Role of fluids in the earthquake occurrence around Aswan reservoir, Egypt

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Received 18 August 2011; revised 22 November 2011; accepted 11 December 2011; published 9 February 2012.

[1] Continuing seismicity for about 30 years near a large western embayment of the Lake Nasser, about 50 km from the Aswan High Dam in Egypt, has led to a debate about the possibility of its relation with the reservoir impoundment. The largest event in the region occurred on 14 November 1981 (M 5.3), 20 km beneath the Wadi Kalabsha embayment, a westward extension of the Lake Aswan. Since then, continuous monitoring of seismic activity has given an excellent opportunity to study the spatiotemporal distribution of seismicity in the area. Most of the immediate aftershocks of the 1981 main shock were located in the Gebel Marawa area at depths between 15 and 30 km. Depths of almost all earthquakes away from this zone were shallower than 12 km. To quantify the effect of the reservoir impoundment on the seismicity of the Aswan area, we calculated changes in stress and pore pressure due to the reservoir impoundment using Green's function approach. The change in Coulomb stress (ΔS) is calculated on the fault planes responsible for majority of the seismicity of the region. We found that for all the seismogenic faults, ΔS is negative, i.e., stabilizing, when we consider the effect of the reservoir load only, whereas it is positive, i.e., destabilizing, when we include pore pressure. For example, at the hypocenter of the main earthquake, shear stress, normal stress, and pore pressure due to reservoir operation are estimated as 5.5, 13.2, and 13.5 kPa, respectively, which suggest that ΔS is -3.1 kPa when we do not consider the effect of pore pressure and 5.7 kPa when contribution from pore pressure is considered. Hence, the seismicity in the Aswan lake region is driven by the pore pressure due to reservoir impoundment.

Citation: Gahalaut, K., and A. Hassoup (2012), Role of fluids in the earthquake occurrence around Aswan reservoir, Egypt, *J. Geophys. Res.*, *117*, B02303, doi:10.1029/2011JB008796.

1. Introduction

[2] The reservoir of the Aswan dam extends up to 500 km toward south and covers an area of about 6000 km^2 along the Nile river (Figure 1). The northern two-third of the reservoir (known as Lake Nasser) is in Egypt and the southern one-third (known as Lake Nubia) of the reservoir is in Sudan. It is the world's second largest reservoir. The reservoir filling started in 1964 and the construction of a 111 m high dam was completed in 1968. The continuing seismicity for about 30 years near a large western embayment of Lake Nasser, about 50 km southwest of the Aswan dam, has led to an obvious debate about its relationship with the reservoir impoundment. Several such worldwide cases have been reported where seismicity in the region appears to be influenced by the reservoir impoundment [*Gupta*, 2002]. From these case histories, perception has dawned over the past several decades that earthquakes may be triggered due to the impoundment of the reservoir after the construction of a hydroelectric dam. There appear to be many factors that control the incidence of earthquakes near reservoirs, for example, preexisting stress state, geological and hydrological conditions, reservoir volume, depth, shape and its loading and unloading rate, type and orientation of preexisting faults, and so on [*Simpson*, 1976]. Reservoir water load and pore pressure effects are the two main causative factors responsible for the perturbation of ambient stress field that lead to the occurrence of such earthquakes. Few quantitative analyses have been done to explain the mechanism of earthquakes near reservoirs. *Gough and Gough* [1976] did a quantitative analysis by calculating reservoir load to explain the earthquakes around Lake Kariba. *Bell and Nur* [1978] and *Roeloffs* [1988] quantified stresses and pore pressure to explain the seismicity near Lake Oroville and Lake Mead in the United States, respectively. *Gahalaut et al.* [2007] estimated the stresses and pore pressure caused by the Govind Ballav Pant reservoir, India, to suggest that seismicity in that region is strongly influenced by the reservoir operations. Recently, *Gahalaut and Gahalaut* [2010] estimated change in stresses and pore pressure caused by the Zipingpu reservoir, China, to suggest that the reservoir

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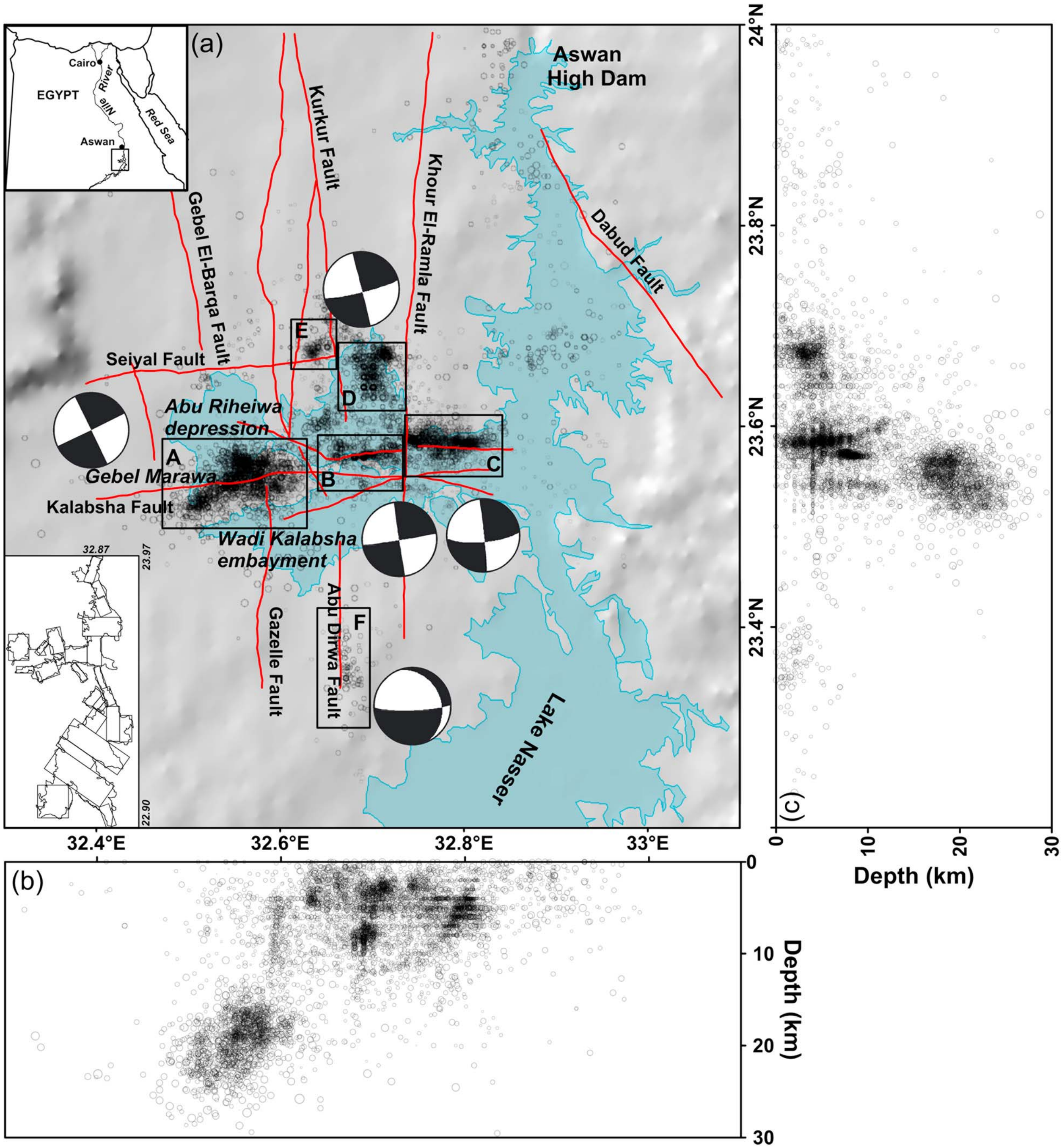

Figure 1. (a) Aswan seismicity and the reservoir on a topographic map with identified faults. Rectangles A to F represent the six zones in which we divide the seismicity for our analysis. Considered focal mechanisms corresponding to each zone are also shown. Focal mechanism is similar for zones E and D. Insets at the top and bottom of the figure show the location and discretization of the reservoir, respectively. (b) Vertical depth section of seismicity along longitude, and (c) same as Figure 1b but along latitude.

impoundment probably did not play any role in the occurrence of the 2008 Wenchuan earthquake.

[3] Despite the fact that the seismicity near the Aswan reservoir is one of the best monitored since 1982, the relationship between the reservoir impoundment and seismicity is not very well studied, and most of the work is of a qualitative nature. Here we simulate the stresses and pore pressure caused by the Aswan reservoir impoundment and quantify its influence on the nearby seismogenic faults.

2. Geology, Tectonics, and Seismicity of the Area

[4] The Aswan region in Egypt is located in the northeastern part of Africa. The surface geology consists of about 500 m thick Nubian sandstone and sediments of age ranging

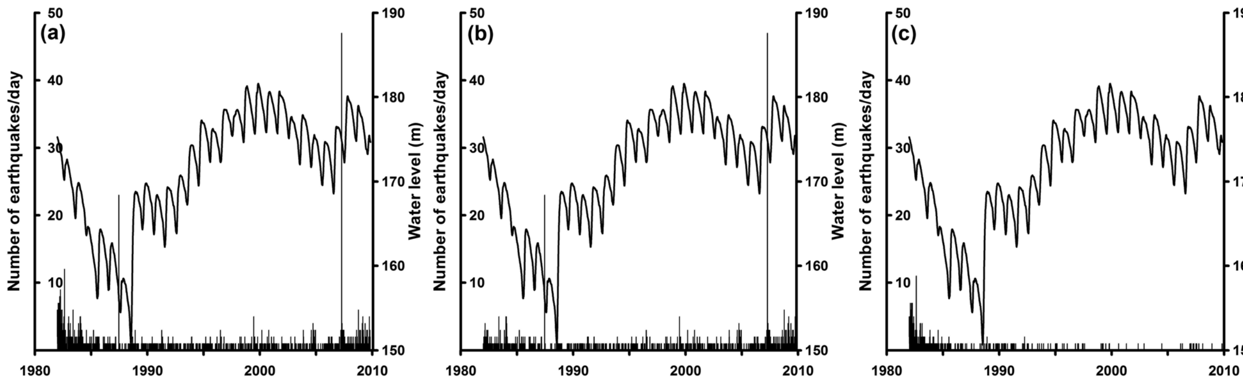

Figure 2. Temporal variation in the reservoir water level and earthquake frequency in the Aswan region for (a) all events, (b) shallow events (0–15 km), and (c) deep events (15–30 km) for earthquakes of $M \geq 2.2$, for which the catalog is complete [*Mekkawi et al.*, 2004]. Note the absence of deeper earthquakes in later period in Figure 2c.

from the Late Cretaceous to the Eocene. The basement of igneous and metamorphic rocks of the Precambrian era is outcropping on the western side of the lake and constitutes the main geological formation of the eastern side. There are Quaternary formations also, represented by the calcite deposits in the area. Geomorphologically, the area around Aswan is almost flat, with relief varying from 150 to 350 m above sea level. In the broad Nubian plain of sandstone, which extends between Wadi Kalabsha and the dam, an outlying remnant of the limestone plateau, named the Gebel Marawa, is the most prominent topographic feature. The entire region is characterized by a conjugate set of almost vertical E-W and N-S oriented strike-slip faults (Figure 1), which extend into the granitic basement and intersect beneath the Gebel Marawa area [*Kebeasy et al.*, 1987; *Issawi*, 1978, 1982]. The Kalabsha fault is an E-W trending en echelon fault of length of about 300 km associated with right-lateral movement. Most of the eastern segment of this fault is located beneath the Wadi Kalabsha embayment. The Seiyal fault too is an E-W trending fault, which is located almost 12 km north of the Kalabsha fault (Figure 1). They together constitute an east-west graben structure occupied by the Kalabsha embayment. The north-south fault system, parallel to the main course of the Lake Aswan, consists of several fault segments in which the Gebel El-Barqa, Kurkur, and Khour El-Ramla faults lie to the north, while the Gazelle and Abu Dirwa faults are to the south of the embayment area (Figure 1). The Dabud fault is a northwest-southeast trending fault, which lies just south of the Aswan dam [*Kebeasy et al.*, 1987; *Issawi*, 1978, 1982]. From the tectonics, geological setting, aerial photographs, and satellite imageries and paleoseismological studies, Kalabsha, Gebel El-Barqa, Kurkur, and Seiyal faults are considered the active faults, which are potential seismic sources. The activity on Khour El-Ramla fault is uncertain; however, it is assumed to be an active fault [*Abou Elenean*, 2003; Woodward-Clyde Consultants, Earthquake activity and stability evaluation for the Aswan High Dam, unpublished report, 124 pp., High and Aswan Dam Authority, Ministry of Irrigation, Egypt, 1985].

[5] Most of the Aswan seismicity is concentrated west of the reservoir in the Wadi Kalabsha area, a large embayment covered by the water of Lake Nasser, which is about 50 km southwest of the Aswan dam (Figure 1). The largest event in the region occurred on 14 November 1981 (M 5.3), 20 km beneath the Wadi Kalabsha embayment. From 1920 to 1981, in the ISC catalog, no earthquake within 200 km of the Aswan dam has been reported [*Kebeasy et al.*, 1987]. In October 1975, two seismic stations, located 60 and 200 km from the Kalabsha embayment, were installed [*Kebeasy et al.*, 1987]. During 1975–1976, these stations operated only for 160 days and only one earthquake could be recorded from the Kalabsha area. Operation of these stations again started in mid-1980. One or both stations were in operation for 217 days from August 1980 to August 1981. Twenty earthquakes of magnitude 2.8 to 3.6 were located from the Kalabsha area during that period [*Kebeasy et al.*, 1987]. Before the 1981 main shock, three foreshocks, two on 9 November 1981 (M 3.6 and 4.2) and one on 11 November 1981 (M 4.5), were recorded from the Kalabsha and Aswan regions by the WWSSN station at Helwan, near Cairo (690 km from the epicentral area at Kalabsha). Two successive aftershocks were recorded with a focal depth of 18 and 22 km on 2 January 1982 [*Hassoup*, 2002]. Since June 1982, a continuous recording of earthquakes by the Aswan seismological center is done by a network, which consists of 13 field stations. Many spatiotemporal studies of earthquakes have been carried out since the installation of this network. According to *Simpson et al.* [1990] and *Kebeasy and Gharib* [1991], except the main shock and most of the immediate aftershocks, which occurred beneath Gebel Marawa at depths between 15 and 30 km, all other earthquakes occurred between 0 and 12 km (Figure 1). Deep seismicity followed the typical aftershock pattern and died down with time while the shallow seismicity still continues (Figure 2) [*Hassib et al.*, 2010]. *Kebeasy and Gharib* [1991] and *Abou Elenean* [2003] suggested that most of the seismicity in the Aswan area is concentrated along the identified fault segments. *Abou Elenean* [2003] derived focal mechanisms of 19 earthquakes, using polarities of *P*, *SV*, and *SH* waves and the amplitude ratios of *SV*/*P*, *SH*/*P*, and *SV*/*SH*, and found that all events show predominantly strike-slip type motion, except the one at Abu Dirwa fault, which shows predominantly normal-type motion (Figure 1). According to *Kebeasy and Gharib* [1991], active fault segments, water load, and time necessary for the water to

move into or out of the pore space are three main factors responsible for triggering seismicity in the area.

3. Analysis of the Effect of Aswan Reservoir Impoundment on the Seismicity of the Region

3.1. Concept and Theory Used in the Analysis

[6] To quantify the effect of stress and pore pressure changes caused by the reservoir impoundment in the presence of tectonic stresses, and their influence on earthquake causative fault planes, we adopt here the Coulomb-Mohr frictional failure criterion of earthquake occurrence, according to which, the change in Coulomb stress, ΔS [*King et al.*, 1994; *Hardebeck et al.*, 1998; *Scholz*, 1990], can be defined as

$$\Delta S = \Delta\tau - \mu(\Delta\sigma - \Delta P), \quad (1)$$

where $\Delta\sigma$ and $\Delta\tau$ are the changes in normal and resolved shear stress due to the reservoir on the considered fault plane. Compressive normal stress is being considered positive. ΔP is the change in pore pressure due to the reservoir operations and μ is the coefficient of friction. $\Delta\tau$ is resolved in the slip direction derived from the earthquake focal mechanism. Positive $\Delta\tau$ and negative $\Delta\sigma$ promote failure. Accordingly, failure is encouraged, referred hereafter as destabilization, if ΔS is positive and vice versa. The role of pore pressure is always to encourage failure by decreasing the normal stress. If an earthquake occurs in the vicinity of a reservoir, then to assess its role in triggering the earthquake, we calculate ΔS due to the reservoir impoundment on the fault plane of the earthquake at its hypocenter. If at the time of the earthquake, ΔS is positive, then this should have a destabilizing effect at the hypocenter and it suggests that the reservoir has a positive role in the occurrence of the earthquake and vice versa. In all our computations, we assumed that the tectonic stresses and background pore pressure did not change between the considered short time period of the reservoir impoundment and the earthquake occurrence, and changes in stresses and pore pressure in that period occurred because of the reservoir impoundment only.

[7] To calculate stresses and pore pressure, we followed the approach of *Gahalaut* [1995] and *Gahalaut and Chander* [2000]. We discretized the Aswan reservoir in map view through a system of 26 rectangles (Figure 1). The depth of the water in each rectangle was assumed constant, and its value was adopted by interpolation, assuming maximum reservoir water depth near the dam, which decreased in each rectangle with distance from the dam in the upstream direction. We did not consider the water load of the entire 500 km long reservoir. We assumed that the water load up to 22.9° latitude from the Aswan dam only contributes in developing stresses and pore pressure. Validity of the assumption lies on the fact that earthquakes occur only up to 23.3° latitude to the south of the Aswan dam. In the Kalabsha embayment, water level is assumed to be 15 m corresponding to 95 m at Aswan dam [*Simpson et al.*, 1990]. Cumulative values of each of the six components of the stress tensor as a result of 26 rectangular water loads, at any observation point, were calculated using 3-D Boussinesq solutions [*Jaeger and Cook*, 1969] in homogeneous, isotropic, and linear elastic half-space. These six components of the stress tensor were used to calculate normal ($\Delta\sigma$) and shear stress ($\Delta\tau$) changes due to the reservoir on a considered plane, of given strike, dip, and rake [*Jaeger and Cook*, 1969]. Followed by *Biot* [1941] and *Rice and Cleary* [1976], change in pore pressure (ΔP) due to the reservoir in a water saturated porous elastic medium is calculated by solving the following diffusion equation:

$$c\nabla^2(\Delta P) = \frac{\partial}{\partial t}\left[(\Delta P) - B\left(\frac{\Delta\theta}{3}\right)\right], \quad (2)$$

where c is the hydraulic diffusivity, B is the Skempton's coefficient, and $\Delta\theta/3$ is the change in mean stress, θ being the sum of normal stresses. Hydraulic properties are considered to be uniform and isotropic in the half-space. ΔP is the sum of ΔP_c and ΔP_d, which are the change in pore pressure due to the instant compression caused by the reservoir load, and the change in pore pressure due to the diffusion of reservoir water load, respectively [*Roeloffs*, 1988]. Thus,

$$\Delta P = \Delta P_c + \Delta P_d, \quad (3)$$

where ΔP_c can be estimated as

$$\Delta P_c = B\frac{\Delta\theta}{3}. \quad (4)$$

To estimate ΔP_d, we follow the Green's function solution of *Gahalaut and Chander* [2000]. The initial or boundary condition, whichever is applicable for the defined problem, can be considered in terms of a source term $S(x,y,z,t)$. Thus, the diffusion equation for ΔP_d can be written as

$$c\nabla^2(\Delta P_d) - \frac{\partial}{\partial t}(\Delta P_d) = S(x,y,z,t). \quad (5)$$

In our case, the actual water-level time series for the Aswan reservoir since the impoundment of the reservoir is considered as the source term. Solution of equation (5) can be written as [*Gahalaut and Chander*, 2000]

$$\Delta P_d(x,y,z,t) = c\int_0^t \int_{-\infty}^{\infty} \int_{-\infty}^{\infty} S(x',y',z',t')\frac{\partial G}{\partial z'}\Big|_{z'=0} dt', dx', dy'. \quad (6)$$

In equation (6), x,y,z and x',y',z' refer to the observation and source points, respectively, where the x, y, and z axes point toward north, east, and vertical downward, respectively. Here,

$$G = \frac{1}{8[\pi c(t-t')]^{3/2}}\left[\exp\left(-\frac{(z-z')^2}{4c(t-t')}\right) - \exp\left(-\frac{(z+z')^2}{4c(t-t')}\right)\right] \cdot \exp\left[-\left(\frac{(y-y')^2+(x-x')^2}{4c(t-t')}\right)\right]. \quad (7)$$

Using the above method for calculating stresses and pore pressure and the concept of the Coulomb stress, we analyzed the effect of the Aswan reservoir impoundment on the seismicity around it.

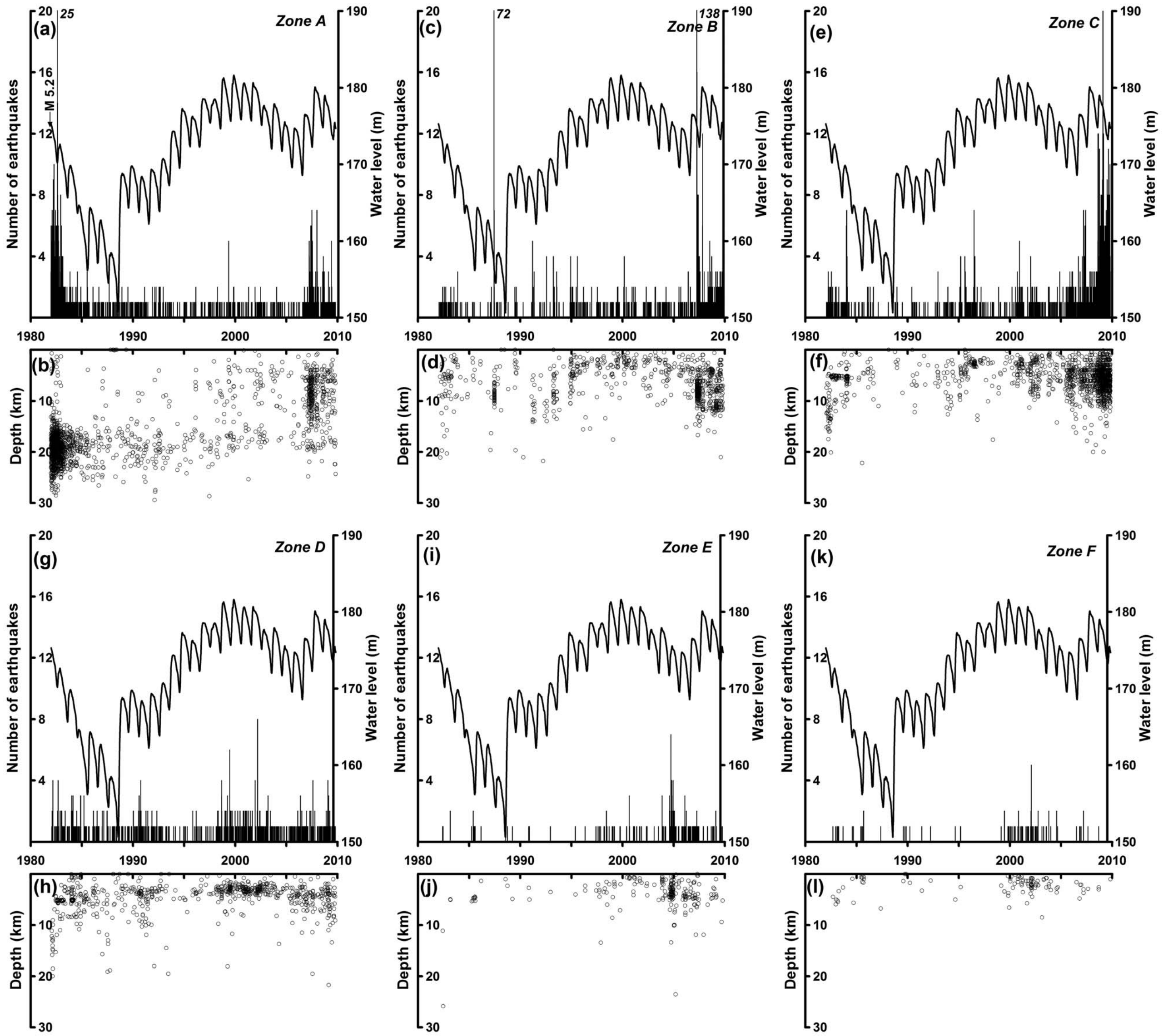

Figure 3. Earthquake distribution in each zone (zones A to F) with time and depth. Here we considered earthquakes of all magnitude.

3.2. Results of the Analyses

[8] Following *Hassib et al.* [2010], we divided the seismicity of the region from January 1982 to December 2009 into six active seismic zones from A to F (Figure 1). In Figure 3, earthquakes of each zone have been plotted with time and depth. In the subsequent sections, we analyze the effect of the reservoir impoundment on the seismicity in each zone.

3.2.1. Analysis for Zone A

[9] Zone A is the Gebel Marawa region, where the 14 November 1981 event and most of its aftershocks occurred. It appears that the seismicity of zone A is associated with the Kalabsha fault (Figure 1). Initial seismicity after the 1981 main shock is concentrated at 15 to 30 km depth. However, in the later period, majority of the earthquakes occurred at a depth less than 15 km (Figure 3b). For this zone, *Mohamed et al.* [2003] derived a strike-slip composite fault plane solution (CFPS) for the events of magnitude 2 to 3.8 from 1997 to 2002, which is consistent with the fault plane solutions (FPSs) derived by other workers [*Abou Elenean*, 2003; *Hassoup and Mizoue*, 1995]. For the main 1981 event, *Kebeasy et al.* [1987] derived a pure strike-slip mechanism, while that given in the CMT Harvard catalog has some normal components. Here for our analysis of the main shock, we consider the FPS by *Kebeasy et al.* [1987] and chose the east-west trending nodal plane as the fault plane, which is approximately consistent with the strike of the Kalabsha fault. To analyze the effect of the Aswan reservoir impoundment on the seismicity of zone A, we calculated $\Delta\sigma$ and $\Delta\tau$ because of the reservoir load on this plane. To calculate pore pressure, we assumed c as 1 m^2/s [*Talwani et al.*, 2007] and a nominal value of B as 0.7 [*Talwani et al.*, 2007] for our analysis of all the zones. ΔP for the entire reservoir loading history is calculated at 20 km depth at the hypocenter location of the 14 November 1981 event (Figure 4).

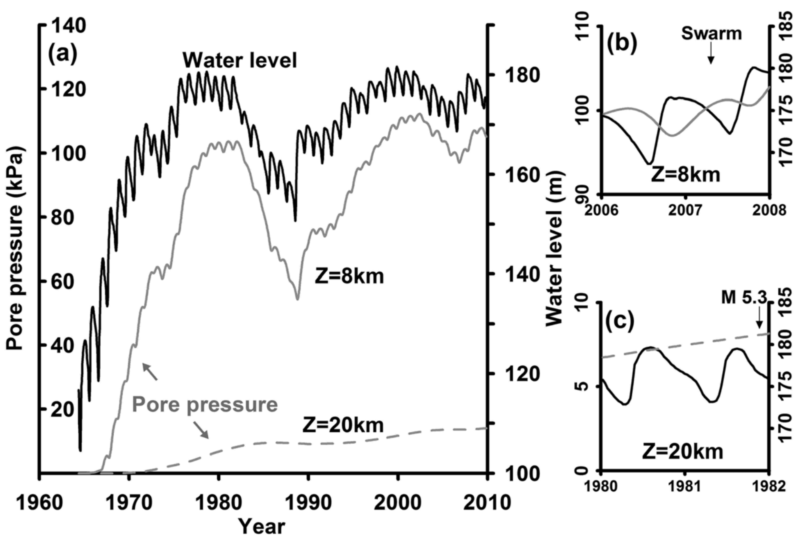

Figure 4. (a) Water-level and pore pressure changes at 8 km, corresponding to the center of the 2007 swarm (see Figure 3b), and at 20 km, corresponding to the hypocenter of the 14 November 1981 earthquake, for the entire period of reservoir operation. Blowups of water-level and pore pressure changes are shown in Figure 4b for the 2007 swarm and in Figure 4c for the 1981 main shock.

Figure 5 shows $\Delta\tau$, $\Delta\sigma$, ΔP, and ΔS (with and without considering pore pressure) in a horizontal plan view at 20 km depth and at the time epoch of the main shock. From the figure, it transpires that ΔS is negative in zone A when the effect of pore pressure is not considered. This implies that the reservoir load actually stabilized the faults in zone A. But when the effect of pore pressure is considered, ΔS becomes positive on faults in zone A, implying that the pore pressure is the main cause to push the causative faults in zone A toward destabilization.

3.2.2. Analysis for Zones B and C

[10] Zones B and C are on the Kalabsha fault and are located to the east of zone A. The temporal and depth distribution of seismicity in each zone is shown in Figures 3c–3f. Earthquakes in both zones occurred at depths less than 12 km. In zone B, two swarms have occurred. The first swarm occurred from 17 to 19 June 1987 during which 27, 7, and 72 earthquakes occurred on 17, 18, and 19 June, respectively (Figure 6a). Depth range of these earthquakes is between 5 and 12 km and magnitude ranges from 0.5 to 3.4. All the earthquakes of this swarm with a magnitude greater than 2.5 occurred on 19 June 1987 and hence, we chose to perform our calculations on the epoch of 19 June 1987 at a depth of 8 km. CFPS of this swarm is predominantly of strike-slip type [*Hassib et al.*, 2010]. The second swarm from 12 to 14 April 2007 occurred at almost the same place as that of the first swarm. During this swarm, about 185 earthquakes (M 0.9 to 4.2) occurred in the depth range of 5 to 12 km. There were 15 events of $M \geq 3.0$ and two events with $M \geq 4.0$. CFPS of this swarm is derived as predominantly strike-slip type with a small normal slip component [*Hassib et al.*, 2010]. Temporal variation in the pore pressure since the impoundment till 2009, at 8 km depth and at the hypocenter of these two swarms, is shown in Figure 4a. A blowup of the pore pressure for 2007 swarm is also shown in Figure 4b, which shows a time lag between maximum pore pressure and peak of water level, which is approximately consistent with the time delay in the occurrence of the swarm with respect to the peak water level (Figure 6b). At greater depth, such variation in the pore pressure is not apparent and also the magnitude of pore pressure decreases drastically (Figures 4a and 4c). Figure 7 shows $\Delta\tau$, $\Delta\sigma$, ΔP, and ΔS (with and without pore pressure) in a plan view at 8 km depth corresponding to the CFPS of the 2007 swarm. ΔS without pore pressure is negative for zone B (Figure 7d). However, pore pressure is very high (Figure 7c) to overcome this negative effect, and hence, when considered, it makes ΔS positive in zone B (Figure 7e). Thus, the pore pressure plays a very important role to destabilize the seismogenic faults in zone B. We performed a similar analysis for the 1987 swarm and arrived at a similar conclusion (Figure 8a).

[11] Our analyses of zone B also apply for zone C, as earthquakes in this zone also occurred on the easternmost part of the Kalabsha segment (Figure 1a) and also the depth of earthquakes in both the zones are same (Figure 3c). In this zone, seismicity started increasing after 2007 and maximum number of earthquakes occurred in 2009 (Figure 6c). We conclude from our analyses of earthquakes in zones B and C that the effect of pore pressure destabilizes the faults in the region.

3.2.3. Analysis for Zones D and E

[12] Zones D and E are located to the north of zones A, B, and C. Earthquakes in these zones occur on the east-west trending Seiyal and several N-S trending faults (Figure 1). Depth range of earthquakes in zone D is shallower than 8 km (Figure 3h); however, most of the earthquakes in zone E occurred at depths less than 6 km (Figure 3j). As majority of the earthquakes in both the zones occurred at 5 km depth, we did our calculations at 5 km depth for both the zones. In zone E, around 125 earthquakes of magnitude 1.3 to 4.1 occurred from August to December 2004 including 15 earthquakes in the range M 3.0–3.7 and one earthquake of M 4.1 (Figure 6e). *Hassib et al.* [2010] derived a strike-slip type focal mechanism for this swarm, which we adopt in

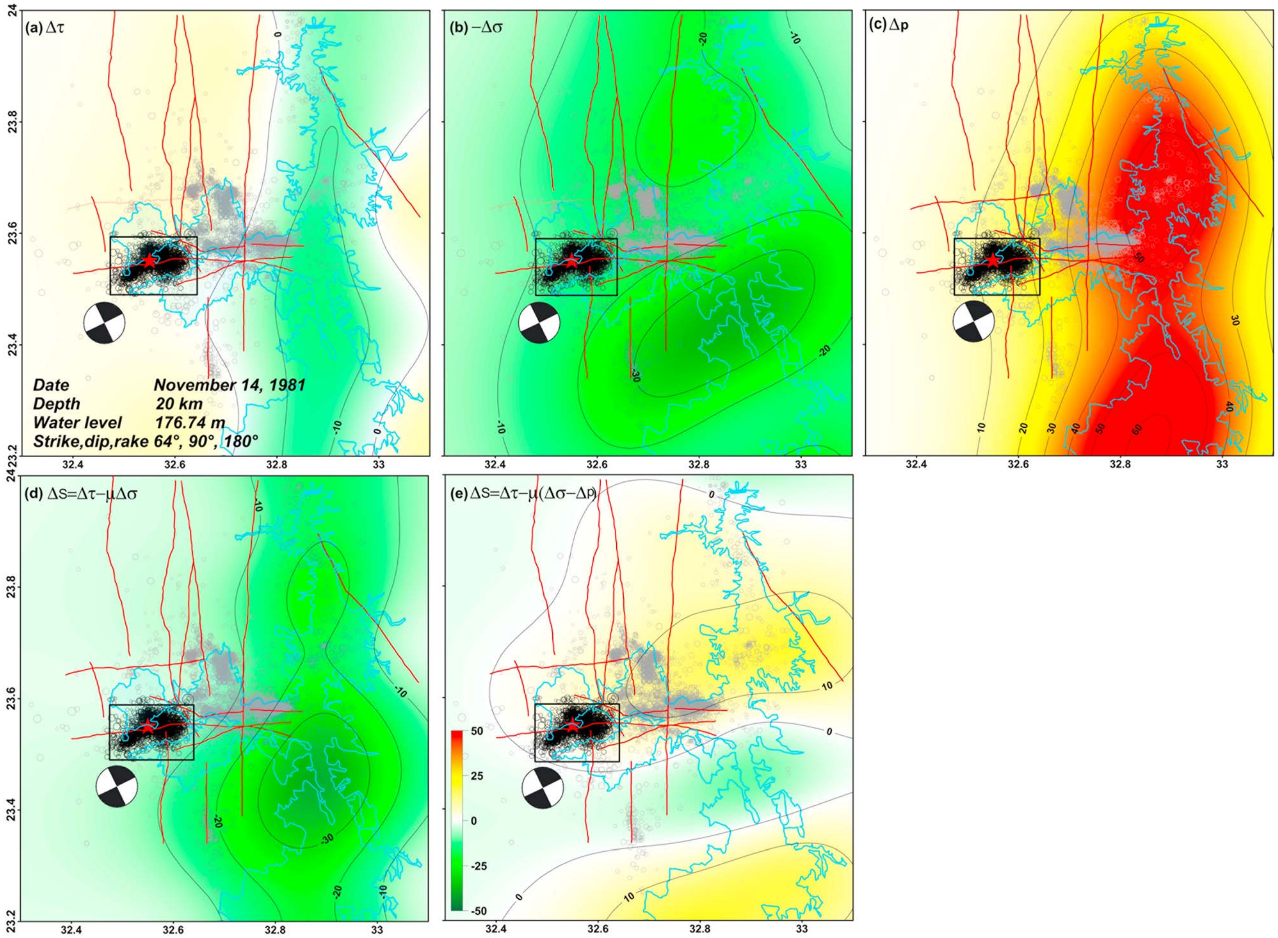

Figure 5. (a) Shear stress, (b) normal stress, (c) pore pressure, (d) ΔS without pore pressure, and (e) ΔS with pore pressure (all in KPa). These calculations are performed at 20 km depth corresponding to the focal depth of the 14 November 1981 earthquake and at the time epoch of this earthquake. Considered focal mechanism (strike, dip, and rake as 64°, 90°, and 180°, respectively) is also shown. These results represent the seismicity of zone A of Figure 1, shown by the rectangle with black color. All other earthquakes are shown by gray color.

our calculations for zones D and E. Since there is an ambiguity whether these earthquakes occurred on the E-W or N-S trending faults, we analyzed the effect of reservoir impoundment on both the planes (Figures 8b and 8c). Results are not significantly different from one nodal plane to the other. Even in this case, fault stability is negative when we do not consider the contribution from pore pressure but positive when we include the effect of pore pressure. In short, for these two zones also, pore pressure brings the faults toward failure.

3.2.4. Analysis for Zone F

[13] Seismic zone F is located south of Wadi Kalabsha embayment. Earthquakes in this zone are clustered on N-S trending Abu Dirwa fault (Figure 1) at a depth shallower than 5 km (Figure 3l). Earthquake frequency in this zone is comparatively low and the magnitude of earthquakes is generally less than 2.5. We did our calculations at the epoch of 9 February 2002 at 5 km depth, when five earthquakes occurred in a day (Figure 6f). *Abou Elenean* [2003] suggested strike-slip connected normal faulting for the earthquakes associated with this zone. *Mohamed et al.* [2003] suggested strike-slip motion along the Abu Dirwa fault. However, we consider the FPS given by *Abou Elenean* [2003] for our analysis as for the pure strike-slip motion [*Mohamed et al.*, 2003], our earlier results of Figure 8c are applicable here also. These calculations (Figure 8c) suggest that most of the earthquakes in this zone do not occur in the region of destabilization even when we consider the effect of pore pressure. Figure 8d shows our calculations corresponding to the FPS of *Abou Elenean* [2003]. These calculations demonstrate that when we consider the effect of pore pressure to calculate ΔS, zone F lies in the region of destabilization. So for this zone also pore pressure is the main causative factor for the occurrence of earthquakes.

4. Discussion and Concluding Remarks

[14] From the above analyses, it appears that the spatial distribution of the seismicity in the Kalabsha embayment area is strongly manipulated by the impoundment of the

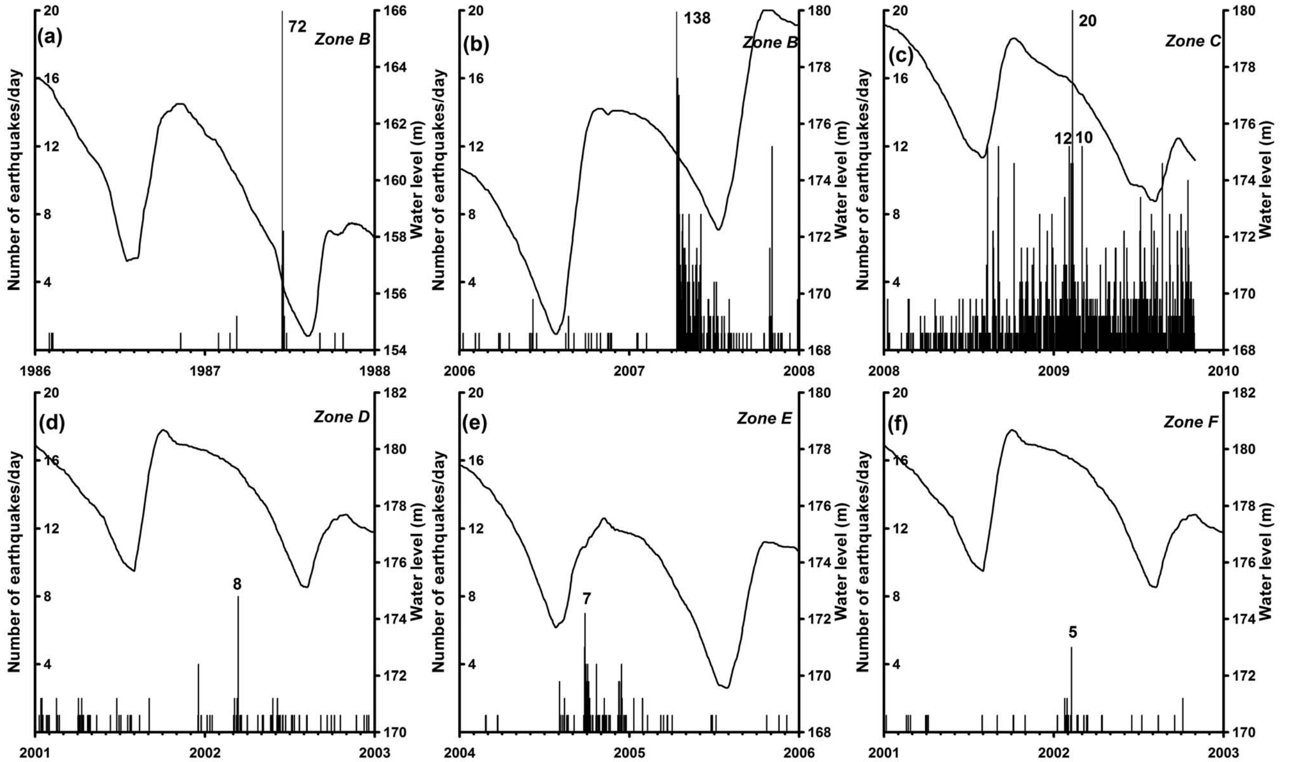

Figure 6. (a–f) All earthquake swarms in zones B–F in the period from 1982 to 2009.

Aswan reservoir. Coincidence of the seismicity with the overlapping region of active faults and reservoir water make our case stronger. Seismicity along Abu Dirwa fault is the only exception where earthquakes occurred away from the water covered area. But as all the earthquakes along this fault occurred at very shallow depths and not very far from the Kalabsha area, pore pressure due to the diffusion process from the reservoir might have played a very important role in this case also.

[15] Other important issues, which may be addressed before reaching any conclusion for the seismicity of this area are (1) the role of Nubian sandstone on our results, (2) the seismicity in the Aswan region started 17 years after the reservoir began to fill in 1964, (3) the effect of the reservoir impoundment on the 14 November 1981 (M 5.3) earthquake as it occurred at 20 km depth and the lack of deep seismicity in the past 10 years, and (4) the absence of good correlation between the temporal variation of water load and earthquakes [*Hassoup*, 2002; *Selim et al.*, 2002; *Mekkawi et al.*, 2004], which is very much expected if the earthquakes of the region are influenced by the reservoir operation. In the following paragraphs we explore these issues.

4.1. Role of Nubian Sandstone

[16] Throughout the studied region, the Nile channel marks the boundary between surface exposure of granite to the east and a westward-thickening wedge of sandstone to the west. In the area where most of the seismicity is located, the thickness of the sandstone reaches about 400 m. The presence of this sandstone layer can have two significant effects. First, water seepage into the sandstone along the entire western edge of the reservoir (bank storage) is documented by deep wells around the reservoir [*Evans et al.*, 1991a, 1991b; *Beavan et al.*, 1991]. Since this bank storage occurs primarily on the western side of the reservoir, it has the impact of shifting the effective center of the load of the reservoir to the west. Second, as discussed by *Simpson et al.* [1990], the groundwater table was raised by as much as 75 m after the Kalabsha embayment area started to flood in 1975. With the 25%–30% porosity [*Evans et al.*, 1991a], this might have eventually increased the effective height of water in the reservoir by up to 25 m in the Kalabsha area, significantly greater than the maximum 15 m reservoir water depth in this region. Since the lateral extent of the flooded sandstone extends beyond the shoreline of the reservoir itself, this additional load will be of larger areal extent as well. Qualitatively, the pore pressure due to the added load from both these effects would further increase the extent and magnitude of the positive ΔS in the Kalabsha area. Also, since zone F receives bank storage from both north and east sides, the earthquakes in the Abu Dirwa region would also be in the zone of enhanced ΔS, which is otherwise located in the marginally destabilized zone (Figure 8d).

[17] There is a significant variability and uncertainty associated with the values of Skempton's coefficient, B, and hydraulic diffusivity, c, for the rock mass in calculating pore pressure. As the diffusion pore pressure (P_d) is much higher than the compression pore pressure (P_c), the value of B does not make much difference in our results, at least qualitatively. As the exact value of c is unknown in granites of this area and globally it has very wide range [*Li*, 1984; *Roeloffs*, 1988], we performed our calculations for $c = 0.1$ to $10\ m^2/s$, a possible range given by *Talwani et al.* [2007] for fractures when seismicity is related to pore pressure diffusion. Here,

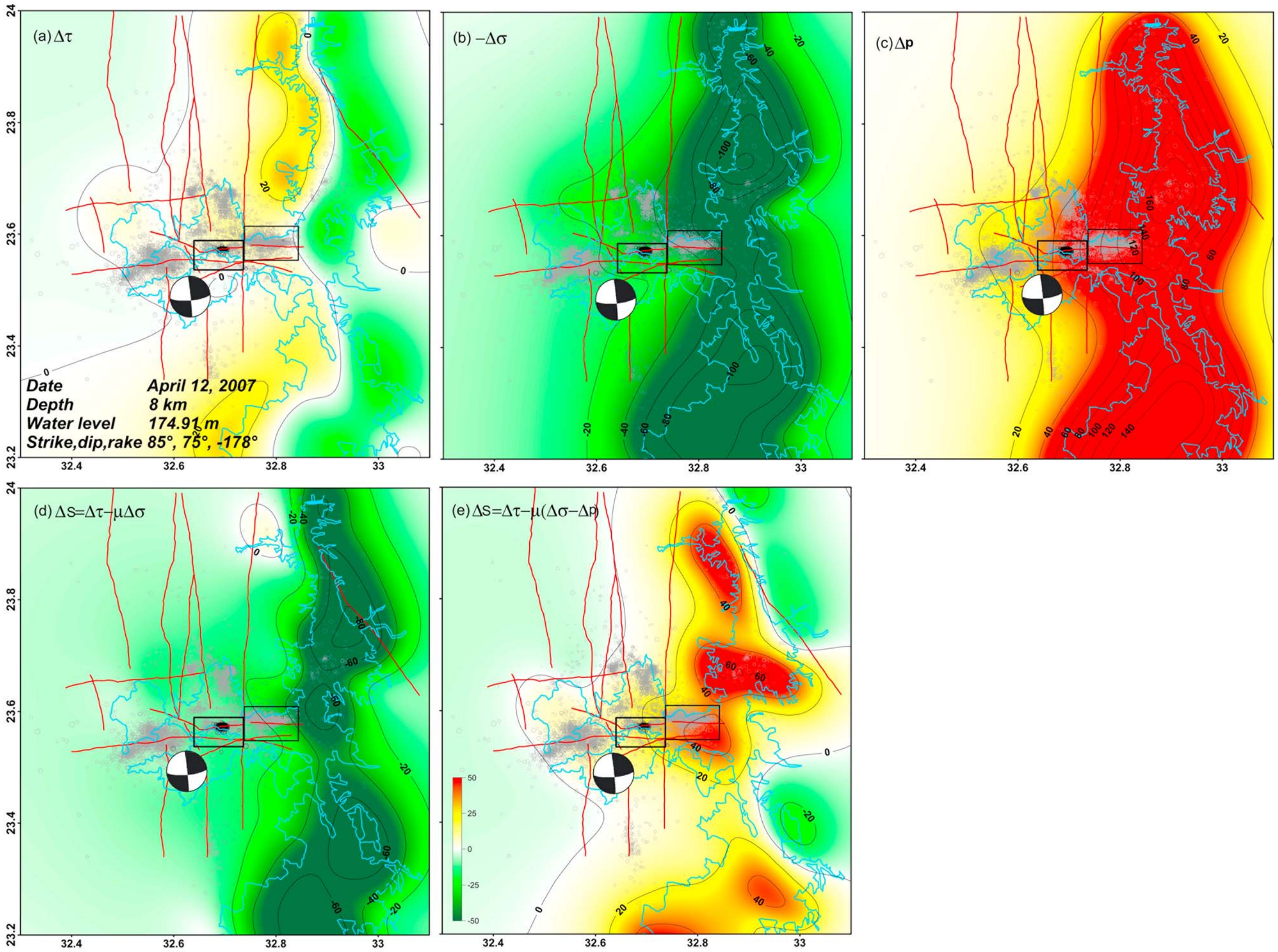

Figure 7. Same as Figure 5 but for time epoch at 12 April 2007 and at depth of 8 km corresponding to the majority of the focal depths of the 2007 swarm in zone B. Focal mechanism (strike, dip, and rake as 85°, 75°, and −178°, respectively) is also shown. Results of this figure represents zone B of Figure 1.

we have presented our results for a nominal value of *c* of 1 m^2/s. For higher values of *c* (e.g., 10 m^2/s), the region of destabilization increases in extent as well as in magnitude in all zones. For 0.1 m^2/s, zone A comes under stabilization. For a value of 0.5 m^2/s, it comes under the marginally destabilized zone. Zones B and C come well within the destabilized zone for the above range of *c*. Zones D, E, and F come marginally in the region of destabilization for these lower values of *c*. However, we emphasize here that it does not weaken our results because in view of the discussion in the previous paragraph, ΔS in our analysis is anyway underestimated as we did not consider the role of water load infiltrated in Nubian sandstone and our theory applies for a fully saturated medium since the impoundment.

4.2. Delay in the Onset of Seismicity With Respect to the Onset of Reservoir Filling

[18] From the available limited data, it appears that before 1980, the seismicity level of the Kalabsha area was extremely low. But from August 1980, few earthquakes were recorded in this area and on 14 November 1981, the largest event of the area (M 5.3) occurred and the seismicity continues even today. This observation, commensurable with the filling history of the area, strengthens our view that the calculated pore pressure along with the contributions due to mass transfer of water from the reservoir into the sandstone played a main role in triggering the seismicity in the Kalabsha embayment area. The Wadi Kalabsha embayment area began to fill in 1974 when the water level in the reservoir exceeded 165 m; before that, water was confined in the old N-S narrow channel of Lake Nasser. After this, the water level continued to increase till 170 m in 1975 and extended toward west in the embayment area and then further exceeded to 177.8 m in November 1978 and reached the Abu Riheiwa depression (north of Gebel Marawa). This water movement made the whole embayment area fully saturated for the first time [*Simpson et al.*, 1990] since the impoundment of the reservoir that began in 1964. Accordingly, the pore pressure in the embayment region started building up in 1975, became significant only after 1978, and was maximum for the first time in 1981–1982 (Figure 4), which ultimately led to the onset of seismicity in 1981 and continues even today.

4.3. Main Shock at Deeper Level and Present-Day Seismicity Only at Shallower Level

[19] From our analysis, we are not able to comment much on the deeper depths of the 14 November 1981 earthquake

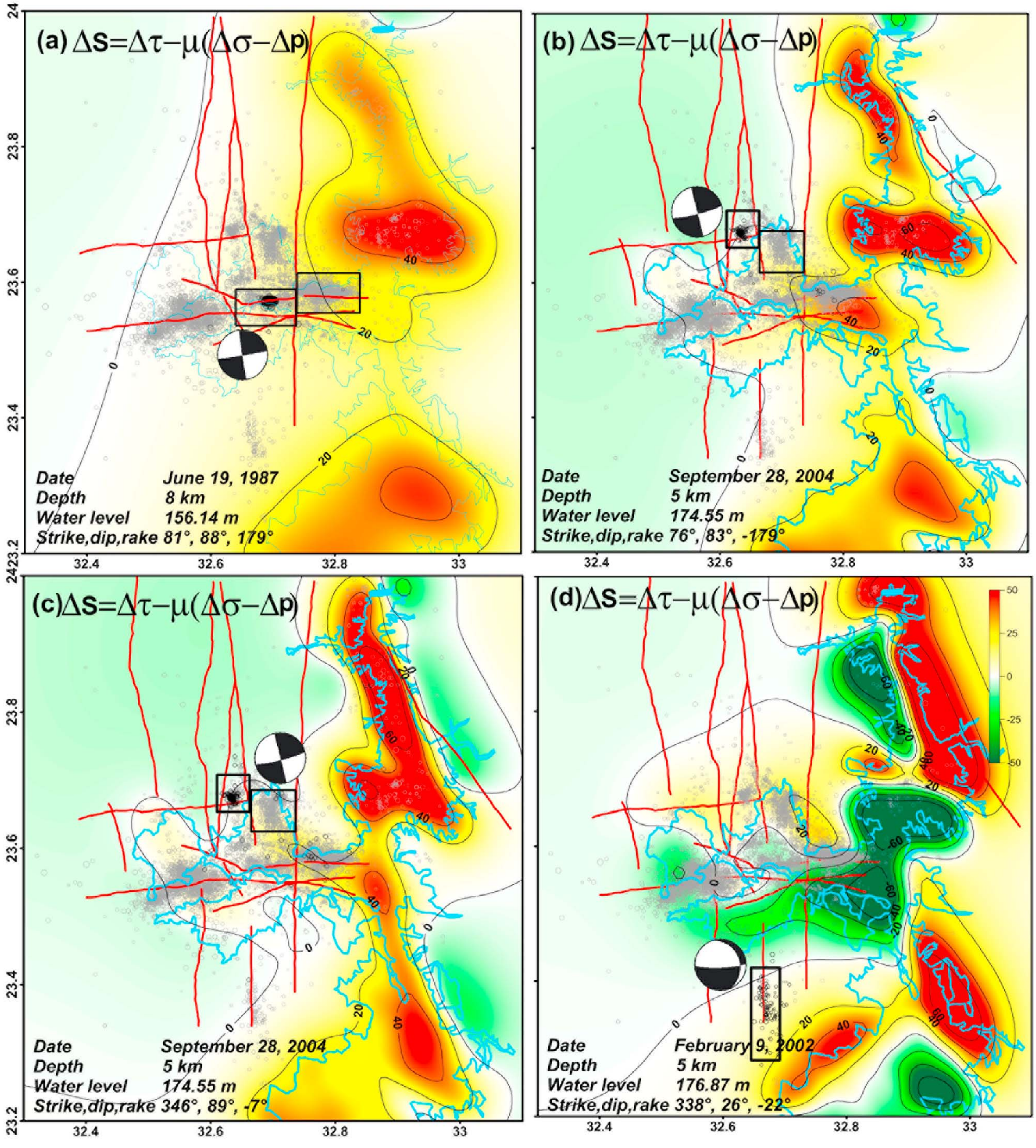

Figure 8. ΔS with pore pressure (a) at the time epoch of 19 June 1987 at 8 km depth for zone B (considered nodal plane has strike, dip, and rake as 81°, 88°, and 179°, respectively) (b, c) at the time epoch of 28 September 2004 for the east-west (strike, dip, and rake as 76°, 83°, and −179°, respectively) and north-south (strike, dip, and rake as 346°, 89°, and −7°, respectively) trending nodal planes at 5 km depth for zones E and D, and (d) at the time epoch of 9 February 2002 at depth 5 km for zone F. Considered nodal plane has strike, dip, and rake as 338°, 26°, and −22°, respectively.

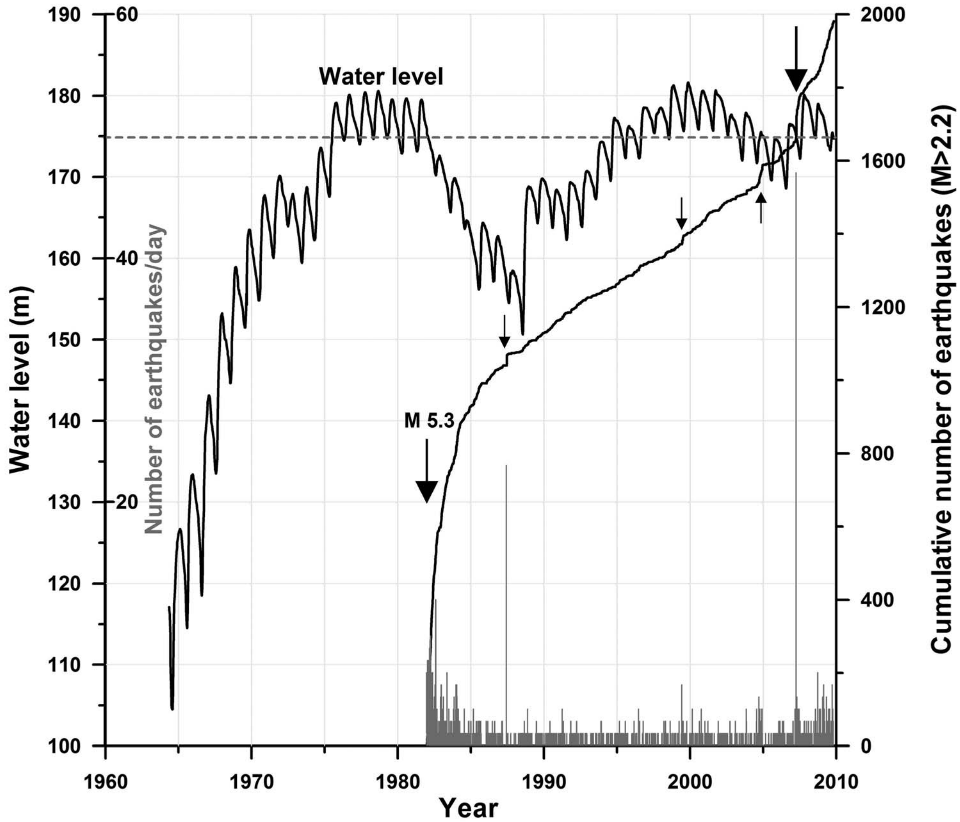

Figure 9. Earthquake frequency (same as in Figure 2a) and cumulative number of earthquakes (from 1982 to 2009) with temporal variation of water level. Arrows mark the time of sudden increase in the seismicity.

and its aftershocks and also on complete migration of seismicity to shallower depths after about 2001. Nevertheless, our analysis shows destabilization at 20 km depth on causative faults (Figure 5). Here, we wish to highlight that in our analysis, we analyze whether the effect of the reservoir is to stabilize or destabilize the causative faults in the region. For the earthquake occurrence, faults should be critically stressed for failure, and the reservoir effect acts only as a trigger for failure, if the reservoir produces a destabilizing effect [*Chander and Gahalaut*, 1997]. So our analysis basically supports the occurrence of earthquakes at deeper depths as well as at shallower depths. The only argument we can give is that the pore pressure changes because of the reservoir, which is the main causative factor in triggering the earthquakes in this case, is very low at deeper depths when compared to that at shallower depths. Pore pressure at 20 km depth is about 10 times lower than that at 8 km depth (Figure 4). This implies that for failure, faults should be more critically stressed at deeper depths than at shallower depths. Hence, in principle, the possibility of occurrence of earthquakes due to reservoir triggering is more at shallower depths than at deeper depths. We suggest that the fault at deeper level responsible for the 1981 main shock was more critically stressed than those at shallower level, and a small increment in the pore pressure led to the occurrence of the main shock and its aftershocks. Since the fault released the strain and was no more critically stressed afterward, further insignificant increase in the pore pressure at that depth (Figure 4) did not lead to continued seismicity at a deeper level. On the other hand, very high pore pressure at shallower depth in the latter period was enough to destabilize the faults for a longer period through small magnitude earthquakes. *Mekkawi et al.* [2004] also proposed that deep seismicity vanished with time because it was not sustained by the reservoir water-level changes. The shallow seismicity, which is still active since 2001, appears to be sustained more efficiently because of water loading at shallow depths rather than at deeper depths.

4.4. Correlation Between Reservoir Water-Level Changes and Seismicity

[20] Similar to the analyses by *Mekkawi et al.* [2004], *Selim et al.* [2002], and *Hassoup* [2002], we too analyzed the correlation coefficient between the water time series and the earthquake time series from 1982 to 2009. Our results are not very much different from that of the earlier researchers who suggested that the correlation is very weak (results not shown here to avoid repetition). To further probe this issue, we plotted individual swarms and/or maximum number of earthquakes in a day in each zone to see the correlation between the water-level series and increased seismicity in each zone (Figure 6). We found that for each zone, epochs of maximum seismicity are not necessarily coincident with the maximum in the water level. Epochs of high seismicity in each zone occurred at various stages of annual water-level series (Figure 6). *Mekkawi et al.* [2004] suggested a cascade

model to justify no or weak correlation in the Aswan seismicity with the annual water-level series. They suggested two classes of earthquakes in the Aswan seismicity. One class is directly driven by the water-level changes while the second class of the earthquakes is triggered by the former as aftershocks. From our analysis, we add that the Aswan seismicity is distributed on various faults with varying depths from 0 to 30 km. As pore pressure is the main causative factor, which includes diffusion process, lag between maximum water level and maximum pore pressure greatly depends upon the relative distance between the earthquake cluster and the reservoir. This will produce a large variation in the lag between the epochs of earthquakes at various distances and the peak of water level. Yet another influencing factor in the correlation between the water level and seismicity in this regard could be the distance-dependent lag caused by the water infiltration in sandstone under Kalabsha region (D. W. Simpson, personal communication, 2011). The above mentioned causes might be the reasons for weak correlation of water-level series and earthquake time series.

[21] We suggest that besides any correlation that may exist between the annual water-level changes in the reservoir and the earthquake occurrence [*Mekkawi et al.*, 2004; *Selim et al.*, 2002], there appears a correlation between the long-term variation in the water level and earthquake occurrence. The first major episode of increase in seismicity in November 1981 appears to be correlated with water-level increase during 1978–1982 (Figure 9). Minor increase in 1987 probably corresponds to the increased aftershock activity of the main 1981 earthquake. The other significant increase in seismicity, which includes one major and three minor episodes after 1999, also appears to be correlated with water-level increase after 1995 (Figure 9). It probably suggests that any appreciable increase in seismicity is basically governed by the water level in the reservoir or, more precisely, the water level in the embayment area. When the water level in the embayment area exceeds a threshold level (which appears to be about 175 m) (Figure 9), the seismicity increases in this region.

[22] In short, we conclude that the occurrence of earthquakes in the Aswan region is strongly influenced by the change in pore pressure from the reservoir operation. All the active faults of the region associated with the seismicity, which are stabilized, when only stresses due to water load are considered, get destabilized when the effect of pore pressure is included. Thus, the seismicity of the Aswan region is driven by pore pressure due to the reservoir impoundment.

[23] **Acknowledgments.** David Simpson provided very constructive comments, which significantly improved the article. We acknowledge the efforts of the staff of the Aswan Seismological Centre in maintaining the Aswan Seismic network and providing the earthquake catalog and water-level data.

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