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2D and 3D Modeling of Airborne Magnetic Data to Estimate Depth to Basement at the Southeastern Part of Egypt

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ABSTRACT

In order to determine the depth of the basement and, subsequently, the thickness of the sedimentary cover, airborne magnetic data was interpreted using 2D and 3D modeling approaches in the southeast of Egypt. The overall objective is to locate areas for potential groundwater exploration required for sustainable development in Egypt. Six magnetic profiles were built and modeled utilizing the digitized reduced to the north magnetic pole (RTP) data using the 2D and 3D modeling methods of the GM-SYS Programs of Geosoft Oasis Montaj version (v.) 8.4. The results were constrained using previous geological, geophysical and drilled wells information. The depth to the basement surface, which was calculated using the findings of six 2D profiles and a 3D model, revealed that the depth of the basement varied between 383 and 2900 meters below the surface of the ground. The findings revealed that there were three separate locations (designated A, B, and C) in the research area's western, central, and southeast that had deeper basements and thicker sedimentary layer (> 1100 m). These three areas may represent major subsurface basins with great potentiality for groundwater and hydrocarbon exploration. The obtained results of the depth to basement are very close with each other and in good agreement with the results of the drilled wells and previous studies. The current study pertains to the sustainable development plan of Egypt 2030 for promising desert areas in particular areas that hold the potential to become zones of development for agricultural purposes.

1. INTRODUCTION

Finding new sources of fresh water is currently in high demand worldwide, particularly in arid places. Therefore, one of the most crucial challenges in such areas is the search for groundwater aquifers. This type of study's application is completely in line with the main and most important governmental priorities (the Sustainable Development Plan 2030), which aim to boost water resources to support future development in a variety of industries. The area under investigation represent one the desert areas that gained more attention form the Egyptian geoverment as well as researchers for groundwater exploration and sustainable development pojects.

The area under investigation is located at the southeastern part of Egypt occupying four distinct geologic regions of Qena, Nile Valley, Kharga Oasis and Dakhla Oasis. It is inclosed between latitudes 24° 15′ and 26° 45′ N and longitudes 29° 00′ and 33° 00′ E and comprising an area of about 129000 Km^2 (Figure 1). It represents a promising area for land reclamation and projects in the future that rely on groundwater for irrigation and domestic use.

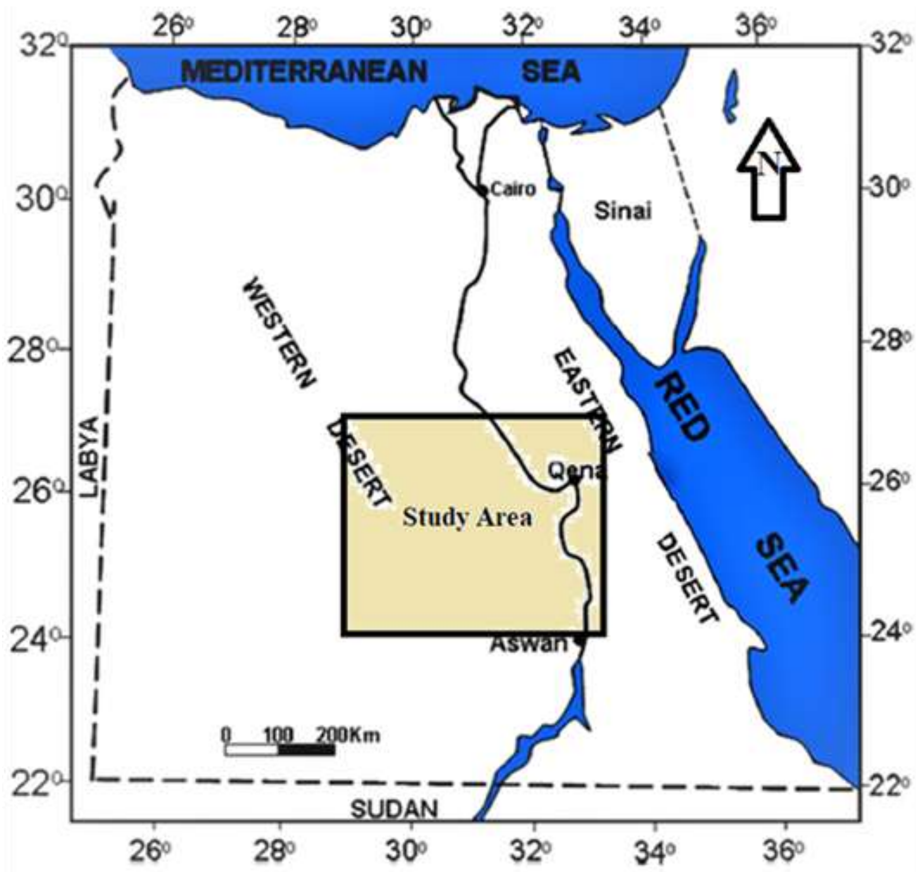


Figure 1: Location map of the studied area

Airborn magnetic data as well as available geological and geophysical information of the study area were utilized to deduce the depth of the basement rocks, and accordingly the thickness of the sedimentary cover that could give some information on the potentiality of groundwater at the study area. This task was achieved by applying 2D and 3D modeling of the aeromagnetic data of the study area. In general, it is very well known that the geophysical methods can be useful in solving many of the subsurface geologic problems [1]. In particular, potential geophysical techniques such as airborn magnetic data considers one of the most effective techniques in determining depth to magnetic source bodies (and consequently the sedimentary cover thickness) and delineating subsurface structures [1]. In addition, magnetic data can be are useful for the geologic, hydrologic mapping and environmental investigations [2, 3, 4 and 5].

Numerous authors who covered various areas of the subject area conducted a number of geophysical studies in the southeasterly desert [6, 7, 8 and 9]. Abdel Zaher et al. [7] indicated that basement depth ranged between 0 to 1500 m (b. s. l.) in the southern section of Egypt's Western Desert, and the largest thickness of sedimentary cover is reported at west Oweinat, southwest of Aswan, Dakhla oasis, and west of Qena town. The research area was investigated by [8] utilizing aircraft magnetic data and is located south of El-Dakhla Oasis in the middle of the western desert in Egypt. The results revealed that multiple methodologies were used to determine the basement depth from aeromagnetic data, and that the depth values produced ranged from 400 to 1,700 m. The geometry of the Qena Bend was examined using remotely sensed and aeromagnetic data by Beshr et al. [9]. The positive anomaly beneath the bend is likely due to a significant uplift at a depth of 750 m, according to the magnetic 2D forward modeling and 3D depth inversion.

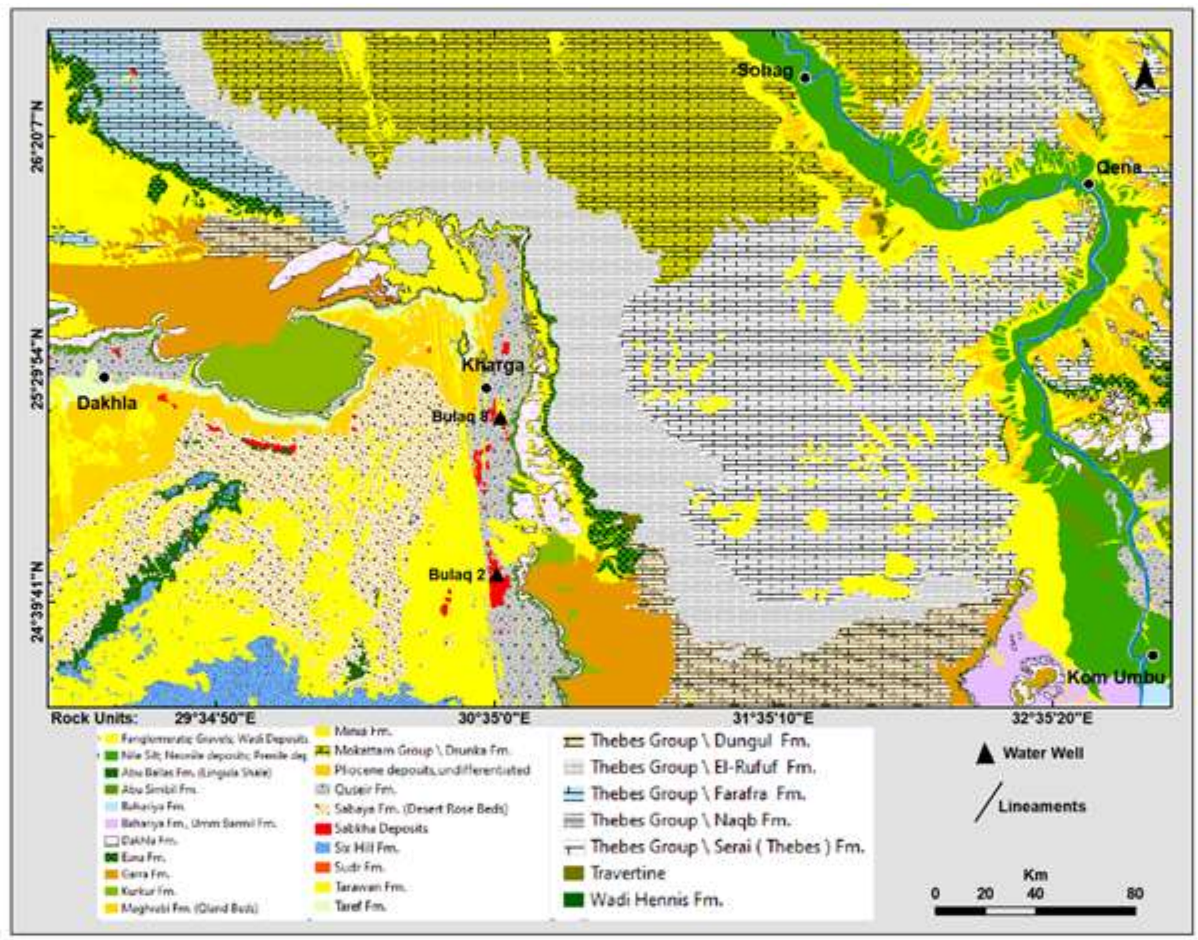
In this work, the thickness of the sedimentary cover and the depth of the basement were determined by interpreting the airborne magnetic data using 2D and 3D modeling approaches. The main goal is to identify possible groundwater exploration sites needed for Egypt's sustainable growth.

2. GEOLOGICAL SETTING

According to the geologic map of Egypt at a scale of 1:500,000 [10] (Figure 2), the research region includes a variety of geological features and geologic units. In the eastern region, Nile Valley deposits predominate, surrounded by plateaus characterized by Early Eocene massive limestones. Along the valley's foot slopes, Cretaceous-Paleocene rocks, primarily marls and shales, are exposed. Fluvial and alluvial sediments from the Pliocene-Quaternary period are present throughout the valley. The sedimentary sequence in this area ranges from 350–400 m near the Nubian–Arabian Shield to 2500 m at the unstable shelf, and it is a part of the stable shelf [11], which is characterized by mild tectonic deformation.

The Nubia Sandstone forms the base of the sedimentary succession in the eastern region, which is followed by the Quseir Shale, which is interspersed with phosphorite horizons near Gabal Abu Had and a phosphatic oyster bed in the south. The Duwi Formation is located above the Quseir Shale and contains three phosphorite beds that are intercalated with shale, marl, and sandstone. The Tarawan Chalk separates the Duwi Formation from the Dakhla Shale, which, in turn, is succeeded by the Esna Shale. The Esna Shale is capped by Lower Eocene limestone forming the plateau's surface. Quaternary deposits consisting of gravels, silt, and sand cover the region [12].

Figure 2: Geological map of the study area deduced from geological map of Egypt. [10]



Significant drainage line Wadi Qena rises from the southern Galala massif's slopes and empties into the Nile at Qena town by flowing north-south. It shows a southward-sloping anticlinal structure and is influenced by a number of fault orientations, including N-S, NNW-SSE, NNE-SSW, and NE-SW, with the NW-SE trend being the most significant [13].

Fault scarps with steep slopes ranging from 38° to 75°, primarily in NW-SE and N-S trends, are present in the southern Wadi Qena area. These fault scarps disseminate alluvial fans, which are mostly made of sand, clay, and gravel. The Pre-Nile flood plains are virtually level and cultivated; they are Quaternary in age and predominantly made of mud, silt, and clay with some sands [14].

The Western Desert is made up of thick sedimentary rocks, principally sandstone, and the Egyptian plateau's resistant limestone cover. It has an average height of 500 meters above sea level. There are only crystalline rocks east of Bir Tarfawi. The Dakhla and Nile Valley basins, two sizable intracratonic basins divided by basement uplifts, are included in the study region. The post Paleozoic rocks in both basins are classified into the Nubian group and upper Cretaceous-Paleogene succession, and they are composed of both marine and continental sediments. Figure 3 generally compares the stratigraphy of the Nile Valley with the Dakhla region in the western part of the research area.

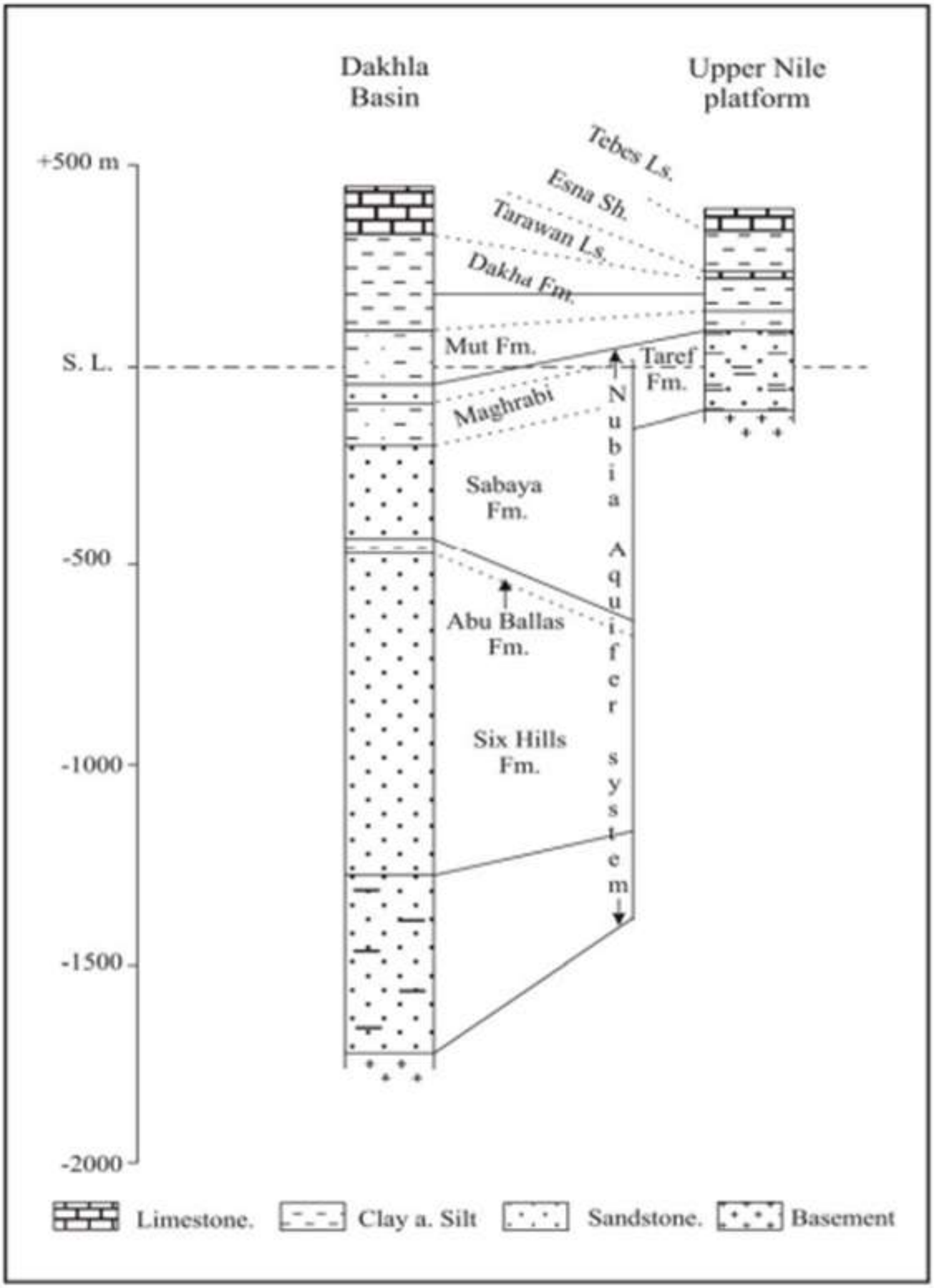


Figure 3: Simplified geological sections of the study area (after Thorweihe, 1990).

The Western Desert features various geomorphological features, including plateaus, depressions, sand dunes, and plains, along with desert oases relying on Nubian aquifers groundwater. Elevations generally remain below 300-400 m a. s. l., except in the southwestern part as shown in the digital elevation model (DEM) [15] (Figure 4). The Great Sand Sea, occupying a vast basin, extends from the northern cliffs of the Gilf Kebir to the southern borders of Siwa Depression, with prevailing winds causing sands to move southeastward. Barchans migrate southward, posing hazards to infrastructure. A limestone plateau covers the central part of Egypt, with elevations ranging from 450-550 m a. s. l. This plateau's landscape was shaped by fluvial dissection during wetter geological ages [16].

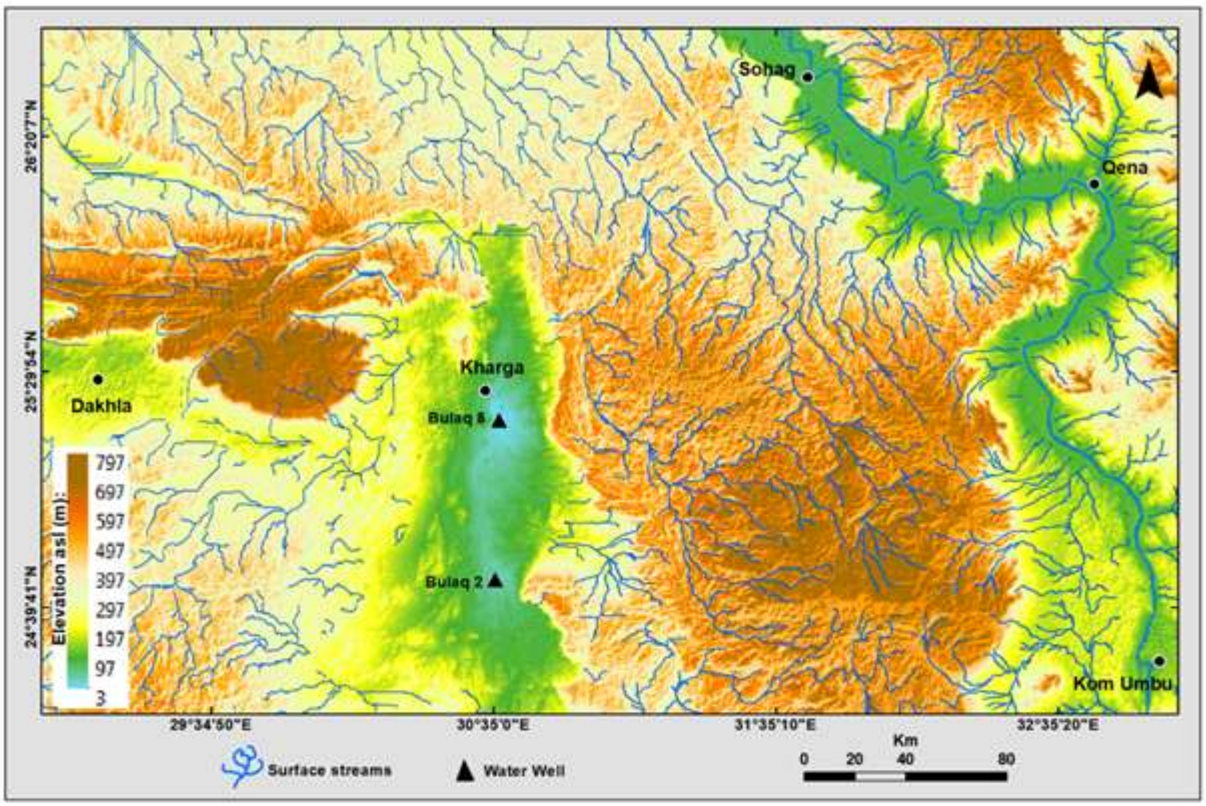


Figure 4: Topographic map of the study area adopted from SRTM (DEM)

A rough eolian plain covered in sand sheets and desert lags can be found in the southern region of the Western Desert. The Kharga Oasis in the New Valley Governorate draws artesian water from the Nubian Sandstone Aquifer, and its geological succession points to the Pleistocene as a possible time when surface water may have once been present. The Dakhla Oasis is one of a number of depressions that run beneath the Libyan Plateau and have a complex geological makeup, including phosphorites, limestone, and shale [17].

3. MATERIALS AND METHODS

The following geological and geophysical data were used to complete the current

- The research area's aeromagnetic map, scaled to 1:500,000, created for EGPC by "western atlas international" [18].

- The main geologic rock units were traced on the geological map of Egypt (scale 1:500.000) produced by EGPC and CONOCO [10].

- Arcinfo v. 10.5 [19], Geosoft Oasis Montaje v. 8.4 [20], and Rockware v. 14 [21], are the software options.

- The digital elevation model SRTM (DEM) v.2 and the basement-accessible drills at the research area (Bulaq 2 and 8 with an average depth of 750m).

-Research on the region's geology and geophysics that have been published.

The aeromagnetic map has been digitized by using Geosoft Oasis Montaj software v. 8.4 [20]. Then the digitized data for the area under study were gridded to a fine grid interval (200 m) using cubic-spline interpolation [21].

In order to generate a geological image of the basement rocks (i.e., depth and magnetic susceptibility), 2D forward modeling is typically applied to the magnetic data. The GM-SYS-2D/Oasis Montaj, which calculates the forward response of the magnetic model using the Talwani and Heirtzler [22] algorithm, was used to conduct it along six profiles that dissected the significant anomalies.

The contrast values for magnetic susceptibility were presumptive. To decrease non-uniqueness and generate models as closely connected to the subsurface as feasible, the depth to basement determined by the Bulaq 2 and 8 dug wells (about 750m) and the findings of earlier research were used as constraints. For the presumptive geologic model, the magnetic field was estimated repeatedly until a good fit between the measured and predicted profiles was achieved. To determine the depth of the basement surface, the depth values of the six profiles are averaged, displayed on a base map, and contoured.

A number of surface grids that each have a susceptibility residual magnetization distribution attributed to it make up the 3D model. Layer susceptibility may be expressed as a constant susceptibility, a vertical susceptibility-depth profile in relation to a "reference surface," or a lateral susceptibility distribution delineated by a grid. Either a constant susceptibility and remnant magnetization or a susceptibility distribution that varies laterally can be used to describe the susceptibility of a layer. Figure 5 illustrates a three-layer model where the parameters "DEN" are constant densities for each layer and "SURF" are filenames for grids defining those surfaces. The input data of the 3D depth model was the RTP, DEM, drilled wells and estimated magnetic susceptibilities of basement rocks. These data were processed using the GMSYS-3D program within the Geosoft Oasis Montaj software v. 8.4.

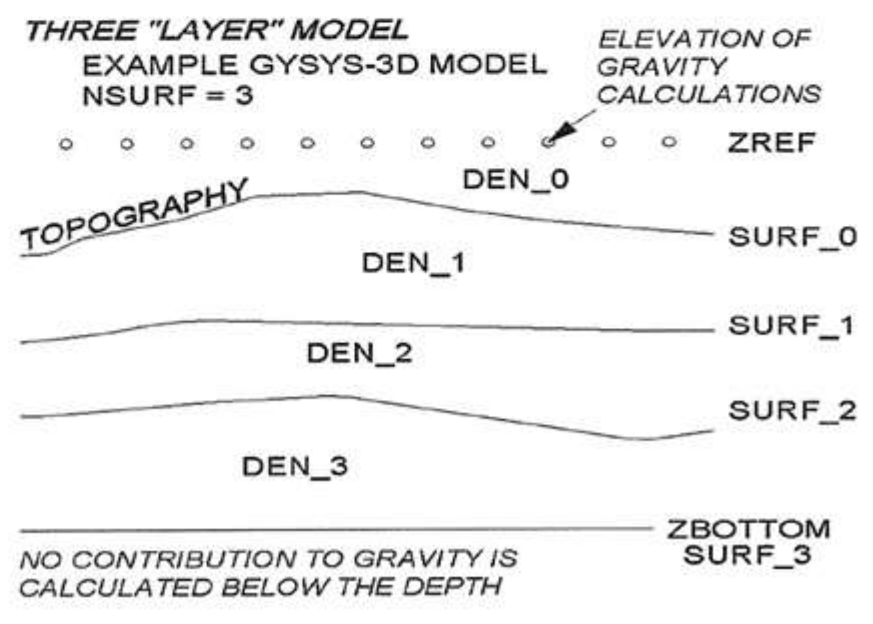


Figure 5: The three-layer model.

4. RESULTS AND DISCUSSIONS

4.1. Reduction to the magnetic north pole (RTP) map

To reduce the polarity effects on the magnetic data of total intensity, a reduction-to-the-pole (RTP) transformation is generally used. In order to align the peaks and gradients of magnetic anomalies precisely over their origins, RTP is a filtering technique.

The digitized RTP magnetic map (Figure 6) showes magnetic anamolies range from 200 nT and -180 nT. The RTP magnetic map could be subdivided into two zones according to the magnetic characters, frequencies and amplitudes of the magnetic anomalies. The first one is a high magnetic zone (>40 nT) that characterized by relatively high magnetic amplitudes and colored by red color. It is encountered in the western, southern parts and some spots in the eastern part of the study area. The shapes of its anomalies are elongated and semi-circle trending in the NW-NE, NE-SW and N-S directions. These anamolies give the impression that these locations refer to shallow depths of the magnetic sources or rocks with high magnetic susceptiblities riches in ferromagnetic minerals (e.g, mafic and ultra mafic rocks) [1].

4.2. Two-dimensional (2D) magnetic modeling

The location of these profiles is shown in figure 6 and their results will be described in detailes in the following.

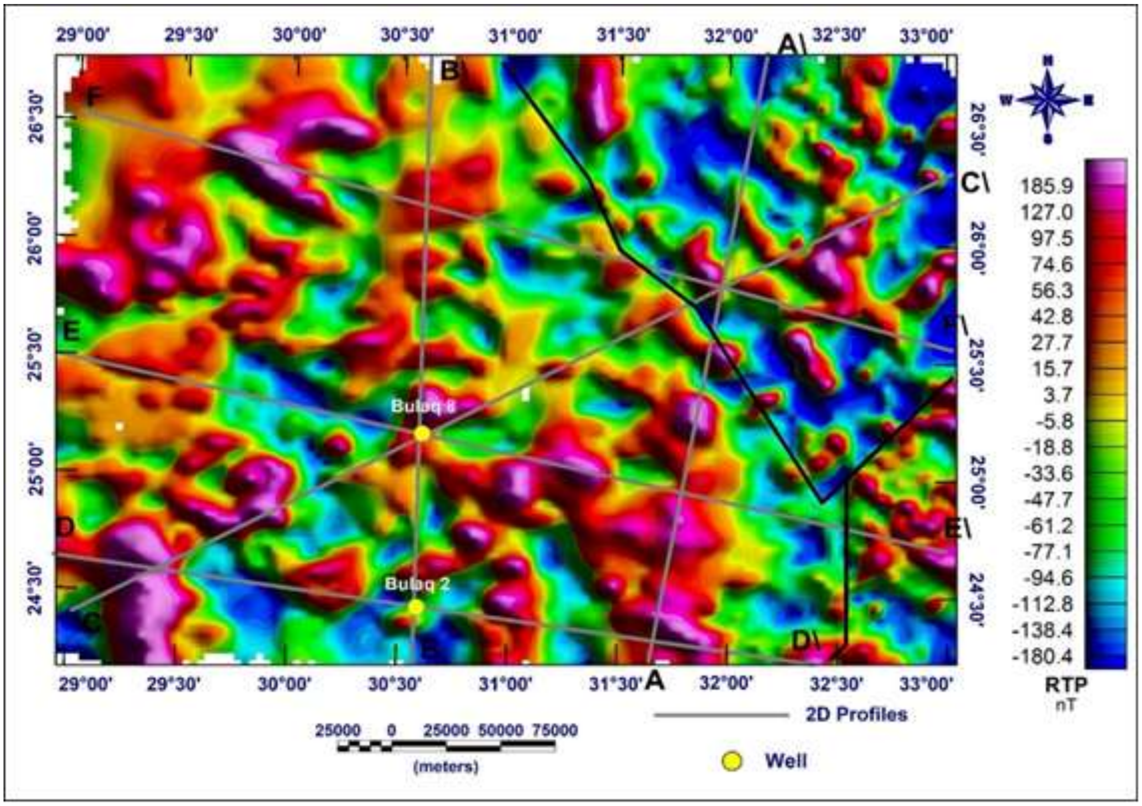


Figure 6: The distribution and location of six profiles on RTP aeromagnetic map

2D Profile (A-A\)

This profile was taken along RTP map along SSW to NNE with length 290 km and shows variation in the basement surface (Figure 7). A further look at this profile reveals a very good agreement between the estimated and observed anomalies, with an error reaching 3.804 (Figure 7). This model consists of four blocks, the upper block represents the sedimentary rocks with magnetic susceptibility value of 0.0 c.g.s.-e.m.u. units and the lower blocks represent the basement rocks. The lower blocks consist of two blocks. The first block occupied the southern part of the profile with magnetic susceptibility value of 0.02 c.g.s.-e.m.u. units. The second block found in northern part of the profile with magnetic susceptibility value of 0.01 c.g.s.-e.m.u. units.

The analysis of this model display that the first part of the profile exhibits shallower values for the basement surface of about 1000 m and the depth of the basement surface become deeper about 4600 m approximately in the center of curve then return to shallow about 2000 m then return to deep about 6000m at the end of the profile.

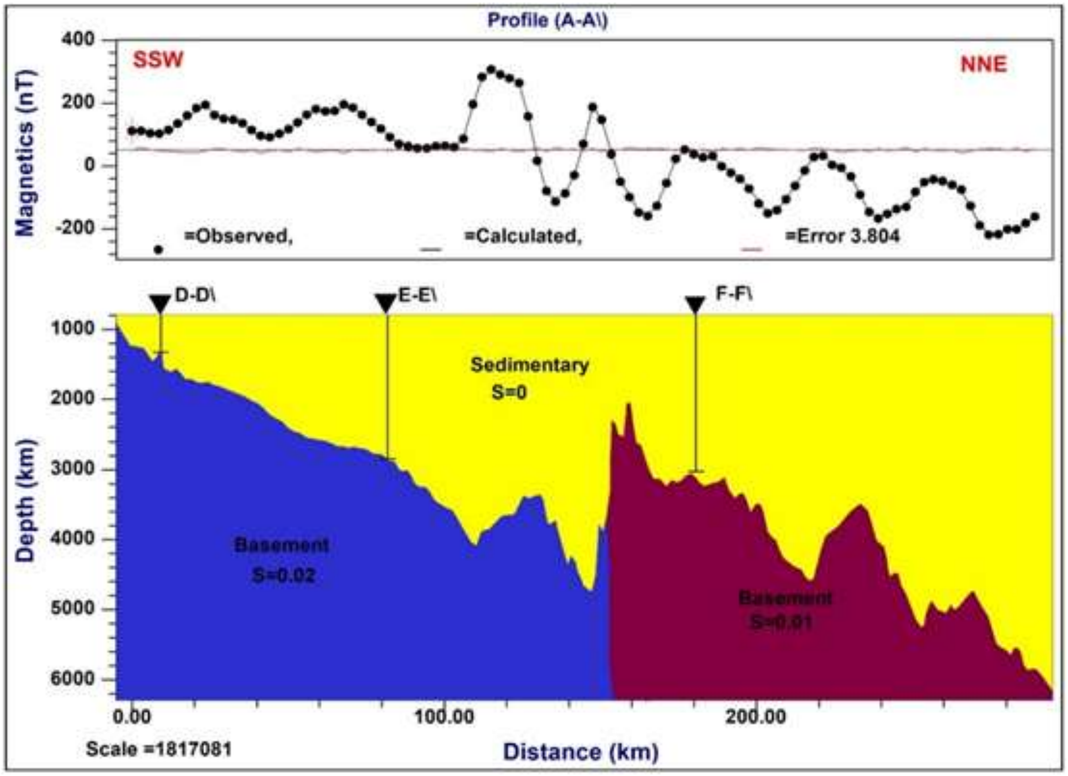


Figure 7: Two-dimensional magnetic modeling along profile A–A\.

2D Profile (B-B\)

In the center of the research region (Figure 8), the second profile (B-B) may be found. The length of this profile is 282 kilometers, with the direction of travel beginning in the south. With an inaccuracy of 5.9, a deeper look at this profile indicates an excellent agreement between the calculated and observed anomalies. The upper section of this model, which has a magnetic susceptibility of 0, represents sedimentary rocks, whereas the lower part, which has a susceptibility of 1, represents basement rocks.

The lower part consists of three blocks with different magnetic susceptibility that show various type and compositions of basements. The first block located at southern part of the profile with magnetic susceptibility value of 0.025 c.g.s.-e.m.u. units. The second block found in central part of the profile with magnetic susceptibility value of 0.02 c.g.s.-e.m.u. units. The third block found in northern part of the profile with magnetic susceptibility value of 0.025 c.g.s.-e.m.u. units.

Between 200 meters in the southern portion of the research region and 2500 meters in the northern part, the depth to the basement along this profile varies. The southern portion of the study region distinguishes shallower basement rocks, and the northern portion of the study area distinguishes deeper basement rocks, according to the association between the magnetic model in this profile and the interpreted basement depth map.

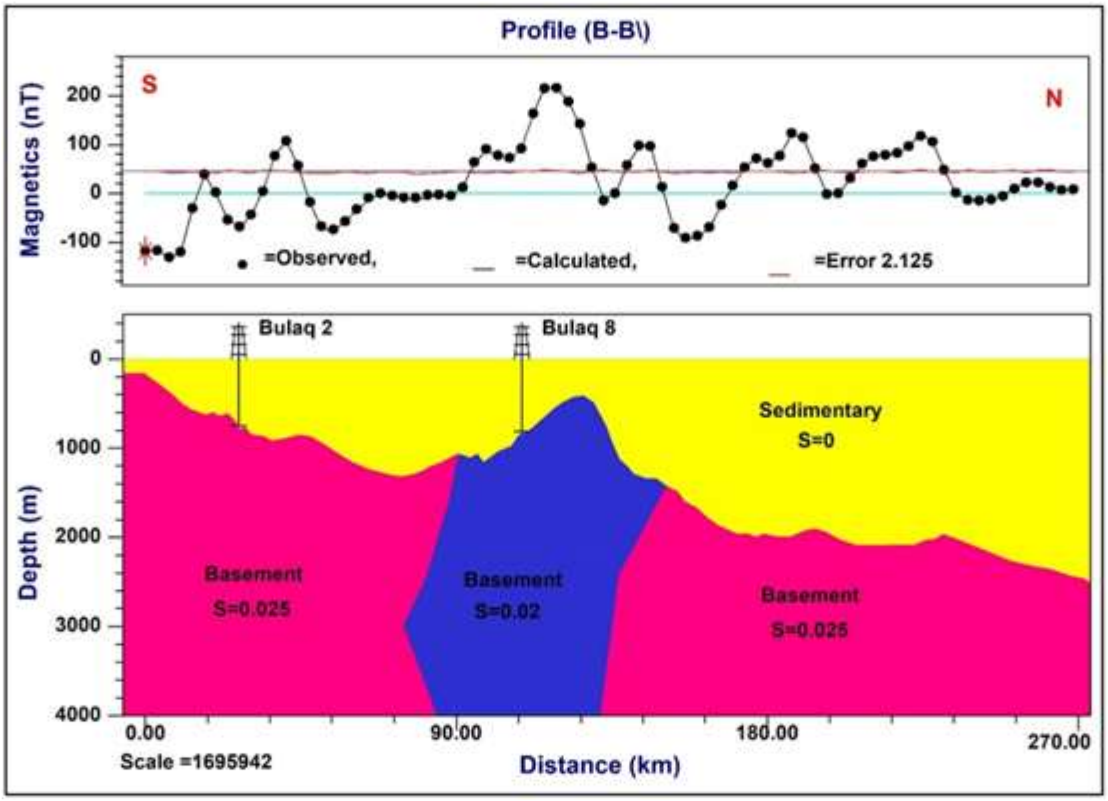


Figure 8: Two-dimensional magnetic modeling along profile B–B\\.

2D Profile (C-C\)

The magnetic values along this profile were traced. This profile is trending from the SW to the NE direction with a total length of about 455 km. With an error reaching 2.764, this profile exhibits a very good fit between the estimated and observed anomalies (Figure 9). The upper part of this model represents the sedimentary rocks with magnetic susceptibility value of 0.0 c.g.s.-e.m.u. units while the lower part of this model represent the basement rocks with various magnetic susceptibility value (0.025 and 0.06). The surface of basement indicates a range of depths oscillating between 200 and 3000 m.

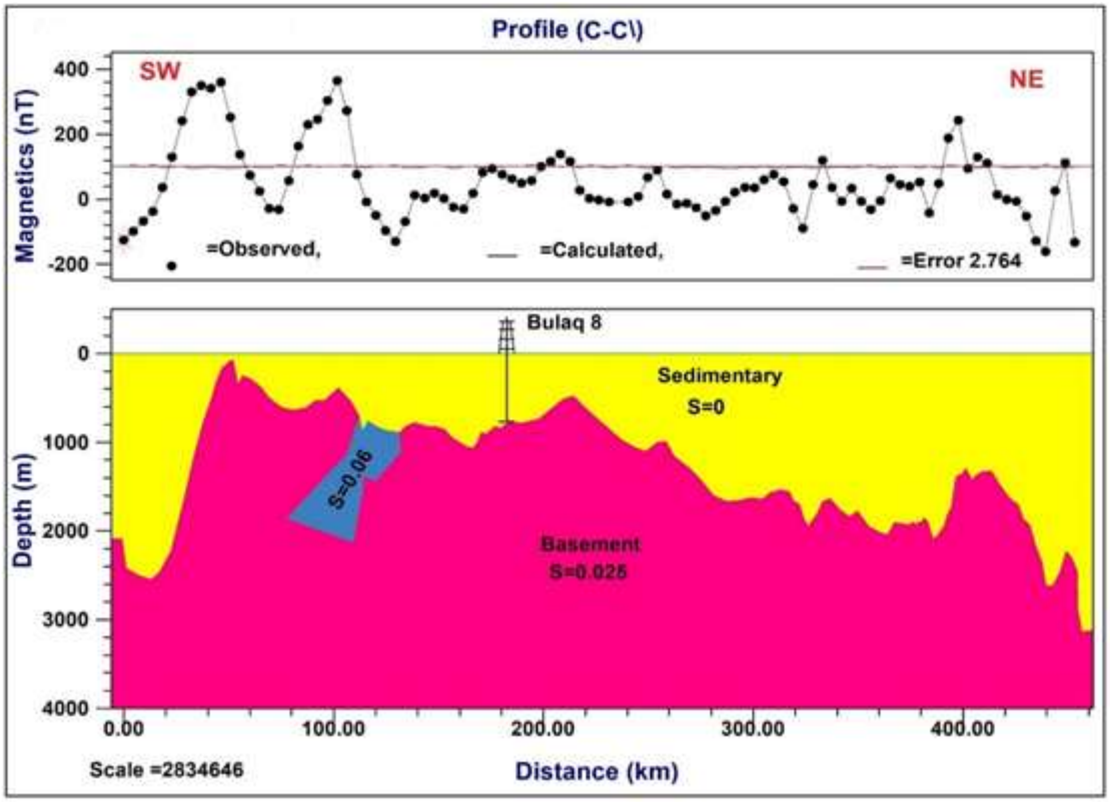


Figure 9: Two-dimensional magnetic modeling along profile C–C\.

2D Profile (D-D\)

This profile was taken along the survey line direction (WNW-ESE) and denoted as D-D\ with total length about 347 km (Figure 10). The RTP magnetic values along this profile were traced. With an inaccuracy of only 2.72, the observed and estimated anomalies fit very well (Figure 10). There are three blocks represented subsidence basement blocks.
The range in magnetic susceptibility (0.0029 to 0.0045 c.g.s unit) assigned for the various blocks across this profile reflects the slight compositional variation of the foundation rocks. While the principal basement that has formed implies a depth range that oscillates between 200 and 1800 meters.

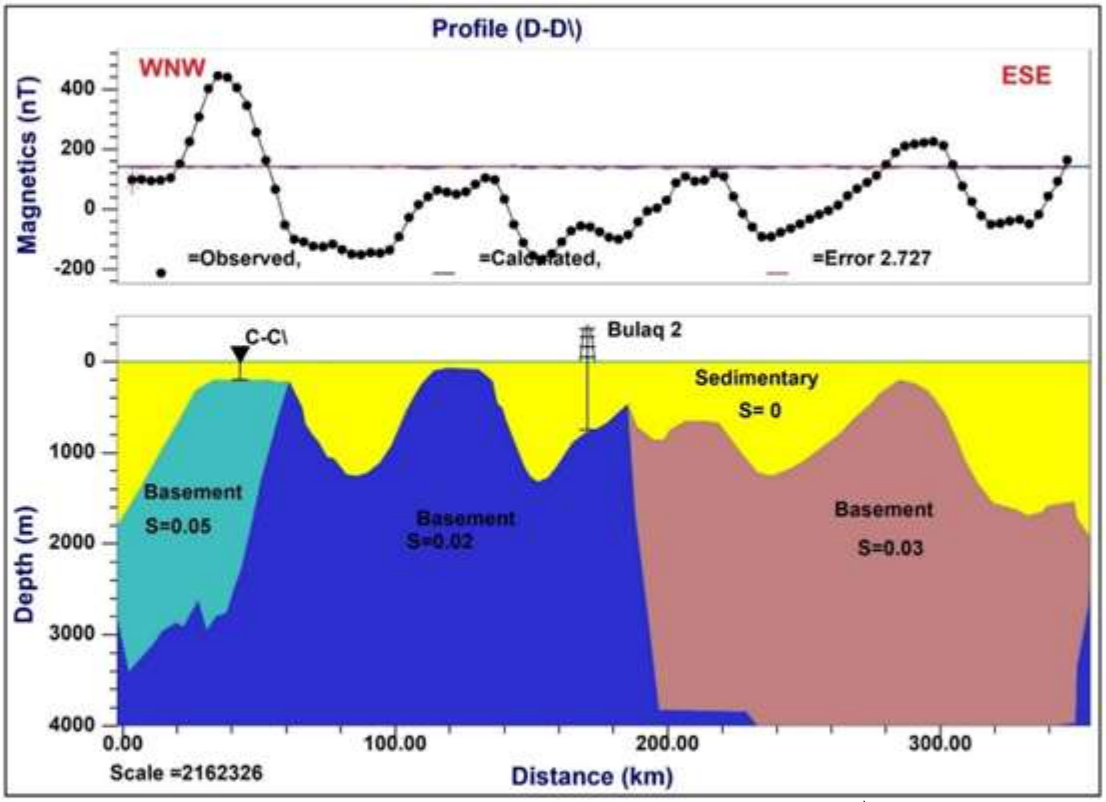


Figure 10: Two-dimensional magnetic modeling along profile D–D\.

2D Profile (E-E-)

It was taken on RTP map along the WNW-ESE direction with total length 422 km and is denoted as E-E\ (Figure 11). This profile was traced together with the RTP magnetic values. The examination of this profile reveals a very good fit between the estimated and observed anomalies, with an error of up to 2.545 nT (Figure 11). This model consists of three blocks, the upper block represents the sedimentary rocks with magnetic susceptibility value 0 c.g.s.-e.m.u and the lower block represents the basement rocks with magnetic susceptibility value 0.025 and 0.04 these values were assumed for this model.

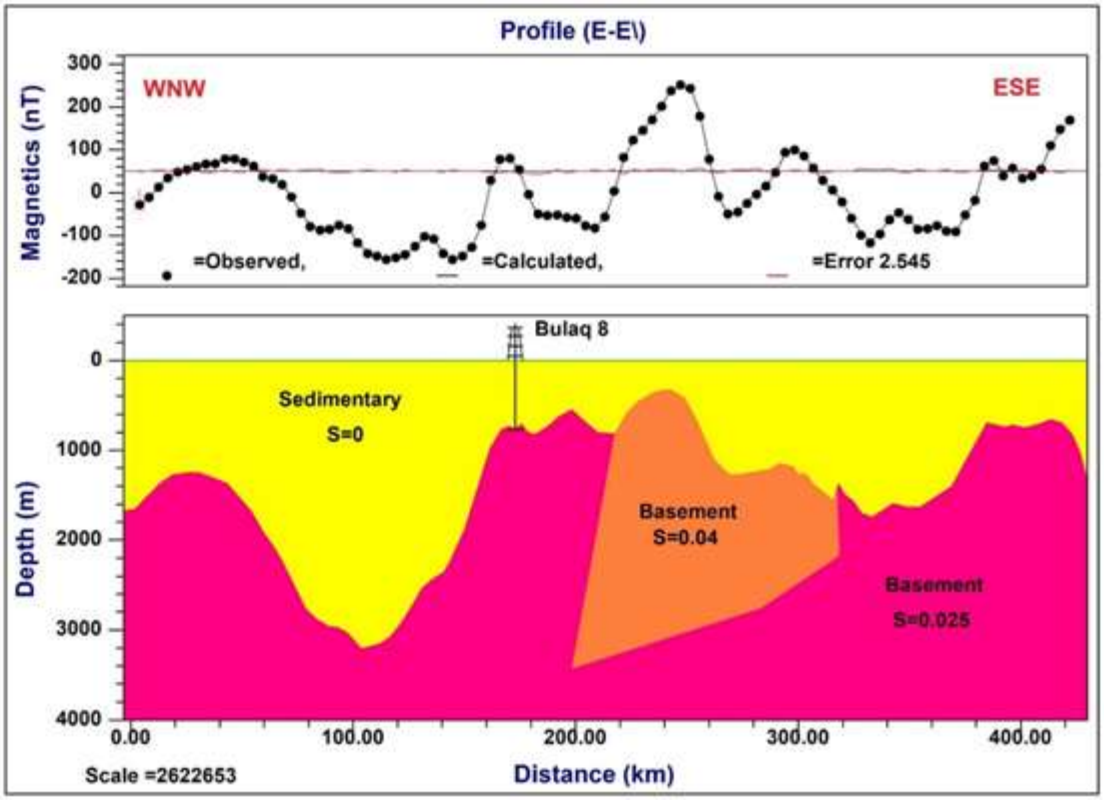


Figure 11: Two-dimensional magnetic modeling along profile E–E\.

2D Profile (F-F\)

This profile running in WNW to ESE- directions with total length 422 km and is denoted as E-E\ (Figure 12). The analysis of this profile shows an excellent fit between the observed and calculated anomalies with error reach 2.896 nT (Figure 12). The assumed magnetic susceptibility of the underlying basement rocks is 0.025, 0.03 0.04 in CGS unit. This profile reflect that the depth of basement at the western part is shallower mean while the depth of basement at the north eastern part is deeper.

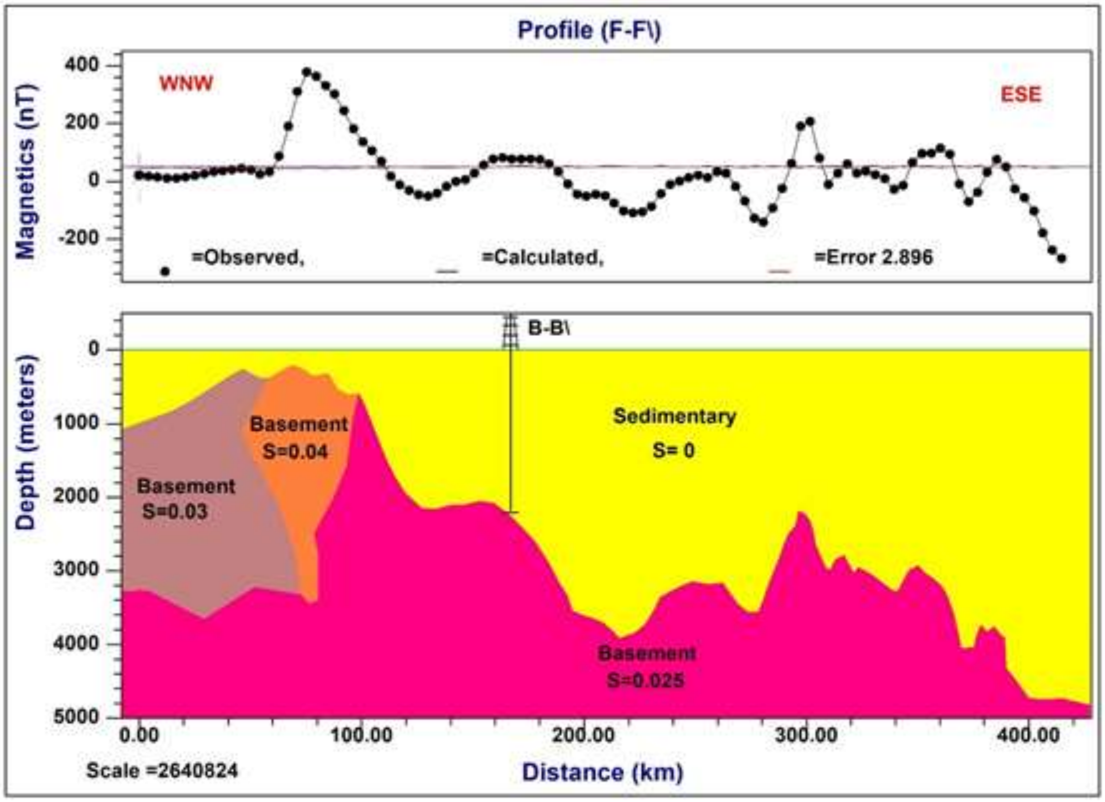


Figure 12: Two-dimensional magnetic modeling along profile F–F\.

By invisiual inspection from the depth resukts of the six 2D profiles that covered the study area, we noticed that lateral change in magnetic susceptibility may refer to different rock composition where high magnetic susceptibility refer to ferromagnetic minerals that distinguish mafic and ultramafic rocks. On the other hand, the low magnetic susceptibility may refer to low concentrations of ferromagnetic minerals of acidic rocks. Moreover the lateral change in magnetic susceptibility may be structuraly controlled.

4.3 Depth map to the basement rocks from 2D results

The depth map of basement surface deduced from the results of the 2D models is shown in figure 13. The results show that the basement depth ranges from about -383 m to about -2900 m below ground surface. These are correlated very well with the depth to basement from the drilled wells (Bulaq 2 and Bulaq 8) and previous studies [7, 8, 9, and 23].The surface of basement at the northwestern, northeastern, southern and southeastern parts were located at shallow depths less than 1500 m which indicate that a thin sedimentary cover, but they increase gradually in northern, western and estern parts to reach depths values more than 1800 m which indicate that a thick sedimentary cover. These parts with thick sedimentary cover may consider potential for groundwater and hydrocarbon exploration projects.

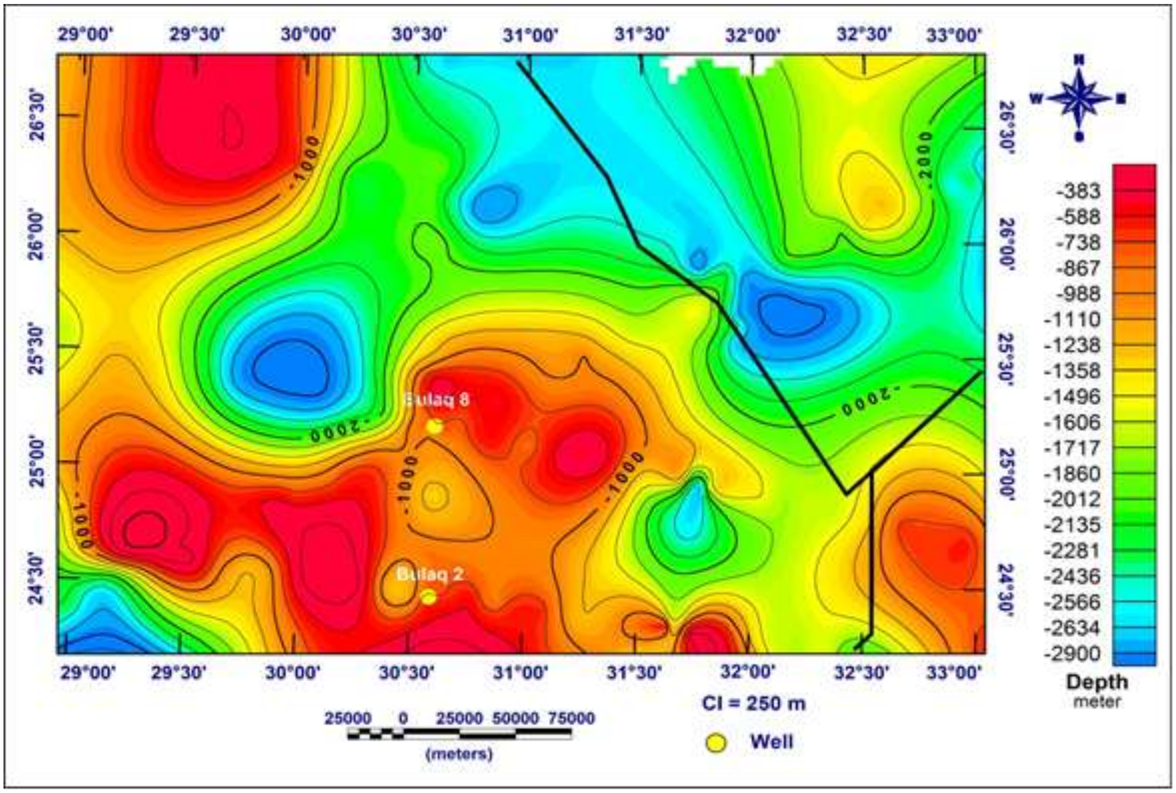


Figure 13: A color contour relief map of the basement depth in the studied area estimated from 2D depth models.

4.4. Three-dimensional (3D) magnetic modeling

Figure 14 displays the outcomes of the 3D modeling of the basement surface. The input data or the 3D depth model was the RTP, DEM, drilled wells and estimated magnetic susceptibilities of basement rocks. These data were processed using the GMSYS-3D program within the Geosoft Oasis Montaj software. Figure 14 shows two layers the upper layer which is the topography surface and the owner layer represents the surface to the basement rocks.

The 3D depth model shows that the basement depth ranges from about -153 m to about more than -1819 m. It is clear that areas labeled with A, B and C display depth to basement surace greater than -1100 m below ground surface. This indicate that these three areas have a thick sedimentary cover and may represent major subsurface basins with great potentiality for groundwater and hydrocarbon exploration. The other portions of the research region, despite the three named sections, are characterized by modest depths to basement surfaces, which are less than -300 m below ground.

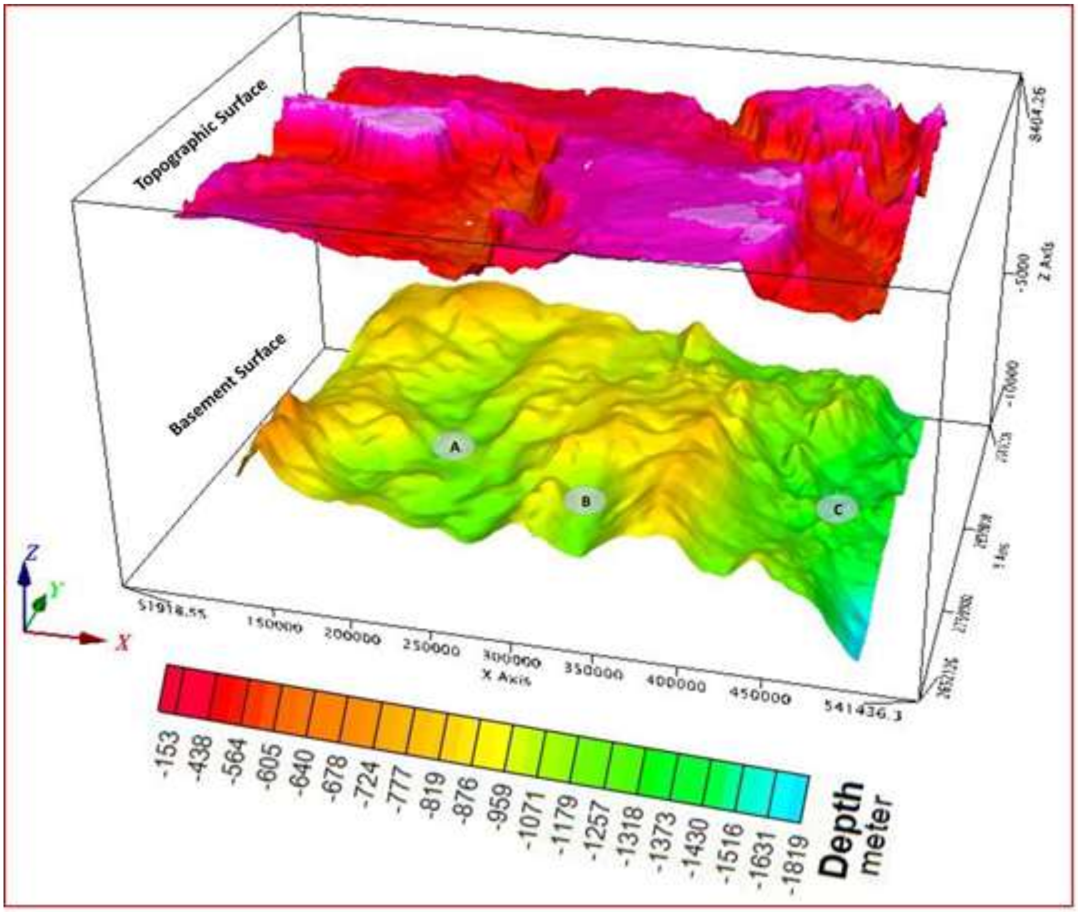


Figure 14: 3D depth modelling results of GMSYS-3D program.

5. SUMMARY AND CONCLUSION

The scope of this work is to estimate the depth of the basement rocks at the southeastern part of Egypt utilizing 2D and 3D modeling techniques of airborn magnetic data of the study area. The obtained results displayed three distinct areas with higher thickness of sedimentary cover (> 1100m) located at the western, central and southeastern parts of the study area. These three areas may represent major subsurface basins with great potentiality for groundwater exploration. It is worth to mention that the obtained results of the depth to basement are in good agreement with the results of the drilled wells and previous studies.

However, it is recommended to use a second geophysical method (e.g., gravity, deep seismic or electromagnetic) at the study site to confirm the results of obtained with the magnetic method. The significant points of the current study that it is pertaining to the sustainable development plan of Egypt 2030 for promising desert areas in particular areas that hold the potential to become zones of development for agricultural purposes or oil basin explorations.

REFERENCES

[1] J. Reynolds, An introduction to applied and environmental geophysics, John Wiley & sons, Chester, 2nd edition, (1997) 710p.

[2] D. Kumar, N.S.K. Murthy, G.K. Nayak and S. Ahmed, Utility of magnetic data in delineation of groundwater potential zones in hard rock terrain, Current Science, 91 , (2006) 1456-1458.

[3] H. Hamza and I. Graba, Challenges of exploration and utilization of hydrocarbons in the Sokoto Basin, Paper presented at International Conference on the Potentials of Prospecting for Hydrocarbons in the Sokoto Basin, Usmanu Danfodio University Sokoto, Nigeria, (2010).

[4] A. S. Abu El-Ata, A. A. EI-Khafeef, S. E. Ghoneimi , S. H. Abd Alnabi , and M. A. Al-Badani, Applications of aeromagnetic data to detect the Basement Tectonics of Eastern Yemen region, Egyptian Journal of Petroleum, 22, (2013) 277-292.

[5] A. Khalil, H.A. Tharwat, S.S. Hassan and H.M. Waheed, Inferring the subsurface basement depth and the structural trends as deduced from aeromagnetic data at West Beni Suef area, Western Desert, Egypt, NRIAG, Journal of Astronomy and Geophysics, 5, (2016) 380-392.

[6] A. A. Omran, S. Raid, E. R. Philobbos and A. B. Othman, Subsurface structures and sedimentary Basins in the Nile Valley area as interpreted from gravity data, Egyptian Journal of Geology, v. 45/1, (2001) pp. 681-712.

[7] M. Abdel Zaher, M. M. Senosy, M. M. Youssef, and S. Ehara, Thickness variation of the sedimentary cover in the SouthWestern Desert of Egypt as deduced from Bouguer gravity and drill-hole data using neural network method, Earth Planets Space, V. 61, (2009) pp. 659–674.

[8] A. A. Bakheit, G. Z. Abdel Aal, A. E. El-Haddad, and M. A. Ibrahim, Subsurface tectonic pattern and basement topography as interpreted from aeromagnetic data to the south of El-Dakhla Oasis, western desert, Egypt, Arab. J. Geosci., (7), (2014) 2165–2178.

[9] A. M. Beshr, A. Mohamed, A. ElGalladi, A. Gaber, and F. El-Baz, Structural characteristics of the Qena Bend of the Egyptian Nile River, using remote-sensing and geophysics. Egypt, J. Remote Sensing Space Sci., V. 24, (2021) pp. 999–1011.

[10] Conoco Coral. Geological map of Egypt, scale 1:500,000. The Egyptian General Petroleum Corporation (EGPC), Cairo, (1987).

[11] R. Said, The geology of Egypt, Amsterdam-New York, Elsevier Publishing Co., (1962) 337 P.

[12] T. M. Abd El. Razik and A. V. Razvaliaev, On the tectonic origin of the Nile Valley between Idfu and Qena, Egypt. Egypt. J. Geol., 16, (1972) pp. 235-244.

[13] H. H. Elewa, R. G. Fathy and E. A. Zaghloul, Groundwater potential of the Southern Part of Wadi Qena Basin, Eastern Desert of Egypt Using Remote Sensing Techniques, Egypt J. Rem. Sens. Spac. Sci., 3, (2000) pp. 135-152.

[14] R. Said, The Geology of Egypt. A.A. Balkema, Rotterdam/Brookfield, (1990) 734 p.

[15] SRTM (DEM), Shuttle Radar Topography Mission (SRTM), (Digital elevation model), USGS (2013).

[16] A. Mostafa, Paleo-karst shafts in the western desert of Egypt: a unique landscape. ACTA CARSOLOGICA 42 (1), (2013) 49-60.

[17] P. Wycisk, Contribution to the subsurface geology of the Misaha trough and the Southern Dakhla Basin. BerlGeowiss Abh (A), 75, (1987) 137-150.

[18] EGPC, Activity of Oil Exploration in Egypt; 1886- 1986.- EGPC, Cairo, (1989) 175 p.

[19] Arcinfo ESRI. ArcGIS 10.8.2 Desktop, Environmental System Research Institute, Inc. Redlands, California. USA, (2021).

[20] Geosoft oasis montaje, V.8.4 Geosoft Software for the Earth Science, Geosoft Inc., Toronto, Canada, (2015).

[21] Rockware software, ver.14, Rockware incorporation for earth science and GIS software, USA, (2010).

[22] M. Talwani and J.R. Heirtzler, Computation of magnetic anomalies caused by two-dimensional structures of arbitrary shape, In: Parks, G.A. (Ed.), Computers in

the Mineral Industries. Stanford University Press, Stanford, USA, (1964) pp. 464–480.

[23] A. Alkholy, A. Saleh, H. Ghazala, M. Al Deep and M. Mekkawi, Groundwater exploration using drainage pattern and geophysical data: a case study from Wadi Qena, Egypt, Arabian Journal of Geosciences, (2023)16:92.