



Detection of Archaeological Ruins Using Integrated Geophysical Surveys at the Pyramid of Senusret II, Lahun, Fayoum, Egypt

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Abstract— Geophysical surveys were conducted in the Lahun area (Fayoum, Egypt). The Lahun area is known to have been the royal necropolis during the period of Senusret II (1897–1878 BC), where he built his pyramid. Integrated magnetic and gravity measurements were applied to investigate five locations in the area. The gravity survey was implemented in the areas where chambers, shafts, or cavity-like structures are expected, and magnetic survey was applied in the areas where mudbrick structures are expected. The magnetic survey was conducted using a Geoscan fluxgate gradiometer, whereas the gravity survey was conducted using a Scintrex CG-5 gravimeter. The geophysical survey successfully revealed anomalies that could be part of the trench between the Queen’s Pyramid and the Senusret II Pyramid, several pits in the eastern and southern sides of Senusret II Pyramid, two chambers that could be royal tombs, and the remains of three large mudbrick structures that could be ancient warehouses.

Keywords: Archeological remains, magnetic, gravity, GNSS.

1. Introduction

Fayoum city is one of the wonderful sites in Egypt, located about 100 km southwest of Cairo. It contains many archaeological features extending from the prehistoric period through ancient Egyptian kingdoms, the Ptolemaic Kingdom and the Roman Empire. The settlement in Fayoum Oasis started during the Old Kingdom (2686–2181 BC). It was then developed during the Twelfth Dynasty (the Middle Kingdom 2040–1782). Senusret II, the fourth pharaoh of the Twelfth Dynasty (1897–1878 BC), established a large irrigation system from Bahr Yussef to Lake Moeris by constructing a dam at El

Lahun (Fig. 1a) and drainage network. El Lahun is a small village in Fayoum. The village was established as a settlement for workers during the Middle Kingdom. Senusret II moved the royal necropolis from Dahshour to El Lahun, where he constructed his pyramid. The pyramid is near the workmen’s village and is known as the Pyramid of Lahun (Mazzone, 2017; Miniaci & Grajetzki, 2017; Moeller, 2021). The pyramid was built from mudbricks over elevated limestone bedrock and it was encased by white limestone.

The importance of this pyramid and its associated complex structures can be emphasized in two points. The first is the fact that Senusret II moved the royal necropolis from Dahshour to El Lahun. The father (Amenemhat II 1929–1895 BC) and the son (Senusret III 1878–1839 BC) of Senusret II built their pyramids in the Dahshour area. The second point is the strange construction of the pyramid itself, where the pyramid entrance is through a vertical shaft in the southeast of the southern pyramid face under the princess’s tomb (Petrie et al., 1923) (typically, in the Old and Middle kingdoms, the pyramid’s entrance is located in the northern face). However, the main outbuildings of the Senusret II pyramid complex in the Lahun area were yet to be discovered. Therefore, a geophysical survey was conducted to investigate the surrounding area of the pyramid. Magnetic and microgravity surveys were conducted to find the remains of the pyramid complex structures. Typically, the pyramid complex contains a mortuary and valley temples with a causeway in between.

Magnetic and gravity techniques have been widely used to depict archaeological features (Abdallatif et al., 2003, 2019; El-Emam et al.,

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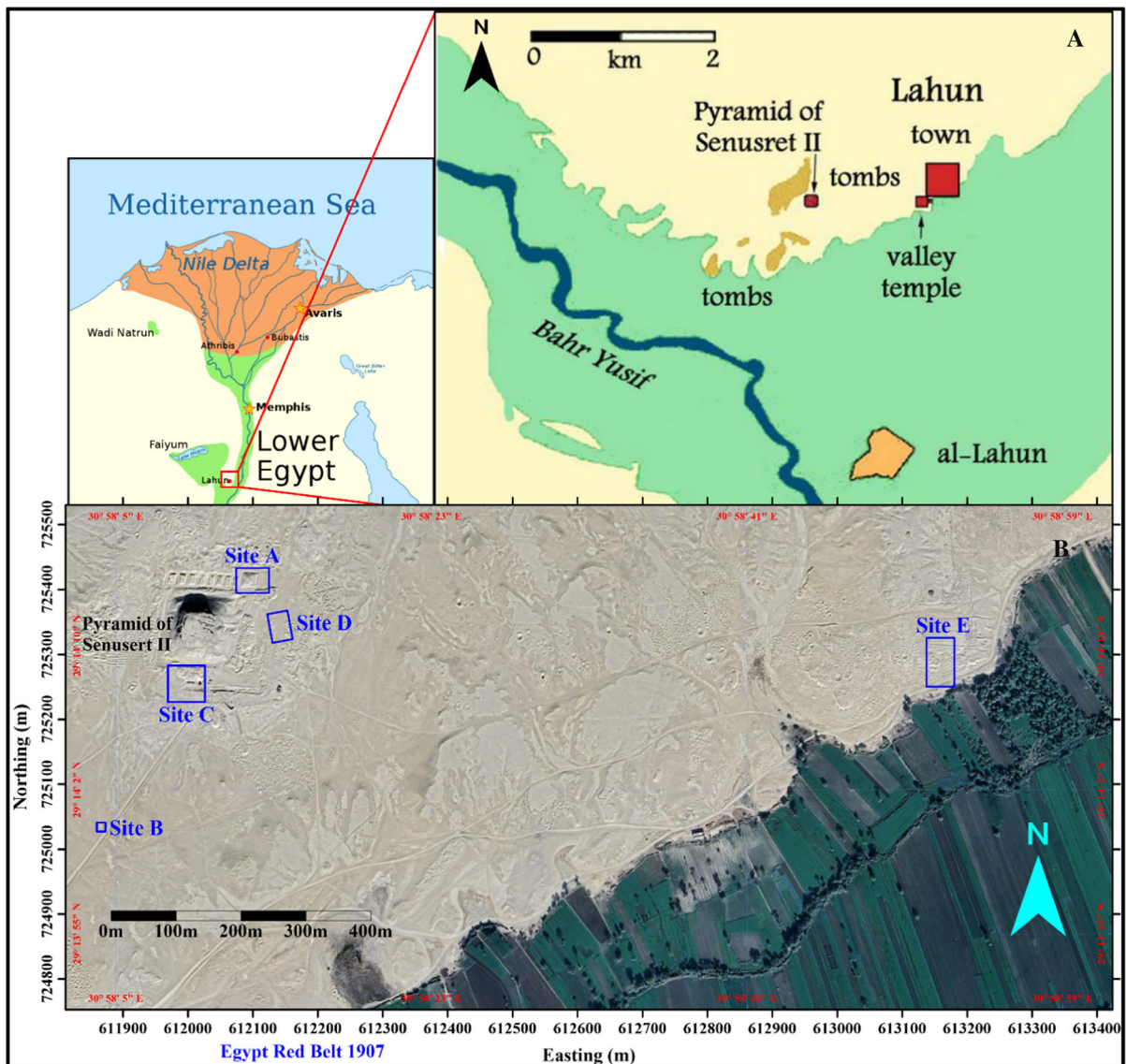


Figure 1

a Sketch of the location of the old Lahun town relative to the Pyramid of Senusret II. b Satellite view showing the Pyramid of Senusret II and the locations of the five study sites

2014, 2021; Hounslow & Chroston, 2002). The choice of these techniques is based on the physical properties of the archaeological remains. The core of the pyramid and most of the associated structures were constructed from mudbrick which can be easily mapped using the magnetic survey. Meanwhile, the shafts and passages are cut in the limestone bedrock forming empty cavities which can be detected by microgravity survey.

Mudbricks are made of mud extracted from the Nile River, which is rich in magnetic minerals. Therefore, the mudbricks have magnetic properties and produce a strong magnetic field. This magnetic field can be measured on the ground surface using magnetometers (good reviews for the use of the magnetic method in archaeology are published by Abdallatif et al., 2019, and Schmidt, 2007).

The microgravity technique is one of the best geophysical techniques for detecting underground cavities such as tunnels and cavities (Butler, 1980; Issawy et al., 2011, Kis & Szabo, 2005; Porzucek & Loj, 2021). Spatial changes in gravity are considered to be related to gravitational anomalies and thus to subsurface features due to differences in density (Seigel, 1995; Telford et al., 1976).

Although this area is very important archeologically, it does not receive much interest from geophysicists, unlike other sites in the Fayoum area such as the Howara area (El-Emam et al., 2014). The only published work on geophysics in the Lahun area is a detailed land magnetic survey on a very small area (around 10 m × 10 m) for a pottery kiln of the Twelfth Dynasty (Abdallatif et al., 2019).

2. Field Survey and Data Acquisition

Five sites were investigated within the area of the Lahun Pyramid complex (Fig. 1b). These sites were chosen close to existing or known archaeological structures. Two sites were surveyed using microgravity, and the magnetic survey was applied in the other three.

2.1. Gravity Data Acquisition and Global Positioning System (GPS)

The microgravity survey was carried out using a Scintrex CG-5 gravimeter (Scintrex, 2006). The CG-5 has a standard resolution of 1 μ Gal and a standard deviation of less than 5 μ Gal.

A base station was spotted at each survey for diurnal and instrumental drift corrections. At each measuring point, the instrument was leveled and its exact location was recorded using GPS. Sites A and B (Fig. 1b) were surveyed using the microgravity. The survey was performed on grid spacing of approximately 1.5 m. A total of 558 stations were collected at Site A (Fig. 2a) along 27 profiles, and 80 stations were collected at Site B.

Site A covers an area of about 2000 m² (40 m × 50 m) around the Queen's Pyramid in the northern side of Senusret II Pyramid to investigate the existence of any chamber or hidden shaft within this

small auxiliary pyramid. Therefore, this site was surveyed using the microgravity technique. Meanwhile, Site B covers an area of 100 m² (10 m × 10 m), a small area on the road leading to the pyramid near a small suspicious hill that contains some limestone boulders.

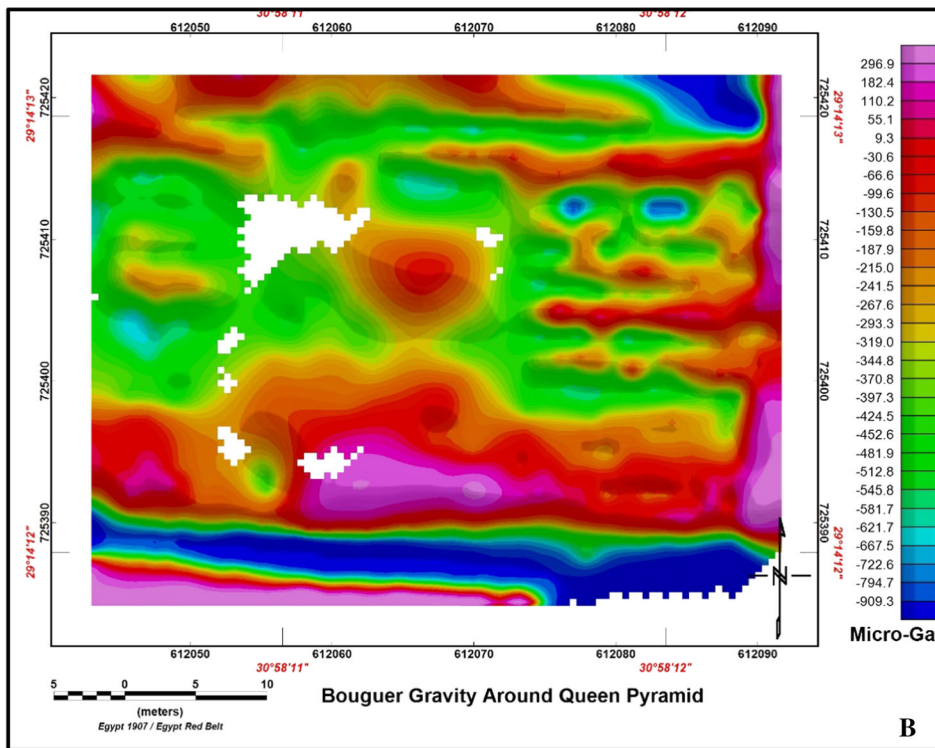
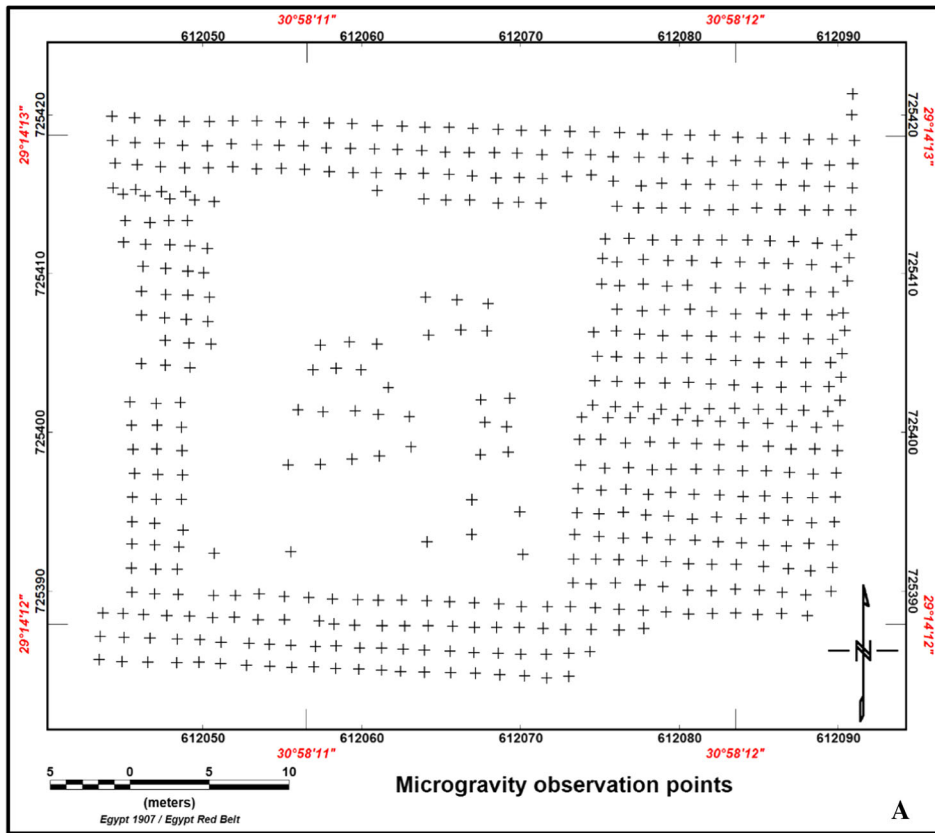
Over the past decade the use of global navigation satellite systems (GNSS) has become common practice in geophysics. Real-time kinematic (RTK) surveying is a relative positioning technique which measures positions using two GNSS antennas in real time. One is set up on a fixed point and is known as the base station. It uses a high-frequency radio to transmit its raw observations to a second unit, known as the rover, and then the rover uses both observations to compute a position relative to the base location in real time. Typically, determining the coordinates of the base station requires sophisticated computations using Precise Point Positioning (PPP) algorithms. The horizontal coordinates of the microgravity measurement points were determined with precision of 1–2 cm using a Trimble R8 GNSS.

2.2. Magnetic Data Acquisition

The micro-magnetic survey was performed using a vertical fluxgate gradiometer model FM256 (Geoscan Research, 2004) which has a resolution of 0.05 nT. Such measurements can reveal the distribution of archaeological remains at moderate depths down to a few meters. The observed anomalies of the vertical magnetic gradient are able to directly identify source boundaries (Herwagner et al., 2000).

Each site was divided into 20 m × 20 m grids. The data were acquired at station separations of 0.5 m along parallel traverses of 20 m length with a spacing of 1 m. The magnetic study was performed at Sites C, D, and E (Fig. 1b). At each site, a zero-reference point has been established to set the instrument to zero vertical gradient.

Site C covers an area of about 3600 m² (60 m × 60 m) located southwest of the Senusret II Pyramid against the discovered Pyramid entrance. The site was surveyed using the magnetic technique at 0.5-m station separation and 1-m traverse separation. There is an argument among archaeologists about the motivations of Senusret II to move the pyramid



◀Figure 2

a Microgravity observation points around the Queen's Pyramid (Site A). The distance between stations is 1.5 m. **b** Bouguer gravity map around the Queen's Pyramid

entrance from the northern side to the southern side of the pyramid. Some archaeologists have suggested that it was for deceiving tomb robbers, while others suggest it was for symbolic or religious reasons. Verner (2001) suggested that it was a combination of religious reasons and to deceive looters. If it was moved for religious reasons, then there is a good chance of finding some structure built to practice such a religious regime.

Site D covers an area of about 800 m² (20 m × 40 m) located at the east side of the pyramid, and was surveyed using 0.5-m station separation and 1-m traverse separation. The site was surveyed to investigate the existence of any remains of the mortuary temple or the causeway. The funerary temple was completely ruined, and what remains are small fragments of granite. Therefore, the magnetic method has a good chance of locating any remains of the temple.

Site E covers an area of 3200 m² (40 m × 80 m) near the Valley Temple to investigate the existence of any other structures associated with the valley temple. This site was covered by a magnetic survey using 0.5-m station separation and 1-m traverse separation.

3. Data Processing and Interpretation

3.1. Gravity Data

Standard gravity data processing usually consists of latitude correction, free-air correction, and Bouguer correction to compensate for the gravity reduction due to the variations in topography and position (Boddice et al., 2018; Hackney, 2020; Long & Kaufmann, 2013; Seigel, 1995). Bouguer anomaly maps are produced from the raw gravity measurements after these corrections. The Scintrex CG-5 instrument performs many corrections to the raw gravity data automatically (e.g., temperature, tilt,

tide, and drift). The readings were corrected automatically for Earth's tide variations. The instrumental drift was estimated by regularly repeated readings at a selected base station at hourly intervals and semi-random returns to other stations within the grid. The daily drifts of the CG-5 gravimeter varied in the range of 37–44 mGal over the 6 days of measurements with an almost linear character of the individual drift curves. Statistical analysis of the repeated station values from different days (i.e. 11% from the total number of points) provided a mean squared error of less than 4 mGal in the measured gravity.

The Bouguer anomalies were calculated as the following equation:

$$BA = g_{obs} - g_{model}$$

$$g_{model} = g_{\varphi} - FAC + BC - TC$$

$$\Delta g_B = \Delta g_{obs} - [g_{\varphi} - FAC + BC - TC]$$

where g_{model} is the model for an on-land gravity survey, g_{obs} is the measured gravity value corrected for instrumental drift and the Earth's tides, g_{φ} is the gravity at latitude φ (latitude correction), FAC is free-air correction (altitude), BC is Bouguer correction (material that comprises the model), and TC is terrain correction (topography).

Density of 2.4 g cm⁻³ was used for the calculation of the planar Bouguer and terrain corrections. The land around the gravity stations was therefore mapped using a Trimble R8 total station, and a detailed topographic model within a 50-m zone surrounding the microgravity grid was constructed. The GPS data were processed using Bernese 5.0 software (Dach et al., 2007). Consequently, it was used for the calculation of the innermost zone terrain correction. The inner zone terrain correction was computed up to a distance of 350 m using a digital elevation model (DEM) with 10-m grid spacing. The threshold distance (outer radius) of 5.5 km, where the far zone terrain contributes more or less equally to all microgravity points, was determined and the corresponding far zone terrain correction was calculated using a DEM model.

The Bouguer anomaly is a superposition of the gravitational attraction of all the rock masses and objects in the surrounding medium. However, the

gravity variations due to the near-surface change in the density distribution of the rock mass are known as local anomalies. Anomalies originating from large sources are called regional anomalies (Nettleton, 1954). There are many analytical methods to estimate the regional anomalies from the Bouguer anomaly map. The difference between the Bouguer anomaly and the regional anomaly is known as the residual anomaly (Skeels, 1967). The regional anomaly map can be estimated from the Bouguer map using polynomial fitting or frequency filters. In the current study, the regional maps were estimated using a low-pass filter with a cutoff of 2.4 m in the wavenumber domain. The Butterworth filter can be defined as

$$\text{BWF}(k) = \frac{1}{\left[1 + \left(k/k_c\right)^n\right]}$$

where k is the wavenumber, k_c is the central wavenumber where the filter has a value of 0.5, n is a positive integer for low-pass filters, usually 8, and for high-pass filters it is a negative integer.

Other processing steps can be applied to separate the deeper sources from the shallower sources or even to give a rough estimate of the source depth. The most well-known technique is the upward continuation. Upward continuation is a mathematical transformation of the gravity anomaly observed at some level to the gravity anomaly that would be observed at a higher level (Jacobsen, 1987; Kebede et al., 2020). The data processing and analysis were performed using Oasis montaj software (Geosoft Inc./ Seequent).

Interpretation of gravity data is rather simple, where negative anomalies represent low-density contrast (low-density materials embedded in a higher density medium) and can represent cavities, tunnels, and shafts. Meanwhile, positive anomalies represent high-density contrast (high-density materials embedded in a lower density medium) and can be produced by buried walls and granite blocks buried in sand or embedded in limestone.

3.2. Magnetic Data

The magnetic data were analyzed using Geoplot software (Geoplot-Geoscan Research, 2005).

Estimates of the vertical magnetic gradient have been widely used in archaeological surveys in Egypt (Abdallatif et al., 2003, 2005, 2019; El-Emam et al., 2014; Herbich, 2003; Kamei et al., 2002; Odah et al., 2005). The raw data were presented in shade plots to determine the main field errors and noise. Several different data-processing techniques (e.g., zero-mean grid, zero-mean traverse, despiking, low-pass filter, and clipping) were applied to eliminate the errors and to improve the acquired data quality.

The darker areas in the processed grayscale magnetic imagery mark positive anomalies and the lighter areas mark negative ones. The magnetic images have an appearance similar to aerial photographs of the surface foundation, making them very useful to archaeologists in any future excavations.

4. Results and Discussion

4.1. Site A (Around the Queen's Pyramid)

The measured microgravity data after correction is presented in Fig. 2b. The Bouguer anomaly map of Site A shows anomalous gravity variation from -900 to 300 μGal . Most of the area shows a negative anomaly in the range -300 to -900 μGal . However, anomalies in the range of 200 to -200 μGal can be seen in different parts of the map.

Strong negative anomalies (less than -800 μGal) are identified from the Bouguer anomaly map.

An elongated anomaly in the east–west direction is located in the southern part of the study area (between the Queen's Pyramid and the Pyramid of Senusret II). Low-gravity values in the Bouguer anomaly map were qualitatively interpreted as an indication of the presence of hidden features such as tombs, caves, corridors, and crypts. High values in the Bouguer anomaly map represent the surrounding materials, which consist of weathered limestone and sandstone clay with a shale matrix. In this site, the negative gravity anomalies could be of archaeological interest as they could represent tunnels, chambers, or corridors. However, the source of these anomalies could be from regional (background that has no archaeological interest) or local sources of archaeological interest. Therefore, separation of the

shallow source from the deep source had been performed.

A low-pass filter with a cutoff of 2.4 m was used to produce the regional anomaly map (Fig. 3a). The regional map is very similar to the Bouguer anomaly map and contains an elongated area of anomalously low values (-400 to -900 μGal) aligned E–W in the southern part (between the Queen’s Pyramid and the Pyramid of Senusret II). Anomalously high gravity values (100 to -100 μGal) in different parts of the map, such as on the southern edge of the Queen’s Pyramid. Other areas with anomalously high values (125 to -100 μGal) can be found scattered within the northwestern part of the study area and on its eastern border.

A high-pass filter with a 2.4-m cutoff was also applied to the Bouguer map to produce the residual map (Fig. 3b). The residual map shows high gravity anomalies (135 – 80 μGal) in the eastern and western sides of the map. The elongated, low-gravity anomaly (-195 μGal) in the southern part of the site (between the Queen’s Pyramid and the Pyramid of Senusret II) is still visible (Fig. 3b). Moreover, horizontal lineaments appear at the eastern side of the Queen’s Pyramid,

By comparison, between the regional and residual maps, most of the anomalies associated with the Queen’s Pyramid are from the regional background, i.e. from a deep source. Only the elongated anomaly in the southern part of the site may be of archaeological interest.

4.2. Site B

Site B is a small area of 100 square meters on the road leading to the pyramid. The site is located beside a small suspicious hill of mud and limestone fragments (Fig. 4a). Archaeologists have recommended that this site be investigated by geophysics. However, the area was only surveyed by gravity because the road has light poles on both sides which will mask the magnetic data completely.

The resulting Bouguer map of the gravity survey (Fig. 4b) shows a gradual change in gravity from south to north with a maximum negative amplitude of -1100 μGal in the northeastern corner of the site. An elongated area of anomalously high gravity values

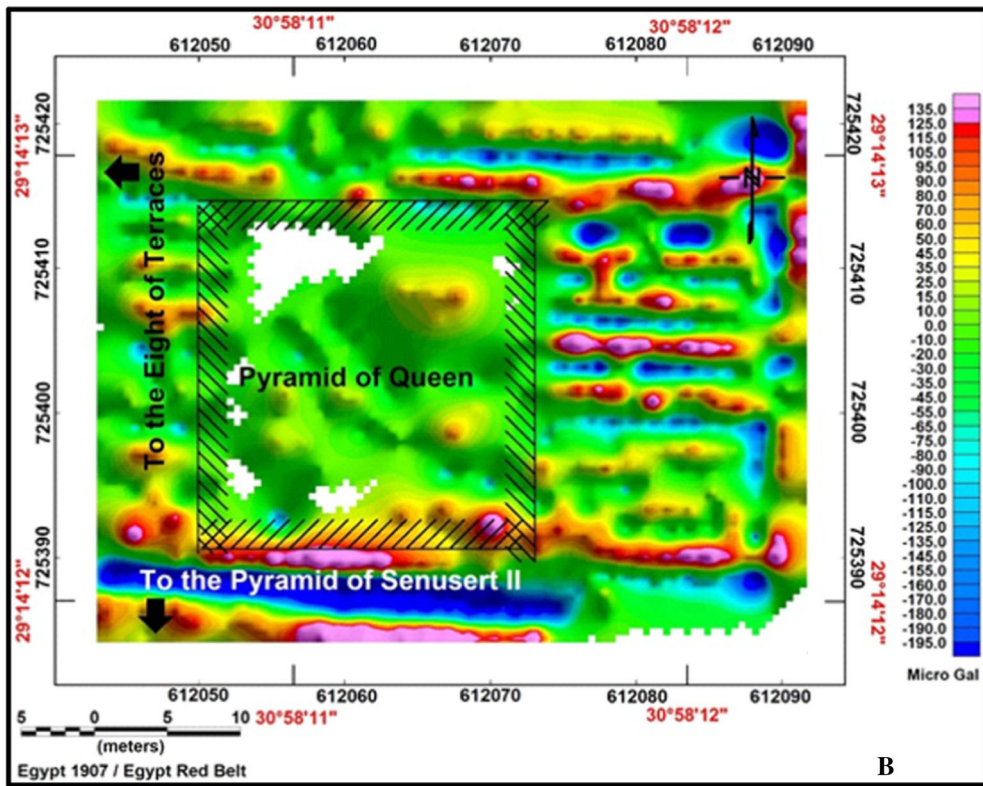
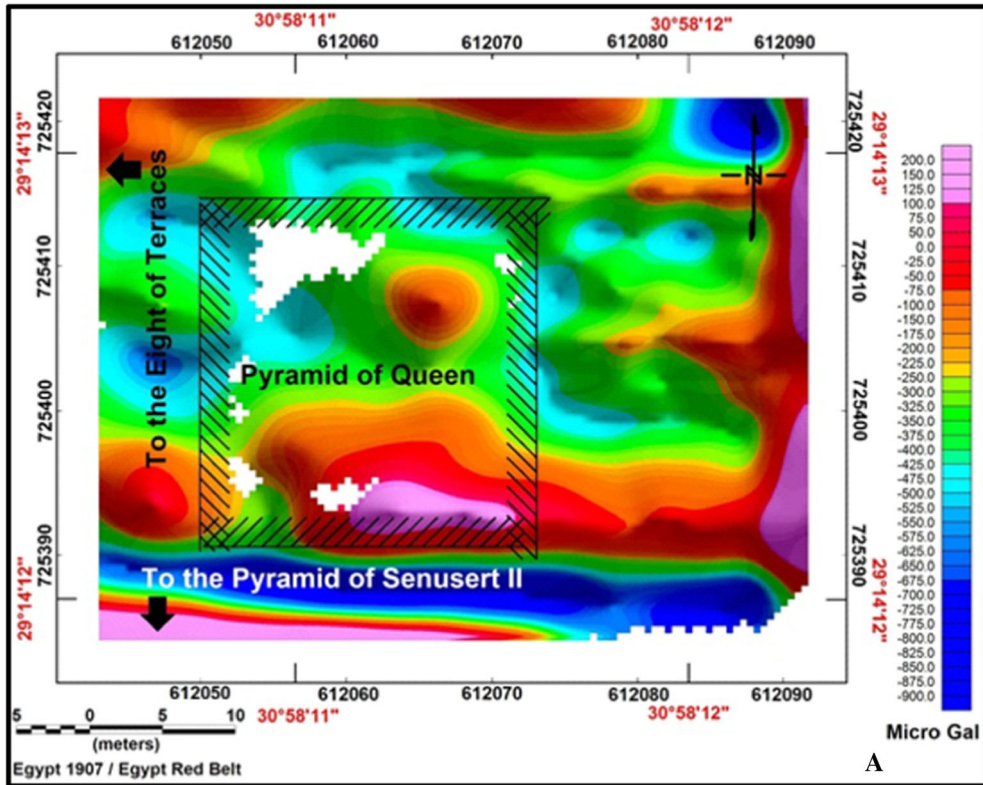
(up to -200 μGal) can be seen in the southern half of the site. In addition, elongated areas of low-gravity values (-600 to -1100 μGal) that trend east–west can be observed in the northern part of the site (Fig. 4b). The low-gravity values in the Bouguer anomaly map indicate the presence of hidden archaeological features.

A low-pass filter with a 2.4-m cutoff was also applied to the data from Site B to produce the regional anomaly map (Fig. 6c). The resulting regional anomaly is almost a weak negative-to-positive gravity anomaly in the range of -50 to 325 μGal . Two positive anomalies (25 to 325 μGal) aligned in the NE–SW direction appear in the southern half of the site. In addition, two negative gravity anomalies (-350 to -100 μGal) appear in the northeastern and western corners of the site.

A high-pass filter with a 2.4-m cutoff was applied to the Bouguer data to produce the residual map (Fig. 4d). The residual anomalies have lower values and smaller areas than the regional anomalies. However, two areas of low-gravity values (-50 to -150 μGal) that have elongated oval shapes and are aligned NW–SE can be seen in the northern part of the study site. This low negative gravity anomaly is of particular interest as it could be buried chambers or tombs. Therefore, the gravity data were also upward continued to produce residual maps for different depths. The anomaly becomes very clear in the continuation maps of 1 m (Fig. 5a) and 4 m (Fig. 5b). The upward continuation maps also show that the anomaly in the center of Site B decreases in size. The negative gravity anomalies in the northern part of the site become very clear. These negative anomalies could be two chambers or rooms present at Site B. The first room to the west is represented by anomaly a in Fig. 5. The second room is located to the east and is represented by anomaly b in Fig. 5. Meanwhile, anomaly c in Fig. 5 could be interpreted as the entrance to these rooms. The anomaly is elongated in the southeast direction in Fig. 5a and shrinks to become very close to anomaly a in Fig. 5b.

4.3. Sites C and D

Sites C and D were surveyed using the magnetic technique. The processed magnetic data of Sites C



◀Figure 3

- a Regional gravity map around the Queen’s Pyramid (Site A).
- b Residual gravity map around the Queen’s Pyramid (Site A)

and D (Figs. 6 and 7) show several strong magnetic anomalies representing circular features (anomaly a, Figs. 6 and 7). These circular anomalies are aligned

in the east–west direction at Site C and in the north–south direction at Site D. However, weaker anomalies with different orientations appear at both sites (anomaly b, Figs. 6 and 7) that can be attributed to ruined structures from mudbricks. Also, some strong circular magnetic anomalies appear on the eastern side of Site C (anomaly c). These anomalies are noise due to metal poles inserted in the ground, while at

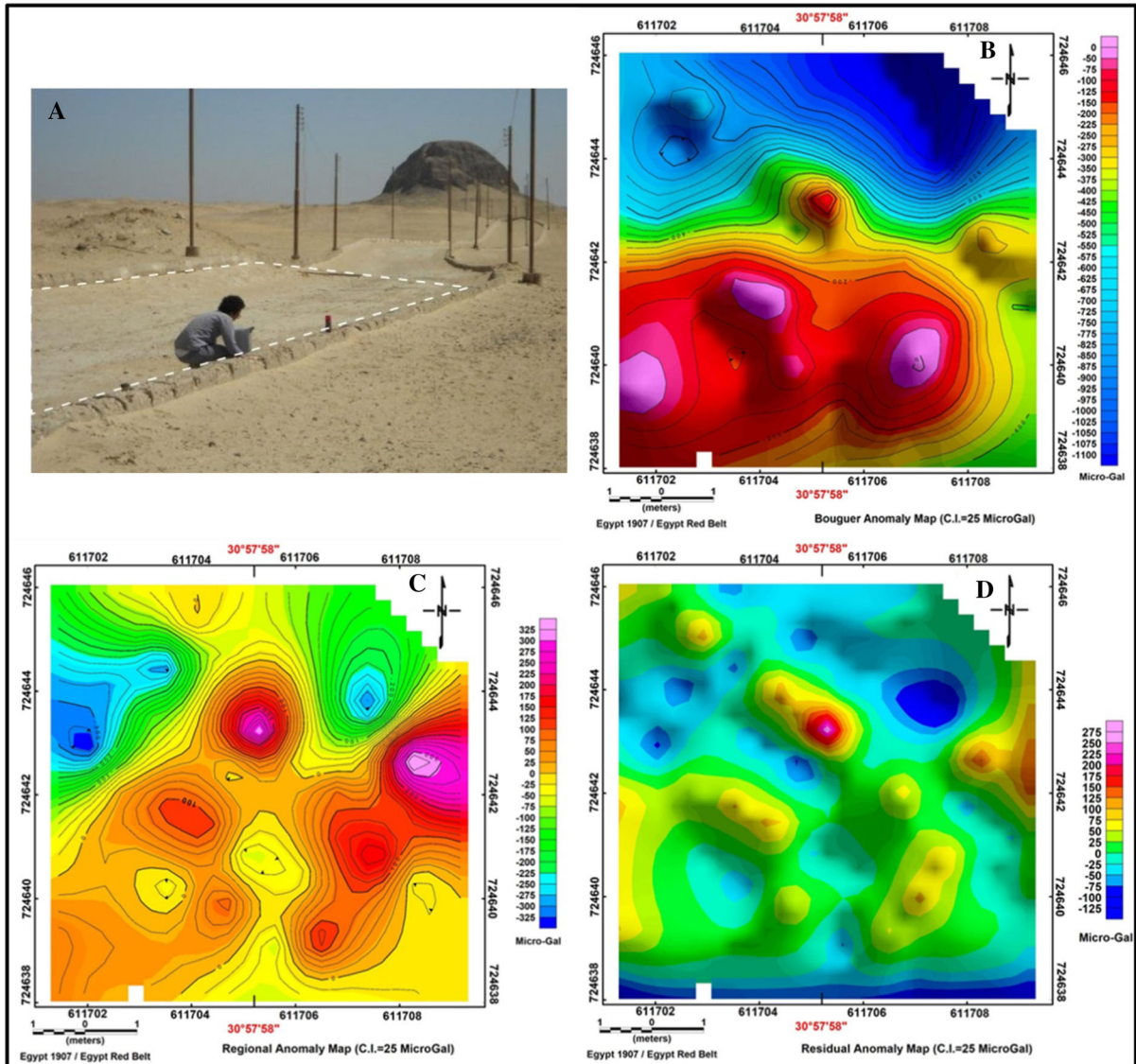


Figure 4

- a Photograph showing the surface features at Site B while conducting the microgravity survey. The Pyramid of King Senusret II is in the background.
- b Bouguer gravity map of the road leading to the Pyramid of King Senusret II;
- c Regional gravity map of the road leading to the Pyramid of King Senusret II.
- d Residual gravity map of the road leading to the Pyramid of King Senusret II

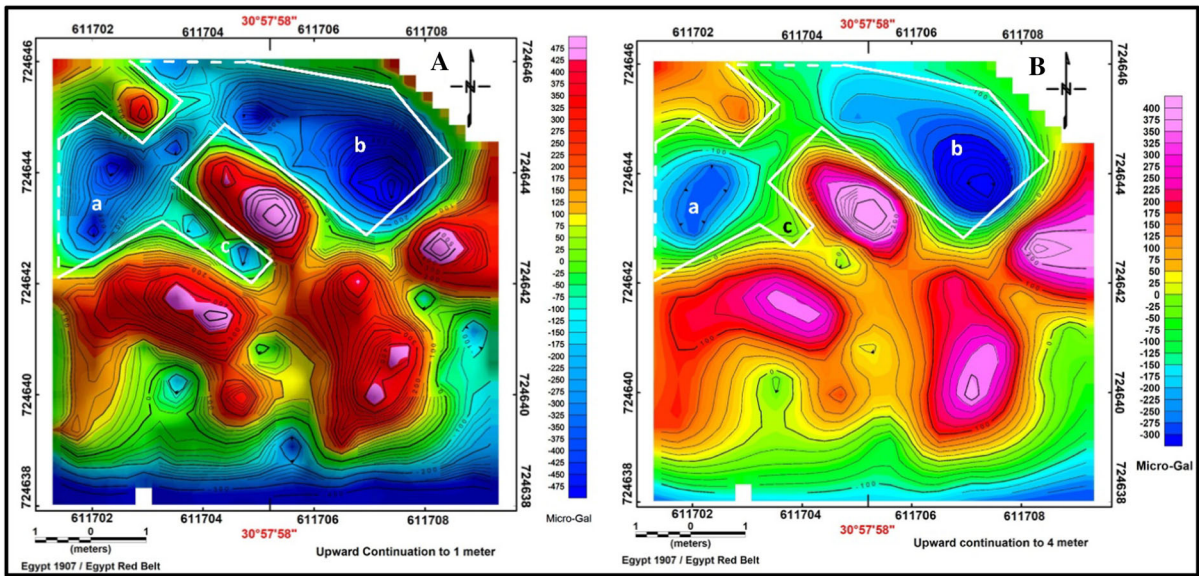


Figure 5

a Upward continuation to 1 m (residual gravity map of Site B). b Upward continuation to 4 m (residual gravity map of Site B)

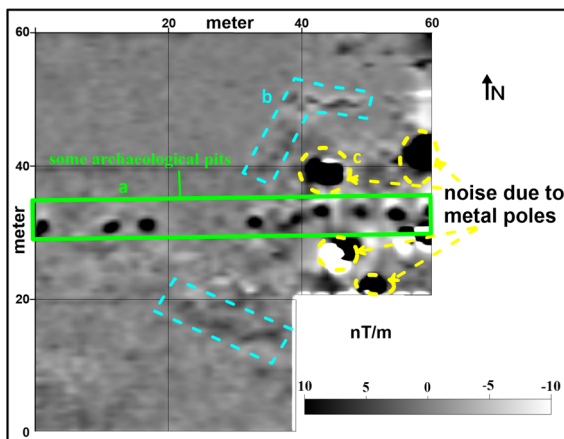


Figure 6

Magnetic anomalies at the southern part of the Pyramid of King Senusret II (Site C)

Site D there are some faint small magnetic anomalies appearing in different locations (anomaly c, Fig. 7) that can be attributed to buried granite fragments.

4.4. Site E

Site E is near the Valley Temple, where it is expected that some archaeological structures associated with the Valley Temple or related to the

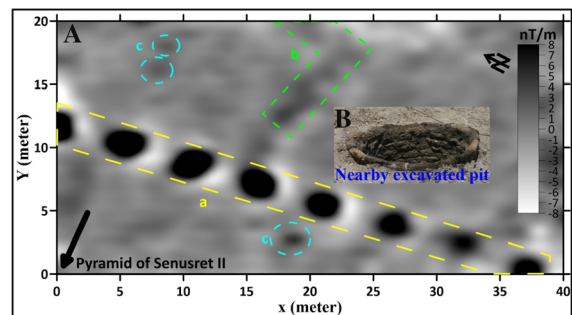


Figure 7

a Magnetic anomalies at the eastern part of the Pyramid of King Senusret II (Site D). b Photograph showing a nearby excavated pit

agriculture activities in the valley will be found. The magnetic survey (Fig. 8) shows three main anomalous areas marked as a, b, and c. These magnetic anomalies are positive magnetic anomalies elongated in the north–south direction that are connected in a square or rectangular shape. These anomalies can be attributed to three buried structures.

5. Discussion and Conclusion

The gravity survey at Site A reveals an elongated anomaly in the southern part of the site that could be

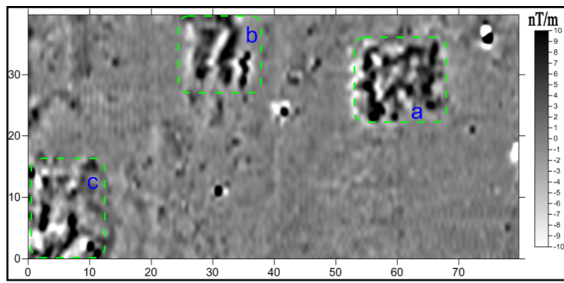


Figure 8

The magnetic image of Site E shows three stores of wheat made of mudbricks, dimensions of 10×10 m each

of archaeological interest. The highly negative values indicate the presence of a corridor or longitudinal cavity between the Queen's Pyramid and the Pyramid of King Senusret II. Historically, it is believed that Senusret II dug a trench around the pyramid to protect it from flooding and rainfall water (Lehner, 2008; Petrie et al., 1923; Verner, 2001). The trench was dug around the elevated limestone core and filled with sand to absorb the rainfall water. This anomaly could be due to the part of this trench that is filled with sand, which has a lower density than limestone. Therefore, it appears as a negative gravity anomaly. The horizontal lineaments on the eastern side of the Queen's Pyramid may be part of the same trench system but on a small scale adequate for the size of the Queen's Pyramid.

The gravity survey at Site B indicates the presence of two negative gravity anomalies at the northern part of the site that could be interpreted as buried chambers (Fig. 5). The first chamber is to the west and the second room is located to the east. An entrance was identified to the south of the first room. The size of the chambers indicates that it could be a royal tomb.

The magnetic survey at Site C was conducted to evaluate the archaeological claims about the motivations behind the decision by Senusret II to move the pyramid entrance to the southern side. The collected data do not show any features to support the idea of religious reasons. However, circular magnetic anomalies were observed at regular distances.

Similar circular anomalies were observed at Site D in addition to three small anomalies that could be due to granite fragments and an additional weak

anomaly could be due to a ruined mudbrick structure that could be part of the funeral temple.

The circular magnetic anomalies spotted in Site C and Site D are a series of pits. These pits are located on the eastern and southern sides of the Pyramid of King Senusret II. These anomalies are associated with the mudbricks used as casing walls for these pits, as they were found at the excavation site near the pyramid (Fig. 7b).

Archaeologically, there are many trees planted following a tradition that began in the Eleventh Dynasty at the Pyramid temple of King Mentuhotep in Deir al-Bahari. It is not known what kind of trees were planted, but it is known that all of the trees were planted on the eastern and southern sides (Fakhry, 1963). A total of 42 trees were planted and may have symbolized the 42 judges who were said to sit in the Hall of Justice at the Court of Osiris (Mark, 2012).

The magnetic image of Site E (Fig. 8) revealed the presence of three anomalous areas about $10 \text{ m} \times 10 \text{ m}$ each. These anomalies represent the remains of large (100 m^2) separate structures made of mudbricks. These may be the remains of warehouses used to store wheat during that time as suggested by the archeologists of the Lahun area.

In conclusion, microgravity and magnetic surveys successfully revealed anomalies that could be part of the trench between the Queen's Pyramid and the Senusret II Pyramid, several pits in the eastern and southern sides of the Senusret II Pyramid, two chambers that could be a royal tomb, and the remains of three large mudbrick structures that could be ancient warehouses.

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Declarations

Conflict of interest The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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