Chapter 1

# An Updated Seismic Source Model for Egypt

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## 1. Introduction

Since the pioneering work of Cornell [1], it is clear that seismic hazard assessment depends on several models, among them perhaps one of the most significant, and usually poorly understood, is the delineation and characterization of the seismic source model for a particular region. Identification and characterization of the potential seismic sources in any region is one of the most important and critical inputs for doing seismic hazard analysis.

In fact, the characterization of seismic source zones depends on the interpretation of the available geological, geophysical and seismological data obtained by many tools such as tectonic studies, seismicity, surface geological investigations and subsurface geophysical techniques [2]. In addition, the characterization depends on the definition of different surface and sub-surface active faults.

Modern investigations on Probabilistic Seismic Hazard Assessment (PSHA) for any region at any scale, requires that the study region should be subdivided into different seismic sources. The issue of seismic source delineation and characterization is often a controversial one in the practice of seismic hazard analyses, both deterministic and probabilistic, as the information available relating to geology and seismotectonics can vary from region to another region.

It has been common practice since the development of PSHA by Cornell [1] and McGuire [3], to utilize areal source zones of seismic homogeneity [4 and 5]. In the classic form, earthquake sources range from clearly understood and well defined faults to less well understood and less well-defined geologic structures to hypothetical seismotectonic provinces extending over many thousands of square kilometers whose specific relationship to the earthquake generating process is not well known [2].

Recent PSHA at a local or a regional scale is usually based on approaches and computer codes (e.g., FRISK: [6]; SEISRISK III: [7]; CRISIS 2014: [8], etc.) that require the study area to be subdivided into seismic source zones which can be generated by delineating a number of polygons over active seismic areas. These polygons, sometimes have a complex shape, which reflects the complexity of the different faults and tectonic trends (e.g., [9]). The delineation will serve for two purposes: i) adequately represents the geological and tectonic setting together with the recorded seismicity, and ii) it allows for expected variations in future seismicity.

## 2. Seismicity and seismotectonic setting of Egypt

Egypt is situated in the northeastern corner of the African Plate, along the southeastern edge of the Eastern Mediterranean region. It is interacting with the Arabian and Eurasian Plates through divergent and convergent plate boundaries, respectively. Egypt is surrounded by three active tectonic plate boundaries: the African-Eurasian plate boundary, the Gulf of Suez-Red Sea plate boundary, and the Gulf of Aqaba-Dead Sea Transform Fault (Figure 1). The seismic activity of Egypt is due to the interaction and the relative motion between the plates of Eurasia, Africa and Arabia. Within the last decade, some areas in Egypt have been struck by significant earthquakes causing considerable damage. Such events were interpreted as the result of this interaction.

Based on the geophysical studies in the territory of Egypt, Youssef [10] classified the main structural elements of Egypt (Figure 2) into the following fault categories: a) Gulf of Suez-Red Sea, b) Gulf of Aqaba, c) east-west, d) north-south, and e) N45°W trends. However, Meshref [11], from the magnetic tectonic trend analysis, showed the tectonic trends which influenced Egypt throughout its geologic history as: a) NW (Rea Sea-Gulf of Suez), b) NNE (Aqaba), c) east–west (Tethyan or Mediterreanean Sea), d) north–south (Nubian or East African), e) WNW (Drag), f) ENE (Syrian Arc), and g) NE (Aualitic or Tibesti) trends.

The seismicity of Egypt has been studied by many authors [e.g., 12-22]. Although Egypt is an area of relatively low to moderate seismicity, it has experienced some damaging local shocks throughout its history, as well as the effects of larger earthquakes in the Hellenic Arc and the Eastern Mediterranean area. In addition, it has also been affected by earthquakes in Southern Palestine and the Northern Red Sea [18].

In Egypt, mostly population settlements are concentrated along the Nile Valley and Nile Delta, so, the seismic risk is generally related to the occurrence of moderate size earthquakes at short distances (e.g., $M_S$ 5.9, 1992 Cairo earthquake), rather than bigger earthquakes that are known to occur at far distances along the Northern Red Sea, Gulf of Suez, and Gulf of Aqaba (e.g., $M_S$ 6.9, 1969 Shedwan, and $M_W$ 7.2, 1995 Gulf of Aqaba earthquakes), as well as the Mediterranean offshore (e.g., $M_S$ 6.8, 1955 Alexandria earthquake) [23].

Egypt is suffering from both interplate and intraplate earthquakes; intraplate earthquakes are less frequent but still represent an important component of risk in Egypt. Shallow-depth seismicity (Figure 3) is concentrated mainly in the surrounding plate boundaries and on some active seismic zones like Aswan, Abu Dabbab, and Cairo-Suez regions, while the deeper activity is concentrated mainly along the Cyprian and Hellenic Arcs due to the subduction process between Africa and Europe.

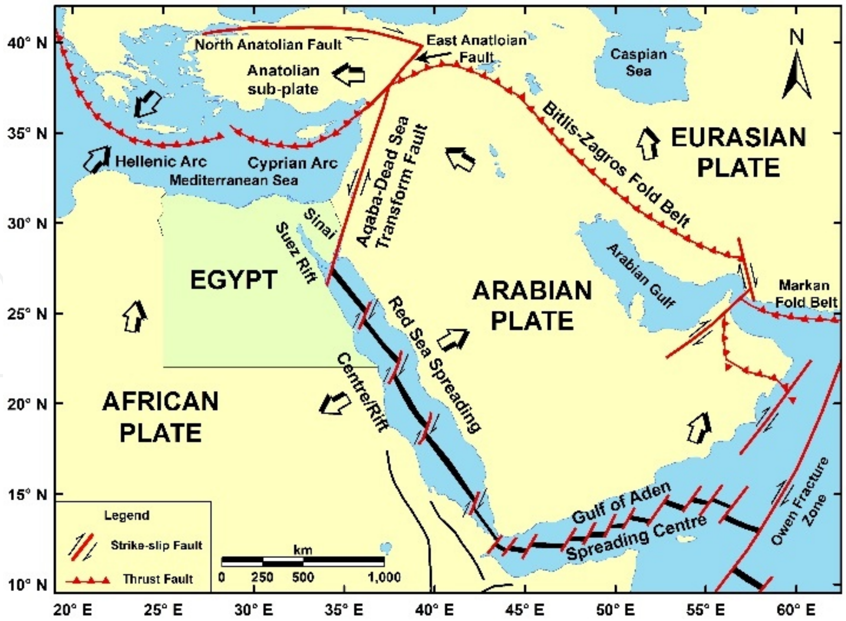


**Figure 1.** Global tectonic sketch for Egypt and its vicinity (redrawn after Ziegler [24] and Pollastro [25]).

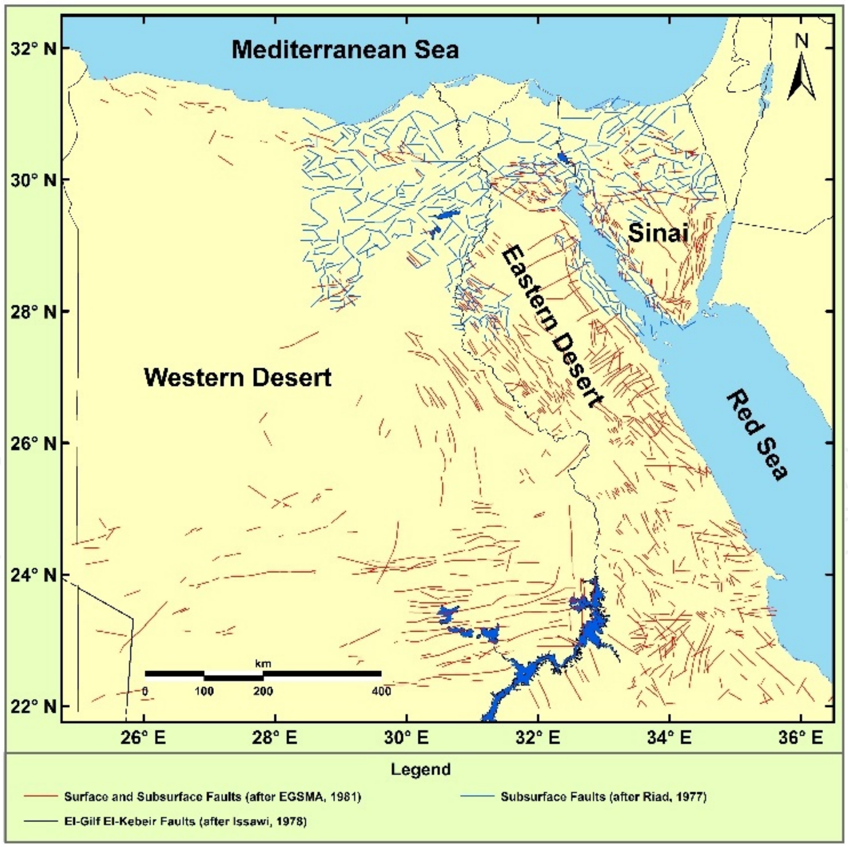


**Figure 2.** Distribution of major surface and subsurface faults. Compiled and redrawn from EGSMA [26] geologic map, from Riad [27], and from Issawi [28].

## 3. Review of seismic zoning studies in Egypt

Seismic hazard assessments for Egypt, based on the zoning approach, has been carried out by many authors in the last decades, based upon the main tectonic features prevailed, the dominant tectonic stresses, the history of seismicity in the region, and the distribution of the recorded earthquakes. These authors were used different criteria to obtain seismic source zonation maps.

Among those studies, those carried out by the following authors: Sieberg [12 and 13], Gergawi and El-Khashab [15], Maamoun and Ibrahim [29], Maamoun *et al.* [16], Albert [30 and 31], Kebeasy *et al.* [32], Kebeasy [17 and 33], Marzouk [34], Fat-Helbary [35-37], Reborto *et al.* [38], Mohammed [39], El-Hadidy [40], Fat-Helbary and Ohta [41], El-Sayed and Wahlstörm [42], Abou Elenean [19 and 43], Badawy [44], Deif [45], Riad *et al.* [46], Abou Elenean and Deif [47], El-Sayed *et al.* [48], Fat-Helbary and Tealeb [49], El-Amin [50 and 51], El-Hefnawy *et al.* [52], Abdel-Rahman *et al.* [53], El-Hadidy [54 and 55], Deif *et al.* [56 and 57], Fat-Helbary *et al.* [58] and Mohamed *et al.* [59].

Egypt was divided into different seismic zones by many researchers, using the distribution of historical and instrumental earthquakes. Maamoun and Ibrahim [29] and Kebeasy [33] divided Egypt into four main seismic trends: i) Northern Red Sea-Gulf of Suez-Cairo-Alexandria, ii) Eastern Mediterranean-Cairo-Fayoum, iii) Mediterranean Coastal Dislocation, and iv) Aqaba-Dead Sea Transform. More recently, Maamoun *et al.* [16] added another two trends to the previous four: i) Hellenic and Cyprian Arcs, and ii) Southern Egyptian trend.

In reviewing the seismicity of Egypt, Kebeasy [17] suggested three main seismic zones: i) Aqaba-Dead Sea Transform, ii) Northern Red Sea-Gulf of Suez-Cairo-Alexandria, iii) Eastern Mediterranean-Cairo-Fayoum zones. In addition, he defined other local seismic zones (e.g., El-Gilf El-Kebeir, Aswan and Qena zones).

Fat-Helbary [36] assessed the seismic hazard for Aswan region. He used both of line sources and area source models. Five active faults in the Aswan region (Kalabsha, Seiyal, Gebel El-Barqa, Kurkur, and Khur El-Ramla Faults) were modeled as seismic lines. On the other hand, six area source zones (Old Stream, North Kalabsha, Khur El-Ramla, East Gebel Marawa, Abu Dirwa, and Kalabsha zones) were considered in the assessment. This study was followed by successive assessments by different authors to include other neighbor regions in Upper Egypt (e.g., [37, 41, 49, 50, 51, 57 and 58]).

Using the relation between the paleo-stresses, the present-day stresses and the distribution of earthquake epicenters, El-Hadidy [40] deduced five major trends in Egypt. They are: i) Pelusium megashear, ii) Eastern Mediterranean-Cairo-Fayoum-El-Gilf El-Kebeir, iii) Nubian-Mozambique, iv) Qena-Aqaba-Dead Sea, and v) Northern Red Sea-Gulf of Suez-Cairo-Alexandria seismotectonic trends. Furthermore, he identified some local zones on the Red Sea, Gulf of Suez, Gulf of Aqaba, Nile Delta, and Cairo-Suez regions.

According to the earthquake distribution, focal mechanisms and the structural and tectonic information, Abou Elenean [19] suggested five seismotectonic sources. They are: i) Gulf of

Suez-Northern Eastern Desert, ii) Southwest Cairo (Dahshour), iii) Northern Red Sea, iv) Gulf of Aqaba, and v) Aswan zones. Deif [45], for a seismic hazard assessment study, delineated four additional seismic sources for the southern part of Egypt. They are: i) Abu Dabbab, ii) El-Gilf El-Kebeir, iii) Wadi Halfa, and iv) Northern Nasser's Lake zones.

Riad *et al.* [46] constructed a more detailed seismic zoning map for Egypt and its surroundings. Their regional delineation consists of five main trends: i) the Greek trend, based on the seismic zone regionalization of Papazachos [61], ii) the Dead Sea trend, which mainly based on the earthquake catalogue of Israel and its vicinity [62], iii) Pelusium and Qattara trend, iv) Eastern Mediterranean trend, and v) Aswan area, in Southern Egypt.

El-Hefnawy *et al.* [52], based on the tectonic regime, seismicity, faults location, and focal mechanism solutions, divided the regional seismicity in and around Sinai Peninsula into 25 source zones. His study was succeeded by a certain number of studies that considered a more detailed zonation for the same area (e.g., [53, 54 and 56]).

Recently, Abou Elenean [43] established a detailed zonation map for whole Egypt and its surroundings, considering the recent seismicity distribution and focal mechanism data. He delineated 41 seismic source zones of shallow-depth earthquakes ($h < 60$ km) in and around Egypt. In addition, he considered 7 seismic sources for intermediate-depth events within the Hellenic Arc (after [63]). More recently, El-Hadidy [55] and Mohamed *et al.* [59] established a new and modified seismic zoning map for Egypt and its surroundings which is based on the compilation of previous studies [53, 57 and 64].

## 4. Data sources

For the construction of any database of seismic sources, there are two basic steps: first, all of the active faults that affect a specific region need to be recognized, and secondly, each seismogenic structure should be seismotectonically parameterized. In order to recognize the active faults, it is necessary to analyze the seismicity. It is common practice to start analyzing the historical and instrumental seismicity that affects the specific region. Like many other places all over the world, the seismicity in Egypt is not homogeneously distributed, neither in frequency nor in density. Historical information is similarly not uniform all over the region.

### 4.1. An updated earthquake catalogue

A complete and consistent earthquake catalogue in a region is essential in order to study the distribution of earthquakes in space, time, and magnitude. In the current work, the identification and characterization of regional seismic source zones is based on a unified compiled earthquake catalogue, after Sawires *et al.* [60], for Egypt and its surroundings which covers the area from 21° to 38° N and 22° to 38° E, and extends from 2200 B.C. until 2013 in the time period.

Different earthquake magnitude scaling relations, correlating different scale magnitudes, were used to develop a unified earthquake catalogue for the study region in the moment magnitude

($M_W$) scale. The dependent events were removed from the catalogue to ensure a time-independent (Poissonian) distribution of earthquakes (Figure 3).

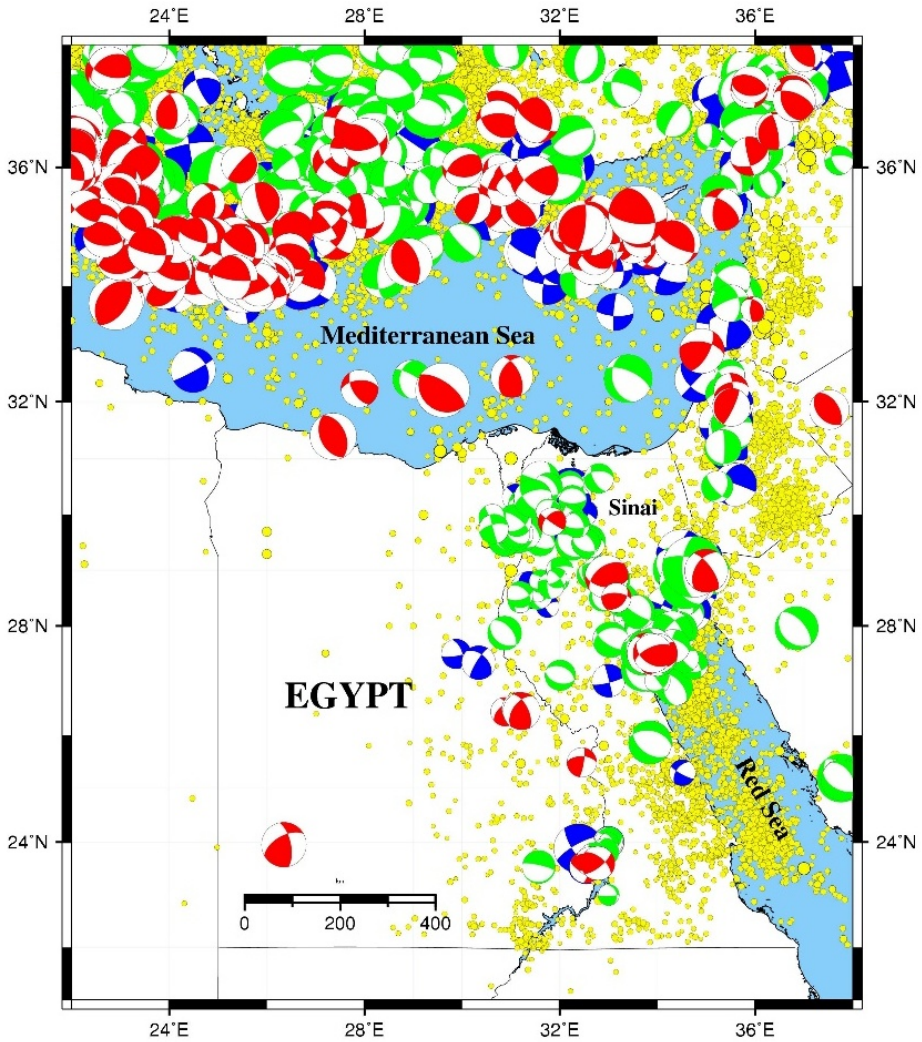


**Figure 3.** Distribution of the seismicity (2200 B.C. - 2013) and focal mechanism solutions (1940 – 2013) in and around Egypt (after Sawires *et al.* [60]). Symbols and focal sphere sizes are in proportion the moment magnitude. Focal sphere colours refer to different fault types (blue: strike-slip; green: normal; red: reverse).

### 4.2. Focal mechanism data

Different local and international sources were examined and focal mechanism data were compiled into a single database. The solutions of the Global Catalogue of CMT Harvard [65], the International Seismological Centre (ISC) [66], the National Earthquake Information Centre (NEIC) [67], the Regional CMT catalogues (RCMT) in the Mediterranean region [68], as well as ZUR-RMT catalogue of the Institute of Technology (ETH) of Zurich were also included in the catalogue. More than 600 focal mechanism solutions were collected covering different active seismic zones (Figure 3) in Egypt and surroundings, spanning the spatial area from 21°

to 38°N, and from 22° to 38°E. Most of them have a magnitude greater than or equal to $M_W$ 3.0, occurring in the time period 1940 to 2013.

### 4.3. Geological, tectonic and geophysical data

Several geological, geophysical and tectonic maps were inspected for the purpose of getting more information about the present active faults (e.g., Aswan region) and also for the identification of the prevailed tectonic and structural trends in the study region. Among these studies are those of Said [69-71], Youssef [10], Shata [72], Neev [73], Neev *et al.* [74 and 75], El-Shazly [76], Riad [27], Maamoun [77], Issawi [78], EGSMA [26], Riad *et al.* [47 and 79], Maamoun *et al.* [16], Sestini [80], Schlumberger [81], Woodward-Clyde Consultants [82], Kebeasy [17], Meshref [11], Barazangi *et al.* [83], Guiraud and Bosworth [84], Abdel Aal *et al.* [85], Philobbos *et al.* [86], and Hussein and Abdallah [87].

### 4.4. Crustal structure data

The crustal structure plays an important role in Seismology. It can be used, as in the current study, for the discrimination between the crustal (shallow-depth) seismicity, the intermediate-depth, and the deeper one.

Several studies have been carried out to evaluate the crustal structure and thickness in Egypt by using different types of datasets coming from seismic reflection surveys, deep seismic sounding, shallow refractions, and gravity (e.g., [34, 40 and 88-108]). In the delimitation of the different seismic zones, the most recent study [108] was taken into our consideration (Figure 4). Their results show that the Moho discontinuity is getting shallow toward the northern and eastern coast of Egypt, and deeper toward Western Desert and Northeastern Sinai. This discontinuity is located at depth of 31-33 km in Greater Cairo and Dahshour, 32-35 km in Sinai, 33–35 km along the Nile River, 30 km near the Red Sea coast, and 39 km towards the Western Desert.

## 5. Detailed description of the new proposed shallow-depth seismic source model

Seismic sources define areas that share common seismological, tectonic, and geologic attributes, and that can be described by a unique magnitude-frequency relation. In terms of PSHA, a seismic source represents a region of the earth's crust in which future seismicity is assumed to follow specified probability distributions for occurrences in time, earthquake sizes, and locations in space [109].

Araya and Der Kiureghian [109] discriminate between seismogenic and seismicity sources. Seismogenic zones lack the development of a clear history relating the contemporary seismic activity to a geologic structure. For such zones, critical gaps in the Quaternary geologic history preclude direct evidence of active faulting. Seismogenic zones are, by far, the most common type of source zone employed in PSHA. Commonly, seismogenic zones are area sources, but the zone type applies also to inferred associations of seismicity with individual faults. On the other hand, seismicity zones are source zones that are defined with no consideration of their relation to geologic structures. They are defined solely based on the spatial distributions of the seismic history, and their use and reasonableness can only be judged relative to the intended use of the final hazard estimate. This will be the terminology used in this work.

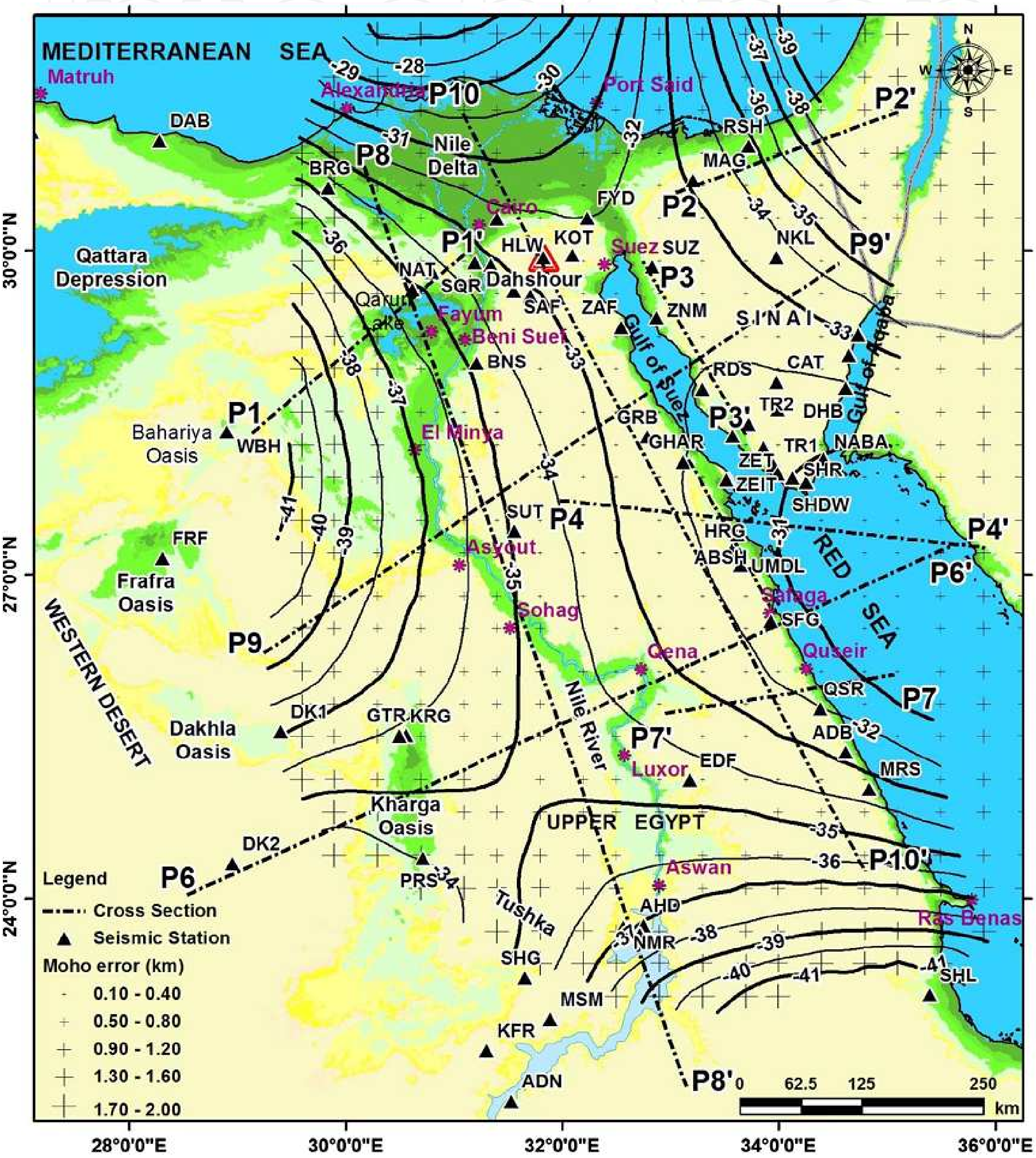


**Figure 4.** Depth of Moho discontinuity in Egypt (after Abdelwahed *et al.* [108]).

As mentioned previously, the separation of the study area into smaller, seismotectonically homogeneous zones is based on criteria mainly related with the present-day tectonic regime, epicenter distribution, focal mechanism data and the location of known faults. In the present work, we decided to employ simple geometric shapes for the definition of the seismic source model. The regional seismicity of concern to Egypt was divided into 28 seismic sources (Figure 5). These zones was related to the tectonic activity of the previously defined local active belts. Thus, the majority of the proposed sources zones can be considered seismogenic zones, except some sources which can be considered seismicity sources. The delineation of the seismicity sources was based upon the earthquake distribution, this is because there is no enough geologic and tectonic data covering these sources. Both seismogenic and seismicity sources are described below in more details. For each of these source zones, the seismicity parameters (b-value and activity rates) were computed by applying the Gutenberg-Richter [110] relationship and using the least square method considering the entire earthquake events within each zone. Moreover, maximum observed magnitude $M_{max}$ was defined using the earthquake sub-catalogue for each source. Those estimated values will serve as initial inputs for a seismic hazard assessment for Egypt in the near future.

The details of the selection of these seismic sources, together with the estimation of its seismicity parameters and maximum observed magnitude, are given below for each source category, which grouped depending on the similarities of the prevailed tectonic environment.

### 5.1. Seismic sources along the Gulf of Aqaba–Dead Sea Transform Fault

The Aqaba-Dead Sea Transform Fault (DST) is a 1100 km long left-lateral strike-slip fault (Figure 6) that accommodates the relative motion between Africa and Arabia [111, 112]. It is a seismically active transform boundary, connecting the Red Sea spreading center in the south to the Northern Mediterranean Triple Junction to the north. Its main left-lateral sense of motion is recognized by minor pull-aparts in young sediments [113], cut and offset of drainage lines and man-made structures (e.g., [114-121]).

The Gulf of Aqaba-Dead Sea Transform Fault (Figure 6) is subdivided into three parts; southern, central and northern [122]. The first part, which starts from the Gulf of Aqaba and passing through the Dead Sea and the Jordan Valley, is characterized by the occurrence of N12°E to N20°E left-lateral strike-slip faults. The second part of the DST is characterized by the occurrence of about 200 km long NNE–SSW restraining bend, where the DST branches into different faults. The major one, called the Yammouneh Fault, which connects the first and third parts of the DST, while the other faults connect the DST with the Palmyride Fold Belt (PFB) [122-124]. The last and the northern part of the DST is characterized by the occurrence of two different N–S striking faults surrounding the Ghab Valley and intersecting through a complex braided fault system with the East Anatolian Fault and the Cyprian Arc [125-127]. This intersection corresponds to the Hatay "fault–fault–trench" triple junction that forms the plate boundaries between Arabia, Africa and Anatolia [128].

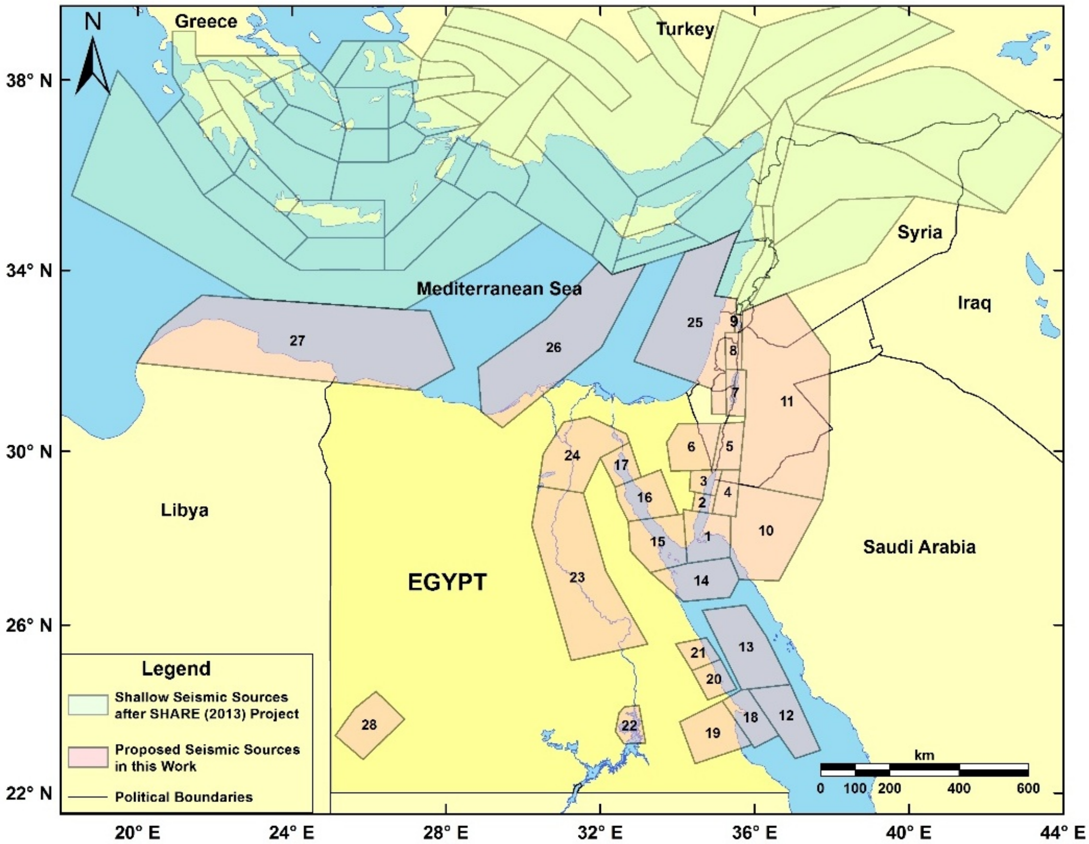


**Figure 5.** Proposed seismic source zones in Egypt and its surroundings.

*5.1.1. Gulf of Aqaba seismogenic sources (EG-01 till EG-04)*

The Gulf of Aqaba experienced the largest Egyptian earthquake ($M_W$ 7.2, November 1995) which struck the area and its effects were extending till Cairo. Over than 1000 aftershocks are recorded. The aftershocks area reached a length of about 110 km, striking N 30° E, which in turn parallel to the Gulf of Aqaba trend [129]. Potential damage was observed at Nuweiba city at the western part of the gulf.

The Gulf of Aqaba has been considered to be the most active seismic area over the last few decades, characterized by swarm activity [130-132]. There is no information about the seismicity of the Gulf of Aqaba until the year 1983. However, from January till April 1983, over than 500 events were reported, reaching a maximum recorded magnitude of 4.8. These earthquake events were felt at different places along the gulf area, as well as along the Arava Valley founding a general consideration [133]. From August 1993 up to February 1994, a large earthquake swarm was associated with relatively high magnitudes, reaching a 5.8 value. This swarm included about 1200 events occurred south to the 1983 swarm. Another earthquake swarm has been recorded and located at the central part of the Gulf of Aqaba on November 2002. Over than 10 events with magnitude above 4.0 were recognized, and many other events with magnitudes below this value. Some of these earthquakes were felt, but without damage for buildings at the epicentral area.

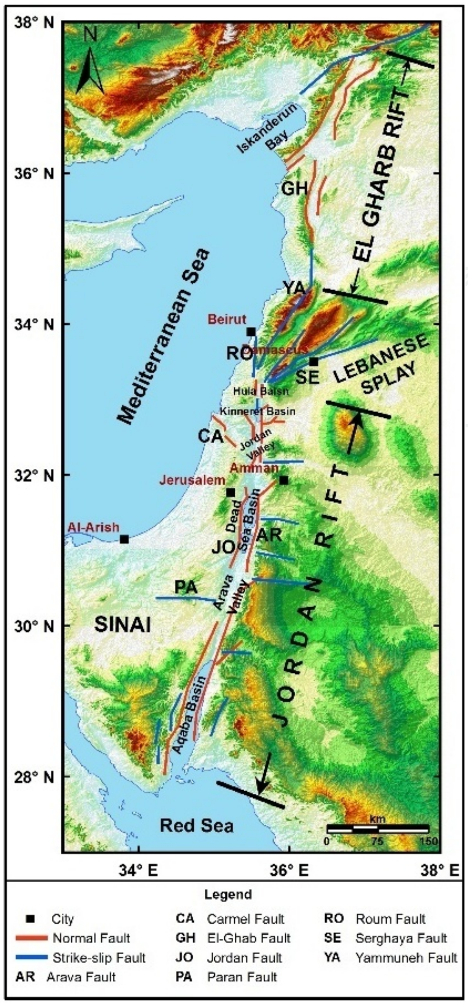


**Figure 6.** The main structural elements along the DST (redrawn after Heidbach and Ben-Avraham [134]).

The interior of the Gulf of Aqaba is occupied by three elongated en-echelon basins transected by longitudinal faults [131]. This en-echelon system produces several tectonic basins, which are forming rhombic-shaped grabens. Thus, three basins in the Gulf of Aqaba are present. They are, from south to north, Tiran “Arnona”-Dakar, Aragonese and Elat “Aqaba” Basins.

The heterogeneity of the focal mechanism solutions for the earthquake events taken place in the gulf area, indicates its geologic structure complexity. Some fault plane solutions exhibit normal faulting, which are related to the faults that form the boundaries of the major basins in the gulf. Others indicate left-lateral motion of the transform [112]. The focal mechanism of the $M_W$ 7.2, 1995 Aqaba earthquake as well as some aftershocks, show a strike-slip movement with predominant normal components, with the exception of only one solution located on the eastern coast of the Gulf of Aqaba, and exhibits strike-slip movement with a little reverse component in the NNW-SSE and ENE-WNW nodal planes [19].

According to the seismic activity, the epicentral distribution and the local tectonics, different seismogenic sources were delineated in the gulf area (Figure 7).

**a.** The EG-01 (Tiran – Dakar Basin) seismogenic source lies at the southern part of the Gulf of Aqaba. It includes the $M_S$ 4.4, February 2, 2006 earthquake. There is no historical earthquakes included in this source zone. The majority of the available focal mechanism solutions inside this area source reflects normal faulting mechanism.

**b.** The EG-02 (Aragonese Basin) seismogenic source lies to the north of the previous EG-01 zone, and is considered the focal area of the $M_W$ 7.2, November 22, 1995 earthquake, which is considered the largest event to occur along the DST in the last century.

**c.** The EG-03 (Elat Basin) seismogenic source located to the north of the EG-02 seismic zone and considered as the extension area of the $M_W$ 7.2, 1995 Aqaba earthquake rupture. It is characterized by a low seismicity level, if compared with the other two zones of the Gulf of Aqaba. Two historical events have been included in this area source, the $I_{max}$ VIII, March 18, 1068, and the $I_{max}$ VIII-IX, May 2, 1212 earthquakes.

**d.** In addition to the previous seismogenic sources, a delineation of a separate and fourth zone is taken place. This source lies to the east of the gulf and characterized by dispersed moderate seismicity. This zone is the EG-04 (Eastern Gulf of Aqaba) seismogenic source. The major earthquake included in this area source is the $m_b$ 4.5 December 26, 1995 earthquake.

Previous focal mechanism solution studies for moderate to large earthquakes located in the Gulf of Aqaba region (e.g., [135-138]) assert the dominance of ENE-WSW extension (N60°-80°E). Furthermore, field studies [139, 140] observed two conjugate faults along the Gulf of Aqaba: NNE left-lateral strike-slip faults parallel to the gulf that release the majority of stress, and a nearly ESE-WNW normal faults along the margins of pull-apart basins. On the other hand, body waveform inversion of the $M_W$ 6.1, August 3, 1993, and the $M_W$ 7.2 November 22, 1995 events, support the occurrence of normal faulting take place along the transverse NNW-SSE and ESE-WNW faults, while left-lateral strike-slip movement occurs along NNE major Aqaba trend [135].

#### *5.1.2. Arava Valley (EG-05) seismogenic source*

The Arava Valley is located to the north of the Gulf of Aqaba. It is an inter-basin zone trending NE-SW. Its faults extend over 160 km from the Gulf of Aqaba to the Dead Sea and provide morphological evidence of essentially strike-slip motion [120]. It is characterized by a low seismicity level compared with the surrounding area, despite clear indications of recent faulting [141]. Klinger *et al.* [120] emphasized the limited earthquake activity in the Arava Valley in the instrumental period. Shapira and Jarradat [133] stated that, from preliminary paleoseismicity studies, the border-faults of Arava Valley generate earthquakes bigger than magnitude 6.0 with an average return period of 1000-3000 years.

There is no historical earthquakes included in this seismogenic source zone. The biggest recorded event is the $m_b$ 5.2, December 18, 1956 earthquake. Two focal mechanism solutions are known in the northern part of this source, both of them exhibiting strike-slip faulting with normal component.

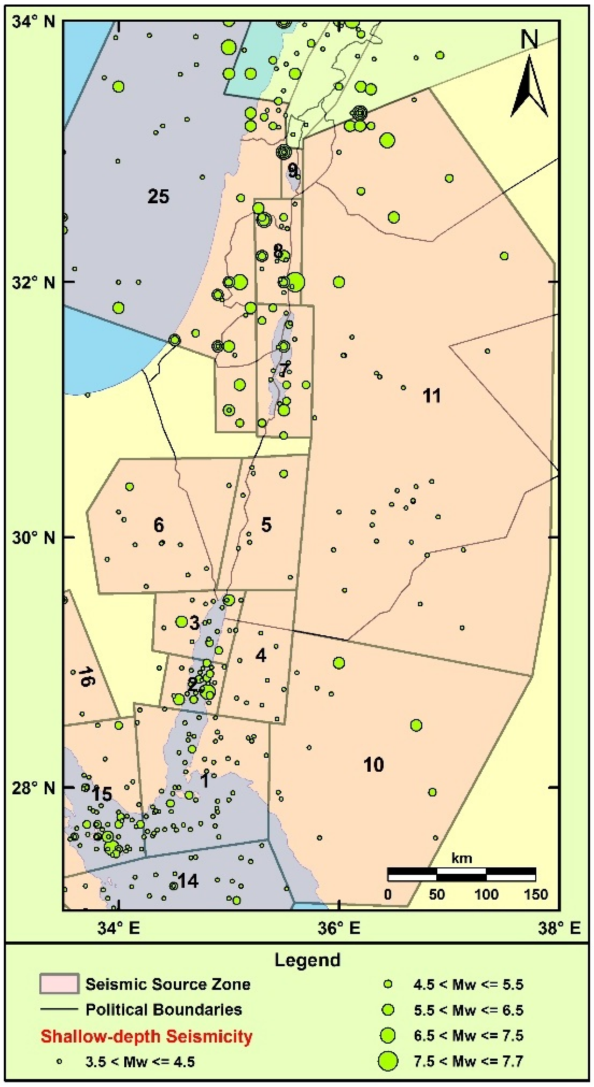


**Figure 7.** Shallow-depth seismicity (h ≤ 35 km) and delineated seismic sources along the Gulf of Aqaba-Dead Sea Transform Fault.

### *5.1.3. Eastern Central Sinai (EG-06) seismogenic source*

An E-W trending dextral strike-slip faults with up to 2.5 km of displacement has been recognized in central Sinai by Steintz *et al.* [142]. It is called the Themed Fault. The Tih Plateau (in central Sinai) is traversed by the Themed Fault, which extends for about 200 km from the vicinity of eastern margin of the Suez Rift to the DST [71]. The Themed Fault has been reactivated along a pre-existing fault, identifying the southern border of the Early Mesozoic passive continental margin of the Eastern Mediterranean Basin in central Sinai [143].

To the north of the previous fault, the central Sinai-Negav shear zone is located, which is proposed by Shata [72] and Bartov [144]. It is a narrow E to ENE trending fault belt discriminating and separating the North Sinai Fold Belt (tectonically unstable area) from the Tih Plateau (tectonically stable area) in middle and Southern Sinai [145].

The EG-06 seismogenic source lies to the west of the previous EG-05 source and to the east of the Sinai sub-Plate. This seismogenic source includes the low seismic activity related to the Themed Fault, central Sinai-Negav shear zone, Paran Fault and Baraq/Paran Fault junction. This source has a great tectonic effect on Sinai Peninsula and its surrounding areas. There is no historical earthquakes included in this source, and the biggest earthquake located in this zone is the $m_b$ 4.8, September 24, 1927 event.

*5.1.4. Dead Sea Basin (EG-07) seismogenic source*

The Dead Sea Basin is characterized by a double fault system that is bounded by the Arava Fault from the east, and by the Jordan (Jericho) Fault from the west, hence it occupies a rhomb-shaped graben between two left-lateral slip faults. The average slip rate on the Dead Sea portion of the transform fault is estimated to be 0.7 cm/yr. [114], which is consistent with the average slip of the overall plate boundary of 0.7-1.0 cm/yr.

Earthquake swarms and a mainshock-aftershock type of activity characterize this seismogenic source. Trenching studies across the Jordan Fault indicate that two large earthquake swarms occurred since about 2000 years ago. One of them is between 200 B.C.- 200 A.D., while the other one is between 700 A.D.- 900 A.D. [114]. El-Isa *et al.* [146] attributes these swarms to subsurface magmatic activity and/or to the isostatic adjustments along the Gulf of Aqaba.

Several historical earthquakes are included inside this source zone. They are the 745 B.C., 33 A.D., 1048, 1212, 1293, and 1458 earthquakes. Their intensities range between VII to VIII. Ben-Menahem *et al.* [147] obtained focal mechanism solutions for some recent events (e.g., the $M_S$ 4.9, October 8, 1970 earthquake) which took place in the Dead Sea area. All solutions indicate a left-lateral strike-slip movement on a sub-vertical fault striking with an average trend of N8°-10°E. However, Salamon *et al.* [112] obtained normal focal mechanism solutions for some relatively recent events. These solutions may be describe the earthquake activity of the N-S striking normal faults bordering the Dead Sea Basin. Field observations confirmed this type of activity [113, 148].

*5.1.5. Jordan Valley (EG-08) seismogenic source*

The Jordan Valley trends in the N-S direction, linking between the Hula Basin to the north and the Dead Sea Basin to the south. The details about its end in the Sea of Galilee are not clear from the surface features [147]. Garfunkel *et al.* [113] noticed a small amount of compression along the valley and near the Jordan Fault trace. Recent earthquake activity along the Jordan Valley is low compared to the Southern Dead Sea Basin. Ten historical events (before 1900) are included in this area source. They are the 1020 B.C., 578 A.D., 580, 746, 854, 1034, 1105, 1160, 1260, and 1287 events. Their intensities range between IV to XI. The most important earthquake included in this source zone is the $I_{max}$ XI, 746 event.

*5.1.6. Kineret-Hula Basin (EG-09) seismogenic source*

To the north of the previous Jordan Valley source are located the Hula (Shamir-Almagor Fault) and Kineret (Kineret-Sheikh Ali Fault) Basins [149]. Seismic activity in the two mentioned basins was located till the Yammuneh Fault (NE-bend of the Dead Sea Transform). This area source, which surrounded by the Roum Fault from the western side and the Jordan Fault from the eastern side, was considered by Shamir *et al.* [150] as a seismogenic step zone. Three historical events are included in this zone. They are the 19 A.D., 419, and 756 earthquakes. The biggest earthquake is the $I_{max}$ X, 19 A.D. event.

*5.1.7. Northwestern Saudi Arabia (EG-10) seismicity source*

To the east of the EG-01 and EG-02 seismogenic sources, the Northwestern Saudi Arabia EG-10 source has been considered. This source zone covers disperse, low seismicity in the north-western part of Saudi Arabia. Two historical events are reported to occur inside this area source. They are the March 18, 1068, and January 4, 1588 earthquakes, both of them with intensity VIII.

*5.1.8. Lebanon (EG-11) seismicity source*

To the north of the previous seismic source and along the eastern boundaries of the EG-04, EG-05, EG-07, EG-08, and EG-09 sources, the Lebanon EG-11 seismicity source has been considered. This area source covers a dense disperse low-magnitude seismicity in Lebanon and Southern Syria. Nine historical earthquakes are located inside this area source. The most important among them are the 972, 1159, and 1182 events. Their felt intensities are $I_{max}$ IX, IX-X, and IX, respectively.

The computed b-value, the annual rate of earthquakes, and the observed recorded maximum magnitude for the delineated seismic sources along the Gulf of Aqaba-Dead Sea Transform Fault are displayed in Table 1.

| Source Zone | b-value | Yearly Number of Earthquakes | | Observed $M_{max}$ |
|---|---|---|---|---|
| | | Above $M_W$ 4.0 | Above $M_W$ 5.0 | |
| EG-01 | 1.13 | 0.9799 | 0.0732 | $m_b$ 4.4 on 2006/02/02 |
| EG-02 | 0.98 | 0.4952 | 0.0521 | $M_W$ 7.2 on 1995/11/22 |
| EG-03 | 0.97 | 0.2763 | 0.0296 | $I_{max}$ VIII-IX on 1212/05/02 |
| EG-04 | 1.01 | 0.1961 | 0.0191 | $m_b$ 4.5 on 1995/12/26 |
| EG-05 | 0.88 | 0.1882 | 0.0251 | $m_b$ 5.2 on 1956/12/18 |
| EG-06 | 1.12 | 0.1853 | 0.0140 | $m_b$ 4.8 on 1927/09/24 |
| EG-07 | 0.87 | 0.3232 | 0.0438 | $I_{max}$ VIII on 1458/11/12* |
| EG-08 | 0.71 | 0.1865 | 0.0366 | $I_{max}$ XI on 0746/--/-- |
| EG-09 | 0.91 | 0.0651 | 0.0080 | $I_{max}$ X on 0019/--/-- |
| EG-10 | 1.03 | 0.1934 | 0.0180 | $I_{max}$ VIII on 1588/01/04* |
| EG-11 | 0.97 | 0.3645 | 0.0388 | $I_{max}$ IX-X on 1159/06/06 |

(*) the most recent event.

**Table 1.** b-value, annual rate of earthquakes, and maximum observed magnitude for the delineated seismic source zones along the Gulf of Aqaba-Dead Sea Transform Fault.

### 5.2. Seismic sources along the Red Sea Rift

The Arabian Plate is continuing to rotate away from the African Plate along the Red Sea Rift spreading center. The Red Sea occupies a long and slightly sinuous NW-trending escarpment-bound basin, 250-450 km wide and 1900 km long, between the uplifted shoulders of the African and Arabian shields. It is part of a rift system extending from the Gulf of Aden to the northern end of the Gulf of Suez. The overall trend of the rift is N30˚W, although a few kinks occur at around 15˚N, 18˚N, and 22˚N.

Depending on the structural setting and morphology of the Red Sea, it can be subdivided into four different zones (Figure 8). Each zone are representing distinct stage in the development of the continental margin and the generation of the mid-ocean ridge spreading system [151, 152]. These zones are:

**i.** *Active sea-floor spreading (Southern Red Sea):* It is located between 15°N and 20°N and characterized by a well-developed axial trough which has developed through normal sea-floor spreading during the last 5 Ma [153-155] or even older, at about 9–12 Ma [156].

**ii.** *Transition zone (central Red Sea):* It is located between 20°N to about 23°20′N, where the axial trough becomes discontinuous, in which the central Red Sea consists of a series of 'deeps' alternating with shallow 'inter-trough zones' [157]. An identical zone may flanks the deep axial trough between the side walls of the shallow main trough on both sides of other zones [151, 152].

**iii.** *Late stage continental rifting (Northern Red Sea):* This zone composed of a wide trough without a distinct spreading center, in spite of a number of small isolated "deeps" is occurred [152].

**iv.** *Active rifting:* This zone representing the expected line along which the Southern Red Sea may be propagate through the Danakil Depression Afar. This zone may be considered separately or it can be added to the first mentioned zone.

Based on the morphological and structural features of the Red Sea, the Egyptian part (northern latitude 22°N) can be divided into three distinct seismogenic source zones (EG-12, EG-13, and EG-14) (Figure 9). Each zone represents different stage of development [159]. The delineation is made, based upon the occurrence of the transverse structures, change of the fault trend along the axial rift and the variety of the seismic activity along the rift axis.

#### *5.2.1. Southern Red Sea (EG-12) seismogenic source*

The EG-12 Southern Egyptian Red Sea seismogenic source represents the northern part of the transition zone. It is characterized by NW-SE trending faults. The boundary proposed by Bonati [160], north latitude 25ºN, is found herein to coincide with the NE-trending transform faults and the associated seismicity. Only one historical event is included in this seismic source, the $I_{max}$ VI-VII, 1121 earthquake.


**Figure 8.** Tectonic framework of the Red Sea region (redrawn after Ghebreab [158]).

*5.2.2. Central Red Sea (EG-13) seismogenic source*

The EG-13 Central Egyptian Red Sea seismogenic source is located to the northwest of the previous zone. It corresponds to the region north of latitude 24º30′N, which consists of a broad main trough without a recognizable spreading center [152]. Recent recorded seismicity could indicate the expected location of the axial rift. In this zone, the degree of seismicity is relatively low and scattered, compared to the previous zone. Like the previous zone, there is only one historical event included here. It is the $I_{max}$ V, 1899 earthquake. The maximum observed magnitude along this source corresponds to the $m_b$ 4.7 ($M_S$ 5.1), July 30, 2006 earthquake.

*5.2.3. Northern Red Sea (EG-14) seismogenic source*

The EG-14 Northern Egyptian Red Sea seismogenic source is characterized by higher seismic activity than the previous two sources. This activity may be due to the juncture between the two gulfs. Daggett *et al.* [161] studies of the low-magnitude seismicity shows that, the high seismic activity of the northern Red Sea is different from the activity at the southern part of the Gulf of Suez. There is no earthquakes related to this area source before the year 1900. In addition, the $m_b$ 5.0 ($M_S$ 5.0) March 22, 1952 event represents the biggest recorded earthquake till now.

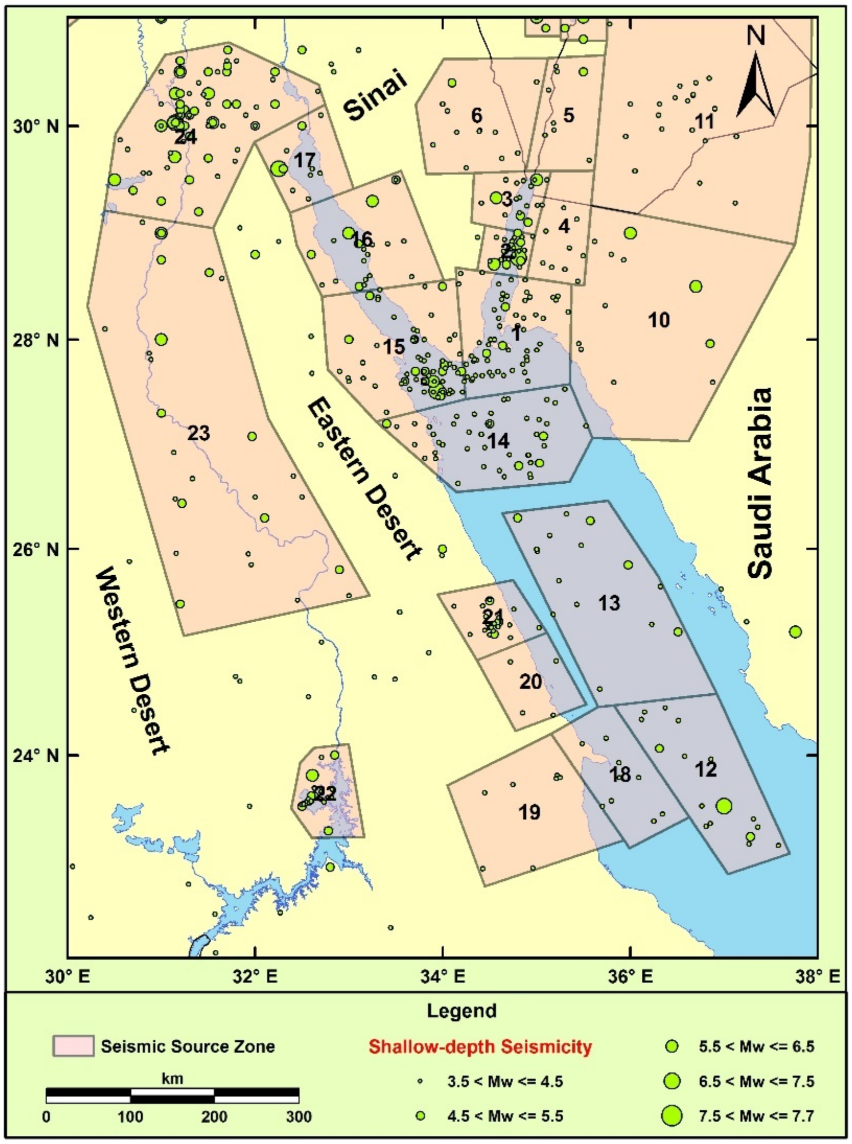


**Figure 9.** Shallow-depth seismicity (h ≤ 35 km) and delineated seismic sources along the Red Sea-Gulf of Suez and the Nile River.

Seismicity parameters for the delineated seismic sources along the Red Sea Rift are displayed in Table 2.

| Source Zone | b-value | Yearly Number of Earthquakes | | Observed $M_{max}$ |
|---|---|---|---|---|
| | | Above $M_W$ 4.0 | Above $M_W$ 5.0 | |
| EG-12 | 1.00 | 0.4359 | 0.0434 | $I_{max}$ VI-VII on 1121/--/-- |
| EG-13 | 0.91 | 0.3029 | 0.0376 | $m_b$ 4.7 on 2006/07/30 |
| EG-14 | 1.13 | 0.6425 | 0.0472 | $m_b$ 5.0 on 1952/03/22 |

**Table 2.** b-value, annual rate of earthquakes, and maximum observed magnitude for the delineated seismic source zones along the Red Sea Rift.

### 5.3. Seismic sources along the Gulf of Suez

The Gulf of Suez is considered to be the plate boundary between the African Plate and Sinai sub-Plate [162]. It extends along a NW trend from latitude 27°30′ N to 30°N. The Gulf of Suez constitutes the northern part of the Red Sea Rift System. It was developed, together with the Red Sea and the Gulf of Aqaba, as one of the three arms of the Sinai Triple Junction [69, 81 and 163-166].

The Gulf of Suez has been interpreted as being a complex half-graben system [139], or an asymmetric graben [167]. It is composed of three successive half-grabens, as mentioned by Moustafa [168], with opposite tilt directions: northern, central, and southern. These distinct half-grabens include several rift blocks of a uniform dip direction. The dip direction, along the Gulf of Suez Rift, changes from the north to the south as: SW to NE and again to SW defining the three half-grabens, respectively.

Two-accommodation zones [169] coexist among these half-grabens which extend transversely across the rift (Figure 10). These are the Galala-Zenima [168] or Gharandal [167] accommodation zone, of broad extension (about 60 km wide) in the north, and the Morgan [168] or Sufr El Dara [170] accommodation zone (20 km wide) in the south. Both zones exhibit a broad range of deformation, including distinct normal, oblique, or strike-slip faults [171], or wide complex zones of normal faulting, trans-tension [172-174] or broad warping [175].

The Gulf of Suez is considered to be an aseismic area during the first half of the last century and this consideration let some researchers (e.g., [176, 177]) to conclude that all the present motion taking place in the Red Sea Rift is transferred into shearing along the DST. Ben-Menahem [178] and Salamon *et al.* [111] studied the seismic activity of the Suez Rift. Fault plane solutions of the $m_b$ 6.1, March 31, 1969 earthquake and other low-magnitude events show that the Gulf of Suez Rift is active which agree with Ben-Menahem and Aboodi [179] results. Considering the tectonic setting, seismicity and earthquake faulting mechanisms, the Gulf of Suez can be divided into three seismogenic sources (Figure 9) as follow.

#### *5.3.1. Southern Gulf of Suez (EG-15) seismogenic source*

The EG-15 Southern Gulf of Suez seismogenic source is distinguished by intensive structural deformation. It is characterized by its relatively high seismic activity. The higher seismicity rate at the southern part of the Gulf of Suez is related to the crustal movements among the three surrounding plates: Arabian Plate, African Plate, and Sinai sub-Plate. Six historical events are included in this zone. Those are 28 B.C., 955, 1091, 1195, 1778, and 1839 events. Their intensities range from VI-VII to VIII. The most important event occurred inside this area source is the $M_W$ 6.8, March 31, 1969 Shedwan earthquake [16, 181]. Three foreshocks and 17 aftershocks ($m_b$ 4.5-5.2) located in the Shedwan Island district are related to this big event. However, Maamoun and El-Khashab [182] mentioned that 35 foreshocks, taken place during the last half of March 1969, were preceding the main earthquake. The focal mechanism solutions of the largest two earthquakes ($M_W$ 6.8, March 31, 1969 and $M_W$ 5.5, June 28, 1972 earthquakes) show a normal faulting mechanisms with negligible shear component along the NW-trending fault plane that it is in agreement with the main axis of the Gulf of Suez [183]. This is also consistent

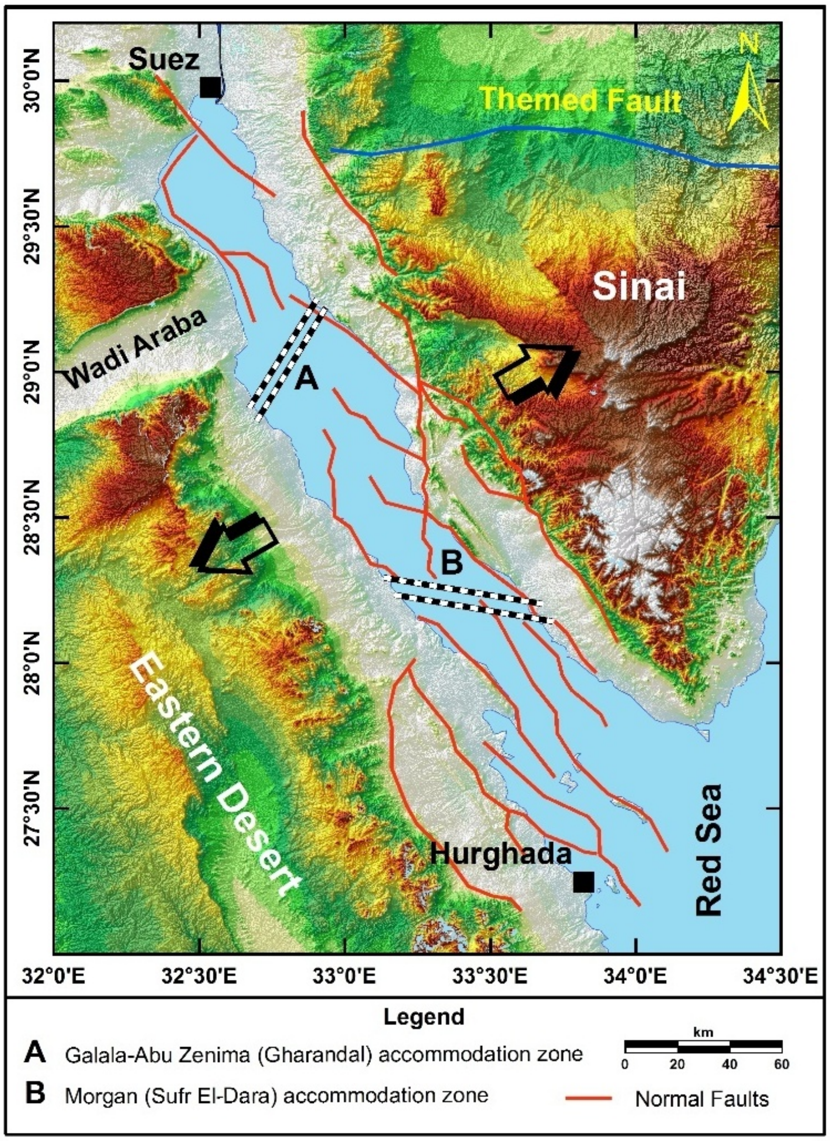


**Figure 10.** Tectonic setting of the Gulf of Suez. Red lines refer to normal faults (redrawn after Meshref [11]; and Younes and McClay [180]).

with the results obtained using the waveform inversion techniques proposed by Huang and Solomon [184].

*5.3.2. Central Gulf of Suez (EG-16) seismogenic source*

The seismic activity in the EG-16 Central Gulf of Suez seismogenic source is relatively low when compared with the previous source. Five historical events are included in this source zone: the 1220 B.C., 1425, 1710, 1814, and 1879 earthquakes. Its intensities range from IV to VII. The most important earthquake inside this area was the $M_S$ 6.2 March 6, 1900 event.

Abou Elenean [20] computed some focal mechanism solutions for earthquakes which taken place in the central part of the gulf, showing generally normal faulting, following the main gulf trend. A few of these events show slight strike-slip component, especially for those events closer to the transfer zones of the three gulf dip provinces [11]. This change, from a purely normal faulting in the southern part to a mixed (strike-slip and normal) movement, supports the separation between the southern and middle seismogenic zones in the Gulf of Suez.

#### *5.3.3. Northern Gulf of Suez (EG-17) seismogenic source*

Finally, the EG-17 Northern Gulf of Suez seismogenic source is characterized by its low seismic activity. Two large earthquakes occurred before the year 1900. They are the $I_{max}$ VI, 742, and $I_{max}$ V, 1754 earthquakes. Focal mechanism analyses for this seismogenic zone indicate normal faulting mechanism. Fault plane solutions by Abou Elenean [20] showed that the events located at the gulf apex show normal faults, generally trending NW-SE to WNW-ESE, and reflect a good agreement with the surface faults crossing the Eastern Desert from the gulf apex towards Cairo.

Abou Elenean [20] concluded that the focal mechanisms of small to moderate size earthquakes based on the P-wave polarities by Badway and Horváth [185-187], Badawy [188] and Salamon *et al.* [112], show the existence of few thrust faulting mechanisms along the Gulf of Suez trend. The author argues that these unexpected mechanisms could be due to the lack of local stations with clear polarities at that time. On the other hand, borehole breakouts analyses performed by Badawy [188] show a different stress direction, inconsistent with the NE-SW tension direction estimated from earthquake focal mechanisms.

Seismicity parameters for the delineated seismic sources along the Gulf of Suez are displayed in Table 3.

| Source Zone | b-value | Yearly Number of Earthquakes | | Observed $M_{max}$ |
|---|---|---|---|---|
| | | Above $M_W$ 4.0 | Above $M_W$ 5.0 | |
| EG-15 | 1.06 | 0.8347 | 0.0721 | $M_W$ 6.8 on 1969/03/31 |
| EG-16 | 0.80 | 0.3085 | 0.0488 | $M_S$ 6.2 on 1900/03/06 |
| EG-17 | 0.86 | 0.1381 | 0.0190 | $M_S$ 6.6 on 1754/--/-- |

**Table 3.** b-value, annual rate of earthquakes, and maximum observed magnitude for the delineated seismic source zones along the Gulf of Suez.

### 5.4. Seismic sources of the Egyptian Eastern Desert

The Eastern Desert of Egypt, structurally, is a part of the Arabian-Nubian Shield. It lies within the fold and thrust belt of the Pan-African continental margin [189]. It is underlain mainly by the Pre-Cambrian basement of igneous and metamorphic rocks, which constitutes the Nubian Shield that had been formed before the Red Sea opening. It is believed that Nubian Shield basement was stabilized during the Pan-African Orogeny (about 570 Ma ago) [190].

Stern and Hedge [191] divided the Eastern Desert belt into three structural domains (Figure 2): northern, central and southern. These domains are separated by two major faults: i) the first is the Safaga-Qena zone, extending from Safaga to Qena, and ii) the second one is the Marsa Alam-Aswan fault zone. The Eastern Desert is characterized by E-W trending faults in the southern part, which changes to ENE-WSW in the middle one, near to Hurghada city. Further to the north, towards the Cairo-Suez District, the main fault trend becomes in the E-W direction.

However, Youssef [10] classified the main tectonic structures developed in the Eastern Desert into three main groups: i) NW-SE trending normal faults parallel to the Gulf of Suez-Red Sea Rift, ii) NE-SW trending faults parallel to the Gulf of Aqaba, and iii) a set of fault system trending nearly in the E-W direction. In addition, there are many simple and open folds with a NW-SE trend and low plunges.

Deif *et al.* [57] quote that the relationship between the earthquake activity in the Eastern Desert and the causal structures is not fully understood, due to the lack of geological and geophysical studies in this region. Furthermore, no historical earthquakes have been reported in the current seismogenic sources [17, 21]. The following seismogenic sources are identified (Figure 9).

*5.4.1. Western Red Sea Coast (EG-18) seismicity source*

In addition to the Red Sea seismogenic sources mentioned above, there are some earthquakes located in the region which extends to the west, from the EG-12 Southern Egyptian Red Sea source till the western coast of the Red Sea. This activity may be related to the block adjustment in this region or to some ocean floor spreading. This source is characterized by a low seismic activity. The biggest observed earthquake is the $M_L$ 4.5, May 23, 1990 earthquake.

*5.4.2. Southern Eastern Desert (EG-19) seismicity source*

This seismicity source exhibit a low seismic activity rate in comparison to the adjacent Red Sea seismic sources. There are no focal mechanism solutions for earthquake events inside this area source. The $M_L$ 4.4, July 15, 1991 earthquake is the biggest recorded event in this zone.

*5.4.3. Southern Abu Dabbab (EG-20) seismicity source*

Depending on both the changes in the seismicity rate and distribution, another seismicity source (EG-20) has been considered to the north of the previous zone. The same as the previous, there is no focal mechanism solutions in this source. The biggest recorded event is the $M_L$ 4.7, January 21, 1982 earthquake.

*5.4.4. Abu Dabbab (EG-21) seismicity source*

The Abu Dabbab region is located in the central part of the Eastern Desert of Egypt. The moderate level of seismic activity and extremely tight clustering of low-magnitude earthquakes at Abu Dabbab suggests that the seismicity in this area is not directly related to regional tectonics. One possible explanation is that the activity is related to magmatic intrusions into the Pre-Cambrian crust, but there is no direct evidence to support this hypothesis [161].

The most important event included inside this area source is the $M_S$ 5.3, November 12, 1955 earthquake. This event is felt in the Upper Egypt in Aswan and Qena cities, and as far as Cairo, but no damage was reported. Its focal mechanism solution has normal and strike-slip faulting components produced by a NNW minimum compressive stress and a NE maximum compressive stress. Fault planes strike roughly E-W or N-S to NE-SW. Another important event related to this area is the $M_W$ 5.1, July 2, 1984 earthquake, which is felt strongly in Aswan, Qena and Quseir cities. A large number of foreshocks and a huge sequence of aftershocks are recorded. The focal depth of the whole sequence was less than 12 km.

Seismicity parameters for the delineated seismic sources of the Eastern Desert of Egypt are displayed in Table 4.

| Source Zone | b-value | Yearly Number of Earthquakes | | Observed $M_{max}$ |
|---|---|---|---|---|
| | | Above $M_W$ 4.0 | Above $M_W$ 5.0 | |
| EG-18 | 1.29 | 0.1566 | 0.0080 | $M_L$ 4.5 on 1990/05/23 |
| EG-19 | 1.15 | 0.1182 | 0.0085 | $M_L$ 3.9 on 1991/07/15 |
| EG-20 | 1.20 | 0.0625 | 0.0039 | $M_L$ 4.7 on 1982/01/21 |
| EG-21 | 0.87 | 0.3714 | 0.0496 | $m_b$ 6.2 on 1955/11/12 |

**Table 4.** b-value, annual rate of earthquakes, and maximum observed magnitude for the delineated seismic source zones of the Eastern Desert.

### 5.5. Seismic sources along Nasser's Lake, Nile Valley and Cairo-Suez region

#### *5.5.1. Southern Aswan (EG-22) seismogenic source*

The geological structural pattern of the Nasser's Lake and Aswan region is characterized by a regional basement rock uplift and regional faulting [192-197]. Faults around the Aswan region, according to their behavior, are grouped into three categories [82]:

**i.** E-W trending faults (Figure 11), as the Kalabsha and Seiyal Faults, which lay to the west of Nasser's Lake. The Kalabsha Fault is about 185 km long right-lateral strike-slip fault. Its slip rate was estimated to be 0.028 mm/yr., and the Seiyal Fault is considered to be similar to that of the Kalabsha Fault [82].

**ii.** N-S trending faults (Figure 11), which can be subdivided into two main sets: *The first set* lies to the NW of Nasser's Lake and consists of three faults: the Gebel El-Barqa Fault, the Kurkur Fault and the Khur El-Ramla Fault. The Gebel El-Barqa is a left-lateral strike-slip fault, with a total length of 110 km. The Kurkur Fault is also a left-lateral strike-slip fault, and it is characterized by its low seismic activity if compared with the neighbor faults. The Khur El-Ramla Fault is about 36 km in length, and it has no direct indication of its sense of movement. *The second set* of faults are lying to the SW of Nasser's Lake, and consists mainly of two faults: the Abu Dirwa and the Ghazala Faults. Abu Dirwa Fault is a 20 km long left-lateral strike-slip fault and it has a very low degree of seismic activity. In addition, for the Gazelle Fault, the analysis of its geomorphic expression shows no active features, and that there is no ground cracks observed along the fault trace. Likely this fault is inactive [192]. The fault planes of this system are nearly vertical (80-85°).

**iii.** The third one is a fault system trending NNE-SSW (Figure 11) and lies to the east of Nasser's Lake. The Dabud Fault, which represents the main fault of this group, is about 36 km length. Geological evidences indicate reverse-slip, opposed to the tectonic setting of the area.

In addition to the previous fault systems, Deif [57] has mentioned three faults located at the High Dam area. They are the Powerhouse, the Spillway and the Channel Faults. Deif [57] provided that the evidence of the occurrence of these faults is hidden below the Aswan High Dam and Nasser's Lake. These three faults show no evidence of being active in the Quaternary, and are considered as inactive with no significant hazard to the Aswan region [82].

No historical earthquakes were reported by Ambraseys *et al.* [18] inside this area source. However, two historical events (epicentral intensity VII) were reported by Maamoun *et al.* [16] to be located at the same place of the $M_W$ 5.8, November 14, 1981 earthquake. These two events occurred in 1210 B.C. and in 1854.

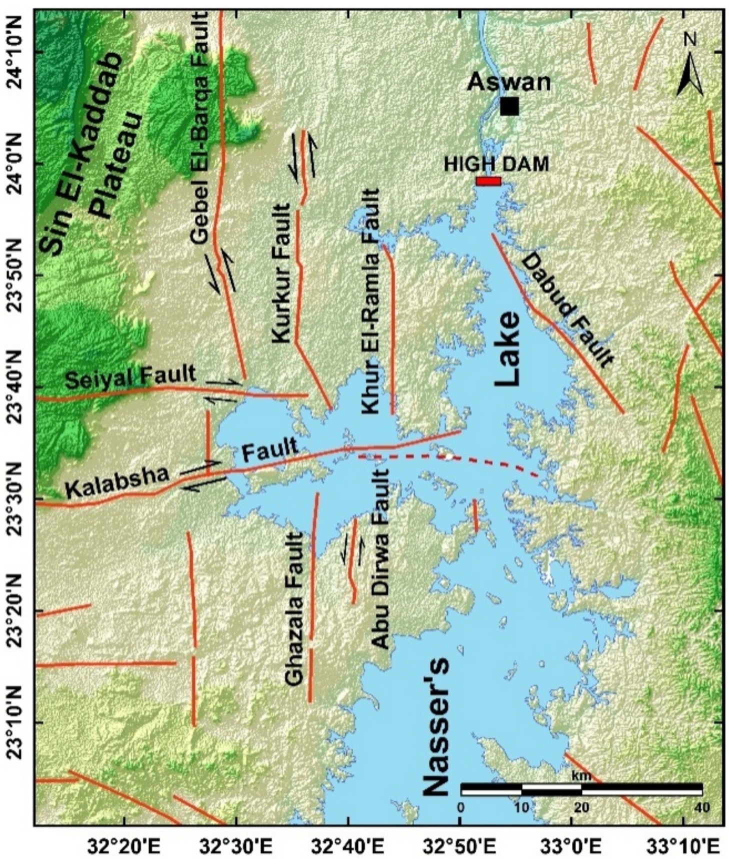


**Figure 11.** Geological and tectonic features around Nasser's Lake (redrawn after Woodward-Clyde Consultants [82]).

Woodward-Clyde Consultants [82] evaluated the fault system in the Kalabsha area and reported that the Western Desert Fault System consists of a set of E-W faults that exhibit dextral-slip displacement, and a set of N-S faults that exhibit sinistral-slip displacement. The E-W faults are longer, and have greater degree of activity in the Quaternary, having larger total slip rates (about 0.03 mm/yr.) than the N-S faults (0.01–0.02 mm/yr.).

Many seismic hazard studies have been carried out in the Aswan area and its surroundings due to its importance and neighborhood to the High Dam (e.g., [51, 57 and 58]). Three alternative seismotectonic models for Aswan area have been considered in these studies. The first model consider the Aswan Area as one seismotectonic model, while in the second one is subdivided into six seismotectonic provinces. The third model is mainly depending on the fault seismic sources. The latter one is based mainly on the well-known defined active faults and its associated seismic activities.

However, this work, the Aswan region and its surroundings is considered as one source zone (Figure 9). The main earthquake that took place inside this area was the $M_W$ 5.8, November 14, 1981 event. This earthquake occurred in the Nubian Desert of Aswan. It is of great significance because of its possible association with Nasser's Lake. Its effects were strongly felt up to Assiut city (440 km to the north from Kalabsha Fault), as well as to Khartoum city (870 km to the south). Several cracks on the western bank of the Nasser's Lake, and several rock-falls and minor cracks on the eastern bank, are reported. The largest of these cracks is about one meter in width and 20 km in length. This earthquake was preceded by three foreshocks and followed by a large number of aftershocks. The focal depth of this earthquake is estimated to be 25 km. The composite fault plane solution of this event indicates a nearly pure strike-slip faulting with a normal-fault component [49, 195].

*5.5.2. Luxor- Southern Beni Suef (EG-23) seismogenic source*

Several geophysical studies have been carried out by many authors using different approaches in individual localities lying along the Nile Valley. The most interesting geological studies in the Nile Valley are those carried out by Said [69-71], Issawi [78], Philobbos *et al.* [86], and El-Younsy *et al.* [196]. All these works were conducted independently and aimed to obtain information about the drainage system, the stratigraphy and structural geology in this part of Egypt.

The Nile Valley is a large elongated Oligo-Miocene rift, trending N-S as an echo of the Red Sea rifting. There is no agreement among scientists, till now, about the origin of the Nile Valley. Some authors [197, 198] supported the opinion of the erosional origin of the Nile Valley, while many others (e.g., [11, 12, 13, 17, 70 and 199]) consider the tectonic origin. This is supported by the fault scarps bordering the cliffs of the Nile Valley, the numerous faults recognized on its sides [70, 71 and 199] and the most recent focal mechanism solutions. Furthermore, geological studies of the Nile Valley show that, it occupies the marginal area between two main tectonic blocks (the Eastern Desert and the Neogene-Quaternary platform), which in turn behaves as a barrier that prevents the further extension of the East African Orogenic Belt activity to the west [71].

From the structural point of view, the faults and joints are the most deformational features observed at the cliffs bordering the Nile stream [69 and 70]. These faults have different directions (Figure 2). The most abundant present the NW-SE and NNW-SSE trends, while others (less abundant) exhibit the WNW-ESE, ENE-WSW and NE-SW directions. Most of the major valleys, at the east of the Nile River, are generated and controlled in a more or less degree by these faults.

To the north of Aswan area, in the region between Luxor and Southern Beni Suef, along the Nile River, there is a low seismicity level, which coincides with the main trend of the Nile River. This active area has been considered as a separate seismogenic source. Several historical earthquakes are reported to occur along the Nile River in this area source that may be due to the high population density along the Nile River in the ancient times. These earthquakes are the 600 B.C., 27 B.C., 857, 967, 997, 1264, 1299, 1694, 1778, and 1850 events. Their intensities range from V to VIII. Focal mechanism solutions exhibit reverse faulting mechanism to the west of the Nile River, in the area between Luxor and Assiut. However, normal faulting mechanism with strike-slip component appears to the north of Assiut till Beni Suef city.

*5.5.3. Beni Suef – Cairo – Suez District (EG-24) seismogenic source*

To the north of the previous zone and to the west of the Gulf of Suez, there is a moderate seismic activity between Beni Suef and Cairo, on the River Nile, till Suez, on the apex of the Gulf of Suez (Figure 9). Three fault trends are affecting the Cairo-Suez district: the first one is trending E-W, which aligned by latitude 30°N, and it is very dominant, while the other two (ENE and NW) are spatially more abundant [200]. The faults are predominantly normal, and have produced a series of fault blocks with a large strike-slip component [200].

Field observations, satellite images, aerial photographs and seismic profiles confirm that the region between Cairo and Suez is active from a tectonic point of view. Seismic activity are noticed along this belt at Wadi Hagul and Abu Hammad. However, the earthquake distribution in this area is very scattered, and cannot be attributed to a specific known fault. This disperse seismicity yields a difficulty in delineating seismic zones. It is assumed that the seismic potential is uniform throughout the zone, although this is not entirely clear.

Sixty one historical earthquakes are related to this area source. The most important among them are the 935, 1111, 1259, 1262, 1303, and 1588 events. Moreover, the most important instrumental earthquake taken place in this source is the $M_W$ 5.8, October 12, 1992 event. Its epicenter was located about 40 km south of Cairo, in Dahshour. It caused a disproportional damage (estimated at more than L.E. 500 million) and the loss of many lives. The shock was strongly felt, and caused sporadic damage and life loss in the Nile Delta, around Zagazig. Damage was extended to reach Fayoum, Beni Suef and Minia cities. The mostly affected area was Cairo, especially its old sections, Bulaq and the southern region, along the western bank of the Nile to Gerza (Jirza) and El-Rouda. In all, 350 buildings collapsed completely and 9000 were irreparably damaged, killing 545 persons and injuring 6512. Most causalities in Cairo were victims of the horrible stampedes of students rushing out from schools. Approximately, 350 schools and 216 mosques were destroyed and there was about 50000 homeless.

Abdel Tawab *et al.* [201] studied the surface tectonic features of the area around Dahshour and Kom El-Hawa, and found a major N55°E trending normal fault at Kom El-Hawa (800 m length of surface trace with a vertical displacement of 40 cm) and a major E-W trending open fracture at Dahshour area (1200 m in length). Maamoun *et al.* [202] concluded that, most of the surface lineaments recorded after the occurrence of the main shocks are trending E-W to NW-SE. Abou Elenean [19] studied the focal mechanism solutions for some earthquakes in Dahshour area, and found normal faulting with a large strike-slip component. The first nodal plane is trending nearly E-W, showing coincidence with the surface lineaments that appeared directly after the occurrence of the $M_S$ 5.9, 1992 earthquake.

In addition to the previous earthquake, there were three important earthquakes located inside this source zone. One of them located to the southwest of Suez, is the $m_b$ 4.9 ($M_S$ 4.8), March 29, 1984 Wadi Hagul earthquake. It was strongly felt in Suez, Ismailia and Cairo. A large number of aftershocks were recorded by nearby temporary stations. The second earthquake was located Northeast Cairo; it is the $m_b$ 4.8, April 29, 1974 Abu Hammad earthquake. It was strongly felt in Lower Egypt (Nile Delta) and Southwest Israel. The last earthquake was the $m_b$ 5.0, January 2, 1987 Ismailia event.

Mousa [203] and Hassib [204] computed two nodal planes trending ENE-WSW and NNW-SSE, with left-lateral strike-slip motion along the second plane, for the Abu Hammad event. They computed the same strike-slip with reverse component for the Wadi-Hagul earthquake. In addition, the mechanism of the Ismailia earthquake shows also strike-slip movement with two nodal planes trending N68° E and S24°E, with steep dip angles (each of them is 80°) [205].

The seismicity parameters for the delineated seismic sources along the Nile River are displayed in Table 5.

| Source Zone | b-value | Yearly Number of Earthquakes | | Observed $M_{max}$ |
|---|---|---|---|---|
| | | Above $M_W$ 4.0 | Above $M_W$ 5.0 | |
| EG-22 | 0.79 | 0.5860 | 0.0946 | $M_W$ 5.8 on 1981/11/14 |
| EG-23 | 0.73 | 0.2948 | 0.0549 | $I_{max}$ VIII on 0857/04/-- |
| EG-24 | 0.99 | 0.5964 | 0.0608 | $I_{max}$ IX-X on 1262/--/-- |

**Table 5.** b-value, annual rate of earthquakes, and maximum observed magnitude for the delineated seismic source zones along the Nile River.

### 5.6. Seismic sources along the Mediterranean Coastal Line

The Mediterranean Coastal area is characterized by small to moderate seismicity. This area is located at the southeastern part of the Mediterranean Sea. It separates between the high seismic activities along the Gulf of Aqaba-Dead Sea Transform Fault and the seismicity of the Mediterranean Sea (Hellenic and Cyprian Arcs). Moreover, it separates the Southern Cyprus seismic activity from the Northern Egypt activity. Hence, this area has been divided into three seismic sources (Figure 12), based mainly on the available focal mechanism data and the seismic activity.

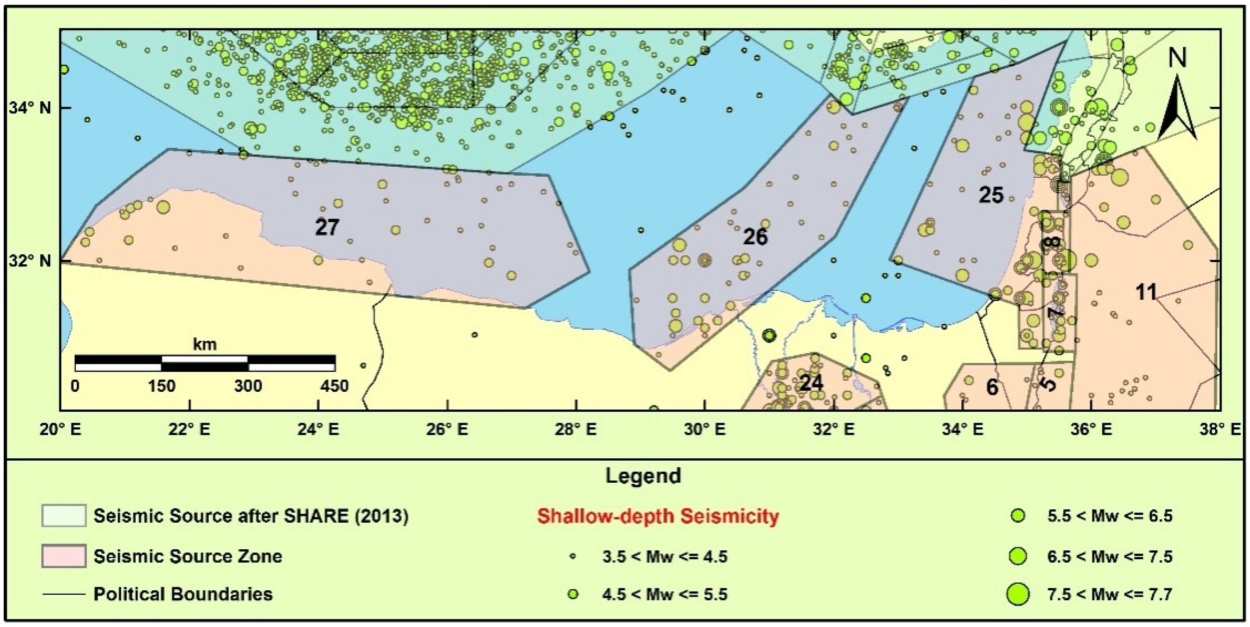


**Figure 12.** Shallow-depth seismicity (h ≤ 35 km) and seismic source zones delineated for the Mediterranean coastal line.

*5.6.1. Eastern Mediterranean Coast (EG-25) seismicity source*

This area source is parallel to the eastern coastal line of the Mediterranean Sea. It is located to the west of the previous quoted sources EG-07, EG-08, and EG-09, and to the southeast of Cyprus. It includes all the seismicity located to the west of the DST, and those earthquakes are not related with the Cyprian Arc. 29 historical events are included inside this area source. The most important among them are the 590 B.C., 525 B.C., 12 B.C., 306, 332, 551, 1269, and 1546 earthquakes.

*5.6.2. Northern Delta (EG-26) seismicity source*

This source is located to the northwest of the Nile Delta region. It extends from Alexandria towards the Mediterranean Sea in NE direction. 23 historical events are included inside this large area source, among them the 796, 951, 955, 956, 1303, 1341, and 1375 earthquakes. Moreover, the $m_b$ 6.5 ($M_S$ 6.8), September 12, 1955 Alexandria earthquake, represents the most important recorded event inside this source. This earthquake was felt in the entire Eastern Mediterranean Basin. In Egypt, it was strongly felt, and led to the loss of 22 lives and damage in the Nile Delta, between Alexandria and Cairo [17]. The destruction of more than 300 buildings of old brick construction was reported in Rosetta, Idku, Damanhour, Mohmoudya and Abu-Hommos. A maximum intensity of VII was assigned to a limited area in Behira province, where 5 people killed and 41 were injured.

Mostly of the focal mechanism data inside this area source reflects reverse faulting mechanism with, sometimes, strike-slip component, except one event, showing a strike-slip motion with a notable normal component (the $M_W$ 4.5, April 9, 1987 event).

http://dx.doi.org/10.5772/58971

*5.6.3. Western Mediterranean Coast (EG-27) seismicity source*

The Western Egyptian Mediterranean Coastal zone is located to the north of the Egyptian-Libyan boundary. Only two historical events are reported inside this source: the $I_{max}$ VIII, 262, and $I_{max}$ VI, 1537 earthquakes. However, the most important recorded earthquake is the $M_W$ 5.5, May 28, 1998 Ras El-Hekma event. This earthquake is widely felt in Northern Egypt. Intensity of VII is assigned at Ras El- Hekma village (~300 km west of Alexandria), and an intensity of V–VI at Alexandria city [206]. Ground fissures trending NW–SE were observed along the beach. Some cracks were also observed in concrete buildings. Furthermore, some people left their houses. The windows rattled and hanging objects swung, but the direction of the ground motion was poorly identified [206].

Recent studies concerning the crustal structure and focal mechanism of the $M_W$ 5.5, May 28, 1998 Ras El-Hekma earthquake suggested that this source is an extension of the compressional stress from the Hellenic Arc. This compressional stress reactivated the old Triassic normal faults as reverse faults, or reverse faults with strike-slip component. This activity coincides with the hinge zone geometry proposed by Kebeasy [17]. Mostly of the focal mechanism analyses data indicate reverse faulting with some strike-slip component.

Seismicity parameters for the delineated seismic sources along the Mediterranean coastal line are displayed in Table 6.

| Source Zone | b-value | Yearly Number of Earthquakes | | Observed $M_{max}$ |
|---|---|---|---|---|
| | | Above $M_W$ 4.0 | Above $M_W$ 5.0 | |
| EG-25 | 0.97 | 0.5204 | 0.0554 | $I_{max}$ X on 1546/01/14 |
| EG-26 | 0.94 | 0.5975 | 0.0688 | $m_b$ 6.5 on 1955/09/12 |
| EG-27 | 0.60 | 0.7134 | 0.1793 | $I_{max}$ VIII on 0262/--/-- |

**Table 6.** b-value, annual rate of earthquakes, and maximum observed magnitude for the delineated seismic source zones along the Mediterranean coastal line.

## 5.7. Seismic sources of the Western Desert

*5.7.1. El-Gilf El-Kebeir (EG-28) Seismogenic Source*

Issawi [28] studied the geology of El-Gilf El-Kebeir region, and concluded that the area is affected by three main faults (Figure 2). The first one is the Gilf Fault, which strikes N-S for a distance of 150 km inside Egypt. Its extension in Sudan is unknown. Its northward extension is not traced. He interpreted this fault as a normal, gravity, strike and hinge type of structure. The second one is Kemal Fault, which limits the northwestern side of the Gilf Plateau. It is normal, strike fault which trends NW-SE. The Kemal Fault intersects the Gilf Fault at its northern end. The third one is the Tarfawi Fault, which has the same trend similar to the Gilf Fault. Its length, in Egypt, is 220 km but it extends in Sudan. He interpreted this fault as a normal, gravity and hinge fault.

The only recorded earthquake in this area source is the $m_b$ 5.3 ($M_L$ 5.7), December 9, 1978 El-Gilf El-Kebeir earthquake. It had a reverse faulting mechanism. Riad and Hosney [207] studied its focal mechanism and concluded that, a shear direction did exist in the basement rocks of the southern part of the Western Desert and has been explained as due to compressional stress resulting from the spreading of the Red Sea. Their fault planes solution shows that the P-axis is almost perpendicular to the Red Sea spreading axis. They concluded that the Gilf Plateau is probably divided into two parts by a fault striking nearly E-W. Some authors [e.g., 208 and 209] pointed out that this activity is linked to the pre-existing weak zones, while, Abou Elenean [19] linked such an intraplate activity to the intersection of more than one local fault.

In the current work, the Gilf El-Kebeir (EG-28) seismogenic source covers the seismic activity in this area, as well as the above mentioned faults.

## 6. Eastern Mediterranean region seismic sources

The Mediterranean region is characterized by a very complex tectonics that can be generally described in the frame of the collision between the Eurasian and African Plates [183, 210-219]. It can be divided into western, central, and eastern basins.

The Eastern Mediterranean region, which defines the region lying between the Caspian Sea and the Adriatic Sea through Caucasus, Anatolia, Aegean Sea and Greece, is one of the world's most seismically active regions. Recent tectonics of the Eastern Mediterranean region has been studied intensely in the last four decades. The Eastern Mediterranean region is known to be seismically active over a period of more than 2000 years based on historical and instrumental records. The tectonic and seismotectonic studies reflect a highly complicated tectonic setting.

It is characterized by two main seismic regions: the Hellenic and Cyprian Arcs (Figure 13). The Cyprian Arc has a similar geometry to the Hellenic Arc and the two are often compared (e.g., [220]). However, the observed seismic activity and the well-known plate movement in the Eastern Mediterranean area, suggest that the previously mentioned arcs are affected by a very distinct tectonic activity. The convergence across the first one (Hellenic Arc) is 20–40 mm/yr. (two to three times faster across the Cyprian Arc). Thus, this biggest displacement level yields in higher seismicity rate at much deeper levels (up to 300 km) [220].

The Cyprian Arc represents a tectonic plate margin separating the Anatolian sub-Plate (to the north) from the Nubian and Sinai sub-Plates (to the south) (Figure 13). It is connected from the west by the Hellenic Arc, and from the east by the Dead Sea and the East Anatolian Faults. In addition, it extends from the Gulf of Antalia, to the west to the Gulf of Iskenderun, to the east. On the other hand, the Hellenic Arc is considered to be the most active seismic region in Europe. It is represents the convergent plate boundary between the African Plate and the Eurasian Plate (Aegean sub-Plate) in the Mediterranean area (Figure 13).

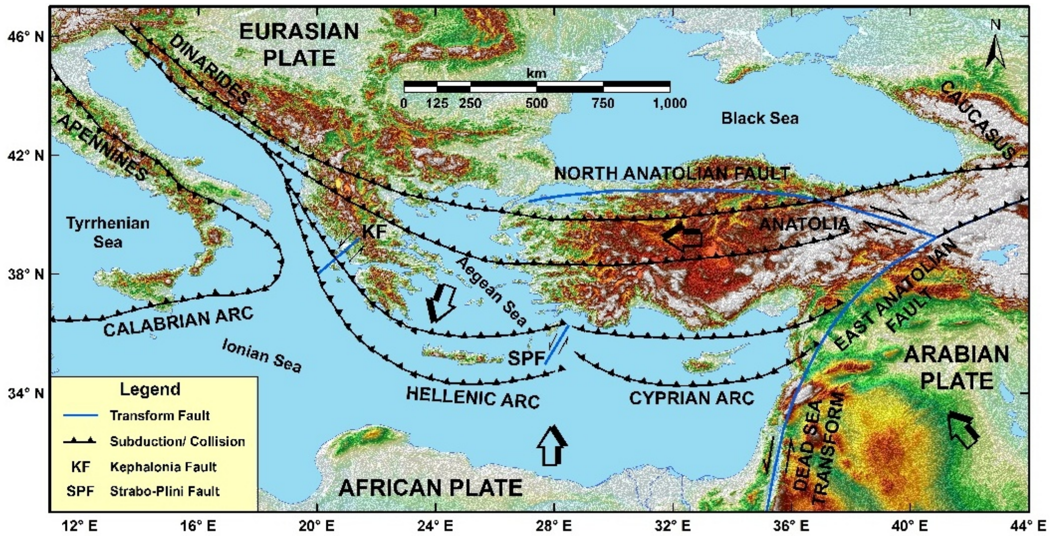


**Figure 13.** Tectonic map of the Eastern Mediterranean region (after Ziegler [221]; Meulenkamp *et al.* [222]; and Dewey *et al.* [223]).

### 6.1. SHARE shallow-depth seismic sources (h ≤ 20 km)

The Seismic Hazard Harmonization in Europe (SHARE) project [224], since the year 2009 till 2013, worked in establishing an appropriate seismic hazard model for Europe and Turkey. This project delivered a seismic hazard reference model for the current use of the European building design and seismic regulations, Eurocode 8 (EC8), that came into force in 2010.

The EU-FP7 European Commission Project (SHARE), aiming at providing an updated state-of-the art time-independent seismic hazard model, envisioned to serve as a reference model for the revision of the EC8 building code. SHARE, in addition, contributes its results to the Global Earthquake Model (GEM, www.globalquakemodel.org), a public/private partnership initiated and approved by the Global Science Forum of the OECD- GSF, aiming to provide a uniform hazard and risk model around the globe.

The Euro-Mediterranean area is complex from a seismotectonic point of view. The plate boundary between Africa and Europe runs roughly west to east from the Mid-Atlantic Ridge to Eastern Turkey with different mechanisms including continental collision, subduction, and transcurrent movement. Moving away from the plate boundary, the stable continental region is also locally rather active.

SHARE inherits knowledge from national, regional and site-specific PSHAs, assessed new data, assembled the data in a homogeneous fashion, and built comprehensive hazard relevant databases. In the frame of this project, the establishment of a seismic source model for Europe and the surrounding areas was considered. This model is built upon the available local and regional models as well as newly defined source zones. It has been developed during eight separate workshops by the SHARE consortium. Almost 80 experts from 28 countries from the informed European-Mediterranean seismological community have participated in building the zonation model.

The principle for seismic source zones is that they represent enclosed areas within which, a uniform seismicity distribution and maximum magnitude is expected. Background sources have been avoided in the sense that all areas have been covered by seismic sources, i.e., even very low seismicity areas are covered with areal source zones. The principles along which seismic source zones in the current model have been constructed are based on information from geological structures on different scales, tectonics and seismicity.

Seismicity also follows these structures well, e.g., as can be seen along the North Anatolian Fault, the Gulf of Corinth and the Hellenic Arc. The use of fault source information has also been done in the delineation of the source zones, especially in the case of the foundation of the sources for Balkans, Greece and Turkey, Italy and Portugal. b-value, annual activity rates, and maximum expected magnitude were computed using different approaches and methods and included in the SHARE project database (www.share-eu.org) [225].

In the current work, 53 shallow-depth seismic sources ($h \leq 20$ km) from the SHARE source model (Figure 5), were considered to the north of Egypt, till latitude 38° N, and covering the Greece and Turkey regions. Some of the events located at this region were felt and caused few damages in the northern part of Egypt (e.g., the $I_{max}$ VIII, August 8, 1303 offshore Mediterranean earthquake, the $I_{max}$ VI, February 13, 1756 and the $M_S$ 7.4, June 26, 1926 Hellenic Arc earthquakes, the $M_W$ 6.8, October 9, 1996 Cyprus earthquake, and the $M_S$ 6.4, October 12, 2013 Crete earthquake). Thus, these source zones have a certain contribution to the seismic hazard in Northern Egypt.

The model in the Greek and Cyprian area build to a large extent upon the previous works of Papiouannou and Papazachos [64] and Papiouannou [226]. The Turkish model [227, 228] is provided as a cooperation between the EMME project and SHARE. The Turkish model is further a hybrid model, in the sense that the area sources have been delineated with respect to the integrated fault line sources from the main faults, like the North and East Anatolian Faults.

### 6.2. Intermediate-depth seismic sources ($20 \leq h \leq 100$ km)

Intermediate focal depth earthquakes occur in the Eastern Mediterranean region (Southern Greece and Turkey) define a Benioff zone of stair shape which dips from the convex side of the Cyprian and the Hellenic Arcs to its concave side (from the Eastern Mediterranean to the Greek and Turkish lands) [229-231]. Some of these earthquakes are moderate to large earthquakes, and constitute a seismic threat for the whole Mediterranean area, including Northern Egypt. Since, because of their magnitudes and focal depths, these earthquakes produce seismic waves of large amplitude and period which travel large distances with low attenuation [232]. Therefore, these earthquakes can contribute to the seismic hazard of Northern Egypt.

In this work, intermediate-depth sources for earthquakes having focal depths ranging from 20 km to 100 km have been delineated. Below this depth (100 km) and considering the large distance from Egypt, deep events have no contribution to the seismic hazard. Thus, 7 intermediate-depth source zones have been considered in the Hellenic and Cyprian subduction zones to cover the intermediate-depth seismicity ($20 \leq h \leq 100$ km) (Figure 14). The zoning was based on the seismicity distribution and the tectonic setting of the region. Seismicity parameters for these intermediate-depth seismic sources are displayed in Table 7.

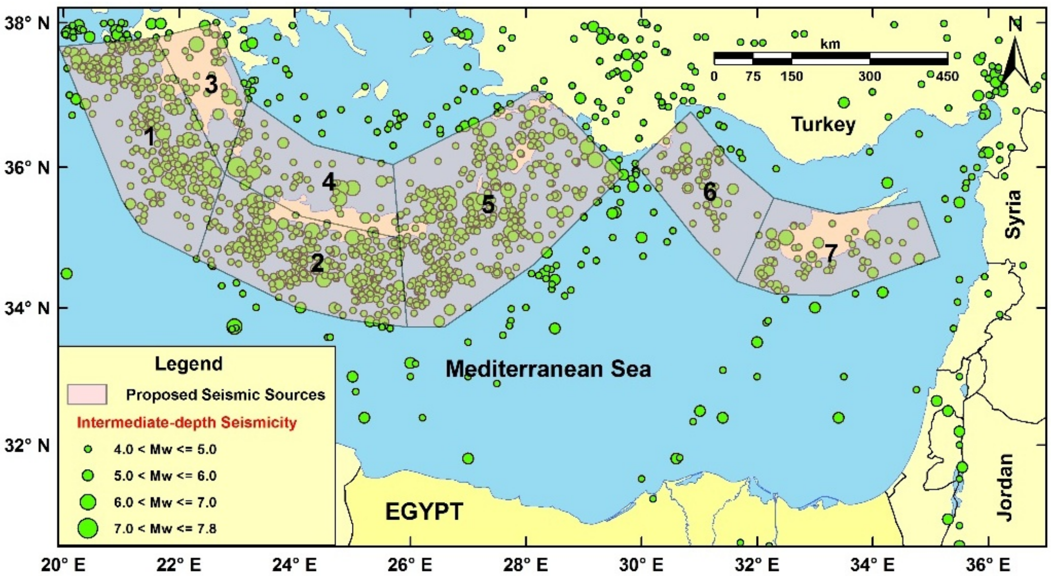


**Figure 14.** Intermediate-depth seismicity (20 ≤ h ≤ 100 km) and delineated intermediate-depth seismogenic source zones for the Eastern Mediterranean region.

| Source Zone | b-value | Yearly Number of Earthquakes | | Observed $M_{max}$ |
|---|---|---|---|---|
| | | Above $M_W$ 4.0 | Above $M_W$ 5.0 | |
| MD-01 | 0.88 | 12.2091 | 1.6212 | $M_W$ 6.9 on 2008/02/14 |
| MD-02 | 0.97 | 14.1395 | 1.5283 | $m_b$ 6.4 on 2013/10/12 |
| MD-03 | 0.78 | 1.9892 | 0.3324 | $m_b$ 6.9 on 1962/08/28 |
| MD-04 | 0.83 | 2.8908 | 0.4316 | $m_b$ 7.2 on 1903/08/11 |
| MD-05 | 0.88 | 14.8782 | 1.9434 | $m_b$ 7.1 on 1984/02/09 |
| MD-06 | 0.93 | 2.2986 | 0.2727 | $M_S$ 5.8 on 1984/04/30 |
| MD-07 | 0.82 | 2.9083 | 0.4409 | $m_b$ 6.5 on 1941/01/20 |

**Table 7.** b-value, annual rate of earthquakes, and maximum observed magnitude for the delineated seismic source zones of the Eastern Mediterranean region.

## 7. Conclusion

To reach a more realistic seismic hazard quantification in Egypt, it is necessary to recognize the seismic source zones, including the seismic activity that can affect different regions all over the country. In the current work, a new seismic source model for Egypt and its surroundings is proposed, using all available geological, geophysical, tectonic and earthquake data, aimed at carrying out seismic hazard studies.

This work presents a detailed review on major tectonic features and the correlation of seismicity with them, to demarcate seismic sources in Egypt and neighborhood. The Gulf of Aqaba-Dead Sea Transform, the Red Sea-Gulf of Suez Rift, and the Cyprian and Hellenic Arcs are the three most active seismotectonic belts in the region, which have produced several large earthquakes in the recent past. On the basis of a comprehensive and critical analysis of the seismotectonic characteristics, different seismic sources are defined to model the seismicity for the assessment of seismic hazard in Egypt.

Focal mechanism solutions data, active faults data, as well as an updated earthquake catalogue for the period 2200 B.C.–2013 are taken into account. Potential seismic sources are modeled as area sources, in which configuration of each seismic source is controlled, mainly, by the fault extension and seismicity distribution.

The proposed seismic source model consists of 28 shallow-depth seismic zones ($h \leq 35$ km) for the Egyptian territory and its surroundings, specified on the basis of mainly seismotectonic and seismicity criteria. In addition, the authors have considered 53 shallow-depth seismic sources ($h \leq 20$ km) for the Eastern Mediterranean region after SHARE (2013). Furthermore, the current model involves 7 delineated intermediate-depth seismic sources ($20 \leq h \leq 100$ km) covering the intermediate-depth seismicity in the Eastern Mediterranean region.

Seismicity parameters (b-value and activity rates) of the Gutenberg–Richter magnitude–frequency relationship have been estimated for each one of the seismic sources. In addition, the maximum observed magnitude for each seismic source zone was reported from the sources sub-catalogues. The coordinates of these seismic source zones and the estimated seismicity parameters can be directly inserted into PSHA after the estimation of the maximum expected magnitude for each source. The computation of seismic hazard for Egypt using these data will form the subject matter of a future paper.

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