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 (~ 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 $R=(8.37\sigma_3-\sigma_1)/(|\sigma_3-\sigma_1|)$, 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): $\sigma_1=55.60$, $\sigma_2=34.25$, $\sigma_3=3.16$, and $R=0.50$. The average misfit between the stress model and all the data is about 5.5°. 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...
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 (S1, S2 and S3) 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].

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

<table>
<thead>
<tr>
<th>No</th>
<th>Date</th>
<th>Location</th>
<th>Fault plane</th>
<th>Fault plane</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Yr Mo Da</td>
<td>Lat. Long.</td>
<td>Nodel Plan1</td>
<td>Nodel Plan2</td>
</tr>
<tr>
<td>1</td>
<td>1993-08-03</td>
<td>28.729 34.553</td>
<td>17.0 235 38</td>
<td>-49 7 62</td>
</tr>
<tr>
<td>2</td>
<td>1993-08-03</td>
<td>28.620 34.400</td>
<td>15.0 139 36</td>
<td>-122 357 60</td>
</tr>
<tr>
<td>3</td>
<td>1993-08-03</td>
<td>28.360 34.080</td>
<td>15.0 142 13</td>
<td>-123 356 79</td>
</tr>
<tr>
<td>4</td>
<td>1995-11-22</td>
<td>28.826 34.799</td>
<td>6.0 188 51</td>
<td>-17 289 77</td>
</tr>
<tr>
<td>5</td>
<td>1995-11-22</td>
<td>29.070 34.730</td>
<td>18.4 196 59</td>
<td>-15 294 77</td>
</tr>
<tr>
<td>6</td>
<td>1995-11-22</td>
<td>28.320 34.210</td>
<td>15.0 202 67</td>
<td>-3 294 87</td>
</tr>
<tr>
<td>7</td>
<td>1995 11 23</td>
<td>29.310 34.480</td>
<td>15.0 199 77</td>
<td>7 108 83</td>
</tr>
<tr>
<td>8</td>
<td>1996-02-21</td>
<td>29.030 34.370</td>
<td>15.0 132 30</td>
<td>-104 328 61</td>
</tr>
<tr>
<td>9</td>
<td>1996 12 17</td>
<td>27.56 34.010</td>
<td>10.0 242 73</td>
<td>144 065 056</td>
</tr>
<tr>
<td>10</td>
<td>1997-03-08</td>
<td>27.600 34.290</td>
<td>10.0 61 47</td>
<td>-156 314 72</td>
</tr>
<tr>
<td>11</td>
<td>1997-05-10</td>
<td>28.260 34.700</td>
<td>10.0 205 60</td>
<td>1 114 89</td>
</tr>
<tr>
<td>12</td>
<td>2000-03-08</td>
<td>28.834 34.731</td>
<td>15.0 309 57</td>
<td>-126 182 48</td>
</tr>
<tr>
<td>13</td>
<td>2000-03-08</td>
<td>28.640 34.570</td>
<td>10.0 230 46</td>
<td>183 -0.10 30</td>
</tr>
<tr>
<td>14</td>
<td>2000-04-06</td>
<td>28.778 34.832</td>
<td>12.0 1422 164</td>
<td>164 309 41</td>
</tr>
<tr>
<td>15</td>
<td>2000-06-25</td>
<td>28.210 33.480</td>
<td>18.0 196 77</td>
<td>-166 103 76</td>
</tr>
<tr>
<td>16</td>
<td>2001-02-07</td>
<td>29.580 35.010</td>
<td>0.9 135 85</td>
<td>-170 44 80</td>
</tr>
<tr>
<td>17</td>
<td>2005 07 23</td>
<td>28.030 34.500</td>
<td>14.3 182 60</td>
<td>-21 283 72</td>
</tr>
<tr>
<td>18</td>
<td>2005 11 23</td>
<td>27.620 34.250</td>
<td>16 113 63</td>
<td>113 250 35</td>
</tr>
<tr>
<td>19</td>
<td>2005 11 11</td>
<td>27.29 34.48</td>
<td>9.2 146 66</td>
<td>124 267 40</td>
</tr>
<tr>
<td>20</td>
<td>2006 02 02</td>
<td>27.88 34.41</td>
<td>2 312 81</td>
<td>60 035 214</td>
</tr>
</tbody>
</table>

\[ \log_{10}N = a - b M \]  \hspace{1cm} (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 \(-1\) (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 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. 3: Seismic zones 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.
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° (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.

The b-value ranges between 0.469-1.1, a region of low b-values found in the southern entrance of the Gulf of Aqaba (~ 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 $R = (\sigma_2 - \sigma_1) / (\sigma_3 - \sigma_1)$, 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°. It was concluded that the maximum regional stress in the Gulf of Aqaba from NE direction, while the minimum regional stress to NW direction.
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.

REFERENCES