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A STUDY OF CRUSTAL DEFORMATION ALONG THE RED SEA REGION USING GEODETIC AND SEISMIC DATA FROM EGYPT AND YEMEN

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A b s t r a c t

Monitoring of recent crustal deformation was carried out using GPS observations to detect the present-day styles and rates of extension, as well as rift-margin deformation along the extent of the Red Sea rift.

For studying the crustal deformation along the Red Sea Region and Gulf of Aden, 12 geodetic stations were established to cover some areas in Egypt and Yemen. The GPS measurements were carried out in April 2000 and November 2001. Analysis of the first and second campaigns of GPS measurements indicates that the magnitude of movements together with the strain parameters is small, but the magnitude of displacement may reach up to 20 mm in some points close to the Red Sea, such as those in Hodeidah (Yemen) and Dahab (Egypt). Moreover, the direction of movement on these points is opposite to each other. Such results are in harmony with the general trend of the tectonics in the Red Sea region. Separate analyses of GPS measurements on geodetic points in Yemen relative to each other show a rate of displacement of about 3 mm. The direction of movement on Sana'a is SW and on Aden is NE.

Key words: crustal movements, GPS data, seismic activity, Red Sea region.

1. INTRODUCTION

The problem of crustal deformation is related to the studies of the geodynamical properties of the upper layers of the Earth. Such phenomena are understood as a continuation of uninterrupted process of tectonic movements in the recent time. Therefore, the main goal of the network in Egypt and Yemen is the study of the crustal deformations associated with the earthquake occurrence in the Red Sea region in order to monitor the crustal movements and reduce the earthquake losses.

The countries around the Red Sea (Egypt, Republic of Yemen, Saudi Arabia, Sudan and Ethiopia) are interesting from the point of view of seismicity of these regions and many seismic stations were erected to register the earthquake activities. The favourite technology using the **G**lobal **P**ositioning **S**ystem (GPS) was performed for monitoring the recent crustal deformations on a large scale. The aim of these studies is the mapping of the tectonic elements presented within the region, to get a better knowledge on the geodynamics and a better understanding of the causes and origin of the earthquakes occurring there. Another aim is to find a possible association between the crustal deformation and earthquake activities in and around the Red Sea region.

2. TECTONIC SETTING OF THE RED SEA REGION

The Red Sea is a narrow ocean basin, separating the African plate from Arabian plate. It is approximately 3000 km long and about 100 to 300 km wide. The margins of the Red Sea are steep fault scarps, as much as 3 km high, that rise sharply from the coast. Elevation on the eastern side is generally higher than on the western side. Most of the seafloor is shallow; only the south-central portion of the sea approaches abyssal depths. The shallow parts of the Red Sea appear to be floored by continental crust thinner than that of the flanking continental areas. The thinning apparently has occurred on a series of listric normal faults (Moores and Twiss, 1995).

The importance of the Red Sea as a model for understanding continental break-up and development of passive margins and ocean ridges has been well documented. Makris and Henke (1992) have deduced from seismic, gravity and other geophysical data, that the early break-up stages of the Arabian plate from Africa, initiating the Red Sea Rift, were mainly controlled by the strike-slip processes. The eastern Red Sea flank was formed through stretching, thinning and diffuse extension and is floored by attenuated continental crust, thus producing the asymmetry observed in seismic sections between the eastern and western flanks of the Red Sea Rift. Plate motion was oblique to the initial orientation of the basin and could no longer be accommodated by the opening of the Gulf of Suez; the en-echlon distribution of gravity and magnetic anomalies, as well as the high heat-flow fields recorded in the northern Red Sea and Gulf of Aqaba oriented due to this process. Similarly, the thinned continental crust between Yemen and Ethiopia is affected by shear-faults that displace the volcanic centres to the east.

Active tectonic development of the Afro-Arabian region continues to the present time, both as spreading in the Red Sea and Gulf of Aden and as uplift and faulting along some sections of the flanks. The present steady-state spreading in the Red Sea and Gulf of Aden began about 5 Ma ago and continues at half-spreading rates of 6 to 7.5 mm/year in the southern Red Sea and about 10 mm/year in the eastern Gulf of Aden (Ambraseys and Melville, 1983; Plafker *et al*., 1987).

3. SEISMIC ACTIVITY IN THE RED SEA REGION

The previous study of the seismicity of the Red Sea indicates the presence of a rather moderate-low shallow seismicity, that is mostly restricted to plate boundaries or plate margins. Many earthquakes have occurred along the Red Sea axial trough and transform faults. The occurrence of earthquakes and the active volcanism within the axial trough indicate present-day rifting (Fairhead and Girdler, 1970). Some of the northeast transform faults to the north of latitude 25°N and south of latitude 22°N are seismically active (El-Isa and Al-Shanti, 1989), while the middle part of the Red Sea, between latitude 22°N and 25°N, appears to be mostly aseismic. The southern Red Sea seems to be more seismically active than the northern part (Gharib, 1999).

Recent seismicity investigations based on data collected from the main seismic observatories in Egypt, Saudi Arabia and Yemen along the Red Sea region and Gulf of Aden show a concentration of earthquake activities along the Red Sea Rift, Gulf of Aqaba and Gulf of Aden (Fig. 1).

The stress field distribution represents a good key for better understanding of the tectonic situation and the direction of relative plate movements. The most common way for studying the seismotectonics of any specified region is done by plotting stress field map on the basis of focal mechanisms, microtectonic analysis or *in situ* stress measurements.

In this study, Harvard CMT solutions have been used to study the regional tectonic stress that causes internal deformation within the Red Sea region. The focal mechanisms are projected using the lower hemisphere projection (Fig. 2). The focal mechanism solutions can be classified according to the locations as:

– The focal mechanism of events along the East African Rift spreading, indicates typical normal faulting mechanism for most parts, with an average tension axis oriented NNE-SSW, reflecting a continental divergent plate boundary.

– The focal mechanism solutions in the Gulf of Aden region shows two types of faulting: normal and strike slip. Normal faulting mechanisms are associated with the spreading while the strike slips ones are related to the existing transform faults. The average direction of the tension axis in the Gulf of Aden is NNE-SSW. For the events that took place at the extreme west of the Gulf of Aden, the majority of the epicentres are associated with the transform faults suggesting strike slip mechanism with a dip

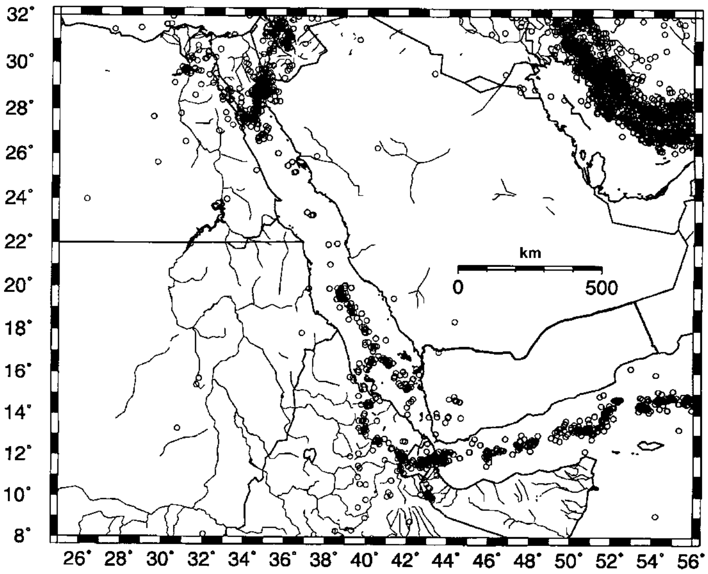

Fig. 1. Seismic activity in the Red Sea region, NEIC data from 1904 to 2002; $m_b > 2.9$.

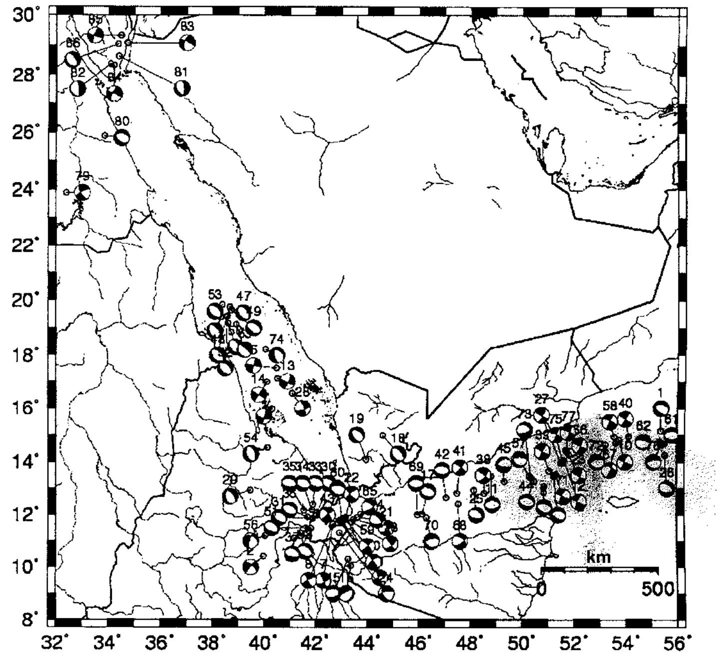

Fig. 2. Harvard CMT solutions for events with magnitude > 5 in the Red Sea region.

slip component. The presence of such a mechanism reflects a westward extension of the transform fault system and extensional mechanism existing in the Gulf of Aden.

– The focal mechanism solutions of the events located in the southern Red Sea suggest pure normal faulting mechanism with a NE-SW trending tension axis. These events took place along the rift valley region, which is characterized by continuous sea floor spreading.

– To the south of the southern Red Sea group, there are other events reflecting strike slip mechanisms. Events Nos. 13, 14 and 22 took place along one of the NNE -SSW transform faults. The plane trending NNE-SSW is indicating a left lateral motion along this transform fault. Event No. 28 took place along NNW-SSE trending fault to the west of the rift valley. The mechanism of this event reflects strike slip mechanism with a left lateral motion along a NNW-SSS trending plane. Some events took place to the east of the rift valley along a NNW-SSE trending fault. The focal mechanism of these events shows a strike slip mechanism along the same trend with a right lateral motion. The focal mechanisms of events Nos. 1, 26, 61, 62 and 76 identify normal faulting trends of nearly E-W direction, the events Nos. 10, 40, 58 and 67 indicate NE-SW transform faults and the events Nos. 12, 23, 27, 66, 71 and 77 identify strike slip faults.

4. SEISMIC ACTIVITY IN EGYPT

Historical documents and registration of seismic activities indicate the concentration of earthquakes in some parts in Egypt. The main zone is located along Gulf of Aqaba where the major earthquakes took place. Other seismic zones with moderate earthquakes are located in the Gulf of Suez area, Abu-Dabab on Rea Sea coast, northwestern part of Egypt, and in the Aswan area (Kebeasy,1990).

5. SEISMIC ACTIVITY IN YEMEN

The seismicity of Yemen is an obvious result of its location on the southern edge of the Arabian peninsula close to the well known active seismic zones of the Red Sea (where an annual sea floor spreading of about 2-3 cm is evident in the NE-SW direction) and the Gulf of Aden (NRP, 1992). The historical seismicity record includes many other damaging earthquakes in various parts of Yemen.

6. GEODETIC NETWORK IN EGYPT AND YEMEN

The establishment of geodetic network is the initial stage for monitoring crustal movement in the Red Sea region. Regional GPS network consisting of 12 stations was established as a first stage in both Egypt and Yemen (Fig. 3). In Egypt, 6 sites were

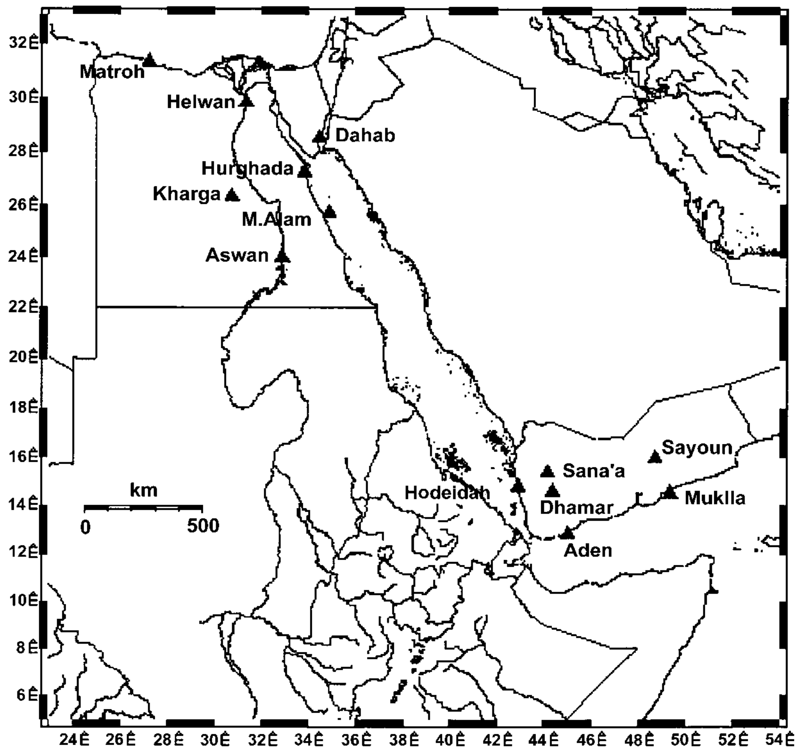

Fig. 3. GPS geodetic network in Egypt and Yemen (▲– GPS station).

fixed at Dahab on the Gulf of Aqaba, Hurghada on the Red Sea coast, Helwan, El Kharga, Marsa Alam and Aswan. These points are already connected with the other geodetic networks in Egypt. In Yemen, 6 sites were established in Sana'a, Aden, El-Hodida, El Mukalla, Sayoun and Dhamar. These stations were fixed using copper bars and cement material. The planning and the establishing of these stations were carried out by the staff of the NRIAG, Helwan, Egypt cooperating with the Department of Earth and Environmental Sciences of the Sana'a University and Geological Survey and Mineral Resources Board, Sana'a, Yemen.

7. GPS MEASUREMENTS AND DATA ANALYSIS

The initial GPS measurements were performed during the period from 24 to 27 April 2000 and repeated from 29 October to 5 November 2001. The minimum elevation angle was 15 degrees and sampling rate interval 30 s. Each epoch of measurements is adjusted separately. Two steps of adjustment to be common by all procedures can be emphasized: First, the adjustment of coordinates was made in the epoch under consideration. Second, the transformation of adjusted coordinates was comprised into the coordinates of the initial epoch. The differences of coordinates at single geodetic station are considered as its movement. The accuracy in determination of coordinates can be expressed, for instance, by error ellipses.

In the present work two repeated geodetic measurements are processed using GPSurvey 2.3, Geomatics, Bernse 4.2 softwares (Brockmann, 1996) and the adjustments have been done using other software. Precise ephemeris was applied in the calculations. The deformation programs were used to perform the computations. The displacement vectors at each GPS station are determined under an assumption that free network adjustment and all the stations in the network are minimized. Horizontal components at each station were computed from the difference of adjusted coordinates of the stations from the second epoch to the first one. The displacement vectors for each epoch of observations are calculated from the coordinate changes.

The displacement vectors (resultant components) of GPS stations in Egypt and Yemen are given in Table 1 and Fig. 4, respectively. The maximum displacement of about 2 cm was recorded at Hodeidah and Dahab stations. The minimum value at Aden was about 3 mm, but in Hurghada and Sana'a the values are about 15 and 10 mm, respectively. The direction of displacement in Sana'a and Hodeidah is 93^o and 83^o from the north, but the direction of displacement in Dahab and Hurghada is nearly opposite with respect to Sana'a and Hodeidah, 260^o and 270^o from the north. These results are in agreement with the tectonic setting and direction of spreading rate of the Red Sea.

Table 1

Rate of horizontal displacements for GPS stations in Yemen and Egypt
for the epoch from April 2000 to October–November 2001

Station	Station coordinates		Rate of displacement and standard deviation				Displacement [mm]	Direction
	longitude	latitude	d_E [mm]	Std	d_N [mm]	Std		
Sana'a	44°11′25″	15°20′53″	9.98	0.91	0.47	0.61	9.991	92.6962°
Aden	45°02′23″	12°48′44″	0.69	0.85	2.74	0.64	2.826	14.1346°
Hodeidah	42°57′13″	14°46′09″	21.65	0.64	2.49	0.53	21.793	83.4392°
Dahab	34°28′11″	28°31′43″	–19.1	0.96	–3.27	0.95	19.417	200.3049°
Hurghada	33°49′56″	27°14′40″	–15.2	0.95	0.19	1.03	15.221	270.7151°

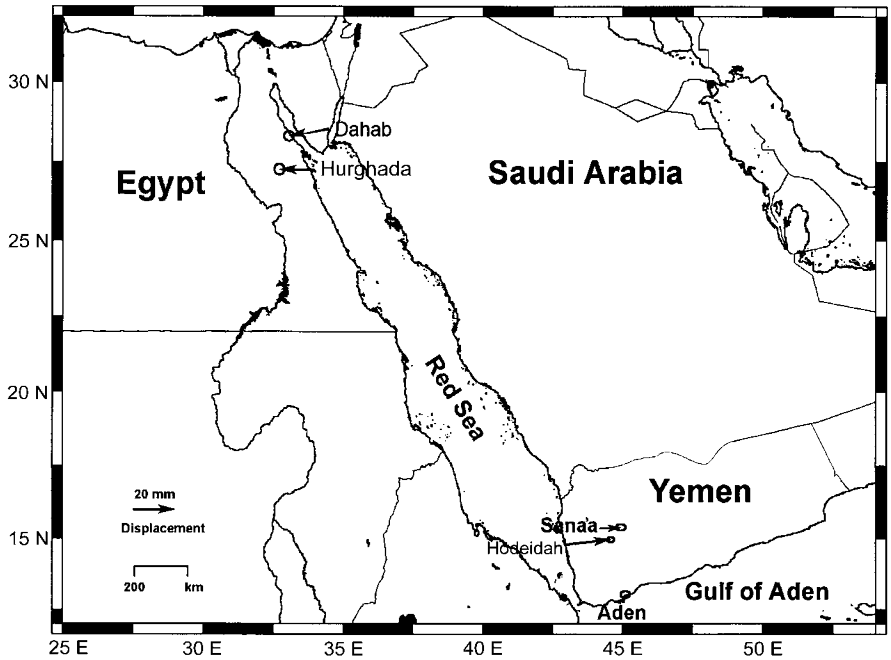

Fig. 4. Horizontal displacement for GPS network in Egypt and Yemen in the period from April 2000 to October–November 2001 (O – error ellipses are indicated).

The adjustment and analysis of Egypt and Yemen networks have been also done separately. The displacement vectors at each GPS station are determined under an assumption that free network adjustment and all the stations in the networks are minimized. The displacement vectors of GPS stations in Egypt and Yemen networks are given in Table 2 and Figs. 5 and 6, respectively.

The horizontal movement seems to be not significant in Egypt, as shown in Fig. 5, while it is significant in Yemen and takes opposite directions between Sana'a and Aden as shown in Fig. 6.

8. DISCUSSION AND CONCLUSIONS

The tectonic active areas were determined by geodetic measurements and compared with geological situation. The rates of movement are especially important at the lines and distances crossing the faults where the dynamic activity can be expected. The strong earthquake in a seismic area can follow the increase of rates of movements as well as strong increase of horizontal deformation (Vyskočil, 1984).

Table 2

GPS stations in Egypt (A) and in Yemen (B), and estimated horizontal displacements for the epoch from April 2000 to October–November 2001

A

Station	Station coordinates		Rate of displacement and standard deviation				Displace-ment [mm]	Direction
	longitude	latitude	d_E [mm]	Std	d_N [mm]	Std		
Dahab	34°28′11″	28°31′43″	–0.03	0.23	0.56	0.31	5.61	356.9335°
Hurghada	33°49′56″	27°14′39″	–0.53	0.23	0.23	0.25	5.78	293.4590°
University	32°52′06″	24°00′07″	0.56	0.22	–0.79	0.29	9.68	144.6686°

B

Station	Station coordinates		Rate of displacement and standard deviation				Displace-ment [mm]	Direction
	longitude	latitude	d_E [mm]	Std	d_N [mm]	Std		
Sana'a	44°11′25″	15°20′53″	–2.20	0.24	–2.13	0.11	3.062	225.9262°
Aden	45°2′ 23″	12°48′44″	2.71	0.24	1.54	0.11	3.117	60.39197°
Hodeidah	42°57′13″	14°46′09″	–0.55	0.48	0.34	0.22	0.647	301.7236°

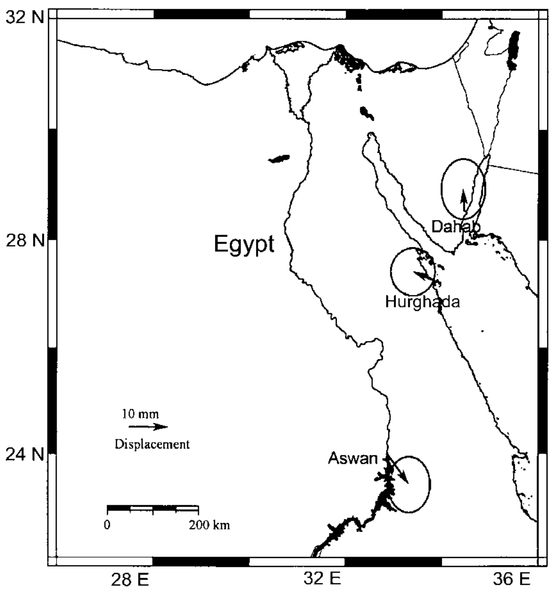

Fig. 5. Horizontal displacement of Egypt network from April 2000 to October–November 2001 (O – error ellipses are indicated).

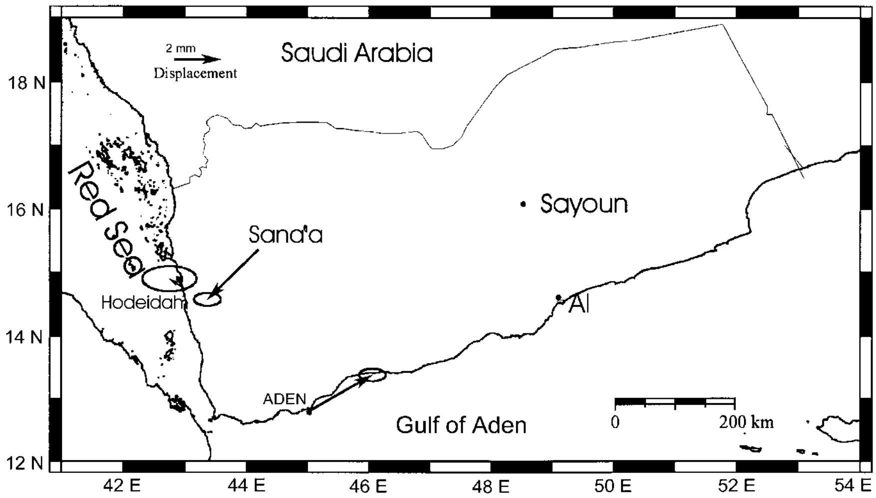

Fig. 6. Horizontal displacement of Yemen network from April 2000 to October–November 2001 (O – error ellipses are indicated).

Contrary to the geological research, the studies of crustal deformation are based on analysis of repeated geodetic measurements and their combination with results of other geophysical investigations. Monitoring the rate of the crustal deformations is considered as valuable information about the seismic activity. This information could benefit seismic hazard assessment and minimize the losses due to earthquake damage or other disastrous events. The results of the movement at all geodetic benchmarks in Egypt and Yemen represent the primary form of the dynamic model for the deformations occurred during the different epochs of measurements.

Red Sea region may be considered as a territory of moderate earthquake activity. The seismicity is concentrated along the Red Sea rift, Gulf of Aqaba and Gulf of Aden.

Geodetic measurements using Global Positioning System are important for detecting crustal deformation in the Red Sea region and the results obtained from these measurements are agreement with the tectonic setting and direction of spreading rate of the Red Sea. The period of measurements is relatively short and further measurements will give good information about the situation of the crustal deformation of the region.

Study of the crustal deformation of the Red Sea region in detail demands establishment of many new geodetic points in the other countries around the Red Sea (Saudi Arabia, Sudan, and Somalia) and repeated GPS measurements for the all stations at the same time.

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