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Seismicity of Sinai Peninsula, Egypt

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Abstract The Sinai Peninsula has a triangular shape between the African and Arabian Plates and is bounded from the western and eastern borders by the Gulf of Suez and Gulf of Aqaba–Dead Sea rift systems, respectively. It is affected by strong and destructive earthquakes (e.g., March 31, 1969 and November 22, 1995) and moderate earthquakes ($m_b>5$) throughout its history. After the installation of the Egyptian National Seismic Network (ENSN), a great number of earthquakes has been recorded within and around Sinai. Consequently, the seismogenic source zones and seismotectonic behavior can be clearly identified. Available data, including both historical and instrumental (1900–1997), have been collected from national and international data centers. While the data from 1998 till December 2007 are gathered from ENSN bulletins. The seismogenic source zones that might affect Sinai Peninsula are defined more precisely in this work depending on the distribution of earthquakes, seismicity rate (*a* value), *b* value, and fault plane solution of the major earthquakes. In addition, the type of faults prevailed and characterized these zones. It is concluded that the Gulf of Aqaba zone–Dead Sea transform zone, Gulf of Suez rift zone, Cairo–Suez District zone, and Eastern Mediterranean dislocation zone represent the major effective zones for Sinai. Furthermore, there are two local seismic zones passing through Sinai contributing to the earthquake activities of Sinai, these are the Negev shear zone and Central Sinai fault (Themed fault) zone. The source parameters, *a* and *b* values, and the maximum expected moment magnitude have been determined for each of these zones. These results will contribute to a great extent in the seismic hazard assessment and risk mitigation studies for Sinai Peninsula to protect the developmental projects.

Keywords Sinai Peninsula · Earthquakes · Seismicity · Central Sinai fault · Negev shear zone

Introduction

Sinai Peninsula has an extension of 380 km long (north–south) and 210 km wide (west–east) and occupies a surface area 61.000 km^2. It is bounded from the west by the Gulf of Suez and the Suez channel and from the east by Gulf of Aqaba, while bordered by the Mediterranean Sea from the north and Red Sea from the south (Fig. 1). It is noticed that a considerable part of the Sinai population has concentrated in dispersed communities within Sinai, while the main population is noticed along the eastern, western, southern, and northern coasts forming big cities, tourist villages, and resorts.

The geology and tectonics of Sinai is largely affected and controlled by the geodynamic processes acting in the Red Sea with its northern bifurcations and eastern Mediterranean regions. The relative movements of the Sinai subplate, Arabian and African plates are accommodated by a system of regional strike–slip and normal faults that run along the Gulfs of Suez and Aqaba and across the Sinai

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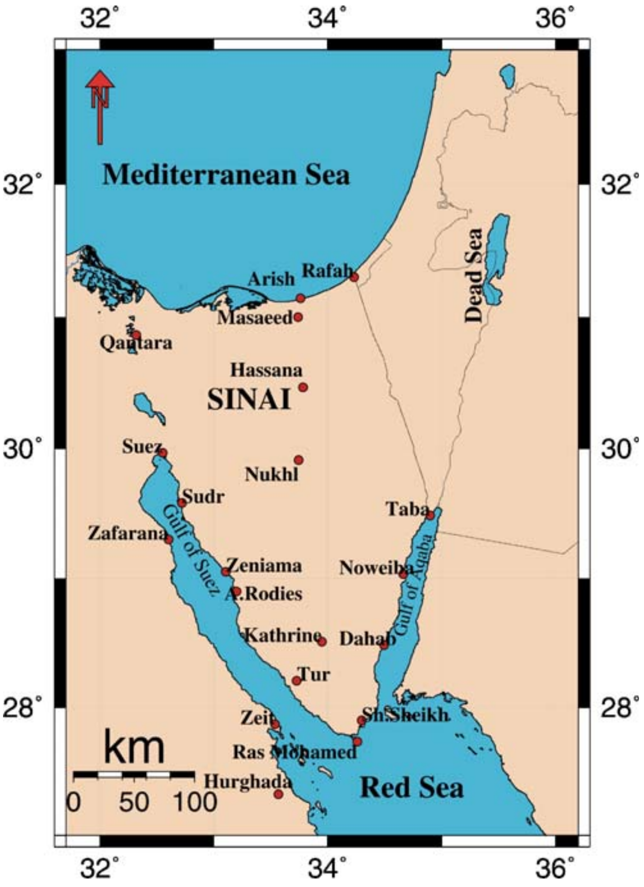

Fig. 1 Location map for Sinai Peninsula

subplate. Movements along these faults led to large and damaging earthquakes. Previous studies on seismicity of Western Arabia (El-Isa and El Shanti 1989), Gulf of Aqaba (El-Shahat 2000), and Sinai (Salamon et al. 1996, 2003) indicate that the main seismic activities are mostly restricted to the plate boundaries along both the Gulfs of Aqaba and Suez. The higher rate of seismic activities at the southern end of the Gulf of Suez is clearly noticed and interpreted as a result of the triple junction between the African, Arabian plates, and Sinai subplate (Ben-Menahem 1979).

The events originate from faults running parallel (or subparallel) to the Gulf of Suez and accommodating motions of different rates of oblique opening in the Red Sea and Gulf of Suez, and the left-lateral strike–slip motion in the Gulf of Aqaba (Daggett et al. 1986). In March 31, 1969, an earthquake (m_b=6.3) occurred at Shadwan Island of the southern end of Gulf of Suez. This earthquake was preceded by 35 large foreshocks and followed by a large sequence of aftershocks (Kebeasy 1990). In 1972, an earthquake swarm occurred at the southern entrance of the Gulf of Suez. The 1983 Gulf of Aqaba earthquake swarm (El-Isa et al. 1984; Merghalani and Bazari 1984; Shapira and Jarradat 1995) caused panic damages within and around the Gulf of Aqaba cities. An earthquake swarm occurred from August 1993 up to February 1994 south of the 1983 swarm. In November 22, 1995, the largest earthquake (M_w=7.3) occurred in the Gulf of Aqaba and caused a widespread damage in the surrounding area with extending effect reaching Cairo (El-Hadidy et al. 1998). Moderate earthquake activities have been observed at different areas inside Sinai Peninsula (Salem 1997). After the occurrence of the October 12, 1992 earthquake, the Egyptian Government financed the construction of the Egyptian National Seismic Network (ENSN), which cover the whole Egyptian territory and can detect and record the majority of local and regional earthquakes as well as teleseismic events.

Taking into account the great development and rapid growing of Sinai Peninsula in the last decade as a national project for the Egyptian government and especially its coasts, a valuation of the geological and tectonic situation represents an urgent need for detailed study of seismicity around Sinai. To achieve these goals, an up-to-date seismicity map for Sinai is necessary and presented utilizing all available instrumental data through the period 1900–2007 together with the historical data that cover a period before 1900 (Poirier and Taher 1980; Maamoun et al. 1984; Ambraseys et al. 1994).

Regional geology and tectonics

Sinai Peninsula is characterized by great variations from the geological and topographical points of view where the igneous and metamorphic mountains, which rise to a height of 2,675 m (Gebel Mousa), form the southern tip of the peninsula (Fig. 2). While the central part is occupied by the subhorizontal Mesozoic to Tertiary sediments of Tih Plateau. North of latitude 30° N, the topography comprises low alluvial plains which are broken by large uplifted Mesozoic domes and anticlines (Syrian arc), such as Gebel Yelleq (1,090 m), Gebel Halal (890 m), and Gebel Maghara (735 m). Northward, these “Syrian Arc” structures sink seaward due to Tertiary down-to-the-basin faulting and are hidden under the Quaternary coastal plain and continental deposits. North of Gebel Maghara and extending nearly to the Mediterranean coast is a broad tract of sand dunes, some of which attain heights of 91 masl. In northernmost Sinai and the offshore area, the sedimentary cover increases in thickness from less than 1,829 m to in excess of 7,620 m. The northeast–southwest trending Pelusium line, which lies 22 to 25 km offshore, represent the oceanic–continental crustal boundary. The Pelusium line had a profound effect on the distribution and type of faulting which occurred in the offshore region during the late Tertiary. Ginzburg and Gvirtzman (1979) postulate that this large increase in sediment thickness and the development of the Mesozoic

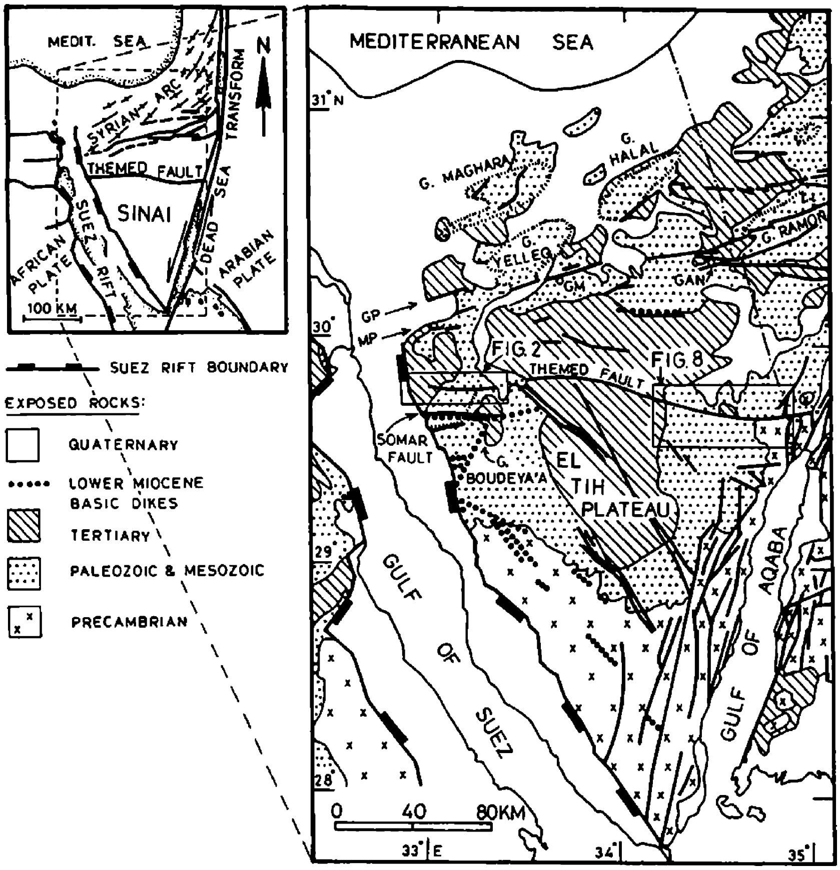

Fig. 2 Simplified geological map of the Sinai Peninsula (Moustafa and Khalil 1993)

platform margin fancies is related to the transition from continental to oceanic crust.

Tectonically, Gulf of Aqaba together with Gulf of Suez resembles the northern extension of the African rift system which constitutes mainly the active seafloor spreading in the Red Sea and the Gulf of Aden with its extension in Djibouti and Afar depression, East of Africa. The wrenching along the Gulf of Aqaba is reflected in the form of strike–slip faults cutting through the basement rocks and the overlying sedimentary section as well as en-echelon folds (Abdel Khalek et al. 1993). The northernward extension of the Gulf of Aqaba leads to the Dead Sea–Jordan transform fault system which links the Arabian plate convergence in southern Turkey with the active seafloor spreading in the Red Sea. The Aqaba–Levant structure is thought to have formed principally by left-lateral shear motion (Freund et al. 1970) with relative displacement ranges from tens of meters up to 9.8 km. The creation of the pull-apart basins is mainly related to the strike–slip motion (Garfunkel 1981) with N–S to NNE–SSW fault trend (Lyberis 1988).

A belt of NE–SW-oriented, doubly plunging folds is well-exposed in the northern part of Sinai Peninsula and extends northeastward to the Dead Sea transform (Fig. 2), forming the major part of the Syrian Arc system of Krenkel (1925). These folds and their associated faults indicate that they were formed by dextral transpression on a set of ENE-oriented, preexisting faults (Youssef 1968; Moustafa and Khalil 1988, 1989; Moustafa et al. 1991; Abdel Aal et al. 1992). These faults are in turn related to the Late Triasssic–Liassic rifting of Afro-Arabia (Dercourt et al. 1986) and formation of passive continental margin in northern Egypt (May 1991). The main deformation in the north Sinai fold belt reached its peak intensity in the early Late Senonian (Abdel Aal et al. 1992) and continued into the post-Early Miocene (Moustafa and Youssif 1990; Moustafa et al. 1991). The north fold belt is bounded in central Sinai by the Tih Plateau (Sadek 1928) where flat-laying Upper Cretaceous to Middle Eocene rocks are exposed.

According to Said (1990), the shifting of the Arabian plate by as much as 105 km in a right-lateral sense along the Dead Sea fault, coupled with a clockwise motion, necessitates and dictates a westerly and clockwise translation of the Sinai plate in order to avoid crowding and overlapping of the continental crust in the Dead Sea–Gulf of Aqaba shear zone. In turn, the bulk of Sinai's gross westerly motion must then be taken up along and within the Gulf of Suez rift, which is a well-defined structural boundary of the Sinai cratonic element, separating it from the African plate. This motion could be further resolved into two net components: one parallel (left lateral) and the other normal (compression) to the rift trend. This sequence of plate motions can simulate compressional and left-lateral shear stresses capable of partially closing the Gulf of Suez. Thus, the reverse sense of deformation, i.e., ductile extension of the crust and right-lateral strike–slip, since at least the late Oligocene time, could have caused the formation of the Gulf itself.

Crustal structure

Changes in the crustal structure along the Gulfs of Suez and Aqaba reflect the different tectonic and geodynamic processes affecting Sinai through its geologic history. Crustal thickness is varied within Sinai from the southern edge to the northern coast along the Mediterranean Sea (Tealeb 1985; El-Azoni 1992) which provides an evidence for the presence of an Early Mesozoic passive margin with thinned continental crust in north Sinai. To the east of Sinai, the thickness of crust (along the Jordan–Dead Sea–Gulf of Aqaba seismic profile) decreases southwards from 27 to 30 km in the northern part, from 30 to 33 km in the central part to a thickness of 21 km in the southern part near Sharm El-Sheikh (Ginsburg et al. 1979). The velocity of the upper and lower crust also decreases from north to south where it ranges from 6.0 to 5.8 km/s and from 6.7 to 6.6 km/s, respectively, while the velocity of the upper mantle is 7.8 km/s. The seismic profile that extends parallel to the eastern side of the Gulf of Suez from Ras Mohammed in the south to Abu Rudes in the north shows that the crustal thickness increases from 20 to 24 km near Ras Mohammed to 32 km at Abu Rudes (Marzouk 1988), while the velocity of the upper mantle along this profile is 7.5 km/s.

Historical seismicity

Egypt is one of the few regions all over the world where evidence of historical earthquake activity have been documented during the past 4,800 years (Kebeasy 1990). The historical or noninstrumental earthquakes are those which were documented based on the retrieval and assessment of original sources of information. These sources chiefly comprise medieval Arabic chronicles and European travel literature and technical studies. The historical earthquakes (Fig. 3) affecting Sinai are collected (Sieberg 1932; Ben-Menahem 1979; Poirier and Taher 1980; Maamoun et al. 1984; Ambraseys et al. 1994). Twenty-five earthquakes were reported to have been felt during the period from 95 BC to 1910 AD at different localities with intensities in the range VI–IX. Some of these earthquakes have a macroseismic magnitude determined from the felt data and ranges from 5.4 to 6.7, while others have no defined magnitude. The assigned intensity values are based on the reported damage which may not be homogeneous either in time or space. The general conclusions from the historical seismicity are arranged as follows:

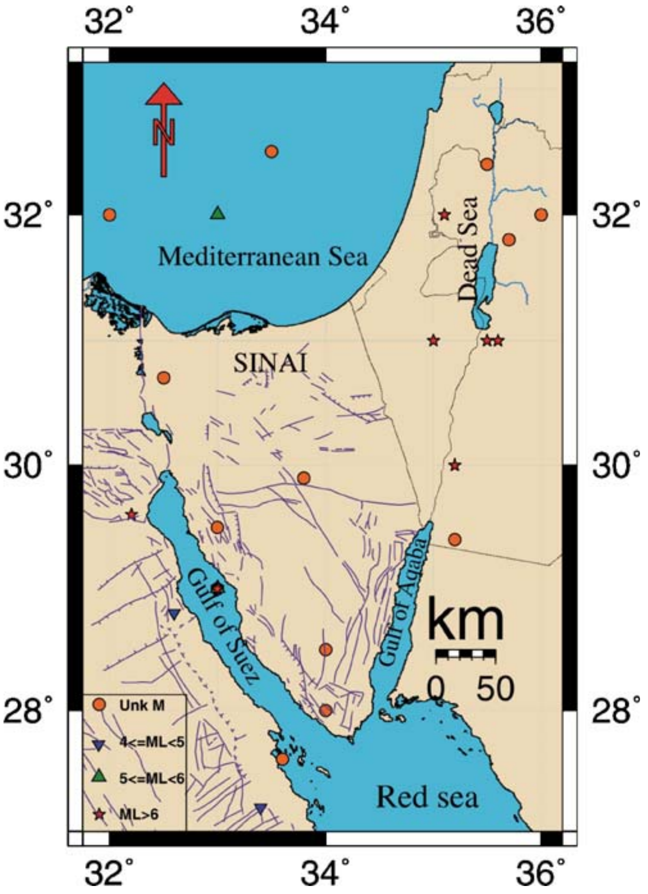

Fig. 3 Distribution of historical earthquakes around Sinai

1. No earthquakes have been reported in the Gulf of Aqaba, except the March 18, 1068 earthquake (latitude 28.5° N and longitude 36.7° E) that occurred in northern Hejaz and caused destruction over hundreds of kilometers in northwestern Arabia and killed 20,000 people. While destructive earthquakes have been reported in the Gulf of Suez, Jordan–Dead Sea transform, and Eastern Mediterranean regions (Ambraseys et al. 1994). In addition, two earthquakes were reported to have been felt in January 6, 1910 at 29.9° N and 33.8° E while the second one was felt in February 12, 1091 at 28.5° N and 34.0° E with an intensity of VI–VII. This earthquake distribution may be due to the past population density in the area.
2. The epicentral distribution of historical earthquakes seems to correlate with the general tectonics of the region. Four earthquakes were reported in the southern

part of the Gulf of Suez, and six earthquakes were documented in the northern part of the Gulf of Suez while there are no reported earthquakes in the central part. Meshref (1990) suggested the model of the Gulf of Suez as separated into three main tectonic provinces. The most significant feature of this model is the presence of a series of major faults that extend along the rift and bound it from both sides. He deduced that there is a regional southwest dip of the tilted fault blocks in both of the northern and southern provinces based on the direction and the amount of down thrown. He assumed that the future spreading axis of the rift will be located in the central part of the rift bounded by the major faults of opposite throw. The central province has a regional northeast dip and bounded from the north and south by two major accommodation zones of flatter dip separating it from the northern and southern provinces. Geophysical and geological observations confirm this model. This distribution of earthquakes coincides well with Meshref's tectonic model where historical earthquakes show that the southern and northern provinces have an activity greater than the central one. Destructive earthquakes concentrated around the Jordan–Dead Sea transform (El-Isa 1985; El-Isa and Hasweh 1988) support this idea.

3. At least nine historical earthquakes have occurred in the Jordan–Dead Sea transform within the period 112–1546 AD (Ambraseys et al. 1994). Six of those are reported with intensities in the range of VII–IX, i.e., with an overall average recurrence period of about 235 years. According to Ben-Menahem (1979), 26 historical earthquakes with magnitude ranging from 6.1–7.7 occurred in the south Jordan–Dead Sea transform in the period 2150 BC to 1973 AD with an average recurrence period of 153 years.

Instrumental seismicity of Sinai

The instrumental recording of earthquakes in Egypt was started in 1903; seismographs were eventually modernized since 1962 by the installation of WWSSS at Helwan Observatory (30 km to the south of Cairo). This is followed by multistages of upgrading. In 1972, by adding a station of three-component long-period seismometers and three-component of short-period seismometers at Helwan. In 1975, three stations were added at Matruh (along the Mediterranean Sea coast), in Aswan and Abu Simple in the southern part of Egypt. On August 1994 and in cooperation with the Japanese International Co-operation Agency (JICA), ten short-period stations were installed covering the southern part of Sinai and Gulf of Suez. At the end of 1997, the ENSN have been installed to cover Egyptian territory including Sinai. Instrumental information of earthquakes during the period from 1900 to August 1997 (Fig. 4) was collected from a number of seismological catalogues and bulletins including those of the International Seismological Centre (ISC 1964–1993), the National Earthquake Information Service (NEIS), and Bulletins of Helwan Observatory and related publications including Sieberg (1932); Gutenberg and Richter (1954); Ismail (1960); Gergawi and El-Khashab (1968); Maamoun et al. (1984); Kebeasy (1990); Ambraseys et al. (1994); Abu El Enean (1997) and others. After the occurrence of the October 12, 1992 earthquake, the Egyptian government decided to establish the ENSN to cover the whole territory of Egypt (Fig. 5). Thirteen ENSN stations are located within the whole region of Sinai, in addition to six stations along the western side of Gulf of Suez. By installing ENSN, the recording of a great number of events (Fig. 6) reflects

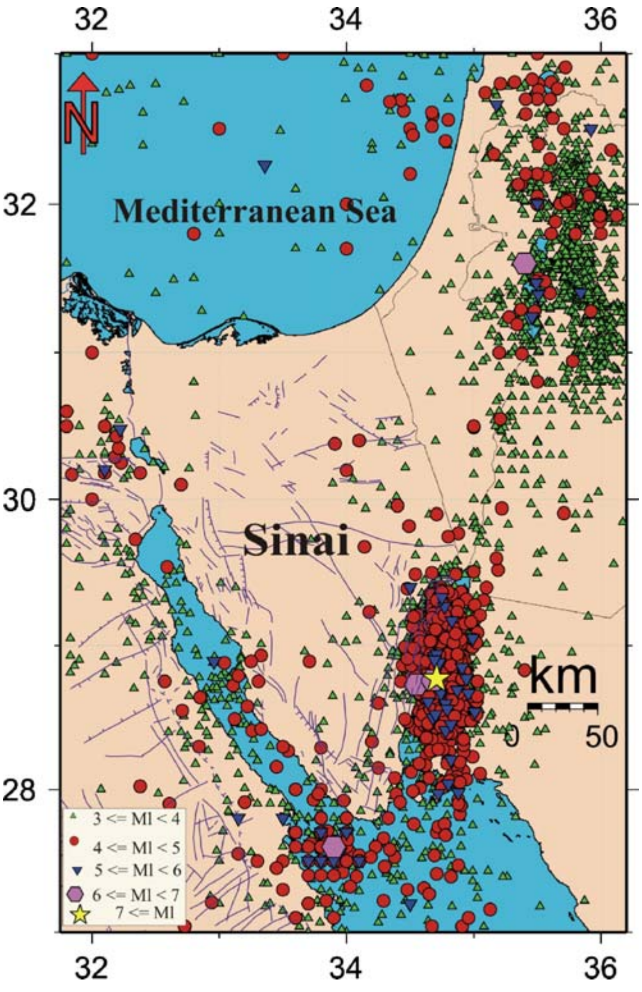

Fig. 4 Instrumental seismicity from 1900 to August 1997 (before ENSN)

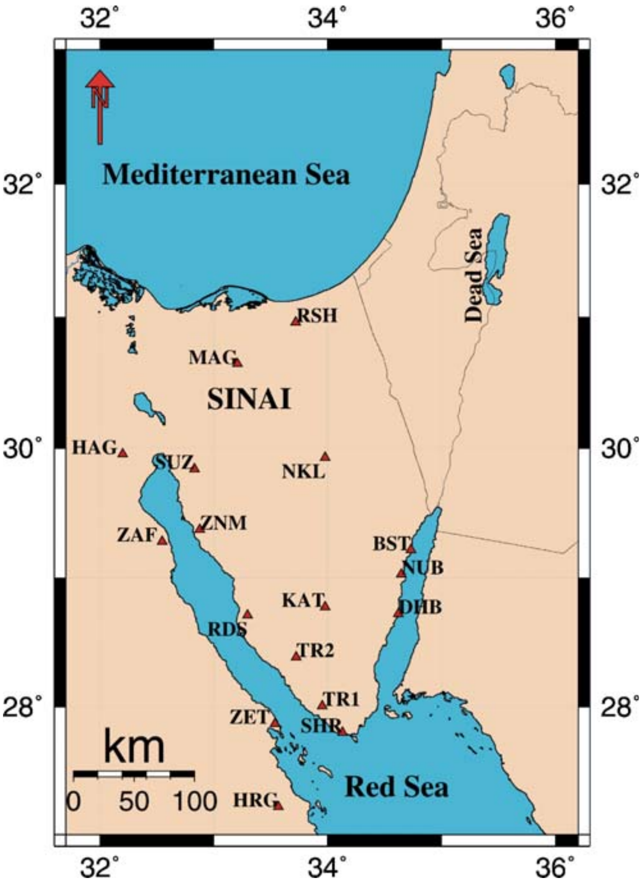

Fig. 5 ENSN around Sinai

higher capabilities of recording small earthquakes and helps in defining new seismic sources. According to the analysis of instrumental earthquake distribution (Figs. 4 and 6), it is noticed that Sinai Peninsula is affected by a number of earthquakes that have occurred within the period of 1900–2007 with wide range of magnitudes in the range $2<M\geq 7.3$. Strong earthquakes, as well as most of events with $M_L\leq 5$, are concentrated into belts and extend along the geologically defined borders and margins of the Sinai subplate. Low–moderate activity is noticed within the Sinai itself. Along the Gulf of Aqaba, many earthquakes are reported to have occurred up to 1983. However, on January 21, 1983, an earthquake swarm occurred inside the Gulf (El-Isa et al. 1984), and on October 18, 1984, about 244 earthquakes ($2\leq M_L\geq 4.9$) were recorded from this swarm. On November 22, 1995, earthquake swarms occurred in the Gulf of Aqaba with magnitudes ranging between 6.4 and 7.3. During this period, many earthquakes have occurred in the Gulf of Suez region between latitudes 27° N and 30° N. The largest earthquake ($M=6.9$) occurred on March 31, 1969 with an epicenter at the entrance of the Gulf (latitude 27.61° N, longitude 33.91° E) at Shadwan island.

Generally and according to the epicentral distribution of both historical (pre-1900) and instrumental earthquakes (1900–2007), Sinai Peninsula is affected by four major earthquake trends, as follows:

1. Gulf of Aqaba–Dead Sea transform zone,
2. Gulf of Suez rift zone,
3. Cairo–Suez District (CSD) zone,
4. Eastern Mediterranean dislocation (Med) zone.

These major trends have been divided into small segments, which has its local characteristics (Fig. 7). In addition, two local seismic zones run inside the Sinai subplate, and these are:

1. Negev shear zone (NSZ),
2. Central Sinai fault (Themed fault) zone (TFZ).

Determination of *a* and *b* values

Frequency–magnitude statistical relation (Gutenberg and Richter 1944) represents the main parameter for the

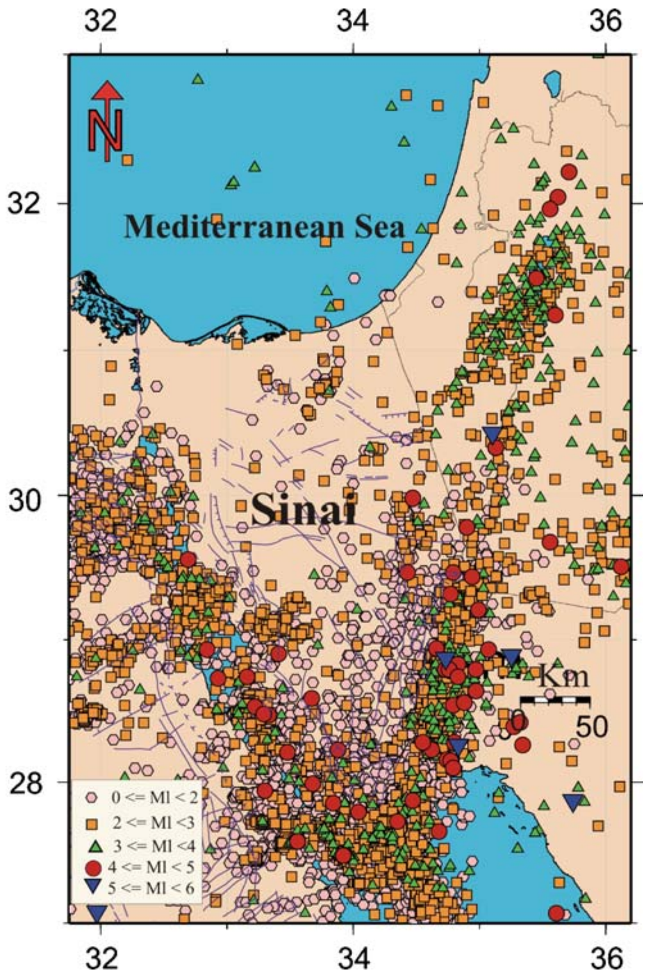

Fig. 6 Instrumental seismicity from September 1997 to December 2007 (after ENSN)

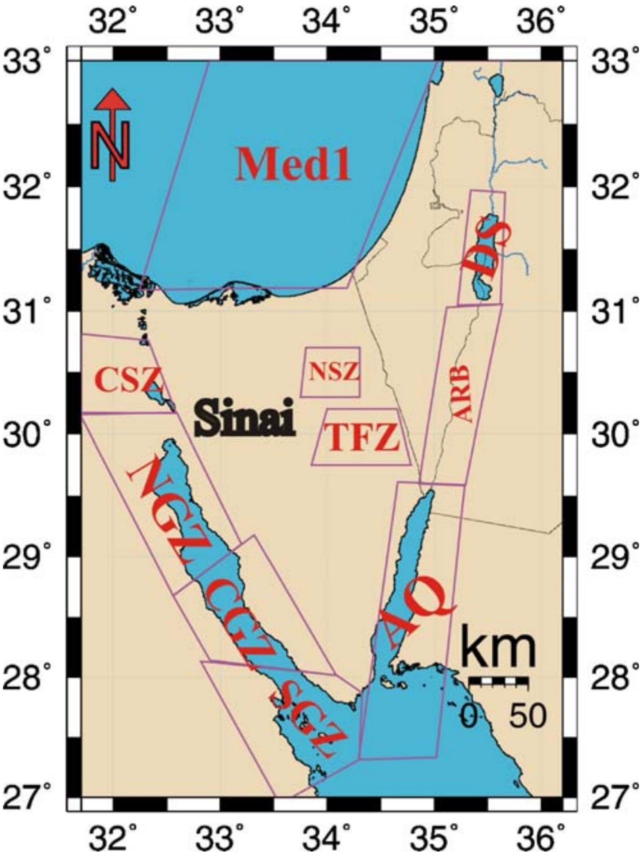

Fig. 7 Seismic zones within and around Sinai

determination of the seismicity of an area. Some conditions should be postulated and applied to this relation: the area must be seismotectonically homogeneous. For this reason, it is necessary to separate the whole study region into seismic zones. For each seismic source, the magnitude distribution was taken as exponential and of the form given by the Richter formula of occurrence frequencies:

$$\text{Log } N = a - bM$$

where N is the number of earthquakes in 1 year in a given magnitude range centered about magnitude M, a and b are constants, and the logarithms are taken to the base 10. The value of a depends on the period of observation, the size of the region, and the level of seismic activity whereas b depends on the ratio of the number of earthquakes in low- to high-magnitude groups. Values of b have been reported to differ from 0.5 to 1.5 approximately and mostly between 0.7 and 1.0 (Isacks and Oliver 1964). Nevertheless, many researchers believe that b varies from region to region and also varies with the focal depth. Besides, its value depends on the stress conditions and on the heterogeneity of the rock volume generating the earthquakes (Karnik 1969).

According to the above-mentioned relation, it could be concluded that there a number of earthquake sources affected Sinai Peninsula and the parameters of these zones are presented in Table 1. Some of the events from each seismic source have been selected (Table 2) as a representative example for the individual source. Fault plane solutions of these events have been determined based on the results of the previous as well as this work (Table 3; Fig. 8).

Seismotectonic source zones

Aqaba–Dead Sea transform

The Gulf of Aqaba zone occupies the southern part of the Dead Sea rift which was formed by the once continuous Arabian–African platform that has been tectonically stable since the end of the Precambrian (Freund et al. 1968, 1970; Le Pichon and Francheteau 1978; Garfunkel 1981). This zone lies to the east of the Sinai plate and has great effect for Sinai and can be divided into a number of segments according to the main direction and the local activities of these segments. These segments are: Gulf of Aqaba zone (AQB), Arava Valley zone (ARV), and Dead Sea zone (DSZ).

Gulf of Aqaba zone

According to Ben-Avraham (1985), the midoceanic ridge of the Red Sea–Gulf of Aqaba system changes to transform fault and runs into the continent. The horizontal motion along the Gulf of Aqaba–Dead Sea rift is left lateral. The Gulf of Aqaba–Dead Sea fault accommodates the relative motion between Sinai and Arabia (Joffe and Garfunkel 1987). It represents the main seismic source along the eastern side of the Sinai subplate.

Kebeasy (1990) considered the Gulf of Aqaba as the Southern extension of the main active Levant fault and stated that the earthquake occurrences are found mainly

Table 1 Determination of a and b values to differentiate seismic sources affecting Sinai

Zone name	$\Delta\sigma$	M_{wmax}	a value	b value
Gulf of Aqaba zone (AQB)	39.5	7.63	4.71	−0.96
Arava Valley zone (ARV)	35.3	7.2	3.82	−0.95
Dead Sea zone (DSZ)	30	7.1	3.94	−0.96
Southern Gulf of Suez (SGS)	30	7.34	4.18	−0.813
Central Gulf of Suez (MGS)	30	6.7	3.50	−0.813
Northern Gulf of Suez (NGS)	30	7.1	3.64	−0.813
Cairo–Suez District zone (CSD)	30	5.4	3.20	−0.81
East Mediterranean zone (Med)	39.5	6.7	3.53	−0.814
Central Negev shear zone (NSZ)	30	3.6	1.42	−0.75
Themed fault zone (TFZ)	30	4.9	1.64	−0.75

Table 2 Source parameters of the selected events for the focal mechanism solutions

No.	Date			Time			Location		Depth (km)	Mb
	Day	Month	Year	Hours	Minutes	Seconds	Longitude	Latitude		
1	30	1	1951	23	7	24	33.4	32.4	10	5.7s
2	18	12	1956	17	53	–	35.5	31.5	10	5.2
3	31	3	1969	7	15	–	33.9	27.6	20	6.1
4	28	6	1972	9	49	35	33.8	27.7	15	5.5
5	29	4	1974	20	4	39	31.7	30.52	33	4.8
6	23	4	1979	13	1	0	35.5	31.24	10	5
7	12	6	1983	12	0	9	33.2	28.5	27	5.3
8	25	1	1985	6	8	3.3	35.51	31.9	27	4.6
9	28	2	1985	16	55	46.7	33.72	27.72	10	4.5
10	31	12	1985	19	42	41	34.9	29.13	9	4.8
11	2	1	1987	10	14	46	32.22	30.46	24	5
12	27	4	1987	20	41	–	35.47	31.27	–	4.2L
13	23	10	1987	16	32	–	35.34	31.19	–	4.1L
14	5	6	1988	18	26	58	33.73	27.98	9	4.5
15	13	9	1990	22	10	7.5	35.11	27.17	10	4.6
16	5	10	1991	18	48	26	32.58	29.52	31	4.3
17	22	10	1992	17	39	1	31.57	29.9	3	4.2
18	27	10	1992	9	4	46	33.11	28.84	10	3.4
19	27	10	1992	11	2	44	33.12	28.85	19	3.9
20	3	8	1993	12	43	5	34.6	28.78	10	5.9
21	3	8	1993	16	33	21.1	34.59	28.79	13	5.4
22	8	11	1993	1	6	2.1	34.65	28.69	8	4.8
23	28	9	1994	9	38	37	32.8	30.65	23	3.8
24	8	9	1995	12	13	22	32.25	29.48	13	4.2
25	22	11	1995	4	15		34.8	28.8	10	6.2
26	22	11	1995	12	47	4.3	34.74	29.3	15	5.1
27	22	11	1995	22	16	55.6	34.77	28.64	10	4.9
28	23	11	1995	18	7	17	34.7	29.33	10	5.2
29	24	11	1995	16	43	45.9	34.74	28.97	10	4.9
30	11	12	1995	1	32	8.1	34.75	28.92	19	4.9
31	21	1	1996	4	59	51.2	34.78	28.8	15	5.1
32	21	2	1996	4	59	51	34.8	28.8	10	5.3
33	14	12	1998	20	48	46	32.69	29.56	18	5.4
34	11	10	1999	20	39	34.3	31.54	28.65	19	5.1
35	28	12	1999	12	5	10.4	31.46	30.24	15	4.8
36	25	6	2000	19	18	48	33.5	28.21	18.1	4.6
37	29	6	2000	14	44	49	31.6	29.53	8	4
38	3	11	2000	21	19	3	32.8	28.93	23.1	4.4
39	12	6	2001	12	43	26.5	31.14	29.64	17	4.2
40	20	8	2001	16	31	52	33.9	27.48	14.4	4.6
41	19	11	2001	20	20	7.7	31.78	30.27	19	3.6
42	20	11	2001	7	42	48.3	34.15	30.34	4.6	3.6
43	20	11	2001	7	56	28.4	34.14	30.33	5.8	2.9
44	17	12	2001	4	25	32.5	30.87	29.56	10	4.4
45	7	8	2002	12	29	36.6	31.12	29.88	16	3.6
46	24	8	2002	20	1	21	31.4	30.14	18.8	4.3
47	18	9	2002	14	56	59	29.88	27.49	10	4.8
48	10	10	2002	13	9	14.5	34.51	29.82	15.4	3
49	5	12	2002	2	21	49	32.2	29.96	23.6	3.6
50	25	3	2004	2	48	35	31.74	30.54	24.7	3.7
51	16	8	2004	22	42	50	32.78	28.94	3.1	3.2
52	12	12	2004	16	51	32.9	33.77	30.09	4.7	2.7
53	20	1	2005	13	41	50	34.68	28.53	15.7	3.2L
54	17	2	2005	10	21	22	33.21	28.57	3.8	2.7

Table 2 (continued)

No.	Date Day	Month	Year	Time Hours	Minutes	Seconds	Location Longitude	Latitude	Depth (km)	Mb
55	11	5	2005	23	9	26	33.5	27.57	4.8	3
56	23	7	2005	14	56	18.5	34.5	28.03	14	3
57	28	10	2005	17	1	37	33.6	27.67	13.5	3.8
58	8	12	2005	1	28	11.5	33.29	27.71	10.7	3.5

at both ends of the Gulf. Until 1983, there was no instrumental information on the seismic activity along the Gulf of Aqaba, while from January up to April 1983, more than 500 earthquakes, reaching a magnitude of 4.8, were recorded. These earthquakes were felt at towns and villages along the gulf, as well as at the Arava Valley causing widespread concern (Shapira and Jarradat 1995). From August 1993 up to February 1994, a large earthquake swarm was associated with relatively high magnitudes reaching 5.8. This swarm included about 1,200 events that occurred south to the 1983 swarm. The centroid moment tensor computed by Harvard University for two of the largest earthquakes with magnitudes 5.8 and 5.6, respectively, shows a north–south striking fault with reverse component. Both earthquakes are possibly associated with the main fault on the land, east of the Gulf of Aqaba.

On November 22, 1995, the largest instrumental earthquake in the Gulf of Aqaba (M_w=7.3) struck the area with extending effect reaching Cairo. More than 1,000 aftershocks were triggered. The length of the aftershocks area reach about 110 km and its strike running N30°E, parallel to the strike of the Gulf of Aqaba. Heavy damage was occurred at Nuweiba City along the western coast of the gulf. On November 2002, earthquake swarms occurred at the middle of the Gulf of Aqaba. More than ten earthquakes with magnitudes ≥4 were recorded and many earthquakes with magnitudes ≤4. Some of these earthquakes were felt but without damage to buildings at the epicentral area. These earthquake swarms indicate that the Gulf of Aqaba segment is the most active part during the last two decades and correlate with the field evidence of recent activity (Garfunkel 1974; Ben-Avraham et al. 1979; Eyal et al. 1981).

It is concluded that the Gulf of Aqaba zone is of great importance due to the occurrence of the largest Egyptian earthquake with a seismic moment magnitude of 7.3 within this segment on November 22, 1995. Also, the seismic activity of this zone is relatively high (a=4.71), as computed in the present study compared with the other zones of Egypt. Great damage and casualties occurred at Nuweiba and Dahab cities along the western coast of the gulf. The seismic activity of the Gulf of Aqaba has led this segment of the transform fault to be considered the most active area in the Aqaba–Dead Sea rift system. The focal mechanism of Aqaba earthquake, 1995, and some aftershocks shows a strike–slip movement with predominant normal components, except one event on the eastern side of the Gulf of Aqaba, which shows strike–slip with reverse component in the NNW–SSE and ENE–WNW trending planes (Abu El Enean 1997).

Arava Valley zone

It is located to the north of the Gulf of Aqaba where the faults of the Dead Sea transform boundary are subaerially exposed at the Arava Valley. The Arava Valley fault in the northern part bounds the eastern margin of the topographic depression, and late Quaternary movement along this fault occurred over a length exceeding 100 km (Garfunkel et al. 1981; Garfunkel 1981). Shapira and Jarradat (1995) stated that, from the preliminary paleoseismicity studies, the border–faults of Arava valley, a few kilometers north of Aqaba City, generate earthquakes stronger than magnitude 6.0 with an average return period of 1,000–3,000 years. Poirier and Taher (1980) located three major historical earthquakes on 1068, 1212, and 1588 with seismic intensities VIII–IX at the Eilat area. Garfunkel et al. (1981) mentioned that two catastrophic earthquakes occurred on 1068 and 1293 at the north of the Gulf of Aqaba.

The Arava Valley is characterized by its low seismicity level compared with its surroundings (a=3.82), but the b value is high (b=1.01), despite clear indication of recent faulting (Gerson et al. 1993). This may be due to the fact that the time for documenting earthquakes is very short to clarify the fault along Arava Valley. Therefore and depending on the low seismic activity rate and the earthquakes epicentral distribution, the Arava Valley could be considered as a separate seismotectonic source.

Dead Sea zone

The trend of the transform boundary shifts from a predominantly north–northeast trend through the Gulf of Aqaba–Araba valley area to a predominantly north–south

Table 3 Focal mechanism parameters of the selected events table

No.	Date			Time			Fault planes parameters				Stress axes				Ref.
	Day	Month	Year	Hours	Minutes	Seconds	NP1		NP2		*P* axis		*T* axis		
							St.1	Dip1	St.2	Dip2	St.	Dip	St.	Dip	
1	30	1	1951	23	7	24	162	34	295	64	165	60	42	17	C (1966)
2	18	12	1956	17	53		251	71	125	30	39	57	269	22	S (2003)
3	31	3	1969	7	15		294	37	113	53	19	82	203	8	Hu (1987)
4	28	6	1972	9	49	35	288	40	121	51	75	82	205	5	Hu (1987)
5	29	4	1974	20	4	39	78	85	347	86	302	10	33	2	H (1990)
6	23	4	1979	13	1	0	277	80	185	75	320	3	51	17	S (2003)
7	12	6	1983	12	0	9	129	86	219	83					Ma (1989)
8	25	1	1985	6	8	3.3	23	72	119	69	160	28	251	2	Bad (1999)
9	28	2	1985	16	55	47	71	55	183	62	221	47	126	4	Bad (1999)
10	31	12	1985	19	42	41	71	56	204	33	17	62	146	13	Bad (1999)
11	2	1	1987	10	14	46	156	80	258	80	112	14	22	0	ME (1988)
12	27	4	1987	20	41		190	80	281	80	325	0	55	14	S (2003)
13	23	10	1987	16	32		90	70	242	22	286	63	82	24	S (2003)
14	5	6	1988	18	26	58	123	74	15	42	222	82	340	4	CMT
15	13	9	1990	22	10	7.5	104	88	199	80	244	23	151	8	Bad (2001)
16	5	10	1991	18	48	26	283	50	153	53	125	62	219	2	Atyia (1997)
17	22	10	1992	17	39	1	173	53	296	54	146	57	55	1	Bad (2001)
18	27	10	1992	9	4	46	312	46	172	51	146	69	243	3	Atyia (1997)
19	27	10	1992	11	2	44	270	49	158	66	116	49	218	10	Atyia (1997)
20	3	8	1993	12	43	5	139	36	357	60	309	67	72	13	HRV
21	3	8	1993	16	33	21	142	33	356	79	257	55	80	34	CMT
22	8	11	1993	1	6	2.1	158	80	62	55	106	26	207	32	Bad (1999)
23	28	9	1994	9	38	37	23	52	117	85	347	30	244	22	Atyia (1997)
24	8	9	1995	12	13	22	123	65	256	34	72	62	195	16	Atyia (1997)
25	22	11	1995	4	15		294	59	196	77	159	31	62	12	PDE
26	22	11	1995	12	47	4.3	207	83	114	67	158	11	252	22	Bad (1999)
27	22	11	1995	22	16	56	202	67	294	87	160	18	65	14	CMT
28	23	11	1995	18	7	17	199	77	108	83	154	4	63	15	PDE
29	24	11	1995	16	43	46	253	73	161	85	210	16	111	27	Bad (1999)
30	11	12	1995	1	32	8.1	191	78	91	51	135	17	239	36	Bad (1999)
31	21	1	1996	4	59	51	132	30	326	61	257	73	52	16	CMT
32	21	2	1996	4	59	51	315	69	59	60	274	38	9	6	Atyia (1993)
33	14	12	1998	20	48	46	294	41	102	50	322	83	198	4	ENSN (2000)
34	11	10	1999	20	39	34	153	72	248	77	111	22	20	3	Bad (2001)
35	28	12	1999	12	5	10	137	59	250	57	103	48	188	1	Bad (2001)
36	25	6	2000	19	18	48	196	77	103	76	59	19	329	1	ENSN (2000)
37	29	6	2000	14	44	49	286	35	109	55	27	79	198	10	Bad (2005)
38	3	11	2000	21	19	3	319	77	56	63	275	29	10	9	ENSN (2000)
39	12	6	2001	12	43	27	112	35	283	48	194	35	81	6	Bad (2005)
40	20	8	2001	16	31	52	180	74	88	83	43	16	135	6	ENSN (2001)
41	19	11	2001	20	20	7.7	155	54	271	60	126	51	32	3	Bad (2005)
42	20	11	2001	7	42	48	22	76	124	49	17	79	39	334	This study
43	20	11	2001	7	56	28	83	72	174	86	16	40	9	309	This study
44	17	12	2001	4	25	33	127	37	302	53	196	82	34	8	Bad (2005)
45	7	8	2002	12	29	37	283	25	90	55	175	79	10	15	Bad (2005)
46	24	8	2002	20	1	21	291	52	68	47	264	67	0	2	ENSN (2002)
47	18	9	2002	14	56	59	349	45	81	81	315	21	210	18	Bad (2005)
48	10	10	2002	13	9	15	236	33	86	59	74	328	13	184	This study
49	5	12	2002	2	21	49	171	41	322	52	176	74	66	6	ENSN (2002)
50	25	3	2004	2	48	35	315	48	101	47	72	296	1	28	ENSN (2004)
51	16	8	2004	22	42	50	78	84	348	87	6	303	2	33	ENSN (2004)
52	12	12	2004	16	51	33	203	55	350	40	72	165	8	−82	This study
53	20	1	2005	13	41	50	11	43	230	54	69	198	5	302	ENSN (2005)

Table 3 (continued)

No.	Date			Time			Fault planes parameters				Stress axes				Ref.
	Day	Month	Year	Hours	Minutes	Seconds	NP1		NP2		*P* axis		*T* axis		
							St.1	Dip1	St.2	Dip2	St.	Dip	St.	Dip	
54	17	2	2005	10	21	22	278	51	152	53	60	124	1	215	ENSN (2005)
55	11	5	2005	23	9	26	346	84	249	45	36	219	25	109	ENSN (2005)
56	23	7	2005	14	56	19	182	60	283	72	35	146	8	50	ENSN (2005)
57	28	10	2005	17	1	37	282	43	155	61	59	114	10	222	ENSN (2005)
58	8	12	2005	1	28	12	281	43	151	59	62	113	8	219	ENSN (2005)

C (1966) Constantinescu et al. (1966), *Hu (1987)* Huang and Solomon (1987), *ME (1988)* Megahed and Dessouky (1988), *M (1989)* Mousa (1989), *H (1990)* Hassib (1990), *CMT* centroid moment tensor solution published by ISC, *S (2003)* Salamon et al. (2003), *PDE* preliminary determination of epicenter bulletins

trend along the Dead Sea basin. Topographically, the Dead Sea occupies the lowest portion of the subaerially exposed transform boundary. Arava fault bounds the eastern side of the Dead Sea basin, in spite of the structural expression of the fault diminishes to the north. The Jordan (Jericho) fault, a major sinistral fault en-echelon to the Araba, bounds the Dead Sea basin to the west. Hence, the Dead Sea occupies a rhomb–graben between two sinistral slip faults (Mechie et al. 2005).

The trenching studies across the Jordan (Jericho) fault indicate that two large earthquakes have occurred in the past 2,000 years: one between 200 BC and 200 AD while the other between 700 AD and 900 AD (Reches and Hoexter 1981). Both swarms characterize the Jordan–Dead Sea transform and with mainshock–aftershocks types of earthquake activity. El-Isa et al. (1984) attributed the swarm phenomenon to the subsurface magmatic activities and/or to the isostatic adjustments in the Gulf of Aqaba. The left-lateral distortion and dislocation of walls of an eighth century palace located west of the main trace of the Jordan fault (Reches and Hoexter 1981) indicate that not all the shear strain is accommodated along the main trace of the Jordan fault, but also some is distributed throughout a border area of the Jordan valley. Figure 8 shows the seismic sources in the Dead Sea rift. The average slip rate on the Dead Sea portion of the transform is estimated to be 0.7 cm/year (Reches and Hoexter 1981), which is consistent with the average slip of the overall plate boundary of 0.7–1.0 cm/year. The focal mechanism for some events in the Dead Sea like the 1971 earthquake shows a left-lateral strike–slip movement with normal component, while the strongest of the event occurred on July 11, 1927. Other three earthquakes have occurred in October 8, 1970, November 8, 1971, and September 2, 1973. The fault plane solution of these shocks indicated a left-lateral strike–slip movement with an average trend of 8–10° N (Ben-Menahem et al. 1976). Table 3 shows the parameters of the focal mechanism for some earthquakes, which are used for determining the Dead Sea zone.

Gulf of Suez Rift

This rift extends northwest along the Gulf of Suez and represents the northerly extension of the Red Sea rift. Much younger faulting was documented in the Gulf of Suez (Garfunkel and Bartov 1977), so the seismic expression of the ongoing information has to be expected. Gulf of Suez was considered to be aseismic during the first half of the last century and this led some researchers to conclude that all the present motion taking place in the Red Sea rift is transferred into a shear on the Dead Sea transform (Le Pichon and Gaulier 1988; Mart 1991). Ben-Menahem

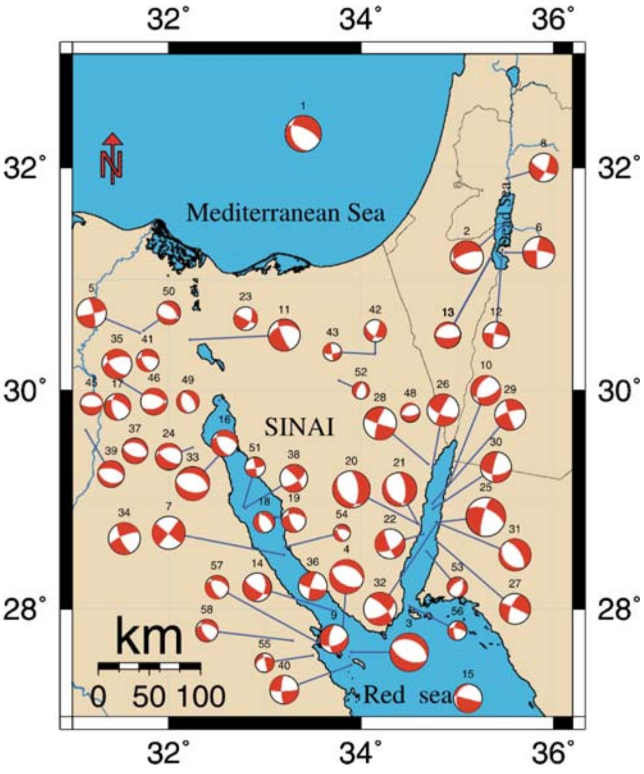

Fig. 8 Focal mechanisms for some selected earthquakes that affected Sinai

(1979) and Salamon et al. (1996) proved the present activity of the Suez rift. The epicentral distribution of the microearthquakes (Daggett et al. 1986) indicates the clustering of the events beneath Jubal Island and scattering of the events beneath the southern borders of the gulf. A linear regression fault plane analysis made of the projected hypocenters onto a vertical plane indicated fault planes strictly parallel or subparallel to the axis of the gulf. The fault plane solutions of the microearthquakes and March 31, 1969 earthquake indicate that this rift is active and consistent with the observations of Ben-Menahem and Aboodi (1971).

The high rate of seismicity at the southern end of the Gulf of Suez is attributed to the crustal movements among the Arabian plate, African plate, and the Sinai subplate, as a result of the opening of the Red Sea extension in the Gulf of Suez and the left-lateral strike–slip motion of the Gulf of Aqaba. Microearthquake studies (Daggett et al. 1986) as well as the observations of the National Research Institute of Astronomy and Geophysics (NRIAG) indicated that although the southern end of the Gulf of Suez is seismically active, activity extends along the length of the gulf. The epicenter distribution at the southern Gulf of Suez extends toward the active median zone of the northern Red Sea.

This belt is characterized by the occurrence of shallow, small–moderate, and large earthquakes. It includes more than 20% of the total earthquakes that were recorded in Egypt using ENSN. The seismological observations confirm the relatively high seismic activity for the southern tectonic province (SGS) of Meshref's model (1990) of the Gulf of Suez. The central tectonic province (CGS) is characterized by its low seismic activity. Therefore, each province can be considered as an independent seismogenic source and endorsing Meshref's model of the Gulf of Suez (Fig. 9).

The seismic activity of this zone is dispersed and declined and can be divided into four separate seismic zones as follows:

(a) Southern Gulf of Suez zone (SGS),
(b) Central Gulf of Suez zone (CGS),
(c) Northern Gulf of Suez zone (NGS).

Southern Gulf of Suez

This zone is characterized by its relative high seismic activity as a result to these movements in the southern part of the Gulf predominant tensile stresses (Shwartz and Arden 1960). Fairhead and Girdler (1971) postulated that the occurrence of a large earthquake (m_b=6.9) in the southern part of the Gulf of Suez zone on March 31, 1969 was preceded by three foreshocks and followed by 17 aftershocks (m_b=4.5–5.2) in the neighborhood of Shadwan Island. Maamoun and El-Khashab (1978) reported that 35 foreshocks during the last half of March 1969 preceded the mainshock. Mckenzie et al. (1970) and Mckenzie (1972) stated that a swarm of earthquakes occurred at this zone. Daggett et al. (1986) recorded a large number of microearthquakes at the southern part of the Gulf of Suez. The focal mechanism of the largest two earthquakes of March 31, 1969 and 1972, which occurred in the southern part, shows a normal faulting and this is in agreement with the main path Gulf of Suez itself.

Central Gulf of Suez

The focal mechanism of the Shukeir 1983 earthquake (m_b=5.3) that occurred at the central part of the Gulf of Suez shows a strike–slip faulting with minor normal component. This earthquake occurred on the transverse structure and not on the marginal faults of the Gulf of Suez (Maamoun 1985). The focal mechanism for smaller earthquakes (Abu El Enean 1997) shows the mixing between the marginal faults and transverse ones. Some of these earthquakes are nearly of a pure normal faulting, while others have a considerable strike–slip component. The seismic activity in the central province is low compared with both of the southern and northern provinces. This phenomenon has been clearly noticed after the establishment of ENSN.

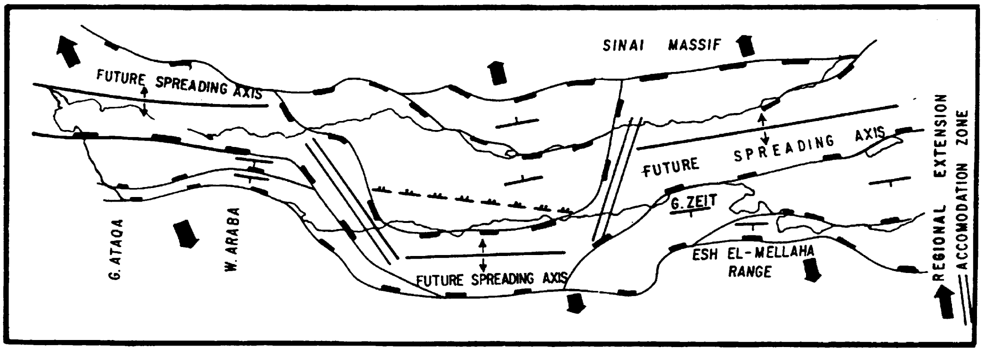

Fig. 9 Tectonic provinces of the Gulf of Suez (Meshref 1990)

Northern Gulf of Suez

This zone is located in the northern part of the Gulf of Suez and characterized by its high activity compared to the central part of the Gulf of Suez. Recordings of this activity are increased recently after the establishment of the ENSN.

Cairo–Suez District zone

North of the Gulf of Suez, eolian dunes and deltaic deposits of the River Nile cover the structures of the Suez rift. The focal mechanism for the Abu-Hammed 1974 earthquake (Mousa 1989; Hassib 1990) gave two planes trending ENE–WSW and NNW–SSE with left-lateral strike–slip motion along the second plane, while the focal mechanism of the Wadi-Hagul 1984 earthquake gave the same strike–slip with reverse component. In addition, the mechanism of the Ismailiya 1987 earthquake shows strike–slip also with two nodal planes trending N68° E, S24° E with steep dip angles (80° and 80°) (Megahed and Dessouky 1988).

The Cairo–Suez district is affected by three fault trends, one of them is the east–west trend, mostly pronounced and almost aligned by latitude 30° N where the other two trends (ENE and NW) are spatially more dispersed.

Eastern Mediterranean zone

According to geodynamic studies for the eastern Mediterranean region, it is concluded that this region is extremely complicated due to overall tectonic synthesis. Maamoun and Ibrahim (1978) attributed the activity of this zone to the continental shelf and the probable deep faults. This trend is parallel to the continental margin, which could be considered as a weak zone. This region suffers of thinning during the Triassic period (Ben-Avraham et al. 1987). The crustal structure at this region plays an important role in controlling the slip rate at trenches, causing active faulting at the passive margins and affecting the seismic pattern at the subduction zones. The offshore area has a severe shortage and the epicentral distribution may be negatively affected by this shortage. Depending on the distribution of earthquake epicenters and their fault plane solutions, this zone can be considered as one of seismic zones that affect only Sinai.

This zone is characterized by the occurrences of small and moderate–large earthquakes (Papazachos et al. 1984). According to the epicentral distribution of these earthquakes, it can be obviously stated that the general trend of this zone is in the NNE–SSW direction. With the establishment of the plate tectonics theory, this zone was recognized as a left-lateral transform between the Arabian and the African plates (Freund 1965; Ben-Menahem et al. 1976; Garfunkel 1981).

Furthermore, two local zones also affect the Sinai Peninsula by generating some small to moderate earthquakes, and these zones are as follows:

Central Negev shear zone

A narrow belt of E to ENE-oriented faults separates the north Sinai fold belt from the Tih Plateau (Fig. 1). This narrow fault corresponds to Shata's (1959) hinge belt and Bartov's (1974) Central Sinai–Negev shear zone. This belt separates a tectonically unstable crustal block in north Sinai from a tectonically stable crustal block in central and southern Sinai (Moustafa and Khalil 1994).

Central Sinai fault (Themed fault) zone

Themed fault have been rejuvenated along a preexisting fault marking the southernmost edge of the Early Mesozoic passive continental margin of the Eastern Mediterranean basin in central Sinai (Moustafa and Khalil 1995). The Tih Plateau is traversed by a very long E–W-oriented fault zone (the Themed fault), which extends for about 200 km from the vicinity of the eastern margin of the Suez rift to the Dead Sea transform (Said 1990). This east–west trending of dextral strike–slip faults with up to 2.5 km of displacement has been recognized in central Sinai by Steinitz et al. (1978).

Discussion and conclusions

Sinai Peninsula (subplate) is located between the Arabian and African plates from the eastern and western directions and is affected by the relative movements between these two plates. The reported earthquakes through the area of study are of crustal origin with shallower depths and some of these earthquakes are accompanied by considerable damages and economic losses. It is noticed that the recent earthquake activities are not only greater than the historical ones but also distributed all over the area which indicates the neotectonic reactivation models of the area. The occurrences of both historical and instrumental earthquakes, seismic activity parameters (a and b values), and fault plane solutions for major events suggest ten of seismotectonic source zones in and around Sinai Peninsula.

The value of constant a ranges from 1.42 to 4.71 for the whole region and its segments. It is clear that the level of seismicity in the southern Gulf of Suez is slightly higher than the central and northern Gulf of Suez segments. The value of a for the Gulf of Aqaba is greater than those of Araba Valley and Dead Sea portions.

The constant b for the Gulf of Aqaba–Dead Sea transform is 0.96, while it reaches about 0.813 for the Gulf of Suez rift and reaches to 0.75 for both Central Negev and Themed continental zones. This variation of *b* value reflects great variation for seismotectonic environments (Hatzdimitrio et al. 1985). It increases as the degree of heterogeneity increases and as the symmetry of the applied stress decreases (Mogi 1962). Accordingly, there are great heterogeneities surrounding the Sinai subplate (the eastern borders are greater than the western borders) and these explain—to a great extent—the variation in the earthquake activities from east to west. While inside the Sinai subplate, the value of *b* is lower than that of both Gulfs of Aqaba and Suez. There is an inverse relationship between the *b* value and the stress level and thus it can be used for earthquake prediction (Scholz 1968). This indicates the variation in the stress distribution in and around Sinai Peninsula (subplate).

This heterogeneity in the stress distribution and its related earthquake activities indicates the great variation in the level of seismic hazard for Sinai Peninsula especially along the eastern, northern, western, and southern coastal strips. More detailed hazard assessment studies for the existed and planned projects along these strips are strongly recommended.

References

Abdel Aal A, Day RA, Lelek JJ (1992) Structural evolution and styles of the northern Sinai, Egypt. Proceedings of the 11th Egyptian General Petroleum Corporation Exploration and Production Conference 1:546–562

Abdel Khalek ML, Abdel Wahed N, Sehim AA (1993) Wrenching deformation and tectonic setting of the northwestern part of the Gulf of Aqaba. Geol Soc Egypt Special Pub 1:409–444

Abu El Enean K (1997) A study on the seismotectonics of Egypt in relation to the Mediterranean and Red sea tectonics. Ph.D. Thesis, Faculty of Science, Ain Shams University, Cairo, Egypt

Ambraseys N, Melville CP, Adams RD (1994) The seismicity of Egypt, Arabia and the Red Sea, a historical review, King Abdul Aziz City for Science and Technology. Cambridge University Press, Amsterdam, p 137

Bartov VY (1974) A structural and Paleogeographical study of the central Sinai faults and domes. Ph.D. Diss, Hebrew Univ., Israel 134

Ben-Avraham Z (1985) Structural framework of the Gulf of Aqaba, northern Red Sea. J Geophys Res 90:703–726

Ben-Avraham Z, Almagor G, Garfunkel Z (1979) Sediments and structure of the Gulf of Aqaba–northern Red Sea. Sediment Geol 23:239–267

Ben-Avraham Z, Nur A, Cello G (1987) Active transcurrent fault system along the North African passive margin. Tectonophysics 41:260–294

Ben-Menahem A (1979) Earthquake catalogue for the Middle East (92 B.C.–1980 A.D.). Boll Geofis Teor Appl 21:245–310

Ben-Menahem A, Aboodi E (1971) Tectonic patterns in the Red Sea region. J Geophys Res 76:2674–2689

Ben-Menahem A, Nur A, Vered M (1976) Tectonics, seismicity and structure of the Afro-Euroasian junction—the breaking of an incoherent plate. Phys Earth Planet Inter 12:1–50

Constantinescu L, Ruprechtova L, Enescu D (1966) Mediterranean–Alpine earthquake mechanisms and their seismo-tectonic implications. Geophys J R Astron Soc 10:347–368

Daggett P, Morgan P, Boulos FK, Hennin SF, El-Sherif AA, El-Sayed AA, Basta NZ, Melek YS (1986) Seiosmicity and active tectonics of the Egyptian Red Sea Margin and the northern Red Sea. Tectonophysics 125:313–324

Dercourt J, Zonenshain LP, Ricou LE, Kazmin VG, Le Pichon X, Knipper AL, Grandjacquet C, Sbortshikov IM, Geyssant J, Lepverier C, Pechersky DV, Boulin L, Sibuet JC, Savostin LP, Sorokhtin D, Westphal M, Bazhenov ML, Laurer JP, Biju-Duval B (1986) Geological evolution of the Tethys belt from the Atlantic to the Pamirs since the Lias. Tectonophysics 123:241–315

Egyptian National Seismological Network (ENSN) (2000) Egyptian Seismological Bulletin 1:52

Egyptian National Seismological Network (ENSN) (2001) Egyptian Seismological Bulletin 2:54

Egyptian National Seismological Network (ENSN) (2002) Egyptian Seismological Bulletin 3:77

Egyptian National Seismological Network (ENSN) (2004) Egyptian Seismological Bulletin 4:69

Egyptian National Seismological Network (ENSN) (2005) Egyptian Seismological Bulletin 5:83

El-Azoni MA (1992) Two-dimensional gravity modeling of the basement down to Mohorovicic discontinuity, northern Western Desert, Egypt. Proceedings of the 11th Egyptian General Petroleum Corporation Exploration and Production Conference Cairo 2:427–434

El-Hadidy S, Mohamed A, Albert RNH (1998) Characteristics of earthquakes activity along the Gulf of Aqaba. Ain Shams University, Faculty of Science Bulletin 36:111–152

El-Isa ZH, Merghelani H, Bazari M (1984) The Gulf of Aqaba earthquake swarm of 1983 January–April. Geophys J R Astron Soc 78:711–722

El-Isa ZH (1985) Earthquake studies of some archaeological sites in Jordan. Oxford Conf. Archaeol. Jordan 2:229–236

El-Isa ZH, Hasweh NK (1988) Seismicity of the southern Jordan–Dead Sea transform. Proceedings of the 3rd Arab Seismological Workshop, March 1986, pp 47–58

El-Isa ZH, El Shanti A (1989) Seismicity and tectonics of the Red Sea and western Arabia. Geophys J 97:449–457

El-Shahat AM (2000) Seismotectonics of the Gulf of Aqaba, Egypt. M.Sc. Thesis, Faculty of Science, Ain Shams University, Cairo

Eyal M, Eyal Y, Bartov Y, Steinitz G (1981) The tectonic development of the western margin of the Gulf of Eilat (Aqaba) rift. Tectonophysics 80:39–66

Fairhead JD, Girdler R (1971) The seismicity of Africa. Geophys J R Astron Soc 24:271–301

Freund R (1965) A model of the structural development of Israel and adjacent areas since upper Cretaceous times. Geol Mag 102:189–205

Freund R, Zak I, Garfunkel Z (1968) Age and rate of sinistral movement along the Dead Sea rift. Nature 220:253–255

Freund R, Garfunkel Z, Zak I, Goldberg M, Weissbrod T, Derin B (1970) The shear along the Dead Sea Rift. Philos Trans R Soc Lond A 267:107–130

Garfunkel Z (1974) The Tectonics of the western margins of the south Arava. Ph.D. Thesis, Hebrew Univeristy, Jerusalem, p 204

Garfunkel Z (1981) Internal structure of the Dead Sea leaky transform (rift) in relation to plate kinematics. Tectonophysics 80:81–108

Garfunkel Z, Bartov Y (1977) The tectonics of the Suez Rift. Israel Geological Survey Bulletin 71:44

Garfunkel Z, Zak Y, Freund R (1981) Active faulting in the Dead Sea rift. Tectonophysics 80:1–26

Gergawi A, El-Khashab H (1968) Seismicity of U.A.R. Helwan Observatory Bulletin No. 76

Gerson R, Grossman S, Amit R, Greenbaum N (1993) Indicators of faulting events and periods of quiescence in desert alluvial fans. Earth Surf Processes Landf 18:181–202

Ginzburg A, Gvirtzman G (1979) Changes in the crust and sedimentary cover across the transition from the Arabian refraction and sedimentary studies in Israel and north Sinai. Sediment Geol 23:19–36

Ginzburg A, Makris J, Fuchs K, Prodhel C, Kaminski W, Amitai U (1979) A seismic study of the crust and upper-mantle of the Jordan–Dead Sea rift and their transition toward the Mediterranean Sea. J Geophys Res 84:1569–1582

Gutenberg B, Richter CF (1944) Frequency of earthquakes in California. Bull Seismol Soc Am 34:185–188

Gutenberg B, Richter CF (1954) Seismicity of the earth and associated phenomena, 2nd edn. Princeton University Press, Princeton, NJ

Hassib GH (1990) A study of focal mechanism for recent earthquakes in Egypt and their tectonic implication. M.Sc. Thesis, Faculty of Science, Assiut University, Egypt

Hatzdimitrio P, Papadimitio E, Mountrakis D, Papazachos B (1985) The seismic parameter b of the frequency–magnitude relation and its association with the geological zones in the area of Greece. Tectonophysics 120:141–151

Huang PY, Solomon SC (1987) Centroid depth and mechanisms of mid-ocean ridge earthquakes in the Indian Ocean, Gulf of Aden and Red Sea. J Geophys Res 92:1361–1382

Isacks B, Oliver J (1964) Seismic waves with frequencies from 1 to 100 cycles per second recorded in the deep mine in the northern New Jersey. Bull Seismol Soc Am 54:1941–1979

ISC (1964–1993) Bulletin of the International Seismological Centre, Edinburgh

Ismail A (1960) Near and local earthquakes of Helwan (1903–1950). Helwan Observatory Bulletin No. 49

Joffe S, Garfunkel Z (1987) Plate kinematics of the Circum Red Sea—a re-evaluation. Tectonophysics 141:5–22

Karnik V (1969) Seismicity of the European area, part I. Reidel, Dordrecht, p 364

Kebeasy RM (1990) Seismicity of Egypt. In: Said R (ed) Geology of Egypt. Balkema, Rotterdam, The Netherlands, pp 51–59

Krenkel E (1925) Geologie Afrikas. Gebruder, Berlin, p 461

Le Pichon X, Francheteau J (1978) A plate-tectonic analysis of the Red Sea–Gulf of Aden area. Tectonophysics 46:369–406

Le Pichon X, Gaulier JM (1988) The rotation of Arabia and the Levant fault system. Tectonophysics 153:271–294

Lyberis N (1988) Tectonic evolution of the Gulf of Suez and the Gulf of Aqaba. Tectonophysics 153:209–220

Maamoun M (1985) Shukeir earthquake June, 12th, 1983, Gulf of Suez, Egypt: radiation pattern of first motion and its tectonic implication. HIAG Bull 5, Ser. B

Maamoun M, El Khashab H (1978) Seismic studies of Shadwan (Red Sea) earthquake. Bulletin of Helwan Institute of Astronomy and Geophysics 184:12

Maamoun M, Ibrahim EM (1978) Tectonic activity of Egypt as indicated by earthquakes. Bulletin of Helwan Institute of Astronomy and Geophysics (HIAG), No. 170

Maamoun M, Megahed A, Allam A (1984) Seismicity of Egypt. Bulletin of Helwan Institute of Astronomy and Geophysics, IV, Ser. B:109–160

Mart Y (1991) The Dead Sea Rift: from continental rift to incipient ocean. Tectonophysics 197:155–179

Marzouk I (1988) Study of crustal structure of Egypt deduced from deep seismic and gravity data. Ph.D. Thesis, Institute of Geophysics, University of Hamburg

May PR (1991) The Eastern Mediterranean Mesozoic basin: evolution and oil habitat. Am Assoc Pet Geol Bull 75:1215–1232

McKenzie D (1972) Active tectonics of the Mediterranean region. Geophys J R Astron Soc 30:109–185

McKenzie DP, Davies D, Molnar P (1970) Plate tectonics of the Red Sea and East Africa. Nature 226:243–248

Mechie J, Abu-Ayyash K, Ben-Avraham Z, El-Kelani R, Mohsen A, Rumpker G, Saul J, Weber M (2005) Crustal shear velocity structure across the Dead Sea Transform from two-dimensional modeling of DESERT project explosion seismic data. Geophys J Int 160:910–924

Megahed A, Dessouky M (1988) The Ismailia (Egypt) earthquake of January 2nd, 1987 (Location, macroseismic survey, radiation pattern of first motion and its tectonic implications). In: 1st Conference on Environmental Studies and Research, Cairo, Egypt

Merghalani H, Bazari M (1984) The Gulf of Aqaba earthquake swarm of 1983. Geophys J R Astron Soc 76:711–722

Meshref WM (1990) Tectonic framework of Egypt. In: Said R (ed) Geology of Egypt. Balkema, Rotterdam, The Netherlands, pp 113–156

Mogi K (1962) Study of the elastic shocks caused by the fracture of heterogeneous materials and its relations to earthquake phenomena. Bull Earthq Res Inst 40:27–30

Mousa HM (1989) Earthquake activities in Egypt and adjacent regions and its relation to geotectonic features in A. R. Egypt. M.Sc. Thesis, Faculty of Science, Mansoura University

Moustafa AR, Khalil M (1988) Late Cretaceous–Early Tertiary dextral transpression in north Sinai: reactivation of the Tethyan continental margin. In: American Association of Petroleum Geologists, Mediterranean Basins Conference, Nice

Moustafa AR, Khalil MH (1989) North Sinai structures and tectonic evolution. Middle East Research Center, Ain Shams University, Earth Science Series 3:215–231

Moustafa AR, Youssif MS (1990) Two-stage wrench deformation at Gebel El Minsherah, north Sinai. Middle East Research Center, Ain Shams University, Earth Science Series 4:112–122

Moustafa A, Khalil MH (1993) Rejuvenation of the eastern Mediterranean Passive continental margin in northern and central Sinai: new dat from the Themed Fault. Geol Mag 131(4):435–448

Moustafa AR, Khalil MH (1994) Rejuvenation of the eastern Mediterranean passive continental margin in northern and central Sinai: new data from the Themed Fault. Geol Mag 131(4):435–448

Moustafa AR, Khalil SM (1995) Rejuvenation of the Tethyan passive continental margin of northern Sinai: deformation style and age (Gebel Yelleq area). Tectonophysics 241:225–238

Moustafa AR, Khawasik SM, Khalil SM (1991) Late Cretaceous–Tertiary rotational deformation in north Sinai (Gebel Yelleq area). Jahrb Geol Palaontol Monatsh 11:643–653

Papazachos BC, Kiratzi AA, Hatzidimitriou PM, Rocca AC (1984) Seismic faults in the Agean area. Tectonophysics 106:71–85

Poirier JP, Taher MA (1980) Historical seismicity in the Near and Middle East, North Africa and Spain from Arabic documents (VIIth–XVIIth century). Bull Seismol Soc Am 70:2185–2201

Reches Z, Hoexter DF (1981) Holocene seismic activity in the Dead Sea area. Tectonophysics 80:235–254

Sadek H (1928) The principal structural features of the Peninsula of Sinai. Proceedings of the 14th International Geological Congress 3:895–900

Said R (1990) The geology of Egypt. Balkema, Rotterdam, Netherlands, p 734

Salamon A, Hofstetter A, Garfunkel Z, Ron H (1996) Seismicity of the Eastern Mediterranean region: perspective from the Sinai subplate. Tectonophysics 263:293–305

Salamon A, Hofstetter A, Garfunkel Z, Ron H (2003) Seismotectonics of the Sinai subplate–the eastern Mediterranean region. Geophys J Int 155:149–173

Salem EM (1997) Seismicity study for El-Maghara area, Northern Sinai. M.Sc. Thesis, Faculty of Science, Alazhar University

Scholz CH (1968) The frequency–magnitude relation of microfracturing in rock and its relation to earthquakes. Bull Seismol Soc Am 58:399–415

Shapira A, Jarradat M (1995) Earthquake risk and loss assessment in Aqaba and Eilat regions. Submitted to the U.S. Aid-Merc Program

Shata A (1959) Structural development of the Sinai Peninsula (Egypt). Proceedings of the 20th International Geological Congress 1956, Mexico, pp 225–249

Shwartz DH, Arden D (1960) Geological history of the Red Sea area. Bull Am Assoc Pet Geol 44:1621–1637

Sieberg A (1932) Handbuck der Geophysik, Band IV, Erdbebengeographie, Borntraeger, Berlin, pp 527–1005

Steinitz G, Bartiv Y, Hunziker J (1978) K/Ar age determination of some Miocene–Pliocene basalts in Israel: their significance to the tectonic of the Rift Valley. Geol Mag 115:329–340

Tealeb A (1985) Spectral analysis of the gravimetric Bouguer anomaly of Egypt for crustal thickness studies. Bulletin of Helwan Institute of Astronomy and Geophysics 5B:63–82

Youssef MI (1968) Structural pattern of Egypt and its interpretation. Am Assoc Pet Geol Bull 52:601–614