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Seismic Hazard of Egypt

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Abstract. Earthquake hazard parameters such as maximum expected magnitude, M_{max}, annual activity rate, λ, and b value of the Gutenberg–Richter relation have been evaluated for two regions of Egypt. The applied maximum likelihood method permits the combination of both historical and instrumental data. The catalogue used covers earthquakes with magnitude $\geqslant 3$ from the time interval 320–1987. The uncertainties in magnitude estimates and threshold of completeness were taken into account. The hazard parameter determination is performed for two study areas. The first area, Gulf of Suez, has higher seismicity level than the second, all other active zones in Egypt. b-values of 1.2 ± 0.1 and 1.0 ± 0.1 are obtained for the two areas, respectively. The number of annually expected earthquakes with magnitude $\geqslant 3$ is much larger in the Gulf of Suez, 39 ± 2 than in the other areas, 6.1 ± 0.5. The maximum expected magnitude is calculated to be 6.5 ± 0.4 for a time span of 209 years for the Gulf of Suez and 6.1 ± 0.3 for a time span of 1667 years for the remaining active areas in Egypt. Respective periods of 10 and 20 years were reported for earthquakes of magnitude 5.0 for the two subareas.

Key words. Egypt, seismic hazard, maximum expected magnitude, annual activity, b-value.

1. Introduction

The quantitative knowledge of seismic hazard for Egypt is important both from the viewpoint of safety for existing structures as well as of further socioeconomic development of the country. Maamoun and Ibrahim (1978) and Maamoun *et al.* (1980) studied both historical and recent earthquakes in Egypt together with focal mechanism solutions of some shocks. They identified two main seismic zones in and around Egypt: the Red Sea–Gulf of Suez seismic zone and the Egypt-Mediterranean coastal zone. They also suggested the existence of three local zones: the Aqaba-Qena zone, Gilf El Kebir-Abu Roash zone and Gaghbub–Ryan zone.

The most active zones nowadays are the Gulf of Suez and several local zones such as Aswan and Kalabsha areas. On 31 March 1969 an earthquake with magnitude $m_b = 6.3$, $M_s = 6.9$ occurred at the entrance of the Gulf of Suez, causing severe damage in Egypt and being strongly felt also in Saudi Arabia (USCGS report). More recently, on 14 November 1981 an earthquake with $m_b = 5.3$, $M_s = 5.6$ occurred in the Aswan area. Eleven buildings were damaged and surface faulting was reported in the epicentral area (NEIS report). The most recent damaging earthquake occurred on 12 October 1992, with $m_b = 5.9$, $M_s = 5.3$ (PDE determination) close to the Cairo area. It was one of the largest earthquakes in Egypt during this century. According to PDE report, at least 541

people were killed, 6500 people were injured and 8300 buildings were damaged or destroyed in the Cairo area only. Preliminary estimation of damages indicate losses of about US$300 million. Reports reveal that many historical constructions (i.e., mosques, pyramides and temples) suffered from the earthquake. The 1992 earthquake is not included here since our analysis is limited to data up to 1987. Generally speaking, earthquakes such as those in 1969, 1981, and 1992 can affect sensitive structures and buildings. To establish an idea about the limits of seismic risk in Egypt, seismic hazard analysis was carried out using the method of maximum likelihood of Kijko and Sellevoll (1990). This method combines scattered data of large historical earthquakes with more consistent data of recent, instrumentally detected earthquakes. This is a suitable method for Egypt, where earthquake data from different time periods have different degree of homogeneity. In the present analysis, two sets of data covering the major seismic zones were treated separately. The two sets comprise (1) Gulf of Suez and (2) the other active zones in Egypt (Figure 1).

2. Comment on the Method

The applied procedure (Kijko and Sellevoll, 1990) is a maximum-likelihood method for estimating the earthquake hazard parameters, such as maximum magnitude, M_{max}, annual activity rate, λ, and b parameter of the Gutenberg–Richter relation. The method allows us to use a catalogue containing different parts: Macroseismic information of strong historical earthquakes as well as instrumental data of more recent events. The former part will hereafter be referred to as the extreme part and the latter as the complete part of the catalogue. The complete part in turn comprises several subparts with different magnitude thresholds of completeness. The method of Kijko and Sellevoll also permits gaps in the data sets, i.e., periods with no reported events. Two values, the upper and the lower magnitude bounds, are given for each event, and this interval is presumed to include the real value.

Actually, the maximum-likelihood procedure is applied when evaluating parameters λ and b. The basic assumptions behind the probability calculations are the Poisson distribution of earthquakes with an activity rate λ and the doubly truncated Gutenberg–Richter distribution of magnitude. Further information has to be utilized for evaluation of M_{max}. Here, the evaluation is performed on the basis of earlier experimental results according to which the largest observed magnitude of the data set provides a sufficient evaluation of the largest expected magnitude. The theory is presented in detail in Kijko and Sellevoll (1990).

3. Earthquake Data

A search for earthquake data was made by using ISC, NEIS and other catalogues. Various publications, in particular the work of Maamoun et al. (1984), were
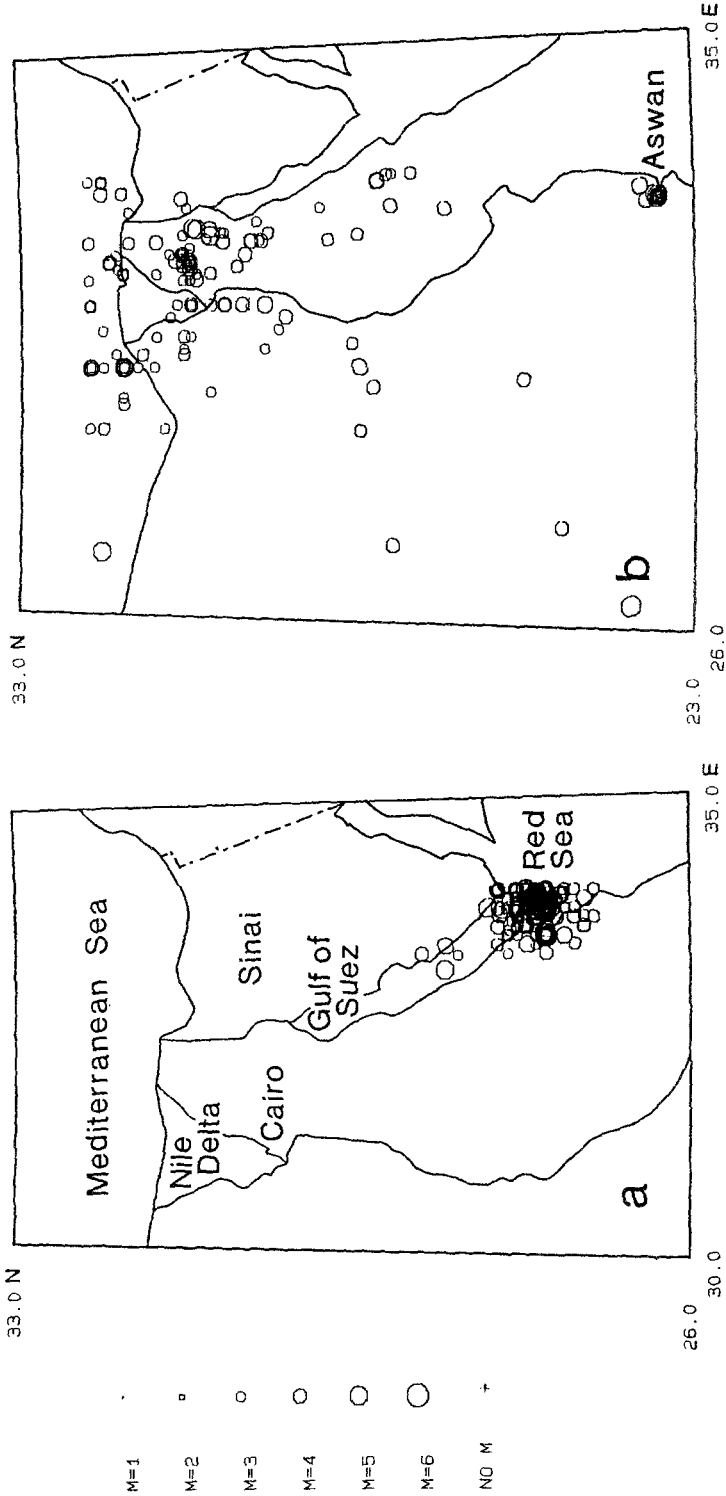
Fig. 1. Distribution of instrumental earthquake epicentres in the two subareas considered in this analysis: (a) Gulf of Suez; (b) other active zones in Egypt. Size of the circles is proportional to magnitude in the range $3.0 \leqslant m_b \leqslant 7.0$. Time period covered is 1906–1987.

considered as well. Comparison between the available data sets showed that the ISC bulletins are complete for earthquakes of magnitude >3.5, while the Maamoun *et al.* (1984) catalogue contains also many smaller events not found in ISC bulletins. The data set we used was derived from the ISC and Maamoun *et al.* (1984) catalogues. To homogenize magnitudes from the two catalogues we used a formula by Maamoun *et al.* (1984). Since earthquakes with small magnitude can be neglected in the context of the present study, our analysis was limited to earthquakes with magnitude ⩾3. Altogether, 956 such earthquakes are reported to have occurred in Egypt in the time period 1906–1987, many with relatively high magnitudes. The largest and most destructive events were already mentioned above.

A similar search was made in a number of publications concerning the historical earthquakes. These include Gutenberg and Richter (1954), Ambraseys (1975, 1983), Poirier and Taher (1980) and Maamoun *et al.* (1984). In total, 22 earthquakes with intensity ⩾VII and probable magnitude ⩾4.5 were found to occur during the time period 320–1906. Another 10 earthquakes had to be ignored because of insufficient information about the magnitude and epicentre location. However, the rest of the earthquakes are well described by Maamoun *et al.* (1984) who provide areas of maximum damages, probable upper and lower limits of magnitudes and intensities as well as other associated features.

4. Subareas

Due to large differences in seismicity level, the area under study was divided into two subareas. The geographic location of earthquake epicentres in the two subareas is shown in Figure 1.

The first subarea is the Gulf of Suez, which represents the most active zone in Egypt. Historically, this area was affected by many earthquakes in the magnitude range 4.0–6.2 (Ismail, 1960; Gergawi and Khashab, 1968; Maamoun *et al.*, 1984). Recently, Daggett *et al.* (1986) reported that on average some 25 earthquakes with magnitude 0.7–3.1 occur daily and swarms with some 200 earthquakes occur once per week in this area. The activity in the Gulf of Suez is related to a number of tectonic elements, like the Red Sea rift axis and the moving adjacent Arabian, Sinai and African plates (Courtillot *et al.*, 1987; Gaulier *et al.*, 1988; Martinez and Cocheran, 1988). Kulhánek *et al.* (1992a, b) showed that the maximum activity is noticed where two or more tectonic elements interact with each other. In total, 688 earthquakes with magnitude ⩾3 are reported to have occurred in this subarea in the time period 1906–1987.

The second subarea includes the Egypt-Mediterranean coastal zone and all other local zones in Egypt (Figure 1). Historically, many earthquakes with magnitudes 4.5–6.5 have taken place in these areas (Maamoun *et al.*, 1984). Also recently, several strong earthquakes occurred there. For example, in 1978 and 1981 Gilf El-Kabir and Kalabsha (Aswan) were shaken by earthquakes with magnitudes 5.1

and 5.6, respectively. El-Shazly *et al.* (1979) and Issawi (1981) studied some of these local zones and concluded that they are structurally controlled by many faults of Miocene–Oligocene age. The distribution of earthquakes epicentres is concentrated along these faults (Kebeasy *et al.*, 1981). More recent studies reveal that there is an on-going reactivation of some of these Miocene–Oligocene faults (El-Sayed, 1989; Mousa, 1989). Altogether, 268 earthquakes with magnitude ⩾3 were reported during the time period 1906–1987 in this subarea.

5. Subcatalogues

The compiled set of data used in the present calculation (all earthquakes with magnitude ⩾3) was divided into two main parts, the extreme part (historical data) and the complete part (instrumental data).

The time period before 1906 was considered to be the extreme part. Four earthquakes with magnitude ⩾5.0 were reported from the Gulf of Suez subarea during the time period 1778–1905. Eighteen earthquakes with probable magnitude ⩾4.5 were reported from the other active zones in Egypt in the time period 320–1905. Most of these earthquakes occurred in the Egypt-Mediterranean coastal zone and two in the Aswan area (Maamoun *et al.*, 1984). The assigned magnitude uncertainty for each historical event is 0.35 or 0.7 as given by Maamoun *et al.* (1984) and as judged by the present authors from uncertainties of macroseismic parameters. The smaller value of uncertainty is ascribed to larger earthquakes with better known geological land features and macroseismic data and the larger value to smaller events with more uncertain data (Maamoun *et al.*, 1984).

The first instrumental data are from 1906, which is here, therefore, chosen as the beginning of the complete part of the catalogue. The complete part was subdivided into two subcatalogues based on the frequency of seismic events (Figure 2). The first subcatalogue corresponds to the period prior to WWSSN operation, i.e., to the interval 1906–1961. In total, 36 earthquakes (magnitude ⩾3) were reported from the Gulf of Suez and 87 earthquakes from the other active zones in Egypt during this time period. Frequency-magnitude diagrams (Figures 3a, 4a) provide reliable indications about the threshold magnitude. As follows from the figures, a magnitude about 5 seems to be a reasonable threshold-magnitude estimate for both subareas. An interval of 0.3 was considered as a realistic magnitude uncertainty for earthquakes of this part of the catalogue. This estimate is a compromise between the magnitude error of the historical data (0.7 or 0.35) and the magnitude error of the more recent data (0.25). Maamoun *et al.* (1984) gave the same value (0.3) for events in this time interval.

The second complete subcatalogue covers roughly the period of operation of the WWSSN, i.e., 1962–1987. As can be seen in Figure 2, the seismicity is at a higher level in the mid 1950s but decreases in the late 1950s. Since 1962, the rate of activity is continuously high. Two earthquake swarms were noticed in this time period, the Shadwan swarm in 1969 and Aswan swarm in 1981 (Figure 2). During
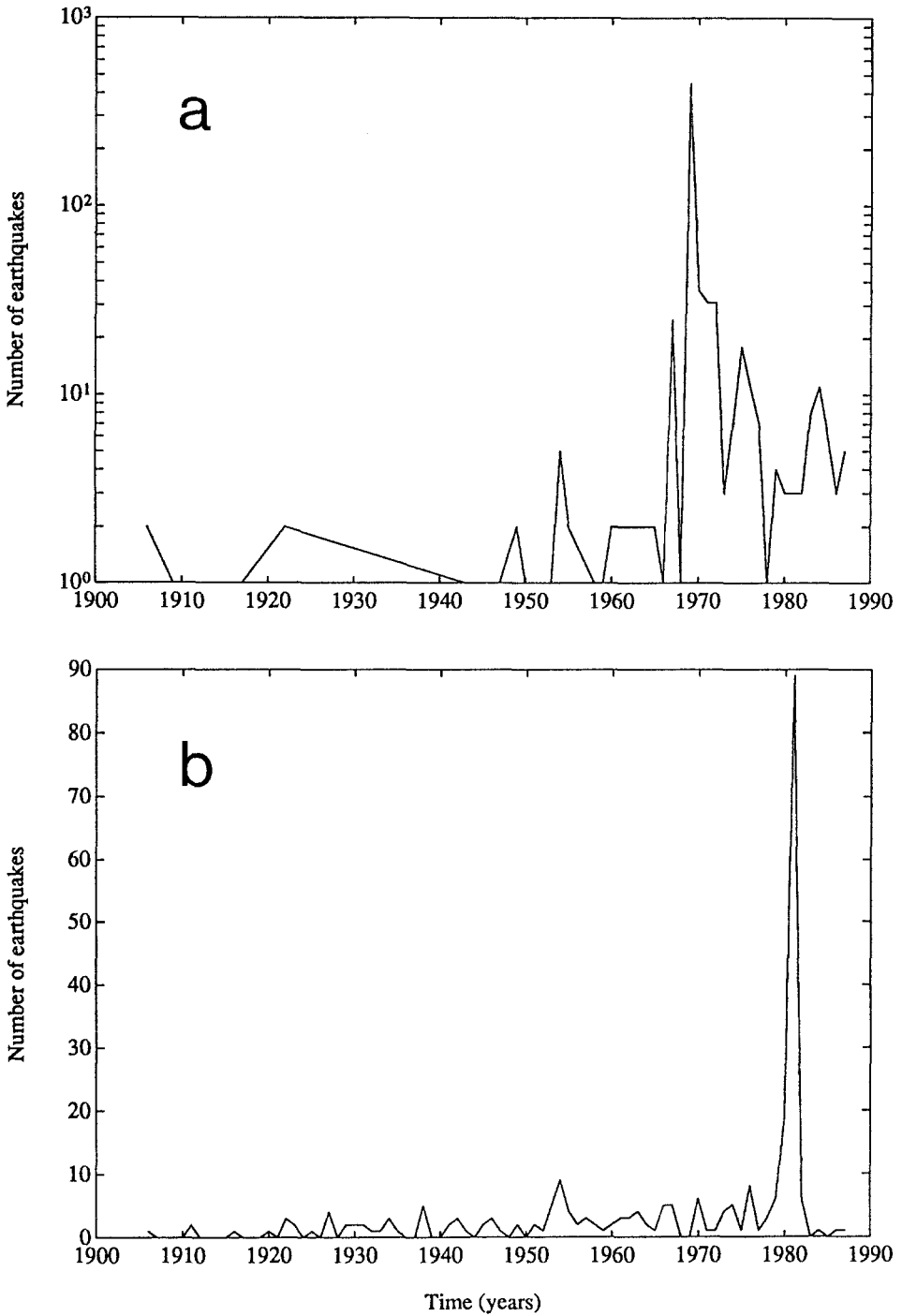
Fig. 2. Temporal annual variation of seismic activity, $m_b \geqslant 3.0$, based on instrumental data: (a) Gulf of Suez; (b) other active zones in Egypt.
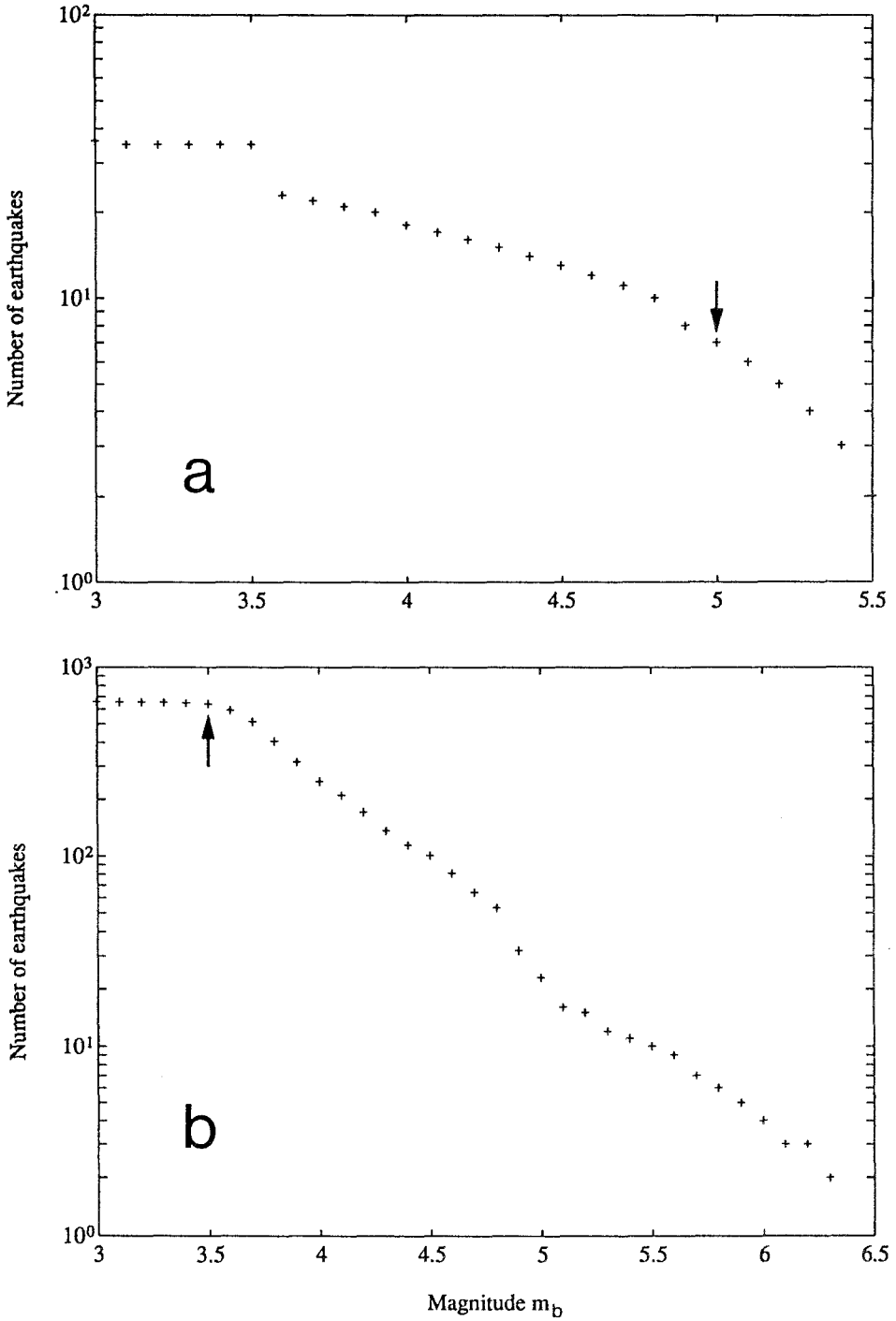
Fig. 3. Frequency-magnitude distribution for the Gulf of Suez area and two different time periods: (a) 1906–1961; (b) 1962–1987. Arrows indicate thresholds of completeness.
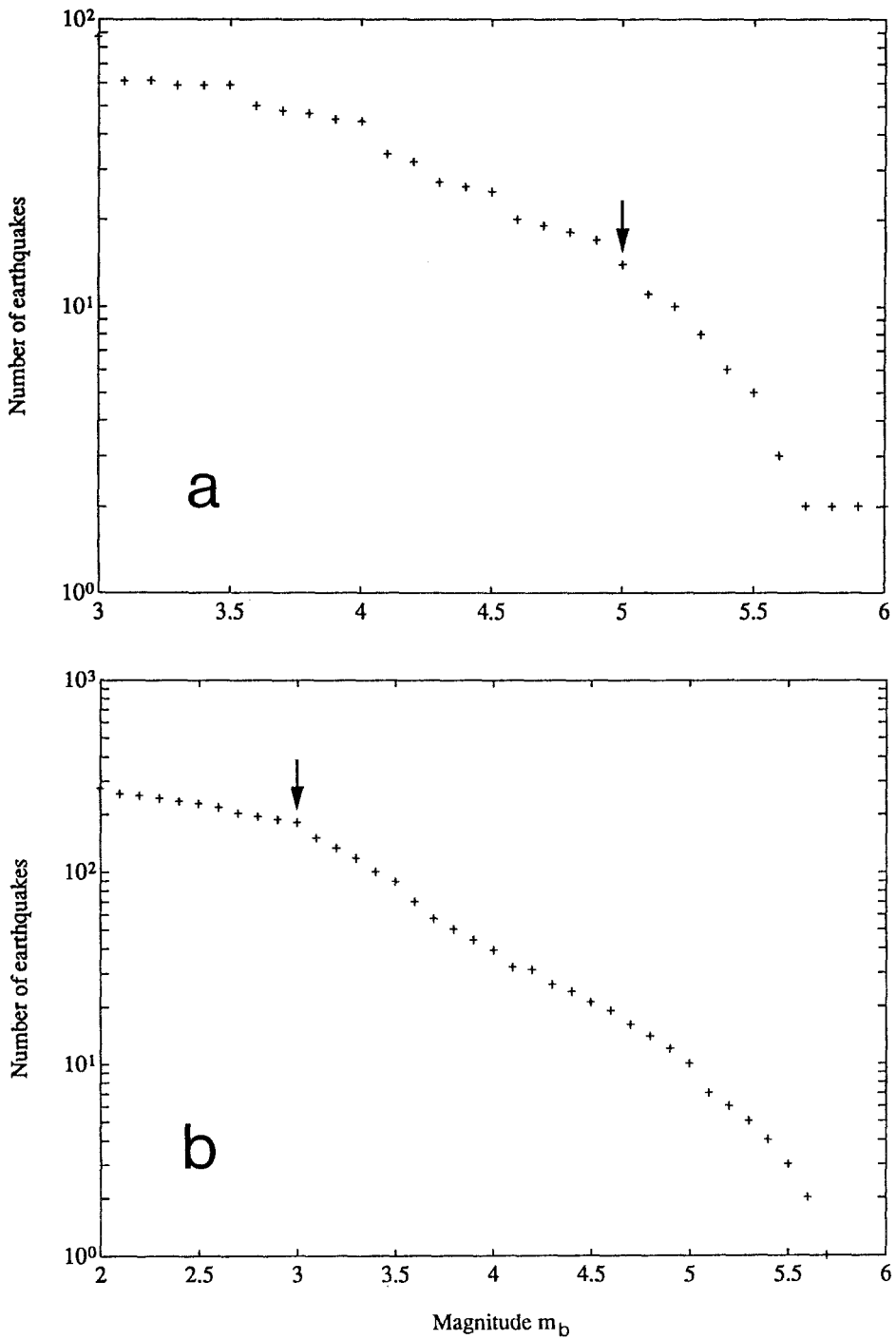
Fig. 4. Frequency-magnitude distribution for other active zones in Egypt and two different time periods: (a) 1906–1961; (b) 1962–1987. Arrows indicate thresholds of completeness.

Table I. Time period, threshold magnitude (TM), magnitude uncertainty (ME) and number of earthquakes (N) for various subcatalogues

Subcatalogue	Time period	Gulf of Suez area			Other active zones in Egypt		
		TM	ME	N	TM	ME	N
Extreme	*	–	**	4	–	**	18
Complete 1	1906–1961	5.0	0.30	36	5.0	0.30	87
Complete 2	1962–1987	3.5	0.25	652	3.0	0.25	181

* 1778–1905 for the Gulf of Suez; 320–1905 for the other active zones.
** 0.35 or 0.70 (see text).

Table II. Seismic hazard parameters

Parameter	Gulf of Suez area	Other active zones in Egypt
b	1.2 ± 0.1	1.0 ± 0.1
λ^a	39.0 ± 2.0	6.1 ± 0.4
M_{max}	6.5 ± 0.4	6.1 ± 0.3

[a] Threshold magnitude of 3.5 for the Gulf of Suez and 3.0 for the other active zones in Egypt.

this period, 652 earthquakes (magnitude ≥ 3) were reported from the Gulf of Suez and 181 from the other active zones. To examine the threshold magnitude in the other active zones, the frequency-magnitude analysis was extended down to magnitudes ≥ 2. As a result, threshold estimates of 3.5 and 3.0 were obtained for the Gulf of Suez and the other active zones in Egypt, respectively (Figures 3b, 4b). Maamoun *et al.* (1984) calculated the threshold magnitude based on all Egyptian earthquake data to 5.0 and 3.6 for the time periods 1906–1961 and 1962–1987, respectively, which is in good accordance with our values. A magnitude uncertainty of 0.25 is taken from Maamoun *et al.* (1984).

Table I summarizes the time periods, threshold magnitudes, magnitude uncertainties and total number of earthquakes obtained for various subcatalogues.

6. Results

Estimates of b, λ and M_{max} calculated for the Gulf of Suez and areas containing the other active zones in Egypt are given in Table II. The relative contribution of data provided by the various subcatalogues in the calculation of b and λ are given in Table III. An independent test has been done by calculating the b-values for Egypt and the Gulf of Suez using the maximum likelihood method of Aki (1965) and Utsu (1966). Obtained average values of 1.2 (Gulf of Suez) and 1.0 (other areas) are in excellent agreement with those given by the present method (Table II). El-Isa and Al-Shanti (1989) and Reborto *et al.* (1992) calculated b for different areas along the Red Sea. For the northern Red Sea area, the lowest values of 0.6 and 0.86 were obtained in the two investigations respectively, for the Gulf of Suez.

Table III.   Relative contribution (%) of various subcatalogues for computation of b and λ

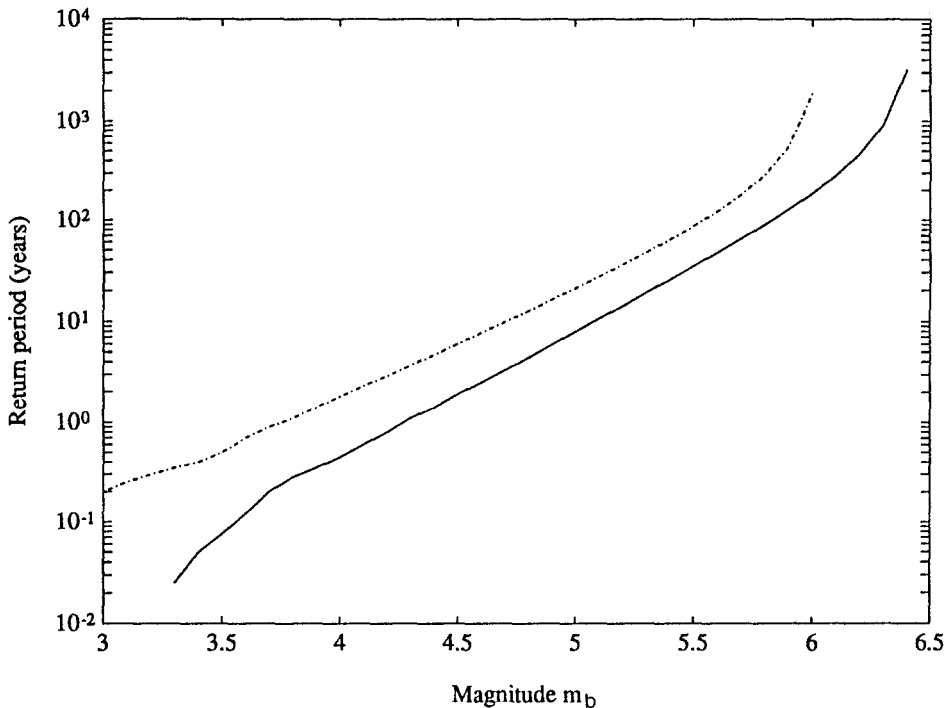| Subcatalogue	Gulf of Suez area		Other active zones in Egypt	
	b	λ	b	λ
Extreme	48	0.9	78	7.7
Complete 1	7	0.8	6	7.1
Complete 2	45	98.3	16	85.2

Fig. 5.   Mean return periods for earthquakes in the Gulf of Suez (solid line) and the other active zones in Egypt (dashed line).

Mean return periods and probabilities of nonexceedance are summarized in Figures 5 and 6, respectively. The annual rate of occurrence and the return period for earthquakes with magnitude 6.0 were also calculated by El-Isa and Al-Shanti (1989) and Reborto *et al.* (1992) for the Gulf of Suez. Their values of the return period (53 and 70 years respectively) are significantly lower than ours, given in Figure 5. This discrepancy is most likely due to the rather small number of events which they have been using in the calculations.

As shown in Table II, the maximum expected magnitude in the Gulf of Suez is 6.5 ± 0.4 for a time period equal to the length of the catalogue, i.e., 210 years.
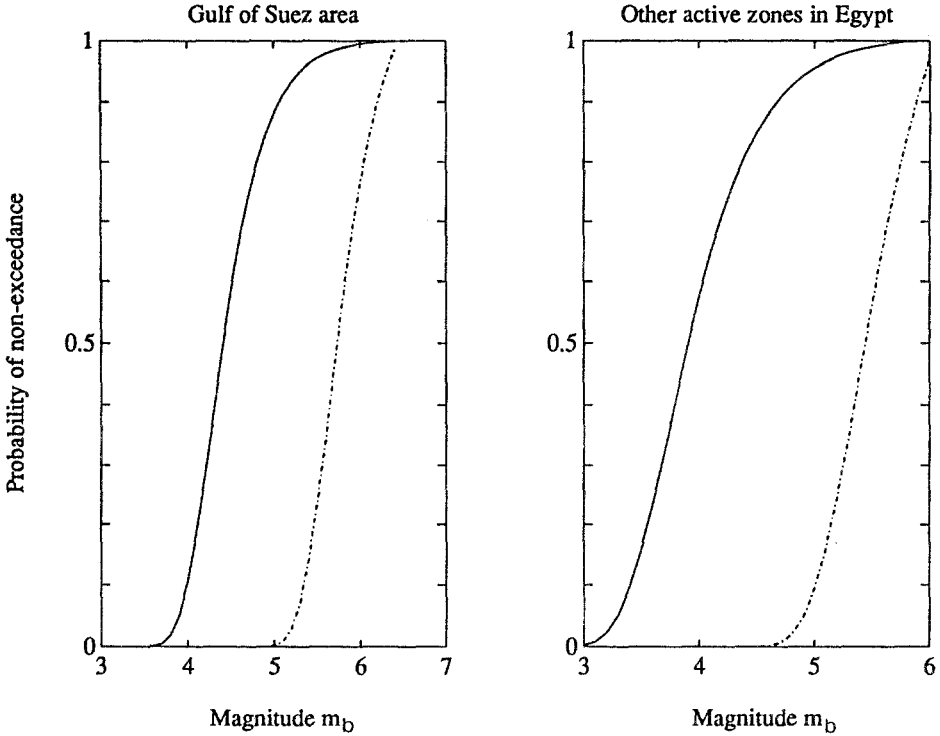
Fig. 6. Probability of nonexceedance for the two subregions. Solid and dashed lines represent probability of nonexceedance in one and 50 years, respectively.

For the other active zones in Egypt, the maximum expected magnitude is 6.1 ± 0.3 for a time span of 1668 years.

7. Discussion

Calculated b-values for different areas reflect the various tectonic situations. The b-value can serve as an indicator of stress concentration, crack density and degree of heterogeneity. As the crustal deformation increases, the b value decreases. For example, in Japan and Taiwan, small b values were observed in areas of high crustal deformation (Mogi, 1962; Welkner, 1967; Wang, 1988). Recent seismic and gravity studies (Bayoumi, 1983; Martinez and Cocheran, 1988; Gaulier *et al.*, 1988) show that the Gulf of Suez is highly deformed and has rather heterogeneous crustal structure. Also, El-Shazly *et al.* (1979) and Maamoun *et al.* (1980) showed that, except for some local parts, the whole Egyptian crust is highly deformed. This may explain the relatively low b value deduced for the Gulf of Suez and other active zones in Egypt when compared, e.g., with the area around the Nile Valley.

Inspection of the Egyptian earthquake catalogue indicates that the calculated return period for large earthquakes is reasonable. For example, the return period for earthquakes of magnitude $\geqslant 5.0$ is around 8 years in the Gulf of Suez and 21 years in the other active zones in Egypt (Figure 5). Earthquakes with these magnitudes and which also caused damage were reported in the Gulf of Suez in March 1952, March 1969, April 1972, and June 1983, and in the other active zones in Egypt in December 1956, November 1981 and October 1992.

It should be emphasized that many of the largest recent Egyptian earthquakes occurred in areas of critical or sensitive structures. For example, the earthquakes of 1969 and 1972 took place close to the largest oil field in Egypt, the event of 1981 occurred upstream close to the Aswan High Dam and the disastrous event of 1992 hit the densely populated area of Cairo. To protect the society and sensitive structures from earthquake risk and to implement further smooth economic development of the country, earthquake hazard parameters should be taken into account in urban planning, large industrial constructions, building of energy resources, etc.

A main conclusion of the present study is that the seismic hazard is significantly higher in the Gulf of Suez area than in the other active zones in Egypt. These two areas are expected to be affected by major earthquakes ($m_b \geqslant 5$) on average once in eight and once in 21 years, respectively.

Acknowledgements

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