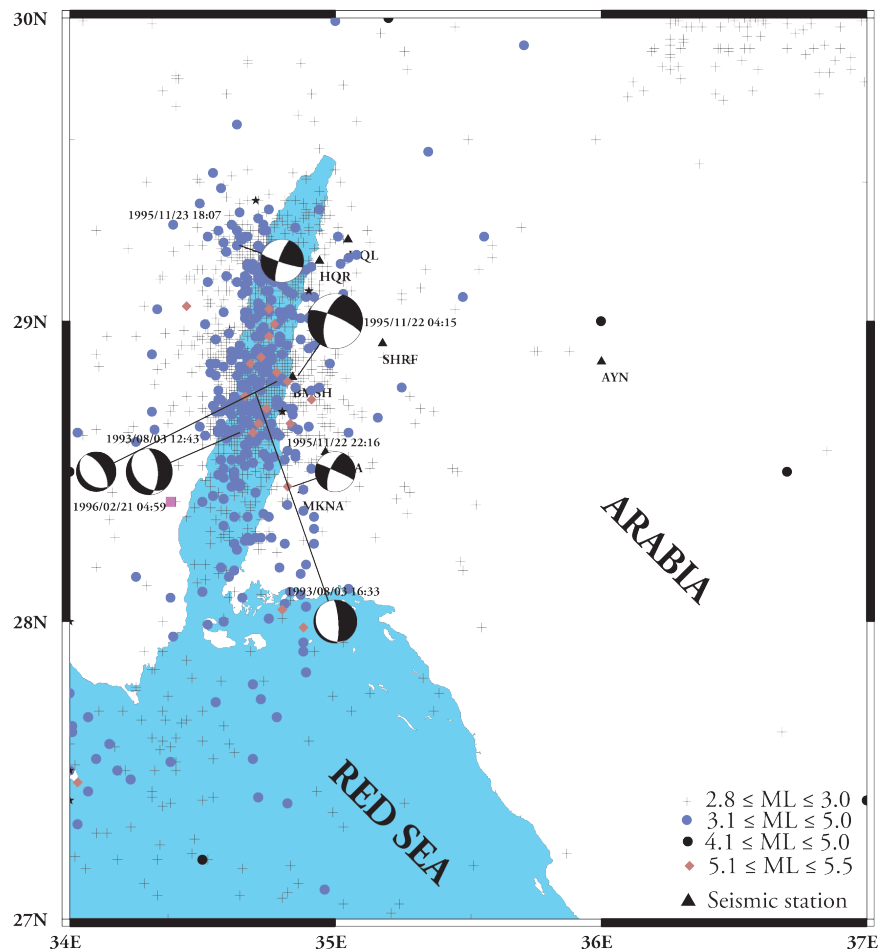


Figure 5. Shows the focal mechanism solution for the mainshocks and the largest aftershocks for both sequence of the 1993 and 1995.

of the Gulf whereas the 1995 aftershock area spread along the Gulf and aftershock density was greater in the northern than the southern part. This may have indicated that earthquakes occurring in the northern part were shallower than those in the southern part of the Gulf and were related to the brittle-ductile transition zone (Al-Shaabi, 1998). This observation was supported by the 1995 aftershocks where the events in the northern cluster were shallower than those in the southern cluster. The surface waves appeared clearly when the earthquakes were located in the north of the Gulf of Aqaba (Al-Shaabi 1998); however, they disappeared from the records when they were located in the south.

Method

HYPO71 software (Lee and Valdes, 1985) was used to relocate all events in this study (± 1.0 km horizontal component error and ± 2.0 depth error) of aftershocks' local migration, both vertically with depth and horizontally in a NE-SW direction corresponding to the general state of extensional tectonic stress in the Gulf of Aqaba and the Dead Sea Transform, according to small-scale structure study (Richard 1987) and focal mechanism study (Al-Arifi 1996). The term 'local migration' has been used to denote a strong aftershock's horizontal movement during a sequence; the term 'jumping' has been used to denote a strong aftershock's vertical movement. The term strong aftershock in this paper means the aftershocks which were felt in at least three towns in the study area. Because all strong aftershocks occurred at a shallow depth not exceeding 20 km, all aftershocks having Md 4.9 and over were felt in at least three towns. The 1993 mainshock occurred at the aftershock area's extreme southern end: 28.45°N and 34.87°E (Figure 3). The aftershocks moved northward.

Figure 4 shows strong aftershocks' local migration regarding the 1993 sequence. On the same day in which the mainshock occurred, activity was concentrated in the north between 28.70-28.85° N and 34.75-34.9° E where two strong aftershocks (Md 5.6 and 4.9) occurred. 80 days after the mainshock the activity moved northwards again where another strong aftershock occurred at 29.0°N and 34.83°E. Activity leaped to the southwest (still north of the mainshock) on the 3rd of November 1993 with another strong shock that occurred at 28.62°N and 34.6°E; activity then moved northwards where the last strong aftershock occurred on the 4th of December 1993 at 28.86°N and 34.41°E.

Figure 4 shows that the 1993 focal depth started with more than 10 km for foreshocks, no foreshock having less than 10 km depth. The mainshock had the depth of 15 km and then the depth reduced with time from 11-12 km for the first two strong aftershocks until the last strong aftershock was at a depth of 2 km. The 1995 sequence was similar, aftershock focal depth becoming reduced as time elapsed. Such 'jumping' could be explained by earthquakes migrating northwards into an area where all seismicity was shallower than in the south of the Gulf. As regards 1995 sequence local migration it was difficult to determine a specific direction for a strong aftershock (even though the aftershocks generally moved northwards).

Results

The focal mechanism solution for the mainshocks and the largest aftershocks for both sequences (1993 and 1995, Figure 5) included the following:

- 1) The 1993 mainshock indicated normal and strike-slip fault dipping 34° to the northwest and striking N 21°E;

2) The largest 1993 aftershock occurring 3 hours and 50 minutes after the main shock indicated left-lateral strike-slip fault dipping 64° to the north and striking $E 04^\circ S$; and

3) The 1995 mainshock indicated left-lateral strike-slip fault dipping 43° to the north and striking $N 09^\circ E$; and

4). The largest 1995 aftershock occurring 35 hours after the mainshock indicated normal and strike-slip fault dipping 31° to the northwest and striking 198° .

Observations regarding these focal mechanism solutions, mainshock locations and the largest aftershocks for both Gulf of Aqaba sequences (i.e. 1993 and 1995) indicated the following:

1) The seismic source for the main shocks for both sequences and their largest aftershocks were completely different (Figure 5);

2) The seismic source of the largest 1993 aftershock and the 1995 mainshock were located in the same fault zone (Figure 5); and

3) There was systematic south to north migration of the earthquakes' seismic sources (Figures 4 and 5). Such systematic northward migration was influenced by the Gulf of Aqaba's main maximum tectonic stress direction (137° according to Al-Arifi, 1996).

Discussion

It has been observed in many cases that mainshock epicentres are very often located at one end of an aftershock zone (Matsuzawa, 1979). This happened in the Gulf of Aqaba with the 1993 and 1995 sequences where the 1993 mainshock was located in the south end of the aftershock zone and below the bottom depth of the aftershock zone. This also applied to the 1995 sequence where the mainshock was located near the southern end of the aftershock zone at a depth representing the bottom of the aftershock zone. Most aftershocks were concentrated between the mainshock and the largest aftershock for both sequences (Figure 3).

Aftershock characteristics give clues regarding the nature of the relatively long-term processes redistributing stress following instantaneous stress changes associated with a mainshock (Wesson, 1987). It seems likely that this was responsible for the concentration of stress in the hypocentral region of the largest 1993 aftershocks prior to and resulting in the nucleation of the 1995 mainshock. Such systematic northward migration led to suggesting an initial model for earthquake migration in the Gulf of Aqaba (Figure 6), although real migration would likely have been more complicated. However, the largest aftershock's epicentre in this model represented the stresses nucleation area and location of the next large mainshock (Figure 6).

Conclusions

An earthquake mechanism for the Gulf of Aqaba fault system has proposed that seismic energy becomes gradually accumulated until it reaches failure point; a large drop in stress during a mainshock (the 1993 mainshock) then caused stress redistribution to the location of the largest aftershock thereby triggering the area to become an area of stress nucleation producing another large mainshock (the 1995 earthquake). Again, the last mainshock's largest aftershock area could have received the next large mainshock. Because a future large earthquake could easily nucleate in the Gulf of Aqaba, more effort is needed to fully understand stress migration and seismic behaviour in this critical set of the southern Dead Sea fault system. However, it should be mentioned here that triggering may have played an important role in the 1995 sequence even though further evidence is needed.

Acknowledgments

This project was financed by King Saud University's College of Science Research Centre Deanship of Scientific Research.

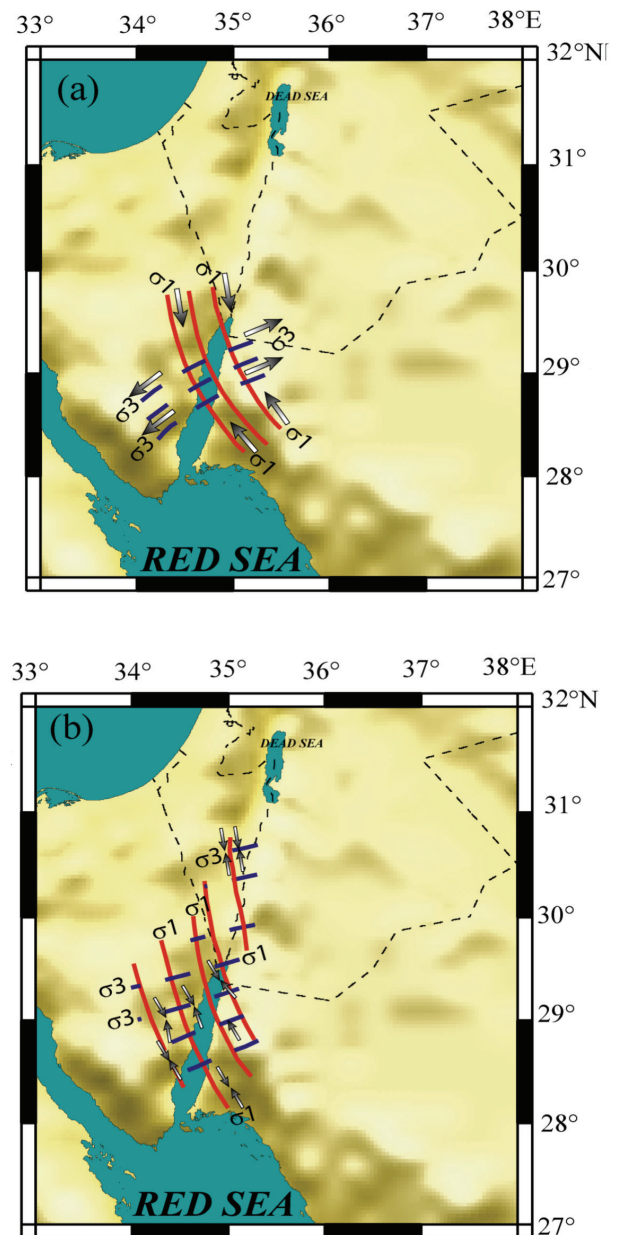


Figure 6. Generalized model for the migration of large earthquakes in the Gulf of Aqaba.

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