TEMPORAL AND THREE DIMENSIONAL SPATIAL ANALYSIS OF SEISMICITY IN THE LAKE ASWAN AREA, EGYPT

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A b s t r a c t

On 28 September 2004 an earthquake swarm with the largest event of magnitude 4.2 occurred in the epicentral area of the 1981 Lake Aswan earthquake ($M = 5.7$), the latest manifestation of seismicity in the area. The swarm is located in a shallow zone along the Rawraw trend, 8 km north of the Kalabsha fault, the main active fault in the Lake Aswan area. The Kalabsha fault is characterized by the presence of shallow and deep seismic zones. The shallow earthquakes have focal depths smaller than 10 km. The sources of deep earthquakes are located at a depth between 14 and 30 km.

Characteristics of seismicity observed from 1982 to 2004 along the Kalabsha and Rawraw faults and the correlation between the temporal variation of seismicity and the water level changes in the Lake Aswan are analysed. The results indicate that the earthquakes in the deep seismic zone along the Kalabsha fault are characterized by a relatively low $b$-values and show greater degree of clustering than the shallow events. The shallow earthquakes along both the Kalabsha fault and the Rawraw trend are better correlated with the water level changes in the Lake Aswan than the deep events. Thus, the shallow events may be classified as seismicity induced by the water reservoir. Migration of seismic sources along these faults toward the shallow part of the crust is also apparent.

Key words: seismicity of the Lake Aswan, faults, shallow earthquakes.

1. INTRODUCTION

Earthquakes induced by the water reservoir impoundment were observed in several places in the world. Reservoir increases stress by adding mass on the reservoir base and/or by increasing the pore pressure under and around the reservoir (Simpson et al., 1988). Some examples of the reservoir induced seismicity were associated with
Fig. 1. Seismicity and geological map of the Aswan area (1982-2003): (a) Location of the study area; (b) Epicentral and geological map; (c) and (d) The east-west and north-south vertical cross sections.
regions of low tectonics dominated by normal or strike-slip faulting, as in the case of Sierran Foothill (Scholtz, 1990). Significant strike slip earthquake ($M = 5.7$) occurred beneath the Lake Aswan in Egypt on 14 November 1981 (Kebeasy et al., 1982). This area is still seismically active and the epicentres are concentrated along the Kalabsha and Rawraw faults (Fig. 1). The earthquake monitoring in Aswan is carried out by a local seismograph network of 13 field stations, which is operated using short period seismometers of type Geotech (S-13) since 1982 until now.

The 1981 Lake Aswan earthquake was located on the east-west trending Kalabsha fault (Kebeasy et al., 1982; Simpson et al., 1990; Awad, 1994). The Seyail fault is another east-west trend located 12 km north of the Kalabsha fault, but its seismicity is low. The Kalabsha and Seyail faults are bounding a graben structure of low seismic velocity zone (Awad, 1994). The Rawraw fault is located 8 km north of the Kalabsha fault, very close to the eastern part of the Seyail fault. There is a north-south fault system running nearly parallel to the main course of the lake in the area. The topography is complicated by structural faults and also by the presence of alkali granites and syenite ring complex. The Nubian sandstone formation and sediments ranging in age from Late Cretaceous to Eocene overlay the Precambrian basement on the western side of the Lake Aswan.

The sedimentary cover, about 500 m thick, forms a generally flat area of low relief varying from 150 to 350 m. The Quaternary formation is represented by the calcite and Nile deposits (Issawi, 1978; 1982). The east-west faults extend beneath the Nubian Plain across the Sinn El-Kaddab Plateau on the west of the Lake Aswan. Igneous and metamorphic rocks are distributed in several localities in the area west of the lake and constitute the main geological formation on its eastern side. The east-west and north-south fault systems affect the sandstone beds of the Nubian Plain by normal and strike-slip faults.

The tectonic features are also dominated by a regional uplift, which characterizes the northern part of the Lake Aswan (El-Shazly, 1977). Data of these features indicate that right-lateral strike-slip movement is dominant along the Kalabsha fault zone.

Earthquakes tend to be concentrated in space and time. Thus, investigations concerned with the spatial and temporal distribution of earthquakes have recently attracted the attention of many geoscientists for further understanding of the earthquake phenomenon.

Variation of the seismicity patterns with time have been correlated with the degree of the medium heterogeneity and/or the mode of the stress accumulation (Mogi, 1967). This study aims to demonstrate some characteristics of seismicity in the Lake Aswan area. The distance between the seismically active segments and Aswan High Dam is approximately 60 km.

Due to the Aswan High Dam construction early in 1964, Lake Aswan started to fill and extend over 350 km along the old Nile River. Monthly distribution of the Aswan seismicity and water level data for the period 1982-2004 is shown in Fig. 2. Several studies have shown the correlation between the temporal distribution of the seismicity and water level variations in the Lake (Kebeasy et al., 1982; Kebeasy and Gharib, 1991; Awad and Mizoue, 1995a; Hassib, 1990; Awad, 2002; and Mekkawi et al., 2004). Also, the spatial and temporal distribution of seismicity, separated into shallow and deep seismic zones, has been studied (Awad, 1994; Awad and Mizoue, 1995a). Shallow events have focal depths of less than 10 km while the deep events extend from 10 to 30 km (Fig. 1). The 14 November 1981 mainshock, as well as the earlier seismicity in this area, were located at the deeper part of the crust around 20 km depth (Kebeasy et al., 1982; Awad, 1994; Awad and Mizoue, 1995a; Hassib, 1990). From a three-dimensional structural seismic velocity analysis, Awad (1994) and Awad and Mizoue (1995b) have shown that the shallow and deep seismic zones are characterized by low and high seismic velocity anomalies, respectively. Seismicity of the deep seismic zone exhibits a tight cluster and is characterized by a permanent low level activity since 1984. In contrast, the shallow earthquakes occurred more frequently and were distributed along different fault segments; e.g. Kalabsha, Seyail, and Kurkur faults (Awad, 1994; 2002; Awad and Mizoue, 1995a; Hassib, 1990; Mekkawi et al., 2004).

Fig. 2. Temporal variation of the seismicity and water level changes in the Lake Aswan area.
3. SEISMICITY OF THE KALABSHA AND RAWRAW FAULTS

The 1982-2003 earthquake catalogue of the Lake Aswan contains more than 4888 events with magnitude ranging from 1 to 5. Most of these events are concentrated along the Kalabsha fault zone and Rawraw trend (Fig. 1). For the present study, the events that fulfill the following criteria were selected: (1) precise hypocentral location (i.e., error < 2 km); (2) magnitude > 2; and (3) the focus located along the geological lineament features, such as the fault trace of the Kalabsha and Rawraw faults. The 1982-2003 earthquake catalogue of the Aswan local seismograph network provides 1700 events on the Kalabsha fault. These events were separated into 1200 deep events (10 km < focal depth < 30 km) and 500 shallow events (Fig. 3). The last sequence was observed in September 2004 with the largest shock of $M = 4.2$ (Fig. 4).

Some statistical analysis techniques of the software package ZMAP have been applied (Malone and Wiemer, 2001) on the 4 data sets of the seismicity catalogues of all, deep and shallow events of the Kalabsha fault and Rawraw segment. The event magnitude in these 4 data sets ranges from 2 to 4.4 with an exponential decay in their

Fig. 3. Histogram of seismicity from 4 data sets: Kalabsha (all, deep and shallow) and Rawraw.
numbers from low to high magnitudes (Fig. 5). The depth distribution of the number of earthquakes in each data set is shown in Fig. 6. The temporal migration of seismic activity along the depth axis is shown in Fig. 7. The evolution between the level of seismic activity in the 4 data sets, i.e., the cumulative number of earthquakes plotted against time, is shown Fig. 8.

Fig. 4. The earthquake swarm along the Rawraw fault in September 2004.

Fig. 5. Histogram of magnitude distribution of the study data sets.
Fig. 6. Histogram of the depth distribution of the study data sets.

Fig. 7. Temporal variation of seismic activity along the depth axis.
Fig. 8. The cumulative number of earthquakes showing the level of seismic activity in each data set.

**Frequency–magnitude distribution**

The frequency–magnitude relationship of earthquakes (log $N = a - b M$) was defined by Gutenberg and Richter (1956), where $N$ is the number of earthquakes in different magnitude classes and $a$ and $b$ are constants. The $b$-value can be estimated using the maximum likelihood method of Aki (1965):

$$ b = \frac{1}{\ln 10(\langle M \rangle - M_{\text{min}})} , $$

where $\langle M \rangle$ is the average magnitude and $M_{\text{min}}$ is the smallest considered magnitude.

Equation (1) characterizes the statistical behaviour of seismic zones in energy domain using the frequency–magnitude distribution of earthquakes. The $b$-value calculated from eq. (1) is 0.84, 0.81 and 1.02 for the Kalabsha fault for all, deep and shal-
Fig. 9. The parameter $b$ of the frequency–magnitude relationship.

low seismicity, respectively. It is 0.99 for the Rawraw seismicity (Fig. 9). The linear fitting of the distribution appears for $M > 2$ events.

The temporal variations of seismicity along the Kalabsha and Rawraw faults is considered as the $b$-value variation, calculated for every 50 events with 5 events overlap between each two successive sets. The temporal variation of the $b$-value is obtained by plotting the averaged $b$-value of an equal time window for the total duration of the catalogue (1982-2003) (Fig. 10).

**Correlation integral method**

In order to evaluate the earthquake clusters of the Kalabsha and Rawraw faults in the spatial domain, the correlation integral method developed by Grassberger and Procaccia (1983) was used. The correlation dimension $D$ is obtained from
The correlation dimension $D$ is estimated by fitting the straight line of the plot $\log C(r)$ versus $\log r$. Here $r$ refers to the distance between each two hypocentres. The minimum and maximum values of $r$ are assigned to be 2 and 5 km, respectively, taking into account the error in the epicentral location and the finite size of the considered fault zone. For the hypocentre distribution (3-D space), the uniform distribution equals 3. It decreases with an increase in the clustering of events. This method of analysis is applied in the present study (Fig. 11).

4. DISCUSSION

The 14 November 1981 Aswan earthquake ($M = 5.7$) occurred along the east-west Kalabsha fault, which is a major trend in the northern part of the Lake Aswan in Egypt (Fig. 1). Its hypocenter was located at 20 km depth (Kebeasy et al., 1982). The Lake
Aswan forms the second largest man-made reservoir in the world. The water level in the lake varies daily and is also characterized by an annual cycle of the water level variation with peak and trough being often observed during November-December and July-August, respectively, of every year. The water level fluctuation in this lake sometime triggers earthquake activity (Fig. 2). Histograms of the temporal, spatial, and magnitude distribution along the Kalabsha and Rawraw (Figs. 3-8) indicate that the seismicity increases sometimes exhibiting a swarm sequence, and decreases again to its permanent low level of activity. The time distribution of this seismicity is consistent with the 1984 Omori law (Awad, 1994). Moreover, the major group of activity took place in the deeper part of the crust, mainly along the vertical extension of the Kalabsha fault. During the early period of this activity, Kebeasy et al., (1982) distinguished the Lake Aswan seismicity as reservoir-induced. Later, Awad (1994) pointed out that the correlation between temporal variations in seismicity and water level changes in the lake is not clearly observed over the years 1982-1991 (Fig. 2). Awad (1994) and Awad and Mizoue (1995a; b) separated the Lake Aswan seismicity into two groups (deep and shallow) based on seismotectonic analyses, in particular a 3-D crustal tomography study. They showed that the seismic activity during August 1982
was concentrated in the deeper zone (10 to 30 km) in the crust and that of the June 1987 occurred at the shallow zone with a depth of less than 10 km.

The variation in the parameter $b$ of the frequency–magnitude relationship has been related to differences in the stress, pore pressure and material heterogeneity (Mogi, 1967; Wiemer and Benoît, 1996; Wiemer et al., 1998). The conditions can provide important constraints for analysing the seismotectonic and hazard potential of a certain region (Malone and Wiemer, 2001). The variations in $b$-values from its normal value of the tectonic nature may be correlated with the presence of the lake reservoir (Schwartz et al., 1996). This variation was correlated with the presence of the magma in volcanic regions (Jolly and McNutt, 1999). A normal value of $b$ is determined in relation to the shallow activity along the Kalabsha and Rawraw faults (1.02 and 0.99, respectively), but the deep Kalabsha sequence is characterized by a slightly lower $b$-value (0.84) (Fig. 8). The temporal variation of the $b$-value is better correlated with the water level variations in the Lake Aswan than the direct number of events (Fig. 9). This correlation is more apparent for the shallow data sets of the Kalabsha and Rawraw faults (Fig. 9). The fluctuation of the water level and $b$-value of seismicity as two independent observations is not smooth. In addition, the $b$-value is here calculated for a limited magnitude range of earthquakes ($2 < M < 4.2$). However, a possible penetration of water across faults and fissures in a highly fractured shallow part of the crust, and its an influence on the stress regime at least within the shallow crust suggest a possible relationship between these correlated observations.

The effect of water level changes in the Lake Aswan may go down in the crust if its cracks, fissures and other physical characteristics are large enough to transport it. The depth dependence of $b$-value could reflect the degree of material heterogeneity and stress conditions (Mori and Abercrombie, 1997). In addition, the presence of a low seismic velocity anomaly in the shallow part of the seismically active zone in the Lake Aswan area (Awad and Mizoue, 1995b) adds another factor, which would play an important role in studying the relationship between the seismicity parameters (e.g., $b$-value) and the water reservoir-effective factors. The low seismic velocity anomaly is an environmental characteristics that describes the instability of the active region where the medium deformation is often high either due to seismic or aseismic causes. The active area contains the most intersected faults in the Aswan region (Fig. 1). On the basis of observations we suggest that at shallow depth (less than 10 km), conditions with more heterogeneous material properties and lower lithospheric stress prevail. The reverse conditions prevail at greater depth (11-30 km). So, the conclusion is that earthquakes in the Lake Aswan area occur due to its tectonics and presence of the Lake Aswan reservoir.

To evaluate the seismicity patterns along the study fault trends, the fractal dimension, 3-D, is examined by applying a correlation integral method described in eq. (2). The 3-D constant (equal to 1.97 and 2.11) is obtained for the shallow seismic events along the Kalabsha and Rawraw faults, respectively (Fig. 11). It is about 1.84 for the
deep events of the Kalabsha fault. In the hypocentre distribution, D, of the uniform distribution equals 3. It decreases with an increase in the clustering of events. Therefore, the earthquake clustering in the deep part of Aswan region is strong. This result is consistent with the presented b-values and is acceptable because the deep earthquakes are often bounded within a roughly planar structure in 2-dimensional space. Furthermore, the seismic deformation is localized in the deeper part of the crust rather than its shallower part.

5. CONCLUSIONS

The seismic region in the Lake Aswan area is still active, generating small magnitude (M < 5) earthquakes. Previous studies (i.e., Awad, 1994; Awad and Mizoue, 1995a; Hassib, 1990; Awad et al., 2002) indicate that the Kalabsha and Rawraw faults are dominated by the strike-slip fault mechanism. However, this study presents different seismicity characteristics of the active fault segments, which are obtained by applying the software package ZMAP. The deep fault segment of the Kalabsha fault has a smaller b and D3 values than those of the shallow segments of the Kalabsha and Rawraw faults. The correlation between the shallow seismicity either on the Kalabsha fault or along Rawraw trend is evident. But for the deep seismicity, this correlation is not apparent. This study suggests that the earthquakes occur in the lake Aswan area due to its tectonics and presence of the Lake Aswan reservoir.

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