The Spatial and Genetic Relation between Seismicity and Tectonic Trends, the Bitter Lakes Area, North-East Egypt

Ahmed M. Hegazi, Tarek A. Seleem* and Hamdy A. Abouelela

Abstract

The Bitter Lakes area was subjected to numerous seismic events which are genetically related to the well-known tectonic trends in NE Egypt. Based on the focal mechanism solutions and structural lineaments analysis, the spatial and genetic relationships of seismicity to these tectonic trends were clarified. The data set included eight focal mechanisms of recently recorded earthquakes that occurred during the period 1984–2003, and the structural lineaments extracted from the enhanced shaded relief image of the study area.

The analysis of the available seismic events might reveal the existence of four alternating NW-trending seismic zones, each of them is characterized by a specific motion. Seismic zones (I and III) are characterized by strike-slip motion, while zones (II and IV) are related to oblique-slip with a predominant dip-slip normal component. Genetically, the seismic events are related to two main tectonic trends; the NW-SE and E-W, respectively. The first one is characterized by NW-trending normal faults clearly associated with the tectonics of the Gulf of Suez rift. The second trend shows strike-slip mechanisms associated with E-W-trending faults coincides with inherited ENE-trending faults. These pre-existing faults were dominated by normal dip-slip motion which has been later rejuvenated with a right-lateral, strike-slip motion.

Actually, the seismicity distribution and tectonic trends in the Bitter Lakes area have been affected by the relative motion among Africa, Arabia, Eurasian plates and Sinai sub-plate.

Finally, it is worth to mention that seismic activities will play a vital role on the future urban and development strategy in the Bitter Lakes area, hence they should be taken into consideration to mitigate their effects.

Keywords
Bitter Lakes; Seismicity; Tectonic trends; Shaded-relief image

Introduction

During the past decades, the north-eastern part of Egypt, including the Bitter Lakes area, has been suffered many seismic activity. However, most seismic activity (more than 70%) has been concentrated in northern Egypt along the geologically documented borders of Sinai subplate (Northern Red Sea and its two branches Suez rift and Aqaba–Dead Sea transform) [1]. This seismic activity caused damage of variable degrees both in property and human life. Many earthquakes were recorded, for example Abu-Hammad earthquake (29th of April, 1974) took place about 65km to the north west of the study area. It had a magnitude of 4.8 body wave magnitude (Mb) and was strongly felt in the Nile Delta region. Also, Wadi Hagul earthquake (29th of March, 1984) occurred in Wadi Hagul, which is located about 35 km to south west of the Suez city. Its magnitude was 4.7 (Mb) and was felt strongly in Suez, Ismailia and Cairo cities. Moreover, moderate and large earthquakes had been increased in the recent years.

Obviously, the Bitter Lakes area is affected by two major active seismic trends; Northern Red Sea-Gulf of Suez-Cairo-Alexandria Glypticm-trend and East Mediterranean-Cairo-Fayum Pelusiac trend. These two active seismic trends are genetically related to the well-known tectonic trends in Egypt. The area of study represents the site of superposition of two different deformational phases: the Late Cretaceous folding phase, with NE-SW oriented axes, and the Early Miocene NW-oriented normal faults of the Suez Rift. The Late Cretaceous folding phase is represented by the ‘Syrian Arc’ which is an intraplate orogen that has been formed by inversion of an older half-graben system as a consequence of the collision of the African and Eurasian plates [2,3].

The Gulf of Suez is the north-western arm of the Red Sea rift system and partly separates the Sinai Peninsula from the remainder of Egypt. The Gulf of Suez- Red Sea- Gulf of Aden rift system has long been recognized as having been formed by the separation of Arabia from Africa [4]. It is a modern example of continental rifting and incipient ocean formation. The rift system was formed by the anticlockwise rotation of Arabian Peninsula away from Africa about a pole of rotation in the central or south central Mediterranean Sea, e.g. [5-8].

The seismic activity is one of the biggest hazard usually associates with property and human losses, and must be taken into consideration during future development strategy. Recently, many local and regional seismic stations were installed in Egypt, enabled the recording of many small to moderated events and the assessment and mitigation of seismicity risk overall the area. Also, National Research Institute of Astronomy and Geophysics (NRIAG) initiated a new GPS network around greater Cairo region and around the Gulf of Suez aiming to study the geodynamics of Sinai Peninsula. Data from three GPS networks have been used to look especially at inland crustal deformation in Egypt. The average horizontal velocity of GPS stations in Egypt was estimated to be 5.15 ± 1.1 mm/year in mostly NNW direction [1].

The seismicity and tectonic features of the NE part of Egypt have been discussed by many researchers, such as [9-13]. Seleem and Abouelela [14] concluded that paleo and recently recorded earthquakes in Wadi Hagul area and its environs led to the formation of two types of geologic structures: brittle and viscous plastic structures. Moreover, the earthquakes that frequently distributed at an average depth (1 to 35 km) within the topmost part of the Earth’s crust were mainly controlled by the Hagul fault zone.
Careful analysis of the focal mechanism of some earthquakes indicated the association with normal and strike-slip faulting within the crust. This association may give an impression that earthquakes seem to have spatial and genetic relation to the tectonic trends forming the architecture of the study area. Hence, one of the main targets of the present work was to decipher the tectonic pattern and try to unravel this relationship around the Bitter Lakes. Also, critical reviewing of the information of both the historical and instrumentally recorded principal earthquakes was crucial.

The main objective of the present study is to record and analyze the different available data concerning seismic activity and geotectonic setting of the study area and its vicinity in order to put a suitable seismotectonic interpretation. Additionally, the construction of many new cities and industrial projects has being planned overall and around the study area. Therefore, the assessment and mitigation of seismicity risk is important due to this fast development and important constructions.

**Geologic Setting**

The Bitter Lakes area represents a part of the transitional zone between the Gulf of Suez rift and the unstable shelf of the northern part of Egypt as suggested by [15,16]. It forms the extreme eastern sector of the Cairo-Suez province, and is bounded by latitudes 29° 38'-30° 31' N, and longitudes 32° 05'-32° 42' E, (Figure 1). The regional geology and tectonic setting of the study area were investigated by many researchers such as [10,17-21].

The study area is covered by sedimentary rocks belong to the Cretaceous, Middle Eocene, Late Eocene, Oligocene, Early Miocene, Middle Miocene, Late Miocene and Pleistocene-Holocene ages, (Figure 2). The Late and Early Cretaceous sediments are exposed in Gebel Shabrawet area, which is constituted of limestone and marl. The Middle Eocene sediments are exposed in Gebel Gineifa area which is mainly composed of thickly bedded limestone occasionally dolomitic. Late Eocene sediments unconformably overly the Middle Eocene sediments, and is composed mainly of fossiliferous limestone and clay intercalations. The Oligocene sediments are of wide distribution in Gebel Geneifa area, where it unconformably overlies the Late Eocene sediments. It is composed essentially of dark brown gravels and ill sorted varicoloured sand and silicified wood. Some doleritic dykes of probable Oligocene age cut through the Late Eocene sediments. The Early Miocene sediments are composed generally of limestone with sandstone and gypseous clay interbeds. The Middle Miocene sediments are consisted fundamentally of non marine sands, sandstones, flint pebbles and gravels and some sandy limestone. Moreover, some silicified wood was recorded in these sediments.
The Pleistocene-Holocene sediments (Quaternary) are composed mainly of sandy clay and clay present around marshes and sabkhas, gravels, gypsum, beach ridges, beach sand, wadi alluvium, sand dunes and eolian sand.

### Tectonic Setting

The Suez Canal region, including the Bitter Lakes area, is intensively affected by different structures that are oriented E-W, WNW-ESE, NW-SE, and NNE-SSW as interpreted from the Landsat image [19]. These structural features are often responsible for the development of the main geomorphologic features within and around the study area, (Figure 3).

Generally, the Suez Canal region is classified tectonically by [22] into two provinces, northern and southern Nile Delta structural provinces (Figure 4). The region extends northward from the E-W-oriented normal faults bounding the northern part of the Cairo-Suez province to the Nile Delta hinge zone, at Port Said Town. The southern structural province is completely covered by Pliocene-Quaternary sediments. Tectonically, the Bitter Lakes area belongs to the southern province which is deformed by a number of E-W-oriented normal faults dividing it, from south to north, into the Bitter Lakes graben and Ismailia horst. The E-W-oriented faults were mostly originally formed in late Triassic-Early Jurassic during the rifting of the African-Arabian plate away from the Eurasian plate. These faults were reactivated to deform the upper Cretaceous rocks and continued to affect the overlying Tertiary rocks [21].

The Jurassic-Cretaceous rocks exposed in this province were deformed by NE oriented, right-stepping en-echelon folds, forming the Great Bitter Lake fold belt, which are terminated against the E-W-oriented faults that bounding the Great Bitter Lake graben. Gabel Shabraweet overturned anticline is the easternmost one in this belt. Hegazi and Omran [20] concluded that the Shabraweet area resulted from a folding phase at the end of the Late Cretaceous. This phase has given rise to a number of asymmetrical overturned anticlines. The thrust faults associated with folds were developed along an ENE direction in the folded Cretaceous rocks, prior to the deposition of the sub-horizontal Middle Eocene rocks. The fault-striae analysis revealed the presence of four distinct brittle tectonic events. The first one was a NNW compressional tectonic regime which prevailed at the end of the Late Cretaceous, and resulted in ENE-oriented thrust faults associated with folds. The second was a N-S compressional stress regime in response to the convergence of Africa and Eurasia, during the Late Cretaceous and mainly during the Eocene. The sense of movement on these faults is purely strike slip. During the third event, a regional extensional stress regime was expressed by N60°E to S80°E trending normal faults. Extensional stress continued through the Oligocene-Miocene times, producing dip-slip normal faulting contemporaneous with the fourth event. This event is represented by a set of N0-40°W trending normal faults, related to the Gulf of Suez rifting.

On the other hand, the Ismailia horst is internally affected by NE oriented folds that dextrally offset by E-W-oriented faults. The northern Nile Delta structural province lies north of the study area. This province is dissected by several E-W trending listric normal faults that bound southward tilted fault blocks of half grabens.

The Oligocene and Miocene rocks filled the low areas between rotated blocks forming several E-W elongated wedge-shaped basins. This province is affected by N-S to NNW, NW and NE to NNE oriented faults.

Combination of data set including the fractures resulted from...
22nd May, 1992 earthquakes, south west the Bitter Lakes and the collected field measurements, indicated that the WNW-ESE to NW-SE and E-W directions are the most active fractures of earthquakes in the Suez Canal region. Moreover, some other NNE-SSW and NW-SE trending fractures could also be detected in the study area as a result of earthquake shock [10].

Extraction and Analysis of Structural Lineaments

Actually, the structural lineaments represent fractures cross cutting the earth’s crust that may have a close relationship to the seismic activities in a certain region. In the present study, the structural lineaments were extracted by applying shaded relief algorithms on SRTM-DEM (90m spacial resolution) of the study area. This technique is widely used for perception of elevation could be attained and combined with other image types to produce a new enhanced one. In most cases, DEM has better resolution than satellite images [23,24]. Techniques of shaded relief were used in cartography to produce the illusion of a 3-D relief map [25]. During the last decades, digital image processing techniques have been developed to display DEMs as shaded relief images. The case of DEM’s shaded relief images and terrain derivative maps (slope, aspect and curvatures) have largely demonstrated their usefulness for lineaments and fault extraction [26].

Generally, the mapping of surface structural lineaments is supported by the existence of geomorphologic features like aligned ridges and valleys, displacement of ridge lines, scarp faces and river passages, straight drainage channel segments, pronounced breaks in crystalline rock masses, and aligned surface depressions [27,28]. The present study was keenly interested in mapping of surface topographically negative lineaments, which may represent joints, faults and, probably, shear zones [27,29,30]. The enhanced shaded relief of SRTM-DEM image is shown in Figure 4, whereas both of the extracted surface (present study) and the subsurface [21] structural lineaments are shown in Figure 5. The azimuthal distribution of the extracted surface and subsurface lineaments are represented as rose diagram (Figure 6).

The parameters of the extracted structural lineaments are listed in Table 1. Careful inspection of the structural lineaments revealed the presence of two prominent trends these are; NW and NNW trends, in addition to subordinate trends; N-S and E-W. Structural trends like ENE, NNE, NNW, and NE appear to be less abundant (Figure 6). It’s worth to mention that the Northern Province is prevailed mainly by WNW direction with maxima of N40°-60°W, followed by NW-SE. Also, the southern province exhibits diversity in lineament orientation, where the WNW-ESE and NW-SW are the most important directions, followed by N-S and E-W trends.

Seismicity of the Bitter Lakes Area

It is well-known that the north-eastern section of Egypt, including the Bitter Lakes area, has experienced numerous moderate earthquakes associated with aftershock sequences, and some significant earthquakes swarm during the last 2000 years with (2≤ Mb ≥ 5) and intensities of (V-VI) according to the modified Mercalli scale as pointed by [31,32]. Information on historical earthquakes is documented in the annals of ancient Egyptian history and Arabic literature. According to [31-33] about 83 events were reported to have occurred in and around Egypt and have caused damage of variable degrees in different localities. One of the major historical earthquakes is 2800 BC Sharquia Province earthquake. This unknown location earthquake was a severe one and caused deep fissures and soil cracks in Tell Basta, Sharquia province which locates to the west of the study area. The estimated maximum intensity of this earthquake is VII in a confined area near this village.

In the current work, detailed information was accomplished using a catalogue of micro to moderate earthquake affected the study area and its surroundings. This catalogue has been compiled by the National Earthquake Information Centre (NEIS), and the International Seismological Centre (ISC). The seismicity data are covering the area between latitudes 29° 38′ - 30° 31′ N, and longitudes 32° 05′ - 32° 42′ E. The data base included location parameter (e.g. date, time, latitude, longitude, magnitude, depth, intensity) and the associated phenomena (e.g. crakes building, surface fractures). This data set was utilized to construct a more complete earthquake catalogue, attempting to achieve a homogenous coverage overall the study area. The epicentres of recently recorded earthquakes during the mentioned period were acquired and mapped (Figure 5), based on their body wave magnitude (Mb).

In general, the northern part of Bitter Lakes area shows relatively low activity, compared to the southern part, (Figure 5). Obviously, the distribution of seismicity seems to follow inherited tectonic trends,
The current study attempted to review the seismological evidences of the recent tectonic activities took place in the Bitter Lakes area. The seismicity distribution in the Bitter Lakes area seems to be spatially correlated with the NW- and EW-oriented faults. This is clearly shown on the epicenters distribution map of the study area (Figure 5), where the epicenters are aligned along these two trends and clustered at the intersections of these two trends.

Seismological approaches such as earthquake focal mechanisms play an important role in understanding the active tectonic processes associated with such earthquakes. In the present work, we focused on the significance of spatial and genetic relationship of seismicity to the tectonic trends, depending on the focal mechanism solutions and structural lineaments analysis. The data set consisted of eight focal mechanisms of earthquakes occurring during the period 1984-2003. Four of them (number 4, 5, 6 & 7) were conducted during the present study, whereas the other four mechanisms (number 1, 2, 3 & 8) were derived from previously published data. The analysis of the data set revealed that the magnitudes of seismic events range from 3.1 to 5.0, and focal depth ranges from 1 to 24 km, (Figure 7 and Table 2).

Based on the analysis of the available data of seismic events and fault plane solutions, the Bitter Lakes area may be arbitrarily subdivided into four alternating NW-trending seismic zones characterized by unique motion. Seismic zones (I and III) are genetically related to strike-slip motion, while seismic zones (II and IV) are related to oblique-slip with a predominant dip-slip normal component. Moreover, seismic events which took place within very short time period are characterized by the same motion (e.g. events no.5 & 6 which are characterized by oblique-slip with a predominant dip-slip normal component).

Furthermore, the fault plane solutions show that the seismic events are related to two main groups of faults trending NW-SE and E-W. Also, most of the earthquakes occurred at focal depths ranging from 1 to 24 km and magnitudes ranging from less than 3 to more than 5 (Figure 7). The existence of the earthquakes along these faults suggests a sub-surface continuation that has been proved by geophysical investigation carried out by many researchers [21].

In the present study, the focal mechanisms of eight seismic events recorded in the Bitter Lakes between 1984 and 2003 were used. The focal mechanism solutions numbers 4, 5, 6 & 7 were carried out during the current study, whereas focal mechanism number 1, 2, 3 & 8 are referred to [9,34-36] respectively. The parameters of these focal mechanisms are listed in Table 1, while the spatial distribution of the available focal mechanism solutions is shown in Figure 8.

Table 1: The number and percentage of extracted lineaments in the northern and southern provinces, the Bitter Lakes Area.  

<table>
<thead>
<tr>
<th>Trend</th>
<th>N-S</th>
<th>NNE</th>
<th>NE</th>
<th>ENE</th>
<th>E-W</th>
<th>NNW</th>
<th>NW</th>
<th>WNW</th>
<th>Total</th>
</tr>
</thead>
<tbody>
<tr>
<td>Northern Province</td>
<td>4</td>
<td>3</td>
<td>2</td>
<td>7</td>
<td>21</td>
<td>7</td>
<td>41</td>
<td>74</td>
<td>159</td>
</tr>
<tr>
<td>Percentage %</td>
<td>2.51</td>
<td>1.88</td>
<td>1.25</td>
<td>4.40</td>
<td>13.20</td>
<td>4.40</td>
<td>25.78</td>
<td>46.54</td>
<td>100</td>
</tr>
<tr>
<td>Southern Province</td>
<td>33</td>
<td>17</td>
<td>9</td>
<td>19</td>
<td>7</td>
<td>25</td>
<td>72</td>
<td>73</td>
<td>255</td>
</tr>
<tr>
<td>Percentage %</td>
<td>12.94</td>
<td>6.66</td>
<td>3.52</td>
<td>7.45</td>
<td>2.74</td>
<td>9.80</td>
<td>28.23</td>
<td>28.62</td>
<td>100</td>
</tr>
</tbody>
</table>

Table 2: The parameters of focal mechanisms in the Bitter Lakes area.  

<table>
<thead>
<tr>
<th>No.</th>
<th>Long. (D M)</th>
<th>Lat. (D M)</th>
<th>Magnitude (ML)</th>
<th>F Depth (Km)</th>
<th>Date (D/M/Y)</th>
<th>Reference</th>
<th>Type of motion</th>
<th>Seismic zone</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>32° 06'</td>
<td>30° 11'</td>
<td>4.7</td>
<td>10</td>
<td>29/03/1984</td>
<td>Attia, 1989</td>
<td>Oblique-slip</td>
<td>II</td>
</tr>
<tr>
<td>2</td>
<td>32° 10'</td>
<td>30° 28.8'</td>
<td>5.0</td>
<td>24</td>
<td>02/01/1987</td>
<td>Megahed and Dessokey, 1988.</td>
<td>Strike-slip</td>
<td>I</td>
</tr>
<tr>
<td>3</td>
<td>32° 13.8'</td>
<td>29° 42'</td>
<td>4.0</td>
<td>13</td>
<td>08/09/1995</td>
<td>Morsy et al., 2011</td>
<td>Oblique-slip</td>
<td>IV</td>
</tr>
<tr>
<td>4</td>
<td>32° 18.6'</td>
<td>30° 04.2'</td>
<td>3.2</td>
<td>16</td>
<td>30/10/2000</td>
<td>Present study</td>
<td>Strike-slip</td>
<td>I</td>
</tr>
<tr>
<td>5</td>
<td>32° 35'</td>
<td>30° 2'</td>
<td>3.1</td>
<td>15.3</td>
<td>16/10/2001</td>
<td>Present study</td>
<td>Oblique-slip</td>
<td>II</td>
</tr>
<tr>
<td>6</td>
<td>32° 22'</td>
<td>30° 16'</td>
<td>3.4</td>
<td>15.6</td>
<td>14/11/2001</td>
<td>Present study</td>
<td>Oblique-slip</td>
<td>II</td>
</tr>
<tr>
<td>7</td>
<td>32° 16'</td>
<td>30° 02'</td>
<td>3.2</td>
<td>23.6</td>
<td>05/12/2002</td>
<td>Present study</td>
<td>Strike-slip</td>
<td>III</td>
</tr>
<tr>
<td>8</td>
<td>32° 21'</td>
<td>29° 49.2'</td>
<td>3.1</td>
<td>04</td>
<td>11/09/2003</td>
<td>Abou Elenean, 2007</td>
<td>Oblique-slip</td>
<td>IV</td>
</tr>
</tbody>
</table>
The Arabian plate is moving towards NNE relative to Eurasia [39] while the African plate is moving in NNW direction, causing crustal spreading along the axis of the Red Sea with a low extensional motion at the Suez Gulf [40].

The second group of mechanisms represents fault populations with average E-W trend in the Bitter Lakes area. These faults demonstrate a pure strike-slip sense of motion with a component of right-lateral, strike-slip motion. The second group of mechanisms coincides with the pre-existing N60°E-S80°E- trending faults that had multiple tectonic histories, where they were recording variable movements. At the end of the Late Cretaceous, they associated with a NNNW compressional tectonic regime which resulted in ENE-oriented thrust faults. In Late Triassic-Early Jurassic they were contemporaneous with a regional extensional stress regime expressed by dip-slip normal movements [20]. Recently, these faults have been rejuvenated with a right-lateral, strike-slip motion as proved by the focal mechanism solution. The E-W-oriented faults were mostly originally formed in late Triassic-Early Jurassic during the rifting of the African-Arabian plate away from the Eurasian plate. These faults were reactivated to deform the upper Cretaceous rocks and continued to affect the overlying Tertiary rocks [21].

Definitely, the majority of inland earthquake focal mechanisms, such that in the Bitter Lakes area are normal with strike-slip component or strike-slip faulting events. The minimum stress, associated with the oblique-slip normal motion, is always sub-horizontal, whereas the greatest stress tends to be sub-vertical. On the other hand, the minimum stress and the greatest stress are always sub-horizontal with the strike-slip motion. Badawy [1] concluded that in northern Egypt, based on the whole dataset, the P axes cluster in a vertical plane of WNW-ESE orientation, and the T axes are almost horizontal and trend NNE-SSW. Guiraud et al. [41] mentioned that the orientations of the principle stresses and the value of R (0.3) suggest that the stress regime in northern Egypt area is of general transtension. However, the current study revealed the presence of local variations where some seismic zones display pure strike-slip regime. The variability of the focal mechanisms may give a clue that slip was taking place on faults of different orientations under a uniform stress field.

Actually, the seismicity distribution and tectonic trends in the Bitter Lakes area have being affected by the relative motion among Africa, Arabia, Eurasian plates and Sinai sub-plate.

Finally, the presence of four alternating NW-SE seismic zones in the Bitter Lakes area may be an interesting point which need further investigation on a large region and supported with extensive data set and more reliable results. Also, it is worth to mention that seismic activities will play an important role on the future urban and development strategy in the Bitter Lakes area, hence they should be taken into consideration to mitigate their hazardous effects.

References

Figure 8: Seismotectonic map of Bitter Lake area showing the possible four seismic zones based on the focal mechanism solutions, projected on stereonet. Dark: Compression; White Dilatation quadrants. The numbering of the focal mechanisms refers to Table 2.


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