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Utilizing Magnetic Gradiometer to Determine the Depth and Geometry of Subsurface Archaeological Features at Abydos Archaeological Site, Sohag, Egypt

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ABSTRACT

The Abydos archaeological site represents one of the most important burial grounds for kings and high court dignitaries in ancient Egypt which is located at about 13 km west of the River Nile along El-Balyana town at Sohag Governorate, Egypt. High resolution gradiometer survey was conducted on the area surrounding the Osirion at Abydos. The main objective of the present work was to detect depth and geometry of any buried archaeological remains located at the site. The gradiometer survey was acquired on an area of 300 x 300 m using proton precession magnetometer, 10m line spacing and 5m station interval. The collected gradiometer magnetic data was corrected and processed using the Geosoft Oasis Montaj. The interpretation of both the high pass filtered and the analytical signal transformation magnetic maps showed very strong anomalies with square and rectangular shapes concentrated on the central, eastern and western parts of the study area that may represent buried archaeological features. The averaged depth of these high magnetic anomalies ranges from 1.1 to 6.9 m below ground surface as confirmed from the radial average spectrum technique and the calculated depth by source power imaging technique ranges between 1.06 m to 5.58 m. The obtained results indicate that the study area is characterized by several buried archaeological features with very well determined geometry and depth where this information can be used as a guide during the excavation process.

INTRODUCTION

Egypt contains one-third of the world's discovered archaeological remains, with much more yet to be discovered, and the pharaonic civilization still retains secrets that have perplexed minds to unearth [1]. There are many stories in Egypt about the random discovery of different types of archaeological features, and planned foreign excavation missions coming from many different countries. Chance discoveries cannot be planned and owing to the cost of large-scale excavation, there is a need for non-destructive, cheap and quick survey methods, such as the magnetic gradiometer technique discussed in this paper.

The Abydos archaeological site represents one of the most important burial grounds for kings and high court dignitaries in ancient Egypt which is located at about 13 km west of El-Balyana town at Sohag Governorate, Egypt (Figure 1). The study area is located to the west of the Osirion behind the temple of Abydos and lies between latitudes 26°10'N and 26°15'N and longitudes 31°53'E and 31°57'E (Figure 1). The study area is flat with no topographical variation, which helped greatly in acquiring the data with no topographical errors. Many excavations activities were carried out within the last century at Abydos site. However, the sands of Abydos are still hiding many untold secrets [2].

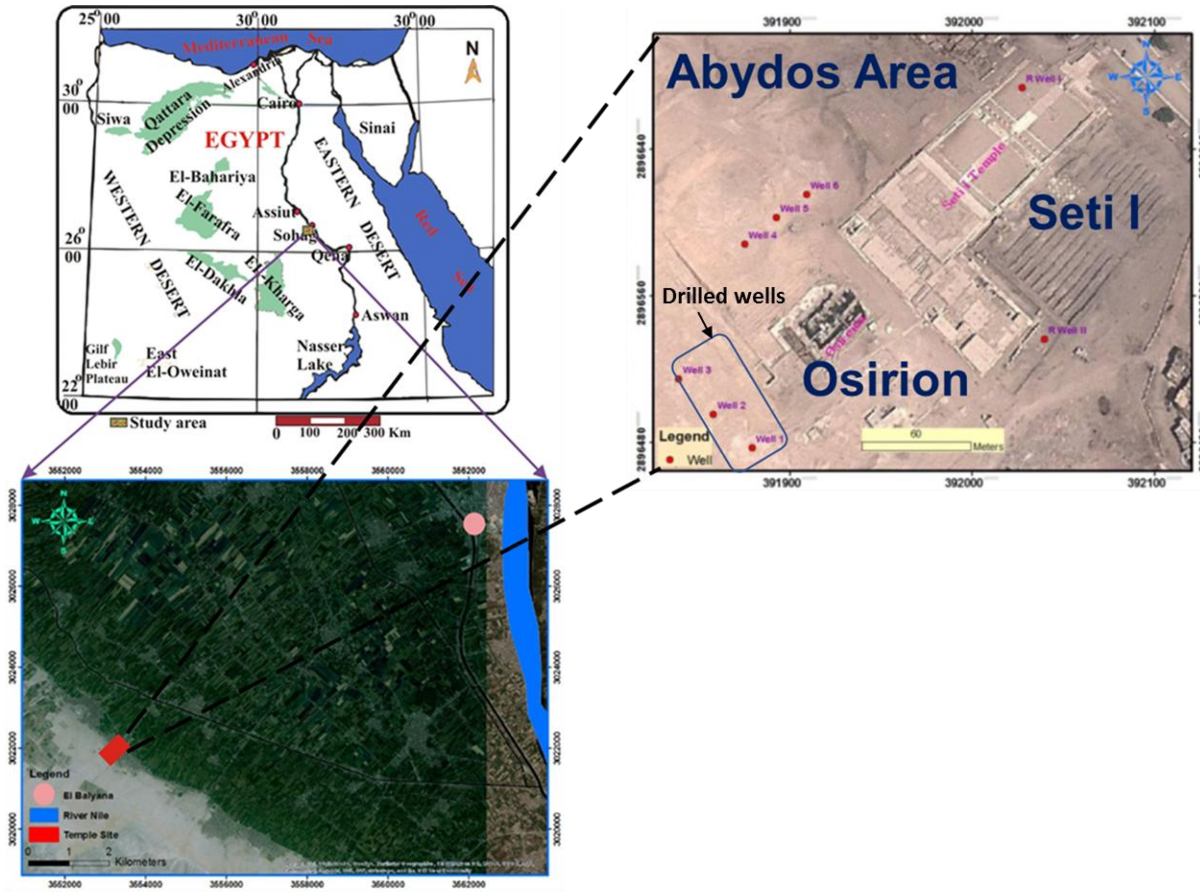


Fig. 1: Location map of the study area with drilled wells (1, 2 and 3) used to describe the local subsurface geology.

Magnetic gradiometer method has proven to be a very effective complementary tool when compared to traditional methods of exploration and problem characterization because they do not cause any damage to discovered and buried remains as a result of drilling, they are also less expensive, more accurate through non-invasive measuring of the strength or alteration of the Earth’s magnetic field across an area [3, 4, 5, 6, 7, 8]. Magnetic gradiometry was assessed as being particularly suitable for the study area west of the Osirion because it can be used to cover large open areas rapidly. Magnetic methods are one of the cheapest, effective tools for such near-surface geophysics and have been used effectively in archeological investigation over 60 years [9,10,11,12,13].

Despite the fact of the numerous geophysical and hydrogeological studies conducted at Abydos archaeological site [14, 15, 16, 17, 18, 19] there are limited research conducted at the area west of the Osirion which address the important need of the current study. The main objective of the present work was to detect depth and geometry of any buried archaeological remains (old pits, tombs and buried walls) located at the area west of the Osirion at Abydos archaeological site. The new archaeological discoveries at Abydos site will not only add cultural value but also indirectly provide economic benefits as it generates considerable revenue for the ordinary people and the government [20].

HISTORICAL BACKGROUND

Abydos is one of the earliest archaeological places in Upper Egypt. It was built since 4000 years ago. The ancient Egyptian Abedju locality (original name of the present Abydos) represents one of the most important burial grounds for kings and high court dignitaries in ancient Egypt where the early pharaohs were entombed. In addition, it symbolizes the site of many ancient temples such as the royal necropolis. The Abydos city became the most venerated district in Egypt, as it was associated with religion of Osiris and the desired burial sites for the earliest and oldest kings like Seti I and Ramses II [21].

Abydos Temple was built on two consequent parts; one lies on Holocene Nile sediments, and the second lies on the older Nile sediments, formed from Nile terrace. Behind the Temple of Seti I, the Osirion was built at 15 m below ground surface, in which the Pharaonic funeral ceremony took place. Abydos reached the height of its glory under these two kings. For political and religious reasons Seti I built a funerary temple there for his father Ramses I and another one for himself. There is practically nothing left of the temple of Ramses I whereas that of Seti I is one of the best-preserved masterpieces of ancient Egypt. The overall layout of the temple of Seti I has been completed by his son Ramses II. Abydos, at the time of Strabo (58 BC, between 21 and 25 AD) was already only just a small center whose importance had whittled down to being a cult site [21]. Some pictures of the great Seti I and Ramses II temples as well as Osirion displayed through (Figure 2).

Fig. 2: Some pictures of (a) the great Seti I temple, (b) the Osirion temple, (c) and (d) Ramses II temple.

GEOLOGICAL SETTING

Geologically, the majority of the Abydos area related to a great extent of the Quaternary to Pliocene sediments overlying, uncomfortably, the Esna Shale which belongs to the Early Tertiary [22] (Figure 3). The base of the section consists of a thick sequence deposits of poorly indurated fluviatile sands (varies in thickness from 20 to 30 m); the Qena Formation [24, 25]. The general lithologic section of the study area, as revealed by [26], consists of five rock units, classified from base to top; a) Pliocene Clay, b) Qena Sands (Upper Pliocene to Lower Pleistocene), c) Kom Ombo Gravel, d) El Ghawanim Formation, and e) the Dandara Formation.

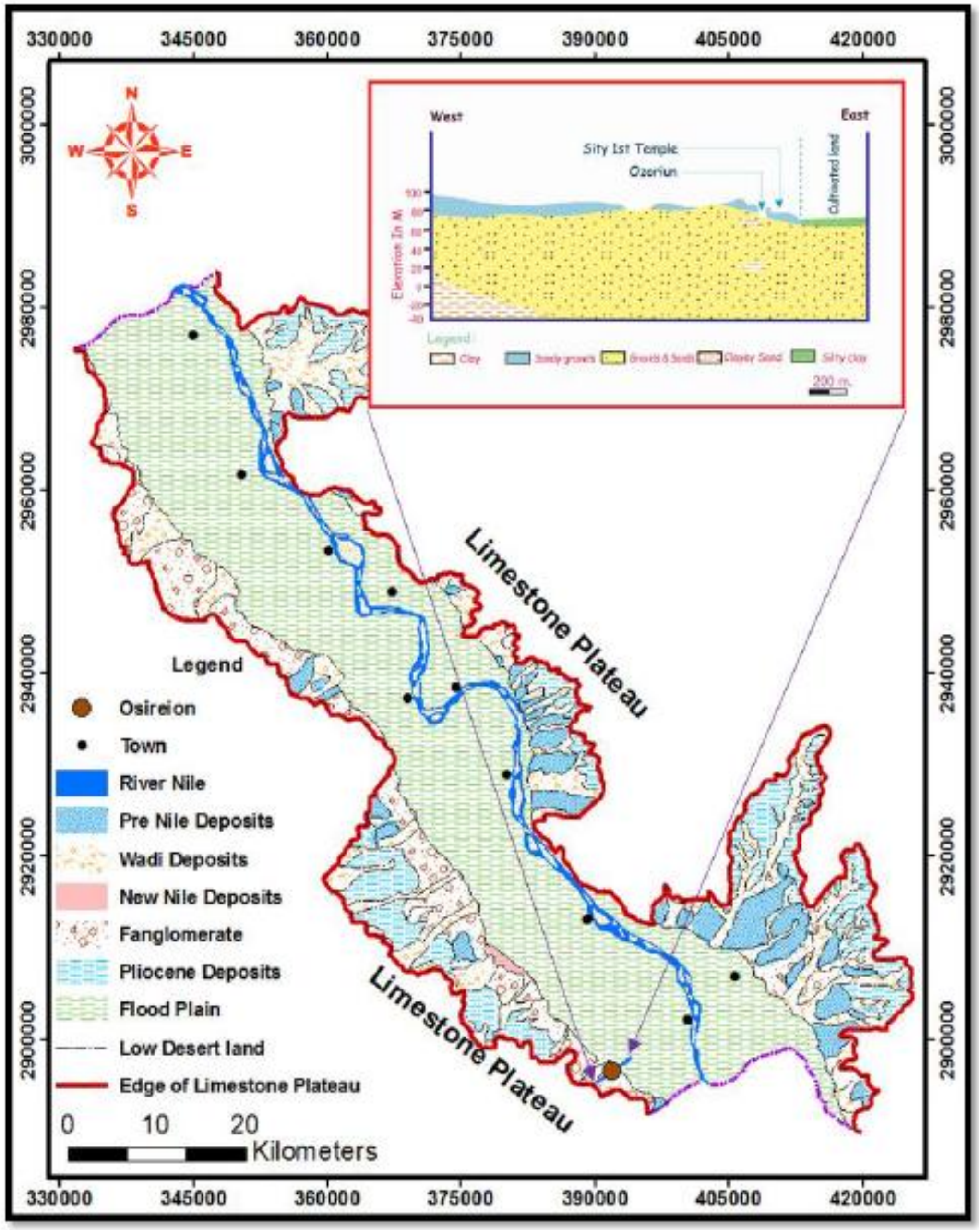


Fig. 3: Simplified geological map of Sohag Governorate, [modified after 23].

At the investigated area, as well as, in most of the Nile Valley, Qena Sands are the major water bearing formation. They thin out towards the west, abutting against the Paleocene to the Lower Eocene Limestone Plateau. Eastwards, in the places of River Nile and its valley, some of these sands are removed by erosion and subsequently silt fill the present Nile and its plain. Based on results obtained from local wells around the Abydos Temple area (well no 1, 2 and 3 as shown on the location map of figure 1), the section of the Qena Sands may reach up to15 m thick [27]. The base of these sands varies from well to another (Figure 4). The sequence of these sands overlies the Pliocene sediments within Upper Nile Valley [28]. At the west of Kom Ombo area, Qena Sands are found to be overlain by gravel beds [29]. However, along the western bank of the Nile between, Sohag and Assiut, the sediments of the Kom Ombo Formation are mostly consisted of fluviatile sands with some gravel interbeds (26). Besides, the lithologic sediments of the Ghawanim Formation consist of cross-bedded fluviatile sands and gravels together, with lenses of conglomerates and interbeds of quarzitic sandstone.

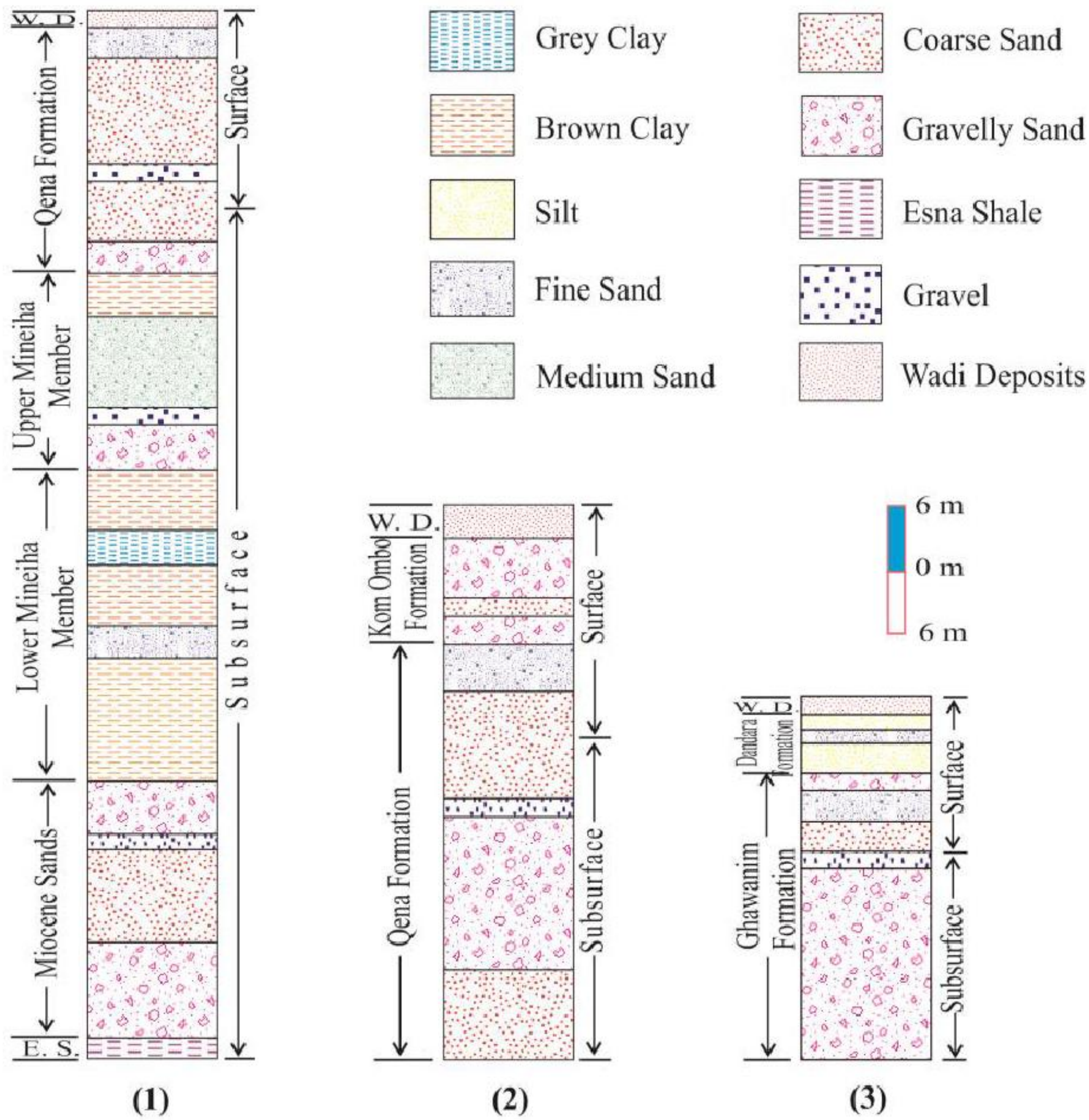


Fig. 4: The stratigraphic sequence west of Abydos area deduced from the drilled wells (1, 2 and 3) located in figure 1 [after 26].

[30] pointed out that Dandara Formation at Abydos area is the upper-most layer of the sedimentary succession, points to a mineral suite of an Ethiopia source. [31] added that, the silt of Dandara Formation is presented as sedimentary sheet, which varies in thickness from a few cm up to 5 m, and occurred above the Kom Ombo gravels. The silt

(mostly of sandy fraction), tends to be calcareous in places, and stained to red paleosol on its top. The previously discussed sequence is truncated by the cultivated silts of the present Nile which form the great flood plain of Upper Egypt .

Generally, the lithologic section of the area which is a portion of the Nile Valley is consistes of river deposits accumulated during the various phases in the river evolution. [28] pointed that, the basal deposits above the Lower Eocene limestone are characterized by various beds of clays with minor silt intercalation These clay layers may be comparable with the Paleonile sediments.

The general structure of Abydos area revealed that the limestone cliff around the area is surrounded by two main faults trending NW-SE and NE-SW, forming a major promontory. These promontories play a serious role in the groundwater flow within the area [27].

MATERIALS AND METHODS

The magnetic method is the oldest branch of geophysics and one of the most widely used geophysical techniques for investigating the earth's subsurface [32]. It has been used mainly to investigate a variety of subsurface exploration issues, including changes in the magnetic properties of rocks and minerals from near the Earth's crust to inside the upper meter of soil, as it is a relatively simple and inexpensive method [32, 33, 34]. It is well known that most archaeological remains that were constructed from clays and mud are rich in magnetic minerals with different percentages according to the conditions of sedimentation and construction methods. These magnetic minerals play an important role in magnetic prospecting for archaeology. Therefore, the land magnetic prospecting is used in archaeological investigations to produce a quick and accurate preliminary image of any buried archaeological features that may exist.

The gradiometer survey is characterized by the fact that it does not require correction operations. The distribution of archaeological remains at shallow depths is frequently reflected by such data. Magnetic susceptibility changes in the subsurface environment are very detectable by modern gradiometers. Because some buried archaeological remains have very small anomalies, the sensitivity characteristic of gradiometers is a significant component in detecting them (several nT). Furthermore, using the gradient technique eliminates the effects of magnetic disturbances and temporal changes in the magnetic field [35]. The study area is located to the west of the Osirion and measures 300 x 300m (90.000 m^2) that divided into 9 blocks labelled from B1 to B9, each block measures 100m x 100m (Figure 5). The corners of the area and each block were marked with wooden sticks and the distances were measured using a non-magnetic tape with 10m line spacing and 5m station intervals.

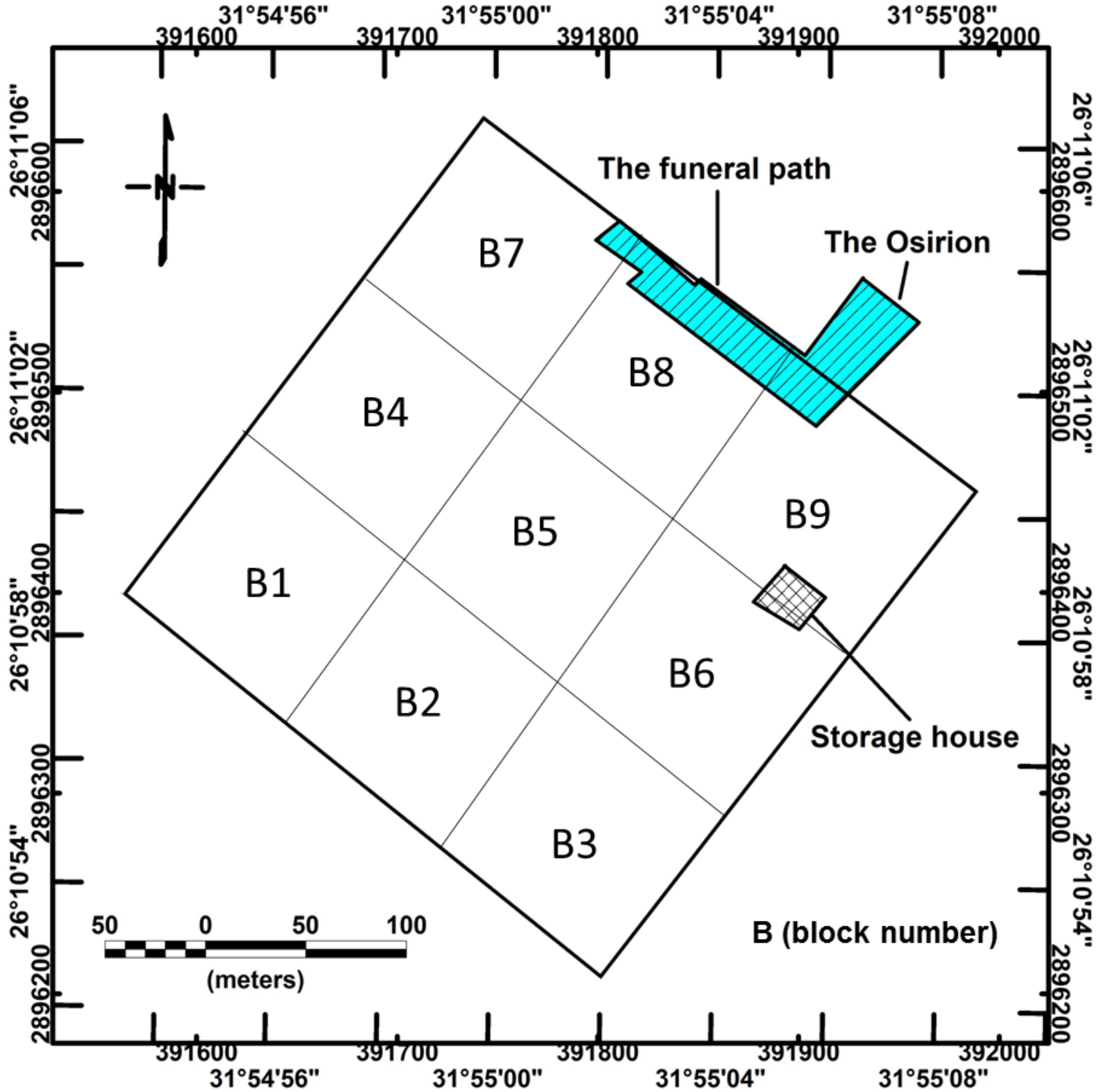


Fig.5. Location map of magnetic surveyed area with blocks (B1 to B9) with line spacing 10m and station interval 5m.

The measurements were started from the top left-hand corner of each grid and followed a zigzag pattern. The study area was surveyed using a G-856 proton-precession magnetometer (Geometrics USA) which is light with high resolution (0.1 nT) and good storage. It was employed as a gradiometer using two sensors in this work. Figure (6) displays the G-856 proton-precession magnetometer (Geometrics USA) used for the magnetic survey and some of pictures of the field work.

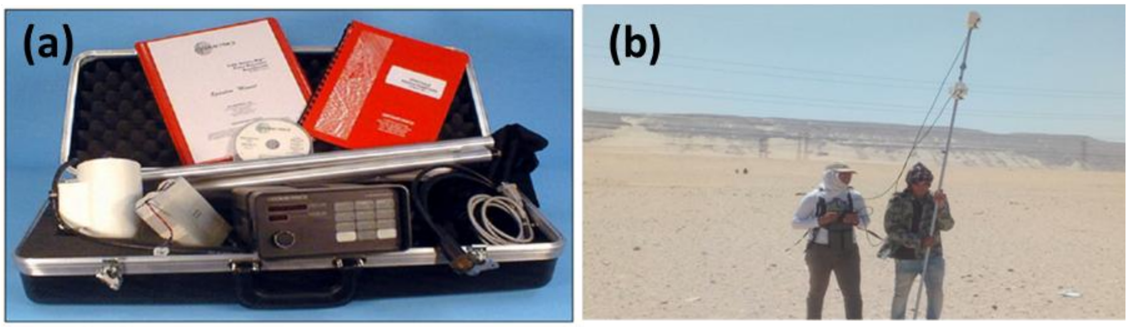


Fig. 6: (a) The G-856 proton-precession magnetometer (Geometrics USA) used for the magnetic gradiometer survey and (b) and a picture of the field work.

The 1st and 2nd sensor height was 1.5m and 2m from ground surface, respectively. The gradient is the difference between the readings of the two sensors divided by the longitudinal distance between them based on the following equation:

$$\frac{\partial f}{\partial z} = \lim_{\Delta z \to 0} \frac{\Delta f}{\Delta z} \qquad (1)$$

Where Δf is the change in f (total field or vertical component) measured over the small distance in sensors heights, Δz.. In the above considerations, it is implied that the magnitude of the field is considered while ignoring its direction, i.e. f is a scalar field quantity. Also, how closely the measured quantity approaches the gradient depends inversely on the separation between the gradiometer's sensors.

The data processing in which we take certain steps that are applied to the raw data obtained from the field in order to reduce or eliminate some common errors (e.g., tilting of the G-856, discontinuities at grid edges, striping of traverses and displacement of the obtained features) that may occur during the field survey and have an impact on the data quality. A typical processing sequence initially would be to display and review the data, clip extreme values from the data, identify the effect of major geological and ferrous responses, remove data collection defects, and finally enhance and present the archaeological response. [1, 34]. The collected magnetic data were processed using the Geosoft Oasis Montaj [36], and the processing steps were implemented through applying high pass filter (HPF), analytical signal transformation (AST) and the depth of the obtained anomalies were calculated using the radially averaged power spectrum (RAPS) and source power imaging (SPI) techniques [37. 38].

The high pass filter (HPF) filter only allows the passage of high frequency signals (near surface) while stop the passage of low frequency signals (deep source). The applying analytical signal transformation (AS) technique expresses the square root of the sum of the squares of the vertical and the two horizontal derivatives of the total magnetic field ΔT. The analytical signal transformation (AS) peaks are symmetrically positioned above their magnetic causative bodies and correlate directly with them, indicating that the AS is independent of the magnetic field's inclination. When the direction of magnetization of the causative bodies is unknown, this eliminates the issues that are typically encountered in the traditional approach of reduction to pole for T. Furthermore, the AS possesses properties that are similar to the magnetic field's derivative features, making it extremely sensitive to edge effects of the causative magnetic bodies [39].

Many authors [40, 41] discussed the application of spectral analysis technique to determine the depth of a magnetic anomaly. Energy spectral analysis provides a technique for quantitative studies of large and complex magnetic data sets. The radial average power spectrum analysis technique is a quantitative technique that will provide us with an average depth of shallow and deep magnetic sources which depends on the transformation of the space domain data into frequency domain by using Fourier transform. Review of the method is given by [42]. The source power imaging technique will provide a map of the depth distribution of the study area. For the radial average power spectrum technique, the energy decay curve includes linear segments, with distinguishable slopes, that are attributed to the contributions in the magnetic data from the residual (shallower sources), as well as the regional (deep sources). The depth of each source ensemble responsible for each segment is calculated by introducing the slope of this segment in the formula [43]:

$$h\ (\text{depth}) = -\text{slope}/4\pi \qquad (2)$$

The Source Parameter Imaging (SPI) is a procedure for automatic calculation of source depths from gridded magnetic data [44]. The calculated depth solutions are saved in a database. These depth results are independent of the magnetic inclination and declination, so it is not necessary to use a pole-reduced input grid. This technique is used as quantitative method to obtain depth to basement by calculating the grid gradient amplitude in X and Y directions. The “x, y” derivatives are calculated by a 3x3 point convolution filter. The “z” derivative is calculated by one-step grid filtering operation to compute the first vertical derivative grid in the forward Fourier (frequency) domain transformation; SPI assumes a step-type source model. The SPI is powerful method for calculating the depth of magnetic sources, its accuracy has been shown to be +/- 20% in tests on real data sets with drill hole control. This accuracy is similar to that of Euler Deconvolution. However, the SPI has the advantage that it produces a more complete set of coherent solution points and is easier to use.

RESULTS AND DISCUSSION

The processing results of the study area divided to qualitative and quantitative interpretations as follow:

1. Qualitative interpretations of the magnetic data

1.1. The gradiometer map

The gradiometric is the effective for detecting small, near surface anomalies, and is therefore very useful in buried archeological remains explorations. Figure (7a and b) shows the obtained gradiometric map with variety of total magnetic gradient values (Figure 7a) and the interpretations of these anomalies shaded with black indicating the possible buried archaeological feature (Figure 7b).

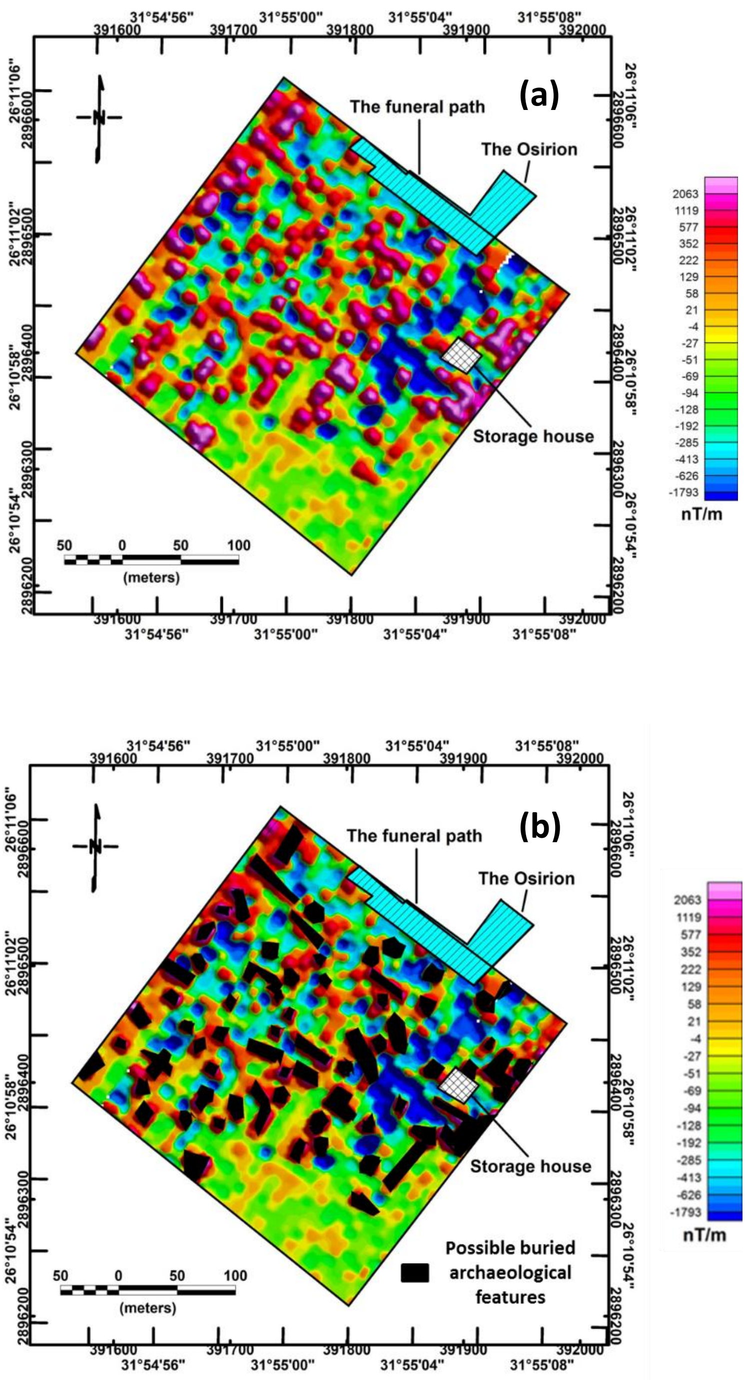


Fig.7: (a) Magnetic gradiometer map of the study area, and (b) interpretation map showing the possible buried archaeological features.

The magnetic gradient (MG) in the gradiometer map (Figure 7a) ranges from -1793 to 2063nT/m. It was divided to group of high (Positive) and low (Negative) magnetic anomalies. The first group is represented by high positive anomalies with TMG greater than 1119 nT/m may indicate to the presence archaeological features under the ground. They are occupied the eastern, western and middle part of the study site. They are characterized by different sizes and shapes. These anomalies take different geometric shapes like square with size ranges from (4 to 8 m^2), and rectangular with size ranges from (15 m x 8 m) to (36 m x 8 m) (Figure 7a).

The second group is represented by the anomalies of moderate and low TMG which ranges from -1793 to 1119 nT/m with irregular shapes (Figure 7a). These features are scattered in different locations in the mapped area. The interpretation of these anomalies is depending on many factors as follow: TMG value, size, diameter and geometry of the anomalies, archeological discovers in the surrounding areas and the magnetic behavior of the materials in archaeological sites. The discovery of mud bricks depends on the contrasts between their magnetic properties and the surrounding soil, and also the interpretation is linked to similar discoveries in other archaeological sites in Egypt such as Karnak [45], Saqqara, Hawara and Al-Qanatir mentioned by [46]. Accordingly, the interpretation of theobtained magnetioc gradiometer anomalies with different sizes and shapes that may represent buried archaeological features are presented in Figure 7b.

The interpretation of the resultant magnetic data was supported with the in-site field observations and surface examples of features exist on the ground surface around the study area in addition to the information gained from the magnetic survey. These surface features expected to be highly similar to the buried obtained one.

Figure 8 (a and b) shows some of the previously discovered archaeological features such as tombs made of mud bricks with rectangular shape (Figure 8a) and kilns made of granite (Figure 8b) [45]. However, Figure 8 (c and d) shows the total magnetic map (Unpublished data) for a site nearby the studied area (Figure 8c) where some discovered archaeological features (tombs made of mud bricks) has been discovered and excavated (Figure 8d). The previously discovered archaeological features (tombs made of mud bricks and kilns) as well as the collected magnetic data at a nearby area to study site (unpublished) are used here to aid in the interpretation of our magnetic survey results.

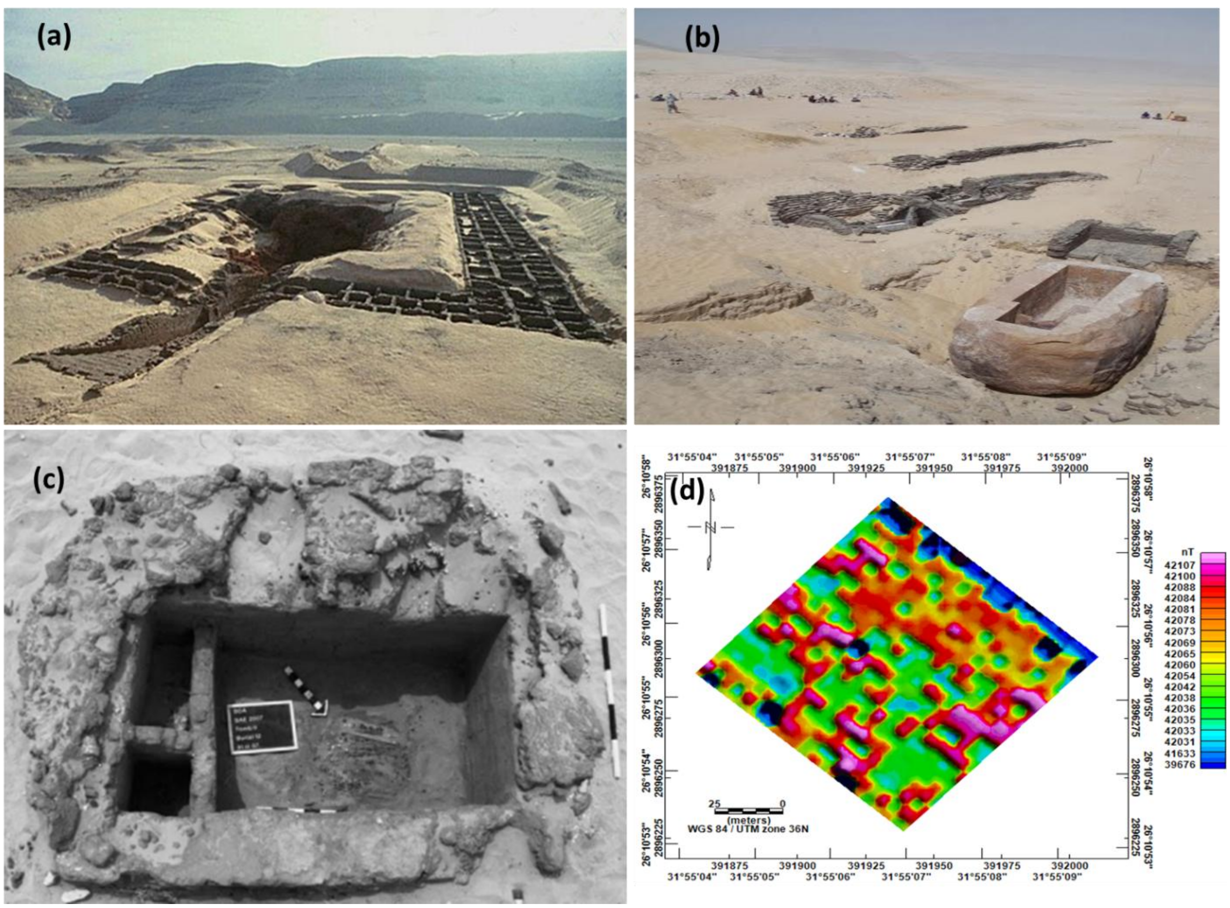


Fig. 8: Some previously discovered and excavated archaeological features (a), tombs made of mud bricks, (b) kilns made of granite at Abydos area, (c) discovered and

excavated tombs made of mud bricks very close to the study area and (d) its total magnetic map (unpublished data).

It is noted that the shape and distribution of the anomalies of the archaeological features discovered in the study area correspond to those in the resultant gradiometer map. The archeological features of the first group may be interpreted as mud bricks features (such as tombs, old pits, buried walls, etc.) and some of anomalies with rectangular shape may be coffin made of granite similar to the discovered granite coffin in the Abydos while the second group features may be interpreted as the subsurface soil layers which surrounded the archaeological targets. These findings are based on the interpretations of gradiometric results in other archeological sites that were conducted by [45, 46] in Saqqara, Karnak Temple, Qantir and Hawara sites. It is noticed that, the magnetic gradient of mud bricks in the three Egyptian sites (Saqqara, Qantir and Hawara), is matching well with the magnetic gradient of the mud bricks at Abydos site, [47] and may be with the unexcavated mud bricks in the current investigated site. Mud bricks, fire bricks, kilns, and other iron-bearing structures are often apparent as detectable positive anomalies.

The interpretation of magnetic data is mainly based on a comparison and correlation between the resulted magnetic anomalies and the historical background or excavated archeological features of the study area. In the present study, most of the proposed archeological features are probably made of mud bricks and some may made of granite.

Magnetic anomaly maps reflect presence of the subsurface causative bodies. This can aid in recognizing the distribution of archaeological remains which is valuable information for excavation process.

1.2. High pass filter (hp) map

The gradiometric map was subjected to the filtration process in the frequency domain by using Butterworth high pass filter with parameters of, degree of filter function is 25m based on the size of the anomalies, the central wave number is 2 (cycle/ground unit), for enhancement the signal characteristics of available data [49].

High Pass Filter (HP) map depends on removal all anomalies with low frequency and mapping of magnetic values with high frequencies and short-wave lengths (shallow sources).It showed very sharp anomalies with values higher than 837nT and have square and rectangular distributed along on the western, central and eastern parts of the study area that may represent mud brick tombs, old fire pits or buried walls or (Figure 9).

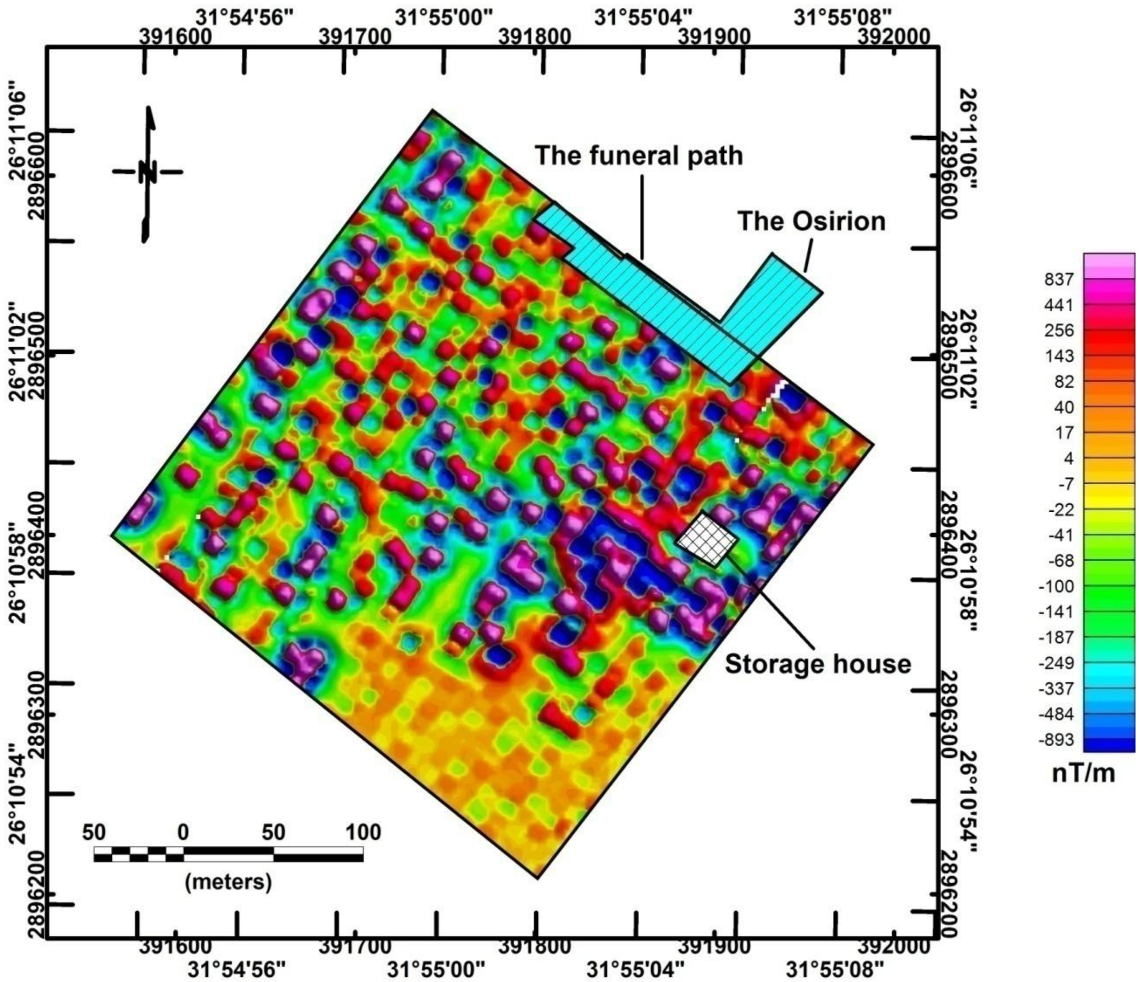
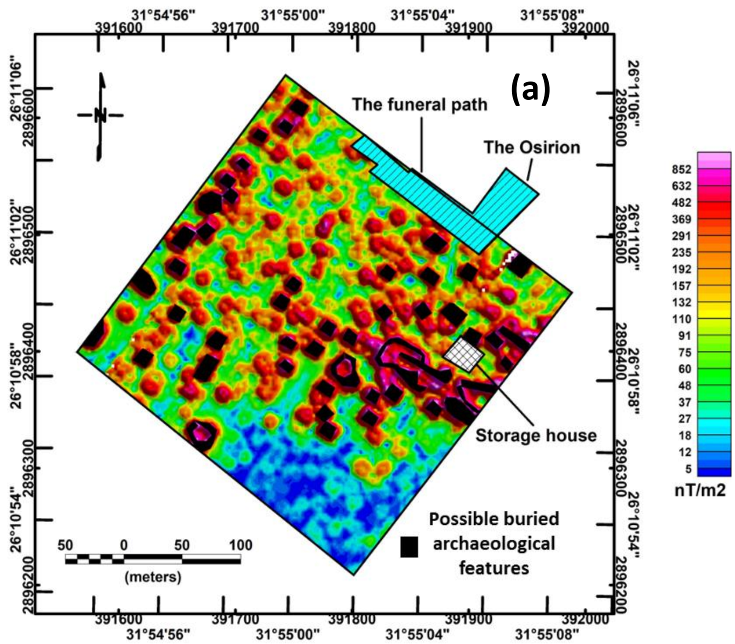


Fig. 9: High Pass Filter (HP) map of the study area.

1.3. Analytical transformation signal (as) map

Applying of the analytical signal methods for interpretation of the magnetic gradiometer data supplies the geometry and locations of magnetic anomalies related to the archaeological sources. The Analytical Transformation Signal (AS) map shows specific anomalies with value ranges from 5 to 852 nT/m^2 as shown in (Figure 10a). This map shows very strong anomalies with values higher than 632 nT/m^2 and their shapes are square and rectangular shape concentrated more intensely in the eastern part than in the western, and there is also a distribution of anomalies in the central parts of the study area that may represent buried walls or tombs, the very low anomalies with values less than 632 nT/m^2 concentrated at the outhern part. Figure 10b shows a tentative map for the interpretation of the analytical signal map displaying the location of the possible buried archaeological feature (tombs and kilns).



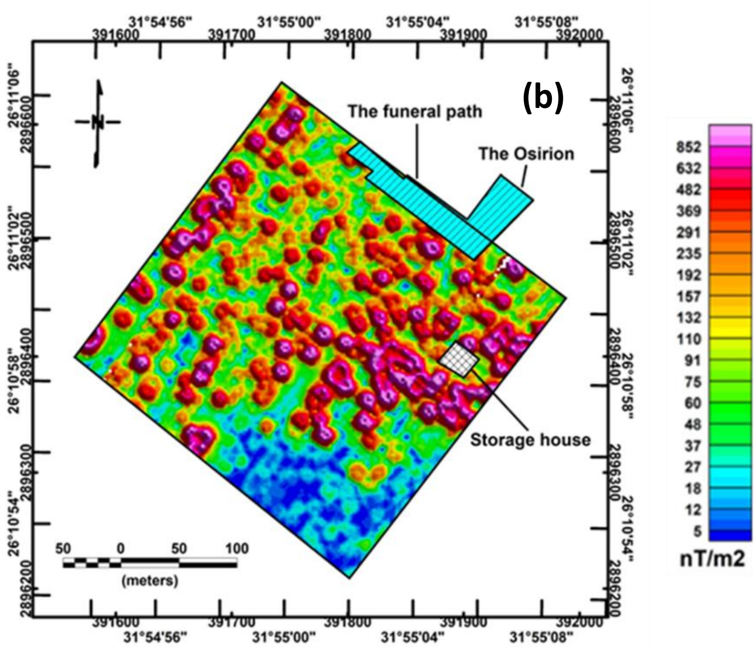


Fig. 10: (a) Analytical Transformation Signal (AS) map of the study area and (b) interpretation of the AS map with possible buried archaeological features.

2. Quantitative interpretations of the magnetic data

2.1. Radially averaged power spectrum (raps) map

The radially averaged power spectrum technique is quantitative explanation of the depth of the magnetic values causing the anomalies. This figure gives general view about an average depth of the shallow and deep sources at the whole study area. The energy decay curve includes linear segments, with distinguishable slopes, that are attributed to the contributions in the magnetic data from the residual (shallower sources), as well as the regional (deep sources). This method depends on plotting the energy spectrum against frequency on a logarithmic scale (Figure 11) showing that the shallow sources are located at depths of 1.79 m while the deeper ones exceed 5.03 m below the measuring level. The wave number of the shallow sources ranging from 90 to 200 and for the deeper sources ranging from 0.0 to 140 calculated from the eq. (2).

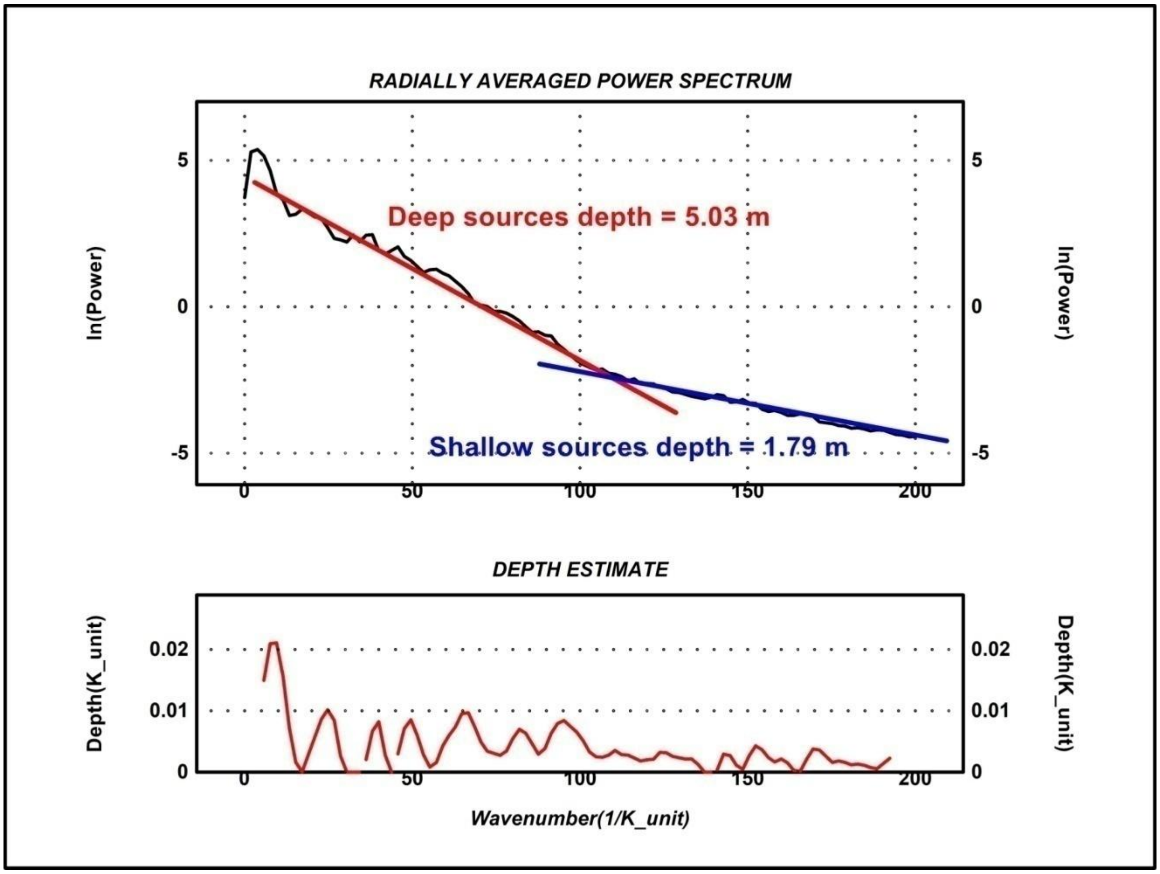


Fig. 11: Detection of the average depth of magnetic gradiometer anomalies by the radial average spectrum (RAS) parameter at the study area.

2.2. Source power imaging (SPI) Technique

Source parameter imaging (SPI) was employed to interpret high resolution land magnetic data using the Geosoft Oasis Montaj [36] for detection the depths to magnetic source over archaeological Abydos site. The results of source parameter imaging (SPI) showed that the calculated depth to magnetic sources ranges between -5.1m to -1.8m as displayed on the map (Figure 12). These results are in consistent with the results of radially averaged power spectrum technique in the study area.

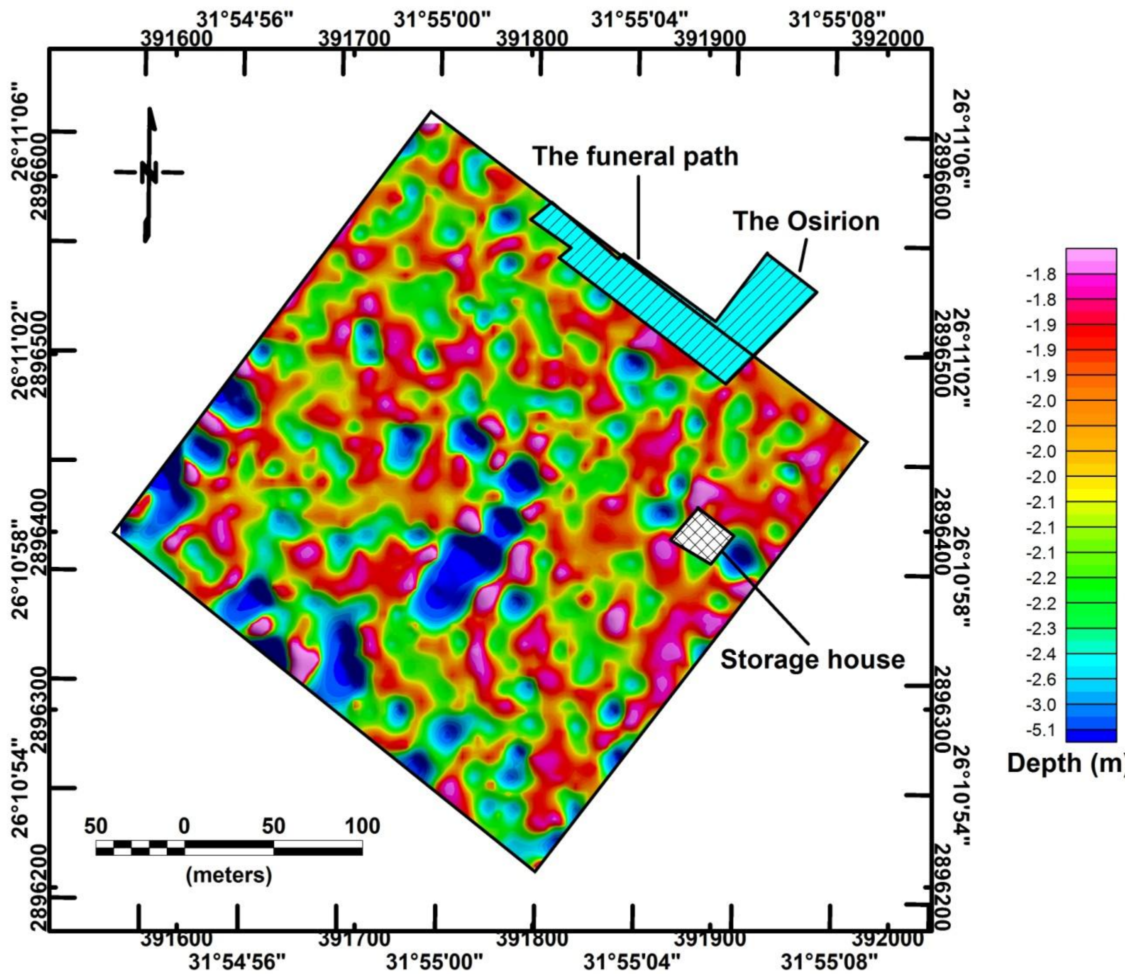


Fig. 12: Detection of depth of magnetic gradiometer anomalies using parameter source power imaging technique (SPI) at the study area.

CONCLUSION

Abydos represents one of the most promising archaeological sites that are located in Sohag Governorate. The present work is concerned with the detection of geometry and depth to buried archaeological remains located at the area surrounding Osirion at Abydos temple of the available magnetic data that may be mud bricks tombs, old pits or buried walls.

The gradiometer results indicate that the study area is characterized by several buried archaeological features concentrated on the central, eastern and western parts of the study area with very well determined geometry (square and rectangular) and depth (1.79 m to 5.3 m). The observed anomalies to a great extent may represent buried tombs made of mud bricks rich in magnetic minerals. This information can be used as a guide during the excavation process It is recommended to use other geophysical techniques (e.g., ground penetration radar, electromagnetic and microgravity) to support these results.

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