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Subsurface structural mapping of Gebel El-Zeit area, Gulf of Suez, Egypt using aeromagnetic data

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The Gebel El-Zeit area is located on the western coast of the Gulf of Suez, Egypt. The areas in/and around the Gulf of Suez are generally important due to their hydrocarbon resources. In this study, we have applied gradient interpretation techniques (Euler deconvolution and analytic signal) to the aeromagnetic data of the Gebel El-Zeit area. The main objective of this study is to identify and delineate the possible subsurface structure of the area that may assist in locating new hydrocarbon prospects. Results of Euler method suggested that, on the eastern and western parts of the area, the basement could be observed on the ground (∼50 m over the ground) and became more deeper on the central part to reach depth of 5 km (from the ground level). Results from the analytic signal method indicated that, the depth to the basement has an average value of 156 m on the eastern side and 758 m on the western side. Generally, the area is characterized by a graben structure bounded by major faults striking in the NW-SE direction.

Key words: Gebel El-Zeit area, magnetic, euler deconvolution, analytic signal, Gulf of Suez, Egypt.

1. Introduction

The Gebel El-Zeit area is located on the western coast of the Gulf of Suez, Egypt (Fig. 1). The study area has a great importance due to its hydrocarbon resources. Several seismic surveys have been applied in the Gebel El-Zeit area to delineate the subsurface structure and its relation to hydrocarbon prospects. In most of these surveys, seismic energy was masked by the Pre-Miocene salt formation (Taha *et al.*, 2002). As a result, seismic mapping of the horizons below Pre-Miocene salt is difficult and unreliable. Therefore, other geophysical studies are recommended to delineate the subsurface structure.

The magnetic method is one of the best geophysical techniques to delineate subsurface structures. Aeromagnetic maps reflect spatial variations in the magnetic field of the earth. These variations are related to distribution of structures, magnetic susceptibilities, and/or remanent magnetization. Sedimentary rocks, in general, have low magnetic properties compared with igneous and metamorphic rocks that tend to have a much greater magnetic content. Thus, many aeromagnetic surveys are useful for mapping basement and igneous intrusions.

In this paper, we attempt to map the subsurface structure and estimate the depth to the basement in the Gebel El-Zeit area using the existing aeromagnetic data. This study is based on the application of gradient (Euler deconvolution and analytic signal) techniques. The advantage of these techniques is that they provide source location parameters using only a few assumptions. However, these methods use structural models such as contacts, thin dikes and horizontal cylinders, which may over-simplify the true situation.

2. Geologic Setting

Several major and minor topographic features (Fig. 1) characterize the Gebel El-Zeit area. The most conspicuous of all is the gravel plain occupying the central lowland part of the area. The area is bordered on the west by the northern part of Ash El Milaha range, and on the east by the relatively high topographic features of the Gebel El-Zeit range, which extends about 14 km in the NW-SE direction, parallel to the Gulf of Suez. The Gebel El Zeit range reachs a maximum elevation of 465 m and is an exposed granite pluton.

The Gebel El-Zeit area represents a typical example of a complex structure of the Gulf of Suez region (Allam, 1988). The Gulf of Suez may be viewed as a great-elongated (400 km long) depression separating the central Sinai Peninsula from the mainland of Africa. In fact, the Gulf of Suez region represents one of the most intensively faulted areas of Egypt. Structural analysis of the Gulf of Suez was carried out using seismic profiles and well data. Because of the thick evaporitic sequence in the upper Miocene, the quality of the seismic records is generally poor (Colletta *et al.*, 1988). The structure of the Gulf of Suez is dominated by normal faults and tilted blocks trending in NW-SE, with sedimentary fill up to 6 km thick (Jackson *et al.*, 1988).

Allam (1988) and Angelier (1985) stated that the Gebel El-Zeit area is characterized by two main faults parallel to the Gulf of Suez (F1 and F2 on Fig. 1). These two faults form a graben system structure taking the direction of NW-SE. These faults bring the granite mass of the northern part of Ash El-Milaha and Gebel El-Zeit ranges in juxtaposition with the younger sedimentary rocks (Farouk, 1965). In ad-

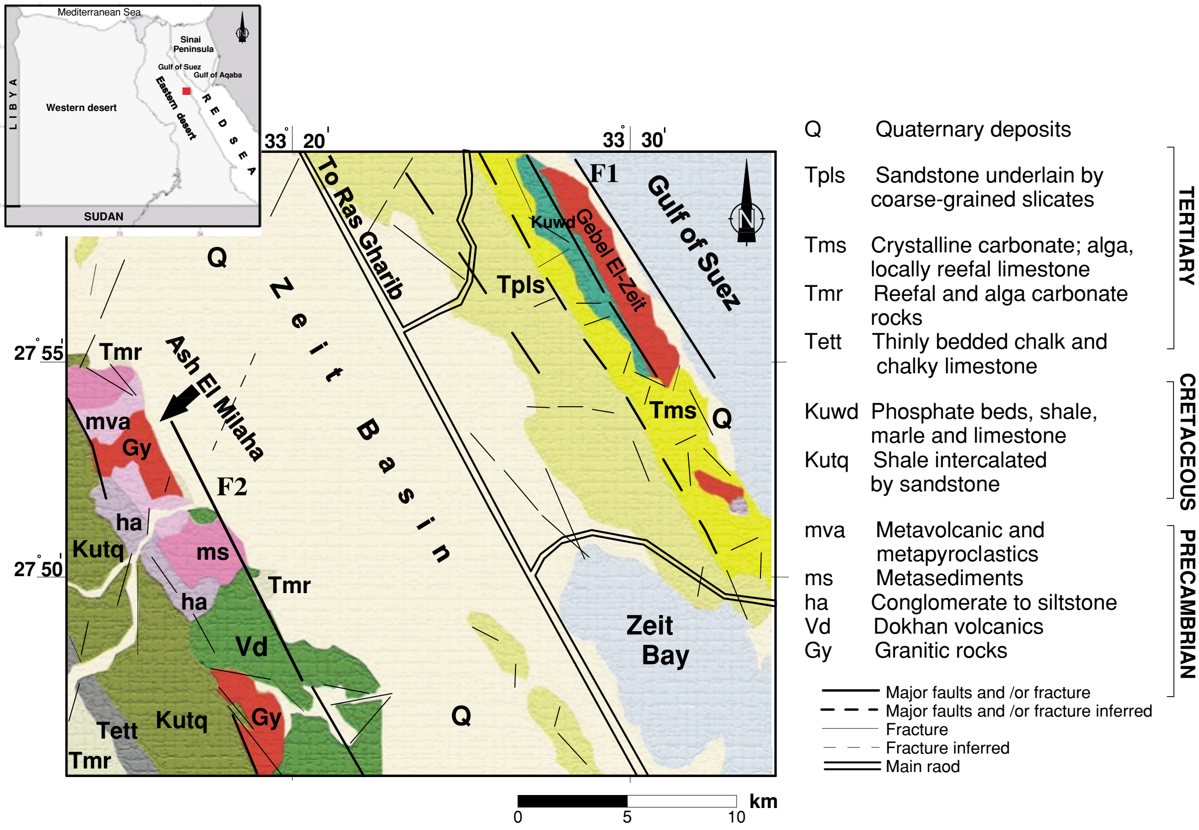

Fig. 1. Location and geologic map of Gebel El-Zeit area, Gulf of Suez, Egypt (after Conoco, 1987).

dition to the main faults, several minor structures, including faults and fractures, are recognized at the western and eastern parts of the area.

3. Aeromagnetic Data

The Gebel El-Zeit area is covered by an aeromagnetic survey conducted by AeroService Division, Western Geophysical Company of America. The aeromagnetic data were obtained using a proton magnetometer with a resolution of 0.01 nT at a mean terrain clearance of 120 m. This survey was carried out along a set of parallel flight lines at 1.0 km spacing and oriented in the NE-SW direction. The data were recorded at a sampling interval of 91 m, (Aero Service, 1984). The data was corrected for the IGRF then exported to (x, y, z) form, then gridded using an interval of 250 m. The net result was total intensity aeromagnetic data of the area (Fig. 2).

In most aeromagnetic surveys, interpretation is inherently ambiguous. So that, all available information should be combined to obtain good results (Salem *et al.*, 1999). In general, heterogeneity and deformation of the basement rocks will lead to short and long wavelength magnetic anomalies, which are easily observed on the aeromagnetic maps. The recorded magnetic anomalies display several trends. It should be stated that magnetic structures do not occur at random, but are generally aligned along definite and preferred axes forming trends that can be used to define magnetic provinces (Affleck, 1963; Hall, 1979).

Figure 2 shows the total intensity aeromagnetic map of the Gebel El-Zeit area. High magnetic gradients are observed over Gebel El-Zeit range (region A), trending in the NW-SE direction (Red Sea trend), and at the southwestern corner of the map (region C), trending in the E-W direction (Tethyan trend). Low magnetic gradients are located in the central part (Zeit basin) and also trend in the NW-SE direction. At Ash El-Milaha range, a negative elongated magnetic anomaly with a value of −120 nT is observed. This anomaly could be related to significant susceptibility contrast between the highly magnetic Dokhan volcanic rocks and the non-magnetic metasediments. A high positive circular anomaly is observed on the eastern part of Zeit Bay (440 nT). A geologic map (Conoco, 1987) of the area gives no geologic correlation for this anomaly.

4. Euler Deconvolution Method

The Euler deconvolution method can be traced back to Hood (1965) who first wrote down Euler's homogeneity equation for the magnetic case and derived the structural index that can be defined as a measure of the rate of change with distance of a field. Thompson (1982) further studied and implemented the method by applying Euler deconvolution to synthetic and real magnetic data along profiles. Reid *et al.* (1990) followed up a suggestion by Thompson (1982) and developed the equivalent method (3D Euler deconvolution), operating on grided magnetic data. The 3D Euler's equation can be defined (Reid *et al.*, 1990) as

$$x\frac{\partial T}{\partial x} + y\frac{\partial T}{\partial y} + z\frac{\partial T}{\partial z} + \eta T = x_0\frac{\partial T}{\partial x} + y_0\frac{\partial T}{\partial y} + z_0\frac{\partial T}{\partial z} + \eta b, \qquad (1)$$

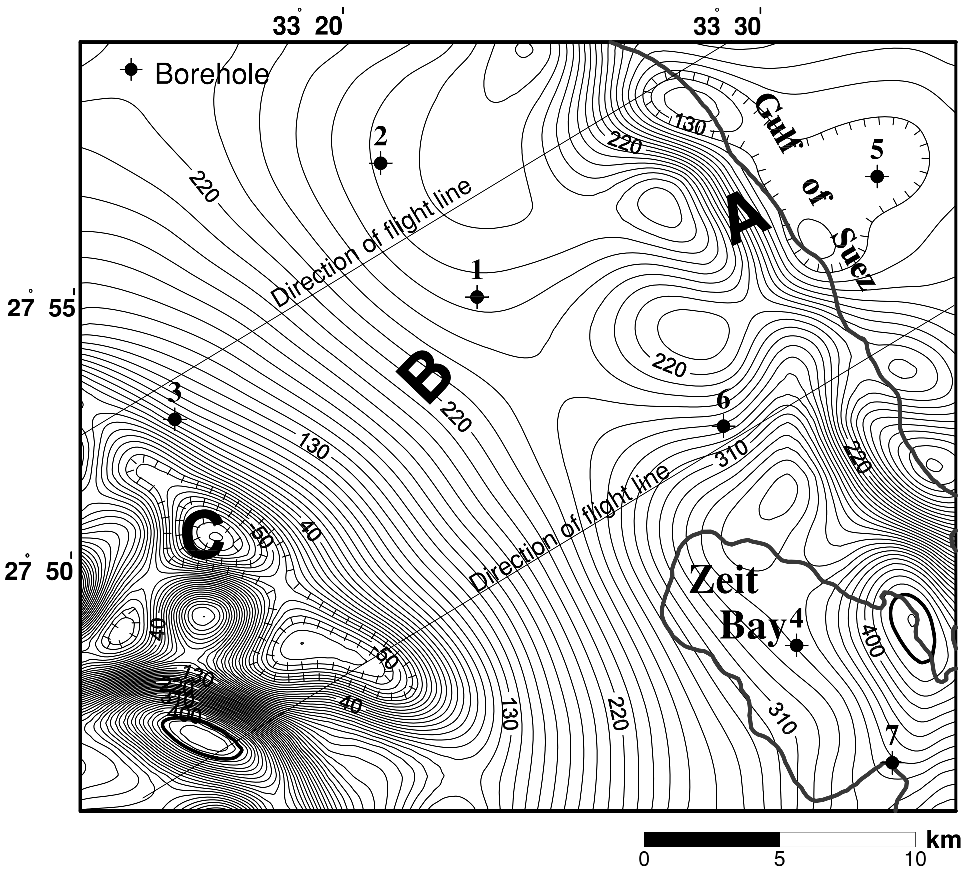

Fig. 2. Aeromagnetic contour map of the Gebel El-Zeit area, (Aero Service, 1984), C.I. = 10 nT. Drill-holes depths are explained in Table 1.

where η is the structural index value that needs to be chosen according to a prior knowledge of the source geometry (e.g. $\eta = 1$ for dike, $\eta = 2$ for a horizontal or vertical cylinder, and $\eta = 3$ for magnetic sphere); b is the base level of the field; ($\frac{\partial T}{\partial x}$, $\frac{\partial T}{\partial y}$, and $\frac{\partial T}{\partial z}$) are the derivatives of the field in x, y and z directions. The field is measured at a point (x, y, and z) and is produced by a point or line source located at a point (x_0, y_0, and z_0). By considering four or more neighboring observations at a time (an operating window), source location (x_0, y_0, and z_0) and b can be computed by solving a linear system of equations generated from Eq. (1). Then by moving the operating window from one location to the next over the anomaly, multiple solutions for the same source are obtained (Ravat, 1996). One of the main disadvantages of the Euler technique is that only a few simple geometries satisfy Euler's homogeneity equation (Blakely, 1995). Additionally, the technique is best suited for sources for which the anomaly attenuation rate is constant such as idealized magnetic sources. For arbitrary sources, the structural index changes with the source-to-observation distance, which may lead to errors in the depth estimate of the source (Ravat, 1996). Another disadvantage of this method is that the structural index must be assumed as prior information. However, Thompson (1982) and Reid *et al.* (1990) showed that the optimum structural index usually yields the tightest clustering of the solutions. Despite this disadvantage, the Euler deconvolution technique commonly gives satisfactory results approximated to the location for complex bodies.

5. Analytic Signal Method

The amplitude of analytic signal (AAS) of the magnetic anomaly is given by Roest *et al.* (1992) as

$$AAS(x, y) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2}. \quad (2)$$

The horizontal and vertical derivatives of the magnetic anomaly are Hilbert transform pairs of each other (Nabighian, 1972). The analytic signal method has been successfully applied in the form of profile data to locate dike bodies (Nabighian, 1972, 1974, 1984; Atchuta *et al.*, 1981). Moreover the approach was further developed by Roest *et al.* (1992) for the interpretation of aeromagnetic maps. Improvements of the approach in the interpretation of aeromagnetic data were also presented by Hsu *et al.* (1996, 1998). Furthermore, Thurston and Smith (1997) presented a variation of the approach (also known as local wave number).The appeal of the method is that the location and depth of the sources are found with only a few assumptions about the nature of the source bodies, which usually are assumed as 2D magnetic sources (contact, horizontal cylinder, or dike). For these geological models, the shape of the AAS is a bell-shaped symmetric function located directly above the source body. In addition, depths can be obtained from the shape of AAS (Atchuta *et al.*, 1981; Roest *et al.*, 1992). Roest *et al.* (1992) pointed out that the depth can be estimated from the shape of the analytic signal based on nonlinear curve fitting. However, solving the non-linear prob-

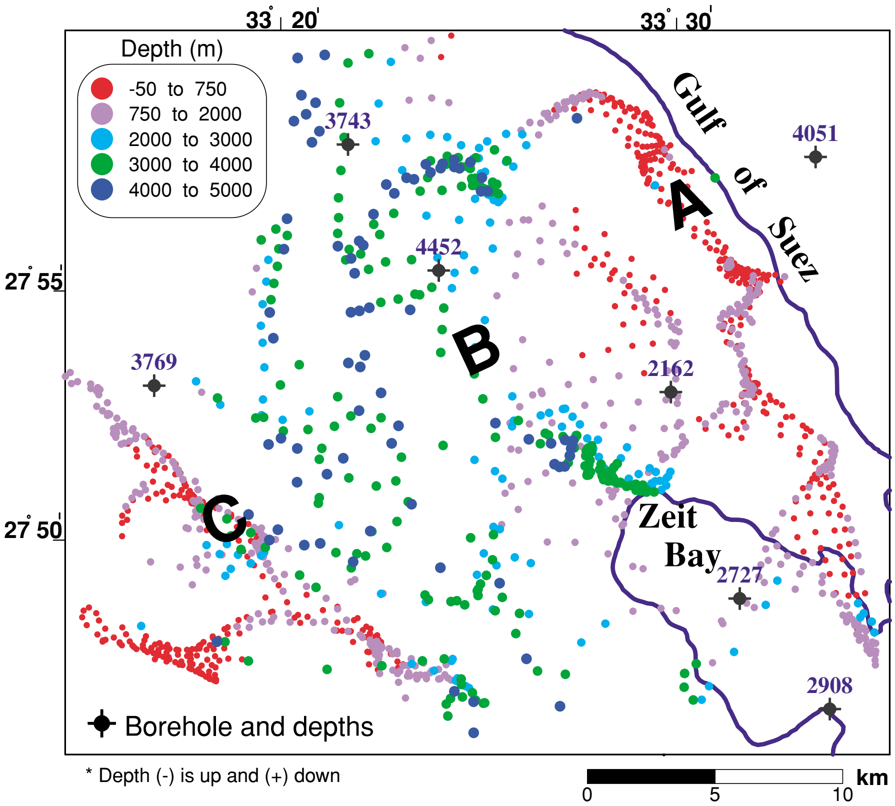

Fig. 3. Euler method solutions of Gebel El-Zeit area using a structure index of 0.5. Drill-holes depths are explained in Table 1.

lem is always difficult. Here, we have developed an alternative method from which the depth for a contact model can be calculated from the analytic signal. The 2D expression of the AAS for a contact model can be written (MacLeod *et al.*, 1993) as

$$AAS(x) = \frac{K}{(x^2 + z^2)^{1/2}}, \tag{3}$$

where K is the magnetization constant and z is the depth to the top of the contact. It is clear that, the analytic signal attains its maximum above the source directly at $x = 0$ as

$$AAS(0) = \frac{K}{z}. \tag{4}$$

Normalizing Eq. (3) by (4), we obtain

$$AAS_n(x) = \frac{AAS(x)}{AAS(0)} = \frac{z}{(x^2 + z^2)^{1/2}}. \tag{5}$$

Squaring and rearranging Eq. (5), we get

$$(AAS_n(x))^2 \cdot x^2 = z^2(1 - (AAS_n(x))^2). \tag{6}$$

It is obvious that the above equation can provide the depth to the contact model from only two normalized analytic signal values. However, due to several sources of errors, multiple values are required to get a good depth estimate. The depth can be obtained from Eq. (6), by least-squares approximation as

$$z = \sqrt{\frac{\sum_{i=1}^{m} (AAS_n(x_i))^2 \cdot x_i^2}{\sum_{i=1}^{m} (1 - (AAS_n(x_i))^2)}}, \tag{7}$$

where m is the number of observations.

6. Application and Results

Since Euler and analytic signal methods are based on the derivatives of the field, noise in the measured data can affect the results. Such noise may come from various sources such as the measurement uncertainty, the removal of the background fields and the computation errors of gradients. Noise reducing techniques such as upward continuation and low pass filters can be implemented to reduce the effect of noise and enhance signal to noise ratio of the observed data (Salem *et al.*, 2004). In this study, we have applied upward continuation with a distance of 0.5 km as a smoothing filter.

6.1 Results of euler method

In our study, we are seeking the magnetic contacts that may delineate the basement beneath sedimentary basins. Theoretically, a structural index of 0 is an appropriate value for contact models. However, this value usually gives unstable results (Barbosa *et al.*, 1999). Therefore, we have assigned a value of 0.5 as a structural index to locate the possible magnetic contacts from the observed magnetic data. Reid *et al.* (1990) and Ravat (1996) discussed adequately the effect of the size of the operating window on the estimation of source location using the Euler technique. Generally, selection of the window size is a function of the grid cell size and should be selected to be large enough to incorporate substantial variations of the total field and its gradients (Ravat, 1996) and small enough to avoid significance effects from adjacent or multiple sources. Calculated solutions from larger windows contain fewer artifacts due to noise (Ravat, 1996). For this study, we used an overlapping moving window of 2.5 km by 2.5 km (10 × 10 data points) for Euler depth estimation.

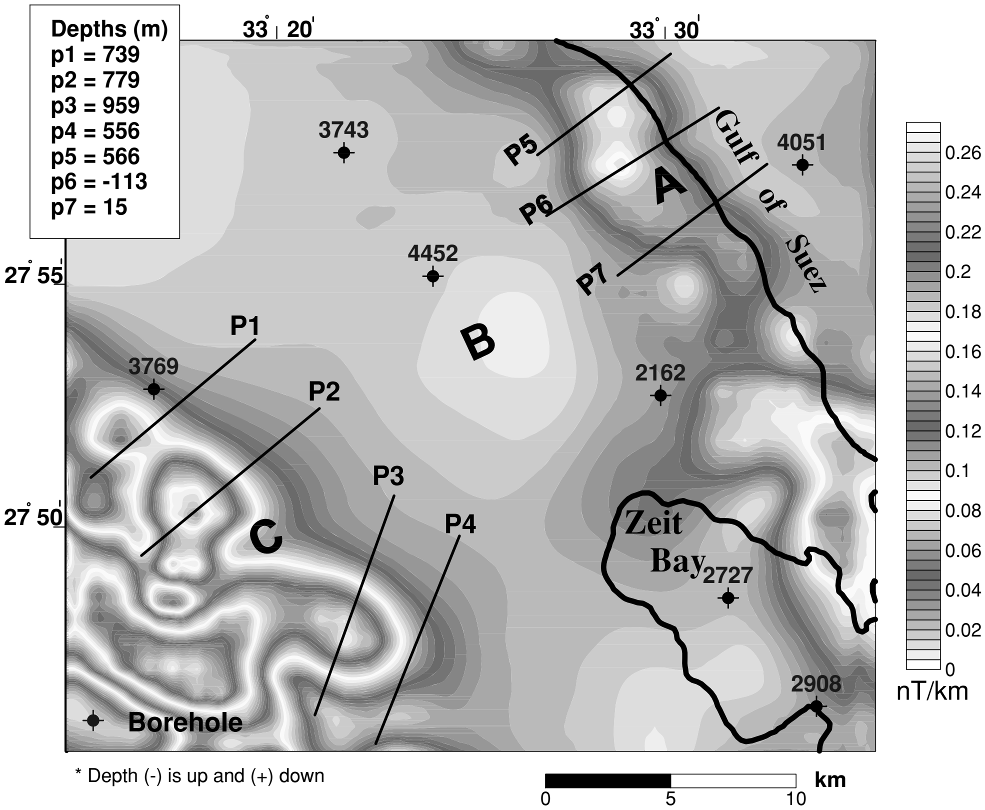

Fig. 4. Analytic signal image map of the Gebel El-Zeit area. P1–P7 are the selected profiles and their estimated depths are listed in Table 2 (see legend), Drill-holes depths are explained in Table 1.

Table 1. Drill-holes and depths of the basement in the study area.

No	Well Name	Depth (m)	Penetration
1	Zeit Bay #1	4452	Upper Cretaceous
2	G. Zeit #2	3743	Miocene
3	Wadi Dib #1	3769	Basement
4	C9A-1	2727	Basement
5	ERDMA-2	4051	Basement
6	Gazwarina #1	2162	Basement
7	QQ 89-3	2908	Basement

Table 2. Estimated depths from analytic signal method at the contacts.

Profile	Depth (m)
P1	739
P2	779
P3	959
P4	556
P5	566
P6	−113
P7	15

Figure 3 shows the Euler source locations with circles colored by the estimated depth values. It is worthy to note that some of the solutions are well clustered and trending in the Red Sea direction (NW-SE), especially in the regions labeled A and C. The source locations A and C have depths ranging from 50 m (over the ground) and 2 km. Source locations within region B are found to be less clustered than those for A and C. The depth values for these source locations ranged between 3 km and 5 km. From the drill hole information, at the region B, basement depth is more than 4452 m (Zeit Bay #1, Upper Cretaceous). Generally, the estimated depth values agree with the depth information obtained from the drill holes (Table 1). Accuracy of the results depends on the signal to noise ratio of the magnetic anomalies. This may explain the poor clustering of region B where anomalies of have lower signal to noise ratio than in other source regions (A and C).

6.2 Results of analytic signal method

The analytic signal signature of the Gebel El-Zeit area was calculated (Fig. 4) from the upward-continued data, in the frequency domain using the FFT technique (Blakely, 1995). Higher values of the AAS are observed at two regions labeled A and C as shown in Fig. 4, which indicates that, these regions have significant susceptibility contrast that give signatures on the map. Moreover, the boundaries of Zeit basin could be easily observed, from Fig. 3, which indicated the effectiveness of the analytic signal method in basin studies. To estimate the depth to the basement from the analytic signal, seven profiles were selected over the regions A and C (in which contacts could be found). Equation (7) was used to calculate the depth for each profile at the contacts between basement rocks and sedimentary basin.

The calculated depth (for each profile) was located at the maximum value of the analytic signal. This maximum is not necessary to be located at the center of the profiles because it depends on the location of the source with respect to the profile (horizontal displacement). All the depths are calculated from the ground level after subtracting the upward-continued distance (500 m) and the terrain clearance distance (120 m). Table 2 shows the depth values derived from the method mentioned before. Generally, the depth values for region A have an average value of 156 m and for region C an average of 758 m. However, the calculated depths from Euler method at region C were ranged between 50 m (on the ground) and 750 m beneath the subsurface and the average calculated depths from the analytic signal about was 758 m. This discrepancy could be explained by the distribution of magnetic rocks along this region at different depths.

7. Conclusions

In this paper, we attempted to add a new insight on the structural setting of the Gebel El-Zeit area from the aeromagnetic data. The study is based on application of Euler and analytic signal methods. Results of these methods help define the main geological trends and depths of subsurface geologic structures. The similarity of the estimated depth values from the Euler and analytic signal method suggests that these methods are very useful to locate subsurface magnetic sources, which reflect the structural framework of the area.

The study area is characterized by a basin structural system taking the direction of NW-SE (Red Sea direction). The basement is exposed on the eastern and western flanks and reaches depths of ~5 km in the central part.

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