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Integrated Assessment of Surface and Subsurface Structural Framework using Aeromagnetic and Remote Sensing Data: A Case Study of Wadi Beizah Area, Central Eastern Desert, Egypt

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THIS STUDY explores the heart of the Eastern Desert, an area rich in geological history and ripe for new discoveries. Advanced remote sensing techniques were employed to map the topographical landscape, unveiling a diverse range of surface structural features. From Late Proterozoic rocks to recent Quaternary deposits, the analysis highlights a variety of lithologies and tectonic fabrics that have shaped the region's history. Utilizing high-resolution elevation data and magnetic field analysis, previously undiscovered patterns were revealed. Mapping of stream networks and subtle elevation changes from the surface data indicates potential pathways for groundwater resources. Furthermore, sophisticated analysis of the magnetic field and elevation data unveils dominant structural patterns present in both the surface and subsurface settings of the study area. These trends, oriented northwest-southeast, northeast-southwest, and north-south, hold immense significance for mineral exploration and future water resource investigations. The findings not only shed light on the complex geological history of the Eastern Desert but also underscore its potential for future development and resource exploration.

Keywords: Total magnetic intensity, digital elevation model, mineral exploration, and water resource investigations.

1. Introduction

The Eastern Desert of Egypt, a region steeped in geological history, holds immense potential for scientific exploration and resource development. Within the landscape lies Wadi Beizah, situated in its central portion (**Fig. 1**). Defined by coordinates of 24°28'07.99" to 24°50'22.45" North and 33°13'08.99" to 33°49'06.71" East (**Fig. 1**), this area has attracted significant attention from geoscientists due to its complex geological features and promising mineral resources.

Previous research has laid the cornerstones for understanding Wadi Beizah's geological structures (Ragab et al., 1989; Faris et al., 1997; Ramadan et al., 2009; Embaby et al., 2016; Rashed, 2017; El Qassas et al., 2020; Sabra et al., 2019; Mohamed et al., 2023; Abd El-Wahed, 2024). However, a gap remains in comprehensively deciphering the surface and subsurface structural framework of this intriguing region.

This study proposes a novel approach by integrating advanced remote sensing techniques with detailed aeromagnetic data analysis. This combined methodology offers a more comprehensive picture of Wadi Beizah's geological characteristics than ever before. By delving deeper into the region's tectonic evolution and the geological processes that formed it, we aim to significantly enhance our understanding. This endeavor not only contributes to the broader knowledge base of geological mapping but also holds significant implications for future mineral exploration and resource management strategies within the Eastern Desert.

2. Geologic Setting

The Wadi Beizah area (**Fig. 2**) boasts a diverse geological history reflected in its layered rock formations and structural framework.

Lithostratigraphy:

The region's geological record can be broadly categorized into four distinct units:

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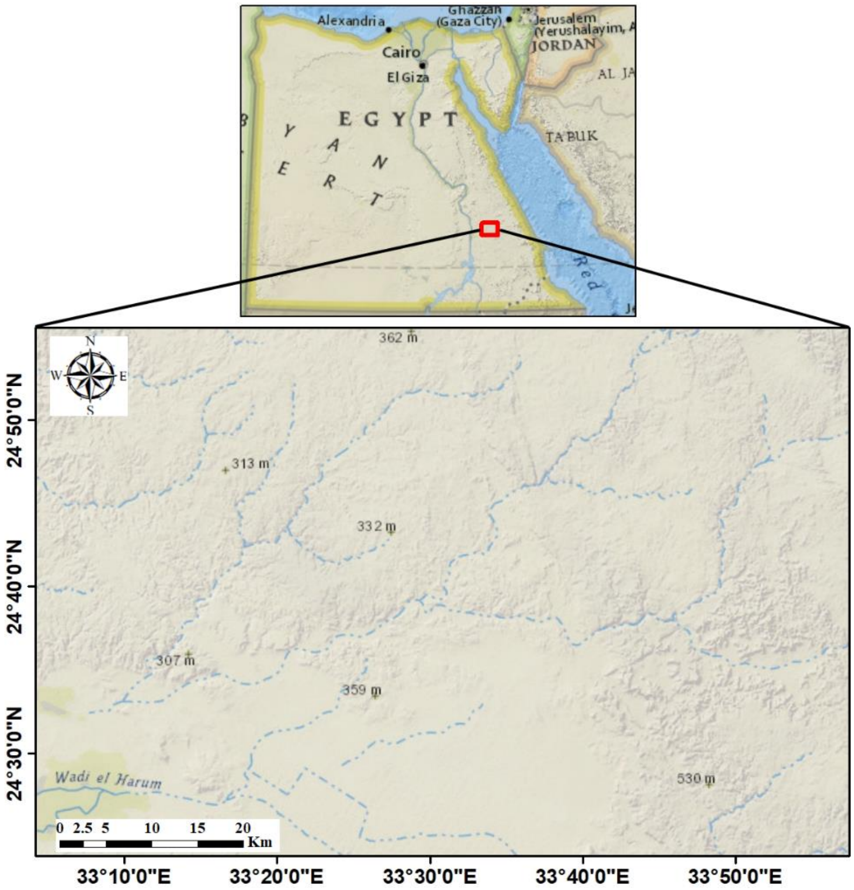


Fig. 1 . Location map of the study area.

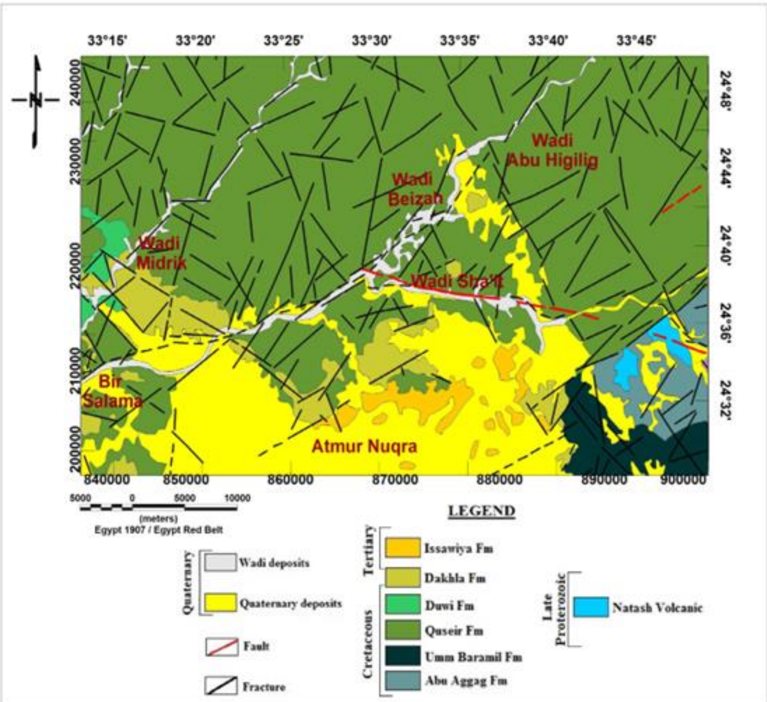


Fig. 2. Geologic map of the study area (Conoco, 1987).

A) Late Proterozoic Rocks: The foundation of the area is built upon Late Proterozoic rocks, specifically the Natash Volcanics. These volcanics are characterized by undeformed volcanic rocks with compositions ranging from basic to acidic and alkaline.

B) Upper Cretaceous Rocks: Overlying the Late Proterozoic basement are sedimentary deposits from the Upper Cretaceous period. These can be further subdivided into five distinct formations:

i) **Abu Aggag Formation**: This formation comprises fluvial (riverine) deposits, dominated by cross-bedded sandstones.

ii) **Umm Baramil Formation**: Similar to the Abu Aggag Formation, the Umm Baramil Formation also consists of fluviatile sandstones.

iii) **Quseir Formation**: Moving towards a shallower marine environment, the Quseir Formation is characterized by littoral (coastal) deposits of varicolored shales, siltstones, and flaggy sandstones.

iv) **Duwi Formation**: This formation represents a shift to a deeper marine environment with phosphate beds alternating with black shales.

v) **Dakhla Formation**: The youngest unit of the Upper Cretaceous is the Dakhla Formation, consisting of dark-grey, shallow marine marls and shales.

C) Pliocene Deposits: A period of continental deposition followed the Upper Cretaceous, represented by the Pliocene Issawiya Formation. This formation comprises fluviatile (riverine) siltstone and claystone.

D) Quaternary Deposits: The most recent deposits within the area are Quaternary in age and consist of unconsolidated materials like alluvial fans, wadi (dry riverbed) deposits, and gravels.

Structural Framework: The complex geological history of the Wadi Beizah area extends beyond the layered rock formations. The region has been formed by various tectonic movements, resulting in a network of faults and fractures. These structural features exhibit three main directional trends (**Fig. 3**):

- **NW-SE**: This trend aligns with the Gulf of Suez-Red Sea trend, suggesting a potential connection to regional tectonic activity.
- **NE-SW**: This trend aligns with the Syrian arc trend, indicating the influence of broader tectonic forces.
- **N-S**: This trend corresponds to the East African trend, highlighting the influence of large-scale continental movements.

Understanding this interplay between the layered rock formations and the structural framework is crucial for deciphering the geological evolution of the Wadi Beizah area.

3. Materials and Methods

This study employs a multi-pronged approach utilizing remote sensing data and aeromagnetic data analysis to unravel the geological framework of the Wadi Beizah area.

3.1. Remote Sensing Data

High-resolution topographic information was obtained through a Digital Elevation Model (DEM) with a 30-meter spatial resolution. This DEM, derived from Shuttle Radar Topography Mission (SRTM) data, was acquired from the USGS Earth Explorer website (https://earthexplorer.usgs.gov/). SRTM-derived DEMs can sometimes contain topographic depressions that appear as anomalies or illogical data points. To minimize these errors and ensure data accuracy, the ArcGIS 10.8 sink fill algorithm was employed to rectify such anomalies.

- **DEM Processing and Lineament Extraction**:

- **Shaded Relief Images**: Eight shaded relief images were created from the DEM using varying sun angles to illuminate topographic features.

- **Automated Lineament Extraction**: A composite image from four initial sun angles was used in Geomatica 10.3 for lineament extraction (**Fig. 8 and 9**).

3.2. Aeromagnetic Data

For subsurface exploration, aeromagnetic data analysis was incorporated into the study. The research utilizes Sheet No. 80 from the 1982 aeromagnetic surveys conducted as part of the Mineral, Petroleum, and Groundwater Assessment Project (MPGAP) (Aero-Service, 1984). This extensive project covered a large portion of the Eastern Desert and a section of the Central Western Desert of Egypt. The flight path for this project is illustrated in **Figure 4**.

To facilitate data processing and analysis, the paper map sheet from Sheet No. 80 was digitized using Didger Software. This process converted the map data into XYZ files containing geographic coordinates and corresponding magnetic field values. These digital files serve as the foundation for subsequent analytical techniques employed in the investigation.

- **Analysis Procedures:**

- **Reduction to the Pole (RTP)**: The RTP method was applied to adjust magnetic anomalies for easier interpretation, as shown in **Figure 11**.
- **Power Spectrum Analysis**: This technique was used to estimate the depths of magnetic sources from the RTP data (**Fig. 12**).
- **First Vertical Derivative (FVD):** FVD analysis was employed to enhance edge detection in magnetic anomalies (**Fig.15**).
- **Euler Deconvolution**: Subsurface contact depths were determined using Euler deconvolution with structural indices set at 0 for contacts and 0.5 for faults (**Fig. 16**).

4. Results and Discussion

This section explores the key findings derived from the analysis of remote sensing data and aeromagnetic data, providing insights into the geological framework of the Wadi Beizah area.

4.1. Surface Morphology and Drainage Patterns

Analysis of the Digital Elevation Model (DEM) (**Fig. 5**) reveals a diverse topographic landscape within the study area. The eastern sector exhibits challenging terrain with mountainous features, reaching elevations exceeding 270 meters. Conversely, the southwestern region is characterized by a flatter landscape with the lowest elevations dipping below 190 meters. This uneven distribution of elevation highlights the presence of varied geomorphological features, reflecting the influence of distinct geological processes on landscape formation.

Stream order analysis, a technique employed to assess drainage patterns (Pareta and Pareta, 2012), identified six primary stream orders and delineated eight distinct drainage basins within the study area (**Fig. 6**). These findings, with each stream order represented by a unique color, highlight the most suitable locations for rainwater drainage, typically concentrated at downstream points where water accumulates.

4.2. Lineament Extraction from DEM

High-resolution DEM data was utilized to generate eight shaded relief images, each corresponding to specific sun angles ranging from 0° to 315°. The initial four images (0°, 45°, 90°, and 135°) were combined to create a composite image (**Fig. 7**). This composite image was then processed in Geomatica 10.3 software to facilitate the automated extraction of lineaments across the study area. The extracted lineaments, displayed in **Figures 8 and 9**, exhibit prominent directional trends extending northwest-southeast, northeast-southwest, and north-south. This methodology provides valuable information regarding the structural trends and underlying geological features.

4.3. Analysis of Aeromagnetic Data

Inspection of the total magnetic intensity (TMI) map (**Fig. 10**) reveals low magnetic values (<42280 nT) concentrated in the northern, northeastern, southern, and southeastern portions of the study area. Conversely, high and moderate magnetic values (ranging from 42280 nT to > 42452.5 nT) are observed in the central, northwestern, and southwestern sectors.

The Reduced to the Pole (RTP) map (**Fig. 11**) further subdivides the area into three distinct magnetic zones based on their magnetic properties. Zone 1 is characterized by high amplitude and dense magnetic field frequencies, ranging from -10 nT to over 230 nT, and is primarily located in the northern, northeastern, northwestern, southeastern, and southwestern regions. Zone 2 exhibits intermediate amplitudes (-10 to -50 nT) and occupies small areas on the southwestern side. Finally, Zone 3 is dominated by low to very low magnetic values (below -50 nT) and is situated primarily in the eastern, central, and minor northern parts of the area.

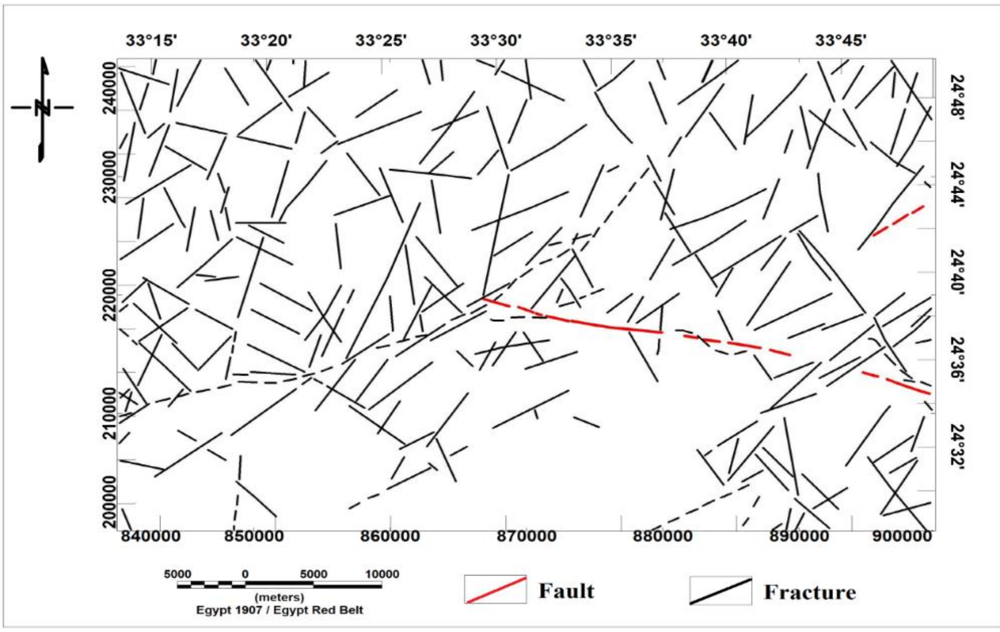
Power spectrum analysis (**Fig. 12**) was conducted on the RTP magnetic data to estimate the average depths of both residual and regional sources. This analysis identified two primary average depth levels, or interfaces: one situated close to the surface at approximately 0.8 km and another deeper level at 1.9 km below the measurement plane. The source depth for two levels was calculated using the following formula:

h (depth) = -slope/4π ………………... Equation (**1**)

Analysis of the regional magnetic map (**Fig. 13**) revealed two key observations:

1. Low zones (negative anomalies) are positioned in the central, southern, and northern fringe regions, with values dipping below zero.

2. A vast and pronounced magnetic anomaly dominates the northern, northwestern, northeastern, southwestern, and southeastern parts of the area.



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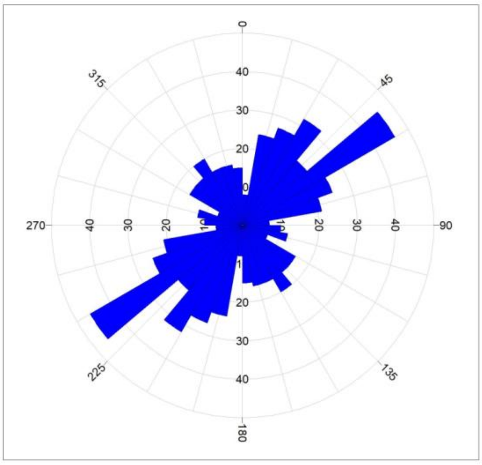

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Fig. 3. a) Geologic fault trends and fractures derived from the geologic map of the study, and b) Rose diagram of geologic lineaments of the study area (Conco, 1987).

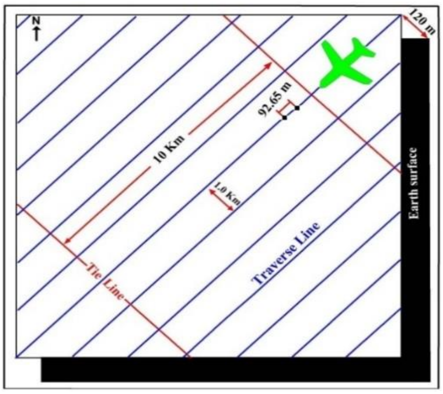


Fig. 4. Flight path of the MPGAP Project (specifications after Aero-Service, 1984).

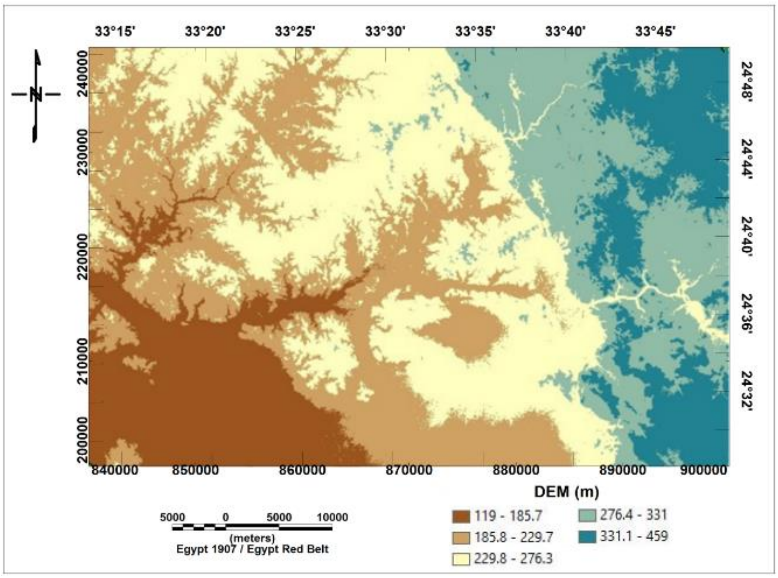


Fig. 5. Digital Elevation Model (DEM) of the study area.

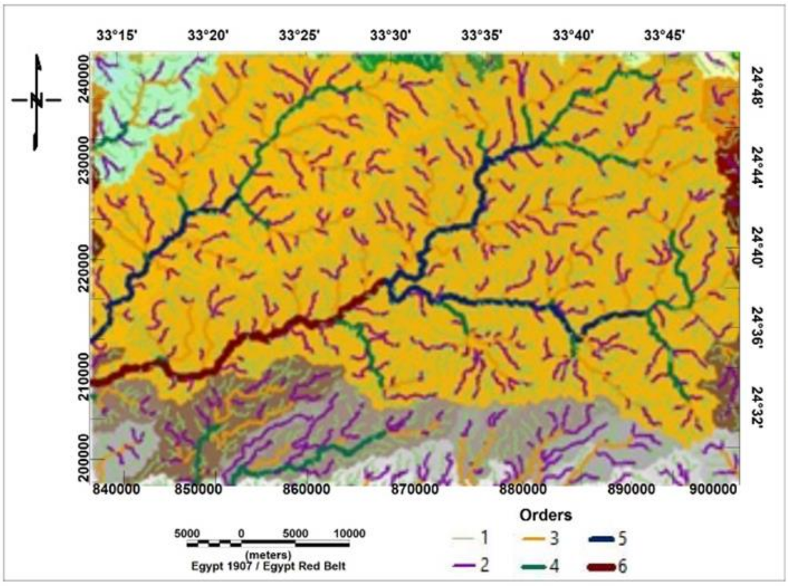
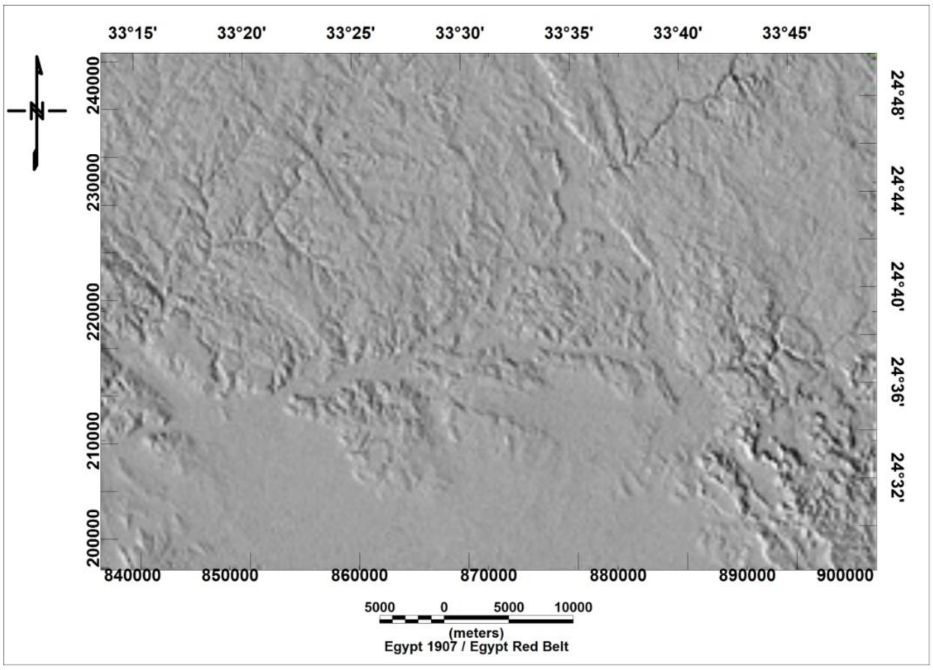


Fig. 6. Stream order within the basins of the study area.



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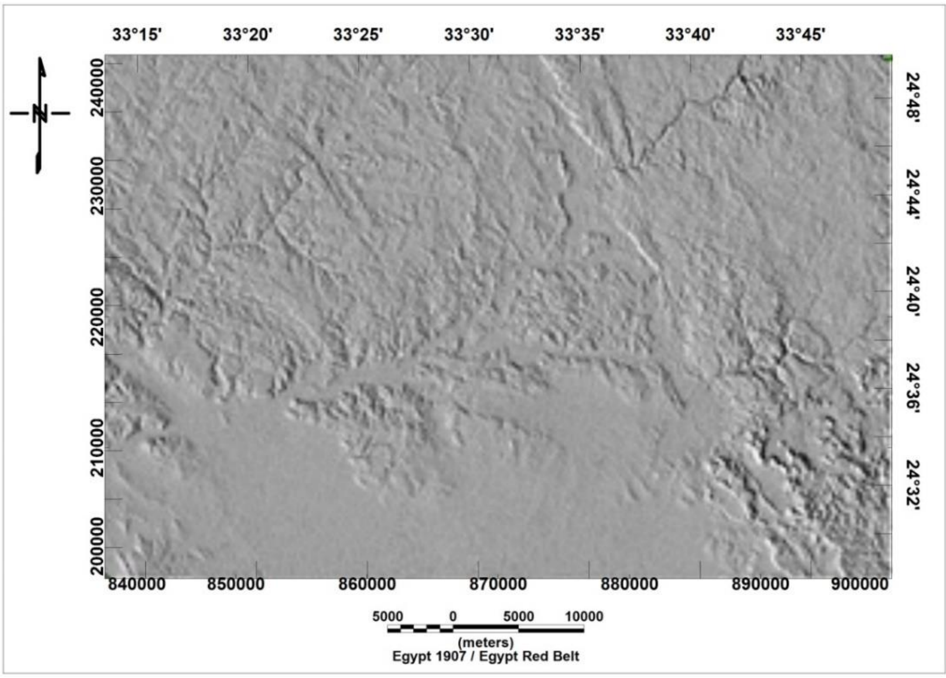

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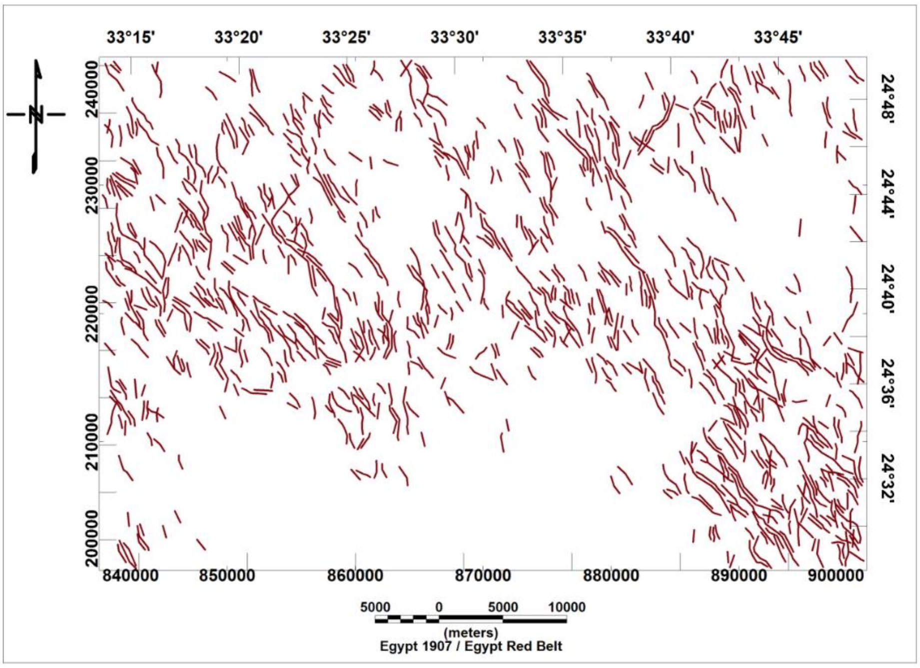
Fig. 7. (a) Shaded relief image created by combining four shaded relief images with sun angles of 0, 45, 90, and 135, and (b) Shaded relief image created by combining four shaded relief images with sun angles of 180, 225, 270, and 315 of the study area.



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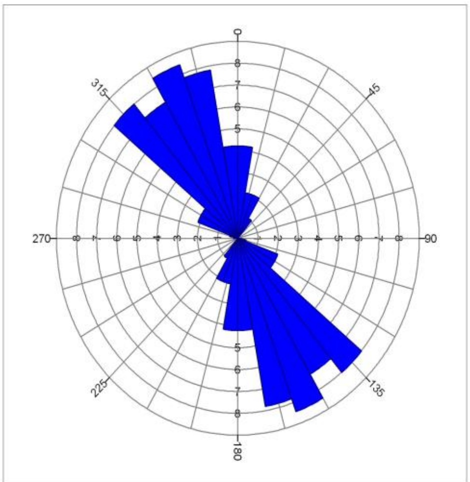


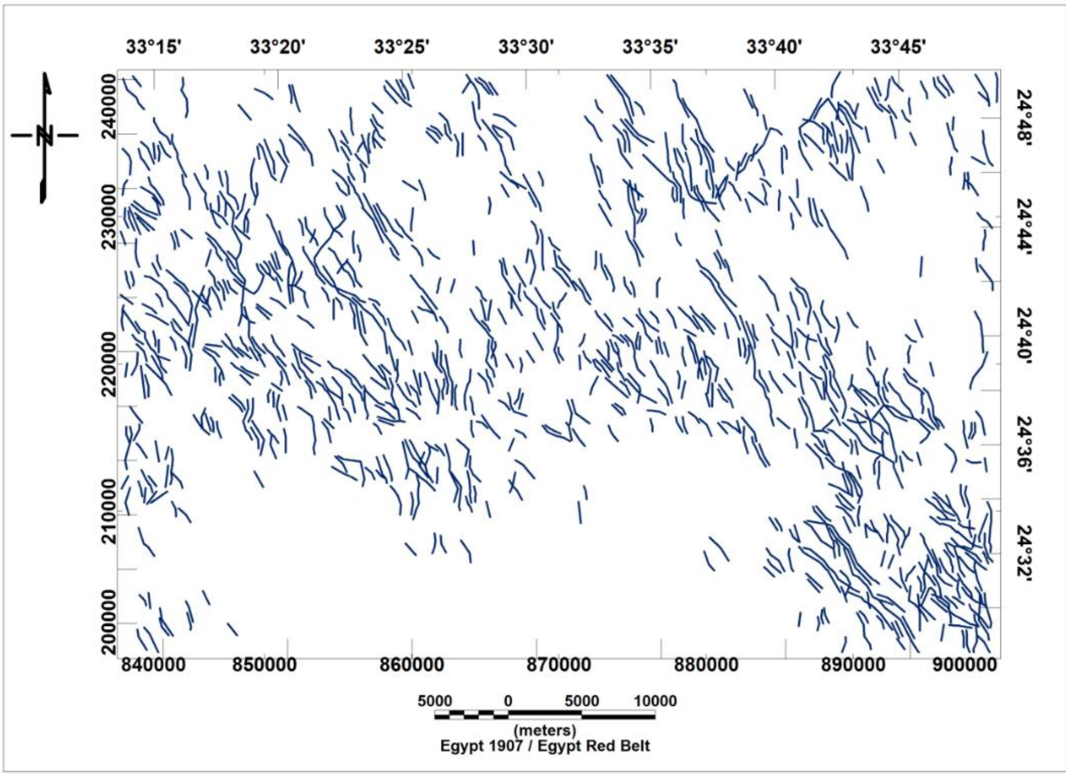
(b)

Fig. 8. (a) Automatic lineament map of combining four shaded relief images with sun angles of 0, 45, 90, and 135, and (b) Rose diagram of the automatic lineament map of the study area.

The residual magnetic map (**Fig. 14**) offered further insights, including:

- Magnetic anomalies with large detailed areal extents observed in the northeastern, northwestern, and southeastern regions, characterized by high magnetic values.
- Additional magnetic anomalies are not present in the regional map, such as those in the southern and central regions. These anomalies in the residual map include linear high magnetic anomalies and potentially deep-seated basic dikes. This observation suggests that these anomalies likely originate from shallow depths.

The first vertical derivative (FVD) map (**Fig. 15**) is a valuable tool for identifying geologic boundaries and edges within the data set (Henderson and Zietz, 1949). The prominent characteristics of the FVD map include readily identifiable edges and geological boundaries, particularly in the eastern and western regions, demonstrating trends aligned with northwest-southeast and northeast-southwest directions.



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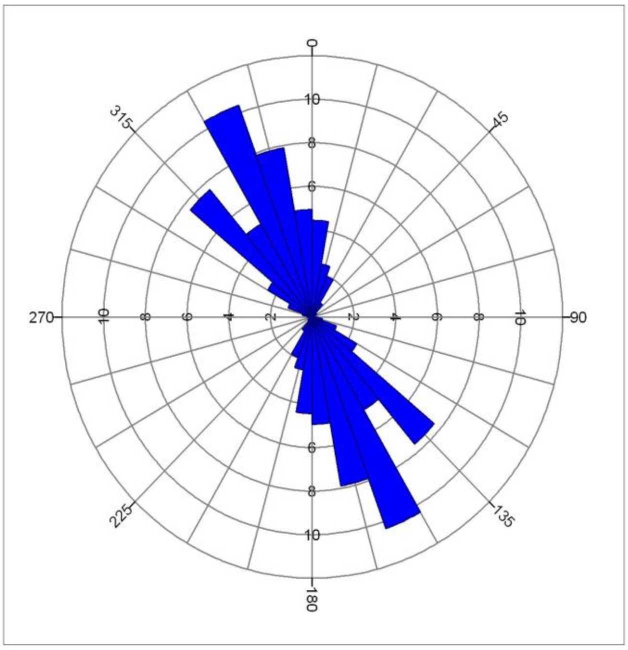

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Fig. 9. (a) Automatic lineament map of combining four shaded relief images with sun angles of 180, 225, 270, and 315, and (b) Rose diagram of the automatic lineament map of the study area.

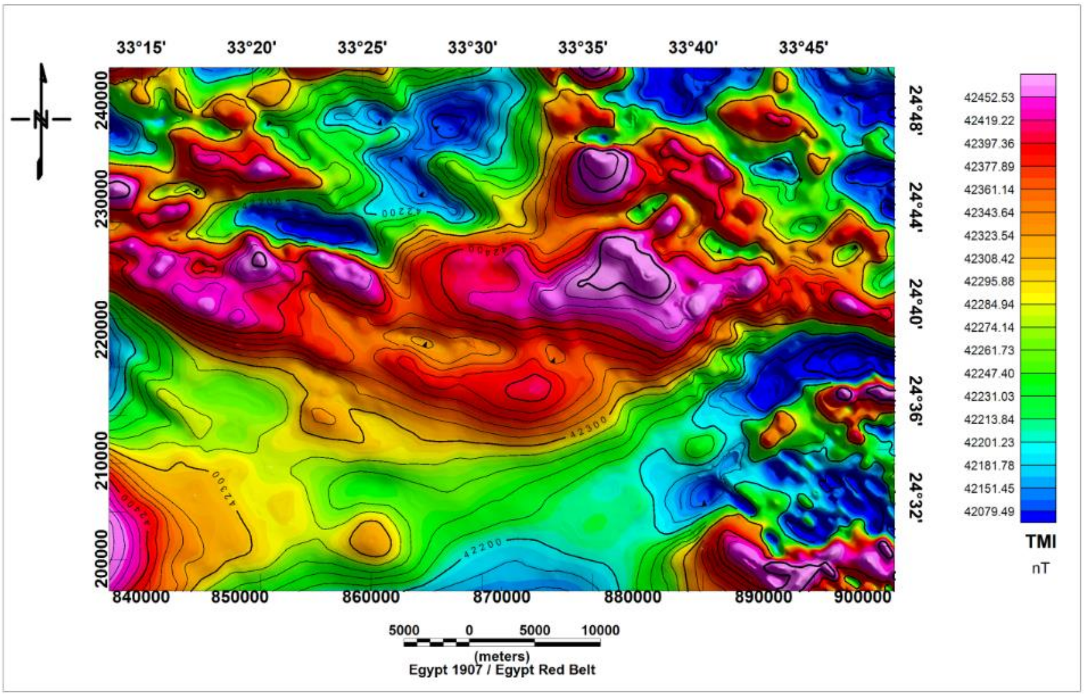


Fig. 10. Total Magnetic Intensity (TMI) Map of the study area.

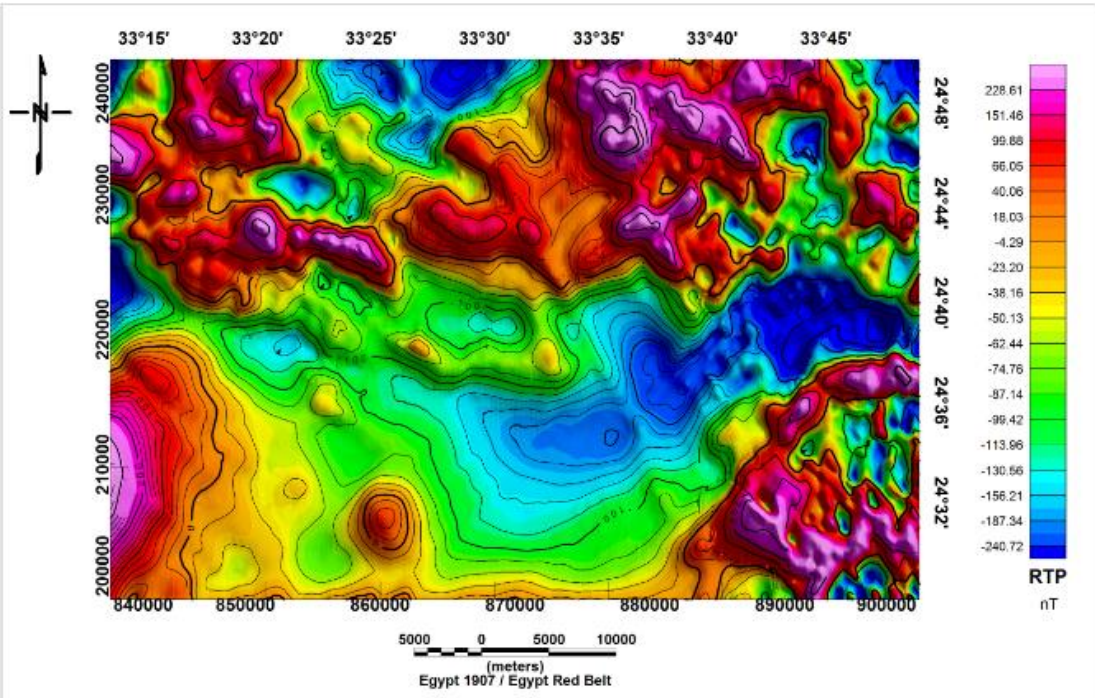


Fig. 11. Reduced to the northern magnetic pole (RTP) Map of the study area.

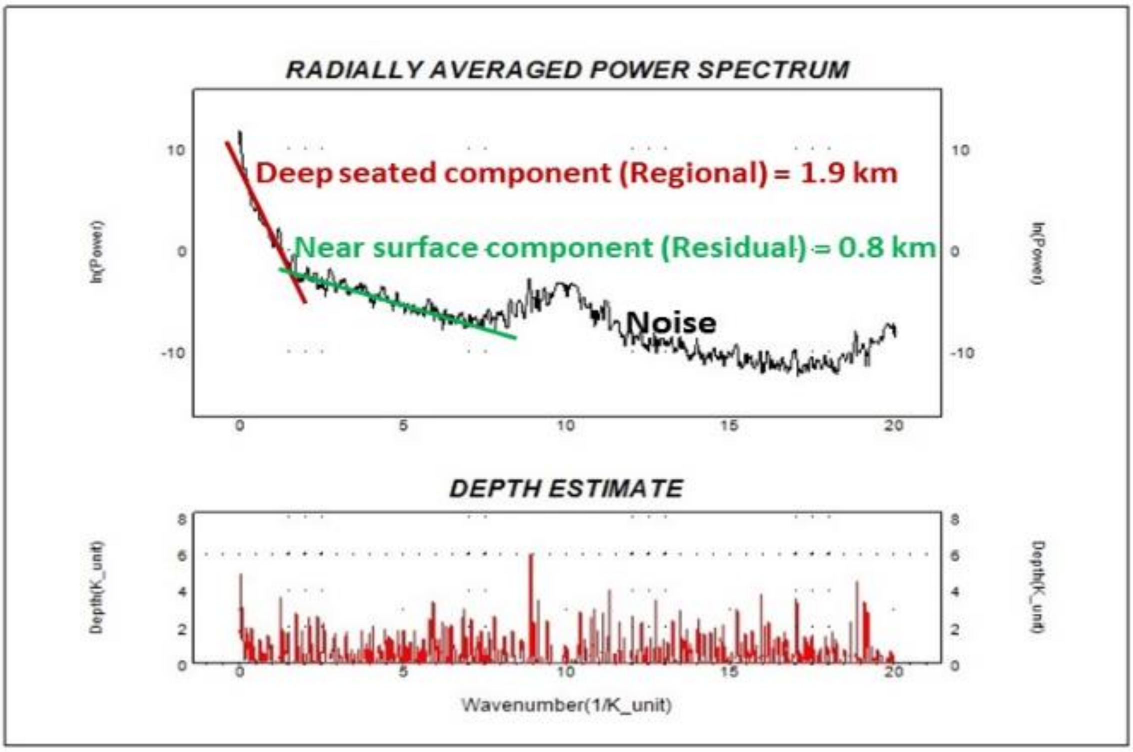


Fig. 12. Radially averaged power spectrum and depth estimate of magnetic data of the study area.

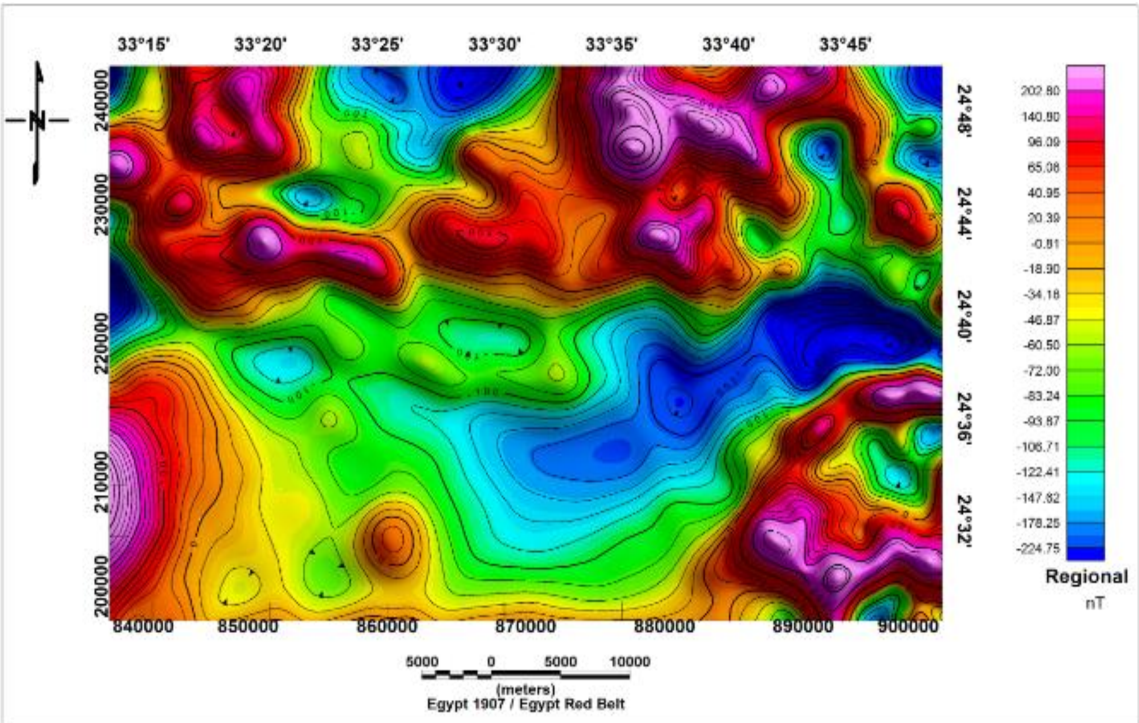


Fig. 13. Regional magnetic anomaly map of the study area with effective cutoff wavelength of 1.69 cycles/grid unit.

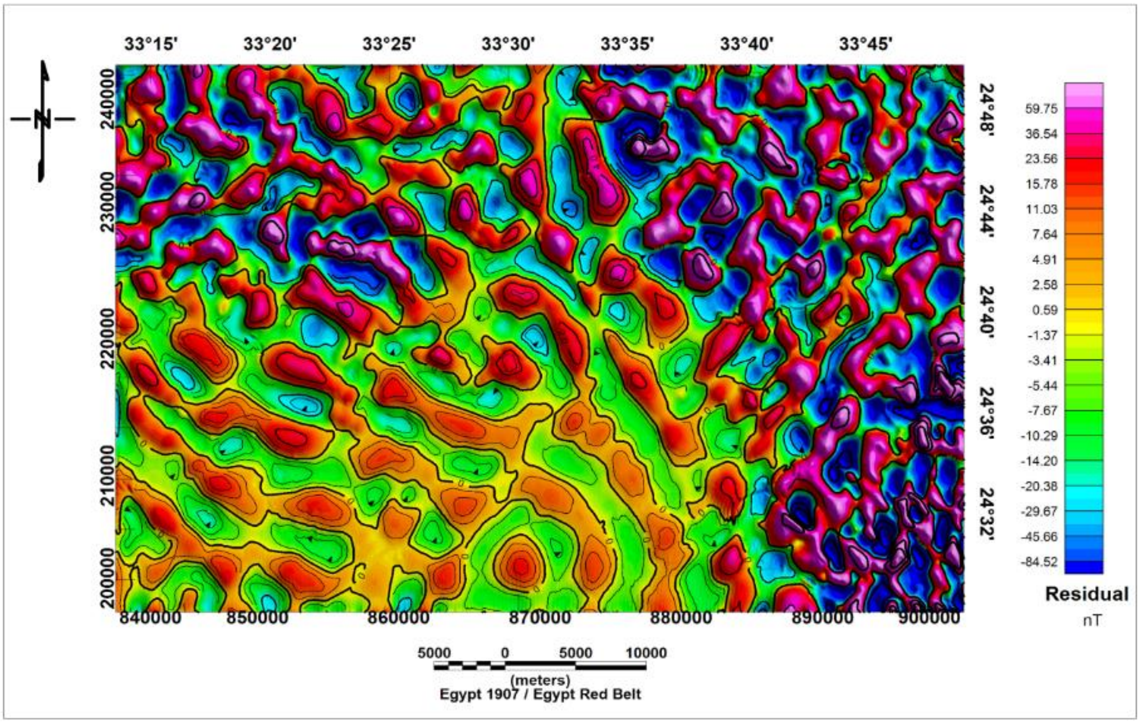


Fig. 14. Residual magnetic anomaly map of the study area with effective cutoff wavelength of 1.69 cycles/grid unit.

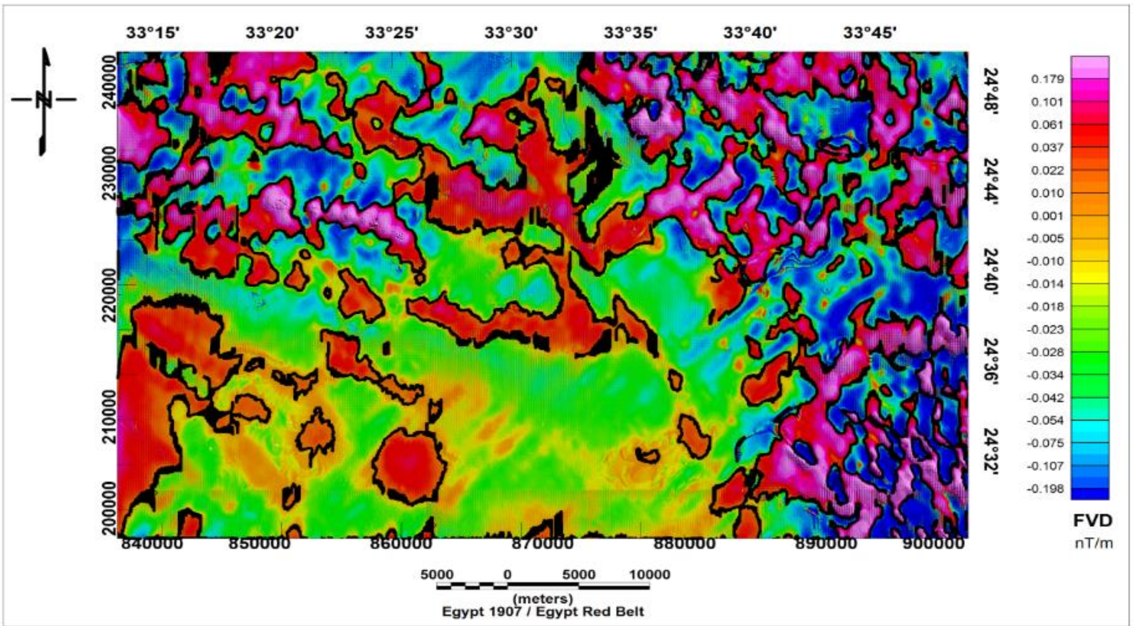


Fig. 15. First vertical derivative map of the study area.

Euler deconvolution, a technique employed to estimate depths based on the RTP magnetic grid (**Fig. 16**). By setting the structural index (SI) to 0 for probable contacts and 0.5 for faults, magnetic anomaly maps were created (**Fig. 16**). These maps depict a variety of subsurface contact depths, ranging from below -51.2 meters to above 234.1 meters.

4.4. Integration of Geological and Geophysical Data

By combining surface geological information with the results of the geophysical analysis of tectonic trends, a comprehensive lineament map was constructed (**Fig. 17**). This map unveils the significant structural framework that has formed the geological setting of the study area. The dominant structural lineaments exhibit three primary directional trends:

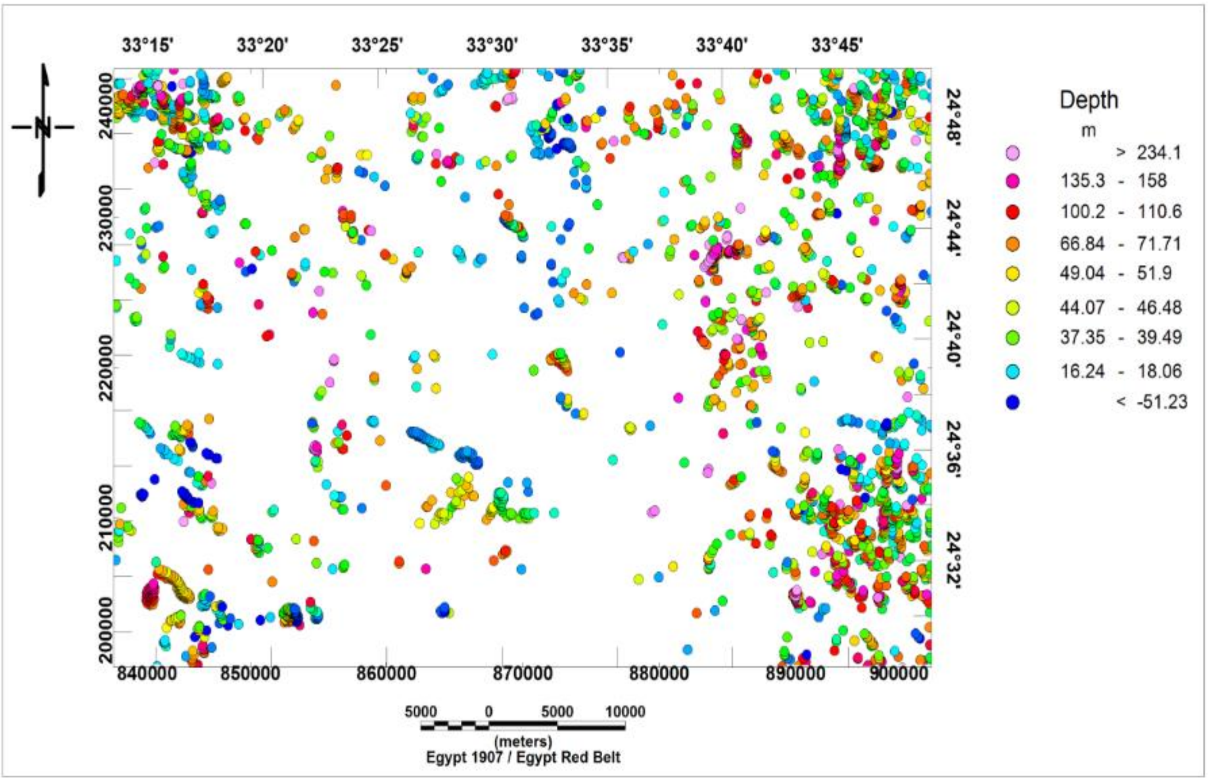


Fig. 16. Euler depth solutions of SI = 0.

• **Northwest-Southeast**: This trend aligns with the established trend documented by Meshref (1971, 1990) between the Red Sea and the Gulf of Suez, suggesting a connection to regional tectonic forces active in that area.

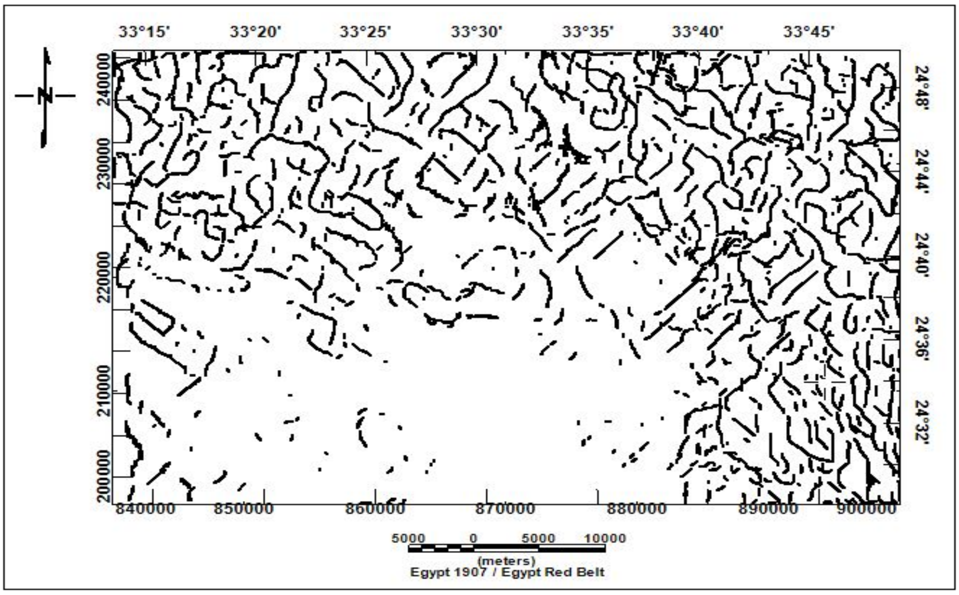
• **Northeast-Southwest**: This alignment parallels the well-known Syrian arc trend, as identified by Meshref (1971, 1990), highlighting the influence of broader tectonic processes on the region.

• **North-South**: This trend aligns with the Meridional or East African trend, as noted by Ghanem (1968), indicating the impact of more distant tectonic activity.

This integration of geological and geophysical data provides a deeper understanding of the tectonic forces that have formed the Wadi Beizah area, offering valuable insights into its geological history.

4.5. Combining Surface and Subsurface Findings

This study underscores the critical importance of integrating surface and subsurface data to achieve a comprehensive understanding of geological settings. A significant interplay between these layers is highlighted by the correlation between surface features and subsurface magnetic anomalies.



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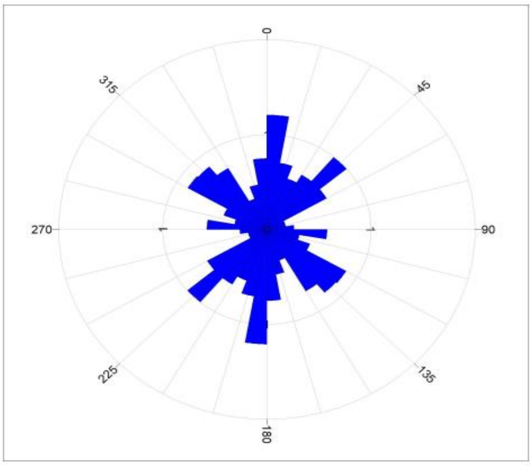

(b)

Fig. 17. (a) Lineaments extraction from magnetic data, and (b) Rose diagram of extracted lineaments from magnetic data of the study area.

- **Surface and Subsurface Correlation**

The alignment of surface drainage patterns with subsurface magnetic anomalies suggests that surface water flow and geomorphology are influenced by underlying structural features. High magnetic values in areas with complex topography indicate that tectonic processes have shaped both surface and subsurface geology.

- **Geological Insights**:

The identified trends, including NW-SE, NE-SW, and N-S alignments, characterize not only surface lineaments but also subsurface magnetic anomalies. This integration offers a clearer perspective on the tectonic forces shaping the Wadi Beizah area and enhances our understanding of its geological history.

5. Impact on Mineral Exploration and Water Resource Management

The study's findings provide valuable insights for mineral exploration and water resource management in the Eastern Desert. The identified structural lineaments and magnetic anomalies highlight promising areas for mineral deposits. High magnetic values in specific zones indicate potential sites for further exploration.

- **Mineral Exploration**:

The presence of significant magnetic anomalies in the northern and northeastern regions suggests a favorable environment for discovering mineral deposits. These anomalies could guide future exploration efforts, targeting regions with high mineralization potential.

- **Water Resource Management**:

The analysis of drainage patterns and surface topography highlights areas where groundwater is likely to accumulate. Identifying these regions is crucial for effective water resource management, especially in arid environments where water is scarce.

6. Challenges and Future Research Directions

While our study provides a thorough analysis of the Wadi Beizah area, several limitations should be noted:

- **Data Limitations:**

- The aeromagnetic data from 1982 may not capture recent geological developments.
- The Digital Elevation Model (DEM), although high-resolution, may not reflect all detailed surface features.

- **Methodological Constraints:**

- Automated lineament extraction might overlook finer geological details.
- The integration of data could benefit from the inclusion of additional geophysical methods.

- **Future Research Recommendations:**

- **Supplementary Techniques**: Employ additional geophysical methods, such as seismic surveys, for a more comprehensive analysis.
- **Ground-Based Studies**: Conduct field surveys to validate and refine remote sensing and aeromagnetic data.
- **Hydrogeological Research**: Investigate the hydrogeological characteristics of identified drainage basins to gain a better understanding of groundwater dynamics.

7. Conclusions

The Wadi Beizah area holds significant promise for future development plans and investment projects. This study employed a multi-disciplinary approach, utilizing both remote sensing data (DEM) and aeromagnetic data analysis, to comprehensively assess the surface and subsurface structural framework of the region. The analysis successfully identified lineaments, both on the surface and at depth, with prominent trends-oriented northwest-southeast, northeast-southwest, and north-south. The strong correlation between these surface and subsurface lineament directions suggests a deep-seated structural control of the geological features of the Wadi Beizah area. This comprehensive understanding of the geological framework paves the way for informed decision-making regarding future development endeavors.

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8. References

Abd El-Wahed, M. A. (2024) Structural analysis of Wadi El Qash area, Central Eastern Desert, Egypt. *Annals Geol. Survey Egypt*, **XXVII**, 79-108.

Aero-Service, (1984) Final operational report of airborne magnetic/radiation survey in the Eastern Desert, Egypt. For the Egyptian General Petroleum Corporation (EGPC) and the Egyptian Geological Survey and Mining Authority (EGSMA), Aero-Service Division, Houston, Texas, USA, **6**.

Conoco, (1987) Geological map of Egypt, Scale (1:500,000), NG 36 SE-Gebel Hamata sheet.

El Qassas, R. A. Y., Salaheldin, M., Asran, S. M., Abdel Fattah, Th. and Rashed, M. A. (2020) Airborne gamma-ray spectrometric data interpretation on Wadi Queih and Wadi Safaga area, Central Eastern Desert, Egypt. NRIAG *J. of Astronomy and Geophysics*, **9**(1), 155-167.DOI: 10.1080/20909977.2020.1728893.

Embaby, A., Razack, M., Lecoz, M. and Porel, G. (2016) Hydrogeochemical Assessment of groundwater in the Precambrian Rocks, South Eastern Desert, Egypt. *J. of Water Resource and Protection*, **8**(3).

Faris, H. H., El-Abd, Y. I. and Hag, E. A. (1997) Interpretation of magnetic and gravity data of Southern Red Sea Coast between El-Quseir and Marsa Alam, Egypt. *Egypt J Geol.*, Egypt, **41**(28), 944 p.

Ghanem, M. (1968) The geology of Wadi Kareim Area, Eastern Desert, Egypt. Unpublished PhD thesis, Cairo University, Giza.

Henderson, R. G. and Zietz, I. (1949) The computation of second vertical derivatives of geomagnetic fields. *J. of Geophysics*, **14**.

Meshref, W. M. (1971) The application of magnetic trend analysis to the interpretation of Egyptian tectonics. Abstracts of papers presented at the *9th Annual Meeting of the Geological Society of Egypt*, 19-21.

Meshref, W. M. (1990) Tectonic framework. In The geology of Egypt, **VII**, edited by Rushdi Said, Balkema, A. A., Rotterdam.

Mohamed, W. H., Elyaseer, M. H. and Sabra, M. E. M. (2023) Structural lineament analysis of the Bir El

Qash area, Central Eastern Desert, Egypt, using integrated remote sensing and aeromagnetic data. *Scientific Report*, **13**, article no 21569, 1-22.

Pareta, K. and Pareta, U. (2012) Quantitative morphometric analysis of a watershed: based on digital terrain model and GIS. *LAP Lambert Academic Publishing*.

Ragab, A. A., Menesy, M. Y. and Diab, M. M. (1989) Petrology and petrogenesis of the older and younger granitoids of Wadi Beizah area, Central Eastern Desert, Egypt. *J. of African Earth Sciences and the Middle East*, **9**(2), 303-315.

Ramadan, T. M., El Mongyb, S. A. and Salah El Deina, S. (2009) Exploration for uranium and thorium mineralizations at Wadi Um Laseifa Area, Central Eastern Desert, Egypt: Using remote sensing technique. Aust. *J. Basic & Appl. Sci.*, **3**(2), 689-697.

Rashed, M. A. (2017) Geology and radioactivity of muscovite leucogranites at north Wadi Abu Rusheid area, South Eastern Desert, Egypt. *Nuclear Sciences Scientific J.*, **6**, 137-152.

Sabra, M. E. M., Abdeldayem, A. L., Youssef, M. A. S., Masoud, A. A. and Mansour, S. A. (2019) Determination of the radiation dose rate and radiogenic heat production of North Gabal Abu Hibban area, central Eastern Desert, Egypt. *NRIAG J. of Astronomy and Geophysics*, **8**(1), 103-111. DOI: 10.1080/20909977.2019.1617556.

التقييم المتكامل للإطار التركيبي السطحي وتحت السطحي باستخدام بيانات المغناطيسية الجوية والاستشعار عن بعد: دراسة حالة لمنطقة وادي بيزة، وسط الصحراء الشرقية، مصر

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[٢] قسم الجيوفيزياء، الهيئة المصرية العامة للثروة المعدنية، العباسية ١١٥١٧، القاهرة، مصر

تتعمق هذه الدراسة في وسط الصحراء الشرقية، التى كانت مفعمة بالنشاط الجيولوجي سابقا, لذا فهى مؤهلة للاكتشافات بصفة غير منقطعة. تم استخدام تقنيات الاستشعار عن بعد لرسم الخريطة الطوبوغرافية لمنطقة الدراسة، مما ساهم فى الكشف عن ان المنطقة غنية بالتراكيب الجيولوجية المختلفة. تسلط التحليلات الضوء على تنوع التتابع الطبقى فى المنطقة, والتى تمتد من الصخور البروتيروزوية المتأخرة إلى الرواسب الرباعية الحديثة، وايضا تلقى الضوء على الحركات التكتونية التي شكلت تاريخ المنطقة. وباستخدام بيانات الارتفاع عالية الدقة وتحليل المجال المغناطيسي، تم الكشف عن أنماط غير مبينة مسبقا. تشير شبكات التدفقات والمصبات والتغيرات الدقيقة في ارتفاعات السطح إلى مسارات محتملة لموارد المياه الجوفية. وفي الوقت نفسه، يكشف التحليل الدقيق للمجال المغناطيسي وبيانات نموذج الارتفاع الرقمي عن الاتجاهات التركيبية السائدة والكامنة في كل من الحيز السطحى والتحت السطحى لمنطقة الدراسة. هذه التركيب الممتدة، من الشمال الغربي إلى الجنوب الشرقي، ومن الشمال الشرقي إلى الجنوب الغربي، ومن الشمال إلى الجنوب، تحوى امكانية كبيرة لتواجد المعادن وموارد المياه الجوفية. تسلط النتائج الضوء ليس فقط على التاريخ الجيولوجي المعقد للصحراء الشرقية ولكن أيضًا على إمكاناتها للتطوير المستقبلي واستكشاف الموارد.