NRIAG Journal of Geophysics, Vol. 1, No. 1, PP. 155- 174 (2002)

PRESENT-DAY CRUSTAL DEFORMATION IN AND AROUND THE CAIRO CITY, EGYPT, AS DERIVED FROM GPS MEASUREMENTS AND ITS TECTONIC IMPLICATIONS

Gamal S. El-Fiky, Mostafa Rabah, Ashraf Mousa,

Khaled Zahran, Ali Raiyan, and Ali Tealeb

(*Received: Nov. 25, 2001; Accepted: Aug. 20, 2002*)

ABSTRACT: ***Five years of Global Positing System (GPS) measurements, during 1996–2000, were used to derive velocity vectors and principal components of strains in and around Cairo city, Egypt. Estimated horizontal velocity vectors in ITRF96 are in the range of 20-27 mm/yr with an average of 24.16 mm/yr in N4°±5°W. We employed the Least-Squares prediction (LSP) technique to segregate the signal and noise in the data. Estimated signals were used to reconstruct the strains; dilatations, maximum shear strains, and principal axes of strains. Obtained strains are portrayed active tectonic environments in and around the Cairo city; (1) dilatational strains show that the northern part of the region is under a compressive strain regime, (2) maximum shear strains show good agreement with the recent crustal activities, and (3) principal axes of the strains indicate that the compressional force acting at the convergent plate boundary between the Eurasian and the African plates affect the southern part of the Nile Delta. Moreover, the principal axes of strains show a good correlation with the S_{Hmax} directions obtained from earthquake focal mechanisms and borehole breakouts.***

INTRODUCTION

Egypt covers an area of about 1000,000 km^2 and located at the northeastern part of Africa. It is bounded to the north by the Mediterranean Sea and to the east by the Red Sea and Gulf of Aqaba (Figure 1). The African continent is considered to be a stable region except the East African Rift, which branches in the northern Ethiopia into the Red Sea Rift and the Gulf of Aden Rift (e.g., Garfunkel, 1981). In eastern Egypt, the Red Sea Rift branches into the Gulf of Suez and the Gulf of Aqaba. At the Mediterranean region the African plate collides with the Eurasian plate. Therefore, faults and lineaments in Egypt tend to appear along three main trends, the Red Sea trend

National Research Institute of Astronomy and Geophysics, Helwan, Cairo, Egypt

(NW-SE), the Gulf of Aqaba trend (NE-SW) and the Mediterranean trend (E-W).

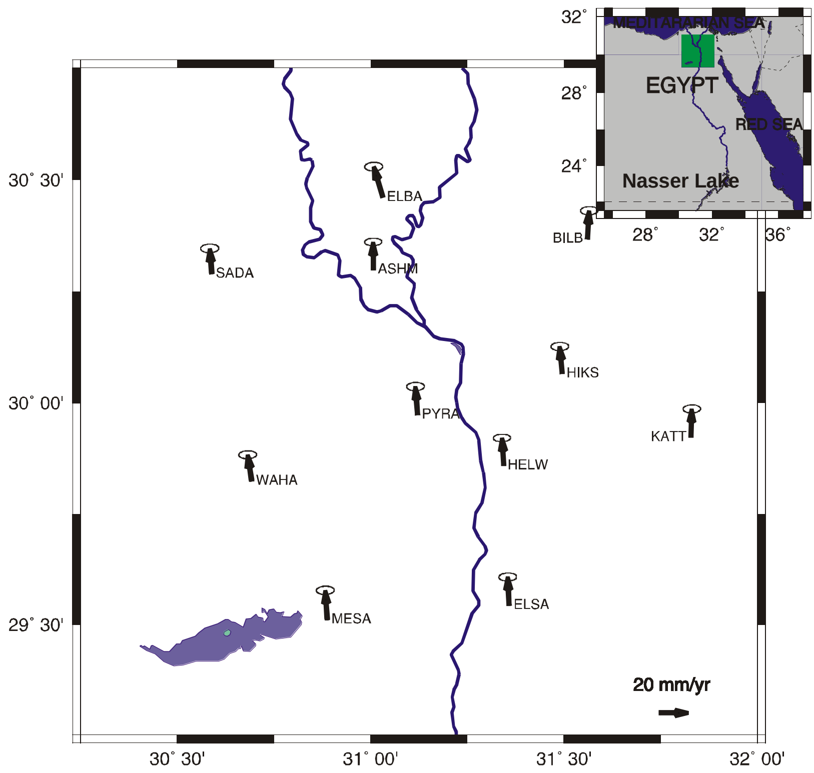

Fig. 1. **Velocity field estimated by repeated GPS observations and its 95% confidence ellipses in ITRF96 reference frame for the period from 1996 to 2000 in and around Cairo city. The inset shows the location of Egypt and the studied region.**

The tectonic framework of the Egypt, including the studied region is shown in Figure (2). Egypt has a wide variety of tectonic processes. The Red Sea is a divergent-type boundary between the Arabian and African plates (e.g., McKenzie, 1970). Dead Sea fault is a transform fault between the Arabian plate and the African plate (e.g., Garfunkel, 1981). The present-day geodynamic deformation in the Northern part of Africa (including Egypt) results from the relative motion among three continental plates, namely: Eurasia, Africa and Arabia (e.g., McKenzie, 1970). Plate motion models (DeMets et al., 1990; DeMets et al., 1994; Jestin et al., 1994) based on the analysis of earthquake slip vectors, seafloor spreading, and fault systems indicate that the Arabian plate is moving in a NNW direction relative to the Eurasian plate at a rate of about 20-25mm/yr. These models also indicate that the African plate is moving in a northward direction relative to the Eurasian plate at a rate of about 10 mm/yr. Differential motion between Africa and Arabia (~10-15 mm/yr) is thought to be taken up predominantly by left-lateral motion along the Dead Sea transform fault (McClusky et al., 2000; El-Fiky, 2000). On the other hand, the Gulf of Suez is thought to be a plate boundary between the Sinai Peninsula and the African continent (e.g., Ben-Menahem et al. 1976; Joffe and Garfunkel, 1987). Tectonic extension of the northern part of the Gulf of Suez is not yet well defined. According to Ben-Menahem et al., (1976), the northwest expansion of Sinai might be extended to the southern Nile Delta.

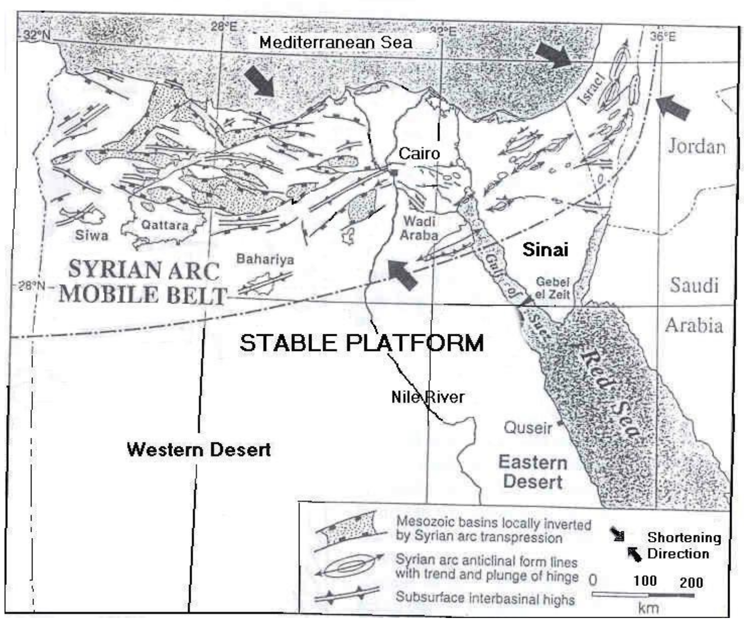

Fig. 2. A simplified tectonic map of the Egypt (modified from Bosworth et al., 1999).

Seismically, Egypt may be considered as a territory of moderate earthquake activity (e.g., Ambraseys et al., 1994). Many authors (e.g., Gergawi and El Khashab, 1968; Maamoun and Ibrahim, 1978; Kebeasy, 1990) have tried to relate the above geologic and tectonic features of Egypt to the distribution of earthquakes in order to determine the main seismic zones in Egypt. The general distribution of earthquakes in Egypt (Figure 3) falls along three major trends (Kebeasy, 1990). The first major trend extends from the northern Red Sea area and along the Gulf of Suez, through the cities of Cairo and Alexandria. The activity along this trend has increased in recent years and is attributed to Red Sea rifting as well as several active faults (e.g., Ambraseys et al., 1994). The second trend extends from the eastern Mediterranean to East of the Nile Delta to Cairo and Fayum region. The first trend intersects the second one in the Cairo city (Kebeasy, 1990). Within this intersection the moderate earthquake of October 12, 1992 (Mb=5.9) occurred. Along the third trend (Levant-Aqaba trend), the seismic activity is large. This is may be related to the active sinistral movement along the Levant Fault system and the Gulf of Aqaba (Chaimov, et al., 1990; Reilinger et al., 1997; Barka and Reilinger, 1997). In addition to those trends, there are several active areas such as southwest of Aswan, Abu Dabbab, and Wadi Hagul west of the Gulf of Suez.

The Cairo region has been the focus of intense geological and geophysical investigations since the occurrence of the 12th October 1992 earthquake (M_b=5.9). This moderate earthquake occurred at Dahshour city, about 25 km southwest the Cairo city. This earthquake caused a widespread damage in Cairo city and its surrounding areas. Therefore, the National Research Institute of Astronomy and Geophysics (NRIAG), Egypt, started a series of geophysical studies in the epicentral area, in and around the Cairo city, to help understanding the physical process of the crust in this tectonically active area (e.g., Abdel-Hafiez, 1995). In addition, near to the epicenter of the 1992 earthquake, two moderate but destructive earthquakes occurred in 1303 and 1847 (Badawy and Monus, 1995; El-Sayed et. al., 1998).

In this study, we used GPS measurements for the period from 1996 to 2000 in and around the Cairo region, and applied the Least-Squares Prediction (LSP) technique for strain fields analysis to investigate the crustal deformations and discuss its characteristics in this tectonically active region.

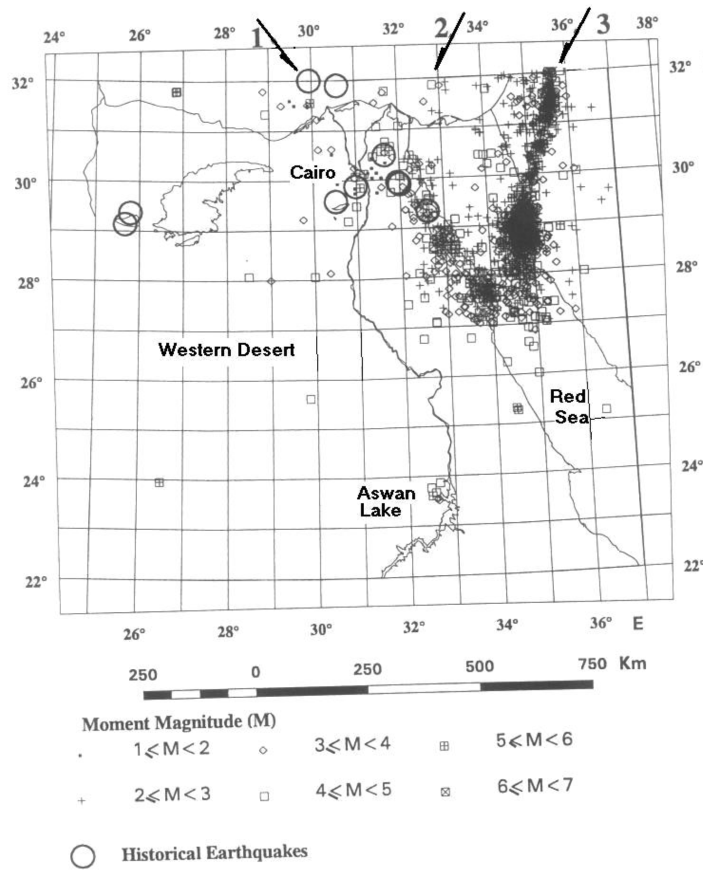

Fig. 3. Epicenters distribution of the earthquakes, which occurred in and around Egypt for the period from 1900 to 1996. The historical earthquakes are shown in the figure too (Modified from El-Araby and Sultan, 2000).

GPS Measurements

GPS techniques have been explosively developed and used for crustal deformation researches since around the beginning of the 1980s in various regions on the world. In and around the Cairo city the GPS measurements were initiated early in 1996. A GPS network consists of 11 sites (Figure 1) has been established at the area around greater Cairo city, in 1995, after the occurrence of the October 12, 1992 earthquake (M_b=5.9) to study the crustal deformation in this important area. The Nile River runs in the middle of this network (Figure 1). The northern part of the GPS network covers the southern part of Nile Delta, whereas its eastern and western parts are deserts. The campaign observations have been repeated in the area each year between 1996 and 2000. The data length spans over five years is long enough for obtaining reliable velocities at sites (e.g., Kato et al., 1998). GPS observations were carried out using dual frequency Trimble 4000SSE and 4000SSI receivers. The sampling interval and elevation were fixed at 30 sec and 15^o respectively throughout the survey.

The GPS data were organized into 24 hours segments covering a UTC day to facilitate the combination of the data with some of the surrounding IGS sites; ANKR, ONSA, KOSG, IISC, BAHR, YAR1, and MAS1 to constrain the site coordinates. Then, the data were processed using the GAMIT software, developed at MIT and SIO (king and Bock, 1991), to produce estimates and an associated covariance matrix of station position for each station with loose constrains on the parameters. To get a combined solution (site positions and velocities), all such covariance matrices are input to GLOBK, which is a Kalman filter. The basic algorithms and a description of this technique are given in Herring et al. (1990) and its application to GPS data in Feigl et al (1993). By introducing global h-file, we have obtained coordinates and velocity vectors at each site in the ITRF96 reference frame (Boucher et al., 1998). Figure 1 shows the horizontal component of the velocity vectors with 95% confidence error ellipses. The horizontal components of these velocity vectors are further used to estimate the strain field by Least-Squares Prediction method.

Monitoring of the crustal strain perturbations in space and time is a key to understand the physical process in the crust as well as to forecast the crustal activity. Dense GPS measurements with long time span provide us with one of the ideal tools to realize this. In the present study, we try to delineate the crustal strain of the greater Cairo using GPS measurements in the data period and discuss its tectonic implications.

STRAINS ANALYSIS

To delineate crustal strains in the Cairo region, we applied the Least-Squares Prediction (LSP) method used by El-Fiky and Kato (1999a). The method is a corollary of the least-squares collocation method developed by Moritz (1962) for the reduction of gravity data. In this method El-Fiky and Kato (1999a) assume that the spatially distribution of geodetic data $\boldsymbol{l}$ is given by the summation of tectonic signal $\boldsymbol{t}$ and noise $\boldsymbol{n}$, so that it is expressed by the following observation equation;

$$\boldsymbol{l} = \boldsymbol{t} + \boldsymbol{n}.$$

Where $\boldsymbol{t}$ is the tectonic signal vector at the observation points and $\boldsymbol{n}$ is the noise vector, which represents the measuring error. Here, the signal is the tectonic deformation that arises from inside and outside of the region. Noise is erroneous fluctuations that are inherent in each of the GPS sites. Such noise stem from some known or unknown sources such as monument instability, underground water flow, or other artificial causes. This noise have to be removed to obtain crustal deformation of tectonic origin. Thus, the problem is to extract the signal $\boldsymbol{S}$ at any arbitrary location from $\boldsymbol{l}$ by some filtering technique, considering that the noise $\boldsymbol{n}$ are limited to only the site or adjacent local regions and tectonic signal $\boldsymbol{t}$ may have rather wider correlations in nature (El-Fiky, 1998). Thus, the hypothesis in which the signal has spatial correlation whereas the noise does not is made use to separate their components. Variance-covariance analysis of data is a good measure to find such spatial correlation. If we assume that the velocity field is isotropic and homogeneous, the covariance of data will only be a function of site distance (e.g., El-Fiky et al., 1997; El-Fiky and Kato, 1999b). We then demean the EW and NS velocity components and calculate the variance $C_l(0) = (\sum l_i l_i)/N$ and covariance $C_l(d_q) = (\sum l_i l_j)/N_q$ of the data for each components. Here, N is the total number of data sites and N_q is the number of data points within a specific discrete distance interval, from which d_q is taken as the median of this assumed interval. Variances are estimated at each observational site whereas covariances are estimated for all site pairs within the assigned distance interval. Thus, obtained variances $C_l(0)$ may include signal and noise, but the covariances $C_l(d_q)$ include only signals according to the above hypothesis.

Plot of the covariances with respect to the distance would be a curve that naturally diminishes with distances. One of a simple mathematical function to express such plots would be a Gaussian function in the following form, $C_l(d_i) = C_t(0) \exp(-k^2 d_i^2)$, which we chose here as the empirical covariance function (ECF). Two parameters $C_t(0)$ and k are fitted from a covariance plot of the data. $C_t(0)$ is the expected variance at the sites and $C_r(0) = C_l(0) - C_t(0)$ is considered to be the noise component at the site. k is an indication of how far the correlation reaches, which has the dimension of the inverse distance.

Once ECF is obtained, we can estimate the signal $\boldsymbol{S}$ at any arbitrary point by the following formula (e.g., El-Fiky and Kato, 1999a);

$$\boldsymbol{S} = \mathbf{C_{st}} \mathbf{C_L}^{-1} \boldsymbol{l}.$$

Where the matrix $\boldsymbol{C_{st}}$ is composed of elements c_{st} ($1 \le t \le N$, $1 \le s \le P$, where P is the number of grid points whose signals are to be estimated); c_{st} is given by $c_{st} = C_{ut}(0) \exp(-k_u^2 d_{st}^2)$ for EW component and $c_{st} = C_{vt}(0) \exp(-k_v^2 d_{st}^2)$ for NS component, respectively, where d_{st} is distance between the data site and the predicted site. The above formula was used to reconstruct velocity vectors (signal) at grid points of 5 km × 5 km mesh covering the study region.

RESULTS AND DISCUSSION

To estimate the crustal strains in the GPS data for the period (1996 – 2000), we used horizontal velocity vectors shown in Figure (1). The averages of velocities in the NS and EW components are subtracted separately from all of the site velocities to remove systematic bias. Then, we applied the LSP as described above to each of the vector components (East-West and North-South) independently. ECF for each of the components are fitted to the data. The parameters of k_u, C_{ut}, and C_{ur} for EW component are estimated to be 0.012 km^{-1}, 40.01 (mm/yr)^2, and 13.5 (mm/yr)^2. While the k_v , C_{vt}, and C_{vr} parameters for NS component are estimated to be 0.015 km^{-1}, 12.0 (mm/yr)^2, and 3.5 (mm/yr)^2, respectively. These parameters are used to compose the covariances matrices and reconstruct displacement vectors (signal) at grid points in and around the Cairo region. Then, the estimated velocities at these grid points are differentiated in space to obtain crustal strains in this data period.

In order to establish a common reference frame for the observational GPS campaigns the mentioned seven IGS stations were selected. These stations have RMS in each velocity component smaller than 1.0 mm/yr in the ITRF96 reference frame. Note that, ITRF96 is adopting the NNR-NUVEL1 plate motion model (e.g., Patrick, et al, 1998; Iwakuni, 2001). The magnitude of the horizontal velocity vectors in ITRF96 is in the range of 20 - 27 mm/yr with an average of 24.16 ± 2.1 mm/yr in N4^o±5^{o}W. The associated errors are bout 3 mm and 1.5 mm in east and north components, respectively. The observed horizontal velocity vectors with error ellipses are shown in Figure (1). Direction of the estimated average velocity is consistent with that for African plate relative to the Eurasian plate by NUVEL-1A (N2^o ± 3^{o}E), but the velocity rate of this region is about two times greater than that estimated for the African plate relative the Eurasian plate by the same model (11±1 mm/yr in N2^o ± 3^{o}E direction). The satellite laser ranging (SLR) observations near HELW (Helwan station) supported the NUVEL-1A rates for northeastern Africa (e.g., Robbins et al., 1995). The problem with SLR observations is that the results have high uncertainties at this station (Helwan, 6 ± 9 mm/yr at 213^o ± 62^o). In fact, long span and denser GPS observations are needed to clarify the high velocity rate in this study.

Figures (4), (5), and (6) are the estimated areal dilatational strains, maximum shear strains, and principal axes of strains, respectively. Although these figures estimated from only five years of data, they well portray characteristics of the tectonic deformation in the Cairo region.

First of all, the dilatational strains shown in Figure 4 indicate that the studied region is separated into two areas: the northern part where compression strain is predominant and the southern part where extensive areal strain prevails. The largest areal compressions reaching more than 0.2 ppm/yr in the northern part might be due to the subduction of the African plate along the Hellenic arc and/or Cyprean arc. El-Fiky (2000) used the velocity vectors at 189 sides derived from GPS observations in the Eastern Mediterranean–Middle East region for the period from 1988 to 1997 to investigate crustal strains field in this tectonically active region. He found that the convergent strain rate is dominant in the northeastern Africa due to the collision of Africa and Eurasia. The strain field in the northern part of the present study is in a good agreement with his analysis. Based on the present analysis, we also can say, the crustal deformation due to the collision of African and Eurasian plates might be extended from plate boundary and covers the southern part of the Nile Delta. On the other side, the large area of extensional strains seems in relation with the tectonic motion along the Gulf of Suez and the deformation along the NW-SE and W-E faults in this region.

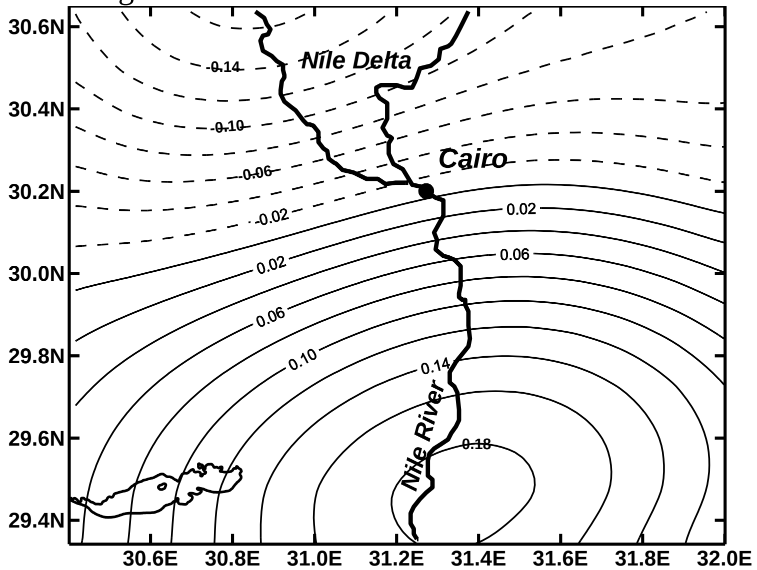

Fig. 4. The rate of areal dilatation of the Greater Cairo region estimated by the LSP technique for the period from 1996 to 2000. Unit is Micro_strain/yr.

Maximum shear strains (Figure 5) show two maxima of high values of strain in the northern and southern parts of the studied region separated by a very low maximum shear strains or almost strain-free zone in the middle of the region. It is interesting to note that at the southern edge of the above low area, the October 12, 1992 earthquake occurred (Figure 5). We should also note that the first GPS campaign was in 1996, about four years after the October 1992 earthquake. Therefore, we may able to say that the accumulated strain in this low zone was totally released by the co-seismic and the post-seismic of the October 1992 earthquake. In addition, the present analysis show that there is no any evidence for earthquake activity in this low zone in the near future. However, there is still possibility for seismic activity in the northern or southern parts of the studied area where the strain rates are high. The above low zone of strains has been confirmed by seismic data. Mohamed (2001) used the seismic data for the period 1910-1999 and Richer's formula (1958) to estimate the earthquake energy release as function of time and location in and around the Cairo city. His results showed that the level of earthquake activity is very low throughout the studied region, except for the Dahshour area for the period 1992-1993.

On the other hand, the strain field in the two maxima in northern and southern areas may not relate to any co-seismic and/or post-seismic movements. The seismicity of this area was very low during the period of our interest; with the largest magnitude of earthquake being recorded was less than 4.0. To, compare the maximum shear strains with the seismic data, epicentres of shallow earthquakes of depth less than 30 km are plotted in the Figure (5). So, the above high strain rates in the in northern and southern areas might be due to the subduction of the African plate under the Eurasian plates and the tectonic motion along the Gulf of Suez as well as the deformation along the NW-SE and W-E faults (Figure 2) in the region. Generally, the low strain rates and low level of earthquake occurrence in the central part of the studied region (the low zone) during the present interval indicate that internal deformation in this region is very small.

The distribution of principal axes of strains (Fig. 6) shows a general contraction of about 0.2 ppm/yr in nearly north-south direction in the northern part of studied region. This may be due to the compressional force acting at the convergent plate boundary between the Eurasian and the African plates. The present analysis indicates that that the effect of this force might be extended to the southern part of Nile Delta.

Badaway (2001) used earthquake focal mechanisms and borehole breakouts in Egypt and compiled the stress field for Egypt including the studied region. His results show dominant NW-SE compression in and around the Cairo city. In spite of the scatter of seismic data and the uneven distribution of sampling sites, the direction of contraction is in general agreement with the strain rate field derived from GPS, (Figure 5), showing a compression strain in NW-SE direction in the northern part of the Western Desert.

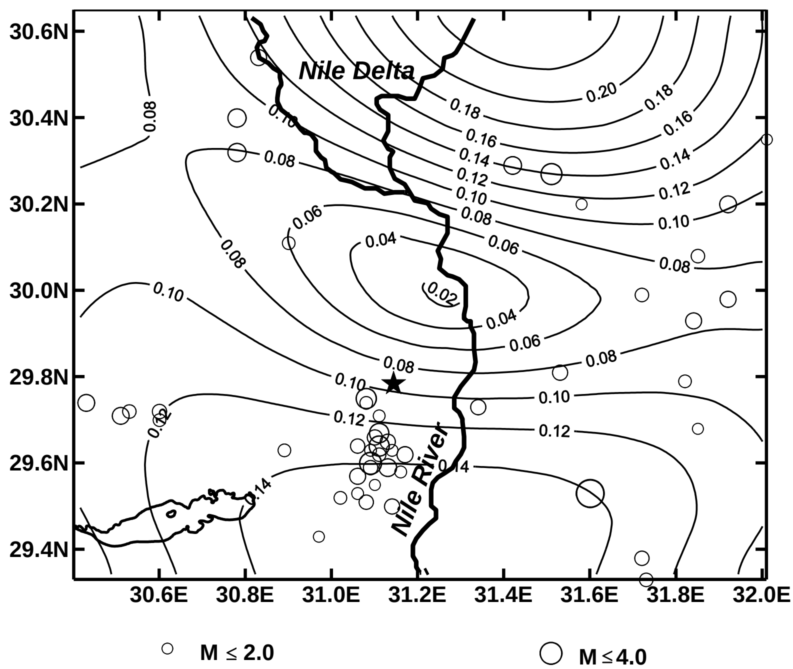

Fig. 5. Distribution of the maximum shear strain rates in the Greater Cairo region estimated by the LSP technique for the period from 1996 to 2000. Unit is Micro_strain/yr. Shallow earthquakes (d<30 km) of magnitude greater or equal to 2.0 from Jan. 1996 to Dec. 2000 are plotted (Egyptian Seismic Network and ISC). Star indicates the epicenter of the October 12, 1992 earthquake.

The Cairo earthquake of 12 October 1992 was considered to be an unexpected event for the Egyptians geophysicists. It occurred in an area, which somewhat considered to be stable with an actually simple tectonic setting. On the contrary, historical seismological evidences are in contradiction with consideration. Based on historical records, El-Sayed et al, (1998) indicated that the greater Cairo region has a history of repeated shaken by similar-size earthquakes. They also found that the repeated interval since 1754 is of about 80 years for such type of destructive earthquakes in this region. In addition, nearby the epicenter of the recent 1992 earthquake there were two moderate but destructive shocks occurred in 1847 and 1920. On the other hand, the region has also been suffering damage from depart earthquakes. The most recent examples of such severe distant earthquakes are the events of 22 November 1995 along the Gulf of Aqaba (M_w=7.2) and of 9 October 1996 at Cyprus (M_w=6.8). Moreover, the analysis for historical records shows that for most of the large earthquakes, which occurred in Egypt or in the surrounding countries, the Cairo city was affected more than other sites in Egypt. This may be due to the fact that a large part of the building stock in the greater Cairo area is in very poor state. On the other hand, we should consider another important factor, that is, the surface geology of Cairo area, which may strengthen the ground motion values during the earthquakes (El-Sayed et al, 1998). The Cairo city is located partially on the tip of the Nile graben and partially within the major Nile Vally graben. The width of the Nile Valley graben is up to several kilometers and filled by sedimentary materials (El-Gamili, 1982). The upper most part is silty to fine sand, water saturated in some areas and sandy partially saturated in other areas. Once this type of soil is strongly shaken, it is highly subject to the liquefaction phenomena. Destruction due to liquefaction could be observed in the Nile flood plain areas (Badawi and Mourad, 1994). As it is mentioned above, earthquake damage in northern Egypt with concentration in the Cairo city has been reported from earthquakes, which occurred as far as Crete, Cyprus, Turkey or Gulf of Aqaba. As it is mentioned above, the latest examples of such earthquakes are the events of 1995 along the Gulf of Aqaba and of 1996 at Cyprus. These two events were located at distances of about 400 and 600 km from the Cairo city, respectively. Although these earthquakes caused relatively minor damages, it indicates that at least some of the buildings in the Cairo are in a poor shape, since normally destruction would not be observed at these long distances. In the view of the historical and recent earthquakes data for Cairo area, the maximum experienced earthquake magnitude is about 6.6 (Ambraseys et al., 1994). Based on the period of historical and recent seismic activity, the Cairo area might probably experience another destructive earthquake in the coming eighty years or so (e.g., Elgamal et al., 1993).

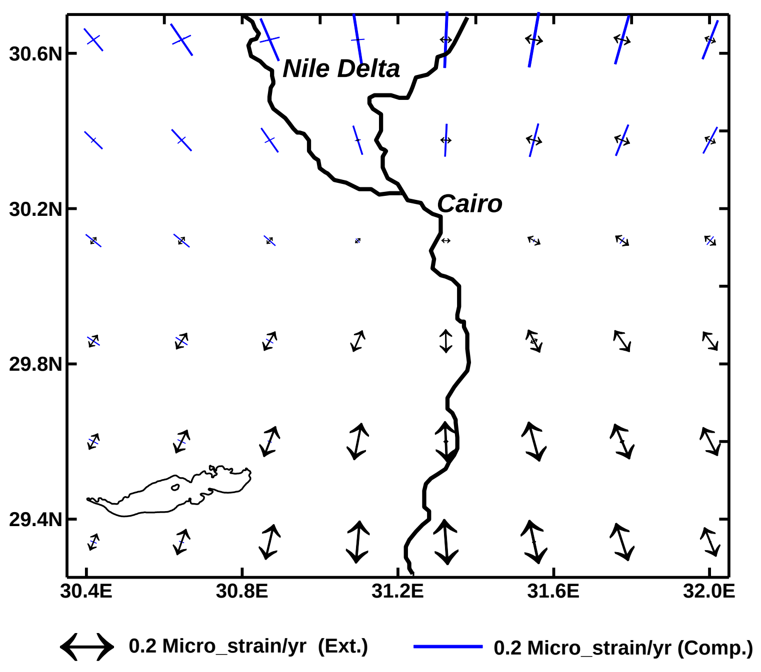

Fig. 6. Magnitude and orientation of principal axes of strains in the of the Greater Cairo region estimated by the LSP technique for the period from 1996 to 2000. Straight bars are compressional strains and arrows represent extensional strains, respectively. Unit is Micro_strain/yr.

Finally, we can say that the Cairo earthquake of 12 October 1992 rings an alarm for the future urban strategy in Egypt. To mitigate the effects of similar future disastrous earthquakes, seismic risk factors should be considered. In addition, we should also realize that building codes might be different for different localities in Egypt. From the economical point of view, it might be cheaper to use proper building codes for different parts of the country, which we can get through the detailed geophysical studies for each region. On the other hand, monitoring variation in the crustal strain in space and time is a key to help understand the physical process in the crust and to forecast the crustal activity. A dense array of continuous GPS tracking network supplemented by a dense seismic network could provide us with one of the ideal tools to realise this. For this purpose the National Research Institute of Astronomy and Geophysics (NRIAG) have installed a modern seismic network and planning to establish a dense arrays of continuous GPS tracking network in Egypt.

CONCLUSIONS

Velocity vectors in ITRF96 obtained from six GPS campaigns during 1996-2000 indicate that the magnitude of the horizontal velocity in and around the Cairo city is in the range of 20-27 mm/yr with an average of 24.16 mm/yr in N4^{o}W. The Least-Squares prediction (LSP) technique has been employed to segregate the signal and noise in the GPS data. Estimated signals were used to reconstruct the strains; dilatations, maximum shear strains, and principal axes of strains. The estimated dilatation strain rate and the maximum shear strain rate are both about 0.12 micro strain/yr in average. A compressional strain regime is observed in the northern part of the studied region, which might be due to the collision of Africa and Eurasia. The large area of extensional strains in the southern part of the studied region may be related to the tectonic motion along the Gulf of Suez and the deformation along the NW-SE and W-E faults in the region. Maximum shear strains show two maxima of high values of strain in the northern and southern parts of the studied region separated by a very low zone of maximum shear strains or almost strain-free zone in the middle of the region. At the southern edge of this low area, the October 12, 1992 earthquake occurred. This indicated that the accumulated strain in this low zone was totally released by the co-seismic and the post-seismic of the October 1992 earthquake. In addition, the present analysis shows that there is no any evidence for earthquake activity in this low zone in the near future. The above low zone of strains has been confirmed by seismic data. The principal axes of strains correlate with the S_{Hmax} directions obtained from earthquake focal mechanisms and borehole breakouts. The principal axes of the strains indicate that the compressional force acting at the convergent plate boundary between the Eurasian and the African plates affect the northern part of the studied region. The present analysis indicates that the effect of this force might be extended to the southern part of Nile Delta.

ACKNOWLEDGMENTS

The authors are very grateful to the staff of National Research Institute of Astronomy and Geophysics, Helwan, Cairo, who participated in the GPS data campaigns used in this study.

REFERENCES

Al-Araby, H. and M. Sultan, (2000): Integrated Seismic risk map of Egypt. Seismological Res. Lett., 71, 1, 53-65.

Abdel Hafiez, H. E., (1995): The role of earthquake analysis for modeling the crustal structure and constructing local magnitude scale. M. Sc. thesis, Ain Shams Univ., Faculty of Science.

Ambraseys, N. N., C. P. Melville, and R. D. Adams, (1994): The seismicity of Egypt, Arabia and the Red Sea: a historical review. Cambridge University Press, New York, pp. 181.

Badawi, H. S. and S. A. Mourad, (1994): Observation from 12 October 1992 Dahshour earthquake in Egypt. Natural Hazards, 10, 261-274.

Badawy, A. (2001): The present-day stress field in Egypt. Annali di Geofisica, 44, 3, 557-570.

Badawy, A. and P. Monus, (1995): Dynamic source parameters of the 12^{th} October 1992 Earthquake, Cairo, Egypt. J. Geodyn., V. 20, No. 2, 99-109.

Barka, A., and R. Reilinger, (1997): Active tectonics of the Eastern Mediterranean region: Deduced from GPS, new tectonic, and seismicity data, Ann. Geofis., 40, 587-610.

Ben-Menahem, A., A. Nur, and M. Vered, (1976): Tectonics, seismicity, and structure of the Afro-Eurasian Junction- The breaking of an coherent plate. Phys. Earth. Planet. Int., 12, 1-50.

Bosworth, W., R. Guiraud, and L. G. Kessler, (1999): Late Cretaceous (ca. 84 Ma) compressive deformation of the stable platform of northeast Africa: Far-field stress effects of the "Santonian event" and origin of the Syrian arc deformation belt. Goelogy, v. 27, no. 7, 633-636.

Boucher, C., Z. Altamimi, and P. Sillard, (1998): Results and anaysis of the ITRF96. IERS technical note 24. Observatory de Paris.

Chaimov, T. A., M. Barazangi, D. Al-Saad, T. Sawaf, and A. Gebran, (1990): Crustal shortening in the Palmyride fold belt, Syria, and implications for movement along the Dead Sea fault system, Tectonics, 9, 1369-1386.

Courtillot, V., R. Armijo, and P. Tapponier, (1987): The Sinai triple junction revisited, Tectonophysics, 141, 181-190.

DeMets, C., Gordon, R. G., Argus, D. F. and Stein, S., (1990): Current plate motions, Geophys. J. Int., 101: 425-478.

DeMets, C., Gordon, R. G., Argus, D. F. and Stein, S., (1994): Effects of recent revisions to the geomagnetic reversal time scale on estimates of current plate motions, Geophys. Res. Lett., 21, 2191-2194.

El-Fiky, G. S., (1998): Temporal change of the crustal deformation and interplate coupling in the Tohoku district, northeast Japan -a new approach. Ph. D. Thesis, Faculty of Science, Tokyo Univ, Japan.

El-Fiky, G. S., (2000): Crustal strains in the Eastern Mediterranean and Middle East as derived from GPS observations. Bull. Earthq. Res. Inst., Univ. of Tokyo, V. 75, No. 2, 161-181**.**

El-Fiky, G. S. and T. Kato, (1999a): Interplate coupling in the Tohoku district, Japan, deduced from geodetic data inversion. J. Geophysical Research, 104, 20,361-20,377.

El-Fiky, G. S. and T. Kato, (1999b): Continuous distribution of the horizontal strain in the Tohoku district, Japan, deduced from least squares prediction. J. Geodynamics, 27: 213-236.

El-Fiky, G. S., T. Kato, Y. and Fujii, (1997): Distribution of the vertical crustal movement rates in the Tohoku district, Japan, predicted by least-squares collocation. J. Geodesy, 71: 432-442.

Elgamal A. W., M. Amer, K. Adalier, and A. Abul-Fadl, (1993): Engineering aspects of the October 12 1992 Egyptian earthquake. Technical Report NCEER93-0018.

El-Gamili, M., (1982): A geophysical interpretation of a part of the Nile Valley, Egypt based on gravity data. J. Geol. (Special vol., part 2), 101-120.

El-Sayed, A., R. Arvidsson, and O. Kulhanek, (1998): The 1992 Cairo earthquake: A case study of a small destructive event. J. of Seismology, 2, 293-302.

Feigl, K. L., R. W. King, T. A. Herring, and M. Rothacher, (1993): Space geodesy measurement of crustal deformation in central and southern California 1984-1992. J. Geophys. Res., 98, 21677-21712.

Garfunkel, Z., (1981): Internal structure of the Dead Sea leakly transform (Rift) in relation to plate tectonics. Tectonophysics, 80, 81-108.

Gergawi, A. and H. El-Khashab, (1968): Seismicity of U. A. R. Helwan Obs. Bull, 76, 1-27.

Herring, T. A., J. L. Davis, and I. I. Shapiro, (1990): Geodesy by radio interferometry: The application of Kalman filtering to the analysis of very long baseline interferometry data. J. Geophys. Res., 95, 12561-12581.

Iwakuni, M., (2001): Tectonics in East Asia and mechanism of stress propation. M. Sc. Thesis, , Faculty of Science, Tokyo Univ., Japan.

Jackson, J., P. Huchon, J. Gaulier, (1994): A comparison of SLR and seismicity in the Aegean region. Geophys. Res. Lett. 21, 2849-2852.

Jestin, F., P. Hunchon, and J. M. Gaulier, (1994): The Somalia plate and the East African rift system: Present-day kinematics, Geophys. J. Int., 116, 637-654.

Joffe, S., and Garfunkel, Z. (1987): Plate Kinematics of the circum Red Sea-A re-evaluation, Tectonophysics, 141, 5-22.

Kato, T., G. S. El-Fiky, E. N. Oware, and S. Miyazaki, (1998): Crustal strains in the Japanese islands as deduced from dense GPS array, Geophys. Res. Lett., 25, 3445-3448.

Kebeasy R., (1990): Seismicity. In the Geology of Egypt Edited by Said R., 51-59, Balkema, Rotterdam.

King, R. W., and Y. Bock, (1991): Documentation for the MIT GPS analysis software. Mass. Inst. of Technol., Cambridge.

Maamoun, M, and E. Ibrahim, (1978): Tectonic activity in Egypt as indicated by earthquakes. Helwan Obs. Bull. no. 170.

McClusky, S., Balassanian, A. Barka, C. Demir, S. Ergintav, I. Georgiev, O. Gurkan, M. Hamburger, K. Hurst, H. Kahle, K. Kastens, G. Kekelidze, R. King, V. Kotzev, O. Lenk, S. Mahmoud, A. Mishin, M. Nadariya, A. Ouzounis, D. Paradissis, Y. Peter, M. Prilepin, R. Reilinger, I. Sanli, A. Seeger, A. Tealeb, M. N. Toksoz, and G. Veis., (2000): Global Positioning System constraints on plate kinematics and dynamics in the Eastern Mediterranean and Caucasus, J. Geophys. Res., 105, 5695-5719.

McKenzie, D.P., (1970): Plate tectonics of the Mediterranean region, Nature, 226, 239-243.

Moritz, H., (1962): Interpolation and prediction of gravity and their accuracy. Report No. 24, Inst. Geod. Phot. Cart., The Ohio State Univ., Columbus, U.S.A.

Mohamed, A. S., (2001): Seismicity and recent crustal movement studies in and around the greater Cairo region, Egypt. Acta. Geod. Geoph. Hung., 36 (3), 353-362.

Patrick, S., Z. Altamimi, and C. Boucher, (1998): The ITRF96 realization and its associated velocity field. Geophys. Res., Lett., 25, 17, 3223-3226.

Reilinger, R., S. C. McClusky, M. B. Oral, R. W. King, M. N. Toksoz, A. A. Barka, I. Kinik, O. Lenk, and I. Sanli, (1997): Global Positioning System measurements of present-day crustal movements in the Arabia-Africa-Eurasia plate collision zone, J. Geophys. Res, 102, 9983-9999.

Richter, C. F., (1958): Elementary seismology. W H Freeman Company, San Francisco, California.

Robbins, J. W., P. J. Dunn, M. H. Torrence, and D. E. Smith, (1995): Deformation in the Eastern Mediterranean, In Proceedings of the First Turkish Int. Sym. on Deformations, 2, pp. 738 – 745, Chamber of Surv. Eng. Ankara, Turkey.