Inferring the Subsurface Basement Depth and Structural Trends of the Northwestern Part of the Western Desert, Egypt, as Deduced from the Potential Field Data

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Abstract: The main goal of the present study is an attempt to determine the sedimentary cover and structural trends in the northwestern part of the Western Desert, Egypt, through the integrated analysis and interpretation of the total intensity and Bouguer gravity as the main source of information. The study was initiated by reducing the total magnetic map to the northern magnetic pole map. Different analytical techniques were applied on both the RTP magnetic and gravity data, including; regional- residual separation using power spectrum method, structural trend analysis and depth improvement for the basement surface from gravity and RTP magnetic data. The depths obtained throughout three methods; power spectrum technique, analytical signal tool and two- dimensional modeling of RTP magnetic data. Where, the depths obtained from the first two methods will be used as a control points in the RTP two- dimensional modeling in order to minimize the error and facilitate the iteration of the suggested models. The basement relief map from gravity and magnetic output has been produced. This map indicates that, the basement depth, generally, increases from north and south to central part of the study area. The sedimentary cover is about 2.0 km in the northern and southern parts with increases to more than 5.4 km in the central, eastern and west central part which represents the major basins and changed gradually in the other parts of the study area. Results of structural trend analysis revealed that, the investigated area is greatly affected by several structural trends; E-W, ENE-WSW, NE-SW and N-S directions. These trends are associated with the Mediterranean Sea, Syrian Arc System and Aqaba System, respectively. Beside, this map has revealed a spatial relationship between the paleotopographic highs and lows in the Precambrian basement and structure and thickness anomalies in the overlying Tertiary sediments.

Key words: 2-d modeling • Gravity data • Magnetic data • Power spectrum • Western Desert

INTRODUCTION

The area of study constitutes the northwestern part of the Western Desert, between latitudes 30° 20' and 31°10'N and longitudes 25°00' and 26°45'E (Fig. 1), covering a total surface area of about 210,000 km². For resource exploration purposes one of the most useful inferences that may be derived from analyses of potential field (magnetic and gravity) data is the depth of crystalline basement beneath sedimentary cover. The available data on which the present work is based on is the total intensity aeromagnetic map of the area which was prepared by Philips Oil Company in 1964, with scale of...
Fig. 2: Geologic map of the study area, after conoco 1985

1: 5000000 and contour interval 25 nT, Bouguer gravity map represents a part of the complied gravity constructed in 1982 for the Egyptian General Petroleum Corporation (EGPC) at scale of 1: 500000 and contour of interval 1 mGal. To achieve the main objectives, both the previously mentioned magnetic and gravity data were subjected to several geophysical processing and techniques involving; 1) reduction of the magnetic data to the northern magnetic pole, 2) Isolation of magnetic and gravity data into their near surface high-pass and deep-seated low-pass components using; Fast Fourier Transform, 3) structural trend analysis, 4) depth estimation for some selected magnetic and gravity anomalies using three spectral analysis techniques; power spectrum technique, analytic signal tool and 2.5 dimensional magnetic forward modeling for three selected RTP magnetic profiles. The resulted gravity and magnetic outputs were interested and correlated qualitatively and quantitatively. Finally, the results obtained from all previously mentioned interpretation methods were integrated with information from drilled wells and an interpreted structural basement map for the study area was constructed.

Geological Setting: The regional surface geology of the northwestern Desert, north of latitude 28° 00 is not considered to be complex nature. Most of the exposed rocks are Tertiary age with only few Cretaceous outcrops at Bahariya and Abu Roash locality. The geologic map of the study area (Fig. 2) is not considered to be complex nature. Most of the area is covered by Miocene deposits. Meanwhile along the coastal area, the Pliocene clastics lie unconformably over the Miocene strata. Lithologically, Said [1] subdivided the Miocene deposits into two well - developed rock units, which are from top to bottom; Marmarica limestone (Middle Miocene) and Moghra Formation (Lower Miocene). Who, added that, a gentle northerly dip is exhibited within the Miocene deposits. Photogeological as well as surface geologic map revealed that the northerly dip is interrupted by simple folds which have general NE-SW orientation. Faults of different trends also exist but mostly of minor displacements. Structurally, Said [1], El-Sirafe [2], Abu El-Ata [3], Meshref et al. [4], Meshref [5] and Hantar [6], dealt extensively, with the geology, structure and tectonic of the north western Desert in detail, that brought out facts about its structural pattern. As a result, the structural picture is no longer simple but proved to be rather complex. For example, Hantar [6] concluded that, north Western Desert, where the study area is located, is dominated by faults many of which are step normal faults having a NE-SW, E-W, NW-SE and N-S trends. Some of these faults suffered strike slip movements during part of their geologic history. More than 110 exploratory wells were drilled in the study area by different oil companies, that worked or still working in the area. Five of these wells (Atoun 1x, Nakhwa- 1x, NW Nakhwa1x, Um Baraka - 1 and Um Baraka - 2 ) were bottomed in the basement rocks, indicating that, the study area characterized by a thick sedimentary section, unconformably overlying the basement rocks of crystalline nature and varying lithologies. Also, these subsurface data are used as a geologic control for depth to basement calculation and for defining the structural setting of the area.
MATERIALS AND METHODS

Gravity and magnetic data, whether at land or sea, contain contributions from sources of interest at shallow depths (high pass) as well as contributions from sources at greater depths (low pass). Magnetic and gravity anomalies can be used to define and estimate the physical properties of the source structures that cause the anomalies and indirectly can be mapped as fault elements. A close inspection of the Bouguer gravity map (Fig. 3), reveals the amplitude of the gravitational field generally increase from 4 mGal at the southwestern part to more than 55 mGal at northeastern corner of the area. The gravity map shows two large areal extent gravity belts. The first one is occupied the eastern part of the area and extending in N-S direction. This belt is composed of two positive gravity anomalies with amplitude ranges between 32 mGal for the southern anomaly to more than 55 mGal for the northern incomple anomaly. These two positive anomalies are separated by a local low gravity may be interpreted to be due to local synclinal structure separating them. The second gravity belt is occupied the western half of the area and is mainly associated with large negative gravity anomalies, especially, the E-W trending large negative gravity anomaly located at the extreme southwestern corner of the area with an amplitude of 4 mGals. In addition to, the gravity anomalies and gradients in the area were align themselves along four major trends; NE to ENE, N-W and N-S. Moreover, it is to be noted that, the two different gravity belts (positive to the east and negative to the west) are separated by a large steep gravity gradient of mainly NW trend. This steep gradient may be interpreted to be due to a large basement fault with the down faulted block to the west and uplifted block to the east.

The qualitative interpretation of the magnetic map of the study area (Fig. 4) shows the general distribution of the magnetic anomaly patterns according to their shape and amplitude as well as the trends of the magnetic anomalies. The difference in the nature of the magnetic anomaly zones is believed to be reflecting variations in the basement composition and structures beneath different positions of the study area. The first magnetic anomaly in the study area represents zones of very high magnetic value (180-216 nT). These values are marked by (pink colour) and located in the central and southern parts of the investigated area as a major belt trends E-W direction. These anomalies indicate that, there are highly magnetic bodies underneath these locations. The second magnetic anomaly represents high magnetic anomalies marked by red colour with intensity 25 nT located at the southeastern part. The last low magnetic anomalies (green to blue colour) represents negative magnetic level (-30 to -214 nT) and extends at the northern and south central parts of the study area. Generally, the pattern of the magnetic anomalies reflects a randomly distributed pattern rather than associated with distinct, large scale features as the gravity anomaly map. In order to delineate the regional basement structural framework and the sedimentary cover of the studied area, several analytical techniques have been developed for the analysis and interpret the magnetic and gravity data in the study area. These raw data cannot be enhanced directly where these measurements are uncertain and it needs the removal of the main magnetic field and computation of the gradients that improve anomalies presentation. These techniques include reduction to the pole, regional-residual separation and structural trend analysis as well as depth improvement.

Reduction to the North Magnetic Pole (RTP): Generally, for good accuracy in interpretation of the magnetic anomaly map, it has to differentiate the hypothetical anomaly from the observed type on the total intensity magnetic map, where the causative body can be directed to the northern pole. An RTP (Reduction to the pole) of the total magnetic field application removes the
asymmetric anomalies caused by the inclination and declination of the earth’s magnetic field from the data such that, centering the anomalies directly above their sources, to what they would have been if the magnetic field were vertical. Reduction to the pole technique was carried out on the total intensity magnetic field using the GX’S [7] within the software [8], where the magnetic inclination was 44.78° N, magnetic declination angle of about 3.44° E and total magnetic field was 43237 nT. The constructed RTP magnetic map (Fig.5), illustrates positive and negative anomalies distributed throughout the area, as well as the total intensity aeromagnetic map. The magnetic anomalies are shifted to their correct positions to the northern direction. Besides, the size of the anomalies became larger, while the polarity and trends of main features approximately still as it is. Added to, the magnetic gradients became more intensive and steeper. Therefore, this RTP signature is marked by a ragged relief with positive and negative anomalies of several amplitudes and wavelengths, with values ranging between 199 and 240 nT. Northward, there is a high E-W gradient which consists of some circular and semicircular anomalies (pink colour). The RTP anomaly in the central and southwestern corner of the study area is shows low gradient zone elongated in approximate NE-SW direction with longer wavelength. In the southeastern corner of the study area, there is another important positive anomaly in the N-S direction with longer wavelength.

Regional - Residual Separation: Filtering of gravity and magnetic data is an essential process prior to analysis and interpretation. The main objective of the filtering process is to condition the data set and to render the resulting presentation in each way as to make it is easier to interpret the significance of gravity and magnetic anomalies in term of geological sources [9]. Regional-residual separation is one of the filtering process that can be used to separate the local structures or shallow sources and regional or broad deep seated sources from the observed gravity and magnetic data. The isolation of available data was carried out on the Bouguer gravity map and reduced to the pole magnetic map (RTP) of the study area depending on the results of the energy power spectrum analysis using [8]. This technique depends on the proper choice of cut-off frequency that passes or rejects a certain frequency value and passes or rejects a defined frequency band. A typical two dimensional power spectrum curve shows two linear segments related to regional and residual components with available frequency bands and wave numbers.

Low-Pass Gravity Map: Close inspection of the regional gravity map (Fig. 6) reveals, two large gravity belts. The first one is occupied the northern and eastern parts of the area, extending in NW and N-S directions. This belt is composed of two gravity anomalies; the first one is located north of latitude 31° 00' N, with amplitude up to 55 mGal in the northeastern corner of the area. Meanwhile, the second anomaly is located at the northern border, south of latitude 30°30'N, with the N-S trend and 31 mGal amplitude. The second gravity belt is occupied the southwestern part of the map and associated with large negative gravity anomaly of E-W trend of amplitude 5 mGal. Also, the map shows, a large steep gravity gradient of mainly NW trend, separated the positive and negative gravity belts. This gradient is mainly interpreted due to a large basement fault with down faulted block to the west and uplifted block to the northeast.

Low-Pass RTP Magnetic Map: The low-pass RTP magnetic map (Fig. 7) delineates two elongated large areal extent magnetic belts. The first one is occupied the
High-Pass Gravity and Magnetic Maps: Both the high-pass gravity and magnetic maps (Figs. 8 & 9) show the distribution of gravity and magnetic field after removing the regional effect. These maps are characterized by dominance of various alternating local positive and negative anomalies of different sizes, shapes and orientations of relatively high frequency, weak amplitude and sharp gradients reflecting different causative magnetic and gravity sources of shallow depth seated origin. However, the high-pass gravity map is characterized by several minor elongated and circular anomalies distributed throughout the study area with amplitude range from -3.5 to 3.5 mGal. The residual RTP magnetic map is almost free of the deep crustal heterogeneities and shows the distribution of the several high and low susceptibility blocks, with amplitude ranging between -85 and 90 nT. From this filtration process, the most dominant trends in the study area are the N-S, NE-SW, ENE-WSW and E-W trends.

Structural Trend Analysis: Magnetic and gravity data are commonly used to map and delineate contacts between rock with differing physical properties and such contact commonly occur along fault boundaries. In petroleum exploration, for example, magnetic and gravity anomalies are used to identify faults in basement lithologies that may control the evolutions and depositional history of the sedimentary basins. In this case, it is important that, the interpreter has an understanding of the structural and lithological framework and regional depositional patterns. In general, these gravity and magnetic anomalies align themselves along definite and preferable axes forming structural trends [10]. Since the interpretation of the observed gravity and magnetic anomalies reflect fairly the subsurface geologic conditions in the investigated area. So, the purpose of this trend analysis is to define statistically the major tectonic trends, which affected the sedimentary section as well as the basement rocks of this area [11]. The structural trends interpreted from gravity, RTP magnetic, residual gravity and residual RTP magnetic data can be recognized in various directions and redrawn on the frequency distribution plot to show the main structural trends affecting the study area (Fig.10). These tectonic trends are regarded as a reflection of compressional and tensional stress forces that take place through different geologic ages. The trends of these anomalies follow the structural grain of the terrain and exhibit considerable variations.
Fig. 10: Frequency distribution curves interpreted from gravity and RTP magnetic data shows the main tectonic trends affecting the study area.

within the buried bodies [12]. The study area was affected by four structural trends (Fig. 10). The first trend in the E-W direction that resulted from residual gravity map (green color curve), with percentage 22.5 %, the second one in the ENE-WSW direction that resulted from gravity and RTP maps (blue and purple color). Their percentages are 10.9 % and 20.5% respectively. The third one in the NE-SW as deduced from gravity map (blue color) with percentage 16.8% and finally the fourth minor trend in the N-S direction as shown from residual gravity and RTP maps (green and purple). Their percentages are 9.5% and 8.5% in decreasing order. These trends may be related to the, Mediterranean Sea trend, Syrian arc system and Gulf of Aqaba trend, related to Abu El-Ata [3].

Depth Improvement: The most universal application of gravity and magnetic data has been to determine the depth to the top of the geologic sources that produce observed anomalies. For hydrocarbon exploration, this is usually equivalent for determining the maximum thickness of the sedimentary section or the location of igneous intrusive in the section. Often, a well-defined boundary between zones with different degrees of potential field relief can indicate the presence of major basement fault [13]. Therefore calculations of the depth to the basement rock are very important to outline, quantitatively, the thickness variation of the sedimentary cover and to delineate the structural relief of the basement rocks and its effect on the overlying deposits. The depth to the basement rocks will be calculated using three different methods; power spectrum, analytic signal and two dimensional magnetic modeling.

Power Spectrum Technique: Spectral analysis of the potential anomaly field however, would indicate an ensemble average depth to the different sources of anomalies and thus help to find out a possible magnetic horizon/layer within the crust [14]. Analysis of the 2D power spectrum of gridded potential field data is most useful and a dependable tool to estimate the source parameters which represented by the average depths to different causative sources [15]. Generally, all spectra of the magnetic/ gravity anomalies include two parts, one in the low-frequency end, which in most cases is easier to approximate with a straight line and denoting deeper discontinuities (Moho and/or Conrad). The second is in the high-frequency end, with an undulating character, denoting shallower sources (basement and/or intrusions). Figs. 11a and 11b reveals the output results of the power spectral analysis for gravity and magnetic data. The analysis of power spectral for gravity and magnetic data indicate that, the average depth to the basement in the study area ranging from 4.8 to 5.9 km.
Fig. 12: Analytic signal of the gravity map of the study area (Line 1-26 are the selected profiles that were used to estimate the depth from analytic signal)

Higher values of the analytic signal are observed through some profiles at different regions as shown in (Figs.12 &13), which was used to calculate the depth for each profile at the top of the contacts. All profiles were selected over the anomalous areas in which the contrasts (density/susceptibility) could be found.

Result of the Analytical Signal Profiles: To estimate the depth to the contacts from the analytic signal method, twenty eight profiles were selected over analytical signal map of gravity data (Fig.12) and nineteen profiles for magnetic data (Fig.13) over the study area. Two selected profile samples (p14 & p24) for gravity and (p3 & p9) for magnetic are displayed in Figs 14 to 17 respectively. The most reasonable depth values of gravity and magnetic profiles are listed in the Table 1. Generally, the depth values for study area have an average values ranged from 2.8 km, to 5.6 km from gravity and magnetic profiles. These results are confirmed by the results obtained from the application of the power spectrum technique and results of available drilled wells as atoun-1x (3.7km) and Um Baraka-1x (4.3 km). The basement depths were picked up from this tool and will be plotted on the map in order to produce the basement surface map.

Two-Dimensional Modeling of Aeromagnetic Data: The two-dimensional modeling techniques of interpretation usually involve the fitting of geophysical parameters to potential data. Strictly speaking, potential molding could be the inverse solution to a potential problem that cannot be done unambiguously. Theoretically, two reversed operations are performed sequentially, the first is a direct modeling process and the second is an inverse modeling process. The direct modeling process transforms the variations reflected by potential field data in an area of study, as shown by the residual potential anomaly mapping to a convenient subsurface geological setting. However, the inverse modeling process matches the calculated potential effects resulting from the inferred potential models with the observed one. With more geological control and well data, we can get information about the surface and subsurface magnetic susceptibility variations, established geological contacts and structural knowledge; the potential modeling can be performed with a higher degree of confidence. The computations of the magnetic effects for the assumed geologic models with complex geometry have been carried out with the aid of a computer program [8] for the arbitrary two-dimensional polygon according to the method of Talwani et al. [18],

Fig. 13: Analytic signal of the gravity map of the study area (Line 1-19 are the selected profiles that were used to estimate the depth from analytic signal)

Analytical Signal Technique: The analytic signal method, known also as the total gradient method, produces a particular type of calculated gravity or magnetic anomaly enhancement map used for defining the edges (boundaries) of density geologically anomalous density or magnetization distributions. The main objectives of the analytical signal process are to: (1) locate boundaries of density/or (susceptibility) contrast from gravity/or magnetic data, (2) transform data so that anomaly peaks centered over their sources, (3) determine depth to source information particularly effective in the one dimensional case and (4) locate the edge of sources in areas of low magnetic latitude (often used as an alternative to reduction to the pole) [10].The analytic signal signature of the study area was calculated from the first vertical gradient of the gravity and magnetic data (Figs.12 & 13), in the frequency domain using the Fast Fourier Transform technique [16,17] using oasis montaj software (2007).
Table 1: Estimated depths from analytic signal method of gravity and magnetic data.

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Fig. 14: Amplitude of the analytic signal of profiles 14 of the gravity data

Fig. 15: Amplitude of the analytic signal of profiles 24 of the gravity data

Fig. 16: Amplitude of the analytic signal of profiles 3 of the gravity data

Fig. 17: Amplitude of the analytic signal of profiles 9 of the gravity data
Talwani [19] and Grant and West [20]. Hjelt [21] determined the criteria for making an adequate two-dimensional computation of various methods existing for calculation of the potential attraction caused by regularly and irregularly shaped bodies through profiles across two-dimensional bodies. The basement topography could be better determined using a smaller sampling interval for both 2D and 3D analysis of the
potential data [22]. In this study two-dimensional magnetic modeling is carried out to determine the shape and depth of the basement surface. The configuration of these layers was iteratively modified for best fit between the observed and the computed magnetic data. To confirm the interpreted magnetic basement structural framework of the study area, three regional magnetic profiles (Fig.5) were modeled using the 2D-forward modeling technique. The selected profiles were taken from RTP aeromagnetic map denoted as AA’, BB’ and CC’. The magnetic susceptibility contrast values for the sedimentary rocks and basement rocks along the three 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 three models are shown in Figs 18, 19 and 20. In these 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. From the investigation of the two-dimensional magnetic model, the profile AA’ (Fig.18) lies in the western part of the area and is directed N-S. The basement is uplifted in the northern and western parts with a depth of about 1.8 to 2.85 km and deepening in the central part with a depth of about 5.3 km at blocks numbers p4, p5 and p6. From the profile BB’ (Fig.19), it can be noticed that the basement surface occurs at a depth 1.5 km in the northern part and the depth increases to the central part of this profile to represent by at 5.7 km and the depth decreases again toward the south to represent by 3.0 km. This means that the depth is increasing from the north toward the central and western side of the model. The two dimensional magnetic models along the profile CC’ (Fig.20) coincides with the N-S direction at the eastern part of the study area. The basement is uplifted in the south central part of the profile of depth ranging from 2.1km to 2.5km in the northern part at blocks numbers p4, p5, p8 and p12 the basement rocks are deepening toward the north central and southern parts of the profile with the mean depth of about 4.5 km. The magnetic susceptibility of the basement shows large variation ranging from minimum of about 1.0 x 10^(-3) to maximum of about 7.0 x 10^(-3) CGS unit. In general, basement has higher susceptibility towards north and south as compared to the center part of the area.

**Basement Depth Contour Map:** The depth values obtained from the 2-D modeling and the other analytical methods were used to prepare magnetic basement depth map (Fig.21). A reasonable detailed basement structure map is an integral part of any regional geological or hydrocarbon evaluation process. A magnetic basement low (thick sedimentary section) traverses the eastern, central and west central sectors of the study area with a maximum sedimentary thickness of 5.4 km. These are deep basement troughs which, trending NE-SW, N-S and E-W respectively. At the longitude 25° 30' and long.26° 00' - 26° 30' E in the north and south parts there is a basement high indicating structural high with a maximum thickness of 2.0km. This basement high is flanked either sides by structural lows. In the west central sector at latitude 30° 40' N and longitude 26° 28' E there is a basement high with maximum thickness of 2.0 km flanked by basement low. The result depths compared to exploratory wells bottomed to the basement like well Atoun-1x (3.7 km depth) and Um-Baraka-1x (4.3 km depth) (Fig.21) and found to be reasonably matching at their locations. Thus, there is spatial relationship between paleotopographic highs on the Precambrian basement and the structural elements in the overlying Tertiary sediments. Therefore, the depth to magnetic basement map has located deep depocenter, high blocks and major sedimentary fairways in the study area.

![Fig. 21: Depth to the basement contour map of the study area](image)
CONCLUSION

Our main contribution in this study has been to present the effectiveness of the potential field data and their interpretation tools to extract information about the regional subsurface structural and depth improvement of the basement surface. Besides, the results coming out of this study facilitate the identification of new features as well as the mapping of known main trends and basement depths that represented in the area of study. Inspection of gravity and magnetic maps reveals that these maps includes a wide elongated positive and negative anomalies with gradually frequency and amplitudes that reveals various causative sources at different depths. The analysis of filtered maps indicate that the high-pass filtered maps shows prominent E-W, ENE-WSW, NE-SW and N-S trends in the various parts of the area. Besides, we notice that the well-defined trends of the high-pass anomalies are still persistent in the low filtered anomalies. This reflects the deep extension of the structures causing the anomalies. The basement cross sections are generated using the 2-D modeling supported by calculated depth data to support the configuration of subsurface basement shape. Where, the depth estimations are conducted by application of the power spectrum, analytic signal and 2-D modeling methods. Therefore, the basement depth contour map clearly divided the area into nearly three sectors i.e. the northern and southern parts with shallower basement depth (about 2.0 km) compared to the center part where the basement is deeper (about 5.4 km). Beside, this map has revealed a spatial relationship between the paleotopographic highs and lows in the Precambrian basement and structural elements in the overlying Tertiary sediments. The results of trend analysis indicated that, the area greatly affected by several structural trends in the E-W, ENE-WSW, NE-SW and N-S directions. These trends are associated with the Mediterranean Sea system (during the Late Tertiary), Syrian arc system (during Middle Mesozoic) and Aqaba system (during the Quaternary). Finally, in this study we opine that the basement depth map are identified to play major role in sediment and hydrocarbon distribution in two ways; basement relief (basement highs and lows) and basement related faults. These two factors are episodic and appear to have controlled the trapping and migration of hydrocarbon in any region.

REFERENCES


