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Interpretation of Aeromagnetic Data of Gebel El-Zeit Area, Gulf of Suez, Egypt Using Magnetic Gradient Techniques

by

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Abstract

This paper documents results of an integrated interpretation technique of magnetic data over the onshore of Gebel EL-Zeit area, Gulf of Suez in Egypt. The objective of this study is to identify the possible subsurface structure of the area that may assist in delineation of promising prospects for hydrocarbon exploration. We have applied magnetic gradient techniques including Euler deconvolution and analytic signal methods to the aeromagnetic data. Results of these methods enabled definition of the geological trends and depths of subsurface geologic structures. The study area is characterized by a basin structure bounded by major uplifting faults striking in the NW-SE direction. Depth to the basement of such basin structure ranges about 1.5 km in the eastern and western parts of the study area and gets deeper toward the central part up to 4.5 km.

Keywords: Gebel El-Zeit area, Magnetic, Euler deconvolution, Analytic signal, Gulf of Suez, Egypt

1. Introduction

Gebel El-Zeit area is located on the western flank of the Gulf of Suez in Egypt, between latitudes $27^{\circ}45' - 28^{\circ}00'$ N and longitudes $33^{\circ}15' - 33^{\circ}35'$ E (Fig. 1). This area has a great importance due to its hydrocarbon resources. Many geophysical works have been applied in this area to delineate the subsurface structure and its relation to hydrocarbon prospects. The work included seismic surveys that can be rated poor due to the problem of masking seismic energy by salt formation. Therefore, other geophysical studies are recommended to delineate the subsurface structures.

Magnetic method is one of the best geophysical techniques to delineate subsurface structures. Generally, aeromagnetic maps reflect the variations in the magnetic field of the earth. These variations are related to changes of structures, magnetic susceptibilities, and/or remanent magnetization.

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Sedimentary rocks, in general, have low magnetic properties compared with igneous and metamorphic rocks that tend to have a much greater magnetic content. Thus, most aeromagnetic surveys are useful to map structures of the basement and intruded igneous bodies from basement complex.

This study deals with an integrated interpretation of the observed aeromagnetic data of Gebel El-Zeit area. Such interpretation is based on application of gradient (Euler deconvolution and analytic signal) methods. The potential advantage of these methods is that they do not assume geologic model. Therefore, they can be applied even when the geological structure cannot be represented.

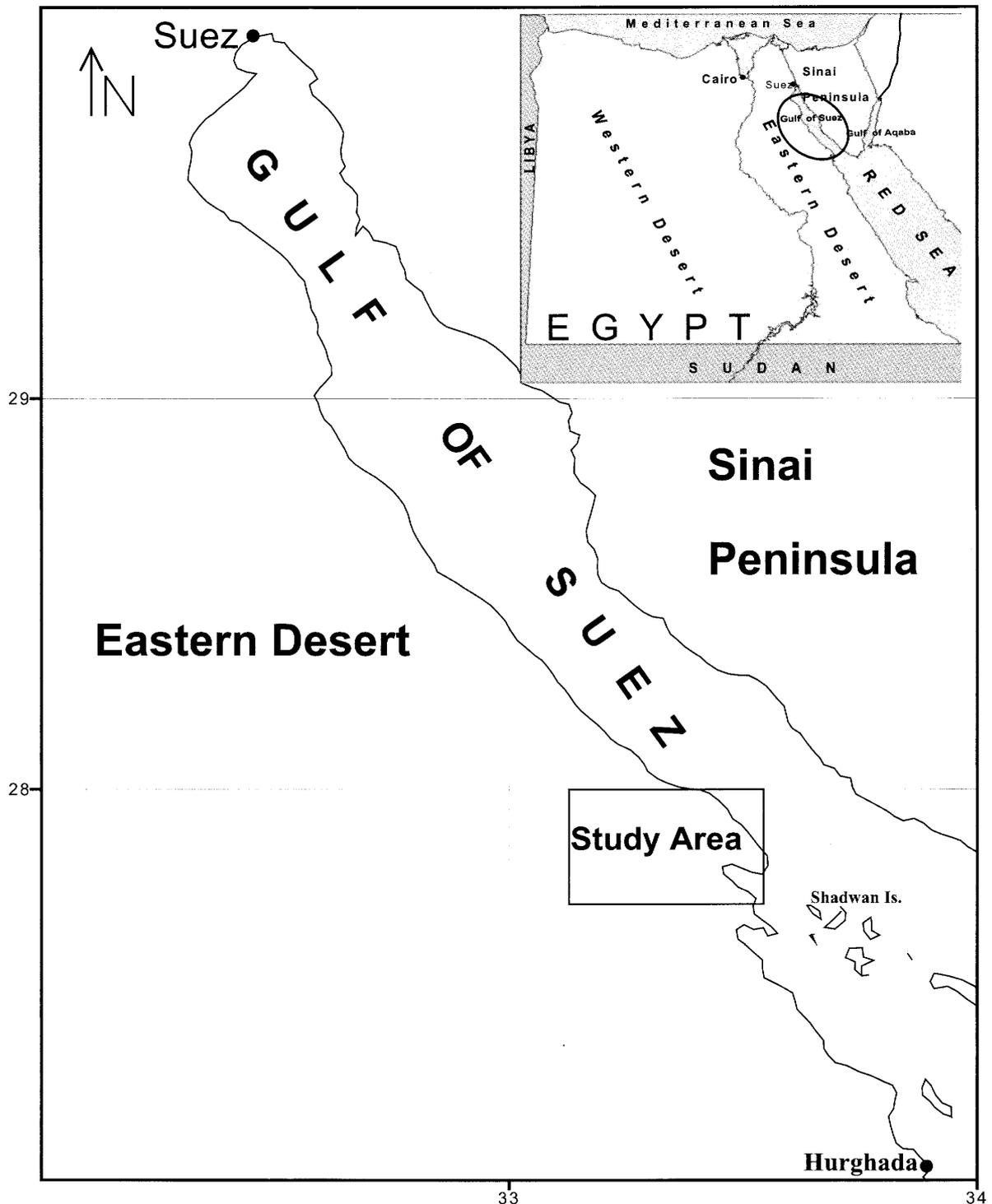


Fig. 1 Location map of Gebel El-Zeit area, Gulf of Suez in Egypt.

2. Geologic Setting

Gebel El-Zeit area is characterized by several major and minor topographic features (**Fig. 2**). The most conspicuous of all is gravel plain occupying the central part of the area and is bordered from the west by the northern part of Esh-Mellaha range, and from the east by the relatively high topographic features of Zeit range which extends for about 30 km in the NW-SE direction, parallel to the Gulf shore line, consisting of separate patches of igneous and metamorphic rocks.

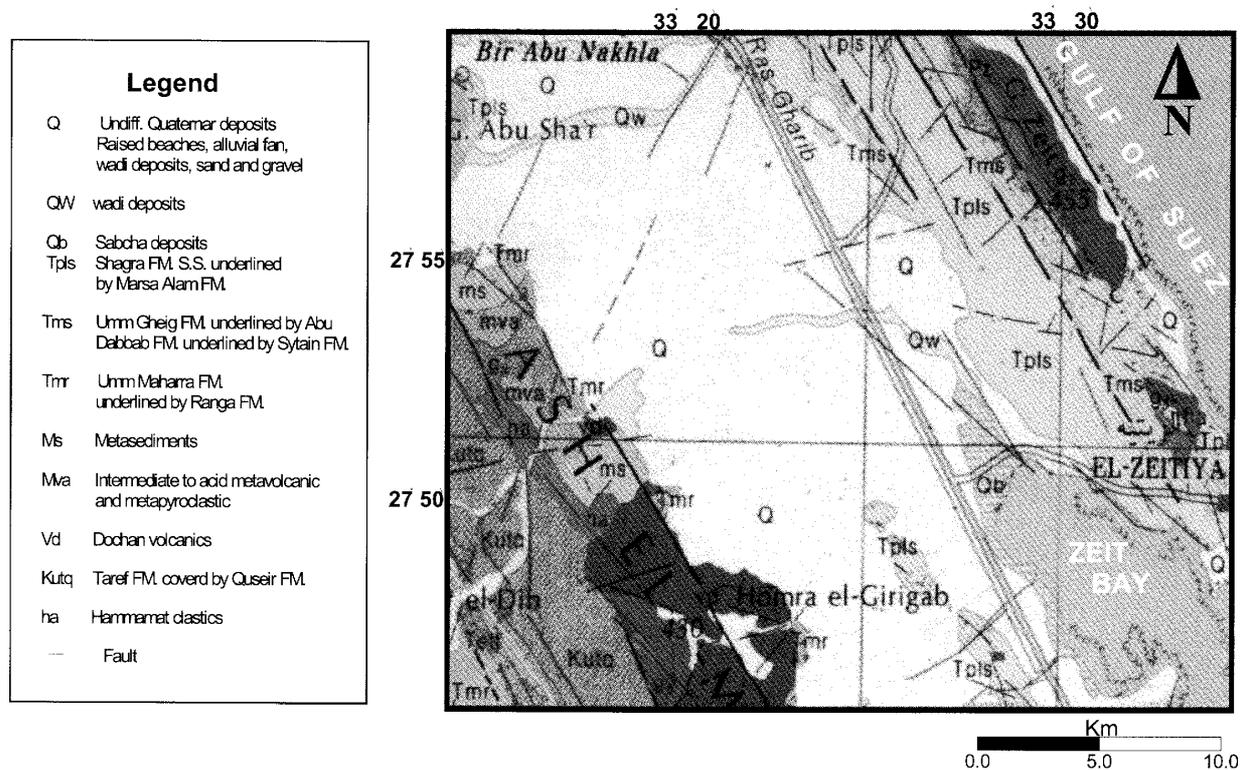


Fig. 2 Geological map of the Gebel El-Zeit area (after Conoco, 1987)

Geomorphologically, the area constitutes a major synclinal feature extending northwestward from Zeit bay to Ras Shukier. This regional synclinal feature is bordered from its western side by a major fault, trending in the NW-SE direction. This fault brings the granite mass of the northern portion of Esh-Mellaha range in contact with the younger sedimentary rocks. Several major and minor structures, including faults and folds, are recognized at the western part of the area taking the NE-SW direction. The eastern portion of the area, generally consists of another set of major and minor faults, most of which are buried below the Miocene sediments. Allam¹⁾ stated that the area is characterized by two main faults parallel to the Gulf of Suez, namely Zeit fault and Ras El-Dib fault. These two faults make the area to be in a form of a Graben structure taking the direction of NW-SE.

3. Aeromagnetic Data

Gebel El-Zeit area was covered by an aeromagnetic survey conducted by Aero Service Division, Western Geophysical Company of America²⁾. 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 a NE-SW

direction. The data were recorded at a sampling interval of 91 m.

In most aeromagnetic surveys, interpretation is inherently ambiguous. So that, all available information should be combined if the best conclusions are to be obtained³. In general, heterogeneity and deformation of the basement rocks will lead to sharp and strong magnetic signatures, which are easily observed on the aeromagnetic maps. The recorded magnetic anomalies display several trends. It should be stated that magnetic trends do not occur at random, but are generally aligned along definite and preferred axes forming trends that can be used to define magnetic provinces^{4,5}.

The aeromagnetic map of Gebel El-Zeit area (**Fig. 3**) shows positive and negative magnetic anomalies, which are distributed throughout the area. Maximum magnetic value (440 nT) was recorded at the southwestern part and the minimum value (-120 nT) was recorded at the western part.

Figure 3 also shows that the area is composed of three main magnetic regions; north east, south west and central region. These regions can be distinguished on the basis of the variations in density of the contour lines, which reflect the variation of intensity of magnetic response. The north-eastern and south-western regions are characterized by low magnetic anomalies trending in the NW-SE and NE-SW (Aulitic or Tibesti trend) directions. The observed magnetic anomalies in the eastern and western regions have a width of 1-3 km with moderately steep gradients, indicating intermediate depth sources. The southeastern part of the area is characterized by a strong magnetic amplitude. Example of such strong magnetic anomalies are corresponding to Esh-Mellaha range and the offshore Zeit bay (**Fig. 2**). The third region, which is located in the central part of the area, is characterized by high magnetic gradient striking in the Red Sea direction.

Visual inspection of the aeromagnetic map (**Fig. 3**) indicated that the most dominant trend in

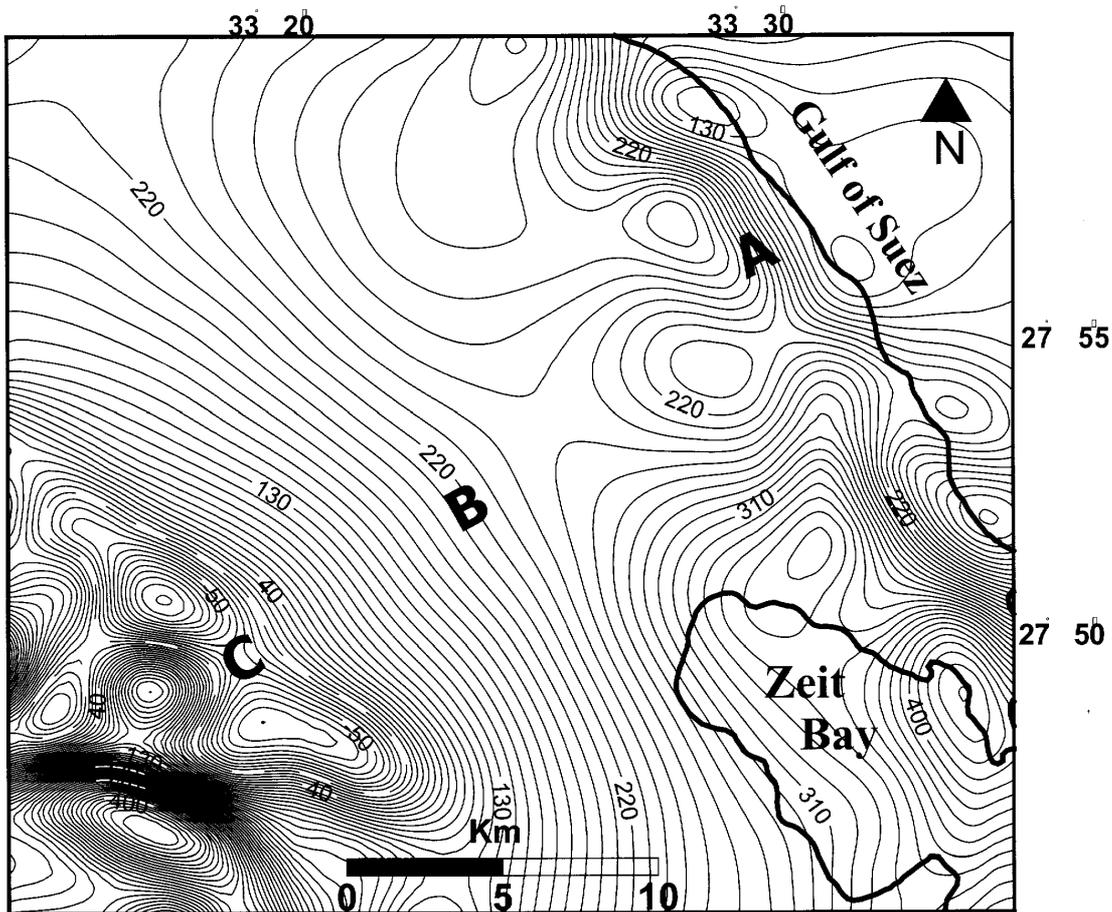


Fig. 3 Aeromagnetic contour map of the Gebel El-Zeit area, (Aero Service, 1984), C.I. = 10 nT.

the Gebel El-Zeit area is the NW-SE direction, which is related to the main trend of the Red Sea. The second dominant trend is found to be in the N-S direction, which is related to the Nubian or east African trend. The least dominant trend is observed in the E-W direction and could be related to the Tethyan trend.

4. Gradient Interpretation Techniques

4.1 Euler Deconvolution

Euler deconvolution can be traced back to Hood⁶⁾ who first wrote down Euler's homogeneity equation for magnetic case and derived the structural index that can be defined as a measure of the rate of change with distance of a field. Thompson⁷⁾ further studied and implemented the method by applying Euler deconvolution to model and real magnetic data along profiles. Reid et al⁸⁾ followed up a suggestion by Thompson⁹⁾ and developed the equivalent method (3 D Euler deconvolution), operating on grided magnetic data.

Potential fields satisfy Laplace's equation outside the source region¹⁰⁾. The total field magnetic anomaly (T) 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) can be expressed as

$$T(x, y, z) = \frac{K}{\sqrt{((x-x_0)^2 + (y-y_0)^2 + (z-z_0)^2)^\eta}}, \quad (1)$$

where K is a constant based on magnetic units, the direction of the inducing field at the surveyed area, and the direction of magnetization. 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). If the total field has a base level of b and derivatives ($\frac{\partial T}{\partial x}$, $\frac{\partial T}{\partial y}$, and $\frac{\partial T}{\partial z}$ in the x , y , and z directions), the 3 D form of Euler's equation can be defined by Reid⁸⁾ as

$$x \frac{\partial T}{\partial x} + y \frac{\partial T}{\partial y} + z \frac{\partial T}{\partial z} + \eta T = x_0 \frac{\partial T}{\partial x} + y_0 \frac{\partial T}{\partial y} + z_0 \frac{\partial T}{\partial z} + \eta b. \quad (2)$$

By considering four or more neighboring observations at a time (an operated window), source location (x_0 , y_0 , and z_0) and b can be computed by solving a linear system of equations generated from equation (2). Then by moving the operated window from one location to the next over the anomaly, multiple solutions for the same source are obtained¹¹⁾.

4.2 Analytic Signal Method

The amplitude of the analytic signal (AAS) of magnetic anomaly can be defined as the square root of the sum of the vertical and two orthogonal horizontal derivatives of magnetic field such as

$$|AAS(x, y)| = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad (3)$$

The horizontal and vertical derivatives of the magnetic field are Hillbert transform pairs of each other¹²⁾. The analytic signal method has been successfully applied in the form of profile data to locate dike bodies^{13, 14, 15, 16)}. Moreover the approach was further developed by Roset et al¹⁷⁾ for the interpretation of the aeromagnetic maps. Improvements of the approach in the interpretation of aeromagnetic data were also presented by Hsu et al^{18, 19)}. Furthermore, Thurston and Smith²⁰⁾ presented

a variation of the approach (also known as local wave number).

The AAS of magnetic anomalies can be easily computed. The horizontal derivatives can be calculated directly from a total field grid using a simple 3×3 difference filter. Also, both the horizontal and vertical gradients can be calculated in the frequency domain using the conventional Fast Fourier Transform (FFT) technique. Also, MacLeod et al²¹⁾ calculated the vertical derivatives from the vertical integral of the magnetic field in order to produce a result that was more similar to the analytic signal of pseudo-gravity.

Another reason for the appealing of the method is that the locations and depths of the sources are found with only a few assumptions about the nature of the source bodies, which usually are assumed as 2 D magnetic sources (for example, 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^{13,21)}. However, depths estimated based on the shape of the AAS are subjective and usually have errors.

In this paper, we have developed a new method from which the depth for a contact model can be calculated from the AAS in a least-squares sense. The 2 D expression of the AAS for a contact model can be written²¹⁾ as

$$AAS(x) = \frac{K}{(x^2 + z^2)^{1/2}}, \quad (4)$$

where K is a magnetization constant and z is the depth to the top of the contact. Using the value of the AAS above the source ($x=0$), equation (4) can be normalized as:

$$AAS_n(x) = \frac{AAS(x)}{AAS_0(x)} = \frac{z}{(x^2 + z^2)^{1/2}} \quad (5)$$

Rearranging equation (5), we obtain:

$$(AAS_n(x))^2 \cdot x^2 + (AAS_n(x))^2 \cdot z^2 = z^2 \quad (6)$$

It is obvious that the above equation can provide the depth to the contact model from single normalized analytic signal value. However, due to several sources of errors, multiple values are required to get a good depth estimate. In a least-square sense, equation (6) can be solved as

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

where m is the number of observations.

5. Application and Results

Euler deconvolution and analytic signal methods can be used to provide source location parameters from magnetic data. Because these methods based on the derivatives of the field, noise can affect the results if they are present in the measured data. Such noise may come from various sources such as the measurements uncertainty, the removal of the main and external fields and the computation of the gradients that enhance the noise. Noise reducing technique such as an upward continuation and a low pass filter can be implemented to remove the effect of such noise and enhance signal to noise ratio of the observed anomalies. In this study, we have applied upward continuation with a distance of 0.5 km to reduce the effect of noise as shown in **Fig. 4**.

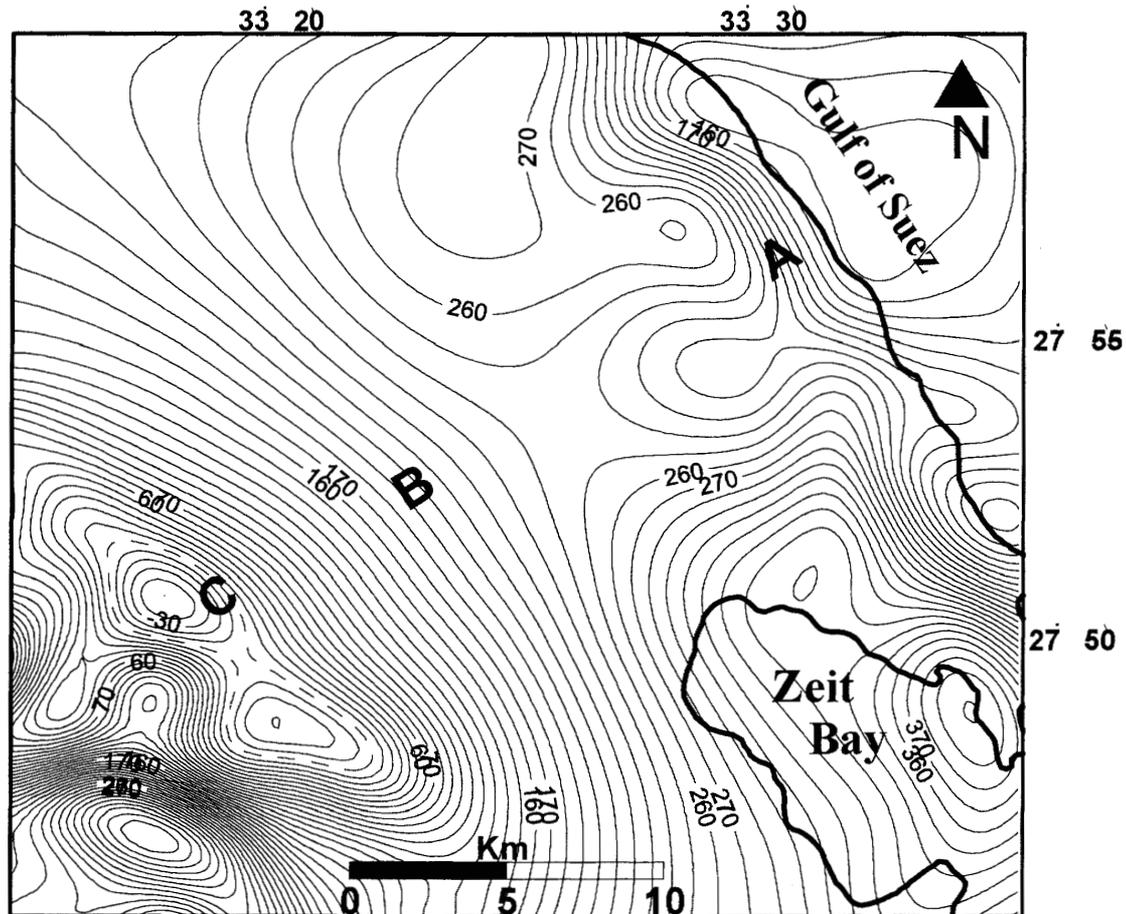


Fig. 4 Upward continuation map of Fig. 3 using a distance of 0.5 km.
C.I. = 10 nT

5.1 Results of Euler Deconvolution

In the Euler method, an estimate of the source location is derived from the anomalous field, its gradients, and the rate of attenuation of the anomaly (which is based on the shape of the source). One of the main disadvantages of the Euler technique is that only a few simple geometrics satisfy Euler's homogeneity equation¹⁰. 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 source¹¹. Despite this disadvantage, the Euler technique gives satisfactory results approximated to the location for complex bodies. Another disadvantage of the method is that the structural index must be assumed as prior information. However, Thompson³ and Reid⁸ showed that the optimum structural index usually yields the tightest clustering of the solutions. In our study, we are seeking for locating the magnetic contacts that may delineate sedimentary basins. Theoretically, a structural index of 0 is an appropriate value for contact models. However, this value usually gives unstable results²³. 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 al⁸ and Ravat¹¹ discussed adequately the effect of the size of the operated window on the estimation of source location using the Euler technique. Generally, selection of the window size is a function of the grid cell and should be selected to be large enough to incorporate substantial variation of the total field and their gradients¹¹. Solutions calculated from larger windows would

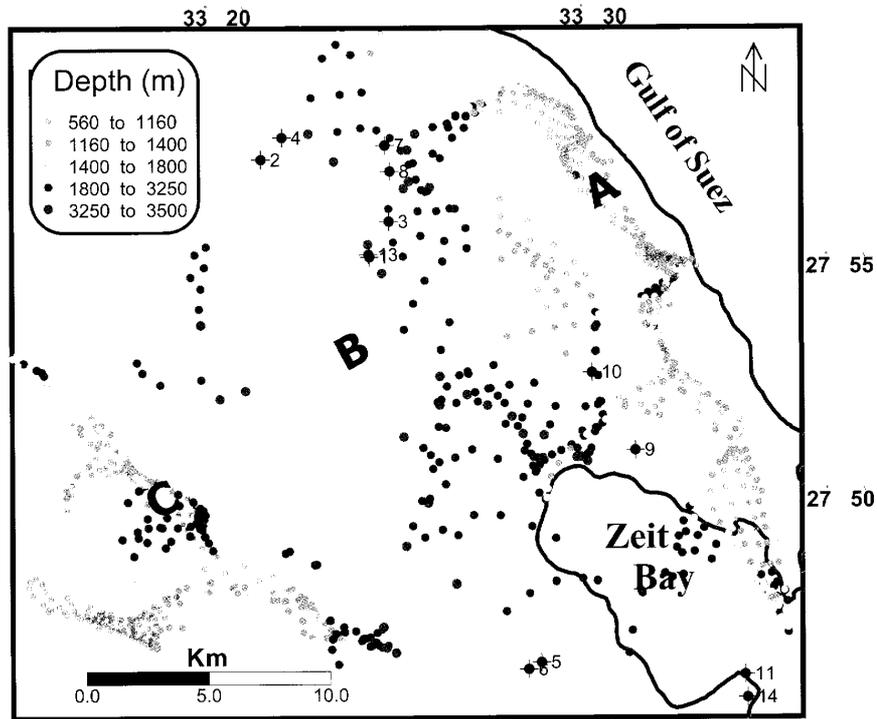


Fig. 5 Solutions of the Euler deconvolution using a structural index of 0.5.

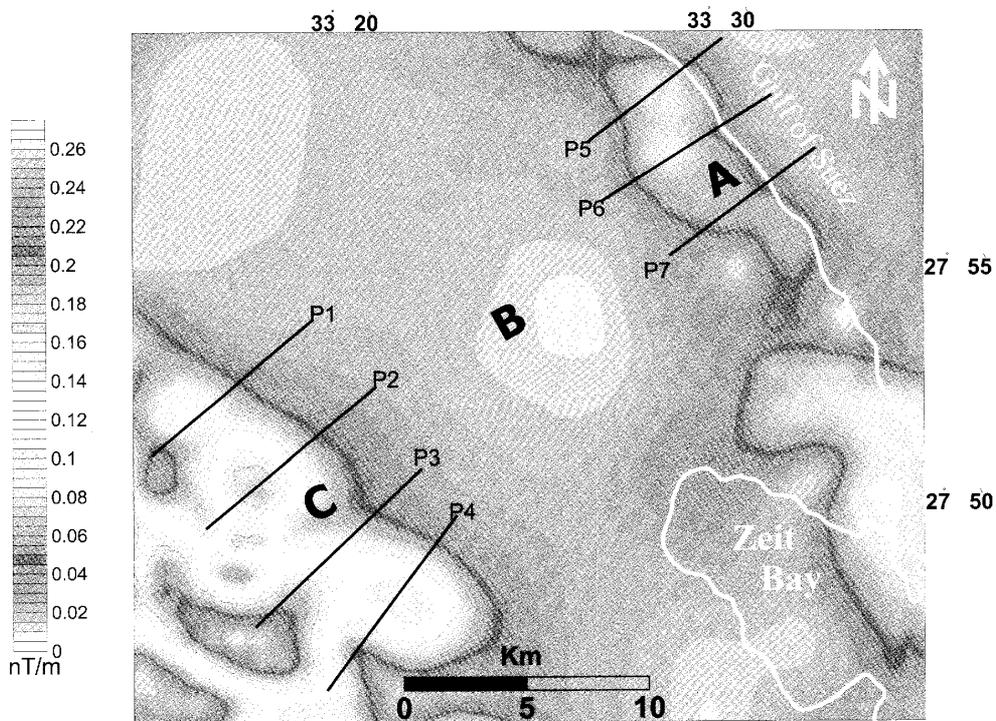


Fig. 6 Analytic signal contour map of the Gebel El-Zeit area.
C.I. = 0.005 nT/ km

contain fewer artifacts due to the effects of noise¹¹. The Euler method was applied in an overlapping moving window of 1 km by 1 km.

Figure 5 shows the derived source locations with circles showing the estimated depth values. It is worthy to note that some of the solutions are well clustered, especially at the regions labeled (A) and (C). Generally, well clustering solutions reflect an appropriate of the structural index.

Table 1 Estimated depth from analytic signal method.

Well no.	Well Name	Depth (m)
1	Zeit Bay # 1	4452.8*
2	Zeit Bay-2	2321.9
3	G. Zeit # 1	3502
4	G. Zeit # 2	3743*
5	N.Ras Bhar # 1	3134.8*
6	N.Ras Bhar # 2	3669.3*
7	Ras Dib # 1	2598
8	Ras Dib # 2	1517.5
9	W. G. Zeit # 1	1954.3
10	Gawarina # 1	2859.2*
11	QQ 89-3	2024.2
12	Ras Elbahar-E#2	1449.7*
13	Ramadan # 1	3760.0

* Depth penetrated to the basement.

Figure 5 also shows that there are two main trends (Labeled A and C) having a good clustering and taking the direction of the Red Sea (NW-SE). The source locations (A) have depth values between 560 m to 1400 m with an average depth of 980 m. The source locations (C) are found with depth values ranged between 560 m and 1800 m with an average depth of 1180 m. Source locations (B) are found to be less clustered than those for (A) and (C). The average depth values for this source locations are ranged between 1800-3500 m. Two wells were drilled (Gebel El Zeit-2 and Zeit Bay-2) to the basement and the estimated depth values are in agreement with the depth information obtained from the drill holes (**Table 1**). Generally, good solutions of the Euler method depend on the amplitude of the anomaly and its gradient. This may explain the poor clustering of (B) where anomalies of these locations are very deep and have low signal to noise ratio than other source locations (A and C).

5.2 Results of Analytic Signal

The analytic signal method assumes that 2 D structures such as contact, dike, and horizontal cylinder structures^{14, 18, 22}. For these models, the maxima of the amplitude of the analytic signal (AAS) are located directly over the edges of the models¹⁷. Macleod²¹ stated that, the analytic signal anomaly marks a magnetic contrast, however, one does not know the sense of the contrast of the analytic signal. Original total field map should be used as a help to resolve these aspects of an interpretation. Since the AAS combines all vector components of the field into a simple constant, a good way to think of analytic signal is as a map of magnetization²¹. In this regards, stronger anomalies can be expected where the magnetization vector intersects a magnetic contrasts at acute angle²¹.

From the upward continued data (**Fig. 4**), the analytic signal signature of the Gebel El-Zeit area was calculated (**Fig. 6**) in the frequency domain using the FFT technique. Higher values of the AAS are observed at two regions labeled (A) at the east and (C) at the west (as shown in **Fig. 6**). The regions (A) and (C) are associated with Gebel El-Zeit and Esh-Mellaha localities. The region (A) and (C) are separated with an area of low gradient (labeled B in **Fig. 6**). Moreover, the contour trends of the AAS for the regions (A) and (C) correlate well with the main structure trends of these

Table 2 Depth information from borehole data.

Profile	Number of data point	Depth (m)
P1	95	1359.0
P2	114	1399.0
P3	106	1579
P4	122	1176.0
P5	132	1186.0
P6	122	507.0
P7	118	635.0

localities. This analytic signal pattern illustrates clearly a graben structure system that characterized the study area.

To apply our depth estimation method from the analytic signal, seven profiles were selected over the regions (A) and (C). Depths were then estimated using a least squares method. **Table 2** shows the depth values derived from the analytic signal. Generally, the depth values for region (A) are ranged between 507.0 m and 1186.0 m, while the average depth values from Euler at the region A is 980 m. The depth values of the region (C) are ranged between 1176.0 m and 1579 m, while the average depth value from Euler at region C is 1180. The similarity of the estimated depth values from both methods (Euler and analytic signal) indicates that these methods are very useful to locate subsurface magnetic sources, which reflect the structure framework of the area.

6. Conclusions

In this paper, we aimed to add a new insight on the structural setting of Gebel El-Zeit area. The study was based on an integrated application of Euler deconvolution and analytic signal methods to aeromagnetic data of Gebel El-Zeit area. Results of these methods enabled definition of the geological trends and depths of subsurface geologic structures. We also present a new method for depth estimation from the analytic signal for contact model. The area is characterized by a basin structural system taking the direction of NW-SE (Red Sea). Depth to the basement of basin structure ranges about 1.5 km in the eastern and western parts of the study area and gets deeper toward the central part up to 4.5 km.

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