Fault plane solutions of the 1993 and 1995 Gulf of Aqaba earthquakes and their tectonic implications

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Abstract
The stereographic projection of *P*-wave first motions for the 3 August 1993 Gulf of Aqaba earthquake, its largest aftershock (16 h 33 min), and for the 22 November 1995 earthquake were constructed using the polarity readings of regional and teleseismic stations. The focal mechanism solutions of the 3 August 1993 mainshock and its largest aftershock represent a normal faulting mechanism with some left lateral strike slip component. The nodal planes selected as the fault imply high similarity in strike and dip. They are related to a local fault striking NW-SE and dipping to the SW. The selected fault planes are in good agreement with the aftershock distribution. For the main shock of the 22 November 1995, the fault plane solution displays the same mechanism (normal faulting with left lateral strike slip component) with a plane striking N-S and dipping to the west. The fault plane is greatly conformable with the direction of the regional tectonics and also with the aftershock distribution. The main trend of the extension stress pattern is in a NE-SW direction, corresponding to the rifting direction of the Gulf of Suez and may be related to the paleostress along the Gulf of Suez and Aqaba during the Middle to Late Miocene.

Key words *seismicity – focal mechanism – tectonics – Gulf of Aqaba – aftershocks*

1. Introduction

On 3 August 1993, an earthquake sequence started close to the west coast of the Gulf of Aqaba. The main shock of this sequence occurred with magnitude $M_b = 5.8$ and was followed by its largest aftershock of magnitude $M_b = 5.4$ four hours after the origin time of the main shock. The location of this event with respect to the main shock indicates that the rupture propagated to the SE direction. On 22 November 1995, another earthquake sequence suddenly took place to the south of the last sequence and inside the gulf. The main shock of this sequence was of magnitude $M_b = 6.7$. This event is considered to be the largest shock that has taken place in this area during this century.

A review of seismicity and seismic history of the Gulf of Aqaba indicates that the seismic activity often occurs as isolated sequences.

In this study, we will combine the tectonic setting, seismicity and focal mechanisms of the recent large earthquakes as an attempt to understand the neotectonic features in the Gulf of Aqaba.

2. Tectonic setting

The Gulf of Aqaba is about 180 km long and 15-25 km wide, occupying the southern part of a major sinistral transform boundary

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known as the «Dead Sea Transform Fault». This boundary is considered to be a boundary connecting seafloor spreading in the Red Sea with the Zagros-Taurus zone of continental collision.

A review of the seismicity and seismic history of Egypt led Hussein (1989) and El-Sayed and Wahlstron (1996) to observe that the current seismic activity is related to Oligocene-Miocene faults. This supports the idea of a recent reactivation of the Oligocene-Miocene stess cycle. The basaltic igneous activity that occurred in the Late Oligocene or Early Miocene is generally interpreted as related to initial faulting in the Gulf of Suez rift (Siedner, 1973; Meneisy and Kreuzer, 1974; Lyberis, 1988). The oldest movements along the Aqaba-Dead Sea fault zone are younger than those in the Suez basin (Eyal *et al.*, 1981). During the Late Miocene, the kinematics of the Red Sea varied from the rifting extension in the Red Sea-Gulf of Suez to sinistral shear movement along the NNE trending Aqaba-Levant transform with opening component of the Red Sea due to oblique drift of the Arabian plate. This aspect led to stagnation of the extension and subsidence in the Gulf of Suez and created a new plate boundary called the Aqaba Levant structure.

The Gulf of Aqaba-Dead Sea fault is one of the most spectacular examples of transform plate boundary type. In the Gulf of Aqaba region, the tectonic movement is mainly sinistral shear motion with an extensional component. Most of the faults along the gulf region show left lateral strike slip mechanism with a minor normal component. Tectonically, the occurrence of these mechanisms is attributed to the extensional motion in the Read Sea and the anticlockwise rotation of Arabian with respect to Sinai along the Dead Sea shear zone.

An earlier structural interpretation of the Gulf of Aqaba suggests that it is built of *en echelon rhomb basins* such as the Dead Sea (Quennell, 1959). This pull apart basin if often developed from the changes in major strike slip trends (*e.g.*, Wilcox *et al.*, 1973; Growell, 1974). Figure 1 shows the generalized tectonic model of the structure of the Gulf of Aqaba.

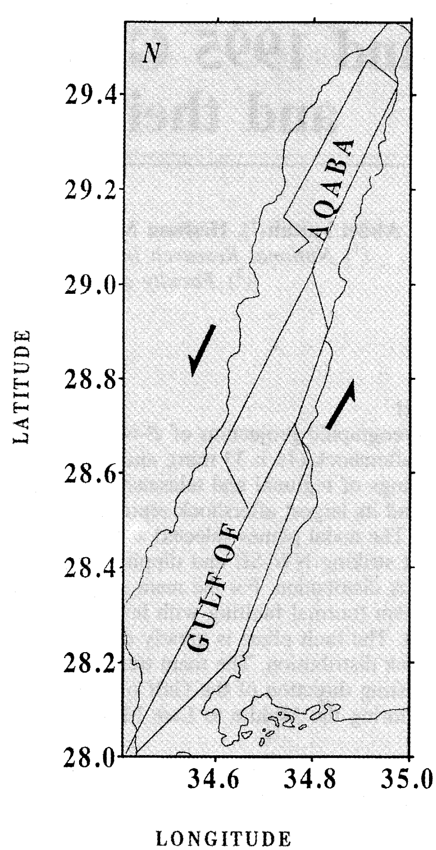

Fig. 1. Generalized model for structure of the Gulf og Aqaba (after Ben-Avraham *et al.*, 1979).

3. Seismicity of the Gulf of Aqaba

In the Aqaba region, a review of the seismicity and seismic history shows that seismic activity has occurred as isolated sequences. The occurrence of these isolated sequences indicates that the seismicity of the Gulf of Aqaba is characterized by foreshock-mainshock-aftershock, mainshock-aftershock and swarm type activity. Seismological studies of the Red Sea and Jordan-Dead Sea transform (Fairhead and

Girdler, 1970, 1972); Ben Menahem *et al.*, 1976; Ben Menahem and Aboodi, 1981) indicate a relatively lower seismic activity in the Gulf of Aqaba and Wadi Araba than in the Red Sea and Dead Sea transform fault.

3.1. *Historical earthquakes*

Several felt historical earthquakes have been reported in Egypt. A total of 58 events were reported to be felt with intensities of V-IX during the period 2200 B.C.-1900 A.D. Some of these earthquakes are reported with poor information regarding the epicentral area; some have locations outside the Egyptian borders. The recent publications of historical earthquakes (Ambrayses, 1994 and Maamoun *et al.*, 1984) reported that some historical earthquakes occurred in the Aqaba region including the shocks of 1068, 1212, 1293, 1458 and 1588 (fig. 2a). On 18 March 1068, a major historical earthquake was felt in the Hejaz and Northern Arabia during the morning and it was reported to have killed about 20 000 people. On 7 April 1588, a strong historical earthquake was felt in Northern Hijaz at sunrise. This was followed by numerous continuous shocks and possibly connected with a continuous activity in the Northern Red Sea (Gulf of Suez) region.

3.2. *Instrumental seismicity*

Earthquake data for the period 1903-1995 were collected from different catalogues and bulletins, including the International Seismological Center (ISC), National Earthquake Information Center (NEIS), Preliminary Determination of Epicenters (PDE) and bulletins of Israel. The seismicity of the Gulf of Aqaba and the Gulf of Suez during the period from March 1903 to December 1993 is shown in fig. 2b.

Recently, the seismic activity in the Gulf of Aqaba region can be summarized in three sequences: an earthquake swarm in 1983 located at the northern part of the Gulf (El-Isa *et al.*, 1984), an earthquake sequence in 1993 which occurred at the center of the Gulf very close to the western coast (this sequence is character-

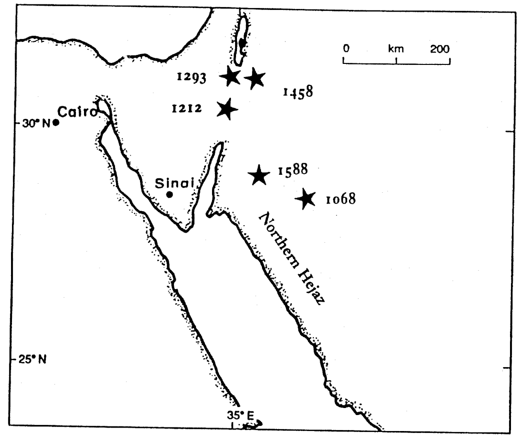

Fig. 2a. Earthquakes of the pre-instrumental period in the Gulf of Aqaba region.

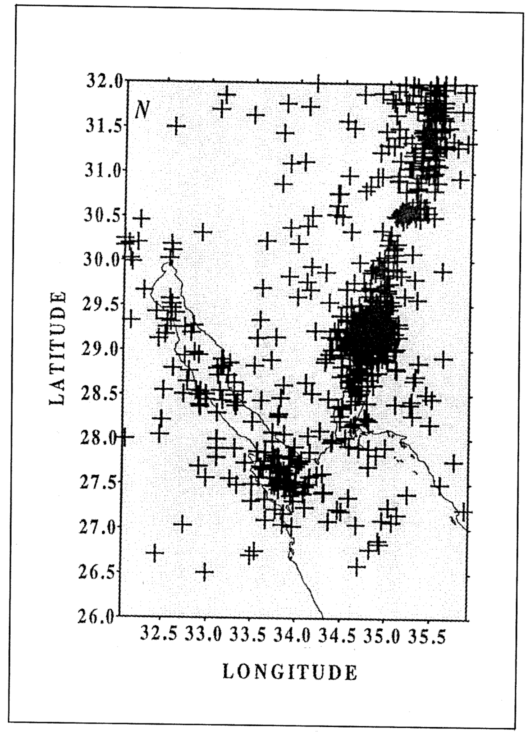

Fig. 2b. Epicentral distribution of the Gulf of Aqaba and the Gulf of Suez earthquakes for the period March 1903-December 1993.

ized by foreshoch-mainshock-aftershock distribution (fig. 3) and includes two large events) and an earthquake sequence in 1995 which is located to the south of the last sequence (this sequence is characterized by mainshock-aftershock distribution; Marzouk *et al.*, 1996).

For the earthquake sequence of 1993, the arrival times of *P* and *S* waves were identified from several Egyptian seismic stations. In addition to these arrivals, the authors collected the available arrival times of *P* and *S* waves from different bulletins, (*e.g.*, the Israel and Jordan bulletins) and some arrivals of the Saudi Arabia seismic network. All of these arrival times were compiled to determine the location of hypocenters by using the HOPO71PC program (Lee, 1990). However, for the earthquake sequence of 1995, the locations of hypocenters were taken from the bulletin of the Hurghada local seismic network (Marzouk *et al.*, 1995).

Figure 4a-c shows the epicentral distribution of the 1993 and 1995 sequences. Figure 4c shows that the aftershock distribution of both 1993 and 1995 sequences tends to concentrate as a cluster around the area between 28.5°-28.7°N and 34.5°-34.7°E. Figures 4a and 4b show the epicentral distribution for each sequence separately. It is evident from these figures that the events do not follow clear linear trends. However, the detailed study of the aftershock distribution for the 22 November 1995 earthquake (Marzouk *et al.*, 1996) showed a clear NNE-SSW trend.

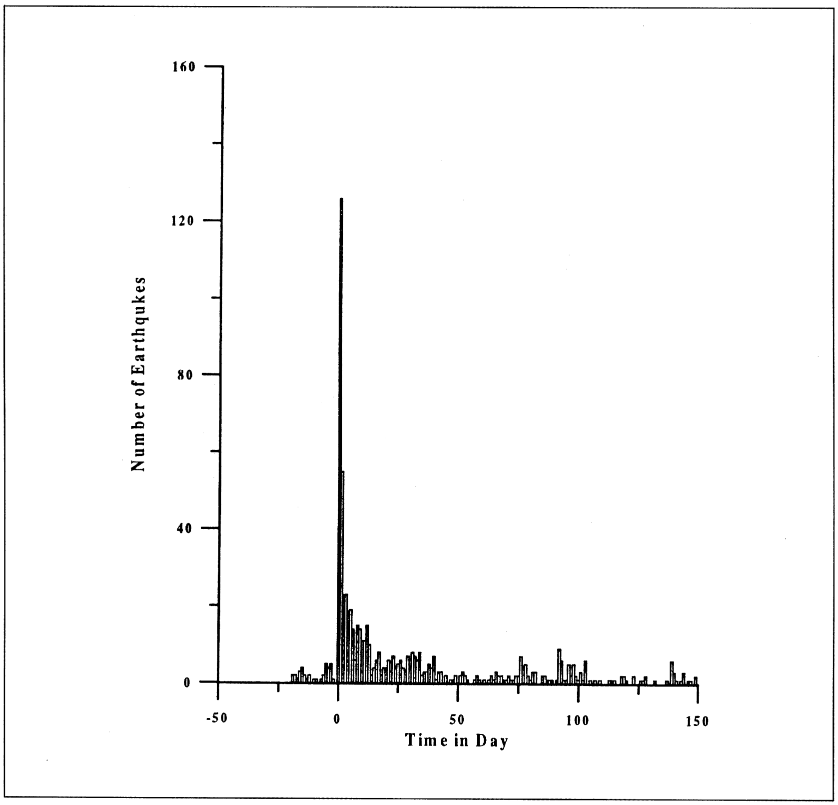

Fig. 3. Foreshock-aftershock pattern for the Gulf of Aqaba earthquake of August 1993.

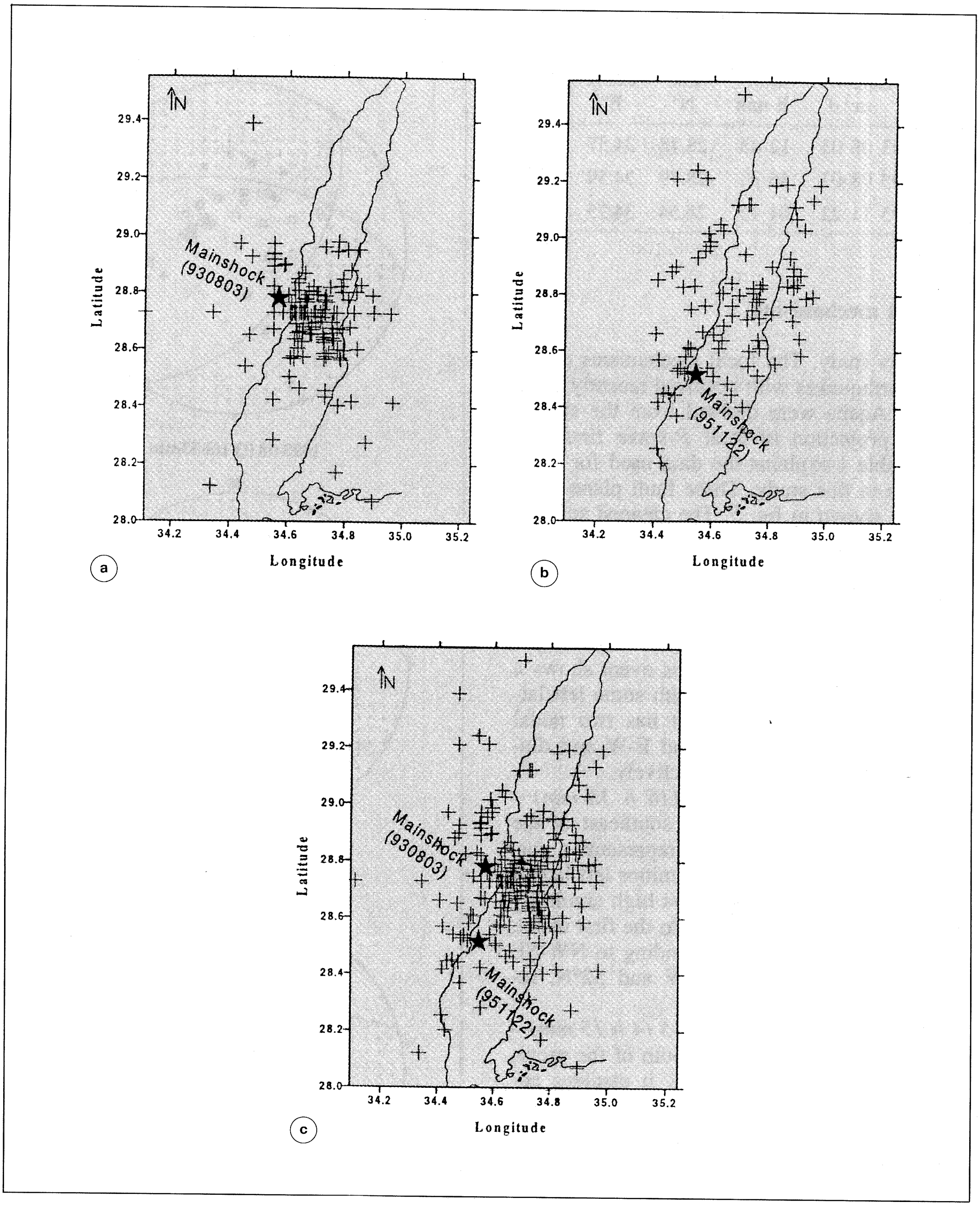

Fig. 4a-c. Epicentral distribution of the Gulf of Aqaba earthquake sequences. a) Earthquake sequence of 1993; b) earthquake sequence of 1995; c) earthquake sequences of 1993 and 1995.

Table I. Earthquake data for focal solutions used in this study.

No.	Date y m d	O.T. h min	Lat. N°	Long. E°	M_b
1	1993 08 03	12 43	28.78	34.57	5.8
2	1993 08 03	16 33	28.79	34.59	5.4
3	1995 11 22	04 15	28.54	34.75	6.7

4. Focal mechanisms

In this study, The focal mechanisms of the larger earthquakes with occurred recently in he Gulf of Aqaba were derived from the stereographic projection of their *P*-wave first motions. Table I explains the data used for focal solutions in this study. These fault plane solutions are shown in fig. 5. The clearest seismograms were read directly by the authors. The polarity data for these events are listed in tables II, III and IV. The focal parameters of the fault plane solutions are listed in table V.

Event of August 3, 1993 (12 h 43 min) – The fault plane solution of this event shows a normal faulting mechanism with some left lateral strike slip component. It has two nodal planes trending to NW-SE and E-W and dipping 55°SW and 53°N, respectively.

Event of August 3, 1993 (16 h 33 min) – This event is located closely southeast of the first event of 12 h 43 min. It represents a normal faulting mechanism with minor left lateral strike slip component. It shows high similarity in strike and dip with respect to the first event. It shows two nodal planes trending to NW-SE and E-W and dipping 56°SW and 52°N, respectively.

Event of November 22, 1995 (4 h 15 min) – This event is located to the south of the previously mentioned events. Also, it displays approximately the same mechanism with two planes trending N-S and WNW-ESE and dipping 58°W and 68°NNE.

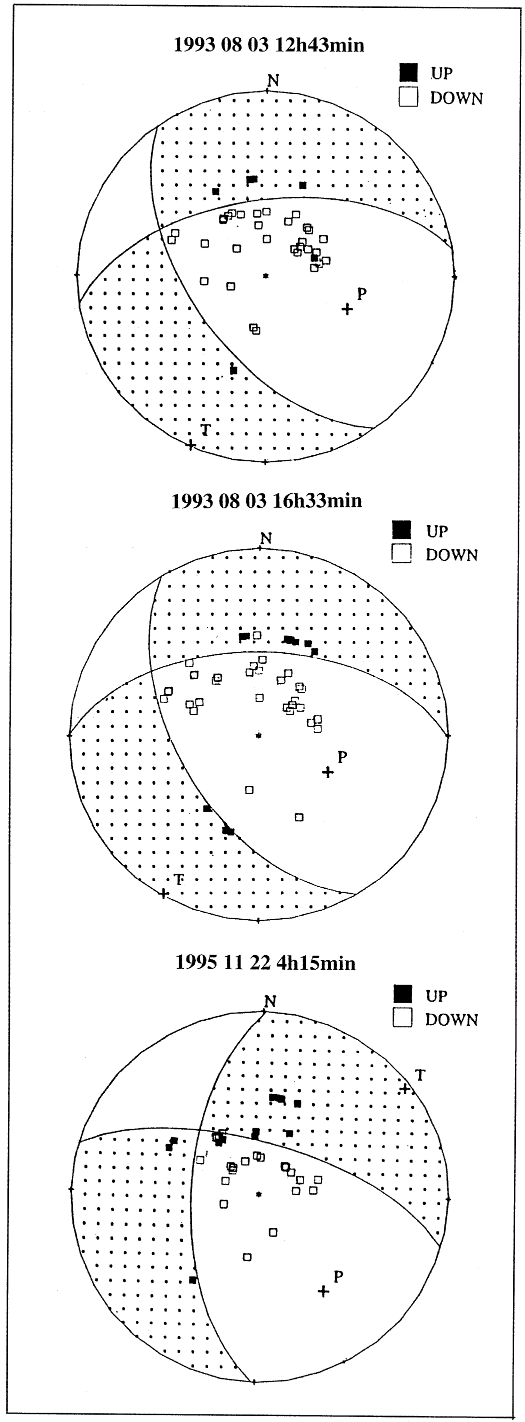

Fig. 5. Focal mechanism solutions of the Gulf of Aqaba events.

Table II. Polarity data of August 3, 1993 (12 h 43 min) event (1).

Station	Polarity	I_0	Az^0
KOT	D	44.41	295.93
HLW	D	44.58	291.47
ASW	U	44.57	198.22
KIV	U	44.57	021.07
CSS	U	44.57	350.50
CIN	U	44.57	329.99
BRNL	D	32.13	332.22
TNS	D	31.87	324.48
CLZ	D	31.84	328.64
MEM	D	31.35	323.29
ANTO	D	30.68	024.96
PAB	D	30.24	298.93
AAK	D	29.91	055.84
LVZ	D	29.06	000.05
KONO	D	29.84	338.18
TRO	D	28.42	351.87
NVS	D	28.08	039.11
ELT	D	27.81	042.03
LSA	D	26.84	074.37
MBO	D	26.64	264.58
NRIL	D	26.25	021.51
LZH	D	24.28	063.52
BOSA	D	24.30	189.52
KMI	D	23.61	076.04
SUR	D	23.01	193.16
ALE	D	22.91	351.55
GYA	D	22.78	073.23
ENH	U	22.47	068.30
HIA	D	21.94	045.71
QIZ	D	21.15	079.53
BJI	D	21.84	056.19
MDJ	D	19.78	047.85
HRV	D	17.60	314.14
MAJO	D	17.28	052.01
ERM	D	17.22	045.29
COL	D	16.50	001.01
BDFB	D	15.80	252.85

I_0 = take-off angle; Az^0 = station azimuth.

Table III. Polarity data of August 3, 1993 (16 h 33 min) event (2).

Station	Polarity	I_0	Az^0
JDRJ	U	46.09	027.61
KFNJ	U	44.68	016.84
MASJ	U	44.65	018.13
SALJ	U	44.64	016.16
MKRJ	U	44.40	017.93
LISJ	U	44.33	017.34
KOT	D	44.17	295.58
HLW	D	44.61	291.47
ASW	U	44.57	198.39
AKUR	U	44.57	198.92
AKSR	U	44.57	195.75
CSS	U	44.57	350.34
ERE	U	44.57	033.07
SIM	D	44.57	358.79
SRN	D	44.57	316.39
ANTO	U	44.57	352.83
KIV	U	44.57	021.03
ZGN	D	44.10	296.43
ATD	D	40.23	154.13
BNG	U	39.30	215.15
AQU	D	38.94	313.91
SSB	D	38.92	312.92
OBN	D	33.47	002.59
MEB	D	33.00	293.86
TNS	D	31.21	324.45
BSN	D	30.84	324.66
DOU	D	30.53	321.46
PUL	D	30.53	355.81
TAF	D	30.25	290.36
ARU	D	30.05	024.95
PAB	D	29.60	298.91
LVZ	D	28.46	000.04
TRO	D	27.85	351.86
NVS	D	27.51	039.11
ELT	D	27.25	042.03
LSA	D	26.31	074.38
NRIL	D	25.73	021.51
CHT	D	25.52	083.28
BOSA	D	23.82	189.54
KMI	D	23.15	076.05
HIA	D	21.52	045.72
BJI	D	21.43	056.20
MDJ	D	19.41	047.86
MAJO	D	16.96	052.02
ERM	D	16.90	045.30
COL	D	16.20	001.01

I_0 take-off angle; Az^0 station azimuth.

Table IV. Polarity data of November 22, 1995 (4 h 15 min) event (3).

Station	Polarity	I_0	Az^0
ABSH	U	47.55	215.83
KOT	U	44.20	301.18
HLW	U	44.66	296.25
MML	U	44.57	010.69
ZNT	U	44.54	006.40
JVI	U	44.58	011.42
KIV	U	44.57	020.81
BGIO	U	44.67	008.30
MOX	D	31.56	328.18
BFO	D	31.49	321.54
KRL	D	31.38	322.75
TNS	D	31.14	324.78
CLZ	D	31.10	328.92
WLF	D	30.84	322.14
BUG	D	30.68	325.82
GSH	D	30.67	324.05
HGN	D	30.58	323.76
ARU	U	29.95	024.81
PAB	D	29.58	299.27
ESK	U	28.68	325.41
DSB	U	28.52	321.08
KEV	U	27.93	356.05
LSZ	D	27.42	188.85
LSA	D	26.28	074.14
KBS	U	25.56	354.54
CHTO	D	23.42	084.13
TATO	D	18.82	069.07
HRV	D	17.23	314.15
KCH	D	17.21	157.43
INK	D	16.99	355.56
INU	D	16.97	053.50
NMR	D	16.68	043.07
KUR	D	16.64	040.66
COL	D	16.13	000.99
SSPA	D	16.10	315.22
DAV	D	15.97	083.32
FFC	D	15.66	336.47
CEH	D	15.51	311.92
SJG	D	15.51	290.83
BDFB	D	15.50	252.84

I_0 = take-off angle; Az^0 = station azimuth.

5. Discussion and conclusions

The combination of seismicity, geological investigations and focal mechanisms displays and interesting detailed picture of the present tectonic movements in the Gulf of Aqaba.

The geological investigations in the surrounding west coast of the gulf after the occurrence of November 22, 1995 earthquake demonstrated that the faults parallel to the gulf are recognized in sinistral strike slip movements which may be anticipated to Quaternary. In addition to these faults, some NNW-SSE oriented cracks exist. These cracks are older than the NNE-SSW oriented cracks.

The epicentral distribution of earthquakes during 1903-1993 delineates the Gulf of Aqaba trend. The recent seismic activity in the Gulf can be summarized in three sequences. These sequences took place in 1893, 1993 and 1995 and show progression from north to south of the gulf, respectively. The aftershock epicentral distribution for the 1993 and 1995 earthquake sequences demonstrates that their aftershocks concentrated as a cluster around a high stress accumulation area between 28.5°-28.7°N and 34.5°-34.7°E. This high stress accumulation area may be interpreted in terms of asperity or barrier. The distribution of aftershocks for each sequence does not show any well defined trend. By analysis of hypocenters for the 1995 sequence (Marzouk *et al.*, 1996), the epicenters showed a clear NNE-SSW trend approximately parallel to the Gulf of Aqaba.

The Gulf of Aqaba transform fault is dominated by a strike slip mechanism with a minor normal component. The study of active faults in the Dead Sea rift (Garfunkel *et al.*, 1981) showed that the currently active faults are of two types, strike slip and normal. The first type is more prominent. Also, focal mechanism studies of the largest instrumentally recorded earthquakes in the region indicate dominant sinistral strike slip motion (Ben Menahem *et al.*, 1976).

The fault plane solutions of the Gulf of Aqaba events represent normal faulting mechanisms with minor left lateral strike slip components. For the two events of 1993, the selected nodal planes and the fault trend imply high

Table V. Fault parameters for the studied events, where (δ) is dip, (ϕ) strike and (λ) rake.

No.	*P*-axis		*T*-axis		Fault plane			Auxiliary plane		
	δ	ϕ	δ	ϕ	ϕ	δ	λ	ϕ	δ	λ
1	52	112	01	203	145	57	−43	261	55	−139
2	56	118	01	210	149	55	−47	271	53	−134
3	40	151	06	56	181	61	−27	285	67	−148

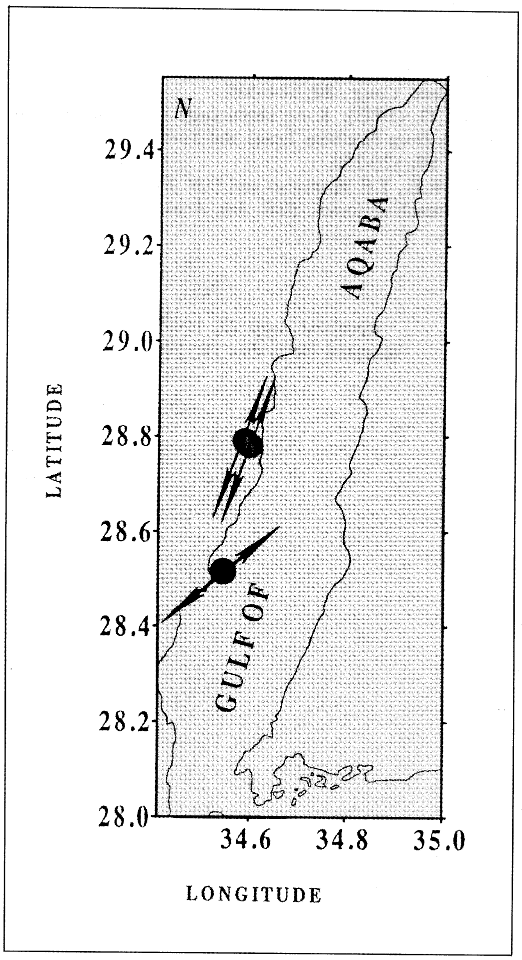

Fig. 6. Stress pattern for the three Gulf of Aqaba earthquakes (12 h 43 min, 16 h 33 min and 4 h 15 min).

similarities in strike and dip. They are related to a local fault trend striking NW-SE and dipping to the SW. The selected fault planes are in good agreement with the aftershock distribution. For the main shock of November 22, 1995, the plane striking N-S and dipping to the west is the fault plane. This is in agreement with the direction of the regional tectonics and also with the aftershock distribution obtained by (Marzouk *et al.*, 1996). The main trend of extensional stress pattern (*T*-axis) for the Gulf of Aqaba earthquakes discussed in this study is in NE-SW direction, corresponding to the rifting direction of the Gulf of Suez and the rifting oblique trend N30°E along the Red Sea (fig. 6). This stress pattern is similar to the paleostress along the Gulf of Suez and Aqaba during the Middle to Late Miocene. This supports the idea of a recent reactivation of Oligocene-Miocene stress cycle.

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