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An up-to-date crustal deformation of Kalabsha fault zone, Aswan, Egypt

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Abstract: Kalabsha fault is located on the western side of Lake Nasser, about 60 km. southwest of the High Dam. This fault was identified as the source of the 14 November 1981 earthquake. It was a 5.6 magnitude earthquake. The seismically active area in the Aswan region is located beneath the Kalabsha fault zone. The eastern part of the Kalabsha fault is located beneath the lake. Geological and seismological evidence indicates that the Kalabsha fault is a right-lateral strike-slip fault with a normal component. A number of studies have been developed since 1982, monitoring seismicity, underground water behavior, and recent crustal movements. The data used in this work consists of GPS data and the catalogue of earthquake. A local GPS network containing nine GPS stations was established around the active part of the Kalabsha fault zone. Data collected from Kalabsha local GPS network during the period from 2009 to 2022, as well as 42 IGS (International GNSS Service) stations, were analyzed. The outcomes after the analysis indicated that the Kalabsha fault is estimated to move strike-slip with an extension component of nearly 1±0.3 mm/yr. and its vertical velocity ranges between 1 and -4 mm/year, which coincides well with the small magnitude of seismic activity recorded in the study area.

keywords: Crustal deformation, Kalabsha fault, GPS, Water level, Seismicity

Introduction

Aswan region is located within the stable platform of Northern Africa. The Nile follows the contact between the surface exposure of the granite of the Eastern Desert to the East, and the sedimentary cover of the Nubian sandstone to the West. Nubian plain covers most of the area southwest of Aswan city and borders the reservoir from the West. Nubian plain is relatively flat as the surface has an average elevation of 200 m above the mean sea-level. The structural pattern of the Aswan region is governed mainly by faulting. The faults crossing the region are classified into E-W and N-S faults. The N-S faults are well represented in the vicinity of the reservoir and affect the sandstone beds of the Nubian plain {1}.

The Kalabsha fault as one of the most active faults in the Aswan region trend towards E-W direction. This fault extends for 185 km. and it splits to the west into several sub-parallel faults. It is a right-lateral strike-slip fault {2, 3}. Several locations along the Kalabsha fault show evidence of multiple fault displacements during the Quaternary. Generally, the Kalabsha fault is a complex geological feature that has had a significant impact on the geology, geomorphology, and cultural history of the Aswan area. Further studies on this fault can provide important insights into the tectonic evolution of the region and the potential for earthquakes in the future.

Methodology and data processing

In order to carry out this study several methodological solutions and equipment were applied. Geophysical and geodetic techniques were used to collect and record information. The seismic data used are collected from the Egyptian National Seismic Network (ENSN) catalogue. While GPS data were obtained between 2009 to 2022 from the Egyptian Geodetic Data Center. By processing GPS data, it was possible to calculate time series analysis and error evaluation using data processing, as well as to calculate vertical and horizontal velocities.

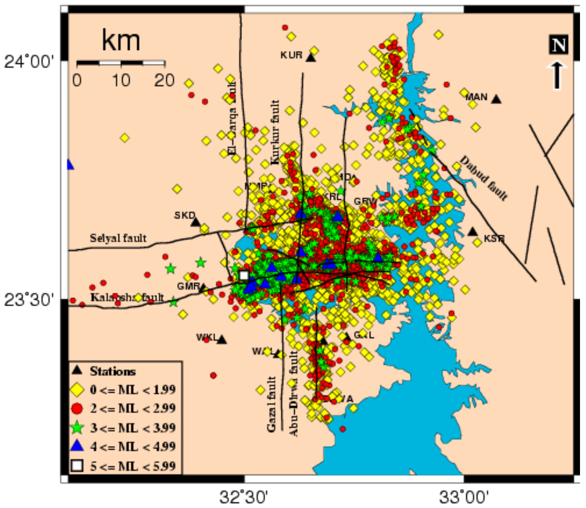

Fig.1: Geographic distribution of seismic activity around the northern part of Lake Nasser during the period from July 1982 to December 2022.

Seismicity

Historically, the Aswan region is characterized by a low level of seismic activity. The pattern of seismicity in the Aswan region suggests that a transition zone lies between the higher level of seismicity within the Red Sea to the lower level of seismicity west of the Nile Valley in the Western desert. The area became tectonically interesting after November 14th, 1981, a 5.6 magnitude earthquake occurred on the Kalabsha fault at 60 km southwest of the High Dam, 17 years after the reservoir began filling. Recently the seismicity has concentrated on the Kalabsha fault zone, particularly along its most are eastern segment, which is located beneath a large area covered by water. Most events (0.1 < M >4.8) are located at the intersection between the E-W and N-S fault trends (Fig.1). The earthquakes are concentrated in the Kalabsha fault zone. Figure 2 shows the spatial distribution between latitude and longitude of the epicenters. The spatial distribution of the epicenters from 1982 to 2022 reveals that the seismicity in the northwestern part of the lake area is clustered on the Kalabsha fault segments. Many studies were carried out in the Aswan region for the determination of sources and causes of earthquakes {4: 5 and 6}. The depth distribution of the earthquake hypocenters is separated into two seismic zones. Shallow earthquakes have focal depths of less than 12 km while the deep events extend from 12 to 30 km as shown in Figures 3, 4 and 5. The deeper activity is taking place where the intersection of the easterly trending of the Kalabsha fault with the northerly trending faults beneath Gebel Marawa. All activity outside the Marawa area is shallow, i.e. 0 - 12 km. Deep events are related to their magnitude. Events of magnitude ≤ 1 occur at a depth less than 12 km, where the depth of the earthquakes increases with increasing their magnitudes. The mechanism solutions are characterized by strike-slip faulting on nearly vertical planes with a small component of normal dip slip. There is a migration of seismic activity towards the east over time.

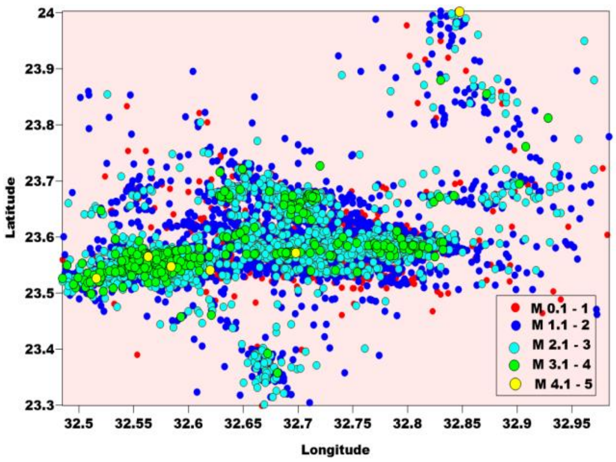

Fig. 2: A cross section showing the spatial distribution between latitude and longitude of the epicenters.

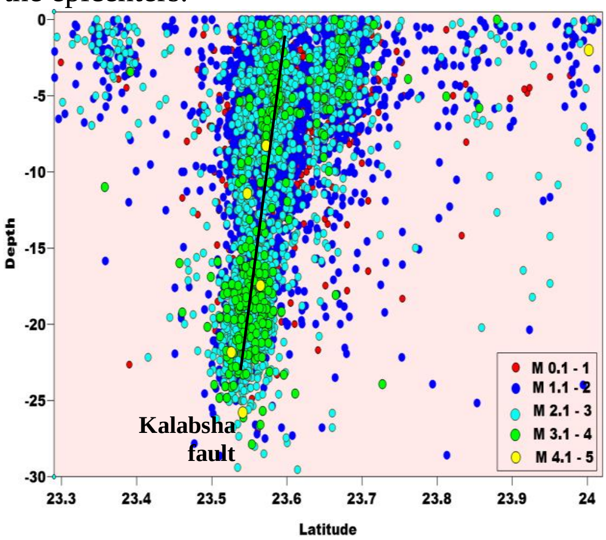

Fig. 3: A cross section showing the spatial distribution between latitudes of the epicenters with respect to their depths (the thick lines represent the vertical active faults).

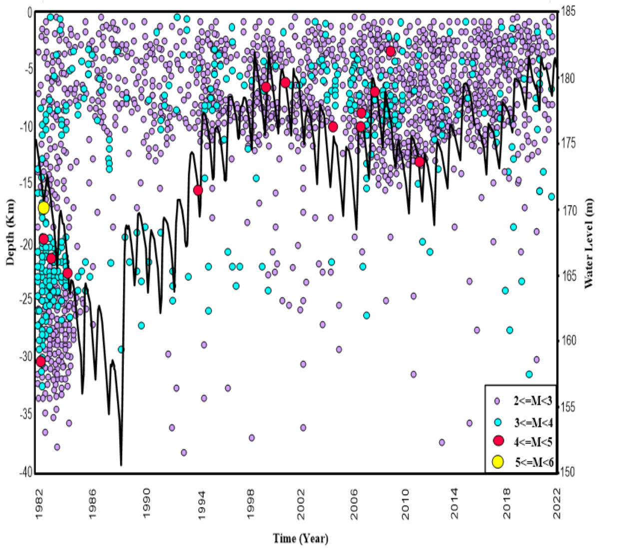

Fig. 4: A cross-section showing the spatial distribution between longitudes of the epicenters with respect to their depths.

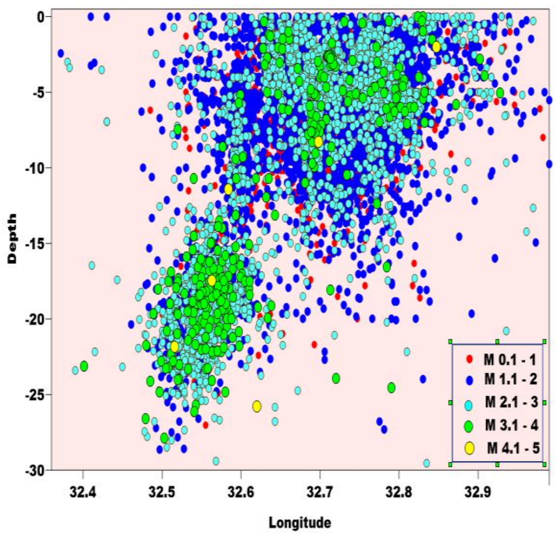

Fig 5: Depth distribution of the seismic activity in the northwestern part of the lake and seasonal fluctuations of the lake water level during (1982 – 2022).

4. Seismicity and the water level variation in the lake

Reservoir-induced seismicity has been reported from many parts of the world. The direct correlation of the pronounced increases in seismicity with the first filling of the reservoir was observed in some reservoirs. However, there are cases in the reservoirs that were directly responsible for the increased seismicity. Some authors restricted the occurrence of these events to the artificial lake of the High Dam reservoir, while others related this activity to tectonic deformation. The seismic activities associated with the reservoir loading are characterized as very shallow and confined to the reservoir vicinity. Some reports mentioned that the possible effects of reservoir impounding are a rapid increase in normal stress due to the load of the reservoir and the gradual diffusion of water pressure from the reservoir to the hypocentral depths. A gradual increase in 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 the Kalabsha area started in 1995 associated with the gradual increase of the water level in the lake and relatively higher seismic activities had been observed {7}. The shallow seismicity increased both in number and magnitude where 7 events of magnitude ranging from 4 to 4.6 have been recorded. Figure 5 shows a good correlation between the shallow seismic activity and the seasonal fluctuations of the lake. Figure 6 shows the daily water level changes in the lake and the magnitude of earthquakes that occurred in the area during the period from 1982 to 2021.

In this study, the relationship between earthquakes and water level changes in the lake is not obvious. The water factor in the reservoir acts as an activating medium in triggering the micro-earthquakes. Increasing the reservoir load is not only because of the water within the reservoir but also due to the significant amount of water stored in the sandstone {7: 8 and 9}. The increased pressure at the base of the sandstone results from the combined influence of both the water in the reservoir and the increased water table in the sandstone. The time required for the water to diffuse into the sandstone may explain the delay between the filling of the reservoir and the starting of the seismic activity in the area. Lateral and vertical variations in permeability, caused by faults and aqueducts, may be important in determining the distribution of water within the sandstone and the access of pore pressure to faults. It is essential to monitor the current distribution of the water table and its changes with time to determine how quickly it will reach equilibrium. The common factors for inducing the earthquakes in Aswan region are: a) Presence of specific geological conditions, b) Tectonic setting, and c) Water loading. The role of the reservoir water loading, as a supplementary source of earthquake events in the region, cannot be neglected. Therefore, it can be understood that, the earthquake activity in the area originated tectonically and the water variation works as an activation medium in triggering small earthquakes. Also, the water with the mud made lubrication or more facility for the fault's movement.

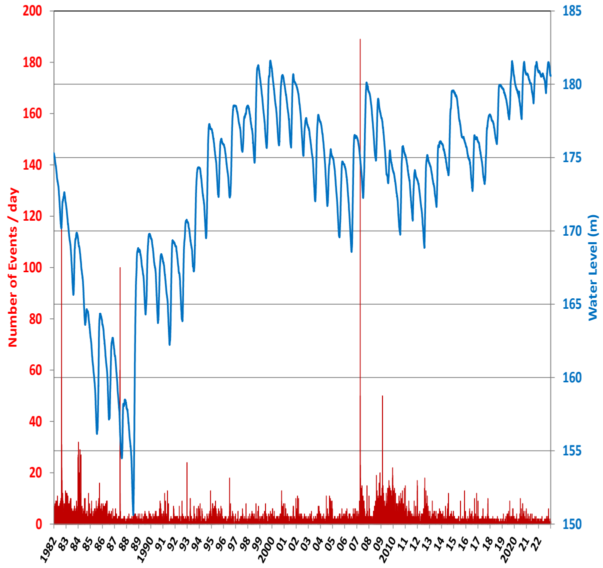

Fig. 6 Relation between the water level in the lake and the earthquakes during the period from 1982 to 2022.

5. GPS measurements and data analysis

The used data was collected from the Kalabsha GPS network during the period from 2013 to 2021, which consists of 9 stations and covers the active part of the Kalabsha fault (Fig. 7). The campaign observations are repeated once a year. The GPS observations are carried out using Trimble receivers R8 under constant conditions, such as: the satellite-masking angle is 5 degrees, the sampling interval is 5 seconds and the observation time in all sessions is 72 hours at all stations. The used GPS data in the present work were processed using the Bernese V. 5.2 software program {10}, and other software for adjustment and deformation parameter calculations was used. In addition, the ITRF2014 datum definition included 33 stations selected from 42 continuous international GNSS service stations (IGS) from SOPAC and UNAVCO. The processing is done on a daily basis that is observed, resulting in a time series of station positions and velocities in ITRF2014.

A free network adjustment assumption was used to determine displacement vectors at each GPS station. GNSS station positions were corrected to obtain more accurate results. Based on the difference between the adjusted coordinates of the stations between epochs, we calculated horizontal components at each station. The direction and amount of horizontal displacement of the points of the geodetic grating were calculated; an ellipse of error was calculated for them, and the horizontal displacements of the points of the grid were determined, resulting from the deformations of the earth's crust in the region associated with the occurrence of earthquakes in the region. These deformations were caused by earthquakes that occurred in the region during this period. This image makes it abundantly evident that there is a straightforward and well-balanced movement on both the eastern and western sides of the Kalabsha fault. It also demonstrates the average direction and the amount of horizontal displacements in the grid area from 2009 to 2022, as a result of the crustal deformations associated with the occurrence of earthquakes in the region during this time period.

Table 1 shows the horizontal displacement velocity including the African plate velocity according to the processed stations in ITRF2014, with vector components 95% confidence error ellipses. All error ellipses around the observation site represent standard error in all directions. The magnitude of the horizontal displacement vectors ranges from 17 to 23 mm/year, ±0.2 mm/year, in the northeast direction as shown in (Fig. 8). Figure 8 depicts the direction and amount of horizontal displacements that occurred in the network area from 2009 to 2022.

To estimate the absolute Euler vectors for the Nubian plate, the 9 GPS stations of the Kalabsha network were used then the Nubian fixed GPS velocities were obtained as shown in Table 2 and Fig. 9. Furthermore, KL14 and KL53 are moving downward at a rate of 2 ± 0.9 mm/yr. and 0.7 ±0.3 mm/yr.; respectively. The rest of the sites are moving upward at a rate between 1 to 4 mm/yr. with a standard deviation from 0.9 to 0.3 mm/yr. as shown in figure 10.

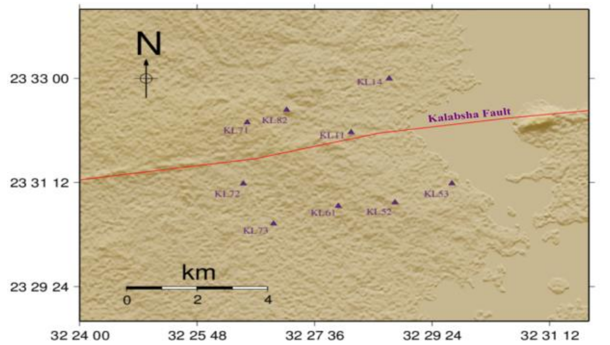

Fig. 7: The location map of the Kalabsha GPS network and the Kalabsha fault.

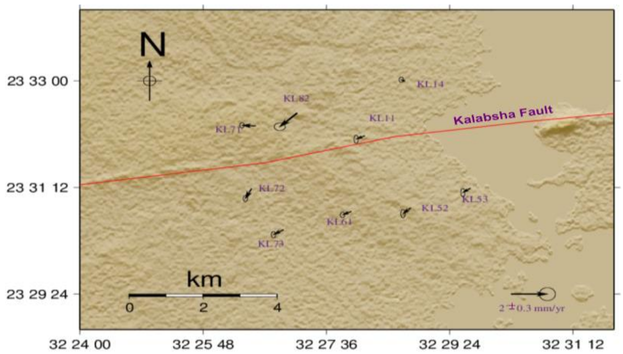

Fig. 8: Annual regional Horizontal velocity in ITRF2014 including the velocity of the African plate during the period from 2009 to 2022.

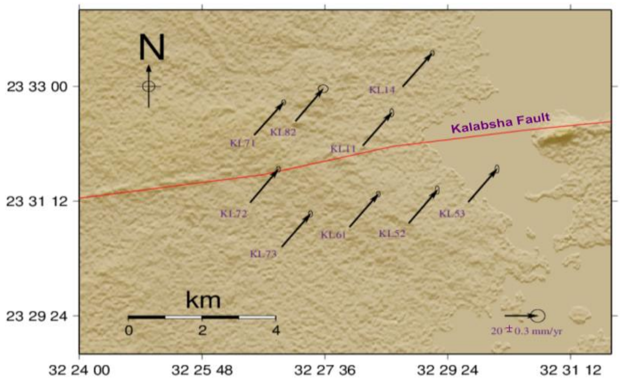

Fig. 9: Annual local horizontal velocity in ITRF2014 during the period from 2009 to 2022.

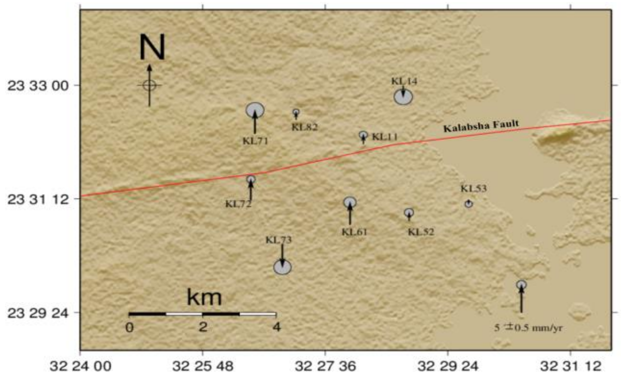

Fig. 10: Annual local vertical velocity in ITRF2014 during the period from 2009 to 2022.

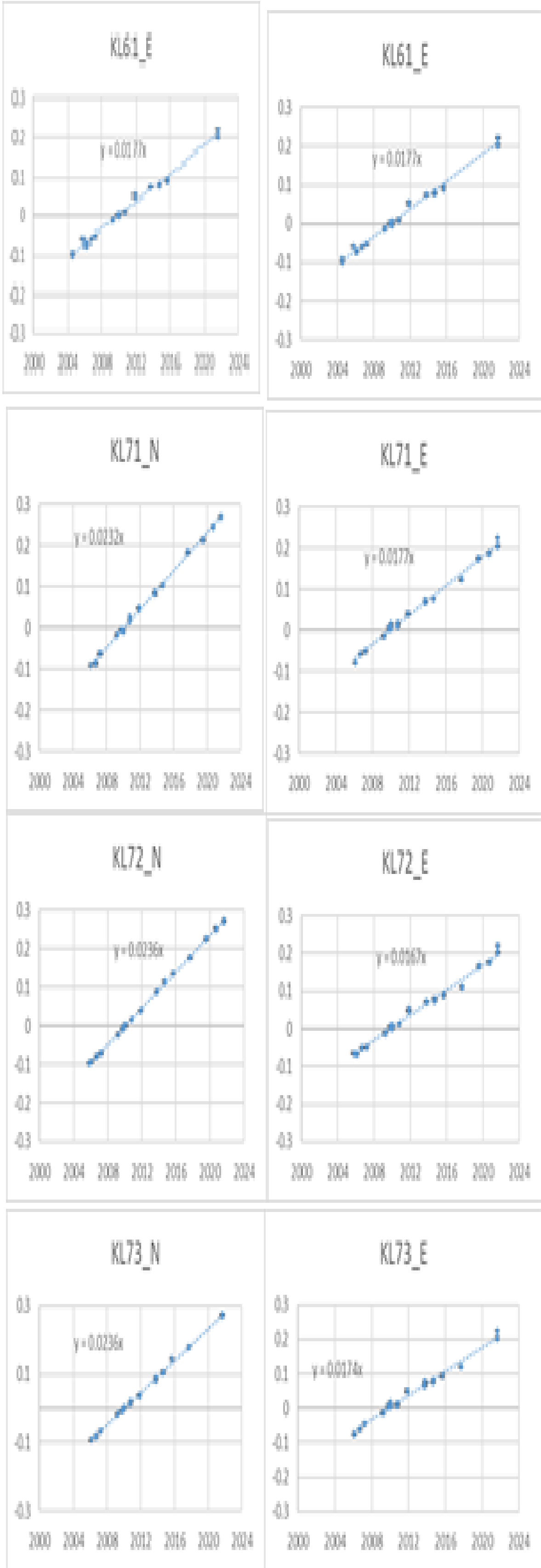

Fig.11: Graphs show the time series in north, and east directions.

Table 1 The geodetic stations and annual regional horizontal velocity in ITRF 2014 including the velocity of the African plate during the period from 2009 to 2022.

St. Name	Long.	Lat.	$V_{e(ITRF)(mm/yr)}$	$V_{n(ITRF)(mm/yr)}$	$\delta_{e(mm)}$	$\delta_{n(mm)}$
KL11	32.46931	23.534506	23.32	17.56	0.10	0.06
KL14	32.479099	23.549967	23.59	17.87	0.12	0.09
KL52	32.480505	23.514254	23.37	17.39	0.09	0.07
KL53	32.49508	23.519761	23.37	17.49	0.190	0.16
KL61	32.466036	23.513239	23.31	17.55	0.123	0.06
KL71	32.442824	23.537311	23.02	17.84	0.123	0.08
KL72	32.441828	23.519678	23.44	17.11	0.139	0.044
KL73	32.449538	23.508103	23.24	17.45	0.150	0.068
KL82	32.452867	23.540954	22.83	16.84	0.108	0.099

Table 2: The geodetic stations and annual local horizontal velocity in ITRF 2014 during the period from 2009 to 2022.

St. Name	Long.	Lat.	$V_{e\ (residual)}$ (mm/yr)	$V_{n\ (residual)}$ (mm/yr)	V_{up} (mm/yr)	δ_e (mm)	δ_n (mm)	δ_{up} (mm)
KL11	32.46931	23.534506	-0.22	1.67	1.67	0.10	0.06	0.42
KL14	32.479099	23.549967	0.08	-2.03	-2.03	0.12	0.09	0.93
KL52	32.480505	23.514254	-0.39	1.49	1.49	0.09	0.07	0.46
KL53	32.49508	23.519761	-0.29	-0.75	-0.75	0.190	0.16	0.37
KL61	32.466036	23.513239	-0.23	4.00	4.00	0.123	0.06	0.63
KL71	32.442824	23.537311	0.04	4.17	4.17	0.123	0.08	0.91
KL72	32.441828	23.519678	-0.68	3.76	3.76	0.139	0.044	0.42
KL73	32.449538	23.508103	-0.34	-4.13	-4.13	0.150	0.068	0.88
KL82	32.452867	23.540954	-0.95	1.42	1.42	0.108	0.099	0.31

6. Time series estimation

Geodetic time series is a temporal variation of the estimated geodetic and geophysical parameters. A lot of information can be extracted from the geodetic time series; it can give information about the stability of each station. The annual velocity of each station and its direction expected time for the activity and extract the seasonal effects of the GNSS observations. The geodetic time series were made for the Kalabsha network from the processing of the GNSS data (13 years). Processing the above GPS data yielded the precise coordinates of all stations. Figure 11 shows the time series graphs in the north, and east directions. In this figure, each small solid circle on the plot represents an independent position estimate typically. The black lines represent the linear horizontal velocity, while the dots represent the individual solution for the campaign. For the deformation analysis results, it can be noticed that most of the deformed stations in all epochs are large in the north direction than in the east where there is an error in its concrete. The magnitudes of the deformed stations are variable from one epoch to another and inhomogeneous over the area. The

orientations of the pressure and tension stresses in the Aswan region are ESE-WNW and NNE-

SSW, respectively.

7. Results and Discussion

Studying of the inducing seismicity from the water level variation in the lake and crustal deformation is of great importance and plays a great roles necessity for the safety of the High Dam body. So, the main objective of the current study is to achieve a better understanding of the seismicity and recent crustal deformation at the Kalabsha fault zone by a suitable treatment based on available earthquake recording and GPS data. This study is an attempt to build a basis for further development of seismic catastrophic risk management models to reduce a risk of large catastrophic losses within the important region in Egypt.

The current study focuses on understanding the structural setting and seismotectonic activity associated with the Kalabsha fault zone. By using the GPS technique, we can detect the vertical and horizontal average velocity in the study area. The results from these data sets are compared and combined in order to determine the main characteristics of deformation and hazard estimation in the Aswan region. Comparing the results of the geodetic analysis to the seismicity in the Kalabsha area, we recognize that the changes in size and direction of displacement vectors have a strong relation with the earthquakes that were recorded in the area. The seismicity is concentrated on the Kalabsha fault zone at the intersection between the E-W and N-S fault trends, particularly along its most eastern segment, which is located beneath a large area covered by water. However, the E-W Kalabsha fault system controls the seismicity in the region. The seismicity can be classified into shallow and deep seismic zones. Shallow earthquakes have focal depths less than 12km and deep events extend from 12 to 30km. The tectonic movement of the Kalabsha fault is the main source of earthquakes in the area, especially earthquakes with $M \geq 4$. The role of the reservoir water loading, as a supplementary source of earthquake events in the region, cannot be neglected. Therefore, it can be understood that, the earthquake activity in the area originated tectonically and the water variation works as an activation medium in triggering small earthquakes.

The final compiled output from the seismic and geodetic analysis focuses on the geodynamical regime of the seismo-active area and it is an attempt to delineate the crustal stress and strain fields. The conclusions of this study try to present a clear preliminary picture of the crustal deformations at the Kalabsha fault area and their role in the earthquake occurrence.

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