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THIRTY FIVE YEARS INVESTIGATION OF THE RESERVOIR INDUCED SEISMICITY IN AND AROUND THE NORTHERN PART OF LAKE NASSER, EGYPT

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خمسة وثلاثون عاماً فى دراسة النشاط الزلزالى الناجم عن البحيرات الصناعية فى وحول الجزء الشمالى من بحيرة ناصر – مصر

الخلاصة: إن أول زلزال تم تسجيله بواسطة الأجهزة فى أسوان كان فى ١٤ نوفمبر ١٩٨١ على فالق كلابشة والذى بلغت قوته ٥,٣ درجة بمقياس ريختر. وقد أوضحت مراقبة النشاط الزلزالى على مدى خمسة وثلاثون عاماً فى الجزء الشمالى من بحيرة ناصر أن النشاط تركز على الصدوع النشطة بالقرب من الجزء الشرقى من فالق كلابشة عند تقاطع فالق كلابشة مع فالق خور الرملة، كما أوضحت دراسة ميكانيكية بؤر الزلازل أن النشاط الزلزالى يحدث على صدوع ذات ازاحة جانبية تحت تأثير اجهاد تكتونى أفقى. فى عام ١٩٩٥ بدأت زيادة تدريجية فى النشاط الزلزالى الضحل تزامنت مع الزيادة التدريجية فى منسوب المياه فى البحيرة وقد لوحظ زيادة نسبية فى عدد من الزلازل فى الفترة من ٢٠٠٧ حتى ٢٠١٦ حيث تركز النشاط على صدعين شرق جبل مراوة تحت مياه البحيرة. ومن المظاهر التى شوهدت فى منطقة خور الرملة حدوث هجرة لبؤر الزلازل من داخل البحيرة إلى خارجها على حواف البحيرة عقب اتساع البحيرة خلال الفترة من ١٩٨٢ حتى ١٩٩٨ حيث انتقلت بؤر الزلازل من الجنوب الغربى إلى الشمال الشرقى عندما ارتفع منسوب المياه من منسوب ١٧٥,٢٩ متراً من سطح البحر عام ١٩٨٢ إلى ١٨١,٣ متراً فى نوفمبر ١٩٩٨ وقد تكون هجرة بؤر الزلازل فى هذه الحالة بسبب تسرب مياه البحيرة إلى الصدوع الموجودة وزيادة الضغط المسامى بها، كما أن حدوث نشاط زلزالى فى بعض الأماكن على حواف البحيرة عقب زيادة منسوب المياه يبين الدور المهم للضغط المسامى فى حدوث الزلازل بالمنطقة. فى هذه الدراسة أيضاً تم حساب قيم (b-value) وهى نسبة عدد الزلازل الصغيرة إلى عدد الزلازل الكبيرة وهى تعتمد على الإجهاد والخصائص التكتونية فى المنطقة وتراوحت بين ١,٠٣ و ١,٠٧.

ABSTRACT: *The first instrumentally recorded earthquake at Aswan province occurred on November 14, 1981 on Kalabsha fault with magnitude of 5.3. Thirty five years of seismic monitoring in the northern part of Lake Nasser (the second largest reservoir in the world) has shown that the epicenters were clustered on the active fault segments near the eastern part of Kalabsha fault at the weakness area of the intersecting of Kalabsha fault with Khor El-Ramla fault beneath the Kalabsha bay (the largest bay of the Lake Nasser). Composite focal mechanisms have been determined for different earthquake clusters. In all cases, the composite focal mechanisms are characterized by strike-slip faulting and horizontal stress axes. A gradual increase in shallow seismicity at Kalabsha area started in 1995 associated with the gradual increase of the lake water level and relatively higher seismic activities have been observed within the time period from 2007 up to 2016. This activity is concentrated mainly on the two fault segments east of Gebel Marawa beneath the lake. The interesting phenomena shown at Khor El-Ramla seismic zone is outward migration of epicentres followed the growth of the reservoir upstream from 1982 to 1998. The epicentres are moved slightly from southwest to northeast as water level increased from 175.29m in 1982 to 181.3m in November 1998. The temporal distribution of the seismic activity east of Gebel Marawa and Khor El-Ramla area from 1982 to 2016 showed an alternating in seismic activity along these two seismic zones. The increasing seismicity at some places on the lake periphery following the seasonal increasing of the lake water level reveals that the pore pressure diffusion plays an important role in triggering earthquakes. The b-value is calculated for seismicity occurred at the most active zones from 1982 to 2016 using the cumulative frequency-magnitude of Gutenberg and Richter relation. The result shows that the b-values are ranged from 1.03 to 1.07.*

INTRODUCTION

Reservoir-Induced Seismicity (RIS) is thought to occur in two ways: (1) by the added weight of a reservoir and (2) by the water that seeps into underground cracks or along a fault. In the first case, the filling of a reservoir with millions, even billions, of tons of water can add stress to faults, causing them to rupture. In the second case, water seeps into the rock and changes the fluid pressure in micro-cracks and fissures in the ground under and near a reservoir. The load effect of the first case is immediate, while the pore pressure effect is delayed because it requires the flow of the water through rock. This delay can cause some reservoirs to begin triggering earthquakes years after the first impounding.

The effect of reservoir loading on the existing stress field has been the subject of several studies (Snow, 1972; Bell and Nur, 1978; Talwani and Acree, 1985; Simpson, 1976, 1986; Simpson et al., 1988; Rajendran and Talwani, 1992; Talwani, 1997) all of them addressed seismicity associated with the initial impoundment of the reservoir.

Seismicity induced by reservoir impoundment has been clearly established at many dam sites. The most recent one is that earthquakes associated with the filling of Lake Nasser (Egypt) where hundreds of smaller earthquakes have followed the November 14, 1981 main shock. Some of the other examples of the association of earthquakes with artificial lakes are Koyna (India), Nurek (Tadjik Republic), Kariba (Zambia), Kermasta (Greece), Monticello (U. S. A.) and Tarbela (Pakistan).

Zoback and Hickman (1982) measured the magnitudes of the principal in situ stresses, pore pressure and permeability in the hypocentral zones of earthquakes induced by impoundment of Monticello Reservoir, South Carolina. The analysis of these data suggests that the earthquakes were caused by an increase in subsurface pore pressure. Chen and Talwani (1998) studied 19 cases of reservoir induced seismicity (RIS) in China. They found that the cases of RIS in granitic rocks (e.g. Xinfengjiang Reservoir) appear to be caused by pore pressure diffusion in fractured rocks.

In this study the investigation of the local earthquakes occurred in and around the northern part of Lake Nasser shows a gradual increase of shallow seismicity started in 1995 associated with gradual increase of the lake water level.

Spatial distribution of Aswan seismic activity

a- The Aswan seismic network and seismic data:

Aswan area is known to be seismically active since the occurrence of the November 1981 Aswan earthquake (Ms = 5.3). Detailed geological and geophysical surveys in the area confirm the existence of a few active faults to the southwest of the High Dam (e.g. Kalabsha, Seiyal and Kurkur faults)**.** In late June, 1982 a telemetered seismic network is installed by National Research Institute of Astronomy and Geophysics and High Dam Authority in cooperation with Lamont-Doherty Geological Observatory. The telemetered network consists of 13 seismic short period stations surrounding the northern part of Lake Nasser. The seismic signals are transmitted from the field stations to the recording center located near the High Dam by radio-link (Simpson et al., 1987). The earthquake hypocenter parameters are determined precisely using the "HYPOINVERSE" location program (Klein 1978).

In 1998 the Seismic Data Analysis Software (DAN ver. 2.56) provided by Nanometrics Inc. (Canada) extracts the digital data of remote sites online from the ring buffer. In 2009 a new system was installed in Aswan network, this system is NaqsServer which is a data acquisition system designed to receive, process, and store serial data, seismic data, and state-of-health information.

b- Data analysis:

Several studies were carried out to describe the seismic activity in Kalabsha area (e.g., Kebeasy et al., 1987; Kebeasy and Gharib, 1991; Hassib, 1997; El-Khashab et al., 2000; Hassoup et al., 2002; Hassib et al., 2003; Hassib and Hggag, 2009). The operation of the Aswan Seismic Network for thirty years allowed us to categorize the seismicity patterns in and around the northern part of Aswan reservoir. The spatial distribution of the epicenters from January 1982 to December 2016 reveals that the seismicity in this area is clustered on the active fault segments or fractures (Fig. 1). These active segments were observed to generate repeated earthquakes.

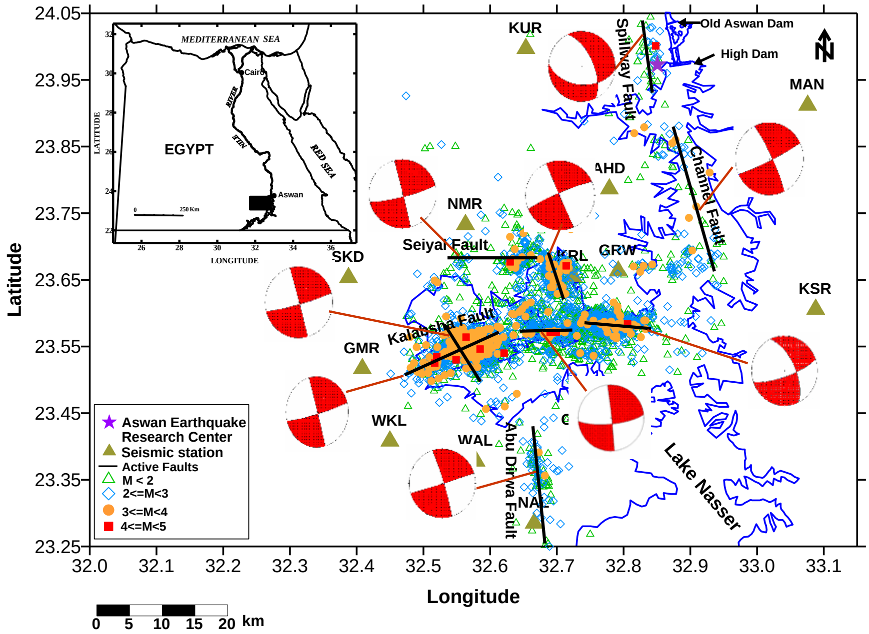

Fig. 1. Seismicity map of Kalabsha area from 1982 to 2016 and composite focal mechanisms for some events occurred on the active faults.

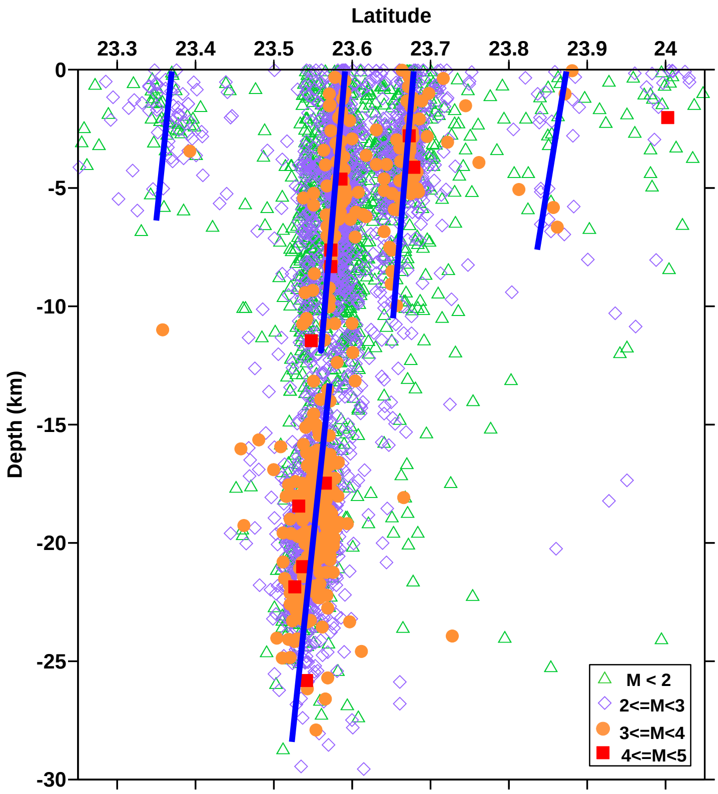

Fig . 2. Cross section showing the spatial distribution (between latitude of 23.25° to 24.05°N) of the epicenters with respect to their depths where the thick lines represent the vertical active faults.

The depth distribution of the earthquake hypocenters shows two separate depth ranges: deeper events with focal depths between 15 and 30 km beneath Gabel Marawa and shallow events with focal depths <10 km at the east and northeast Gabel Marawa. It can be seen that the active faults are nearly vertical (Fig. 2). Prior to the occurrence of main shock of Nov 14, 1981, no activity has been recorded from Kalabsha area. This did not mean that there was no activity before this earthquake but it may be attributed to the lack of seismic stations in the area, but it also means that there was no significant activity before that period.

Seismic migration

The map and vertical sections in Figure (3) show a closer look of the earthquakes distribution in the Khor El-Ramla zone. The continuous lines in the map refer to periphery of the Lake Nasser at three different levels (Dahab, 1977). The open circles are the earthquake epicenters for the period from 1982 to 1998. This activity was concentrated around the periphery of level 170m although the water level reached 181.3 in November 1998. The closed circles represent the activity during 1999 and 2000. This activity was concentrated in a new seismic spot on the lake periphery of level 180m. Although we have used the same recording instruments and the same software for the data analysis, this Figure shows that the activity during 1999 and 2000 has migrated from southwest to northeast followed the growth of the reservoir upstream. This seismic migration occurred as a result of increasing water level during 1998, 1999 and 2000. During this period the water level exceeded 180m and covered a new fractured area. The diffusion of water into pre-existing fractures reduces the coefficient of friction between clays and rocks fill the pre-existing fractures and lubricate the fault walls. The fault walls slide under the effect of the horizontal tectonic stress prevailing in Kalabsha area. This may explain the occurrence of the earthquakes in a new seismic spot in Khor El-Ramla zone.

The alternating occurrence of seismicity

The continues monitoring of seismicity in and around the northern part of Lake Nasser shows clustered seismic activity at two seismic zones (Fig. 4). These two zones are Khor El-Ramla (zone A) and east Gabel Marawa (zone B). They were observed to generate repeated earthquakes. The thirty five years temporal distribution of seismicity occurred at these two seismic zones revealed an alternating occurrence of seismic activity between them (Fig 5). This figure shows relatively high activity in zone (A) compared with activity in zone (B) from 1982 to 1986 followed by quiescence time for two years. During this quiescence time an abruptly seismic swarm took place at zone (B) in June 1987. After this swarm, a quiescence period lasted from 1988 to the end of 1992 at zone (B) whereas the considerable seismic activity took place at zone (A) during this quiescence period.

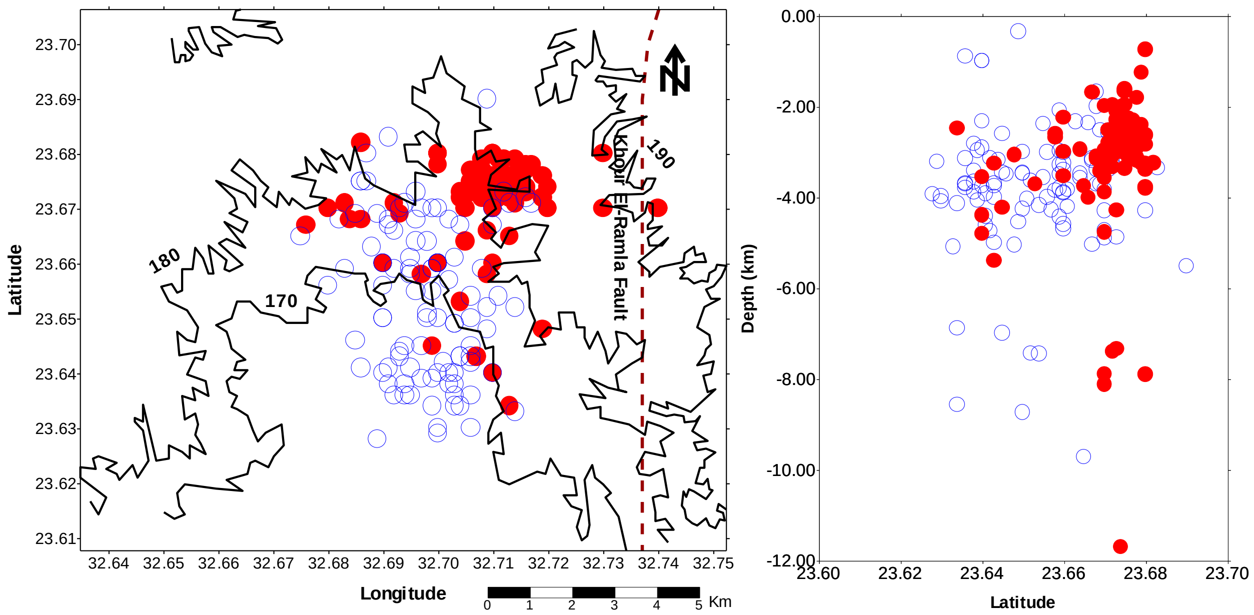

Fig. 3. A closer look of the earthquakes distribution and vertical section in the Khor EL-Ramla zone. The continuous lines in the map refer to periphery of the Lake Nasser at three different levels. The open circles are the earthquake epicenters for the period from 1982 to 1998. The closed circles represent the activity during 1999 and 2000.

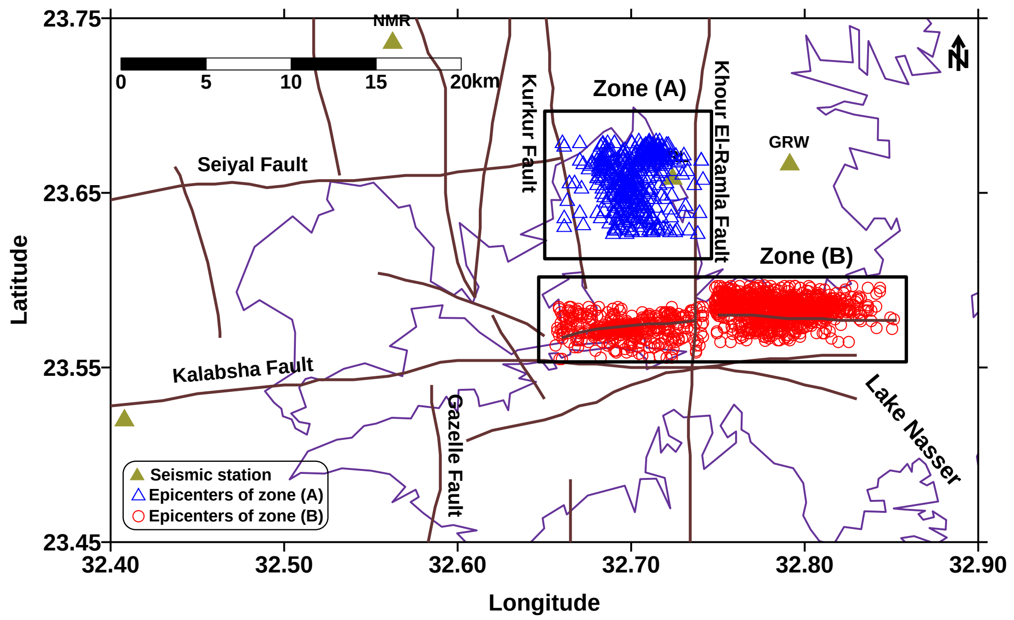

Fig. 4. Spatial distribution of seismic activity at Khor El-Ramla area (zone A) and East Gebel Marawa area (zone B) from 1982 to 2016.

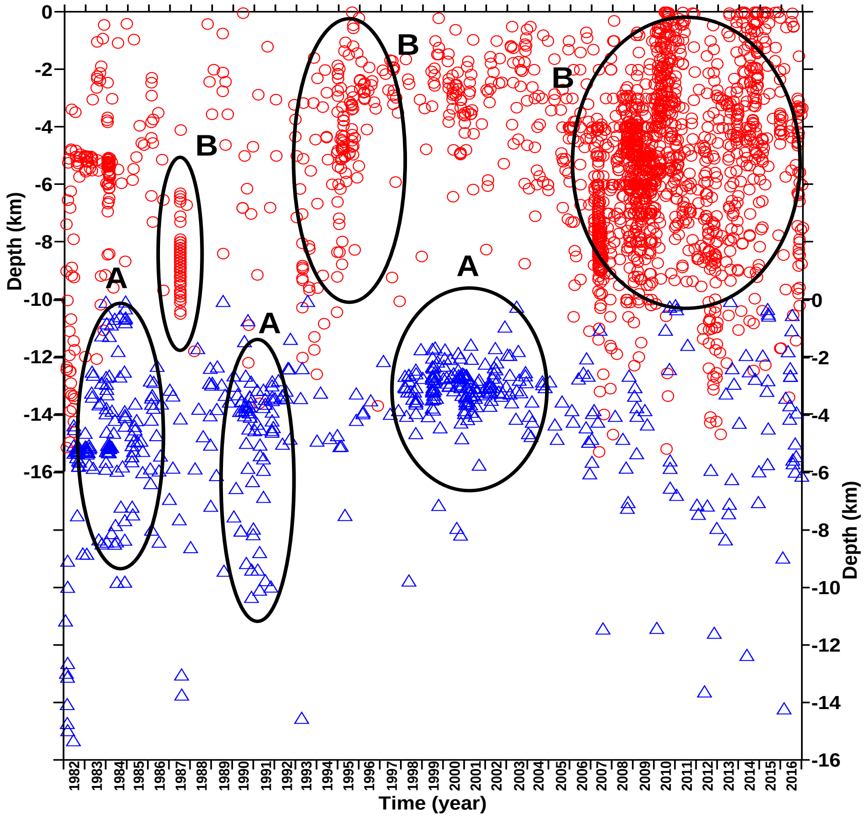

Fig. 5. Depth and temporal distributions of seismicity occurred at Khor El-Ramla area (zone A) and East Gabel Marawa area (zone B) from 1982 to 2016. The right and left axes represent the depth scale for zone (A) and zone (B) respectively.

Again a quiescence period started at zone (A) from 1993 to the end of 1997 whereas seismic activity occurred at zone (B) during this time. The relatively high activity occurred at zone (A) compared with activity in zone (B) from 1998 to 2004 and followed by low activity period extended to the end of 2016. During low activity period of zone (A) the noticeable high activity took place at zone (B). This alternating occurrence of seismicity between zones (A) and (B) and the quiescence intervals reflect the stress release and rebuild new stresses. According to this phenomenon it can be expected high seismic activity at zone (A) in the near future.

Earthquakes triggered by pore pressure diffusion

A clear case of earthquakes triggered by pore pressure diffusion is shown at Abu Dirwa fault area. This fault is approximately 20 km long and located about 55 km southwest of the Aswan High Dam (Fig. 6). The analysis of seismic records from 1982 to 2016 showed few events occurred on Abu Dirwa fault during the time period extended from 1982 to 1998. The total number of events occurred during that period was 21 events with the maximum magnitude of M_L=2.9. It's been noted that, the lake water level was less than 180 m during the period from 1982 to August 1998. The water level exceeded 180 m in September 1998 and reached 181.3m on November 12, 1998. The increasing of the water level continued and exceeded 180m in 1999, 2000 and 2001.

The relationship between the number of events occurred on Abu Dirwa fault and the changes in water level from 1982 to 2016 is shown in figure (7). The figure shows that the seismic activity increased since 1999, immediately following the water level increasing in November 1998, which reached 181.3m and covered the northern end of Abu Dirwa fault. The seismic activity began to increase on February 24, 1999, approximately three and half months after the water level exceeded 181m. Most of these earthquakes were shallow (depth < 4 km) and had magnitude less than 3, except three events of magnitude 3.0, 3.2 and 3.5 occurred on June 19, 1999, February 19, 2011 and February 2, 2014 respectively. The seismicity persisted until September 2004, and then began to decay, as the water level decreased below 180m. Although the seismicity is located about 5km away from the lake periphery (Fig. 6), this study revealed a clear correlation between the lake water level and seismic activity occurred on Abu Dirwa fault for the period from 1982 to 2016 (Fig. 7). The seismicity in such case appears to be related to the diffusion of water from the reservoir which increases the pore pressure at the hypocentral depths. The pore pressure reduces the coefficient of friction between the fault walls which slide due to effect of the horizontal tectonic stress prevailing in the area.

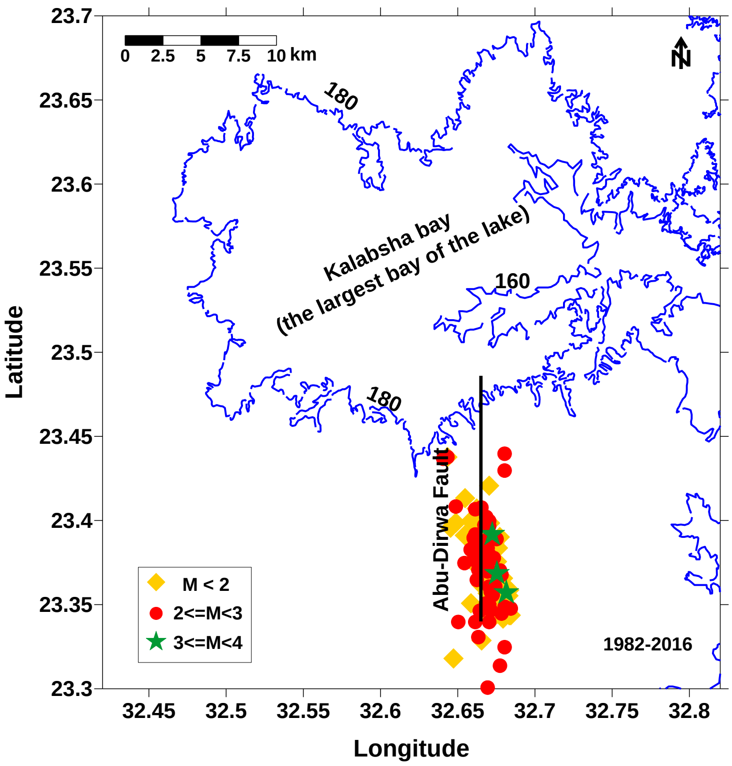

Fig. 6. A closer look of the earthquakes occurred on the Abu Dirwa fault area. The continuous lines in the map refer to periphery of the Lake Nasser at two different levels. The open circles are the earthquake epicenters from 1982 to 2016.

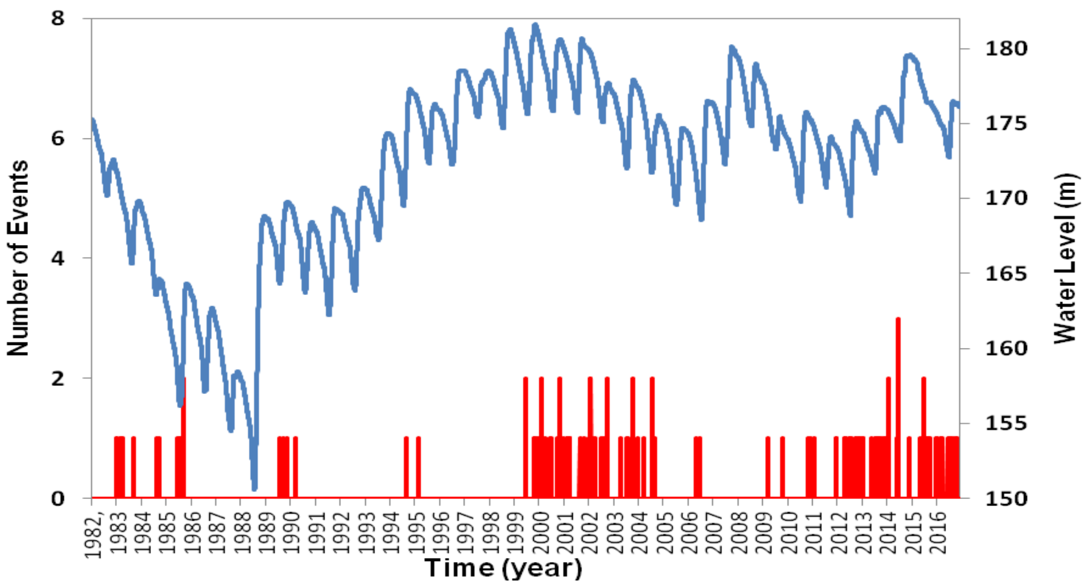

Fig. 7. The relation between the lake water level and seismic activity occurred on Abu Dirwa fault for the period from 1982 to 2016.

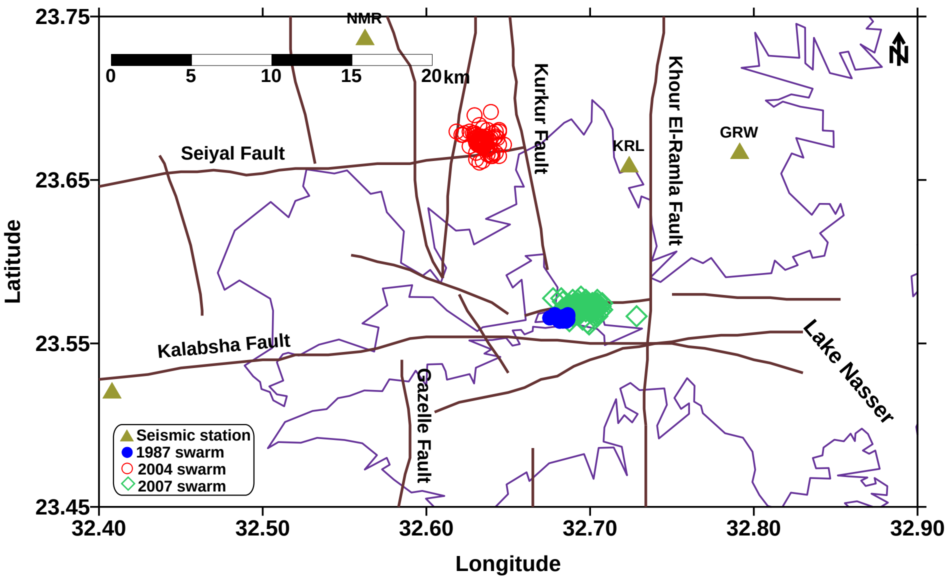

Fig. 8. Spatial distribution of the three earthquake swarms occurred in the northern part of Lake Nasser.

Earthquake swarms

Earthquake swarms are events where a local area experience sequences of many earthquakes occurred in a relatively short period of time. The length of time used to define the swarm itself varies, but the United States Geological Survey points out that an event may be on the order of days, weeks, or months. They are differentiated from earthquakes followed by a series of aftershocks by the observation that no single earthquake in the sequence is obviously the main shock. For example in the United States there was the so-called "Mogul earthquake sequence" that began in February 2008 near Reno, Nevada and continued for several months, ending in November 2008. Between February and April the swarm produced more than 1,000 quakes of small magnitude, although the largest measured was 4.7 (Jansen et al., 2019).

In June 1987 a seismic swarm in the Lake Nasser region occurred abruptly within a relatively quiet period of earthquake activity (Awad 1994; Awad and Mizoue 1995a). This swarm is strongly clustered on a fault segment about 8 km in length beneath the lake water. This fault segment takes the E-W direction follows the Kalabsha fault system about 45 km southwest of the Aswan High Dam (Fig. 8). The June 1987 swarm lasted from June 17 until June 19. Altogether 149 microearthquakes were identified, among them 7 events in the magnitude range of M_L=3.0-3.7. The events of this swarm are concentrated between depths of 2 and 5 km.

A second earthquakes swarm lasted from August 3 until December 15, 2004 where 93 events occurred at the intersection of Seiyal fault with the Kurkur area faults including 14 events in the magnitude range of M_L=3.0-3.7 and one event with magnitude of M_L=4.1. The depths of these earthquakes ranged from 2 to 5 km.

On April 12, 2007 a third earthquakes swarm abruptly started and strongly clustered on the same fault segment of the June 1987 swarm (Fig. 8). The swarm of April 2007 lasted from 12 to 14 April, where 262 events were recorded. This swarm is characterized by earthquakes of relatively larger magnitude than the earthquakes of June 1987 swarm. There were 15 events in the magnitude range of M_L=3.0-3.7 and two events with magnitude of M_L=4.0 and 4.2 (Hassib et al., 2010).

Relationship between the water level and swarm sequences

The fluctuation of the water level at Lake Nasser, provided by the High Dam Authority, have been correlated with the three swarm sequences (Fig. 9). This Figure shows that both 1987 swarm and 2007 swarm occurred during the decreasing of the water level, whereas the 2004 swarm occurred during the increasing of the water level.

The occurrence of the 1987 and 2007 swarm sequences during the decreasing of the water level are similar to foreshock-aftershock series started on September 16, 2004 in the western Pyrenees, Spain, when the water level at Itoiz reservoir was near the summer's minimum (Ruiz et al., 2006).

Since the 1987 and 2007 swarm sequences occurred on a fault segment beneath the lake water (Figs. 8), these activity may be attributed to the change in fault strength ΔS according to the following equation of Bell and Nur (1978):

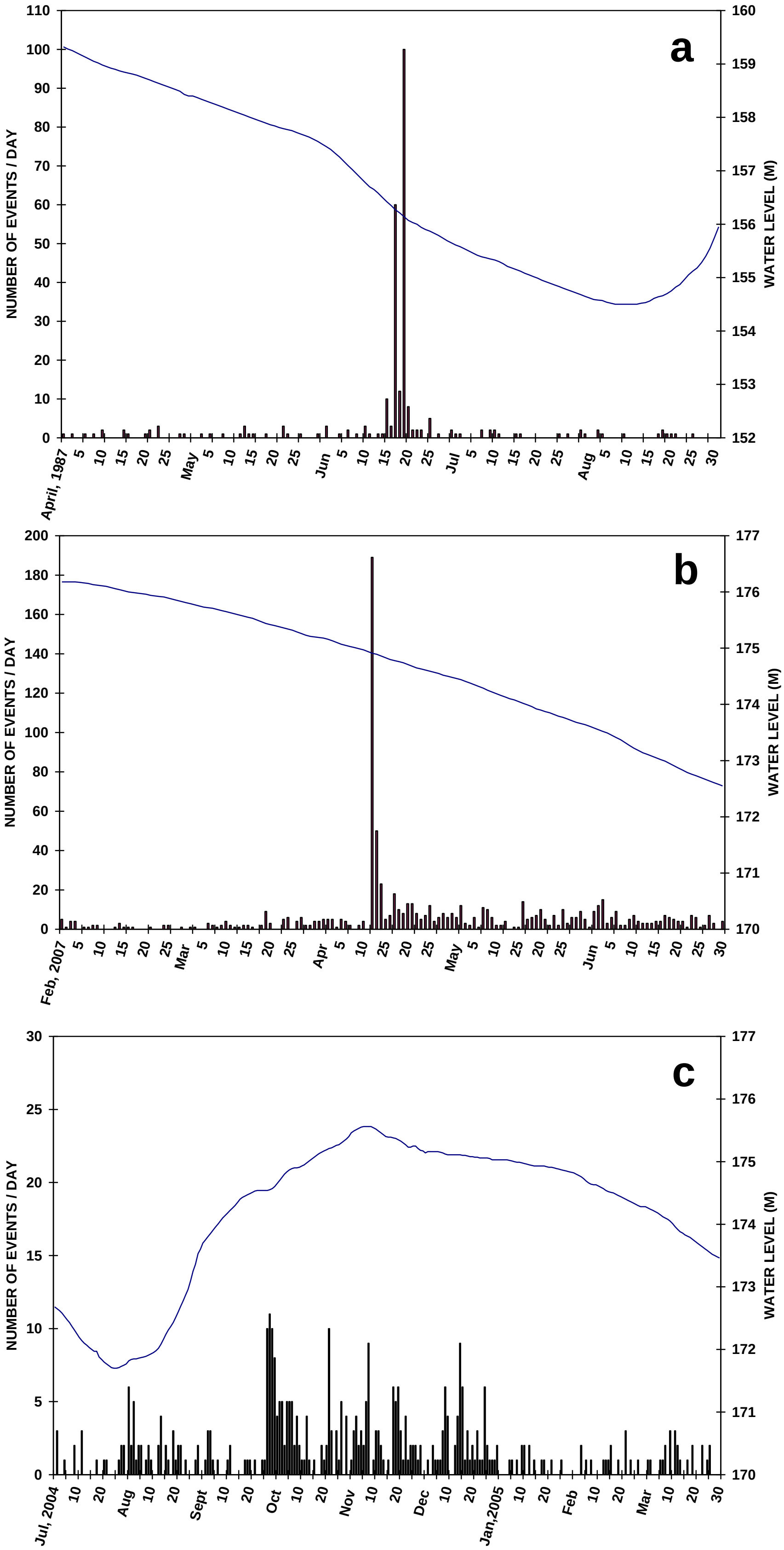

Fig. 9. Relationship between the water level and the three swarm sequences. (a) For 1987 swarm, (b) for 2007 swarm and (c) for 2004 swarm.

$$\Delta S = \mu_f (\Delta\sigma_n - \Delta_p) - \Delta\tau$$

Where $\Delta\tau$ and $\Delta\sigma_n$ are changes in shear stress on the fault in the direction of slip and compressive normal stress across the fault, respectively. μ_f and Δ_p are the coefficient of friction and change in pore pressure, respectively. Failure occurs when ΔS decreases below a threshold level. From this equation, it can be noted that a decrease in ΔS can be brought by a decrease in $\Delta\sigma_n$ (unloading) or an increase in pore pressure.

The 2004 swarm occurred on the periphery of the reservoir at the intersection area of N-S and E-W trending faults (Fig. 8). This swarm associated with increasing water level that started on July 27 and reached its maximum level on November 6. The location of seismicity on the periphery of the reservoir, distant from the deepest part of the reservoir suggests that the 2004 swarm is probably caused by seepage of large quantities of water into this fault that increase the pore pressure at the hypocentral depths. The increase in the pore pressure in addition to the tectonic stress prevailing in the area play a significant role in the earthquake triggering (Hassib et al., 2010).

General view of water level and seismicity at Lake Nasser:

A gradual increase of the lake water level began in 1988 and reached 178.55m in 1996, 178.52m in 1997. The water level exceeded 180m in 1998, 1999 and 2000 where the maximum water level reached 181.6m in 1999. A gradual increase in shallow seismicity at Kalabsha area started in 1995 associated with the gradual increase of the lake water level and relatively higher seismic activities have been observed within the time period from 2007 up to 2016 (Fig. 10). The shallow seismicity increased both in number and magnitude where 7 events of magnitude ranged from 4 to 4.6 have been recorded. Figure (10) shows a good correlation between the shallow seismic activity and seasonal fluctuations of the Lake.

***b*-value characterization:**

The ***b***-value is a measure of the relative number of small to large earthquakes that occur in a given area in a given time period. In particular, the ***b***-value is the slope of the frequency-magnitude distribution. The classical frequency-magnitude distribution, FMD, (Gutenberg and Richter, 1944) is commonly used: $\log N = a - bM$ where N is the cumulative number of earthquakes with magnitude equal to or larger than M, and a and b are real constants that may vary in space and time. The parameter a characterizes the general level of seismicity in a given area during the study period i.e. the higher the a value, the higher the seismicity. The parameter b is believed to depend on the stress regime and tectonic character of the region (Allen et al., 1965; Mogi, 1967; Scholz, 1968; Hatzidimitriou et al., 1985; Tsapanos, 1990). An Increased heterogeneity or crack density results in high ***b***-values (Mogi, 1962) whereas an increase in applied shear stress (Scholz, 1968; Urbancic et al., 1992) or an increase in effective stress (Wyss, 1973) decreases the ***b***-value. A smaller ***b***-value probably means that the stress is high in the examined region. Decreasing ***b***-value within the seismogenic volume under consideration has been found to correlate with increasing effective stress levels prior to major shocks (Kanamori, 1981). Higher ***b***-values are often associated with high thermal gradients and increases in pore pressure (Warren and Latham, 1970; Wyss 1973).

The ***b***-value is normally 1.0 but for shorter time windows it varies significantly depending on the tectonic setting of the seismically active region (Pacheco et al., 1992; Wiemer and Wyss, 1997; Singh et al., 2008; Singh and Chadha, 2010; Singh, 2014). Many evidences suggest that b can act as a stress meter in the crust which came from the fact of asperity (Wiemer and Wyss, 1997; Singh, 2014). A lower value of b implies that the region is under higher applied shear stress, and a higher value of b indicates that the area is already gone through the tectonic events. The inverse relationship between the concentration of stress at epicentral region prior to the occurrence of the earthquakes and the ***b***-value is evidently of particular interest in the prediction of major earthquakes (Parasad and Singh, 2015).

The ***b***-value is calculated for seismicity occurred at five seismic active zones in the northern part of the Aswan Lake from 1982 to 2016 using the cumulative frequency-magnitude of Gutenberg and Richter (1944) relation. These zones are the most active zones in the area (Fig. 11).

***b*-value of the Marawa seismic zone (zone No.1):**

It is the zone of the highest seismic activity which is located beneath Gebel Marawa. The seismicity is clustered along two intersect lineaments one of them taking NW-SE direction the other one taking NE-SW direction. The seismicity at Marawa is almost concentrated between depths of 15 and 30 km. The calculated *b*-value for seismicity occurred in this zone is 1.03±0.041 (Fig. 12a).

***b*-value of the East Marawa seismic zone (zone No.2):**

The activity of this zone is clustered about 20 km east of Marawa zone on the fault segment about 8 km length beneath the lake. The activity of this zone is concentrated in a vertical plane with depth between 0.5 and 12 km. The ***b***-value calculation of this zone is found to be 1.05±0.026 (Fig. 12b).

***b*-value of the seismicity east of Khor El-Ramla fault (zone No.3):**

The activity of this zone is clustered on the fault segment about 10 km length beneath the lake. This zone is characterized by high seismic activity since 2007. This activity is concentrated between depths of 0.5 and 12 km. The ***b***-value calculation of this zone is found to be 1.07±0.046 (Fig. 12c).

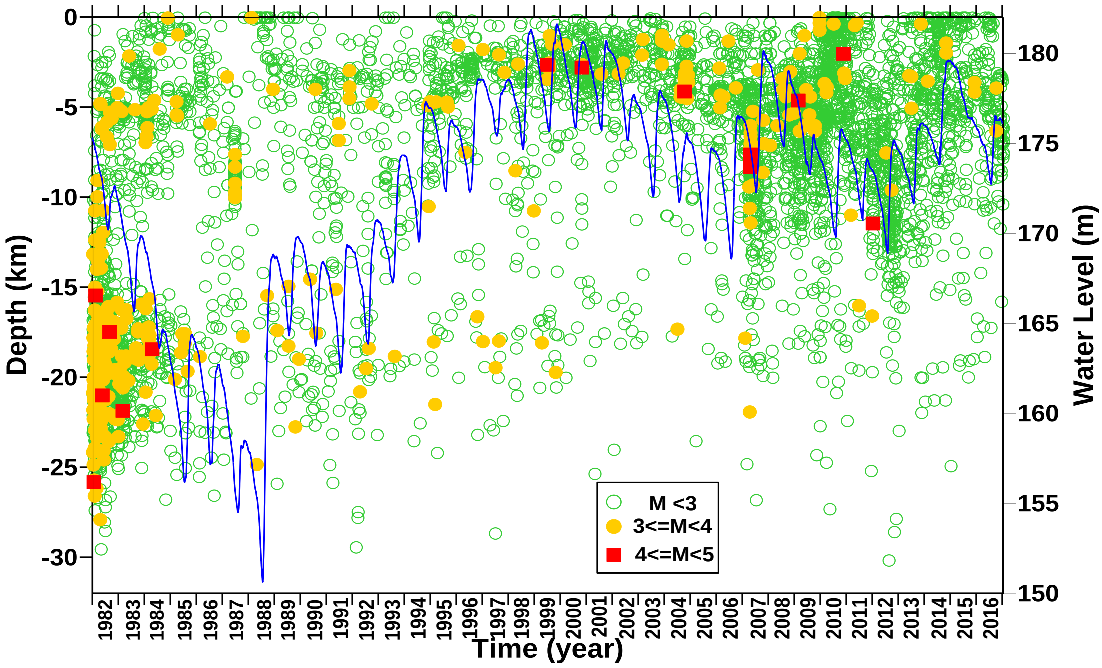

Fig. (10): Depth distribution of the seismic activity in Kalabsha area and seasonal fluctuations of the lake water level from 1982 to 2016.

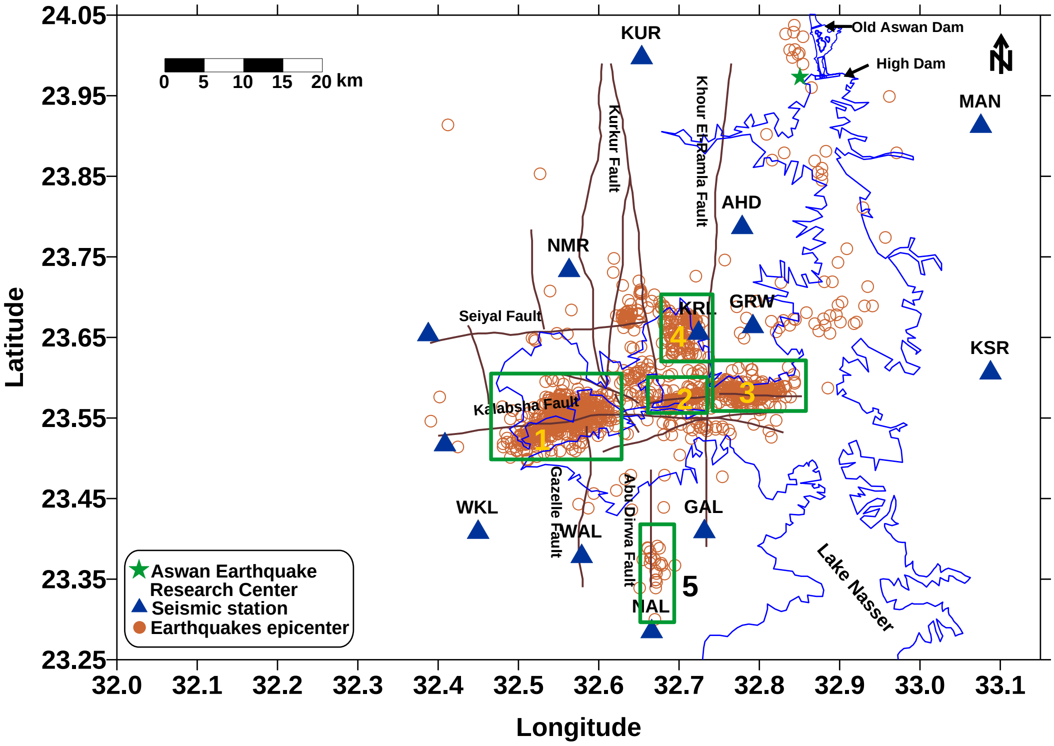

Fig. 11. The most active seismic zones in the northern part of the Lake Nasser.

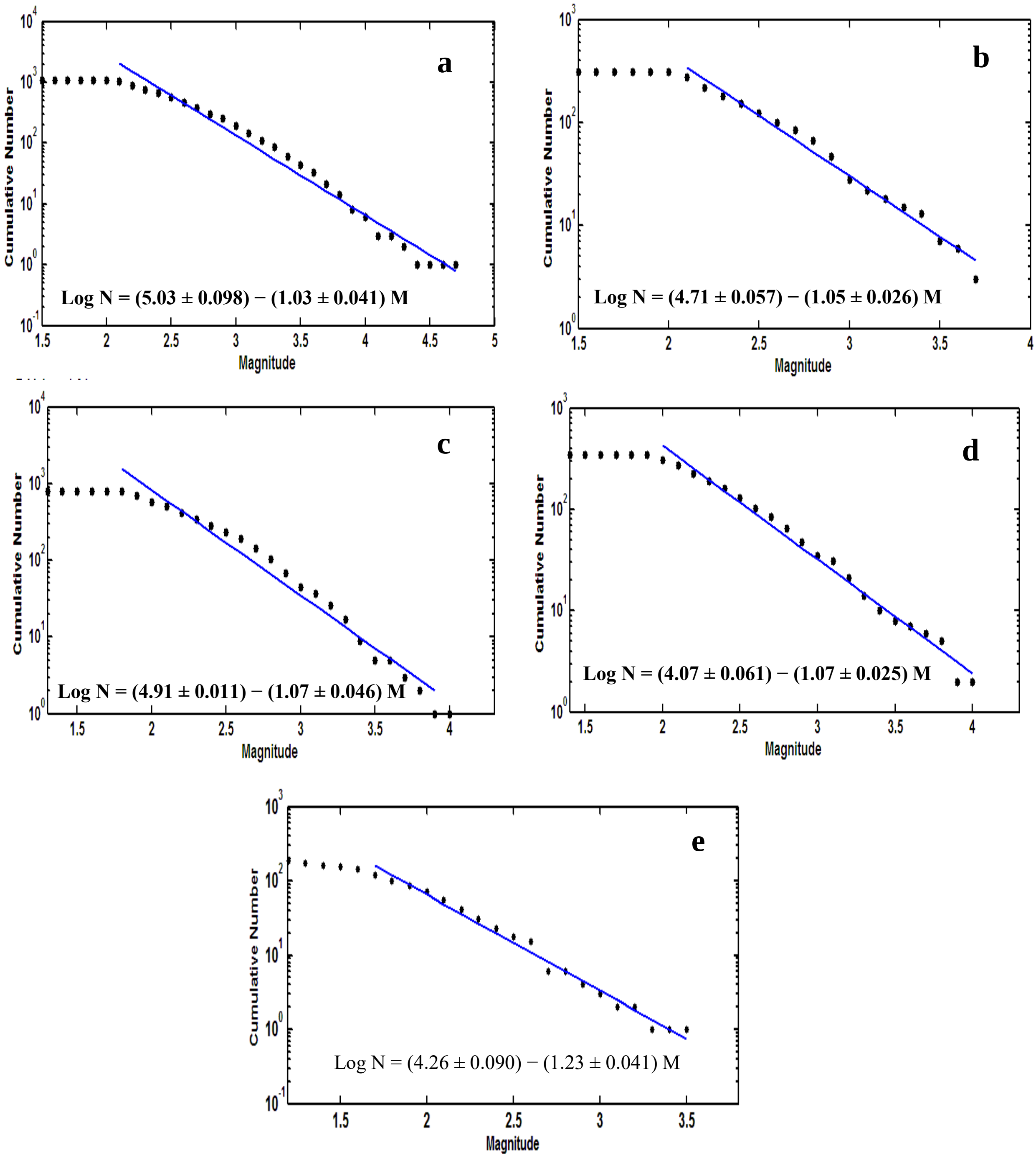

Fig. 12. The b-values for seismicity occurred at five seismic active zones in the northern part of the Lake Nasser from 1982 to 2016.

***b*-value of the Khor El-Ramla seismic zone (zone No.4):**

This zone lies west of the surface trace of the Khor El-Ramla fault near the (KRL) seismic station. The events of this zone are concentrated between depths of 0.5 and 10 km. The calculated ***b***-value of this zone is found to be 1.07±0.025 (Fig.12d).

***b*-value of seismicity occurred on Abu-Dirwa fault (zone No.5):**

The seismicity of this zone is concentrated on Abu-Dirwa fault. This fault is a north-trending active fault; it is about 55 km southwest of the Aswan High Dam and is approximately 20 km long. The calculated ***b***-value of this zone is found to be 1.23±0.041 (Fig. 12e).

From this study of ***b***-value characterization of these five active zones we can conclude that the high seismicity of these zones with high ***b***-values may be associated with high heterogeneity and low strength in the crust. The low strength is attributed to the diffusion of water from the lake which increases the pore pressure at the hypocentral depths.

CONCLUSIONS

Thirty five years of the seismic monitoring in Northern part of Lake Nasser allowed us to categorize the seismicity patterns in the area. The spatial distribution of the epicenters from January 1982 to December 2016 reveals that the seismicity in this area is clustered on Kalabsha fault and active fault segments or fractures. The composite focal mechanisms for different earthquake clusters are characterized by strike-slip faulting and horizontal stress axes.

The study of the activity in the Khor El-Ramla seismic zone shows an interesting phenomena. There is an outward migration of epicentres from the lake interior to the lake periphery followed the growth of the reservoir upstream from 1982 to 1998. The epicentres are moved slightly from southwest to northeast as water level increased from 175.29m in 1982 to 181.3m in November 1998. This migration may be occurred by diffusion of reservoir water into pre-existing fractures and trigger slip on these pre-existing fractures.

Another case of earthquakes triggered by pore pressure diffusion is shown at Abu Dirwa fault area. The seismicity began to increase since February 1999, about three and half month after the lake water level exceeded 181m and covered the northern end of Abu Dirwa fault. It is clear that the Abu Dirwa seismicity is not related to the reservoir loading because the seismicity is concentrated about 5 km south of the lake periphery.

Thirty five years temporal distribution of seismicity occurred at Khor El-Ramla zone and east Gabel Marawa zone revealed an alternating occurrence of seismic activity between them. According to this phenomenon it can be expected high seismic activity at Khor El-Ramla zone in the near future due to the low seismicity of Khor El-Ramla zone comparing with the seismicity of east Gabel Marawa zone since 2007.

During the past 35 years the spatial and temporal distribution demonstrate occurrence of three swarm sequences. The first swarm occurred in June 1987 on a fault segment about 8 km in length beneath the lake water. The second swarm sequence took place at the intersection of the Seiyal fault with Kurkur fault about 10 km to the north of the June 1987 sequence. This swarm occurred during the period from August to December 2004. The third swarm occurred in April 2007 at the same location of 1987 sequence. The relationship between the lake water level and the swarm sequences showed that both 1987 swarm and 2007 swarm occurred during the decreasing of water level, whereas the 2004 swarm occurred during the increasing of the water level.

A gradual increase in shallow seismicity at the northern part of reservoir started in 1995 associated with the gradual increase of the water level and showed a good correlation between the shallow seismic activity and seasonal fluctuations of the Lake. The relatively higher seismic activities have been observed within the time period from 2007 up to 2016. The shallow seismicity increased both in number and magnitude where 7 events of magnitude ranged from 4 to 4.6 have been recorded.

The ***b***-value is calculated for seismicity occurred at the most active seismic zones in the area from 1982 to 2016 using the cumulative frequency-magnitude of Gutenberg and Richter relation. The result shows that the ***b***-values are ranged from 1.03 to 1.07. The high seismicity of the most active zones with high ***b***-values may be associated with high heterogeneity and low strength in the crust.

One of the important results of this study revealed the effect of the water infiltration into the pre-existing fractures which increases the pore pressure at the hypocentral depths. This result is consistent with the result of Gahalaut and Hassoup (2012) and Telesca et al., (2012c) in considering the pore pressure played a main role in triggering seismicity in and around the northern part of Lake Nasser.

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