Egyptian Geophysical Society
EGS Journal, vol. 4, No. 1, 177-187 (2006)

MAGNETOTELLURIC AND AEROMAGNETIC INTERPRETATION AT FAYOUM-CAIRO DISTRICT, NORTHERN WESTERN DESERT, EGYPT

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تأويلات تيارات المغناطيسية الأرضية وخرائط المغناطيسية الجوية بطريق القاهرة – الفيوم، شمال الصحراء الغربية، مصر

الخلاصة: تقع منطقة اقليم الفيوم–القاهرة فى الجزء الجنوب الغربى من مدينة القاهرة، التى تأثرت بالعديد من الزلازل. طبقا لتصريحات الشبكة القومية للزلازل التابعة للمعهد القومي للبحوث الفلكية والجيوفيزيقية، قد حدث زلزال فى ٣١ يوليو سنة ٢٠٠٥ فى منطقة الدراسة قوته ٤،٢ بمقياس ريختر .طريقة التيارت المغناطيسية الارضية تعطى افضل الطرق للبحث عن السوائل الموجودة فى الفوالق التى تؤدى الى الشاذات الجيدة التوصيل للتيار الكهربى. الاهداف المرجوه من هذه القياسات متنوعة. ايجاد مواقع الفوالق النشطة بالنسبة للنشاط الزلزلى بمنطقة الفيوم–القاهرة وعلاقتها بالتراكيب الجيولوجية ذات المقاومات الكهربية بواسطة التيارت المغناطيسية الارضية. وقد اخذ قطاع من التيارت المغناطيسية الأرضية يمر بمنطقة الدراسة لتوضيح التراكيب الجيولوجية البعيدة ذات المقاومات الكهربية. وايضا خريطة الشاذة المغناطيسية الجوية استخدمت لتبيين التراكيب الجولوجية الضحلة.

ABSTRACT: *The Fayoum–Cairo district lies in the south western part of Cairo, which is affected by several earthquakes. According to the Egyptian Network Seismology of National Research Institute of Astronomy and Geophysics (NRIAG), the last one occurred in the 31st July, 2005 (Magnitude = 4.2 in Richter scale). Magnetotelluric (MT) method can offer good opportunity to detect crustal fluids along faults due to their high electrical conductivity anomalies. The targets of these measurements are various. Its always desired to determine the location(s) of active fault(s) to study the connection of the Fayoum–Cairo seismicity and MT resistivity structure. A single MT profile was carried out across the area in order to investigate the deep resistivity structures. Beside RTP aeromagnetic anomaly map was used to delineate the shallow structures.*

INTRODUCTION

The area under study is located in the northern part of Egypt between latitudes 29° 40' N & 29° 55' N and longitudes 30° 55' E & 31° 20' E, occupying a total surface area of about 1225 km^2 (Fig. 1). The earthquake activity in Egypt is moderate (M≤6); but some events caused extremely severe damage to recent and historical constructions (Fig. 2b). The MT survey was conducted along eight stations on a northeast-southwest trending profile, selected perpendicular to the regional geologic structures and extremely for about 20 km of the study area (Fig. 2a).

The Magnetotelluric method (MT) is an electromagnetic (EM) technique that is used to determine the electrical resistivity structure of the earth by measuring natural magnetic and electric fields at the surface. Two dimensional (2-D) inversions were applied to (MT) data. The reduced to the pole (RTP) aeromagnetic map compiled by the Western Digital Company (1983) has been used for determination of subsurface structures. Filtering, power spectrum and 2D-magnetic modeling were applied to the RTP aeromagnetic data.

Recent MT studies on active areas **(**Soyer and Unsworth, 2006**;** Unsworth et al. and the INDEPTH-MT team, 2005; Mekkawi et al., 2005; Mekkawi, 2003; Bedrosain et al., 2002 and Unsworth et al., 2000) showed that the MT method could be used to delineate the electrical resistivity structures (anomalies) along the fault zones. The low electrical resistivity is attributed to high porosity and fluids present in the highly fractured zone.

Meshref et al. (1980) analyzed the magnetic trends in the northern part of Egypt and stated that the basement rocks in the Western Desert have been affected by two fault systems having large vertical and horizontal displacements. The oldest E-W and ENE faults are intersected by the youngest NW and NNW ones. Abuel ata (1990) based on seismic and gravity data, outlined three structural highs and two lows included in the study area:

- The Abu Roash high that strikes in the NNE-SSW and then ENE-WSW directions.
- Elsagha high which is oriented NW-SE directions.

- The Elfaras-Elfayoum high, which is oriented in ENE-WSW and NNW-SSW directions. Ghazala, 2001 concluded that four significant tectonic zones characterize the area of study:

  1- Nile Valley graben

  2- East Nile Valley uplift

  3- Ginidi basin and

  4- Kattaniya uplift.

The main aim of this study is to analyze the magnetotelluric and magnetic data and correlate them with the geological information, in order to define the significant fault patterns, which are responsible for the structural development of its geological units. To achieve this goal, various methods and techniques of analysis were applied to interpret the magnetotelluric and magnetic data of the study area.

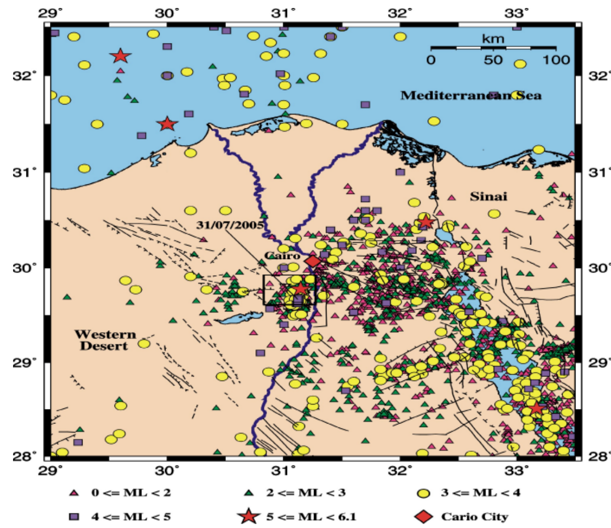


Fig. (1). Location map of the studied area and seismicity map from 1900 to 2005, a part of Northern Egypt (Awad et al., 2006).

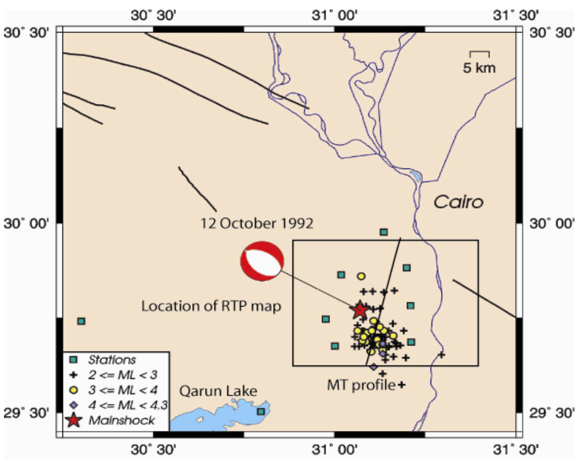
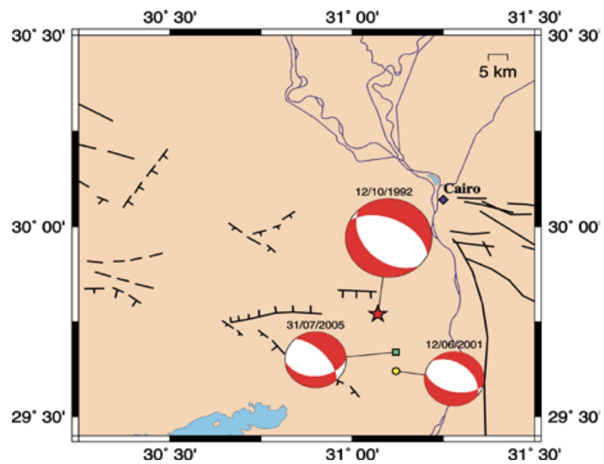


Fig. (2a). Location map of RTP aeromagnetic & MT profile with focal mechanism of the 12th October, 1992, earthquake (M=5.9), Fayoum-Cairo District, Egypt (Awad et al., 2006).



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Available Geologic Information

From the geological point of view, the area extends from the southwest of Cairo to Gabal Qatrani at to east and northeast of the Qarun Lake. This lake covers an area of about 200 km^2; it has a length reaching about 40 km along its east-west axis, while its maximum width is less than 15 km in the north-south direction (Fig. 2a). It is at an average elevation of about 45 m below sea level. The desert borders the lake from the north and partly eastward, while cultivated land encircles it from the southwest and southeast. The lake receives most of the drainage of the cultivated lands, coming through El-wadi drains (Sweidan, 1986). Recent deep drilling in the study area (Fig. 6 and Table 1) has shown that a simple geologic structure affects the relatively thick cover of younger sediments. An intricate geologic structure made up of a large number of swells and basins conceals beneath it. The geological units of the study area started from Middle Eocene, to Recent Nile sediments (Naeim et al., 1993).

Fayoum-Cairo province became tectonically active after the active earthquake, which stroked the area in 12th October 1992 of M=5.9 (Awad et al., 2006). The recent suffered earthquake (Fig. 2b) occurred 30 km southwest of Cairo on the 31st July 2005 with medium magnitude (M = 4.4) took our attention to carry magnetotelluric measurements (MT) in the area. The structure of the study area is dominated by faults, many of which can be identified from seismic and well data. The majority is steep normal faults, and most of them have a long history of growth. Some of the normal faults suffered strike-slip movements during a part of their history. Strike-slip movements seem to have affected the orientation of many of the old fold axes. The strike-slip movements were probably related to the lateral movements which the Africa plate underwent during Jurassic and Late Cretaceous (Said, 1990).

Magnetotelluric Data

Magnetotelluric technique (MT) provides information about the electrical resistivity distribution of the earth's subsurface. It is based on the relationship between transient electric and magnetic fields, which are measured at the earth's surface. The main source of the fields is the natural fluctuations of the earth's magnetic field, which occur over a wide spectrum of frequencies. The magnetic field diffuses into the earth and induces electric currents, the so called telluric currents, which in turn cause secondary magnetic fields. The recordings are processed into frequency-dependant responses and then used for the interpretation of the earth's resistivity (Schnegg, 1998).

A good MT site must be protected against weather effects, like wind and direct heat from the sun. It must be setup at least 300 m away from a road, since trucks would generate noticeable variations in the magnetic field at shorter distances. Choosing a convenient site to perform MT sounding requires some experience. Inhabited areas and power lines must be kept at least 4-5 km away. Distance to railway lines should be even larger, particularly for DC trains. The magnetotelluric measurements carried out along eight stations on a single northeast-southwest profile that is perpendicular to earthquakes activity, along 20 km. MT instruments developed at Geoimpex-Poland for long period measurements were used. The fluxgate magnetometer and telluric amplifiers allow to record field variations in the period range from 1 to 10000 seconds. In the telluric lines of about 100 m length, unpolarised electrodes were used. The average recording for each station was about four days. For more detail about field measurements and instruments used to collect MT data (Elbohoty and Mekkawi, 2005).

Processing of MT Data

For natural source fields, in the frequency domain, the horizontal electric ($E_{x,y}$) and the horizontal magnetic ($H_{x,y}$) are connected via a linear relationship (Yungul, 1996):

$$\begin{aligned} E_x(\omega) &= Z_{xx}(\omega)H_x(\omega) + Z_{xy}(\omega)H_y(\omega) \\ E_y(\omega) &= Z_{yx}(\omega)H_x(\omega) + Z_{yy}(\omega)H_y(\omega \end{aligned} \qquad (1)$$

or in a matrix form

$$\begin{vmatrix} E_x \\ E_y \end{vmatrix} = \begin{vmatrix} Z_{xx}\, Z_{xy} \\ Z_{yx}\, Z_{yy} \end{vmatrix} \begin{vmatrix} H_x \\ H_y \end{vmatrix} \qquad (2)$$

Usually, the components of the impedance (Z) are used to calculate the apparent resistivity functions ρxy and ρyx and phase functions φxy and φyx

$$\rho_a(\omega) = \frac{1}{\omega\mu_0}\left|Z(\omega)\right|^2 \qquad (3)$$

$$\rho_a(\omega) = \frac{1}{\omega\mu_0}\left|Z(\omega)\right|^2 \qquad (4)$$

$$\varphi_{ij}(\omega) = \arg(Z_{ij}(\omega)) = \tan^{-1}\{\operatorname{Im} Z_{ij}(\omega) / \operatorname{Re} Z_{ij}(\omega)\} \qquad (5)$$

where ω is the angular frequency and μo is the magnetic permeability of the vacuum. The impedance tensor and its random errors are estimated using least square method (Pedersen, 1989).

A similar relation exists between the vertical magnetic field intensity (H_z) and the horizontal components magnetic field ($H_{x,y}$) (Schnegg 1998):

$$H_z(\omega) = AH_x(\omega) + BH_y(\omega) \qquad (6)$$

a length: $T(\mathrm{Re}) = \sqrt{\mathrm{Re}(A)^2 + \mathrm{Re}(B)^2}$ and

an angle: $\vartheta(\mathrm{Re}) = \arctan\dfrac{\mathrm{Re}(B)}{\mathrm{Re}(A)}$ (7)

a length: $T(\mathrm{Im}) = \sqrt{\mathrm{Im}(A)^2 + \mathrm{Im}(B)^2}$

and an angle: $\vartheta(\mathrm{Im}) = \arctan\dfrac{\mathrm{Im}(B)}{\mathrm{Im}(A)}$ (8)

where T (Re,Im) and θ(Re,Im) are tipper or induction arrows (TP) with length and angle. In the 2D case the real component of induction arrow points away from regions which are good conductors.

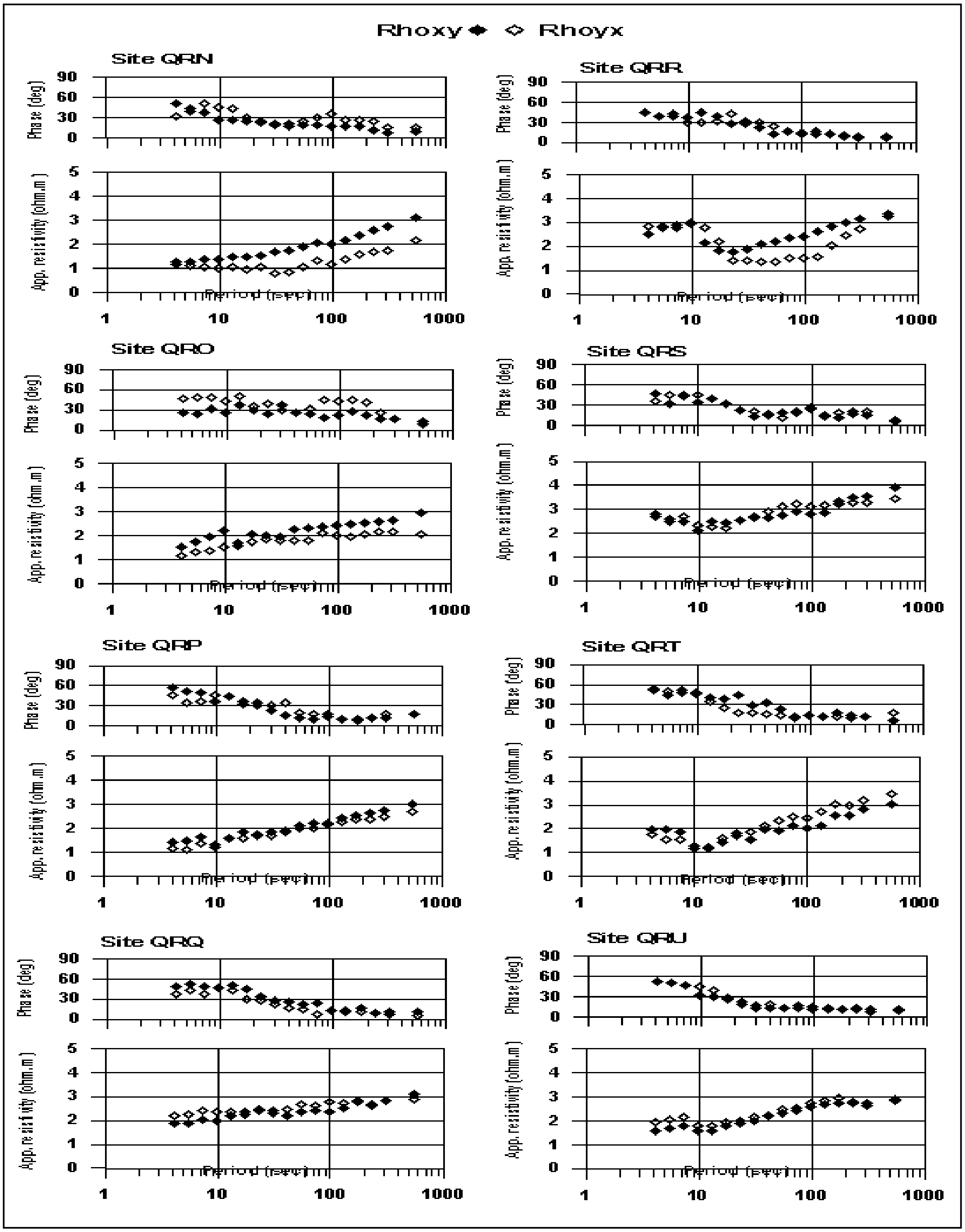

Fig. (3). Apparent resistivity and phase computed for the impedance tensor Zxy (TE) and Zyx (TM) , Fayoum-Cairo District, Egypt.

Fig. 3 shows the apparent resistivity (Ωm) and phase (degree) computed for two polarizations Zxy (TE) and Zyx (TM) at the sites QRN to QRU. The MT curves are very similar from site to site along the whole profile. The apparent resistivity modes Zxy diverge above a period of 1 sec., indicating 2D geometry. The two modes steadily increase from values of hundreds of Ωm at the surface (1 second) to thousands of Ωm. That is no surprise, since the profile is never far away from the high-resistive rocks (granite). Zxy curves are gently increasing between 1,000-10,000 Ωm, whereas Zyx curves show decreases, hinting at a deep conducting body (fault or dyke?) embedded into a resistive matrix.

In the induction arrows diagram (Fig. 4), it is noticed that between the stations QRQ and QRR (induction arrows directed in opposite direction) the presence of a good conductor and a similar case between stations QRT and QRU, indicating two faults in the studied area.

Two-Dimensional Modeling and Interpretation of MT Data

Simultaneous inversion of transverse electric (TE), transverse magnetic (TM) modes and tipper (real induction arrows only) was carried out using REBOCC inversion program (Siripunvaraporn and Egbert 2000). The static shift distortion parameters were set free, so that the program could automatically adjust the values. The results of the inversion are shown in (Fig.5) after 12 iterations, the inversion finds a model with R.M.S. misfit of 1.5. The 2D model shows a region of a good-conductive material, that is located in the depth between 0.1 and 5 km. In the central part, there is a zone of high resistive rocks (granite).

Aeromagnetic Data

The qualitative interpretation for the constructed magnetic maps, aims to get a clear view of the subsurface structures, estimate of the relative depth of magnetic anomalies sources. It deals with the description of anomalies, especially their symmetry, strike, extension, width, amplitude and gradients (Nettelton, 1976).

The quantitative interpretation has been used to determine the depth of shallow subsurface structures (faults and dykes), basaltic intrusions as well as the basement complex of the studied area. The method of interpretations includes radially averaged power spectrum and 2D magnetic modeling. The analysis and processing were done by specialized computer program (Geosoft V.4.3, 1993).

The clear investigation of the RTP aeromagnetic map (Fig. 6) compiled by the Western Digital Company (1983), revealed that the magnetic field increases up in the area with a maximum relief of about 110 nT in the eastern part and decreases to a minimum of about 170 nT in the southern part. It includes several local anomalies in the central, southwestern and northeastern parts of the studied area. These anomalies have different reliefs, polarities and shapes. The general magnetic trends of these regions are almost NW-SE, NE-SW and E-W.

Several zones of high and low magnetic values are present. The magnetic highs are separated from magnetic lows by steep gradients. The elongations of magnetic contour lines and their gradients in the central part of the study area indicate that it is structurally-controlled by faults having major axes in NW-SE and E-W directions. The high magnetic anomalies in the northwestern side can be attributed to the occurrence of subsurface basic intrusions of high magnetic contents. Fault axes as well as the directions of magnetic anomalies are trend in the NW-SE and NE-SW in the northwestern, central and the southern parts of the study area.

Processing of Aeromagnetic Data

Frequency filtering represents a major component of magnetic data processing. As a rule, digital filters are used for signal enhancement, that is to remove unwanted noises, and enhance the desired signals. The nature of "noises" and "signals" varies from case to case or even from a stage of processing to another according to its target. In this study, 2D filtering was applied to the RTP aeromagnetic map. The wavelength linear filtering of the RTP magnetic data is carried out utilizing three types of filtering, these are:

a- Low-pass filter: It is defined as the filters which passes the long wavelengths and reject all wavelengths smaller than the cut–off wavelength.

b- High-pass filter: It emphasizes short wavelengths and eliminates wavelengths larger than the cut-off wavelength.

c- Band-pass filter: It passes wavelengths within a certain range (Peter and John, 1970).

In the present study, filtering technique was performed using a cut-off frequency that ranges between 0.08 cycle/ unit data and 2.0 cycle/ unit data. The high-pass filtered map **(**Fig. 7) elucidates high-frequency and short-wavelength spot-like magnetic anomalies, which are inferred as residual components. The majority of these local magnetic anomalies are located in the central and southern parts of the study area. These anomalies are distributed with two defined trends (NW-SE and NE-SW).

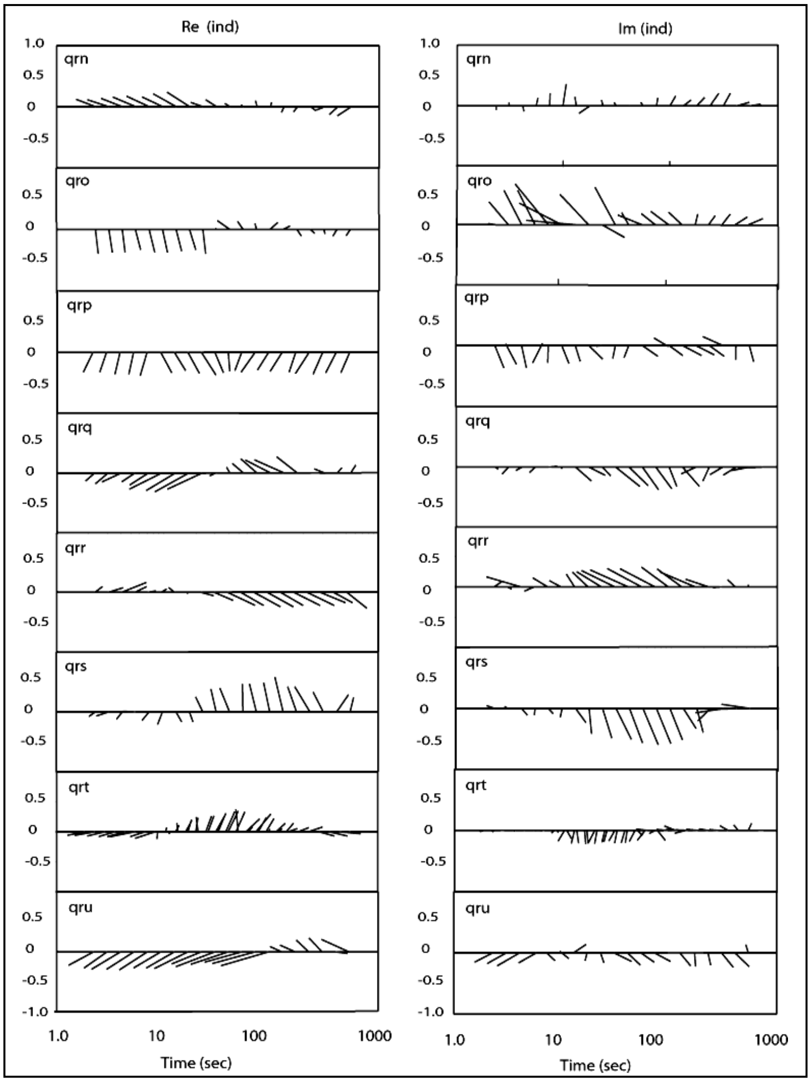

Fig. (4). Real and imaginary induction arrows (Tipper), Fayoum-Cairo District, Egypt.

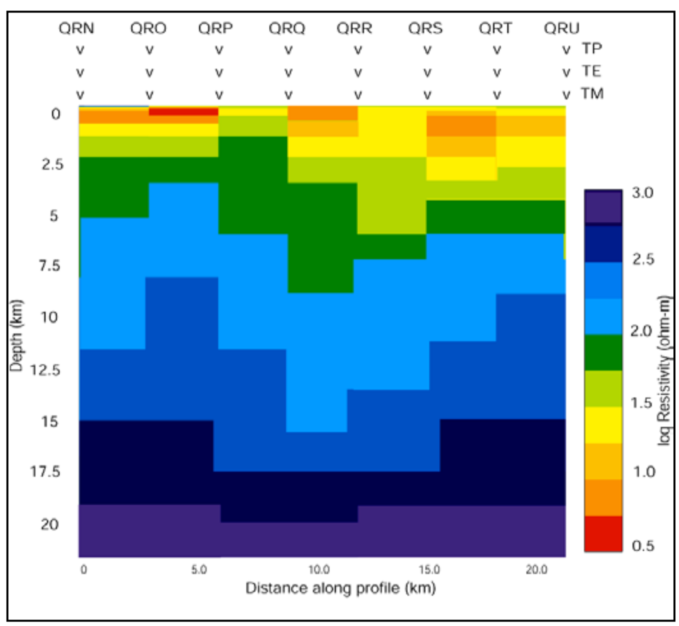

Fig. (5). Final 2-D model based on MT data along a Profile crossing Fayoum-Cairo District. The location of active faults in Dahshour (between stations QRQ and QRR) in NE-SW direction and the symbols above the model identify the MT sites.

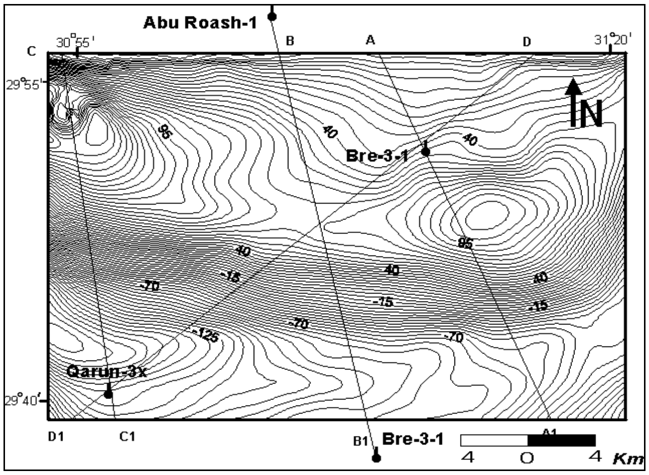

Fig. (6). RTP aeromagnetic anomaly map of the studied area (compiled by the Western Digital Company, 1983), showing the locations of 2-D modeling profiles (A-A1, B-B1, C-C1 and D-D1) and boreholes data, Fayoum-Cairo District, Egypt.

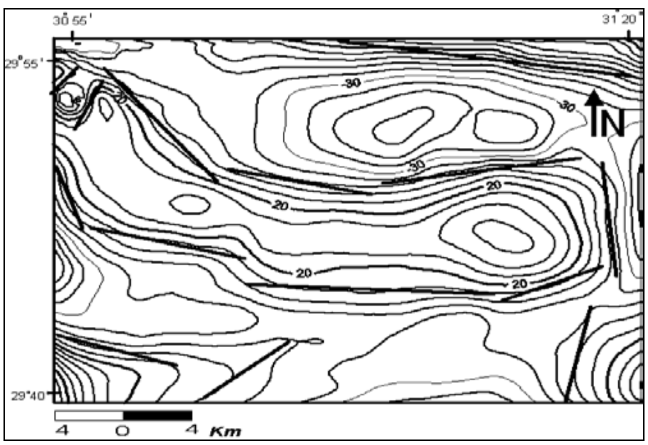

Fig. (7). High-Pass Filter of the RTP aeromagnetic map, Fayoum-Cairo District, Egypt.

However, the prominent NW-SE anomalies lie the northeastern and central parts of the study area. Meanwhile, the NE-SW trending anomalies lie in the northern and southeastern corner of the study area. They are retained but with shorter wavelength than in the original filtered ones. This indicates that the prominent fault trends on the RTP aeromagnetic map extend in the subsurface up to shallow depths. Moreover, the random orientation of small-scale anomalies reflecting that the shallow subsurface has been affected by different stress regimes of the neo-tectonics that may have not affected deep-seated rocks.

The band-pass magnetic filtered anomaly map (Fig. 8) shows that the well-defined trends of anomalies on the RTP aeromagnetic map still persist. However, some smooth regional anomalies that appear not be related to a subsurface structures are most probably a result of regional variations in the magnetization or magnetic susceptibility of the rocks at medieval depths.

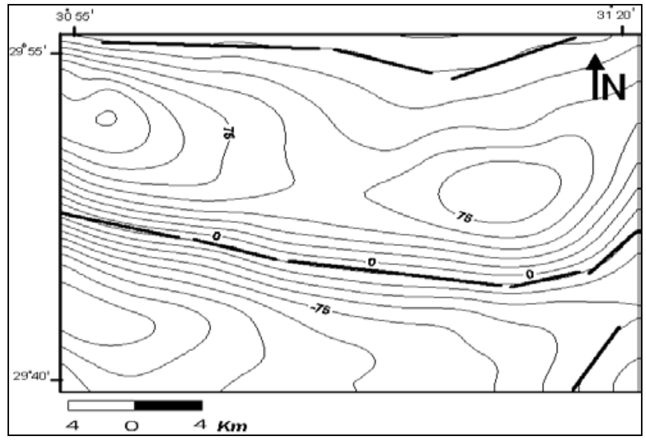

Fig. (8). Band-Pass Filter of the RTP aeromagnetic map, Fayoum-Cairo District, Egypt.

The low-pass magnetic filtered anomaly map (Fig. 9) shows a pattern of gradual rotation of magnetic trends from NE-SW and NW-SE to a E-W trend. As the low-pass filtered anomalies give view about the subsurface deep depths, then the gradual rotation of trends implies that the two suggested stress regimes (NE-SW and NE-SW) were contained to the shallow depths where the E-W one dominated only in the deepest part. The deep-seated zone seems to be affected by an E-W stress trend.

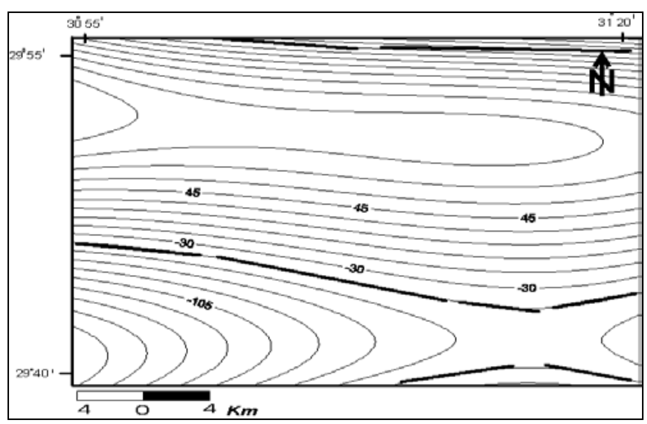

Fig. (9). Low -Pass Filter of the RTP aeromagnetic map, Fayoum-Cairo District, Egypt.

Depth Estimation

The depth to the top of causative magnetic bodies is a useful tool for finding the configuration of the sedimentary basins, and sometimes for locating major structures in basement rocks. Calculation of the depth to the top of the source or the depth to the bottom of the source can be made from the shape of the anomalies, or the shape of the power spectrum computed from potential field data. In this study, Spectral frequency analysis method was used to calculate the depths of the causative bodies utilizing the magnetic data.

Radially average power spectrum method is used to determine the depths of volcanic intrusions, depths of the basement complex and the subsurface geological structures. Several authors, such as Bhattacharyya (1966), and Spector and Grant (1970), Garcia and Ness (1994), Mauirizio et al. (1998), explained the spectral analysis technique. It depends on the analysis of the magnetic data using the Fourier Transform of the spectral, map and its complex conjugate. It is a function of wavelengths in both the X and Y directions. In the present study, the Fast Fourier Transform (FFT) was applied on the RTP aeromagnetic data (Fig, 10) to calculate the energy spectrum. As a result, a two-dimensional power spectrum curve was obtained on which three main average levels (interfaces) at depth 0.55 km, 1.35 and 3.95 km below the measuring level were revealed for the deep seated, intermediate level and near surface magnetic components respectively.

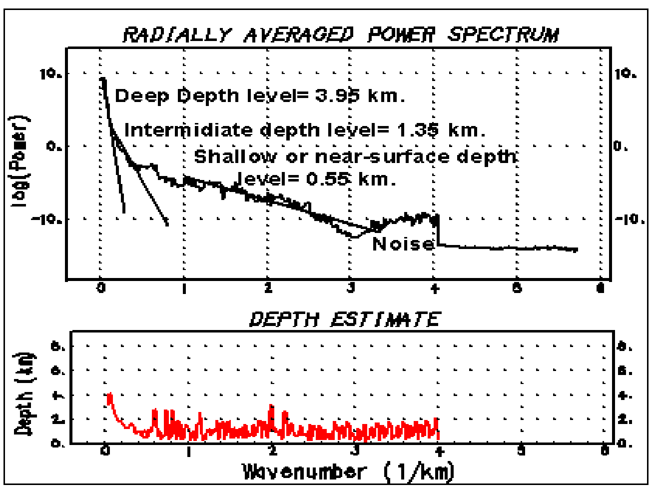

Fig. (10). Radially averaged power spectrum (upper) and the resultant depth estimates (lower), RTP aeromagnetic anomaly map, Fayoum-Cairo District, Egypt.

Two Dimensional (2-D) Modeling of Aeromagnetic Data

Such models assume the earth as two dimensional, i.e., it changes with depth (the Z-direction) and in the direction of the magnetic profile (i.e. the X-direction, perpendicular to the strike), while the strike length of the body (i.e. the Y-direction) is considered to be infinite. The magnetic modeling involves four separate parameters: top surface, bottom surface, magnetic susceptibility contrast, and the observed magnetic anomaly. If three of these parameters are known or assumed, the fourth may be calculated. The forward modeling specifies the first three items and calculates the anomaly.

To confirm the interpreted magnetic basement structural framework of the studied area, four regional magnetic profiles (Fig. 6) were modeled using the 2D-forward modeling technique and available well information in the study area (Table 1). The selected profiles were taken from RTP aeromagnetic map and denoted as A-A1, B-B1, C-C1 and D-D1 (Fig. 6). The magnetic susceptibility contrast values for the sedimentary rocks and basement rocks along the four structural cross-sections were assumed. The magnetic field was calculated iteratively for these geological models, until a good fit was reached between the observed (dots) and calculated (line) profiles. The four models are shown on Figures 11, 12, 13 and 14. On these four figures, the horizontal x-axis represents the horizontal distance in km along the profiles, while the vertical axis is the magnetic field scale in nT and the lower part represents the depth scale in km. The magnetic susceptibility of the basement rocks ranges between 0.003 to 0.004 S.I. units. The magnetic field responses computed for the geological models used magnetic declination of 2.0º east and magnetic field inclination 42º. The regional magnetic field intensity utilized was 42700 nT.

Table 1. Available well information that were used in 2D magnetic modeling (see Fig. 6), Fayoum-Cairo District, Egypt.

Name of well	Formation at end of drill	Total depth (m)
Abu Roash1	Basement	1916
Bre-3-1	Albian (Late Cret.)	3293
Bre-6-1	Basement	2268
Qarun-3x	Late Eocene	3840

From the investigation of the two–dimensional magnetic model A-A1 (Fig. 11), it can be noticed the eastern and western part is deeper than the central part. This mean that the depth is increasing from the central toward the eastern and western side of the model the basement is uplifted in the central part with a depth of 2.5

km, while the depth in the deepest part of the model is 3.5 km. The profile B-B1 (Fig. 12), lies in the central part of the area and directed NW-SE. The basement is uplifted in the northern and central parts with a depth of 1.25 km, and deepening in the southern part with a depth of 2.95 km.

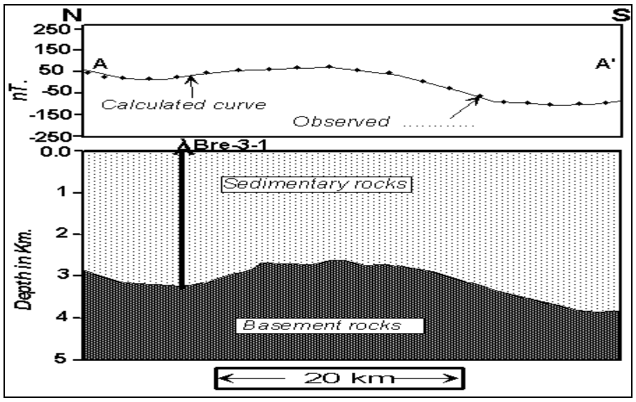

Fig. (11). Two-dimensional magnetic mode along profile A-A1 of the aeromagnetic map, Fayoum-**Cairo District, Egypt.**

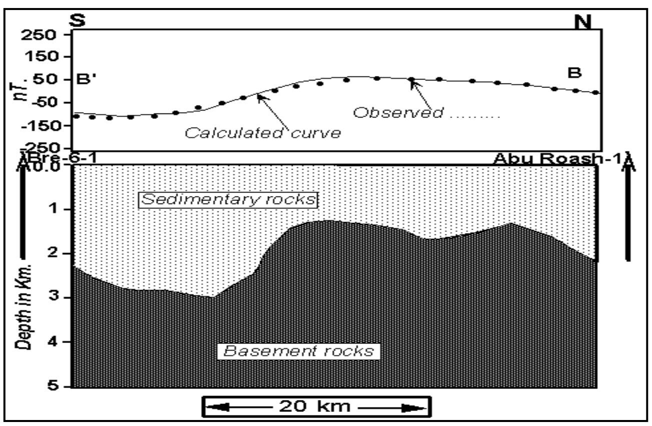

Fig. (12). Two-dimensional magnetic mode along profile B-B1 of the aeromagnetic map, Fayoum-Cairo District, Egypt.

Two dimensional magnetic models along the profile C-C1 (Fig. 13) lies in the western part of the area and directed nearly N-S. The basement is uplifted in the northern part of the profile with a depth of 1.8 km and deepening toward the southern part of the profile with the depth of 4.1 km. The profile D-D1 (Fig.14) lies in the northeastern and southwestern part of the area. The basement is uplifted near the northern part of the model, with a mean depth about 3.8 km, and the general deepening toward the central part, with a basement depth of 4.1 km.

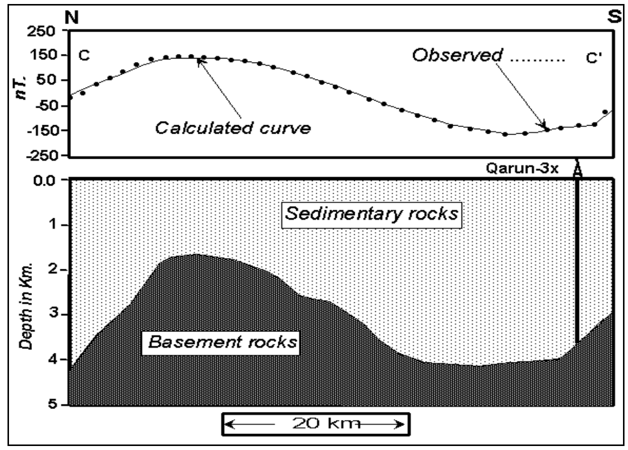

Fig. (13). Two-dimensional magnetic mode along profile C-C1 of the aeromagnetic map, Fayoum-Cairo District, Egypt.

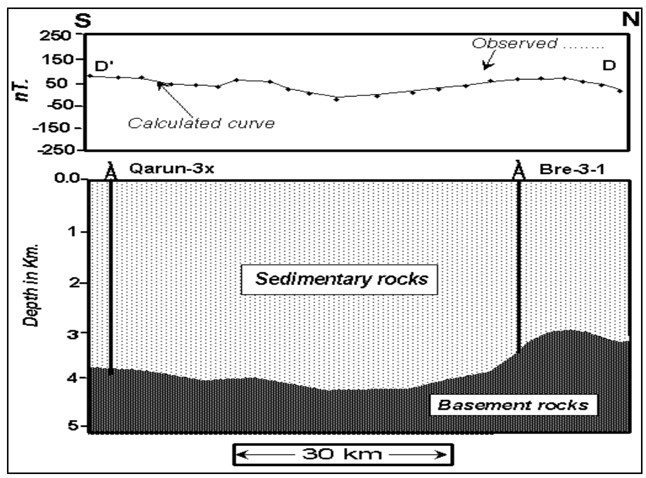

Fig. (14). Two-dimensional magnetic mode along profile D-D1 of the aeromagnetic map, Fayoum-Cairo District, Egypt.

CONCLUSION

The present study is devoted for the transformation and interpretation of the magnetotelluric and RTP aeromagnetic data through the integration of some geophysical techniques in order to detect of subsurface major structural elements affecting both the sedimentary section and the underlying basement complex. Close examination of the different anomalies through the RTP aeromagnetic map reveals that, the study area is characterized by intensive positive magnetic anomalies with different amplitudes. These anomalies may be attributed to the occurrence of subsurface basic intrusions of high magnetic content at different depths. Besides, it can be noticed that, the elongated magnetic anomaly zones in the northern part of the study with steep gradients could indicated the occurrence of subsurface faulting trending principally in the NW-SE and NE-SW directions. These faults may be responsible of the recent earthquakes in the study area.

The results obtained from the induction arrows (tipper) and the two-dimensional magnetotelluric inversion model yielded a clear imaging of deep active faults that affect and could be responsible of earthquake activity in the studied area. These faults may be activated by the presence of fluids along fractured zones. Most probably increasing stresses could reduce the porosity of the fractured zones then reactivated these faults after certain time.

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