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The present-day stress field in Egypt

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Abstract
The present-day stress field has been investigated by the analysis of the directions of maximum horizontal stress (σ_1) inferred from earthquake focal mechanisms and borehole breakouts in Egypt. The results indicate that strike-slip and normal faulting movements characterize the majority of the earthquake focal mechanisms; only a few events are of reverse faulting type. The analysis of 35 mechanisms suggests that the present-day stress field in Southern Egypt is dominated by a strike-slip stress regime (SS) and it is mainly transtensional (NS: normal faulting with strike-slip component) in Northern Egypt. The orientation of *P*-axes reflects that the maximum horizontal stress (σ_1) in Southern Egypt is uniform and aligned to nearly E-W direction while in Northern Egypt it is aligned with an even mix of NW-SE and nearly E-W compression. Along the Gulf of Aqaba, the southern part of the Dead Sea Fault (DSF), the focal mechanism solutions indicate that the maximum horizontal stress is presently oriented NW-SE, corresponding to a strike-slip mechanism in concert with geological evidence. More detailed investigations have been performed for the Gulf of Suez. We compare our results to the near-surface stress measurements from borehole breakouts to see if there is a change in orientations with depth. Shallow stress directions derived from borehole breakouts are not consistent with the deep stress directions derived from earthquakes focal mechanisms. About 73% of 30 borehole breakouts measurements indicate NW-SE alignment of the maximum horizontal stress and 27% are ENE-WSW. The direction of σ_1 inferred from the focal mechanism solutions is changing from NE-SW to ENE-WSW. Therefore, at least in this area, the stress direction is not constant throughout the crust.

Key words *stress field – focal mechanisms – breakouts – stress regime – Egypt*

1. Introduction

The present-day stress field in Egypt is of importance to understand the tectonics of the Northern Red Sea - Gulf of Aqaba plate boundary, the possible existence of an active Sinai subplate, the present level of tectonic activity in the Gulf of Suez rift and the impact of the Mediterranean subduction/plate convergence on the North Africa passive continental margin. The state of stress in the lithosphere is controlled by local forces (*i.e.* stress concentration due to structure heterogeneity, crustal loading, and asthenosphere thermal anomalies) and regional more uniform forces directly related to the plate motion and interaction (*i.e.* ridge-push, viscous shear force at the asthenosphere-lithosphere boundary). Local variations in stress orientations and relative magnitudes exist at a variety of scales and may be due to several forces acting on the lithosphere (Forsyth and Uyeda, 1976; Richardson *et al.*, 1979; Zoback, 1992; Badawy, 1996; Badawy and Horváth, 1999a).

It is difficult to estimate the magnitude of stress from geological data. However, there are different categories of geological and geophysical data that allow the determination of the magnitude and orientation of the stress tensor. Although the absolute stress magnitude information was available only for limited regions, information on relative stress magnitude or stress

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regime could be inferred from earthquake focal mechanisms and *in situ* stress measurements.

The stress tensor is defined using standard notation with compressive stress positive when $\sigma_1 > \sigma_2 > \sigma_3$. Furthermore, σ_v indicates the vertical stress, while σ_1 and σ_3 stand for the maximum and minimum horizontal stress respectively. Following Anderson (1951) three stress regimes can be defined on the basis of relative stress magnitudes: 1) extensional stress regime ($\sigma_v = \sigma_1$) corresponding to normal dip-slip fault; 2) strike-slip regime ($\sigma_v = \sigma_2$) corresponding to faulting with horizontal slip, and 3) thrust faulting stress regime ($\sigma_v = \sigma_3$) corresponding to reverse dip-slip faulting. The stress field can be transitional between the above regimes if two of the stresses are approximately equal in magnitude. A stress field of the form $\sigma_v = \sigma_1 > \sigma_3$ can produce a combination of both normal and strike-slip faulting, whereas a stress field of the form $\sigma_1 > \sigma_v = \sigma_3$ produces a combination of strike-slip and thrust faulting. Another possible end member for stress magnitude $\sigma_1 = \sigma_3$ is radial compression or radial extension depending on whether the horizontal stress is greater or less than the vertical principle stress respectively.

The World Stress Map (WSM) project provided unique database on the orientation and relative magnitudes of the stress field in the Earth's lithosphere (Zoback, 1992). This project has made a large amount of crustal stress data available and accessible for many regions all over the world. However, it is not the case for Northern Africa where the stress information is relatively absent. Therefore, the purposes of this study are twofold: to reconstruct the present-day stress field in Egypt to fill the gap on stress information in Northern Africa and, additionally, to compare the shallow and deep crustal stress orientations on the basis of new borehole breakouts and earthquake focal mechanisms in the Gulf of Suez.

2. Tectonic framework and seismicity of Egypt

The analysis of the geological history of Egypt in the framework of global tectonics suggests that most of the major geological features can be explained in terms of the interaction of global tectonics. Egypt entered the Phanerozoic during a period of rapid continental growth through Pan African arc accretion. Phanerozoic rocks are dominated by relatively undeformed and unmetamorphosed sedimentary strata, with the most intense tectonic activity and, in fact, responsible for modern continental margins of the Northeast Africa. At the end of Pan African continental growth, Egypt was at mid-latitude in the southern hemisphere. The Red Sea and Eastern Mediterranean had not formed and Egypt was a continuous continental mass with Saudi Arabia to the east and Turkey to the north on the southwestern corner of Gondwanaland. The Paleozoic was a period of relative stability in the Egyptian geologic record following major late Precambrian/early Cambrian Pan African activity. Sedimentation for most of the Paleozoic was controlled by global eustatic sea-level changes, with clastic sediments probably derived primarily from Pan African highlands. The start of Mesozoic was accompanied by tectonic and magmatic activity continuous from the end of the Paleozoic, whereas, the end of the Mesozoic and the end of Cenozoic appear to reverse this continental growth with rifting first from the north coast (Mediterranean Sea), then from the east coast (Red Sea). Egypt therefore appears to be entering a new phase of the Wilson cycle of opening and closing of oceans (Morgan, 1990).

Since basement rocks are the oldest rocks in Egypt, they are expected to record all tectonic events affecting Egypt since early Precambrian to the present. The best geophysical tool for mapping tectonic trends of deeply buried basement rocks is magnetic. A magnetic trend statistical analysis using results of all aeromagnetic surveys in Egypt (Meshref, 1990) yields several tectonic trends that have affected throughout its history: N-S (Nubian or East African trend); N-NE (Aqaba trend); E-W (Tethyan trend); W-NW (Darag trend); E-NE (Syrian Arc trend); NW (Red Sea or Suez trend) and NE (Aualitic trend).

Local seismicity provides us with a wealth of data containing detailed information on both the structures and the stress field acting now in the area under study. The latter phenomenon is preferentially studied by investigating the mechanisms of seismic sources. Egypt is considered to be one of the few regions of the world where evidence of earthquake activity has been documented for the last 5000 years (Badawy, 1996, 1999). Although information of historical earthquakes is documented, it cannot be regarded as complete since much of the older Egyptian literature was lost creating gaps in the earthquake record. Moreover, earthquake shows dating differences among different authors (Poirier and Taher, 1980).

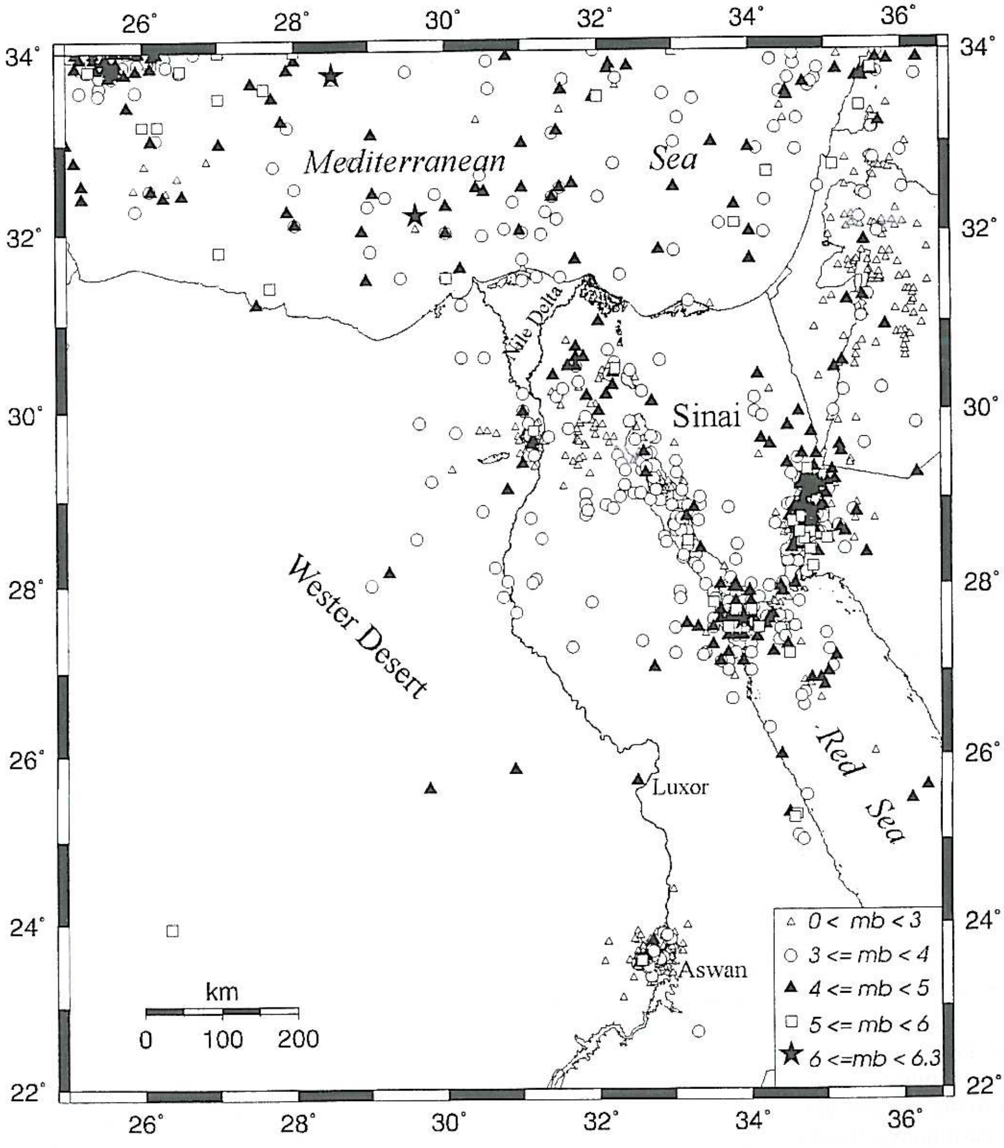

Fig. 1. Seismicity map of Egypt from 1900 to 1999 (ISS data files from 1900 to 1963 and ISC data files from 1964 to 1999).

The instrumental recording of earthquakes started in Egypt as early as 1899 at Helwan observatory. However, the first study of the local and micro-earthquakes recorded by Helwan seismic station was given by Ismail (1960).

The spatial distribution of earthquake epicenters in Egypt (fig. 1) suggests that the main activity occurred in northern part of the Egyptian territory. The relative motion of the Sinai subplate with respect to the Arabian plate (Gulf of Aqaba and Dead Sea) and to the African plate (Gulf of Suez) represents the main source of this seismic activity. Therefore, earthquakes that occur in Northern Egypt are mainly related to the plate boundaries (Badawy, 1996, 1998; Badawy and Horváth, 1999b). Actually, on basis of earthquake distribution, Egypt can be divided into two tectonic provinces: Northern Egypt (north of 27°N) and Southern Egypt. The first province is more seismically active than the second. Moreover, the stress regime and orientations throughout the two provinces are totally different.

3. Stress indicators

Different types of geological and geophysical data are used to infer tectonic stress information: earthquake focal mechanisms, borehole breakouts, *in situ* stress measurements (hydraulic fracturing and overcoring) and observation of recent striation and alignment of volcanic feeders. Quite often different types of data suggest that one of the principal stress axes (σ_1, σ_2, σ_3) is close to vertical. In this case the direction of the stress ellipsoid can be defined by specifying the azimuth of one of the horizontal principal axes (Zoback, 1992).

The different stress indicators provide data on stress magnitude and orientation over considerable depth ranges. For example, the geologic data (fault slip and alignments of volcanic feeders) suggest information about often active near to the surface, whereas, borehole breakouts and earthquake focal mechanisms are used to derive stress information in the upper and the lower crust respectively.

3.1. *Borehole breakouts*

In situ stress measurements are used to determine the direction and magnitude of the local stress at the surface and at various depths. These measurements include borehole breakouts, hydraulic fractures and overcoring.

Although the breakout analysis was established as a reliable stress determination technique only in the last two decades, it probably represents the greatest potential for producing new data especially in relatively aseismic regions. The analysis technique was first described by Cox (1970) and later Babcock (1978) extended his initial analysis to greater number of wells. For the first time, Bell and Gough (1979) interpreted these fractures as a stress-related phenomenon. The identification and interpretation techniques of well bore breakouts have been described in detail in numerous publications (*e.g.*, Zheng *et al.*, 1989; Bell, 1990; Zoback, 1991).

The borehole breakout data are especially important because they generally sample a depth interval intermediate between earthquakes focal mechanisms, other *in situ* stress measurements and geological stress indicators. They also provide multiple observations over considerable depth ranges (Zoback, 1992).

During the last three decades an intensive hydrocarbon exploratory drilling has been carried out in Egypt. Most of exploratory wells are in the Gulf of Suez region and many of them have adequate logs for breakout analysis. The elongation in well bore diameters in two orthogonal directions were normally measured by four-arm caliper moving from the bottom to the top of the well during routine dip logging surveys. In a vertical well which penetrates an isotropic rock column, borehole breakouts will form in the direction of the minimum horizontal (σ_h) stress (Gough and Bell, 1982; Plump and Hickman, 1985; Zheng *et al.*, 1989). Therefore, the direction perpendicular to the borehole elongation, which results from the breakouts, will indicate the direction of the maximum horizontal (σ_H) stress (Aadnoy, 1990).

Thirty borehole breakout observations are available in the Gulf of Suez region (table I and fig. 2a,b). We followed the rank of the World Stress Map project (Zoback, 1992). The data

Table I. Borehole breakouts stress data in the Gulf of Suez.

No.	Lat. (°) N	Long. (°) E	Azimuth of σ_H	Depth (km)	Quality (Q)
1	27.70	33.50	118	2.99	B
2	28.00	33.36	108	2.70	D
3	27.90	33.50	102	0.77	B
4	27.87	33.49	115	0.94	B
5	27.80	33.70	111	2.29	C
6	27.43	33.68	117	1.78	C
7	27.83	33.70	111	2.97	B
8	27.57	33.71	106	3.18	C
9	27.71	33.76	127	0.79	C
10	27.37	33.82	87	1.50	B
11	27.32	33.79	89	1.35	B
12	27.43	33.73	110	1.69	B
13	27.55	33.75	106	0.79	B
14	27.58	33.70	95	0.95	B
15	27.65	33.73	125	1.38	C
16	27.73	33.84	85	0.88	B
17	27.74	33.45	115	1.64	B
18	27.69	33.75	165	2.35	D
19	27.75	33.72	135	2.15	C
20	27.82	33.52	75	1.25	B
21	27.85	33.47	112	0.79	B
22	27.79	33.30	118	3.12	B
23	28.15	33.25	123	0.89	C
24	27.88	33.92	88	1.45	B
25	27.71	33.65	126	2.30	C
26	27.80	33.53	79	1.25	B
27	27.93	33.52	114	3.00	B
28	27.62	33.64	83	0.73	B
29	27.72	33.70	145	2.25	C
30	27.74	33.65	124	0.94	B

Lat. (°): latitude in degrees. Long. (°): longitude in degrees. Depth: the mean depth of breakout occurs in a well. Quality B: at least six distinct breakout zones in a single well and/or an average of breakouts in two or more wells in close geographic proximity with combined length > 100 m; both with SD < 20°. Quality C: at least four distinct breakout zones in a single well and/or an average of breakouts in two or more wells in close geographic proximity with combined length > 30 m; both with SD < 25°. Quality D: less than three consistently oriented breakouts or < 30 m combined length in a single well with SD > 25°.

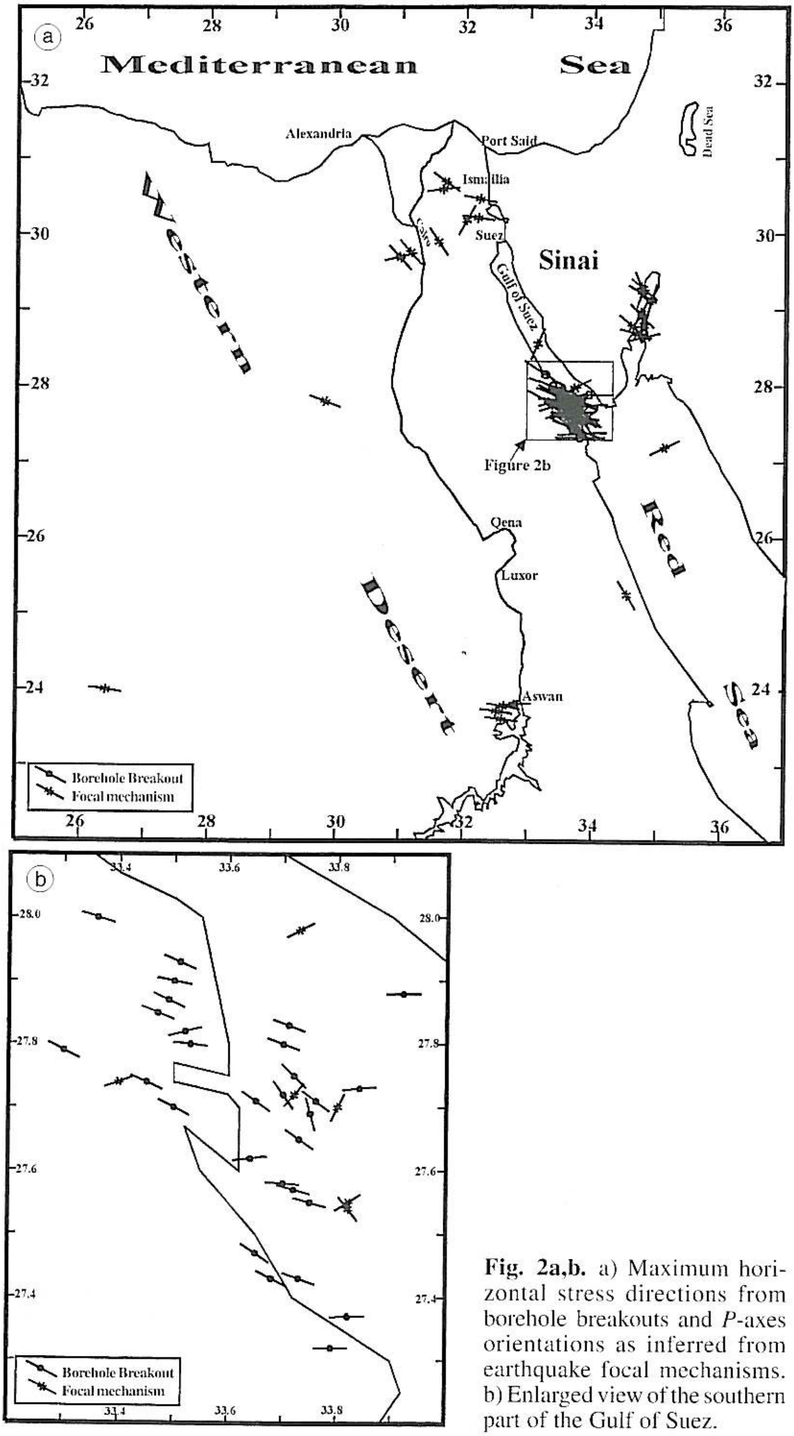

Fig. 2a,b. a) Maximum horizontal stress directions from borehole breakouts and *P*-axes orientations as inferred from earthquake focal mechanisms. b) Enlarged view of the southern part of the Gulf of Suez.

have been classified on a scale from A to D with A representing the highest quality. The bulk of the measurements have a B quality (19 observations, 63.3%), 9 observations have a C quality (30%) and 2 observations have a D quality (6.7%).

3.2. *Fault plane solutions*

Earthquake focal mechanisms are used as a basic tool in the determination of regional stress. Although the focal mechanism solutions are the most abundant stress indicators in the World Stress Map (58%) they are affected by the ambiguity described by McKenzie (1969). However, the focal mechanism solutions of moderate and large earthquakes can appear as a first order information on the orientation of the regional stress. The average direction of *P* and *T* axes from a number of focal mechanism solutions are generally good indicators of regional largest (σ_1) and least (σ_3) stress directions as suggested by numerous authors (*e.g.*, Raleigh *et al.*, 1972; Smith, 1977; Eaton, 1979; Mercier *et al.*, 1979; Zoback and Zoback, 1980; Gephart and Forsyth, 1984; Philip, 1987; Badawy, 1996; Badawy and Horváth, 1995, 1999a).

For the definition of stress regimes, the threshold values of the plunge of the *P*, *B* and *T* axes can be used (Zoback, 1992). The stress regime categories are based on Anderson's (1951) classification: NF (normal fault), NS (predominately normal faulting with strike-slip component), SS (strike-slip fault), TS (predominately thrust faulting with a strike-slip component) and TF (thrust fault). If the axes do not fit into these categories, the stress regime is assigned undetermined (U).

Thirty-five focal mechanisms for earthquakes have been determined by using *P*-wave polarities technique for events with body wave magnitude greater than 4.0. The bulletins of the International Seismological Center (ISC) are used for the polarity information. A stereographic projection of *P*-wave polarities from different stations (with their azimuths and corresponding incident angles) on the lower half-hemisphere is used in this study. The quality of these focal mechanism solutions fall into three categories A, B and C, depending on the earthquake magnitude and reliability of each solution (where A representing the highest quality). The polarity observations of all focal mechanisms are shown in fig. 3. Both the azimuth and plunging of the principle stress axes (*P*, *B* and *T*) are given in table II.

4. Present-day stress field

The azimuth of the maximum horizontal stress from borehole breakouts and *P*-axes from earthquakes focal mechanisms are shown in fig. 2a,b. From this map we can speculate that the alignment of the maximum horizontal stress is changing from NW- SE to nearly E-W all over the studied area. However, there are remarkable deviations from this general trend. This non-uniform stress orientation may be attributed either to depth variation or to the quality of these stress indicators. In Northern Egypt the maximum horizontal stress direction varies between NW-SE and nearly E-W compression. However, in Southern Egypt (Aswan region) it is uniform and aligned to nearly E-W direction. Throughout the Gulf of Aqaba, the directions of the maximum horizontal stress are mostly oriented NW-SE. This orientation is consistent with the strike-slip tectonics along the Dead Sea Fault.

Strike-slip and normal faulting movements characterize the majority of the earthquake focal mechanisms; only a few events are of reverse faulting type (fig. 4). The analysis of earthquake focal mechanisms, in comparison with borehole breakouts and geological stress information, indicates that the present-day stress field in Northern Egypt is mainly transtensional (NS: predominately normal faulting with strike-slip component) and Strike-slip regime (SS) in Southern Egypt (fig. 3, table II).

The depth distribution of maximum horizontal stress in the Gulf of Suez is shown in fig. 5a,b. It is clear that within the crust the stress orientations are not constant and there is no correspondence between the shallow stress directions (borehole breakouts, fig. 5a) and deep stress directions (earthquake focal mechanisms, fig. 5b). About 73% from 30 borehole breakouts meas-

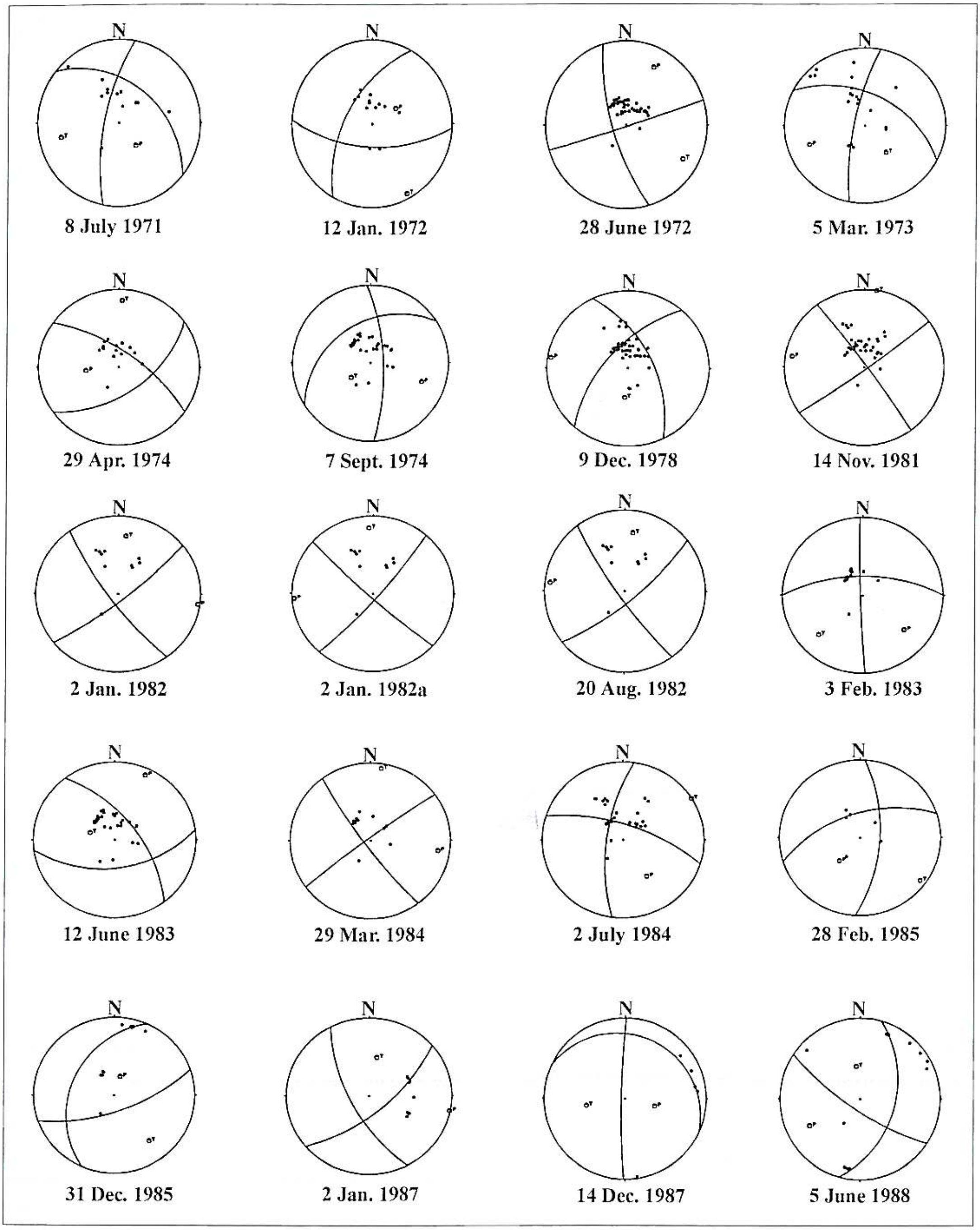

Fig. 3. Fault plane solutions in Egypt (1970-1997) for earthquakes of magnitude greater than 4.0. The polarity observations at each station are shown as dots, open if the polarity was dilatational and solid if it was compressional.

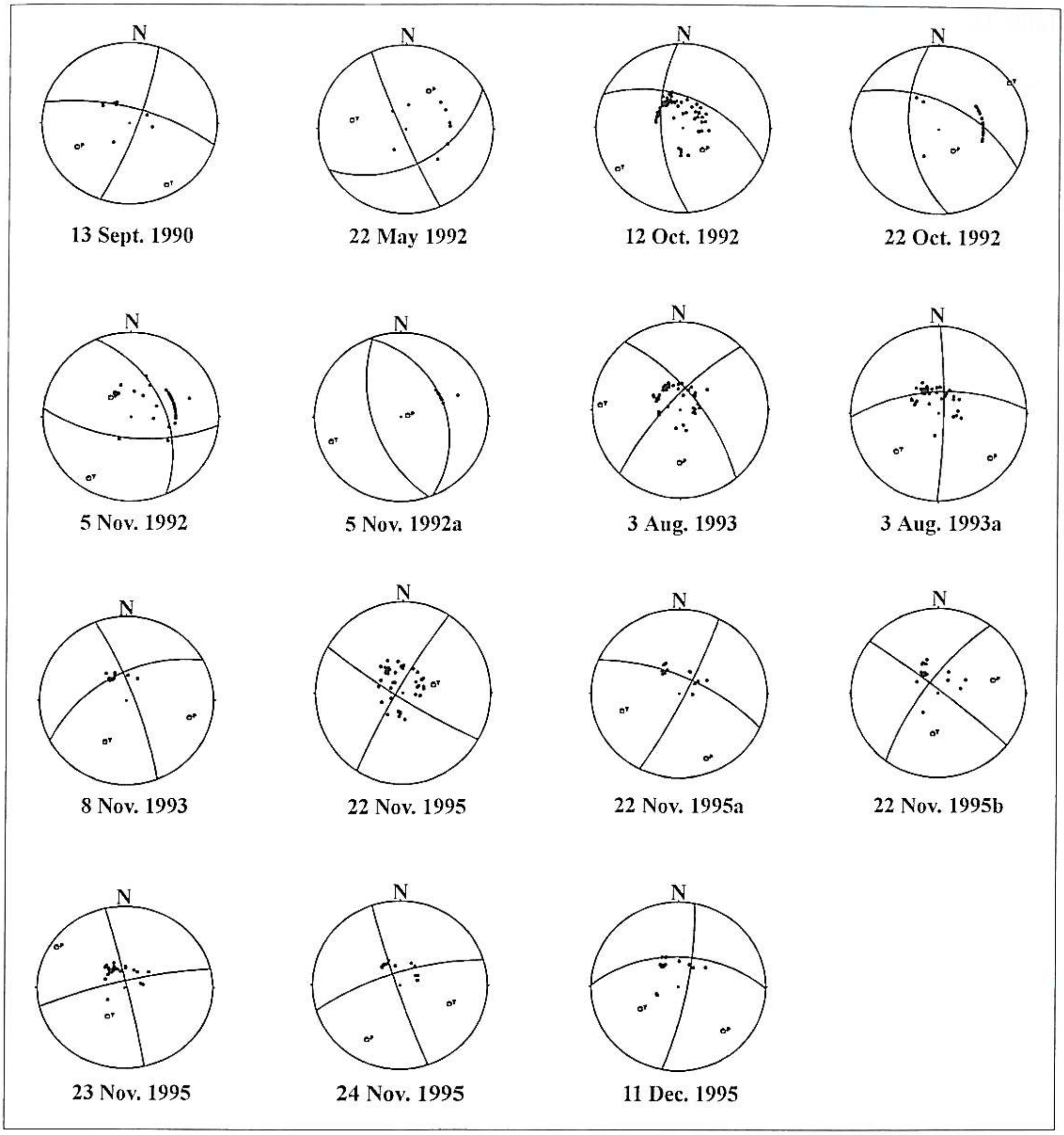

Fig. 3 (*continued*).

urements reflect NW-SE alignment for σ_1 with a vector average of 120° and 27% are ENE-WSW with a vector average of 85°. While, the direction of σ_1 inferred from the focal mechanism solutions is changing from NE-SW to ENE-WSW.

5. Discussion and conclusions

The main objective of the current paper is the determination of the present stress in Egypt on the basis of earthquake focal mechanisms

Table II. Azimuth and plunging of principal stress axes (*P*, *B* and *T*) from earthquake focal mechanisms.

No.	Day	Month	Year	Lat. (°) N	Long. (°) E	M_b	*P*-axes Azm.	*P*-axes Pl.	*B*-axes Azm.	*B*-axes Pl.	*T*-axes Azm.	*T*-axes Pl.
1	08	07	1971	27.54	33.82	4.8	142	53	358	32	257	18
2	12	01	1972	27.55	33.82	5.1	58	52	245	38	152	4
3	28	06	1972	27.70	33.80	5.5	26	15	247	70	120	12
4	05	03	1973	27.74	33.40	4.6	250	18	357	41	143	43
5	29	04	1974	30.59	31.64	4.8	264	45	102	44	3	9
6	07	09	1974	27.80	29.80	4.1	110	20	8	28	233	56
7	09	12	1978	24.00	26.39	5.2	278	2	10	41	186	49
8	14	11	1981	23.78	32.63	5.1	279	5	100	85	9	0
9	02	01	1982	23.71	32.52	4.2	98	1	192	74	7	10
10	02	01	1982a	23.80	32.80	4.0	266	2	167	81	357	9
11	20	08	1982	23.61	32.60	4.7	277	4	175	72	8	19
12	03	02	1983	29.27	34.78	4.8	130	4	28	71	227	17
13	12	06	1983	28.55	33.13	5.0	24	5	118	35	287	55
14	29	03	1984	30.21	32.19	4.8	99	9	258	80	8	4
15	02	07	1984	23.25	34.53	5.1	148	33	328	58	58	0
16	28	02	1985	27.72	33.72	4.5	221	47	32	43	126	5
17	31	12	1985	29.13	34.90	4.8	17	62	241	20	146	18
18	02	01	1987	30.46	32.22	5.0	101	1	192	53	11	37
19	14	12	1987	30.69	31.69	4.1	126	43	23	14	280	42
20	05	06	1988	27.98	33.73	4.5	242	20	136	38	352	46
21	13	09	1990	27.19	35.11	4.6	244	23	43	66	151	8
22	22	05	1992	30.18	32.01	4.5	30	35	162	44	280	26
23	12	10	1992	29.76	31.14	5.8	138	52	332	37	237	6
24	22	10	1992	29.90	31.57	4.2	146	57	324	33	55	1
25	05	11	1992	29.69	30.97	4.6	315	54	118	35	214	8
26	05	11	1992a	29.70	30.98	4.5	77	81	340	1	250	9
27	03	08	1993	28.78	34.75	5.8	181	28	13	61	274	5
28	03	08	1993a	28.79	34.59	5.4	131	14	13	61	228	24
29	08	11	1993	28.69	34.65	4.8	106	16	353	53	206	32
30	22	11	1995	28.81	34.80	6.1	166	0	257	80	76	50
31	22	11	1995a	29.30	34.74	5.1	158	11	48	66	252	22
32	22	11	1995b	28.64	34.77	4.9	77	24	323	72	187	38
33	23	11	1995	29.21	34.75	5.2	303	4	5	80	208	46
34	24	11	1995	28.97	34.74	4.9	210	16	328	72	111	27
35	11	12	1995	28.92	34.75	4.9	135	17	24	49	239	36

Lat. (°): latitude in degrees. Long. (°): longitude in degrees. M_b: body wave magnitude. Azm.: azimuth. Pl.: plunging.

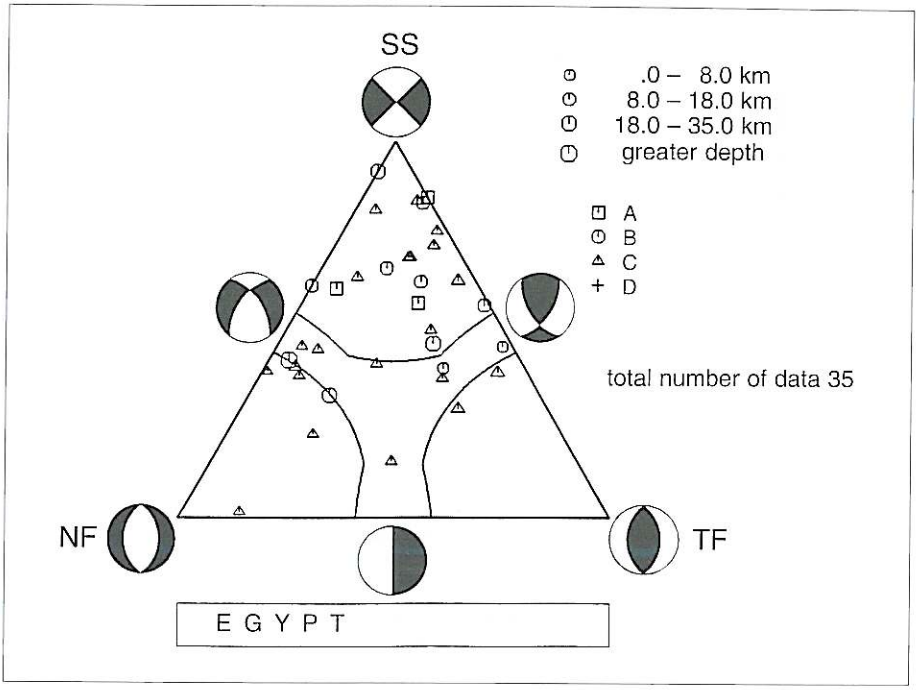

Fig. 4. Triangle diagram showing the distribution of different earthquake focal mechanisms. The classification of fault type according to WSM (Zoback, 1992) is SS: Strike-Slip; NF: Normal Fault, and TF: Thrust Fault. The different symbols and letters (A, B, C and D) indicate the quality of earthquake focal mechanisms (see the text), where A represents the highest quality. The symbol size is directly proportional to the depth of earthquakes.

and borehole breakouts measurements. Egypt is located in the northeastern part of the African plate. Although the motion of Africa in a hot-spot reference frame is very slow (Minster and Jordan, 1978), the absolute velocity trajectories can be determined. Zoback (1992) suggested that in Northeastern Africa and Arabia the trajectory is about N-S, bending progressively towards NW-SE. In addition to the absolute plate motion, the plate boundary forces remarkably control the intra-plate stress pattern (Forsyth and Uyeda, 1976; Richardson *et al.*, 1979; Zoback, 1992). In other words, the general stress pattern is consistent with the motion away from Atlantic and Indian Ocean spreading axes and collision to the north with Eurasia.

However, a remarkable deviation from this general trend has been found in Egypt where the orientation of the maximum horizontal stress is not uniform. In Northern Egypt it is even a mix between NW-SE and nearly E-W directions. A zone of NW compression along the northern boundary of the African plate was also suggested by many authors (*e.g.*, Badawy, 1990; Udias and Buforn, 1991, 1993; Rebai *et al.*, 1992; Zoback, 1992) consistent with the collision of Africa and Eurasia. In Southern Egypt the orientation of the maximum horizontal stress is relatively uniform and aligned to E-W direction. This trend can be considered as a spatial extension of the stress field present in the northern part of Central Africa suggested by Zoback (1992). Moreover, for Western and North Central Africa an approximately E-W orientation of maximum horizontal stress was observed in breakouts data from 11 wells covering an area of about 1000 km^2 in Sudan (Bosworth *et al.*, 1992).

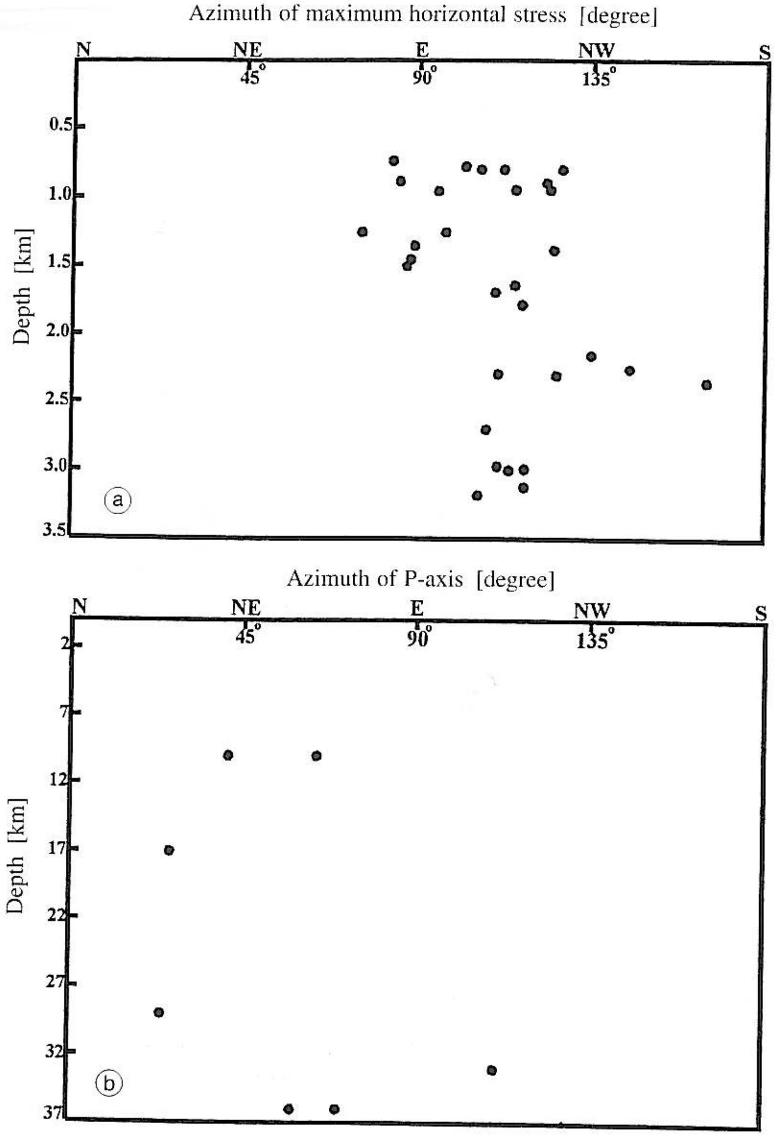

Fig. 5a,b. The depth distribution of maximum horizontal stress directions in the Gulf of Suez region: a) borehole breakouts; b) earthquake focal mechanisms.

In brief, the constrictive stress field and deformation in Egypt result from the combined effects of the collision between the Africa and Eurasia to the north and rifting to the east and southeast.

A comparison of shallow stress (borehole breakouts, fig. 5a) and deep stress directions (earthquake focal mechanisms, fig. 5b) along the Gulf of Suez indicates that within the crust the stress orientations are not constant. About

73% from 30 borehole breakouts measurements indicate NW-SE alignment of the maximum horizontal stress while six earthquake focal mechanisms show an even mix of NE-SW and ENE-WSW directions. This ambiguity in the stress orientations conforms with the two phases of rifting in the Gulf of Suez and Northern Red Sea region.

The paleostress pattern of the Gulf of Suez has been determined by many authors (*e.g.*, Lyberis, 1988; Steckler *et al.*, 1988; Bosworth and Strecker, 1997). Lyberis (1988) suggested that the extension direction changed from ENE-WSW to E-W from early Miocene to Plio-Quaternary. Bosworth and Strecker (1997) argued that the extension direction rotated from approximately NE-SW to NNE-SSW during the Pleistocene. Correlating the present-day stress pattern with the paleostress distribution, it can be speculated that the present stress along the Gulf of Suez is still under rotation. In the forthcoming work more comprehensive stress data base will be elaborated by new earthquake focal mechanisms especially after the installation of the Egyptian Seismological Network (ESN) that helps us to better understand the kinematics of active faults in this region.

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