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Statistical trend analyses of gravity data from Egypt and their tectonic significance

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ABSTRACT

This paper attempts to statistically identify the main tectonic trends in northern Egypt. Two methods were applied to the Bouguer anomaly map. The first method uses raw data derived from the Bouguer anomaly map; the second employs residual fields of Bouguer anomaly data. This investigation led the authors to identify seven principal tectonic trends.

The graphical-numerical technique identifies the extents of the major and minor trends, while autocovariance succeeded in picking seven trends at different depths. Two of these seven trends were recorded only at shallow depth. This means that forces creating them were active during recent geologic times. This phenomenon supports the concept that forces creating the Gulf of Suez, which is an extension of the Red Sea Rift, preceded the forces creating the Gulf of Aqaba whose tectonic extension lies towards the north in the Dead Sea.

Three major tectonic zones are recognised, each of which has different tectonic characteristics. These findings are supported by conclusions arrived at by other researches using different methodologies.

INTRODUCTION

This paper deals with the application of statistical techniques in the field of tectonics. More specifically, the paper examines the applicability of two techniques in the analysis of gravity field, namely the graphical-numerical and the two-dimensional autocovariance methodologies to yield values, for geologic dislocations and trends at different depths below ground.

It is not intended to provide a complete discussion of these techniques but a brief historical introduction will be given.

Graphical-numerical techniques began with the work of Buchheim & Lauterbach (1954) on the analysis of micromagnetic measurements of the earth and were developed further by Neuman (1954), Kaspar (1962), Affleck (1963), Mundt (1969) and Tealeb (1977). The two-dimensional autocovariance analysis was initiated by Horton *et al.* (1964) and expanded by Mundt (1969), Marcak (1973) and Tealeb (1977). Their work showed that this method can be employed successfully to differentiate between trend directions of deep-seated and shallow-seated tectonics. This method which uses different residual fields culminated from many techniques of trend elimination with polynomials of first and second orders (Agocs 1951; Zurmuhl 1957) and filter techniques (Kertz 1966).

Regardless of the methodology used, the analysed values of gravity variations can be obtained directly from either the Bouguer anomaly map or by interpolation.

REVIEW OF MAJOR STRUCTURES OF NORTHERN EGYPT

The area under investigation (Fig. 1) belongs to the unstable shelf area of Egypt (Said 1962) which was affected throughout its geological history by deformation and diamorphism. These forces led to the development of depressions, deposition of thick sedimentary successions and the formation of folds and faults. Said (1962), Youssef (1968) and Moody (1973), described these structures in four terms: Erythrean (NW–SE), Aualitic (NE–SW), East-African (N–S) and Tethyan (E–W) patterns.

Based on the analysis of the satellite photographs of Egypt, Halsey & Gardner (1975) identified two sets of tectonic trends: major and minor.

Major trends were:

(a) The Suez trend (N 35° W). This belongs to the Precambrian era and rejuvenated subsequently during Hercynian (Pre-Carboniferous), Laramide (Late Cretaceous) and Alpine (Late Tertiary) orogeny.
(b) The Aqaba trend (N 15° E). This trend belongs to the Late Tertiary orogeny.
(c) The Qattara trend (N 60° E). It is considered as a Precambrian trend and was reactivated during Hercynian and Laramide orogeny.

Minor trends were:

(a) Aualitic (N 40° E) trend: This trend is generally related to the dynamic history of Qattara as a second-order basement-rooted system.
(b) East African (N–S) trend. It is considered as a Late Tertiary age movement.
(c) Tethyan (E–W) trend. It is related to the Precambrian and Late Tertiary compressions.
(d) N 60° W trend. It was developed during upper Jurassic-Lower Cretaceous.

MATERIALS AND METHODS

THE GRAPHICAL-NUMERICAL TECHNIQUE

This technique was applied to the Bouguer anomaly map which was prepared by different international geophysical companies. The process of compilation was executed under the supervision of the General Petroleum Company of Egypt in 1967. A scale of 1:500000 and a contour interval of 1 $\mu m/s^2$ (mgal) were used. The raw Bouguer anomaly map is too bulky for inclusion in this paper. Based on the anomaly map and the morphological characteristics, the study area was divided into ten relatively homogeneous sectors.

The lengths and directions of anomalies (azimuth measured clockwise from the geodetic north) of the axes were measured. The lengths of the anomaly axes, weighted for fixed azimuth intervals (10°) were summed up and the relative frequency distributions were computed. These were plotted as Rose-diagrams and histograms respectively. The peak frequencies of the Rose-diagrams, or the common maximum

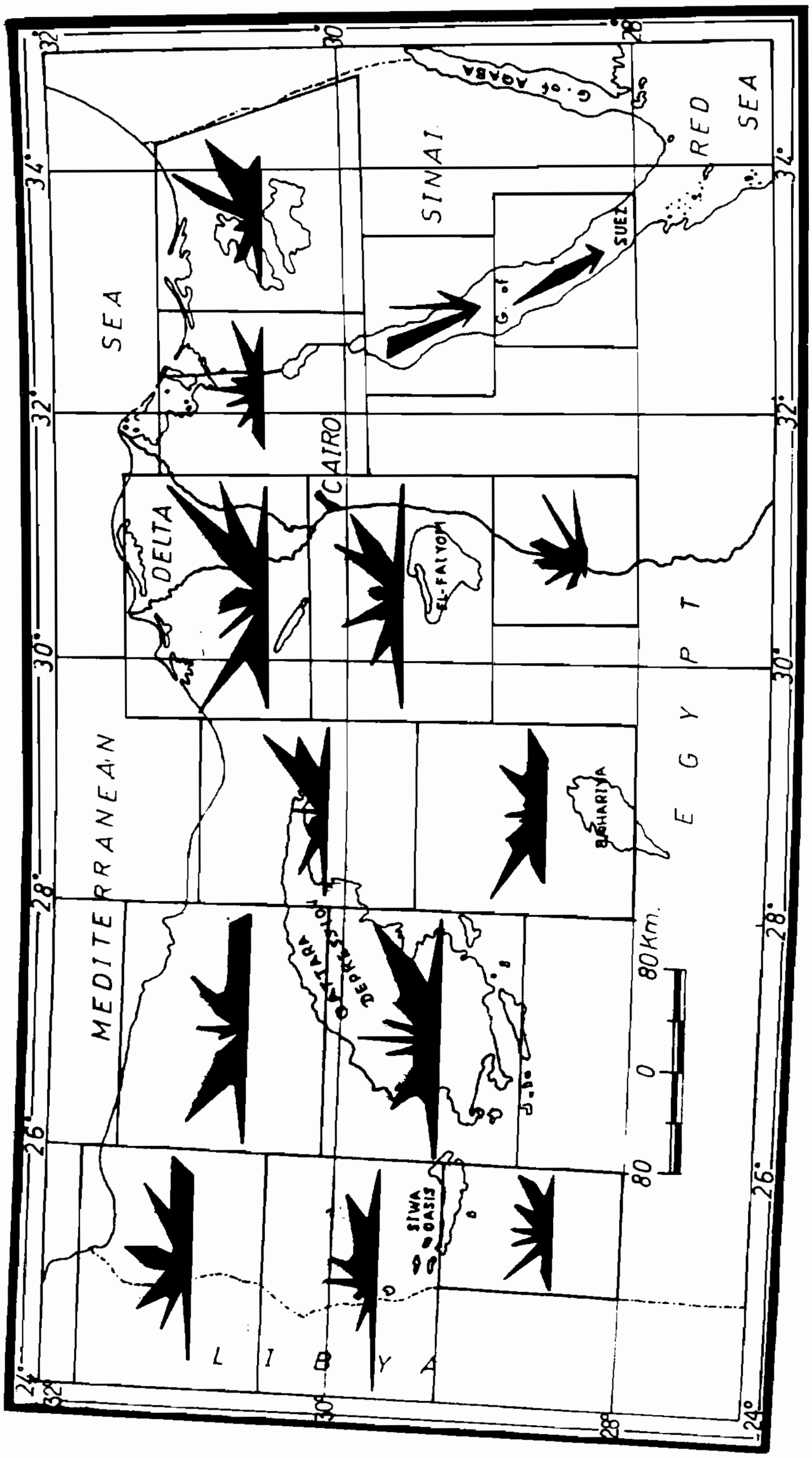

Fig. 1. Tectonic trends of the Bouguer anomaly of northern Egypt.

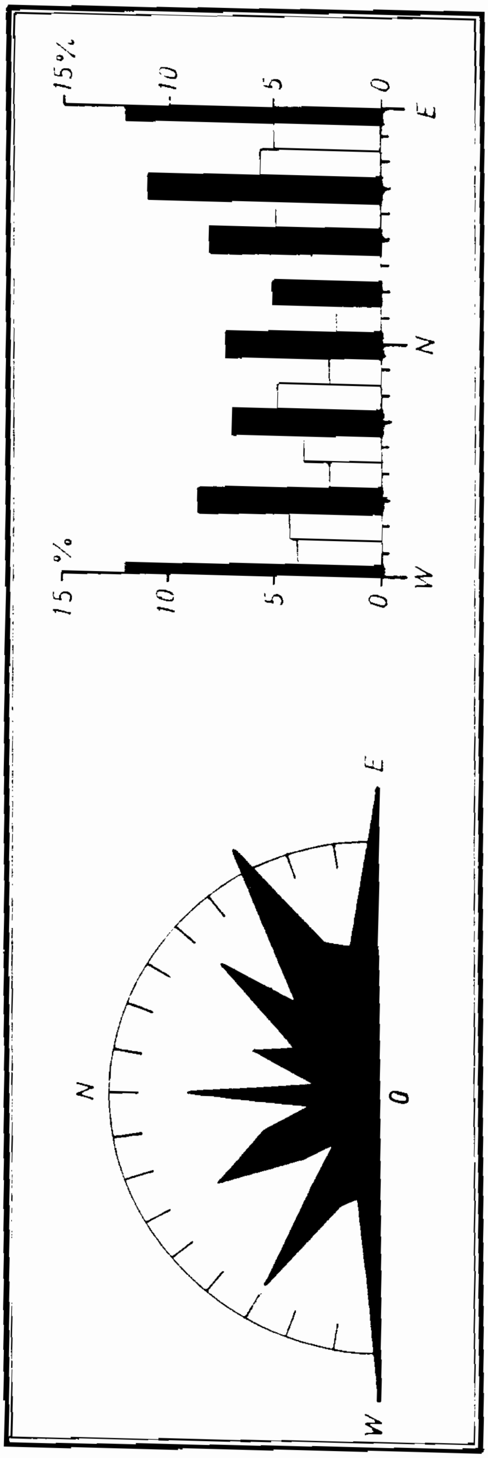

Fig. 2. Rose-diagram and histogram representing the predominant anomaly trends in northern Egypt.

of the histograms represent the predominant directional trends of the anomalies (Fig. 2).

THE TWO-DIMENSIONAL AUTOCOVARIANCE TECHNIQUE

This technique was not applied to the Bouguer anomaly map itself but to its residual fields. Each field reflects the gravity effects of different depth zones within the crust. These zones helped to recognize the direction trends predominant in the shallow and deep horizons. The analysis was carried out on the residual fields of 30 overlapped sub-areas, which covered all of the ten sectors under study.

For the calculations of both the residual fields and the autocovariance functions, a grid of the original Bouguer anomaly map values was digitized at 5 km intervals. To ensure the applicability of this technique, the size of the interval had to be related to one-half of the minimum wavelength of the gravitational anomaly in the region of northern Egypt.

The analysis includes two homogeneous residual fields obtained from low and high-pass filtering of the Bouguer anomalies (Kertz 1966; Tealeb 1977) and four homogeneous residual fields obtained after the elimination of linear and quadratic trends from both the Bouguer anomalies and its filtered gang (smoothed field) (Agocs 1951; Zurmuhl 1957; Tealeb 1977). The first residual field delineates shallow sources between 4 and 6 km while the second residual field delimits deep sources between 16 and 19 km. Thus, the analysis of these residual fields serves to predict the trend directions predominant in the shallow zones (sedimentary cover and basement surface) and the trend directions predominant underneath the basement surface. For discrete samples $f(X, Y)$ in square grid at regular intervals, the autocovariance functions $R(r, s)$ and $R(r, -s)$ have been used according to the definite equation by Horton *et al.* (1964).

$$R(r, s) = \frac{1}{(N-r)(N-s)} \sum_{X=1}^{N-r} \sum_{Y=1}^{N-s} f(X, Y) f(X+r, Y+s) \quad ,$$

$$R(r, -s) = \frac{1}{(N-r)(N-s)} \sum_{X=1}^{N-r} \sum_{Y=S+1}^{N} f(X, Y) f(X+r, Y-s) \quad ,$$

$$r, s = 0, 1, 2, \ldots, m \quad ,$$

where r and s are the possible displacements in the X and Y directions respectively, N^2 the number of samples and m the maximum permissible pitch of correlation ($m \leqslant \frac{1}{5}N$).

According to the symmetrical property of the autocovariance, the functions $R(-r, -s)$ and $R(-r, s)$ need not be computed, because $R(-r, -s) = R(r, s)$ and $R(-r, s) = R(r, -s)$.

The calculated autocovariance values were plotted against the variables r, s. A contour map was then constructed from these values. The direction of maximum autocovariance, e.g. high correlation, represents the predominant trend direction of the analysed anomalies (Fig. 3).

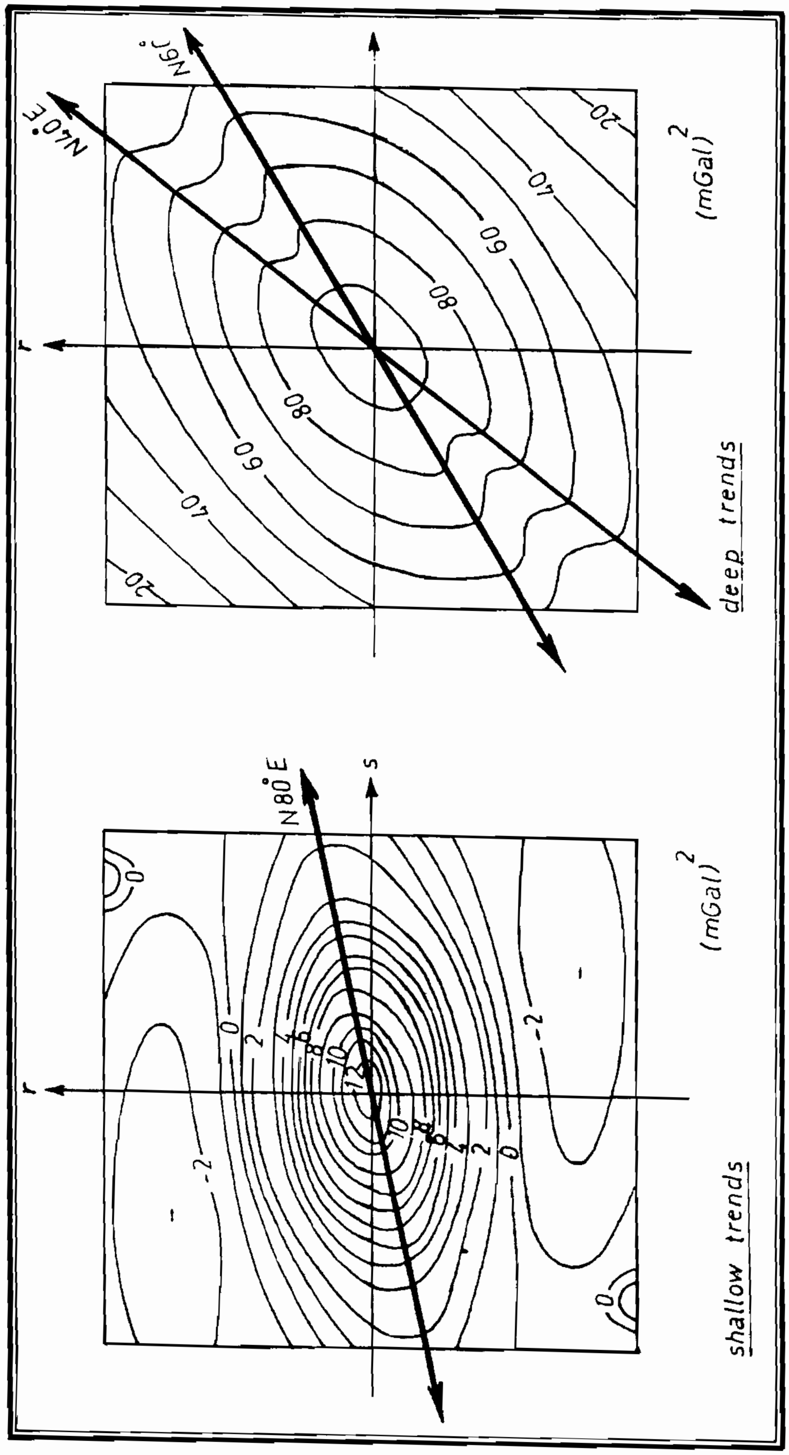

Fig. 3. Autocorrelation functions of two residual fields representing shallow and deep structures in northern Egypt.

TECTONIC SIGNIFICANCE OF THE INTERPRETED ANOMALY TRENDS

At this point, it is perhaps appropriate to say that the Bouguer anomaly map is a reflection of the following parameters:

(a) Thickness of the earth's crust, e.g. depth and relief of the Moho-surface.
(b) Thickness, petrographical state and structure of the individual strata of the earth's crust.
(c) Considerable tectonic dislocations in the earth's crust.

The tectonic trends identified in this paper fit smoothly in the established tectonic configuration of the region. In accordance with the recognized tectonics of the shallow and deep zones of the crust, northern Egypt is divided into three different tectonic regions which are outlined in Figs 4 and 5 by continuous and dashed lines.

In a few sectors, especially in the area between Latitudes 29° and 32°N, and Longitudes 24° and 30°E, the recorded directions of trends are mainly the same in both deep and shallow zones. In other sectors, a slight angle of shift of a few degrees (mostly 5–10°) is recorded. The agreement of trend directions in the different depth zones of the northern Egyptian crust provides a clear indication that these sectors have been affected throughout their geologic history by various unidirectional tectonic movements. The detection of the trend directions E–W, N 60° E, N 40° E, N 30° W and N–S, in both the deep and shallow zones is believed to be due to tectonic movements which followed the same direction throughout the geological history. These movements started in the Precambrian and were rejuvenated in the late geological times, possibly during Late Tertiary. This was supported by the work of Abdelhady, Tealeb & Sabry (1981) who used seismic and logging data. The other trends recorded in the N 60° W and N 20° E directions are thought to be due to tectonic movements which affected the area in Late Tertiary after the deposition of a thick column of sedimentary rocks in huge geosynclinal areas.

Generally speaking, it is well known that the areas of Africa, Europe and Asia were affected by different tectonic movements which began as early as the Paleozoic and continued until Late Tertiary with the evolution of the old Tethys (McKenzie 1970; Dewey *et al.* 1973). Such movements and interactions resulted in the development of different tectonic plates and zones. Complex interaction between the different plates in Europe, Africa and Asia were considered by McKenzie (1970) to be still active between a number of adjacent microplates.

The trend predominant in the N 30° W (Suez) direction was recorded in both the deep and shallow zones, whereas the trend in the N 20° E (Aqaba) direction was recorded in the shallow zones only. These results indicate that the Suez trend direction is possibly older than the Aqaba trend direction. The movements which contributed to the Suez trend direction started in the Precambrian era and were rejuvenated during the Late Tertiary, whereas the Aqaba trend direction was possibly developed during the Late Tertiary.

From the tectonic point of view, the Suez and Aqaba trend directions were considered as two ideal fracture (shear) systems which may result from a northern horizontal compressive force oriented in N 10° W direction (Youssef 1968; Halsey & Gardner 1975). This concept was rejected by Ben-Menahem *et al.* (1976). On the basis of the analysis of different recent earthquakes, they suggest a simple tectonic picture in which left lateral motion with compression occurs along N–E trending

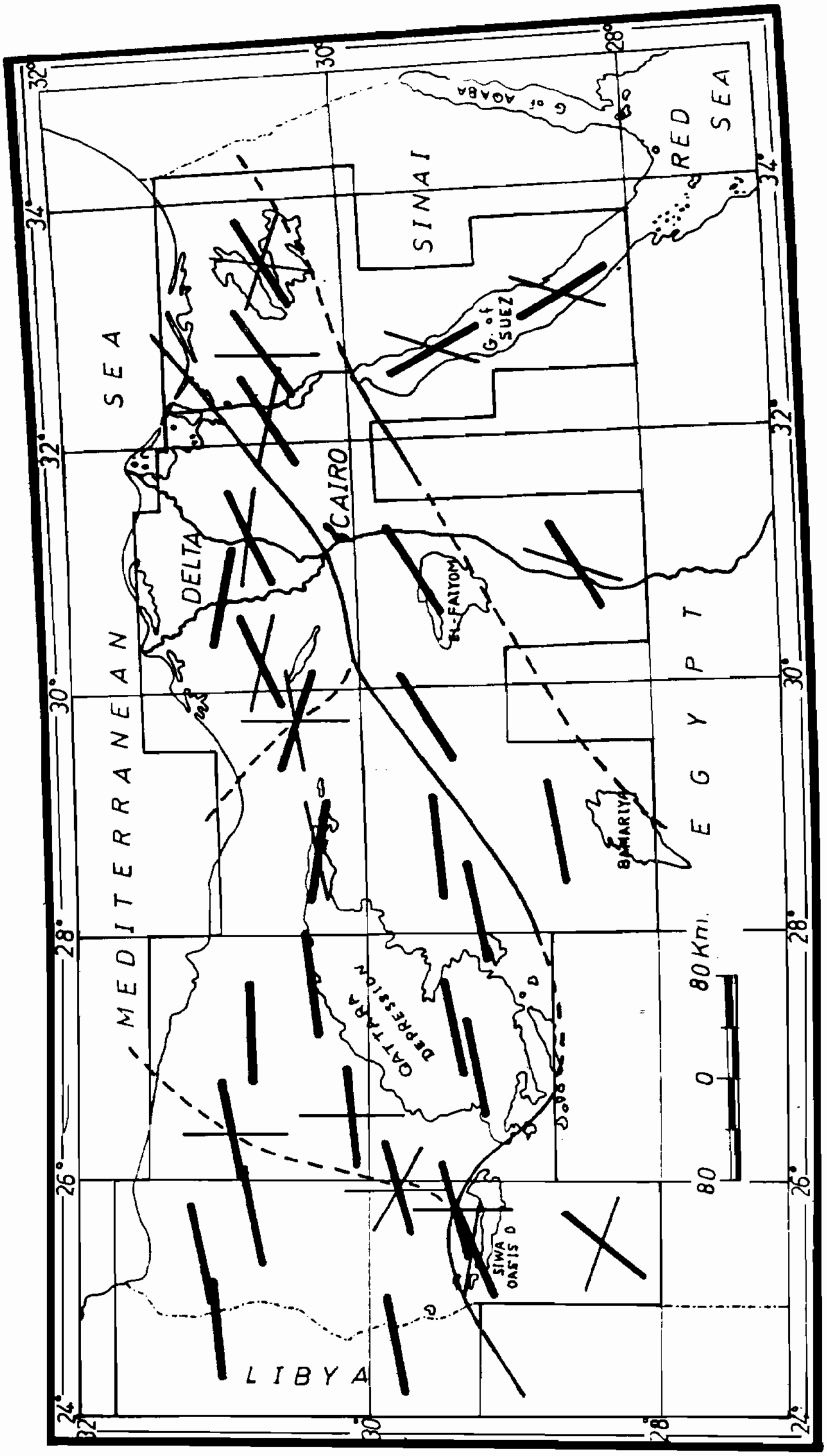

Fig. 4. Trends of the shallow structures in northern Egypt.

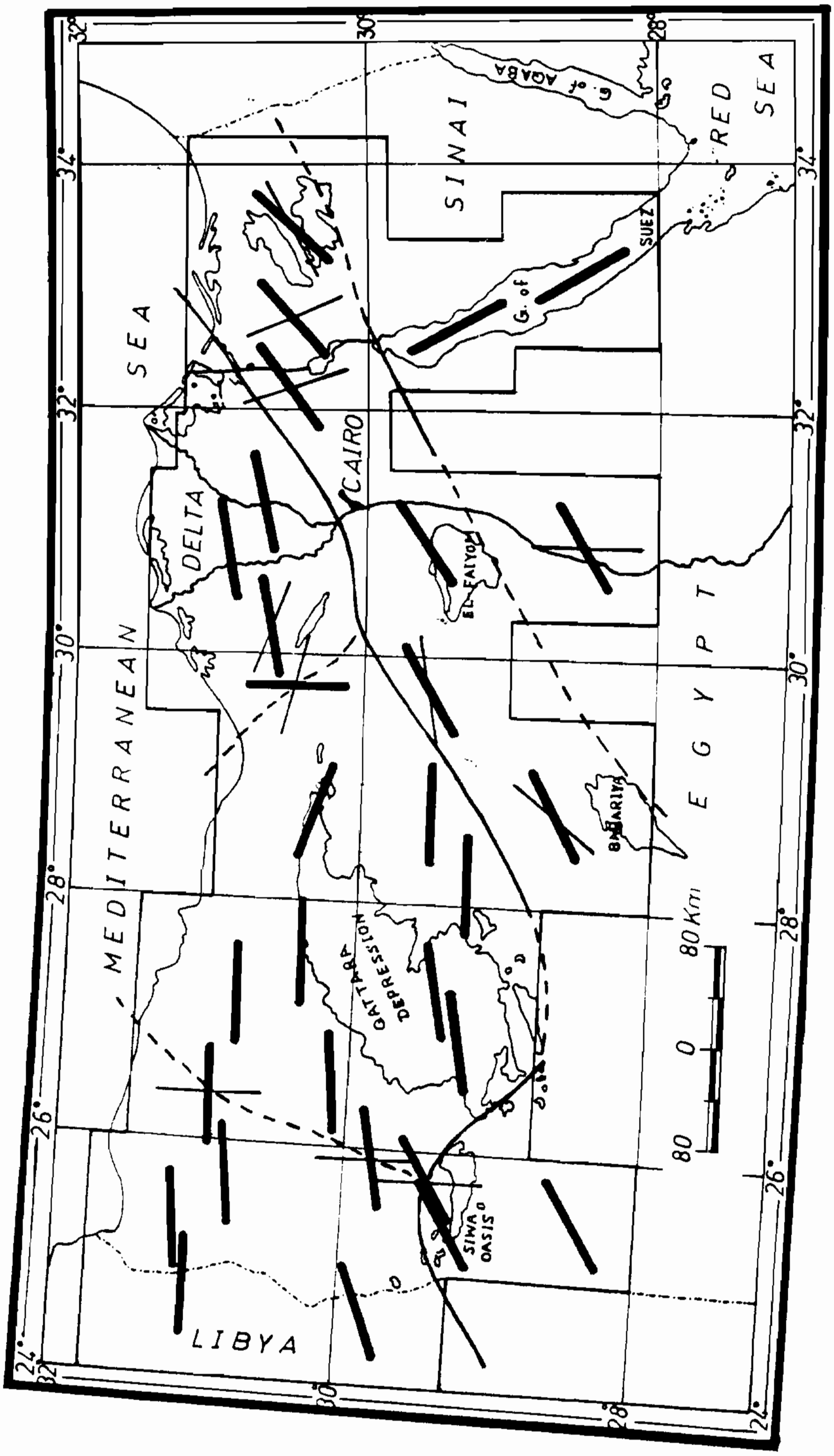

Fig. 5. Trends of the deep structures in northern Egypt.

faults including the Gulf of Aqaba and its extension, and a left lateral motion with tension on N–W trending branch faults including the Gulf of Suez and its extension.

However, from the point of view of forces, the Aqaba and Suez trend directions resulted from a force oriented in N 10° W direction as suggested by Youssef (1968) and Halsey & Gardner (1975). On the contrary it is argued by Ben-Menahem *et al.* (1976) that two main types of forces caused the other movements.

The Suez trend direction is possibly the result of a tensional force which started in the Precambrian and was rejuvenated during the Cenozoic period. The Aqaba trend may result from a younger compressional force which originated in the later geologic times, possibly the Late Tertiary.

RESULTS

TRENDS INTERPRETED FROM APPLICATION OF THE GRAPHICAL-NUMERICAL TECHNIQUES

The results are given in the form of Rose-diagrams (Fig. 1), which underscore the variability of the frequency distribution of the tectonic trends among the ten sectors. In each of these sectors there are seven major trends. These trends have been divided into 20° intervals. Data supporting the Rose-diagrams are given in Tables 1 and 2. The sector-to-sector and trend-by-trend results have been averaged out into an overall picture depicting the tectonic trends (Fig. 2).

From Table 2, it is clear that the value of frequency distributions of the anomaly trend in the N 30° W direction in the area of the Gulf of Suez (Sector X) is very different from that in other sectors of northern Egypt. In order to get acceptable values for the distribution of the anomaly trend directions in all the other areas of northern Egypt, we have excluded the results of the Gulf of Suez from the calculations. The resulting summary of the frequency distributions of anomaly trends are presented in Table 3.

TRENDS INTERPRETED FROM AUTOCOVARIANCE

The analysis was carried out on the residual fields of 30 overlapped sectors. The analysis includes two homogeneous residual fields picked after low and high-pass filtering of Bouguer anomaly (Kertz 1966; Tealeb 1977), and four homogeneous residual fields picked after elimination of linear and quadratic trend from both Bouguer and the filtered data (Agocs 1951; Zurmuhl 1957). It was decided to delineate trends within the sedimentary section down to the basement surface.

Fig. 3 demonstrates the autocovariance function of two residuals of Bahariya area, one of which represents shallow zone trends, while the other represents deep zone trends.

The seven major trends recorded were: E–W, N 60° E–S 60° W, N 60° W–S 60° E, N 40° E–S 40° W, N 30° W–S 30° E, N–S and N 20° E–S 20° W. The N 60° W–S 60° E and N 20° E–S 20° W trends, however, were recorded only at shallow depths. These trend directions are believed to have developed in the recent geologic times. The predominant shallow and deep trends are shown in Figs 4 and 5 respectively. In these figures the first and second order trends are represented by thick and thin bars.

Table 1. Predominant anomaly trends identified in northern Egypt

Mean trends	Trend limits \ Sector	I	II	III	IV	V	VI	VII	VIII	IX	X
E–W	N 80° W–N 80° E	E–W	E–W	E–W	E–W	E–W	E–W	E–W	E–W	E–W	
N 60° E	N 70° E–N 50° E	N 60° E		N 60° E	N 60° E	N 60° E	N 60° E	N 60° E	N 60° E	N 60° E	
				N 40° E	N 40° E	N 40° E					
N 40° E	N 50° E–N 30° E										
			N 30° E				N 30° E				
N 20° E	N 30° E–N 10° E										
		N 20° E						N 20° E		N 20° E	N 20° E
N–S	N 10° E–N 10° E			N–S	N–S	N–S	N–S	N–S	N–S	N–S	N–S
			N 20° W				N 20° W	N 20° W			
N 30° W	N 20° W–N 40° W			N 30° W		N 30° W			N 30° W	N 30° W	N 30° W
		N 40° W			N 40° W						
			N 50° W	N 50° W			N 50° W	N 50° W			
N 60° W	N 50° W–N 70° W				N 60° W	N 60° W			N 60° W		N 60° W
		N 70° W		N 70° W						N 70° W	

Table 2. Distribution of the Bouguer anomaly trends

Trend direction	Reference name	Sector / Trend limits	I	II	III	IV	V	VI	VII	VIII	IX	X	Total area
E–W	Tethyan	N 80° W–N 80° E	23·5	27·7	22·0	23·0	19·1	24·4	24·0	25·2	19·1	0·0	20·7
N 60° E	Qattara	N 70° E –N 50° E	20·0	17·6	24·0	18·6	24·5	21·6	22·2	19·0	20·5	0·0	18·8
N 30° W	Suez	N 20° W–N 40° W	10·3	7·6	7·4	11·7	11·1	9·6	10·2	8·1	17·0	60·0	15·3
N 60° W		N 50° W–N 70° W	13·2	21·4	10·4	19·0	12·4	12·9	14·0	24·6	12·2	10·9	15·1
N 40° E	Aualitic	N 50° E –N 30° E	7·0	13·5	24·6	17·8	10·3	12·2	11·5	12·6	10·5	0·0	12·0
N–S	E. African	N 10° E –N 10° W	16·0	4·5	5·5	8·1	10·5	11·5	11·1	5·5	9·8	22·5	10·5
N 20° E	Aqaba	N 30° E –N 10° E	10·0	7·7	6·1	1·8	12·1	8·8	7·0	5·0	10·9	6·6	7·6

Table 3. Distribution of the Bouguer anomaly trends excluding sector X

Trend direction	Reference name	Trend limits	Distribution of the anomaly lengths %
E–W	Tethyan	N 80° W–N 80° E	23·0
N 60° E	Qattara	N 70° E –N 50° E	20·9
N 60° W		N 50° W–N 70° E	15·6
N 40° E	Aualitic	N 50° E –N 30° E	13·3
N 30° W	Suez	N 20° W–N 40° W	10·3
N–S	E. African	N 10° E –N 10° W	9·2
N 20° E	Aqaba	N 30° E –N 10° E	7·7

CONCLUSIONS

The statistical trend analysis was carried out by the graphical-numerical and the two-dimensional autocovariance methods. The anomalies were interpreted at shallow and deep horizons and provided valuable information about tectonic trends present in that area and its developmental history. The interpreted features are in harmony with Halsey & Gardner (1975) and Tealeb (1977). The first (graphical-numerical) method gives the direction of major and minor extents while the second method is helpful in studying trends at different depths. On the basis of these studies, it may be concluded that the tectonic movements are not uniform all over the ten sectors.

Three major tectonic zones were identified: zone 2 and 3 were uniform but zone 1 represents 3 sub-zones which are the Nile Delta, the Qattara Depression and the Libyan Egyptian Borderland.

Sector X shows anomalous features in the frequency distributions as compared to the other sectors. This shows that the tectonic history of the Gulf of Suez does not conform with the general evolution of northern Egypt. The trends in the Suez region appear to be an extension of the Red Sea Rift trend. Agreement between the deep and shallow Suez trends suggests that this is an older feature predating the formation of the Gulf of Aqaba. This is supported by the work of Menahem *et al.* (1976).

REFERENCES

Abdelhady, Y.E., Tealeb, A. and Sabry, A.M. 1981. Geophysical analysis of Northern Egypt and Libya. 4th International Conference on Basement Tectonics, Oslo, Norway, pp. 221–23.

Affleck, H. 1963. Magnetic anomalies trend and spacing patterns. Geophysics **28** (3): 379–95.

Agocs, W.B. 1951. Least square residual anomaly determination. Geophysics **16** (4): 686–96.

Ben-Menahem, A., Nur, A. & Vered, M. 1976. Tectonics, seismicity and structure of Afro-Eurasian junction–the breaking of an incoherent plate. Physics of the Earth and Planetary Interiors **12**: 1–50.

Buchheim, E. & Lauterbach, R. 1954. Isoanomalen Richtungsstatistik Hilfsmittel tektonischer Analyse. Gerlands Beitr. Geophysik **63**: 88–98.

Dewey, J.E., Pitman III, W.C., Pyan, W.B.F. & Bonnin, J. 1973. Plate tectonics and evaluation of the alpine system. Geol. Soc. Am. Bull. **84** (10): 3137–80.

Halsey, G.H. & Gardner, W.C. 1975. Tectonic analysis of Egypt using ERTS-1 satellite data. A lecture delivered at the General Petroleum Company. Nasr City, Cairo, Egypt.

Horton, C.W., Henpkins, W.C. & Hoffman, A.A.J. 1964. A statistical analysis of some aeromagnetic maps from the north western Canadian Shield. Geophysics **29** (4): 582–601.

Kaspar, M. 1962. Methoden der Isoanomalen Richtungsstatistik und Geräte für numerich-graphische Auswertung mikromagnetischer Messungen. Geophys. Geol. **4**: 29–38.

Kertz, W. 1966. Filterverfahren in der Geophysik. Gerlands Beitr. Geophysik **75**: 1–33.

Marcak, H. 1973. Application of the covariance function to the determination of principal tectonic directions from gravimetric and magnetometric maps. Publ. Inst. Geophysics, Polish Acad. Sci, Warsaw **60**: 121–25.

McKenzie, D.P. 1970. Plate tectonics of the Mediterranean region. Nature **226**: 239–43.

Moody, J.D. 1973. Petroleum exploration aspects of Wrench-Fault tectonics. Am. Assoc. Petr. Geol. Bull. **57** (3): 449–76.

Mundt, W. 1969. Statistische Analyse geophysikalischer potentialfelder hinsichtlich Aufbau und Struktur der tieferen Erdkruste. Abh. Geomagn. Inst., Berlin, D.D.R.

Neuman, W. 1954. Praktische Untersuchungen der Isoanomalen Richtungsstatistik Freiberger. Forschungshefts, C13, Berlin.

Said, R. 1962. Geology of Egypt. Elsevier, Amsterdam, 577 pp.

Tealeb, A. 1977. Die Anwendung verschiedener statistischer Interpretationsverfahren gravimetrischer und geomagnetischer Felder in nord-Aegypten und besonderer Berücksichtigung des Vergleiches ihrer Leistungsfähigkeit Dissertationsschrift. ZIPE, Potsdam, D.D.R.

Youssef, M.I. 1968. Structural pattern of Egypt and its interpretation. Am. Assoc. Petr. Geol. Bull. **52** (4): 601–14.

Zurmuhl, R. 1957. Praktische Mathematik fur Ingenieure und Physiker. Springer Verlag, Berlin.

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التحليل الاتجاهي الاحصائي للبيانات التثاقلية
من شمال مصر ومدلولاتها التكتونية

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المملكة العربية السعودية

علي عبدالعظيم تعيلب
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حلوان ، مصر

خلاصة

بني هذا البحث على تطبيق طريقتين رئيسيتين مختلفتين في الاحصاء الاتجاهي التحليلي على شواذ البوجير الموجودة على خارطة التثاقل للمنطقة قيد البحث في شمال مصر . الطريقة الأولى طريقة عددية بيانية بسيطة تستخدم فيها مباشرة شواذ البوجير ، وهي طريقة مجدية في كشف النقاب عن معظم الصفات التكتونية الموجودة . أما الطريقة الثانية فهي تباين مشترك ذاتي في بعدين ، وتطبق على متبقيات المجال التثاقلي المختلفة في العمق ، من أجل التعرف على الصفات التكتونية الشائعة عند الأعماق المختلفة من القشرة الأرضية .

لقد توصل المؤلفان إلى التعرف على سبعة اتجاهات رئيسية للصفات التكتونية وهي شرق ـ غرب ، وشمال ٦٠° شرق ـ جنوب ٦٠° غرب ، وشمال ٦٠° غرب ـ جنوب ٦٠° شرق ، وشمال ٤٠° شرق ـ جنوب ٤٠° غرب ، وشمال ٣٠° غرب ـ جنوب ٣٠° شرق ، وشمال ـ جنوب ، وشمال ٢٠° شرق ـ جنوب ٢٠° غرب .

الاتجاهان شمال ٦٠° غرب ـ جنوب ٦٠° شرق ، وشمال ٢٠° شرق ـ جنوب ٢٠° غرب ، يؤثران في الوحدات الصخرية عند النطاقات الضحلة فقط بينما الصدوع في الاتجاهات المتبقية يظهر تأثيرها على صعيد الوحدات الصخرية في النطاقات الضحلة والعميقة على السواء . وقد استعان المؤلفان بالجداول والخرائط العديدة لعرض نتائجهما بصورة تطبيقية .