GRAVITY AND GEODETIC CONTROL OF GEODYNAMIC ACTIVITY NEAR ASWAN LAKE, EGYPT

Jan Mrlina [1], Anwar H. Radwan [2], El-Sayed A. Issawy [2], Ali Rayan [2], Salah M. Mahmoud [2]

Abstract

Geodynamic investigations in the Aswan Lake region were started after the M=5.5 earthquake in 1981, triggered by the lake water fluctuations. Besides establishing the seismological networks, also the geodetic observations focused on the Kalabsha and Sayal fault zones were started. It was found that the Kalabsha fault is an active dextral strike-slip with normal component indicating uplift on its southern side. However, the annual velocity rates in both components do not exceed 2 mm/y, and do not therefore represent extremely active faulting. We also launched gravity monitoring in 1997, and performed another two campaigns in 2000 and 2002. The observed non-tidal temporal gravity changes indicate rather the flood water infiltration into the porous Nubian sandstone, than tectonic stress effect. The station nearest to the lake exhibited about 60 μGal positive gravity change within the 1997-2002 period.

Key words

gravity monitoring, surface movements, Lake Aswan, groundwater change

1. Introduction

The Kalabsha region at the NW side of Aswan Lake (Fig. 1) has become a subject of geosciences' investigations after the earthquake of November 14, 1981 (M=5.5). Various projects were initiated to study the seismicity, horizontal and vertical displacements, groundwater fluctuations in boreholes, etc. (J. Geodynamics, Special issue, Vol 14, No 1-4, 1991). The target was to evaluate tectonic activity around the Kalabsha and Sayal faults along which most earthquakes occur (Fig. 1). Indications of stress-strain geodynamic activity were revealed by repeated terrestrial geodetic measurements in the 1980s, replaced later by the GPS observations (Sakr, 1998). Randomly also precise levelling observations have been carried out since late 1980s. However, it was also concluded that the water load from the Lake has significant impact on the level of seismicity. The varying seasonal and long-term load has a triggering effect on the active segments of the faults. At the same time, it has also a substantial influence on the water moving in and out of the pore space in the rocks.

The Kalabsha area to the west of the Aswan Lake is built of the Late Cretaceous Nubian formation (mostly sandstone) overlying the basement granites (Issawy, 1978). The thickness of the sediments increases from the Lake to the West. In the area under study, the thickness is about 200 - 400 m. The most active faults are the Kalabsha and Sayal ones trending E-W, and some faults in the N-S direction (Fig.1).

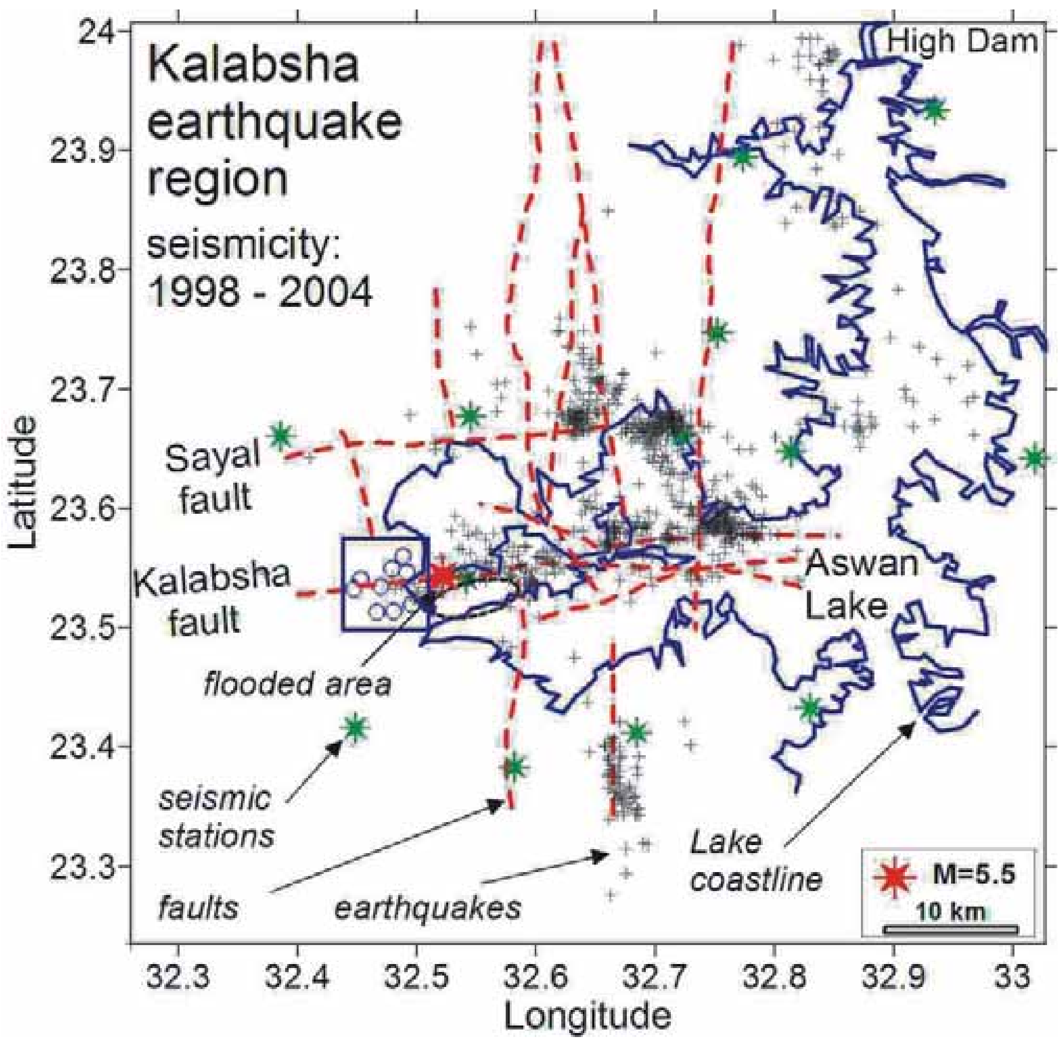

Fig 1: *Scheme of northern part of the Aswan Lake region, location of seismological stations and observed earthquakes. Lake coastline changes significantly after seasonal and long-term water level fluctuations. The area under study is marked by a rectangle with gravity stations (blue circles).*

There were some singular attempts to apply gravity measurements to geodynamic investigations in the Kalabsha region in the late 1980s and early 1990s, but these either used low resolution gravimeters, or did not succeed to perform repeated campaigns (Groten and Tealeb, 1995). Mrlina et al. (2003), on the contrary, performed two campaigns of repeated gravity in 1997 and 2000 in the Kalabsha, Sayal and Kurkur networks. They showed that beside tectonic signal, the groundwater level changes due to infiltration of the lake water may be indicated, too. Another gravity campaign performed in 2002 by the same team is described in the following text.

2. Crustal deformation

Kalabsha geodetic network was installed in the seismically active part of this fault in 1984. Monitoring of crustal deformation was carried out around the active Kalabsha fault using terrestrial technique in 1986–1992 (Mahmoud, 1994; Abdel-Monem, 1997). There was a lack of observation during 1992 - 1997. Afterwards, the terrestrial technique has been replaced by the Global Positioning System (GPS) since 1997 (Sakr, 1998; Mohamed, 2001). Three-dimensional vectors can be obtained from GPS data, whereas none of the conventional techniques alone provides this information. Moreover, GPS offers more observational comfort in very harsh desert conditions at 22° N latitude.

GPS measurements are carried out once per year on all stations using Trimble receivers 4000SSI. The measurements were performed under constant conditions (elevation mask 15 deg, sampling rate 30 sec, data analyzed with Bernese v. 5.0 Software). The network was tied to the IGS/ITRF2000 frame. The rates of the horizontal displacement velocity with the error ellipses were calculated. The magnitudes of displacements from epoch to epoch indicate that the Kalabsha area suffers from variable strains. From Fig. 2 it is obvious that the Kalabsha fault is a dextral (right-lateral) strike slip; with small annual velocity rates, in general bellow 2 mm/year.

Within the Kalabsha geodetic network two N-S trending levelling traverses crossing the Kalabsha fault were established. Mohamed (2001) concluded that, in general, the subsidence increases towards the Lake coast which reflects the water loading effect. At the same time the area north of the Kalabsha fault exhibits relative subsidence as well. The annual average displacement rate of 1.2 mm/y and 0.5 mm/y,

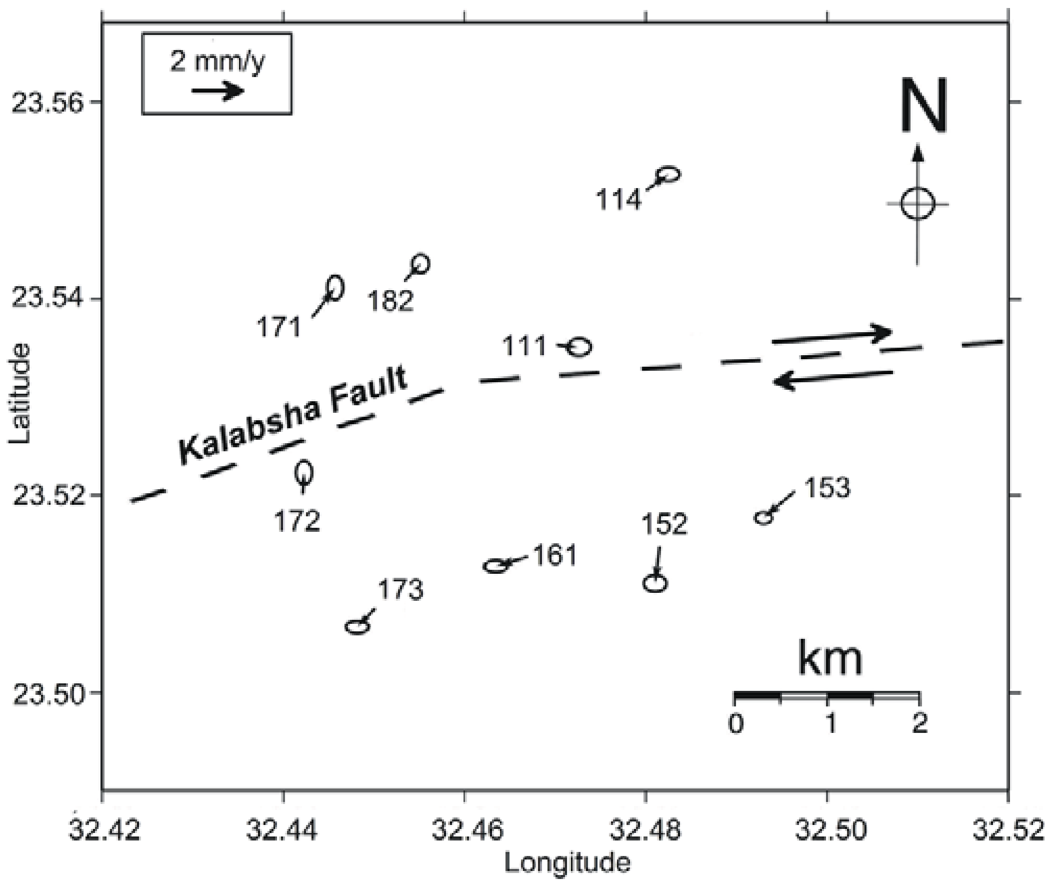

Fig. 2: Horizontal displacement vectors based on GPS observations along Kalabsha fault for the period from 1997 to 2007 (after Mekkawi et al., 2008). Displacement velocity is given graphically by length of vectors (compare with 2 mm/y scale).

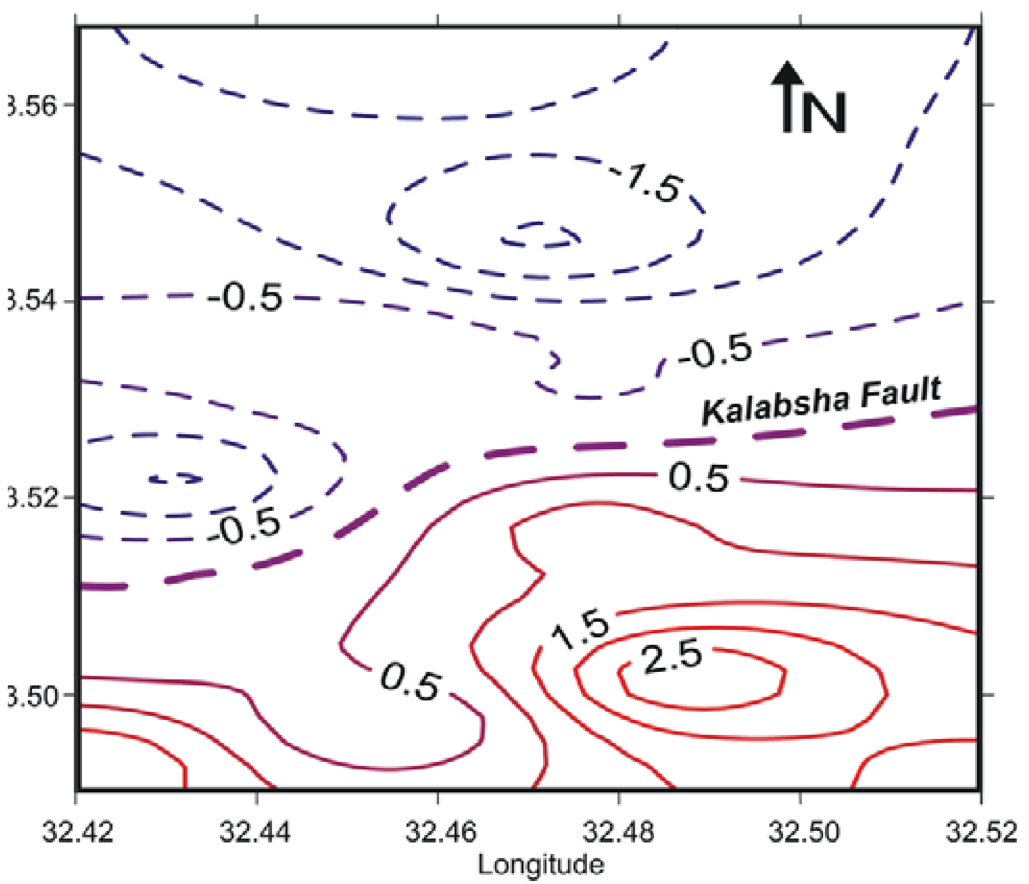

Fig. 3: Isolines of vertical displacement annual rate (in mm/year) based on GPS and levelling observations along Kalabsha fault for the period from 1997 to 2007 (after Mekkawi et al., 2008).

respectively, can be deduced from these data for both blocks. However, more recent results of Mekkawi et al. (2008) do not exhibit significant water loading effect, but rather confirm the clear relative displacement between N a S part of the area, while the highest rate of uplift (2.5 mm/y) is indicated near the station 153 in the SE corner of the area, see Fig. 3.

3. Changes of gravity field

With respect to the presence of tectonic stress, as well as surface and groundwater fluctuations, we decided to introduce repeated gravity measurements to the spectrum of investigation activities in the Kalabsha region. We intended to maintain the same conditions for repeated gravity campaigns. This means that neither instruments, nor the operators should be changed. Two gravimeters used were:

- LaCoste&Romberg (LCR) D-188 (IG Prague) with 1 μGal (10^{-8} m/s^2) resolution and the SRW-E feedback of +-12 mGal range, frequently calibrated on the Czech latitude calibration line.
- The LCR G-1043 (NRIAG Helwan) calibrated according LCR D-188.

Mutual calibration was performed on about 55 mGal difference between the Aswan City (absolute gravity point) and the High Dam Base (field crew operational base). The detailed field procedures were described by Mrlina et al. (2003). The target for the gravity network was to minimize total gravity range of the network, as this is a good way to reduce residual calibration discrepancies between various gravimeters. Fortunately, as given in Table 1, this range was very small, only 11 mGal.

The first two campaigns were evaluated by Mrlina et al. (2003). In January-February 2002 we performed one more campaign of repeated gravity measurements in the same network. The periods of all gravity campaigns were as follows:

Campaign 1 – November 1997
Campaign 2 – November 2000
Campaign 3 – January-February 2002.

Gravity measurements were processed using special in-house software targeted at the elimination of outlier readings on repeated stations, and at the accurate drift correction. The field conditions were difficult, as the terrain is sandy and rocky desert, with high temperatures experienced even during "winter" periods. Principal environmental disturbing factor was, however, strong wind. Despite such conditions, the data accuracy was good enough for the purpose. In Table 1 the error values are given for all the three campaigns 1997 – 2000 – 2002. As well, the estimation of the confidence level of calculated gravity changes between consequent campaigns is presented. The final values equal to around 7 μGal. The calculated polygon closures for the 2000 campaign are presented in Fig. 4. Again, the maximum value is 7 μGal. The local reference was set at the station KHL0 with respect to its most distant position from the Lake. All gravity differences are considered as relative to this

Tab.1: *Total range of the Kalabsha gravity network, accuracy of observations in particular campaigns and estimated accuracy of temporal changes of gravity between consequent campaigns (m).*

gravity network	***range*** mGal	***m 97 / 00 / 02*** μGal	***m (dG) 97/00*** μGal	***m (dG) 00/02*** μGal
Kalabsha	11.20	4.8 / 6.0 /5.1	7.70	7.00

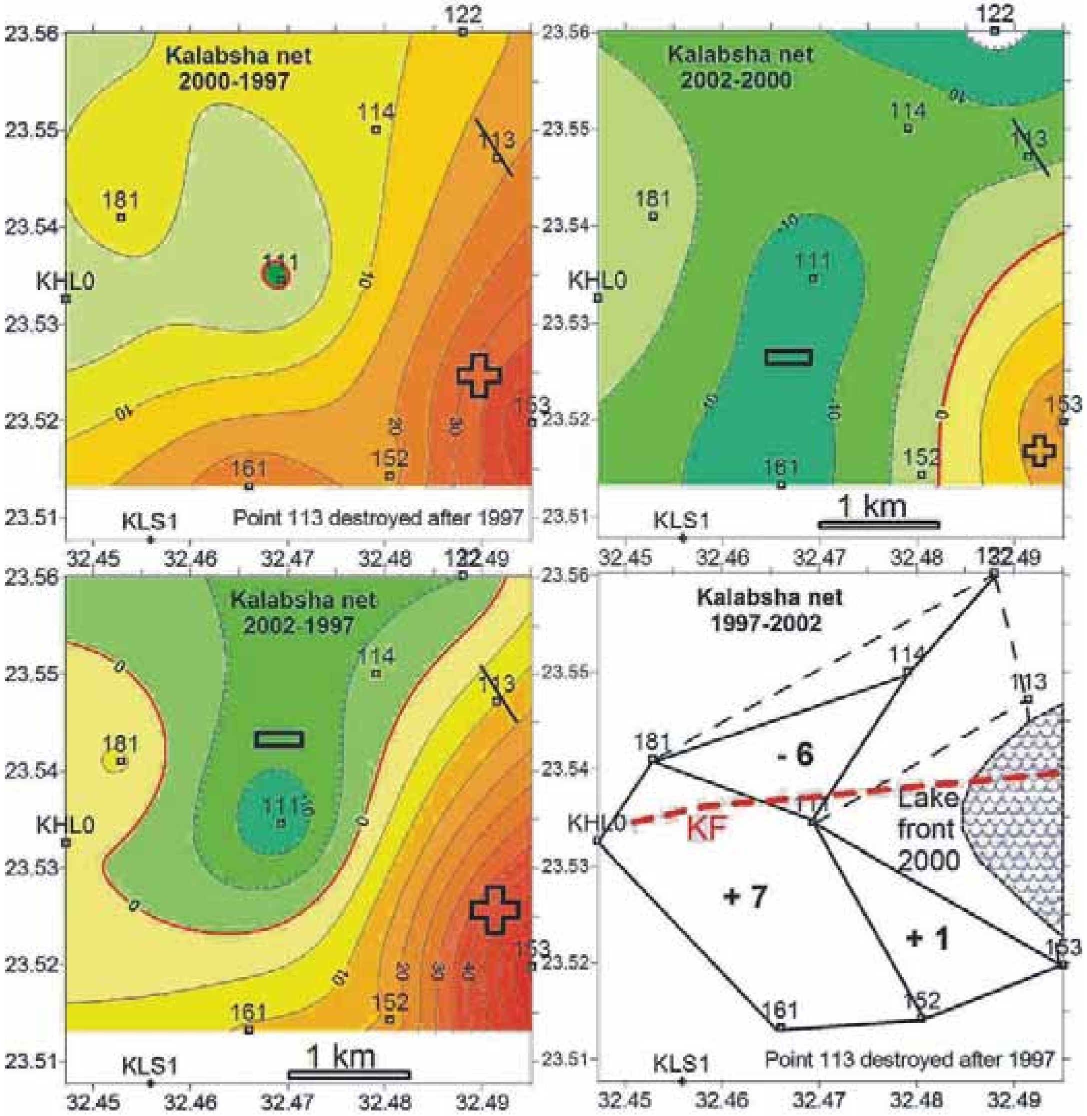

Fig. 4: ***Significant temporal gravity change was observed between 1997 and 2000 at station 153, the closest to the Lake. This station indicated further increase of gravity in the following period 2000-2002.Gravity change contour interval 5 µGal. The scheme of the network shows polygon closures (µGal) in the 2000 campaign. Local reference point = KHL0.***

base. At the time of gravity campaigns, the GPS measurements were carried out in order to indicate possible significant surface displacements. Observed displacements are, however, negligible (Fig.3) with respect to possible impact on the change of gravity (1 cm vertical displacement corresponds to 2 µGal only).

In Fig. 4, the temporal non-tidal gravity changes in the Kalabsha area are presented in the form of contour maps for 1997-2000, 2000-2002, and the total change of over 4 years for the period 1997-2002. The first period 1997-2000 is characterized by pronounced gravity change increasing from West to East. This is particularly truth in the southern block (south of Kalabsha fault), where the highest value is present at the station 153, nearest one to the coastline of the Lake. The western stations KHL0 and central 111 display minima of gravity changes. The difference from KHL0 to 153 exceeds 40 µGal. The anomalous value at 153 was attributed to the water loading effect of the increased water level of Lake Aswan already by Mrlina et al. (2003). The difference in water level in the Lake between 1997 and 2000 was +2 meters with large aerial extent very close to 153 (about 200-250 m), see Fig. 5. The effect of a 2-m thick water layer was estimated less than 5 µGal. recently, it has been proved that for the distance of 200 m, and vertical difference (12 m) between the Lake flood water layer and the station 153, the effect is less than 2 µGal.

Mrlina et al. (2003) studied only this first period of 1997-2000. They considered the loading effect, comprising the stress change (compression) in the rock massif, which may produce a density difference and consequently a change of the observed gravity. After the last campaign in 2002 we found that during 2000-2002 most of the area exhibited negative gravity change of low amplitudes (less than 15 µGal), caused probably by groundwater decay backwards to the Lake, with the exception of the station 153. The area around this point seemed to continue increasing the gravity signal with similar, but positive amplitude of +15 μGal. In the total gravity change 1997-2002, most of the area shows low gravity changes of ±15μGal. Central and northern parts exhibit rather low negative change. The striking anomaly of temporal gravity change is related to the station 153, as the total amplitude exceeds 60 μGal for the whole period under study.

In order to explain such gravity signals, 2.5D gravity modeling was performed along a profile running parallel to the stations 161-152-153 and further to the Lake coastline. Two versions of such model are demonstrated in Fig. 6 that represents two different explanations of gravity signals. Both models comprise the flat layer of increased Lake Level (thickness 2 m).

- Model A – Infiltration zone: This model implies the water infiltration into a dry zone in the forehead of the Lake, considering that in the "low" season (spring) there is no water on surface at this area. As well, there was no water in the previous years before 1998, see Fig. 5, as in 2000 (in the model) the level was about 180 m (MSL). It means that the floods in 1998-1999 delivered water that could saturate the sandstone. The shape of this infiltration edge is, of course, speculative, but fits well the observed data.
- Model B – Increase of groundwater level: This model just simply assumes the general increase of groundwater level due to surface Lake water level maxima in the studied periods. The shape of the groundwater anomalous layer would likely decline smoothly westwards (here simplified by a rectangle).

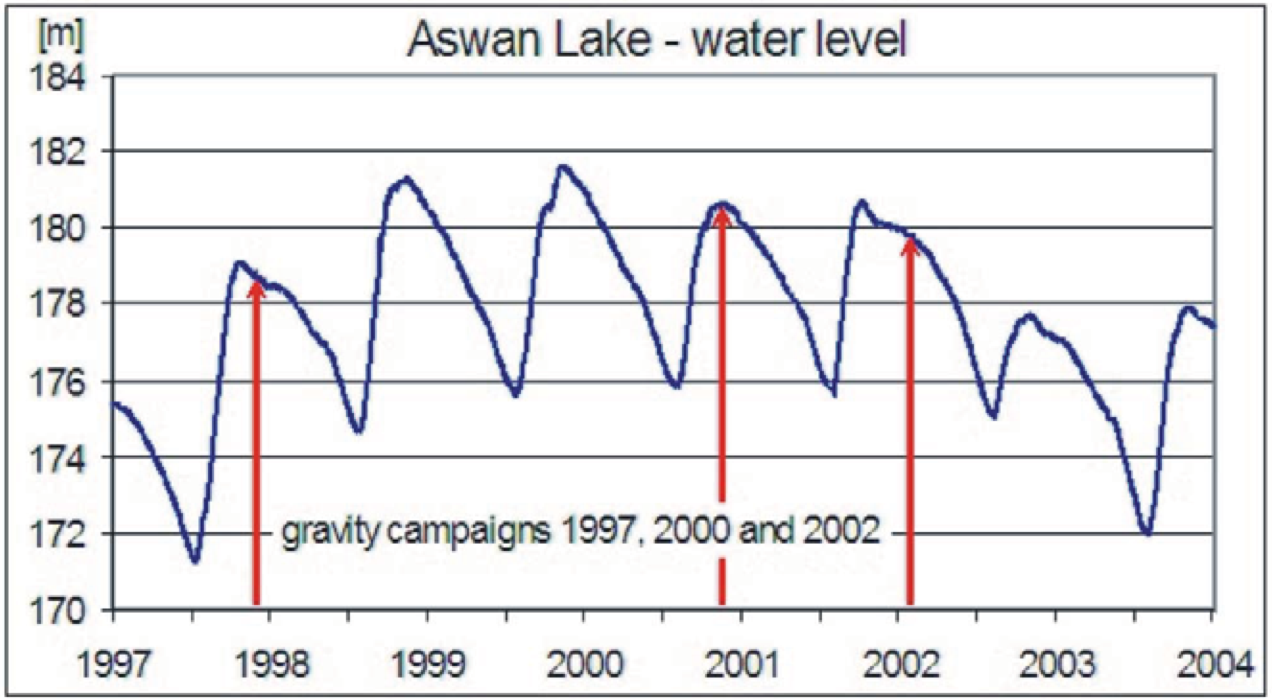

Fig. 5:* *Detailed Aswan Lake water level during the 3 gravity campaigns - differences up to 2.20 m. After the 10-years maximum in 1999, the level began to drop again.

In Fig. 6 it is clear that both models can provide reasonable amplitude of gravity change to fit observed data (station 153). If we assume that there are more stations located between 153 and Lake Coastline, we could observe much stronger signals, especially in case of model A; (infiltration wedge). Few stations were calculated on the Lake surface, as if measured "by ship". In this area, the 2-m thick water layer plays very significant role, as expected. As for the station 152, the Model B with increased groundwater level is more suitable. Until we can constrain these models by independent source of information, they are both speculative. Most likely, a combination of both models would bring us closer to reality.

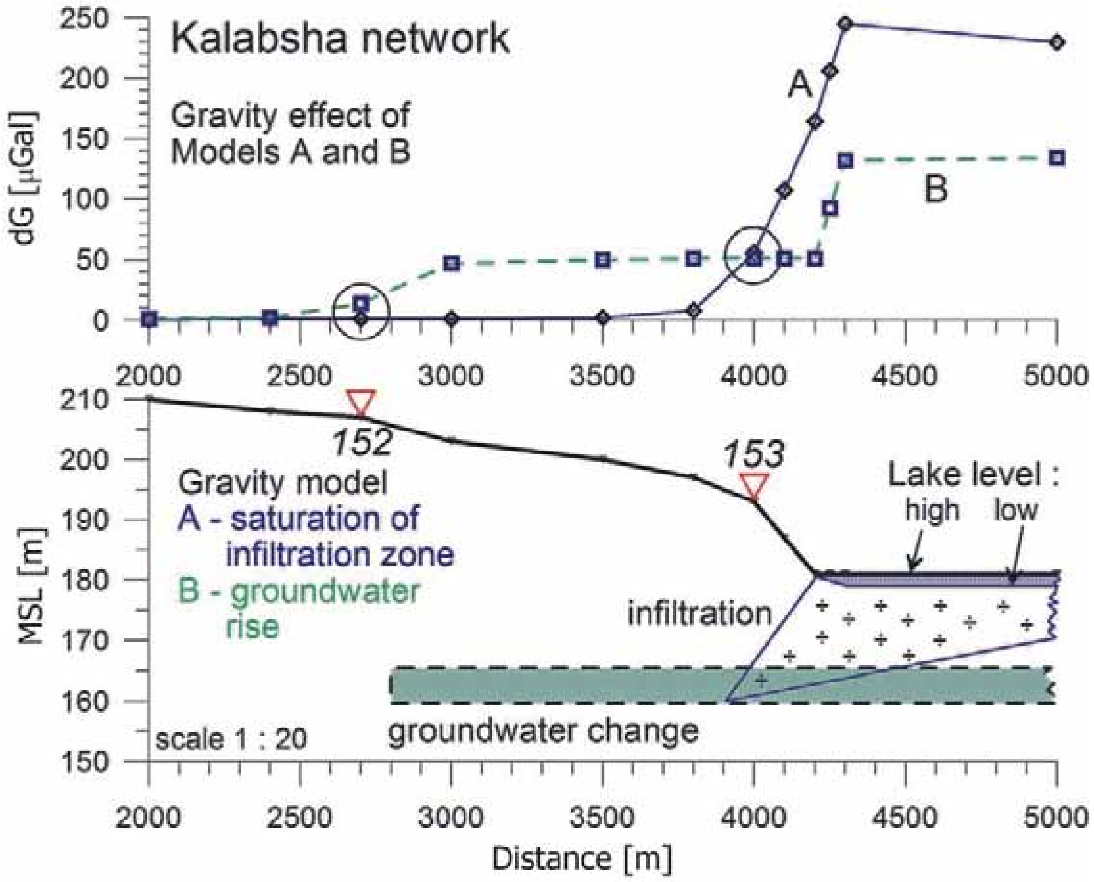

Fig. 6: Profile along stations 161 (not in figure) 152 - 153 down to the Lake water level at the end of 2000 (WSW-ENE).Two models were calculated. Besides 2 m of increased surface water level with 1.00 g/cm^3 density of water. Model A suggests infiltration into the porous Nubian sandstone. Model B represents simplified rise of groundwater level, the depth of which is only estimated from distant sources.

Groundwater rise can be initiated not only by downward saturation by surface water, but also by the water loading effect, when vertical stress (compression) may lead to the decrease of pore space in the rock massif, and consequently to such a rise of groundwater level.

The density differences were estimated from a set of the Nubia sandstone samples measured in a laboratory in the Czech Republic. Considering the average porosity of 20 %, the density difference of dry and water-saturated sandstone 20 %, the density difference of dry and water-saturated sandstone of 0.20 g/cm^3 was used. Such parameters make this formation a pronounced hydrocarbon reservoir in some other parts of Egypt, mainly in the Gulf of Suez and the Red Sea fields.

4. Conclusion

The presented investigations of geodynamic activity in the Kalabsha area on the west bank of the Aswan Lake revealed the three main results:

- There are active surface displacements around the E-W trending Kalabsha fault zone. The vertical ones indicate uplift of the southern block, the horizontal ones the shear stress along the zone. The Kalabsha fault can therefore be characterized as a dextral (right-lateral) strike-slip with normal component, which is in general agreement with fault plane solutions of frequent earthquakes (mostly $M < 4$).
- Significant seasonal and long-term variations of the Lake water level can trigger not only earthquakes, but also pore pressure changes, rock massif saturation and groundwater level fluctuation.

- All these phenomena may directly or indirectly produce observable gravity signals, if enough volume of the porous Nubian sandstone gets involved.

Despite there have been no more earthquakes of $M \geq 5.5$, all the presented investigations suggest that the area is still active and may possibly evolve into another strong event. That justifies continuation of seismological, as well as geodetic and gravity monitoring regarding any possible risk for the High Dam. The groundwater behavior will be a subject of further study, as the area undergoes an attempt of agricultural production. In such a case our project may serve as an example converting into application.

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Authors:

[1] Institute of Geophysics ASCR, Prague, Czech Republic; jan@ig.cas.cz

[2] National Research Institute of Astronomy and Geophysics, Helwan, Cairo, Egypt; radwan99@nriag.sci.eg