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Seismicity and kinematic evolution of middle Egypt

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Abstract

Based on historical and instrumental seismicity as well as recent GPS measurements, the seismicity and kinematic evaluation of middle Egypt is presented. Middle Egypt suffered in historical times by six major earthquakes and the Ramses II temple on the west bank of the Nile in Luxor, was almost destroyed by an ancient event. The temporal distribution of recent earthquakes (1900–1997) is highly scattered with only nine events recorded. Only after the installation of the modern Egyptian national seismograph network (ENSN) the seismic record of middle Egypt increased with a total of 280 earthquakes from 1998 to 2004. Focal mechanism solutions of the largest five events during the ENSN's operation period reveal reverse faulting mechanism with minor strike-slip component on the west bank of the Nile, while a normal faulting mechanism dominate in the eastern side. The orientations of both P- and T-axes are consistent with the Red Sea-Gulf of Suez stress field. Dynamic source parameters of these five events were derived from P-wave spectra as well. Three campaigns of GPS measurements were carried out for the middle Egypt network that established after the first instrumental earthquake on 14 December 1998 in this area. The velocity vectors for each epoch of observations were calculated and deformation analysis was performed. The horizontal velocity varies between 1 and 4 mm/year across the network. The deformation pattern suggests significant contraction across the southeastern sector of the study area while, the northwestern part is characterized by an extension strain rates. High shear strain is observed along the epicenteral area of the $M_w = 4.0$ June 2003 earthquake possibly reflecting the stress accumulation stage of a seismic cycle.

Keywords: Seismicity; GPS; Kinematics; Focal mechanism; Source parameters; Nile Valley; Middle Egypt

1. Introduction

Egypt is recognized as a moderate earthquake activity region with frequent moderate events. Most of its seismicity is concentrated in northern Egypt (Fig. 1). The relative motion between Africa, Arabia plates and Sinai sub-plate represent the main source of earthquakes along the northern Red Sea and its two branches Gulf of Suez and Gulf of Aqaba (Badawy, 1996, 1998; Badawy and Horváth, 1999a,b,c). Outside this relatively active zone only few inland earthquakes are reported in Egypt (Badawy, 2005a).

The first instrumental event recorded within the investigated area (hereafter, middle Egypt) which is a part of the Nile Valley and comprises parts of the Western and Eastern Deserts of Egypt (25°–28°N and 30°–33°E) was recorded by ENSN on 14 December 1998 of $M_w = 4.5$. After this earthquake NRIAG accelerated a monitoring program of earthquake and crustal movements' observations. A geodetic network of eight stations was installed in the middle part

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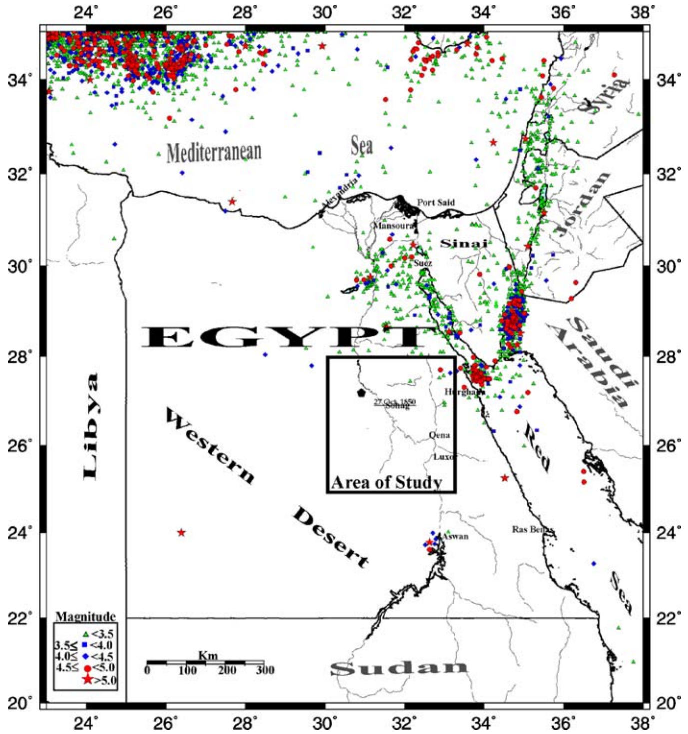

Fig. 1. Spatial distribution of earthquakes foci in Egypt. The inside box delineate the investigated area (see the text for more detailed). October 27, 1850 historical earthquake is also presented.

of the Nile Valley covering the area between Assuit and Qena north and south respectively (Fig. 2(A)). Nowadays, great governmental efforts have been directed to invest in the middle Egypt region including oil and gas explorations, retrofitting the monuments and historical places (e.g. temples, tombs and old tunnels). New industry and big economic project such as constructing new cities are planned as well. So far the seismicity and kinematic evaluation of middle Egypt is essential in order to mitigate the risk. The present study reports, for the first time, an evaluation of earthquake activity in middle Egypt mainly based on the catalog compiled by Badawy (2005a) and preliminary results of three GPS campaigns.

2. Geological and tectonic setting

From a geologic point of view, middle Egypt consists of an extended sedimentary plateau of Eocene age, characterized by low relief topography with general inclination towards the west direction (Said, 1990). Elevation of the plateau reaches to 300 m above sea level and performs on its eastern side a sharp scarp facing the Nile Valley. The main tectonic trends which controlled middle Egypt are NW–SE fault trending parallel to the Red Sea-Gulf of Suez, N–S and NE–SW trends. Indeed the NW–SE fault system appears to have a profound influence on the structure of middle Egypt from the north of Luxor-Qena bend to the north of Assuit (Bakheit, 1989; Youssef et al., 1994). However, the NE faults trends are structurally controlled the Nile bend near Qena (El-Hakim, 1978). Said (1981) reveals that the Nile Valley lies along seism-active belt.

Several geophysical studies were carried between Qena and Assuit to reconstruct the subsurface structures (e.g. El-Gamili, 1964; Senosy, 1997; El-Kottob, 2003). They found that more or less the same surface fault trends also affect the basement of middle Egypt. Moreover, the basement generally includes high regional structural (dome) complicated by wedge faults. The sedimentary successions section unconformable overlying the crystalline basement has variable thickness between 500 and 3000 m.

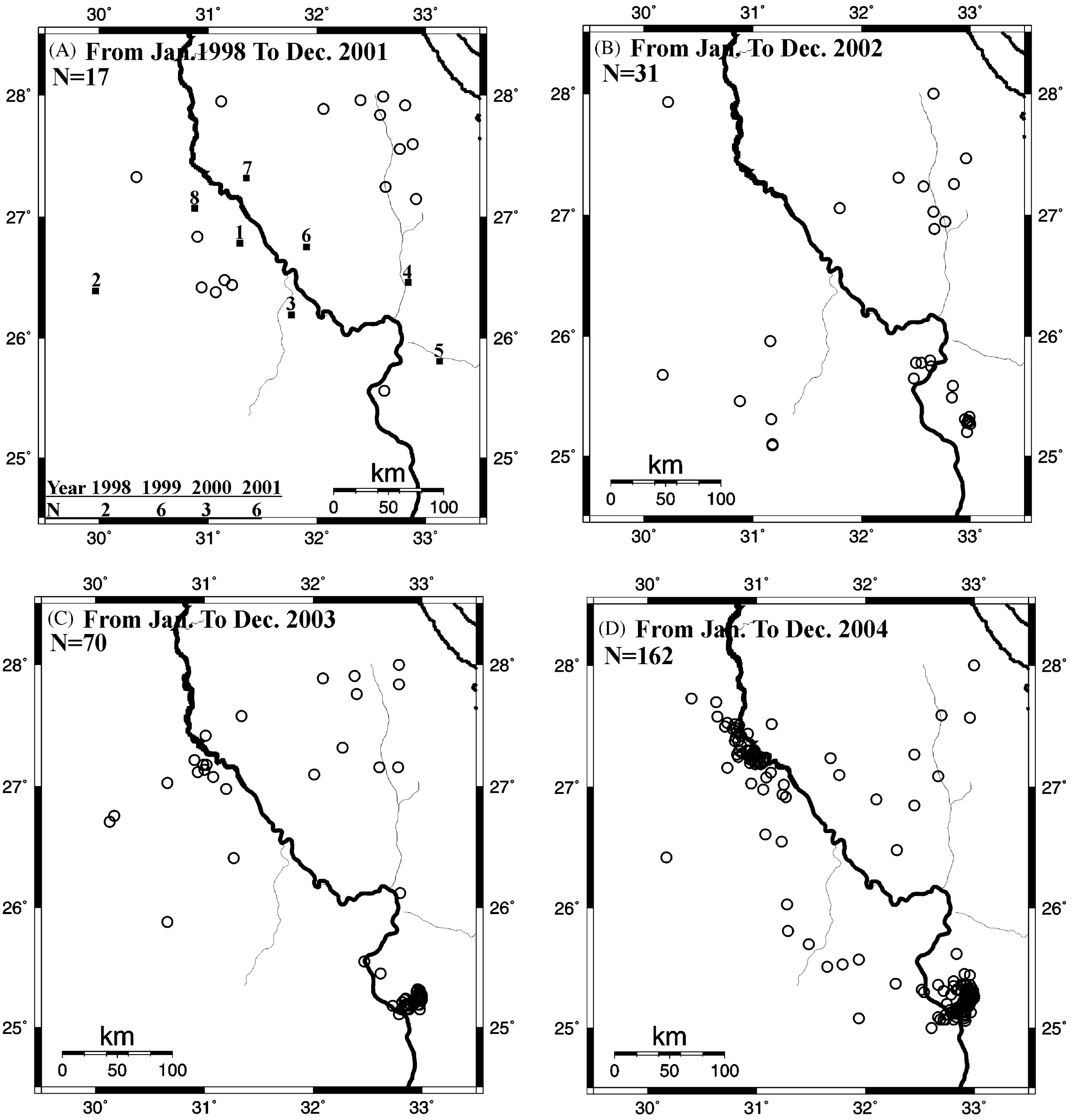

Fig. 2. Seismicity maps of central Egypt throughout different period after ENSN operation. Closed squares and numbers denote to GPS stations.

3. Seismicity of middle Egypt

Although, Egypt is not considered a seismically active region, historical earthquakes are reported since the last five millennia with intensities up to VI. For example the Ramses II temple on the west bank of the Nile in Luxor, was almost destroyed by an ancient earthquake.

3.1. Instrumental seismicity

Based on the catalog compiled by Badawy (2005a) we evaluate the recent earthquake activity of middle Egypt. From 1900 to 1997 (pre-ENSN operation period) only nine earthquakes were recorded in the investigated area with M_L from 3.5 to 4.5. Unfortunately, available earthquake information reveals many apparent seismic gaps, many of which may reflect missing data due to scarce of seismograph stations and consequently the detect-ability of microearthquakes. Such

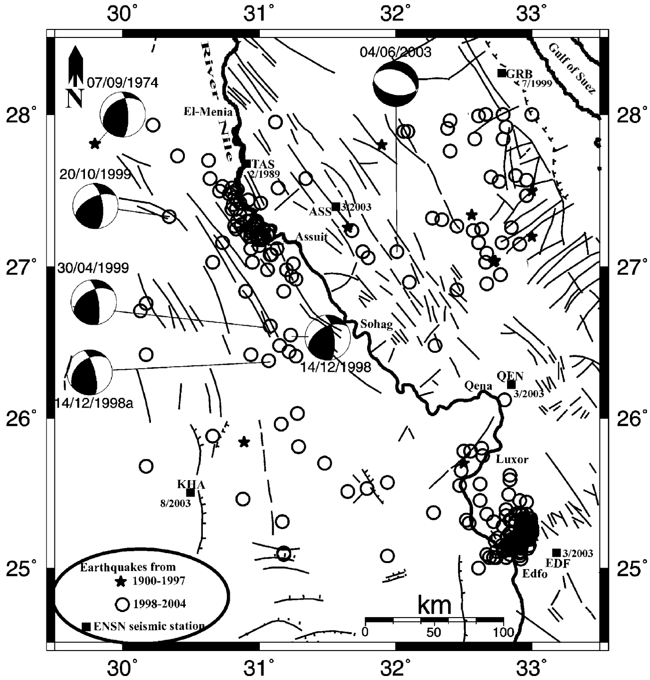

Fig. 3. Seismotectonics map of central Egypt. Stars represent earthquakes from 1900 to 1997 (only nine events); open circles from 1998 to 2004 (280 events). Fault traces are also drawn (Egyptian Geological Survey, 2003) (date beside seismic stations gives the operation date).

case introduces a difficulty in understanding the stress cycle and the recurrence rates since the temporal distribution is essential in earthquake hazard analysis.

Seismicity of Egypt has been significantly enhanced since the operation of ENSN that allowed to record events with magnitudes as low as 0.5 (Badawy, 2005a). The installation of ENSN also resulted in a large increase in number of micro, small and moderate earthquakes. For middle Egypt, the total recorded earthquakes from 1998 to 2004 are of 280 events. The large majority of them (92%) are microearthquakes and remaining ones are small earthquakes having magnitude less than 5.0. The temporal distribution reflects a progressive increase in the recording earthquakes from 1998 to 2004 (Fig. 2), where ca. 59% of the events is reported in 2004 (Fig. 2(D)). This is mainly attributed to the dense distribution of seismic stations and complete installation of ENSN by the end of 2003.

The spatial distribution of earthquake foci in middle Egypt has revealed two clusters located west of Assuit and north of Edfo cities in the northwestern and southeastern sectors of the study area, respectively (Figs. 2 and 3). These two clusters are started to nucleate at their location in 2002 and 2003 (Fig. 2(B) and (C)). Along the first cluster where the first instrumental event triggered on 14 December 1998 was located. Indeed the activity tends to occur in a NW–SE direction consistent with the main tectonic trends affecting the area (Fig. 3). As well as, a historical earthquake on 27 October 1850 was reported as felt with intensity VI (Badawy, 1999) in the same area of the first cluster. The area between Edfo and Luxor, where the second cluster was located, was also suffered by two historical earthquakes.

3.2. Focal mechanism solutions

The focal mechanism solutions for the largest five earthquakes have been determined using P-wave polarities. The parameters of these events are listed in Table 1. The preparation of the data comprised a band-pass filtering, in most cases between 1 and 15 Hz, to achieve a better signal to noise ratio. Then the polarities were determined from P-signals on the vertical component. Azimuths and take-off angles were calculated based on the crustal model derived by Marzouk (1988). Only events with minimum 15 polarities were considered. We used the program code Pman by Suetsugu (1998). The results coming from the Pman program are summarized in Fig. 2. The focal mechanisms of earthquakes located on the west bank of the Nile represent reverse faulting mechanism with strike-slip component, while normal faulting occurs in the eastern bank. The obtained reverse faulting mechanisms are in a good agreement

Table 1
Source parameters of the largest five earthquakes at middle Egypt from 1998 to 2004

Date	Time	Latitude	Longitude	M_w	R (m)	M_o (N m)	$\Delta\sigma$ (MPa)	μ (cm)
14 December 1998	20:45	26.44	31.22	4.4	580	5.2E15	11.7	6.4
14 December 1998a	21:15	26.38	31.07	3.6	380	2.4E14	4.4	1.8
30 April 1999	23:28	26.48	31.15	4.1	410	1.6E15	10.2	10.1
20 October 1999	13:43	27.33	30.34	3.6	390	2.7E14	4.5	1.9
04 June 2003	09:14	27.10	32.01	4.0	350	1.0E15	10.2	8.7

with the mechanism of the only available earthquake (07 September 1974) that occurred on the west bank of the Nile before ENSN operation (Badawy, 2001a,b, 2005a,b).

The double-couple model does not allow to separate the real plane from the auxiliary plane. However, the spatial distribution of seismicity with a NW–SE trend parallel to both surface and subsurface major fault trends (Fig. 3) support the NNW–SSE striking nodal planes to be the rupture plane.

The NNE–SSW and WNW–ESE orientation of tensional and compressional stress axes respectively are consistent with the regional stress field affecting whole Egyptian territory (Badawy, 2001a,b; Badawy and Horváth, 1999c). The opening of the northern Red Sea and its two branches Gulf of Suez and Gulf of Aqaba represents the main source of stress and crustal deformation in the region.

3.3. Source parameters determinations

Assuming a simplified circular source model and using displacement spectra, it is possible to determine the dynamic source parameters of a given earthquake. In the following we use the model of Brune (1970, 1971) for simple waveform data, and the analysis was restricted to the P-waves. We selected P-wave signal windows that avoid contamination from other phases and maintain the resolution and stability of the spectra. A cosine taper was applied to the selected data. The Fourier amplitude spectrum was calculated using an FFT routine applied to vertical components. The antialias filter for ENSN instruments has a cut of frequency of 40 Hz. To avoid problems associated with the visual determination of spectral parameters we applied a least square fitting technique based on Brune's model.

According to Brune's model, the source dimension is related to the corner frequency (f_o) by

$$r = \frac{0.37v}{f_o}$$

In this equation r is the radius and v is the P-wave velocity (6.5 km/s) near the source. Zero frequency intercepts (Ω_0) are utilized to estimate the seismic moment (M_o) following Brune (1970):

$$M_o = \frac{4\Pi\rho v^3 H\Omega_0}{R(\Theta, \phi)}$$

where ρ is the density (2.6 g/cm^3), H the hypocentral distance and R (Θ, ϕ) is the radiation pattern coefficient. In the present study a rms average over the focal sphere of 0.51 for the P-wave has been used (Fletcher, 1980).

In order to evaluate stress drop from seismic data, a time history of slip must also be prescribed from a model. For a circular rupture model the stress drop ($\Delta\sigma$) and average displacement ($\bar{u}$) are given by

$$\Delta\sigma = \frac{0.44M_o}{r^3}$$

and

$$\bar{u} = \frac{M_o}{\mu\Pi r^2}$$

where (μ) is the shear modulus. The averages of source parameter estimates of the studied earthquakes at different stations of the Egyptian national seismograph network are reported in Table 1. Two examples of velocity records, time windows and P-wave spectra of the December 14, 1998 earthquakes are shown in Fig. 4.

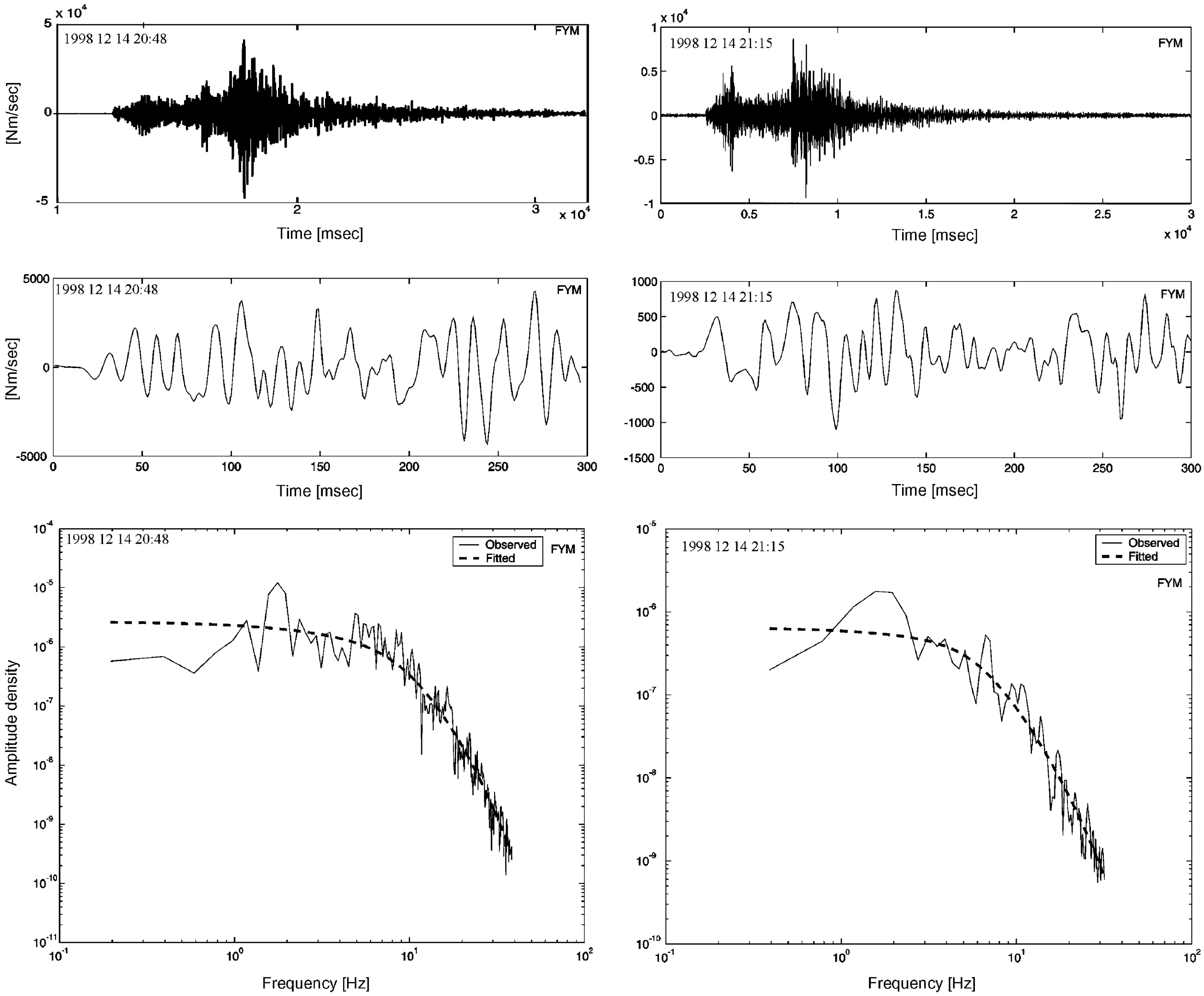

Fig. 4. Velocity record, P-wave time windows and spectra of December 1998 two earthquakes at FYM station.

4. Recent GPS observations

After the occurrence of the felt earthquake on 14 December 1998, National Research Institute of Astronomy and Geophysics (NRIAG) has initiated a geodetic network consisting of eight stations covering the area from Assuit to the Qena in order to study recent crustal deformation (Fig. 2(A)). The initial geodetic measurements were performed in April 2000 and were repeated in September 2001 and January 2003 using GPS receivers Trimble 4000SSI. The sampling interval and elevation were fixed throughout the survey at 30 s and 15°, respectively. The GPS observations were carried out during a 3-day campaign.

Processing of baselines analyses were performed using GPSurvey V. 2.3 software packages (Trimble, 1997) and other programs for adjustment and deformations parameters calculations (Bányai, 2003). The IGS precise ephemeris was applied in the calculation of the baselines. The displacement vectors at each GPS station were determined under an assumption of free network adjustment. Horizontal components at each station were computed from the difference of adjusted coordinates of the stations from one epoch to another and from the last epoch to the first. The displacement vectors for each epoch of observations were calculated from the coordinate changes. Considering the confidence limit, most of these displacement vectors can be mainly attributed to deformation of the study area.

The horizontal components of the displacement vectors with 95% confidence error ellipses are shown in Fig. 5. The error ellipses mean here the standard error in all direction around the observed site. The horizontal displacement vectors

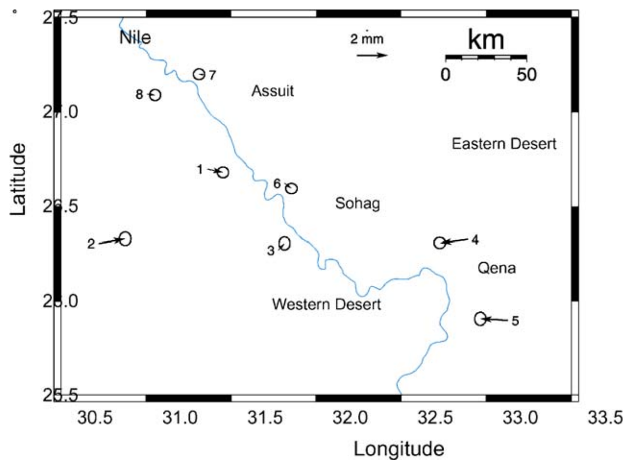

Fig. 5. Rate of horizontal displacement vectors for the period from April 2000 to January 2003.

are small magnitude and in the range of 1–4 mm/year. Some stations of the network indicate significant changes while other stations indicate no significant changes through the period of observations. The magnitudes of the movements are not homogeneously distributed over the area. East–west relative movements with relatively large magnitudes are recognized throughout the southern part of the network. While, there is no unique trend in the other sectors (Fig. 5).

The horizontal components of the displacement vectors are used to estimate the strain tensor parameters: dilatations, maximum shear strains and principal axes of strain are estimated within the observation periods. Although the obtained values are relatively small and sometimes are non-significant a preliminary interpretation of the crustal deformation in middle Egypt could be attempted. The dilatational strains (Fig. 6) show that the southeastern part of the network is dominated by shortening while the extensional strain rates are prevail in the northwestern part.

The total amount of maximum shear strain accumulation during the present interval is relatively small and shown in Fig. 7. The maximum shear strains increase towards the northeast and decreases towards the south and southwest. The epicentral area of the $M_w = 4.0$ June 4, 2003 earthquake is located within the area characterized by the maximum shear strains thus reflecting the energy accumulation deformation process. Since, the crustal deformation processes could occur during the accumulation of the energy within the earth's crust and during the different phases of energy releasing. This implies that this area of the network was suffering pre-seismic deformation during the last campagin (January 2003), while a dramatic increase in general earthquake activity should be expected.

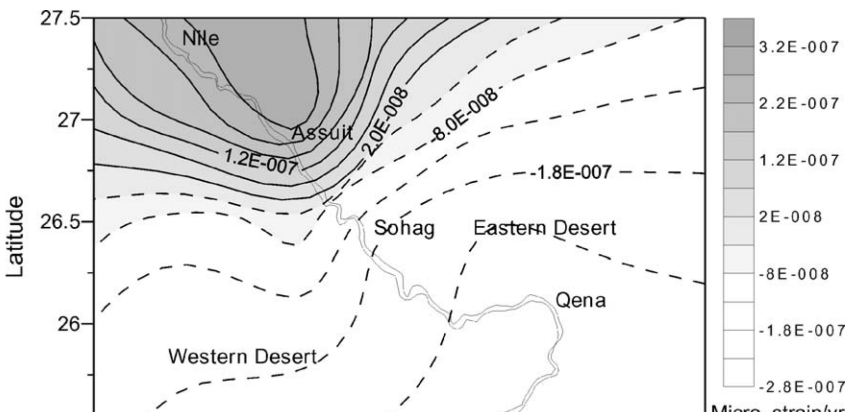

Fig. 6. Distribution of the dilatation strain rates for the period from April 2000 to January 2003.

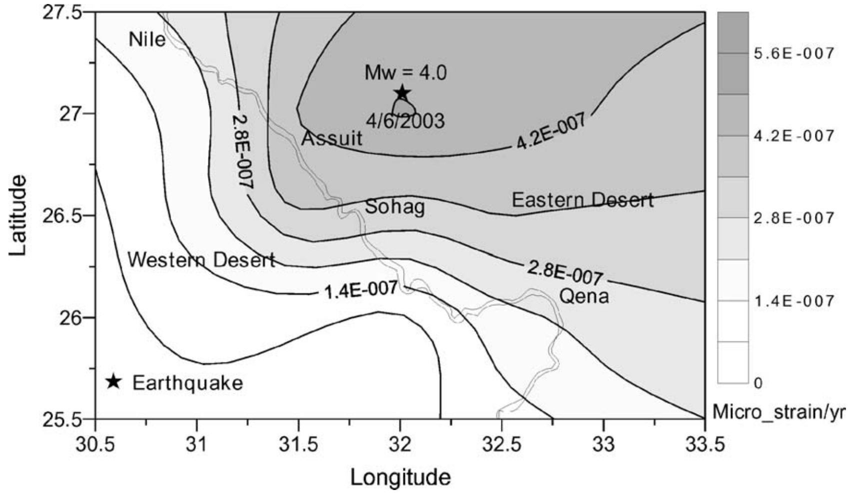

Fig. 7. Distribution of the maximum shear strain rates for the period from April 2000 to January 2003.

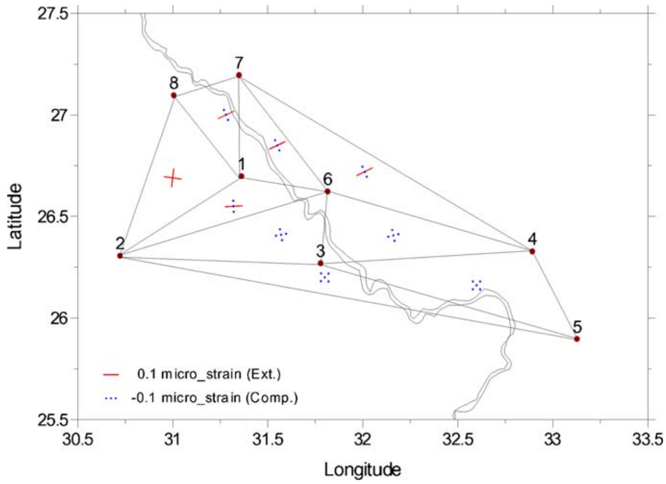

Fig. 8. Magnitude and orientation of principal axes of the strain rates for the period from April 2000 to January 2003.

Magnitudes and orientation of principal axes of the strain rates across the nine triangles of the network are calculated and plotted in Fig. 8. The compression is prevailing in the southern triangles while extension is predominant in the northwestern part of the network area. There are some balance between compression and extension in other triangles. The results of these analyses represent the framework of the dynamic model for the deformation, which occurred in the middle Egypt region during the different epochs of the measurements.

5. Discussion and conclusions

The present-day tectonics of Egypt is shaped by deformation related to the collision between the Africa and Eurasia plates and the rifting along the Red Sea. Additionally, the Sinai sub-plate is a key for understanding the role played among the Suez rift and the Aqaba-Dead Sea transform fault. Geodetic data show that the African plate is moving NW with respect to Eurasia with a velocity of 6 mm/year (McClusky et al., 2000). Recent GPS results show spreading rates along the Red Sea decreasing from 14 mm/year at 15°N to 5.6 mm/year at 27°N and left-lateral strike-slip motion of 5.6 mm/year along the southernmost segment of Aqaba-Dead Sea fault (McClusky et al., 2003). As well as, the recent analysis of CGPS observations shows the left-lateral motion of the Dead Sea fault (northern segment) at a rate of about 2.8 mm/year and slight spreading of the Suez rift (Wdowinski et al., 2004). The average horizontal velocity of GPS sites in Egypt is 5.15 mm/year mainly in a NNW direction with respect to Eurasian plate (Badawy, 2005b). Generally, both magnitudes and directions of the estimated average velocity vectors in Egypt are consistent with McClusky et al. (2003), however, slower than NNR-NUVEL-1A (DeMets et al., 1994). This discrepancy may support the existence of Sinai sub-plate that accommodated part of the motion.

Although the motion of GPS sites in Egypt is low and therefore subject to improvements, we attempt here to interpret our results in the framework of local or regional deformation pattern. Indeed, the relative motion between Africa, Arabia, Eurasian plates and Sinai sub-plate plays a big role in the processes of the present-day low crustal transient deformation in middle Egypt. Transient deformation in the Earth's crust is one of the important sources of information about the processes that trigger seismic events. Measurements of transient deformation and the stresses that cause it can provide information on the material properties of fault zones and adjacent lithosphere. It has been detected on or near fault zones at various parts of the earthquake cycle.

Much of this deformation is accommodated by small or very small magnitude earthquakes (such as in our case for middle Egypt), so it has been primarily detected using geodetic techniques such as strain-meters, SAR interferometry (InSAR) and GPS or by local seismic networks. Transients are often detected after moderate or large earthquakes nearby and include triggered slip on faults other than the one that produced the earthquake, afterslip on or near the co-seismic rupture and viscous and poroelastic deformation in the lower or upper lithosphere. Other transients are not obviously associated with nearby earthquakes but are associated with other static or dynamic stress changes, or they occur episodically in association with seismic tremor.

In this study, we have interpreted one of such event where transient deformation has produced relatively small and very small magnitude earthquakes in middle Egypt. All reported earthquakes either pre-ENSN (1900–1997) or post-ENSN (1997–2004) in middle Egypt having $M_w < 4.5$. The horizontal displacement vectors for the middle Egypt campaign-GPS network show small magnitudes and in the range of 1–4 mm/year. Indeed these values are highly compatible with the horizontal velocities of GPS stations at northern Egypt networks (Badawy et al., 2001, 2003; Mahmoud, 2003) and Aswan network changing from 2 to 4 mm/year showing an average of 3.1 mm/year (Mahmoud, 2003; Badawy, 2005b). This confirms the concept of a stable shelf for the upper and middle Egypt (Said, 1962) and suggests that the whole Egyptian territory behaves as a coherent block.

According to strain field estimations from different GPS campaigns, the middle Egypt region has suffered from variable tension and compression through the time observations. The principal strains of all campaigns indicate extensions in NE–SW direction and compression in NW–SE direction. Style and direction of the geodetic deformations are consistent with seismic deformation (i.e. earthquakes focal mechanisms) in middle Egypt. The estimated magnitudes and the inferred local deformation field is in agreement with regional stress pattern, where the dominating stresses are the result of both shortening due to NW convergence between African and Eurasian plates and extension due to the opening of the Red Sea.

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