

## Seismicity and Stress-Tensor Inversion along the Gulf of Aqaba

Abu bakr A. Shater and Sallah M. Mahmoud

National Research Institute of Astronomy and Geophysics, Egypt

**Abstract:** The Gulf of Aqaba itself is usually described as the succession of three deep pull-apart basins, elongated in the N-S direction. The goal of this work was to study the seismicity and to estimate the stress field acting in the Gulf of Aqaba region. The Gulf of Aqaba earthquakes is mainly concentrated in four zones; the first zone is located between latitude 27.3-27.8 and longitude 34.3-34.5 degrees in the Hume Basin in the southern entrance of the Gulf. The second zone is located along the Arnona fault between 28.3-28.6 and longitude 34.5-34.7 degrees; the third zone is located between latitude 28.8-29.0 and longitude 34.6-34.8 degrees in the Aragonese Basin and fourth zone is located in the Aqaba Basin between latitude 29.1-29.2 and longitude 34.7-34.8 degrees. The b-value ranges between 0.4-1.1, a region of low b-values found in the southern entrance of the Gulf of Aqaba ( $\sim 0.46$ ) followed by a relative increase toward north. The orientations of fault planes and slip directions indicated by a population of earthquake focal mechanisms can be used to determine best fit regional principal stress directions and  $R=(8,37\sigma_2-\sigma_1)/(\sigma_3-\sigma_1)$ , a measure of relative magnitudes, under the assumption of uniform stress in the source region. The technique has been applied to 20 events from the Gulf of Aqaba earthquake sequence for which we have found best fit stresses (plunge and azimuth):  $\sigma_1=55.60$   $\sigma_2=34.256$   $\sigma_3=3.161$  and  $R=0.50$ . The average misfit between the stress model and all the data is about  $5.5^\circ$ . It was concluded that the maximum regional stress in the Gulf of Aqaba from NE-SW direction, while the minimum regional stress to NW-SE direction (extension).

**Key words:** The Gulf of Aqaba • Focal Mechanism • Seismicity • Regional Stress

### INTRODUCTION

The Gulf of Aqaba is known to be one of the seismic active area, it is northeastern arm of the Red Sea and located at the southern portion of the Dead Sea transform, On 22 November 1995 the largest earthquake instrumentally recorded in the area, with magnitude  $M_w$  7.3, occurred in the Gulf of Aqaba. The main rupture corresponding to the strike-slip mechanism is located within the Gulf of Aqaba, which forms the marine extension of the Levantine fault, also known as the Dead Sea fault. The Levantine fault accommodates the strike-slip movement between the African plate and the Arabian plate. The Gulf of Aqaba itself is usually described as the succession of three deep pull-apart basins, elongated in the N-S direction. Klinger *et al.* [1] (Figure 1).

The magnitude of completeness,  $M_c$ , is important for all seismicity-based studies. Considerable spatial and temporal variations in  $M_c$  are common in seismicity catalogs and can be introduced by changes in the configuration of the seismic network or the processing approach. Assessing  $M_c$  is important for analyzing

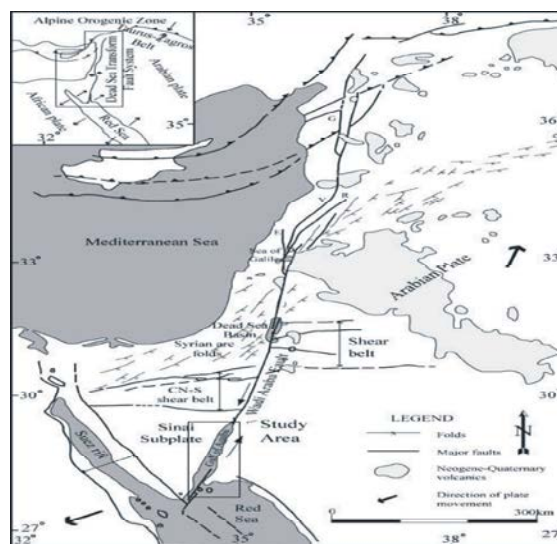


Fig. 1A: Regional map of the tectonic setting of the study area (modified after Garfunkel and Ben-Avraham[5]) and Schematic diagram of the structure of the Gulf of Aqaba showing location of active faults and pullapart basins.

aftershock sequences, because completeness changes with time, in particular during the first days of the aftershock sequence Wiemer and Katsumata [2].

Scholz [3] was the first to recognize that b-value has a clear relationship with the stress in a volume of rock. Recent studies with different global and regional seismic catalogs show that b-value is significantly lower for events associated with thrust as compared to normal and intermediate for strike-slip faulting Schorlemmer *et al.* [4]. Because faulting type is directly governed by the orientation and magnitude of stress regime of an area, it is evident that stress has considerable effect on *b*.

Over time, seismic networks generally become denser with more technologically advanced instruments capable of recording smaller events. Seismic catalogs are becoming more and more accurate with the help of improved location algorithms, velocity models and increased computational power. Taking full advantage of these positive developments, researchers have recently performed many excellent studies on b-value that tend to support its relationship with stress.

One of the most evident effects of stress release in the crust are tectonic earthquakes.

Due to the large amount of existing earthquake focal mechanisms from regional studies. Focal mechanism data provide information on the relative magnitudes of the principal stresses, so that a tectonic regime can be assigned.

A stress inversion determines the orientation of the principal stresses ( $S_1$ ,  $S_2$  and  $S_3$ ) that minimize the average difference between the slip vector and the orientation of maximum shear stress on the inverted faults. This angle is commonly called “misfit angle”. Different algorithms of stress inversion have been developed by various authors (the most common routines are described by Gephart and Forsyth [6] and Michael [7]).

Different types of stress indicators are used to determine the tectonic stress orientation. They are grouped into four categories:

- Earthquake focal mechanisms
- Well bore breakouts and drilling-induced fractures
- In-situ stress measurements (overcoring, hydraulic fracturing, borehole slotter)
- Young geologic data (from fault-slip analysis and volcanic vent alignments)

A detailed description of the different methodologies can be found in Zoback and Zoback [8], Zoback and Zoback [9], Zoback *et al.* [10] and Sperner *et al.* [11].

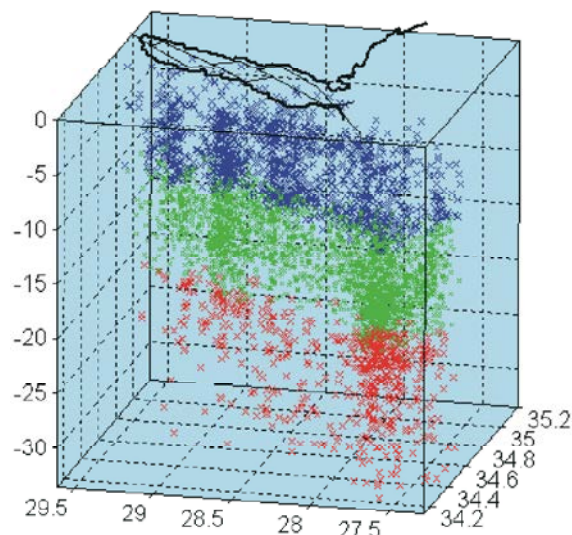


Fig. 2: Seismicity of the study area from the present catalog.

## Data

**Seismicity:** Based on the nature of our study area and the characteristics of our catalog. A total of 4880 Hypocenters for the Gulf of Aqaba were obtained from the Egyptian National Seismic Network (ENSN) catalog. The magnitude of the events used in the study ranges from 0.1 to 4.7, with a period range from Jan 1997 to May 2010. Figure (2) shows the Seismicity map of the study area from the present catalog.

**Stress Tensor Inversion:** The orientations of fault planes and slip directions indicated by a population of earthquake focal mechanism from 20 events in the Gulf of Aqaba earthquakes used to determine best fit regional principal stress. Focal mechanism Parameters for the Gulf of Aqaba were obtained from the Egyptian National Seismic Network (ENSN) bulletin and International Seismological Centre (ISC). As shown in table 1.

## Methodology

**Seismicity:** The computer code ZMAP is used to mapping b values. This technique explained in detail elsewhere (Wiemer [12], Wiemer and Benoit[13], Wiemer and McNutt[14] and Wiemer and Wyss [15]).

The frequency-magnitude distribution (FMD) of earthquakes, which was first introduced by Ishimoto and Iida [16] and Gutenberg and Richter [17], has a power-law relationship, such that:

Table 1: Fault planes parameters

No	date			Location		Fault plane						
						Nodel plan1			Nodel plan2			
	Yr Mo Da	Hr Mn	Sec	Lat.	Long.	Depth	Strike	Dip	Rake	Strike	Dip	Rake
1	1993-08-03	12:43	05.36	28.729	34.553	17.0	235	38	-49	7	62	-117
2	1993-08-03	12:43	14.50	28.620	34.400	15.0	139	36	-122	357	60	-69
3	1993-08-03	16:33	23.60	28.360	34.080	15.0	142	13	-123	356	79	-83
4	1995-11-22	04:15	11.94	28.826	34.799	6.0	188	51	-17	289	77	-139
5	1995-11-22	04:15	26.20	29.070	34.730	18.4	196	59	-15	294	77	-149
6	1995-11-22	22:16	57.20	28.320	34.210	15.0	202	67	-3	294	87	-157.
7	1995 11 23	18:07	26.50	29.310	34.480	15.0	199	77	7	108	83	166
8	1996-02-21	04:59	56.80	29.030	34.370	15.0	132	30	-104	328	61	-82
9	1996 12 17	11 31	30.78	27.56	34.010	10.0	242	73	144	065	056	153
10	1997-03-08	15:21	02.30	27.600	34.290	10.0	61	47	-156	314	72	-46
11	1997-05-10	23:01	46.90	28.260	34.700	10.0	205	60	1	114	89	150
12	2000-03-08	14:22	02.30	28.834	34.731	15.0	309	57	-126	182	48	-48
13	2000-03-08	14:22	28.50	28.640	34.570	10.0	230	46	183	-0.10	30	309
14	2000-04-06	06:37	34.00	28.778	34.832	12.0	1.422	164	54	-68	309	41
15	2000-06-25	19:18	48.50	28.210	33.480	18.0	196	77	-166	103	76	-13
16	2001-02-07	03:39	00.40	29.580	35.010	09.0	135	85	-170	44	80	-5
17	2005 07 23	14:56	32.20	28.030	34.500	14.3	182	60	-21	283	72	-148
18	2005 11 23	00 48	57.00	27.620	34.250	16	113	63	113	250	35	53
19	2005 11 11	15 34	08.70	27.29	34.48	9.2	146	66	124	267	40	39
20	2006 02 02	09 49	49.90	27.88	34.41	2	312	81	60	035	214	323

$$\log_{10} N = a - b M \quad (1)$$

whereas  $N$  is the cumulative number of earthquakes greater than or equal to magnitude  $M$  and  $a$  and  $b$  are constants describing the activity and slope, respectively. Here, we focus on the parameter  $b$ , or  $b$ -value, which describes the ratio of occurrence of small to large earthquakes. Globally,  $b$ -value is  $\sim 1$  (e.g., Stein and Wyssession [18]).

**Stress Tensor Inversion:** The actual inversion is performed using a Fortran code based on Gephart and Forsyth [6].

The program is described by Gephart and Forsyth [6], Gephart [19] and Gillard and Wyss [20]. In discussions of the significance of focal mechanisms the P, B and T axes are taken as approximations of the maximum S1, intermediate S2 and minimum S3 compressive stress directions. One justification for this is that if the principal stress directions were oriented along the P, B and T axes, the nodal planes would represent orientations of maximum shear stress, which might be reasonable loci for new fractures. Also, this determination of principal stress directions does not require the identification of one of the nodal planes as the true fault plane, since the orientations

of the P, B and T axes are fixed by the focal mechanism, independent of the choice of fault plane.

In the inversion a grid search of stress models is performed to find the one which requires the smallest total rotation of all the fault planes that is needed to match the observed and predicted slip directions; the method allows for errors in orientations of both the fault planes and slip directions. By using a grid search of stress models rather than a linearization scheme, It is able to perform a realistic error analysis and thus establish confidence limits for the preferred regional stresses. The method can be used to investigate possible stress inhomogeneities during earthquake sequences by analyzing subsets of the data population.

Two main assumptions need are made: 1) the stress tensor is uniform in the crustal volume investigated; 2) on each fault plane slip occurs in the direction of the resolved shear stress. In order to invert the focal mechanism data successfully for the direction of principal stresses, one must have a crustal volume with faults representing zones of weakness with different orientations in a homogeneous stress field. If only one type of focal mechanism is observed, then the direction of the principal stresses would be poorly constraint (modified from Gillard and Wyss [20]).

## RESULTS AND DISCUSSION

**Seismicity:** Several seismological studies have already addressed the rupture process of the 1995 earthquake Klinger *et al.* [1], Zuhair H. El-Isa [21], Fattah *et al.* [22] and Pasquale and De Matteis [28].

Three seismic swarms were recorded in 1983, 1990 and 1993 which affected different parts of the Gulf, with magnitudes up to ~6 El-Isa *et al.* [25] and Abou Karaki *et al.* [26]. These swarms probably relate to episodes of extensional faulting on ~NS trending normal faults as indicated by the focal mechanism of the largest shock in 1993 (e.g. Fattah *et al.* [22]).

The Gulf of Aqaba earthquakes is mainly concentrated in four zones; the first zone is located between latitude 27.3-27.8 and longitude 34.3-34.5 degrees in the Hume Basin in the southern entrance of the Gulf. The second zone is located along the Arnona fault between 28.3-28.6 and longitude 34.5-34.7 degrees; the third zone is located between latitude 28.8-29.0 and longitude 34.6-34.8 degrees in the Aragonese Basin, the fourth zone is located in the Aqaba Basin between latitude 29.1-29.2 and longitude 34.7-34.8 degrees. Figure 3 shows the density of earthquakes distribution along the Gulf of Aqaba.

The result of the analysis is presented in figure (4a) illustrates the magnitude of completeness ( $M_c$ ) calculated

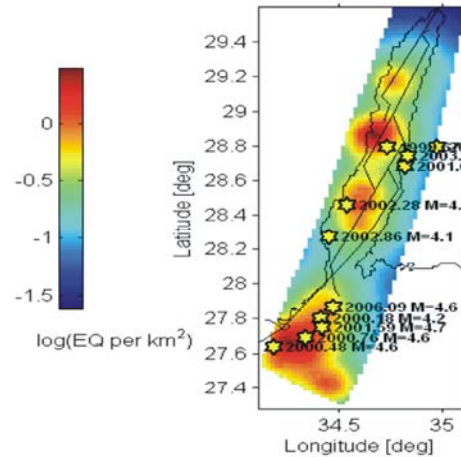


Fig. 3: Seismic zones along the Gulf of Aqaba

to be 1 using the maximum curvature method and b-value equal 0.58 for the entire interface catalog.

The frequency-magnitude distributions are significantly different, with particularly small b-values for the southern entrance of the Gulf of Aqaba, where five earthquakes larger than or equal to 4.0 occurred. Similar small b-values zone in eastern side of the Gulf of Aqaba between latitude 28.5° N to 29° N where three earthquakes larger than or equal to 4.0 occurred, followed by a relative increase toward north the b-value ranges between 0.469-1.1. Figure (4b) shows the cross section of the b-values along the Gulf of Aqaba.

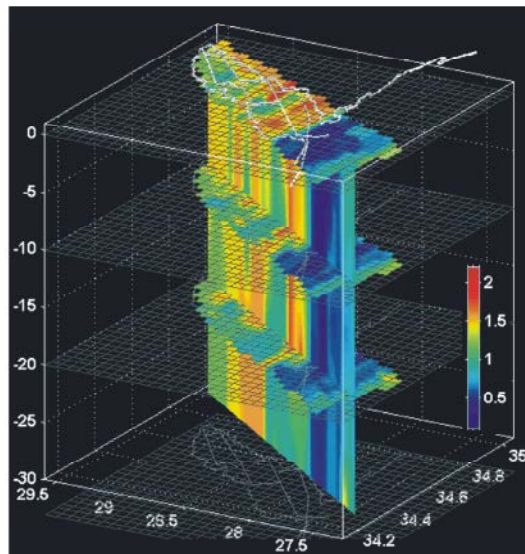
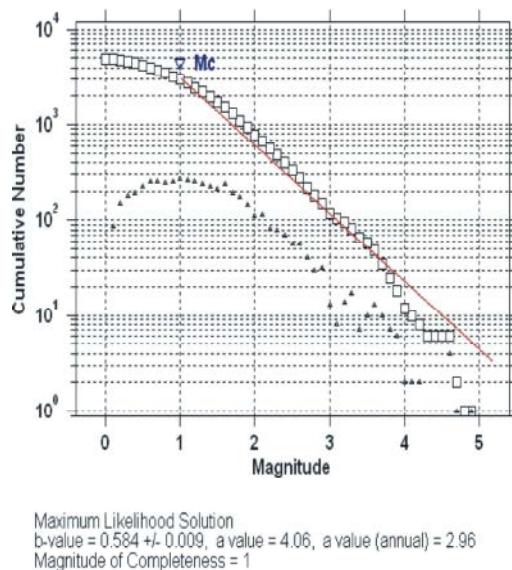


Fig. 4: a) The b-value of the over all catalog and magnitude of completeness ( $M_c$ ) in both the cumulative form (squares) and non cumulative form (triangles).  
b) Cross section of the b-value along the Gulf of Aqaba in 3D view.

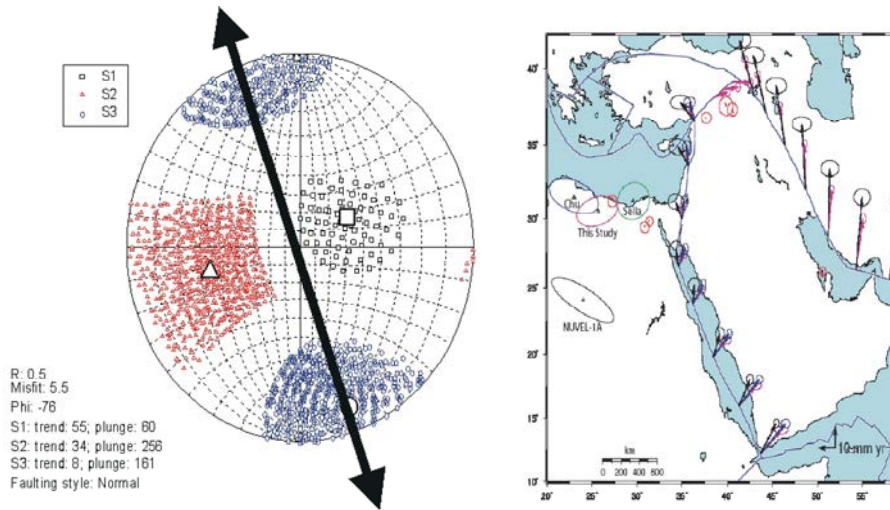


Fig. 5: (a) Polar projection of the stress-tensor inversion results. (b) Motions are for Arabia relative to the adjacent plate by using GPS (after McClusky, *et al.* [32] ).

**Stress Tensor Inversion:** Stress is believed to be the most important variable controlling triggering, earthquake occurrence and interactions. Many interesting results have been obtained by Hardebeck [23], Helmstetter *et al.* [24], Dwivedi and Hashimite [29] and. McFarland *et al.* [30].

If a number of focal mechanisms are compiled for a series of earthquakes in a region, then cluster analyses may be performed on the P and T axes to determine estimates of regional compression and tension directions. Many workers, including Zoback and Zoback [9], Zoback *et al.* [10] and Sperner *et al.* [11] while recognizing the aprecision of such determinations, suggest that groupings of P and T axes from a number of fault plane solutions are generally good indicators of regional maximum and minimum compression directions.

Several inversion algorithms have been proposed in the past (e.g., Gephart and Forsyth [6], Michael [7], 1991 and Gephart [19] and have been shown to compute consistent results Hardebeck and Hauksson [27] and Katsushi [31].

The orientations of fault planes and slip directions indicated by a population of earthquake focal mechanisms can be used to determine best fit regional principal stress directions and  $R = (\sigma_2 - \sigma_1) / (\sigma_3 - \sigma_1)$ , a measure of relative magnitudes, under the assumption of uniform stress in the source region. The technique has been applied to 20 events from the Gulf of Aqaba earthquake sequence for which we have found best fit stresses (plunge and azimuth):  $\sigma_1 = 55.60$ ,  $\sigma_2 = 34.256$ ,  $\sigma_3 = 3.161$  and  $R = 0.50$ . The average misfit between the stress model and all the data is about  $5.5^\circ$  (figure 5a). This result is consistent with GPS results McClusky *et al.* [32] as shown in figure 5b.

## CONCLUSIONS

Using a seismic catalog of 4880 events from January 1997 and May 2010, the seismicity of the Gulf of Aqaba is studied and map of b-values Under the Gulf of Aqaba is created.

The Gulf of Aqaba earthquakes is mainly concentrated in four zones; the first zone is located between latitude 27.3-27.8 and longitude 34.3-34.5 degrees in the Hume Basin in the southern entrance of the Gulf. The second zone is located along the Arnona fault between 28.3-28.6 and longitude 34.5-34.7 degrees; the third zone is located between latitude 28.8-29.0 and longitude 34.6-34.8 degrees in the Aragonese Basin, the fourth zone is located in the Aqaba Basin between latitude 29.1-29.2 and longitude 34.7-34.8 degrees.

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## ACKNOWLEDGMENT

We would like to express our sincere gratitude and appreciation to Prof. E.M. Ibrahim and Prof. Hesham Mousa and all the Egyptian National Seismic Network (ENSN) staff.

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