SciEn
Journal of Engineering Advancements Vol. 07(01) 2026, pp 38-45 https://doi.org/10.38032/jea.2026.01.004

Assessment of Groundwater and Mineralization Potentials of Jada and Environs Northeastern Nigeria Using High-resolution Aeromagnetic Data

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Received: July 18, 2025, Revised: October 11, 2025, Accepted: February 10, 2026, Available Online: March 31, 2026

ABSTRACT

This study analyzes high-resolution aeromagnetic data over Jada and its environs to evaluate groundwater and mineralization potentials. The research was conducted in three stages: data acquisition, analysis, and interpretation. Regional-Residual Separation (RRS) was employed to extract residual data, which was further processed using spectral analysis to determine Depth to Magnetic Sources (DMS) and analytic signal (AS) methods to delineate lineaments (L). The results indicate that the susceptibility values of the Total Magnetic Intensity (TMI), and Residual Magnetic Intensity (RMI) maps range from -35.3 to 173.7 nT, and -3.0 to 151.0 nT, respectively. The depths of deeper magnetic sources (D1) vary from 0.530 to 1.960 km, while shallow magnetic sources (D2) range from 0.423 to 0.622 km. The analytic signal map (ASM) exhibits values from 0.008 to 0.178 nT, while the lineament density map (LDM) ranges from 0.52 to 4.71. Structural trends derived from the anomalies and lineaments indicate multiple tectonic cycles have shaped the area, with predominant lineament orientations in the NE-SW direction. The findings suggest that the region holds promising potential for mineralization and groundwater accumulation.

Keywords: High-Resolution Aeromagnetic; Regional-Residual Separation; Spectral Analysis.

1 Introduction

The magnetic method is a key geophysical technique used to explore and extract natural resources like minerals, groundwater, oil, and geothermal energy. Its early application in petroleum exploration offers a reliable regional assessment of subsurface features. This method is also critical for geothermal research, helping to locate zones suitable for sustainable energy generation. In this study, magnetic data from the Nigerian Geological Survey Agency (NGSA) is analyzed using Oasis Montaj software and techniques such as regional-residual separation, spectral analysis, analytic signal processing, and source parameter imaging [1]-[4].

Spectral analysis, as a statistical tool, is applied to determine the average depth and topography of magnetic source bodies across a study area. It offers insights into basement characteristics but not precise depth measurements. Analytic signal processing, on the other hand, sharpens the clarity of magnetic anomalies by calculating both horizontal and vertical derivatives. This allows for accurate mapping of subsurface structures like faults, fractures, and folds are indicators of areas with high groundwater potential and mineralization [5],[6].

Aeromagnetic surveys provide extensive data for creating geological maps and locating mineral-rich areas. Their consistent availability and utility in detecting hidden igneous bodies and sedimentary structures make them indispensable in mineral and geothermal prospecting. Research has highlighted the effectiveness in identifying buried formations that are essential for locating groundwater, oil, and mineral deposits, even in complex sedimentary environments [7].

The technique is particularly powerful for analyzing sediment thickness and determining the depth of basement rocks, especially in sedimentary basins. Strong magnetic contrasts between igneous/metamorphic and sedimentary rocks make basement delineation more accurate. Spectral analysis also supports geothermal gradient estimation, helping evaluate potential geothermal reservoirs valuable in regions aiming to diversify energy resources [5].

Overall, this study seeks to reduce Nigeria's reliance on oil by improving mineral and groundwater resource assessments in the Jada area (Fig. 1). By examining sediment thickness and mapping structural lineaments using aeromagnetic data, the research identifies zones with high resource potential. These insights not only support exploration but also aid in public water development and economic planning.

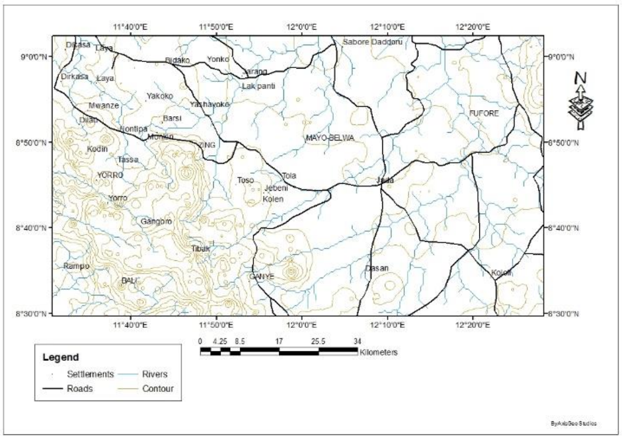

Fig. 1 Research Region Topographic Map (After [8]).

The Adamawa Massif, located in Eastern Nigeria, forms a key component of the Basement Complex and is geologically bounded by the Yola Trough, Benue Rift, and Mamfe Embayment. The region displays a wide array of rock types, such as Migmatite-Gneisses, various Granites, and Pegmatites. Recent studies in areas like Monkin have revealed even more

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rock varieties, including Granodiorites and Fine-Grained Granites. Of particular interest is the Benue Trough, which is enriched with uranium deposits linked to nearby Fine-Grained Granites, adding economic value to the area's geology [9].

Geoscientific research in regions like Mutum-Biyu has uncovered dyke-like structures and a dense network of lineaments features like faults, joints, and shear zones shaped by ancient tectonic forces. The dominant structural trends, mostly NE-SW and N-S, reflect influence from the Pan-African Orogeny, while others suggest even older tectonic events. Aeromagnetic data further confirms these regional structural orientations, reinforcing the area's complex tectonic evolution and its implications for mineralization and groundwater flow [10].

The geological history of the Massif is rooted in the Precambrian, featuring a Migmatite-Gneiss Complex that has been altered by the intrusion of Pan-African Granitoids. These formations evolved through multiple metamorphic and tectonic phases, including the Pan-African Orogeny, during which the West African Craton collided with the Pan-African Mobile Belt. As a result, Syn-to Post-Collisional Plutons formed and were later exposed by uplift. Today, the region comprises a rich mix of granitic, metavolcanic, and metasedimentary rocks (Fig. 2) that collectively offer valuable insights into the tectonomagmatic evolution of West Africa [11].

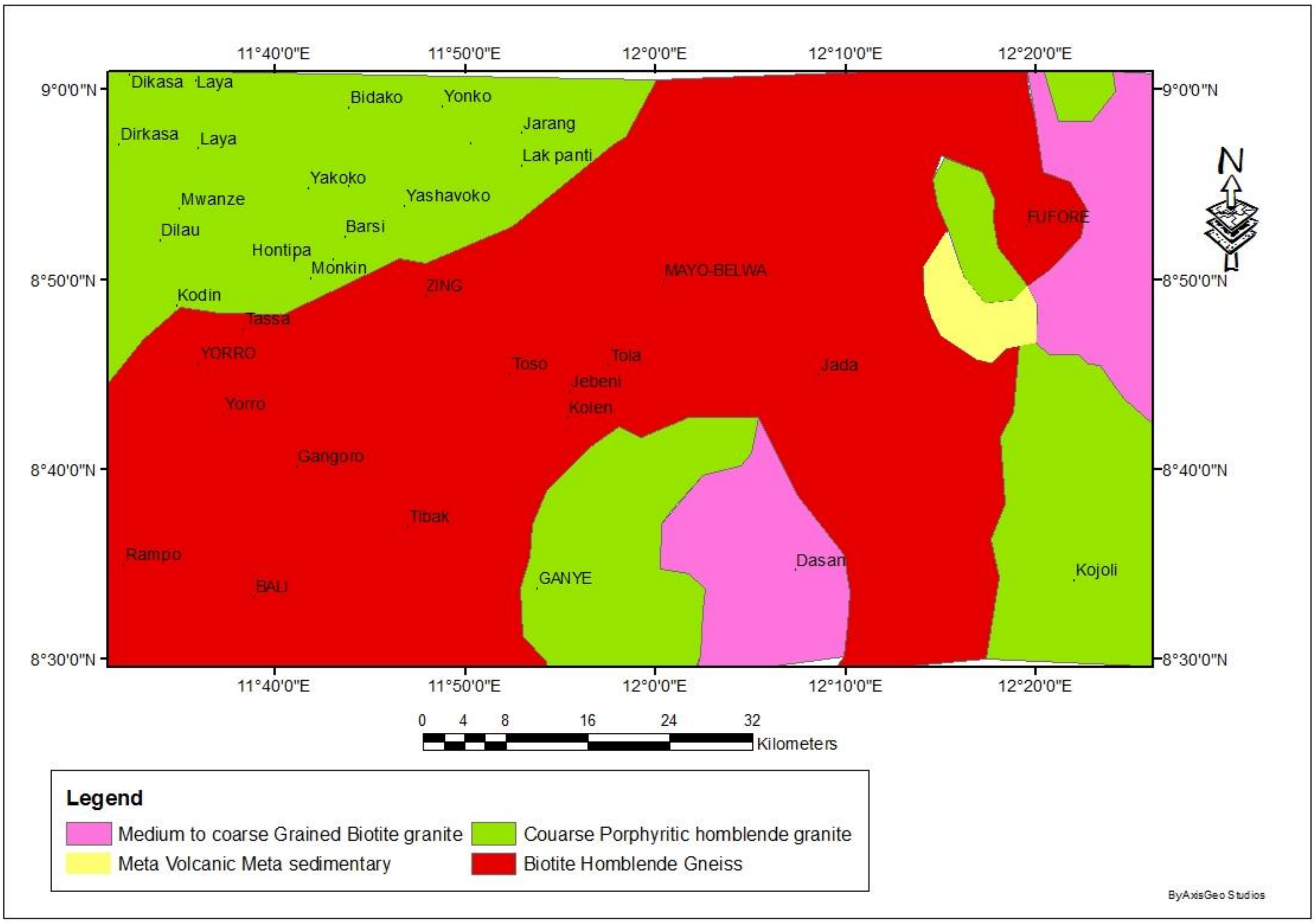

Fig. 2 Study Area Geologic Map (After [12]).

2 Materials and Methods

2.1 Aeromagnetic Data Acquisition

The aeromagnetic data utilized in this study, spanning two sheets of 30′ × 60′, (Fig. 3) was acquired in digitized form provided by the Nigerian Geological Survey Agency (NGSA), stemming from a high-resolution airborne survey conducted by Fugro Airborne Surveys between 2004 and 2009. This survey featured NW-SE flight lines at 500 m spacing and 2000 m NE-SW tie-line spacing, flown at a nominal altitude of 80 m with data captured at 0.1-second intervals, providing superior anomaly resolution compared to traditional high-altitude methods. All magnetic data corrections and processing were handled by Fugro, with the data acquisition and compilation funded collaboratively by Government of Nigeria and World Bank as the Sustainability programme for Mineral Resources Project.

The Total Magnetic Intensity (TMI) map reveals anomalies predominantly trending in the NE-SW and NW-SE directions, with N-S and E-W trends appearing as minor features. The magnetic susceptibility values for TMI range from -35.3 to 173.7 nT.

2.2 Separation of broad-scale and local variations

Regional-residual separation was conducted using the polynomial fitting method, where a low-order polynomial was used to model the regional magnetic field and isolate residual anomalies. This technique, grounded in statistical theory and implemented via the least squares method, enabled the systematic approximation of the regional field and the extraction of residuals defined as the difference between the observed and fitted magnetic field. Using Oasis Montaj Software version 7.0.1, the team processed and visualized the results, generating both residual (Fig. 4) and regional magnetic maps that underpin further geological interpretation. Similar trends observed on the TMI were also peculiar to the Residual Magnetic Intensity (RMI) map. The magnetic susceptibility values RMI range from -88.8 to 86.3 nT [13]-[16]

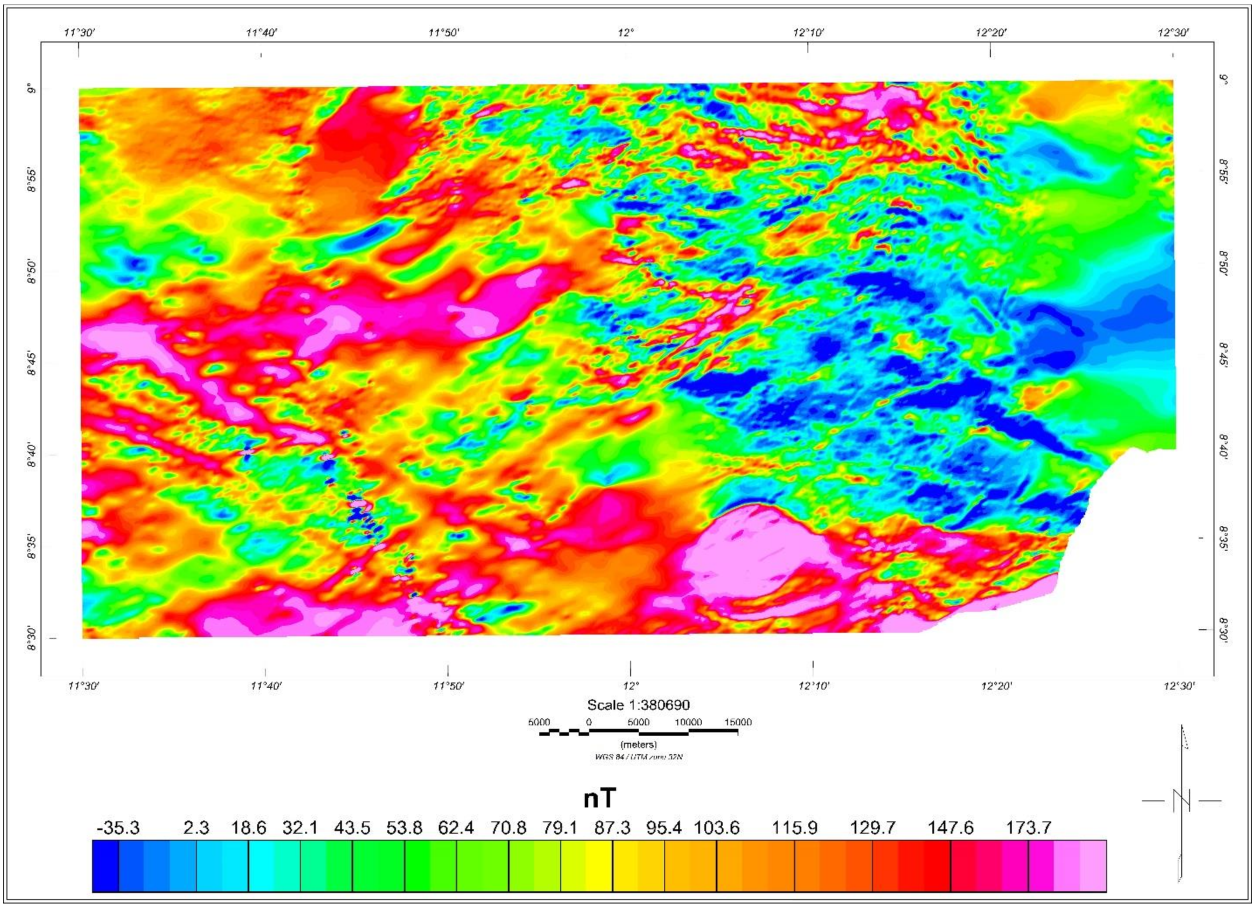

Fig. 3 Total Magnetic Intensity Map of the Area

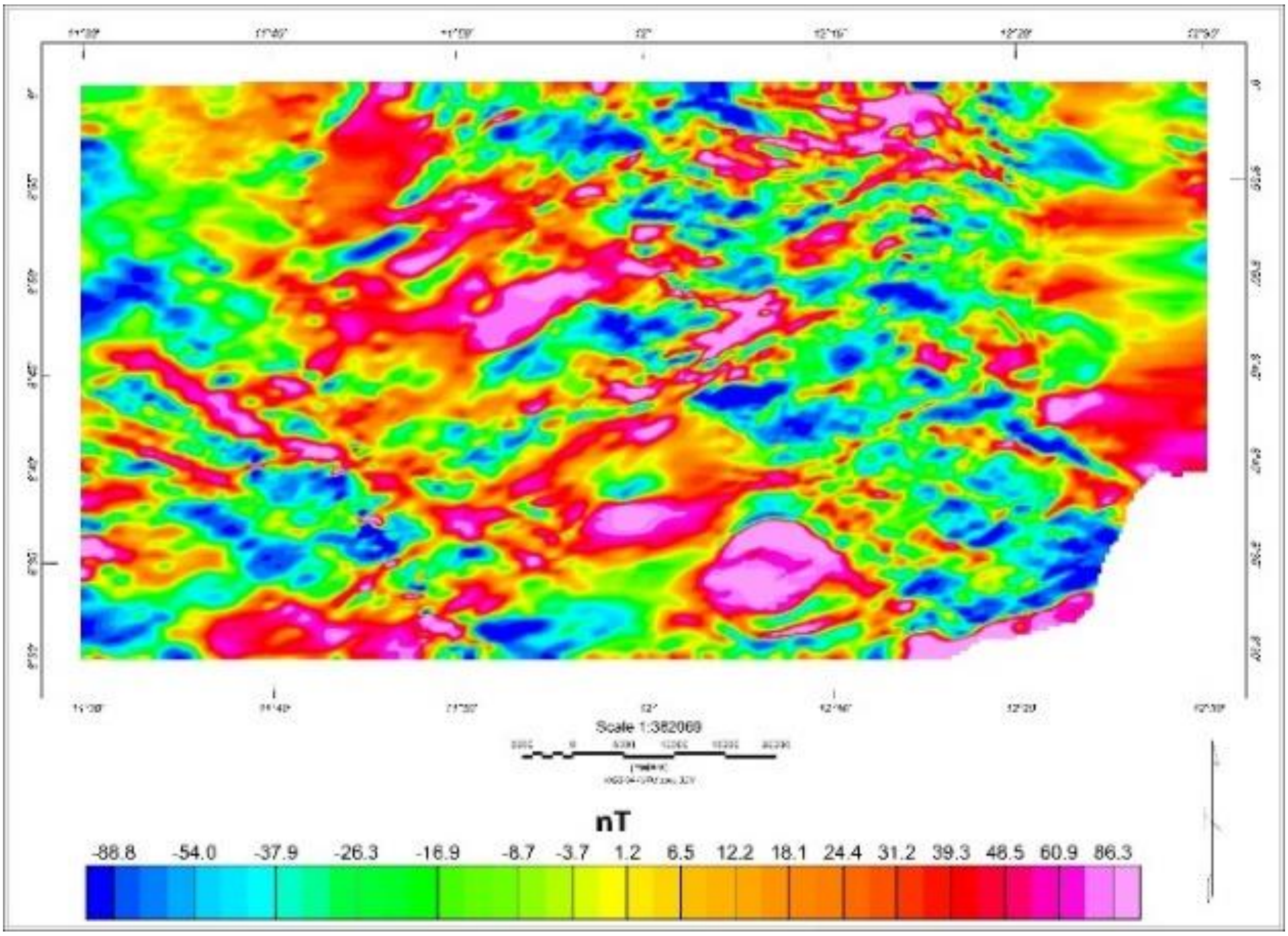

Fig. 4 Residual Magnetic Intensity Map of Area

2.3 Spectral Analysis

Spectral analysis is an essential technique in aeromagnetic studies, allowing researchers to estimate the average depth of buried magnetic sources beneath sedimentary basins. By examining the widths and slopes of magnetic anomalies in aeromagnetic profiles, this method applies statistical principles like those outlined by [17]-[20] to deliver reliable insights into the structure of the Earth's subsurface.

In this research, residual magnetic field data were transformed into a frequency spectrum obtained through a two-dimensional fast Fourier transform (FFT). The resulting radial spectrum was divided into segments whose slopes represent the depths of different subsurface layers. An average energy-frequency spectrum was computed, and low-frequency components prone to error were excluded. These analyses produced depth estimates corresponding to subsurface bodies, enabling accurate mapping of geological features vital for mineral and groundwater exploration using the following equation.

$$Z = \frac{lD}{2\pi} \qquad 1$$

Where $l = slope$; =length of a square side of the block.

The aeromagnetic data for this research was segmented into eighteen 10′ × 10′ blocks, each covering approximately 18.3 km by 18.3 km, arranged in a 3 × 6 grid. To analyze the frequency characteristics of the magnetic anomalies within each block, Fast Fourier Transformation (FFT) was applied. This transformation enabled the computation of the Power Spectrum of the magnetic field data. The spectral analysis was performed using a combination of Oasis Montaj Software and MATLAB, providing a robust framework for identifying depth-related signals from the magnetic signatures in each block (Fig. 5). This technique enhances the resolution of subsurface feature detection, particularly useful for estimating source depths and guiding further geophysical interpretations.

2.4 Analytic Signal Method

The Analytic Signal method was applied directly to the residual data, effectively identifying horizontal locations of contacts and layer edges, regardless of dip or inclination. This method enhances or amplifies energy within the data, improving anomaly detection.

The Analytic Signal is derived from the first derivative of the vertical component of the magnetic field, combined with horizontal derivatives. Due to its sensitivity to both vertical and horizontal gradients, it is more susceptible to noise compared to the Horizontal Gradient method [21]. However, it is particularly effective in highlighting the intensity of intrusive bodies.

In two-dimensional potential field analysis, the Analytic Signal of the data is expressed as [6]:

$$A(x) = \varphi_x \ _{+} i\varphi_z \qquad 2$$

Where φ_x and φ_z is a horizontal and vertical Derivative.

The 2-D Analytic Signal Amplitude (ASA) of the Potential Field is

$$/A(x)/ = \sqrt{\varphi_x^2 + i\varphi_z^2} \qquad 3$$

[22] write the analytic signal in 3D as a vector encompassing the horizontal derivatives and their Hilbert Transform, and the 3D Analytical Amplitude of the Potential Field measured on a horizontal plane as Ø (x, y):

$$/A(x, y)/= \sqrt{\varphi_x^2 + \varphi_{y+}^2 \varphi_z^2} \qquad 4$$

For this research, the Analytic Signal Map (Fig. 6) was used to produce Lineaments, which were manually drawn and extracted using ArcGIS Software to produce the Lineament Map of the area.

3 Results and Discussion

This study evaluates the groundwater and mineralization potential of Jada and its environs in Northeastern Nigeria using aeromagnetic data. The analysis employed Regional-Residual Separation, Spectral Analysis, and Analytic Signal techniques to assess sediment thickness and lineament trends in the area. Table 1 presents the depth estimates for deeper (D1) and shallow (D2) magnetic sources, ranging from 0.530 to 1.960 km for deeper sources and 0.423 to 0.622 km for shallow sources. The results of D1 and D2 were used to produce Fig. 7 and Fig. 8 to further aid interpretation. D1 are generally used for hydrocarbon exploration where the sediment thickness is up to the required standard. D2 are areas for mineralization and groundwater exploration. The identification of shallow magnetic sources (D2) for mineralization is echoed in [23] study, which used aeromagnetic and aeroradiometric data to locate hydrothermal alteration zones associated with gold deposits. They employed techniques like first vertical derivative and analytic signal to map lineaments and depth estimates.

Table 1 Summary of Deeper (D1) and Shallow (D2) Magnetic Source Depths of the Area.

Serial No.	(D1)	(D2)
1	0.941	-
2	0.989	0.507
3	0.530	0.512
4	0.613	-
5	0.549	-
6	1.960	0.527
7	1.200	0.593
8	0.768	-
9	1.620	0.575
10	1.420	0.423
11	0.630	0.614
12	0.985	-
13	1.130	0.609
14	0.603	-
15	1.370	0.622
16	1.360	0.507
17	1.480	0.522
18	1.670	0.483
Total	19.818	6.494
Mean	1.101	0.541

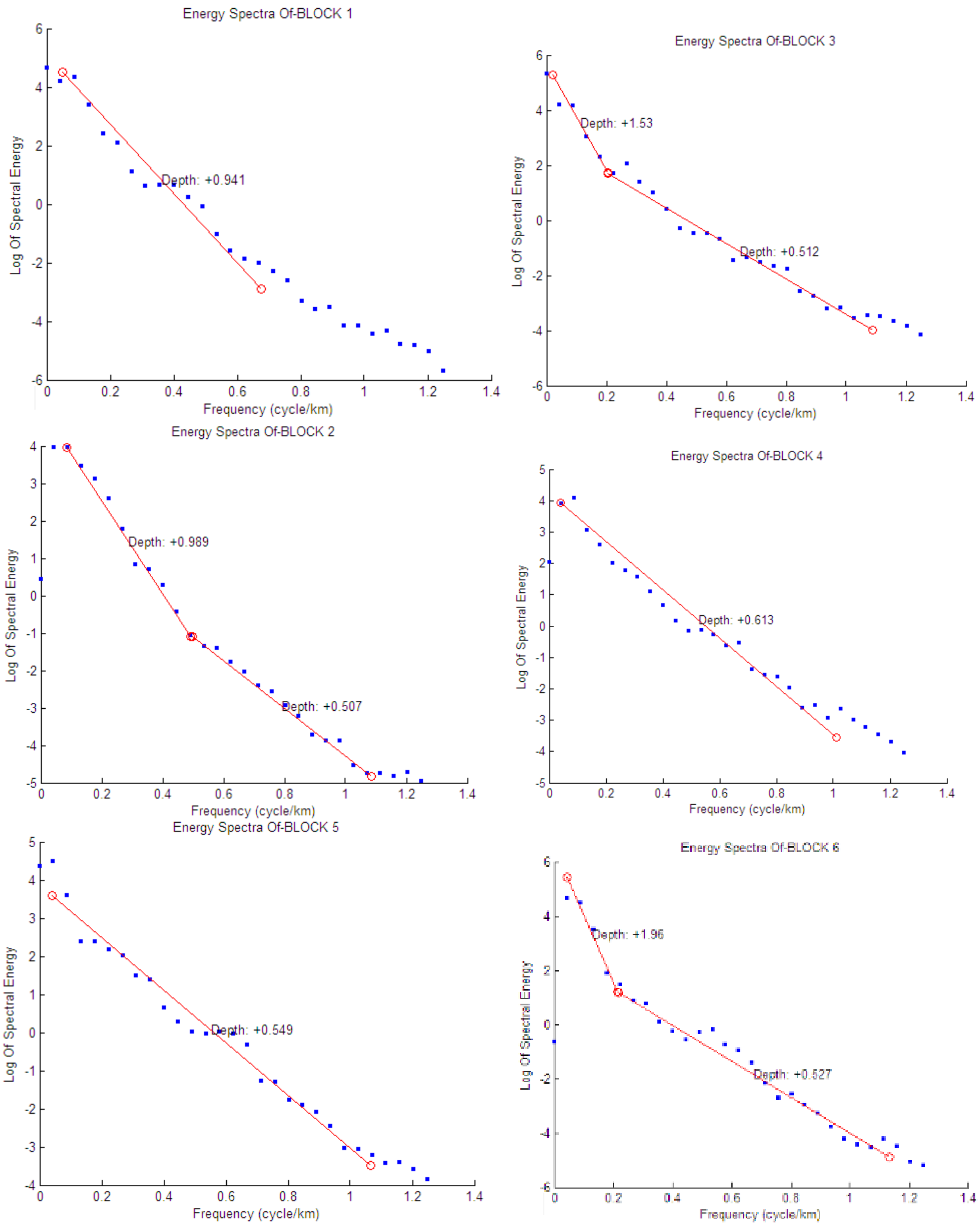

Fig. 5 Graphs of Spectral Blocks 1 to 6 of the Area

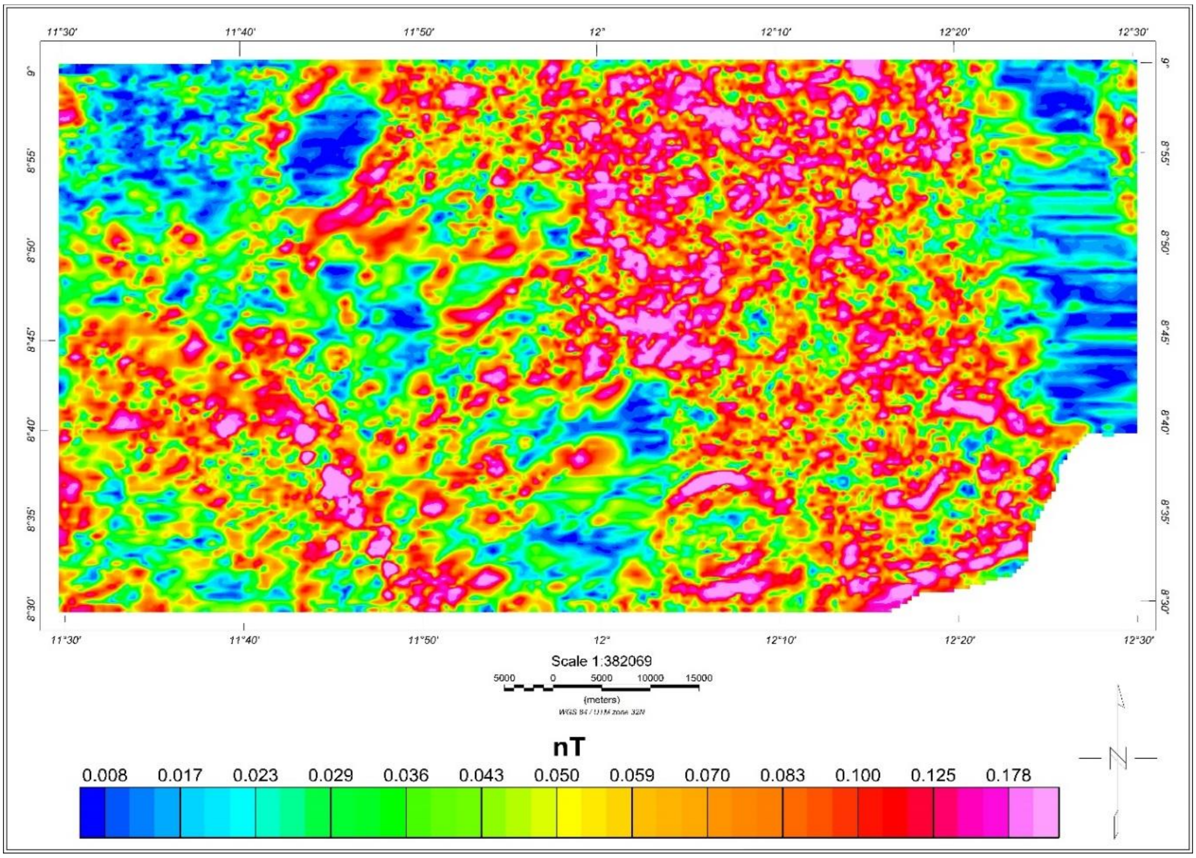

Fig. 6 Analytic Signal Map of the Area

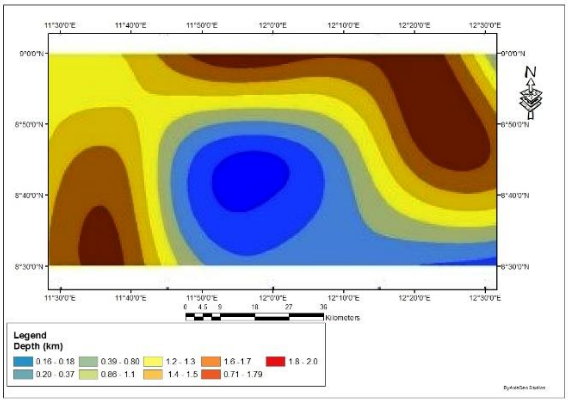

Fig. 7 Deeper Magnetic Source Depth (D1) Map of the Area

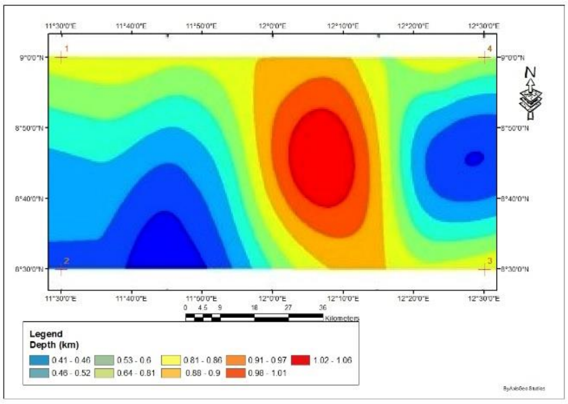

Fig. 8 Shallow Magnetic Source Depth (D2) Map of the Are.

Further analysis involved applying the Analytic Signal method to the RMI map to identify fractures that are crucial for mineralization and groundwater potential. The extracted lineaments were manually delineated (Fig. 9) and plotted on a Rose diagram (Fig. 10), which showed that the majority of the 269 mapped lineaments trend NE-SW, followed by E-W and NW-SE orientations. Minor trends include N-S orientations. These structural features indicate multiple tectonic episodes that have influenced the basin.

To enhance interpretation, a Lineament Density Map was generated (Fig. 11), revealing that the NW and NE parts of the study area have the highest density of lineaments, marking them as potential sites for mineralization and groundwater exploration [22]. The Analytic Signal Map values range from 0.008 to 0.178 nT, while the Lineament Density Map values vary from 0.52 to 4.71.

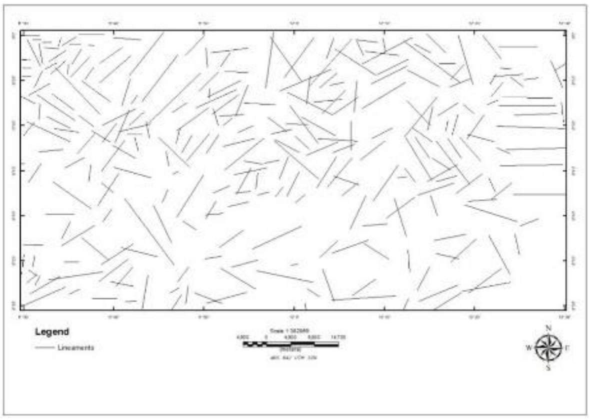

Fig. 9 Lineament Map of the Area.

The use of Analytic Signal and Spectral Analysis to assess sediment thickness and lineament trends aligns with the work of [24] in Ekiti State. They applied Total Magnetic Intensity (TMI), Analytic Signal (AS), and Total Horizontal Derivative (THD) to delineate groundwater zones in a crystalline basement terrain.

The use of lineament analysis for groundwater exploration correlates with the regional study by [25] in Abuja. They applied the first vertical derivative (1VD) and ArcGIS lineament extraction to identify groundwater targets in structurally deformed basement terrains. The D1 depth range of 0.530–1.960 km aligns with deeper magnetic basement depths used in hydrocarbon exploration across Nigeria's sedimentary basins [26]. The D2 range of 0.423–0.622 km is consistent with shallow magnetic sources linked to mineralization zones and aquifer targets in basement terrains [27].

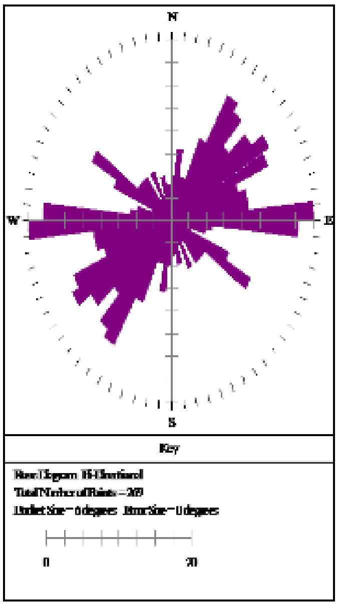

Fig. 10 Rose Diagram Map of the Area

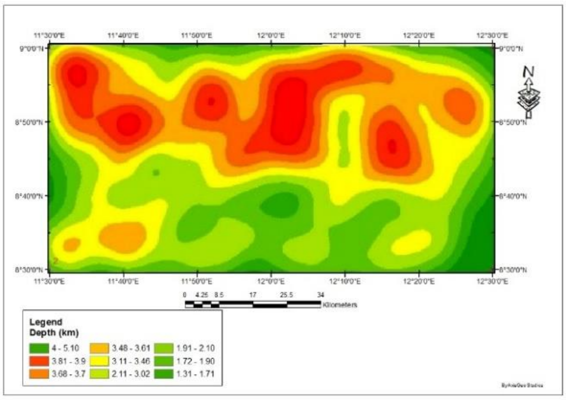

Fig. 11 Lineament Density Map of the Area.

The identification of NE–SW, NW–SE, and NNE–SSW lineament trends as structural controls for groundwater and mineral deposits is widely supported as recurrent across Nigeria and serves as conduits for mineralizing fluids and groundwater recharge [24]. [28] used Landsat MSS data and GIS tools to map lineaments and assess groundwater occurrence in Osara Dam, Itakpe–Okene Area (North-Central Nigeria). Their Rose diagram revealed dominant NE–SW and NW–SE trends, like the findings of this study. High lineament density zones were linked to groundwater recharge and structural control. [29] applied LANDSAT ETM+ imagery and geological mapping to assess groundwater potential in Lafia and Environs (Nasarawa State). Their Rose diagram showed dominant N–S and NW–SE lineament trends, and lineament density maps identified zones of high fracture concentration as favourable for aquifer development. [30] used integrated Landsat TM data and field studies to characterize lineaments and their tectonic significance in mineralization in Mambilla Plateau (Northeast Nigeria). They identified NE–SW, NW–SE, and N–S trends, which are similar to trends of this study as structurally significant, with high lineament density zones correlating with hydrothermal alteration and mineralization.

In mineralization and groundwater exploration, shallow sediment thickness is a key parameter, as it indicates near-surface igneous intrusions. These intrusions can host mineral deposits associated with magmatic activity. Additionally, the overburdened regolith serves as a reservoir for groundwater accumulation, making it a prime target for groundwater exploration [27], [28].

Lineaments, representing subsurface fractures, are critical zones for groundwater accumulation and hydrothermal deposits. The interconnected fractures facilitate hydrothermal alterations, leading to mineral deposition that can be exploited for economic development [24], [29], [30].

4 Conclusion

The evaluation of mineralization and groundwater potential zones in the study area was conducted using aeromagnetic data to identify and delineate regions suitable for further exploration. The analysis of results indicates that the area exhibits significant potential for mineralization and groundwater accumulation, as evidenced by interpretations of sediment thickness and lineaments. Shallow magnetic source depths are potential areas for mineralization as they are sites for near surface late magmatic intrusions. areas with high interconnected lineament densities are potentials sites for groundwater accumulation and hydrothermal mineral deposits.

4.1 Recommendation

The findings of this research indicate significant groundwater and mineralization potential in the study area. To further validate these results, additional geological investigations are recommended, including resistivity and electromagnetic methods. These techniques will provide more comprehensive subsurface data, enhancing the accuracy of mineral and groundwater exploration efforts.

Acknowledgments

The authors sincerely appreciate the Nigerian Geological Survey Agency for providing access to the digital high-resolution aeromagnetic data used in this study. Their support was instrumental in facilitating this research.

Authors Contributions Statement

K. Ezekiel: Conceptualization, Methodology, Software, Writing – Reviewing and Editing; **M. A. Senguro**: Data Curation; **M. A. Garba**: Software, Validation, Visualization, Investigation, Writing – Original Draft; **H. Musa**: Supervision

Conflict of Interest Statement

The authors declare no competing financial or non-financial interests, nor any personal relationships, that could influence the work reported herein.

Funding Information

This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Generative AI statement

No generative AI/LLM was used in any stage of this manuscript.

Data Availability Statement

Data supporting the findings of this study are available from the corresponding author upon reasonable request.

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