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Magnetic Anomaly Analysis Reveals Mineral Potential in the Udi Region of south-eastern Nigeria

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Abstract

Geophysical data processing techniques were employed to investigate the mineral potential of the Udi region in south-eastern Nigeria. High-resolution aeromagnetic data were analyzed using multiple methods, including magnetic anomaly mapping, source edge detection (SED), analytic signal (AS), source parameter imaging (SPI), and 3D inversion. Significant magnetic anomalies, ranging from -28.1 to 135 nT, correlate with known mineral deposits, including limestone, iron ore, lead-zinc (Pb-Zn) sulfides, and coal. Depth estimates for potential mineral sources range from 280 to 3600 m. Linear trends in Euler solutions suggest the presence of faults and fractures, which are likely to influence mineral emplacement. 3D inversion models corroborated these findings, revealing subsurface structures with contrasting magnetic susceptibilities. This study confirms known mineralization and identifies new prospective areas for future exploration.

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Keywords: *Aeromagnetic analysis, structural interpretation, mineral prospectivity, subsurface modeling, geophysical inversion, depth estimation*

1. Introduction

The Udi region in south-eastern Nigeria is of significant geological interest due to its complex subsurface structures and rich mineral resources. The region has been identified as a potential hotspot for mineral exploration (Abraham et al., 2024a; Onwuka et al., 2010), but detailed subsurface evaluations of these deposits are limited. Surficial assessments indicate the presence of mineral-bearing rocks such as limestone, iron ore, clay, lead-zinc (galena and sphalerite), glass sand, gypsum, and coal. However, the extent and depth of these deposits have not been thoroughly investigated. This study focuses on the application of magnetic data to explore and map the geological structures hosting these mineral resources.

Magnetic surveys have proven effective in mineral exploration, particularly in areas abundant in magnetite and other magnetic minerals (El-Kelani, 2020). These surveys provide valuable insights into the structure of these magnetic bodies and often offer information about the structural system of mineralization (Abraham et al., 2024a, 2024b; Couto et al., 2017; Leâo-Santos et al., 2015; Obaje, 2009; Büyüksaraç et al., 1998). The method has also provided valuable insights into the subsurface by detecting variations in the Earth's magnetic field caused by the presence of ferromagnetic minerals (Usman et al., 2024a, 2024b; Abraham et al., 2022; Reeves, 2005). Magnetic surveys are particularly effective in regions with complex geology, where traditional methods may fall short. The application of the magnetic method in south-eastern Nigeria has shown promise in identifying and characterizing mineral deposits, offering a non-invasive and cost-efficient alternative for identifying mineral deposits (Ugodulunwa et al., 2021; Abraham et al., 2022).

The study area covers geographic latitudes 6°00′ and 6°30′ N and geographic longitudes 7°00′ and 7°30′ E within the sedimentary terrain of south-eastern Nigeria (Figure 1). It covers an area of about 3025 km^2 and consists of many major settlements that are engaged in various forms of farming and localized mining activities.

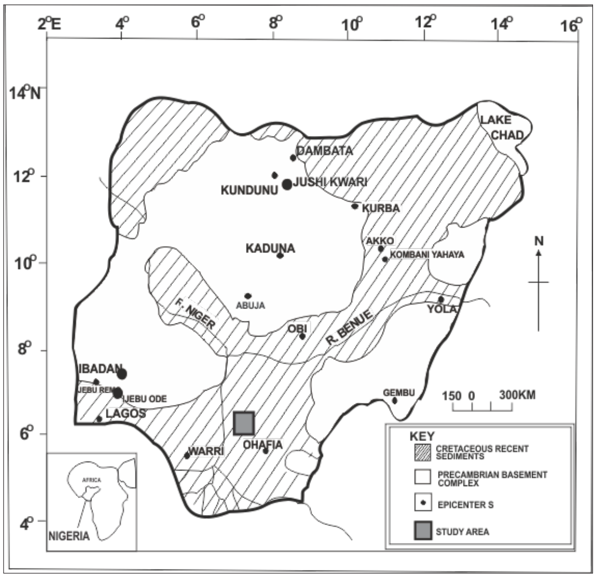

Figure 1. Map of Nigeria showing the study area (modified from Abraham et al., 2018)

In Udi, coal mining dates back to 1916, when it was exploited by the Nigerian Coal Corporation (NCC) at Onyema coalfield, which was later industrialized in October 1977 (Onwukeme, 1995). Although both local and industrial coal mining activities have stopped in the area for some time due to the alternative discovery and industrial exploitation

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of fossil fuel in the nation, there are no formal evaluations of their subsurface host structures, neither has the location, geometry, and estimate of other possible deposits been sufficiently assessed.

Some geophysical studies conducted within the region have investigated the groundwater potentials (Onwe et al., 2022; Ekwe et al., 2020; Onwe et al., 2019), with a few highlighting the diverse mineralization potentials (Ugodulunwa et al., 2021; Abraham et al., 2022), particularly in areas like the Udi region, which is known for its rich deposits of coal, limestone, and other economically significant minerals (Obaje, 2009). The geophysical characterization of these resources has been relatively limited, emphasizing the need for comprehensive studies that leverage advanced geophysical techniques. Therefore, this study aims to analyze the subsurface structures in the Udi region using aeromagnetic data to determine their mineralization potential. Specifically, we propose to map structural trends, estimate depths of key geologic features, and evaluate their significance in guiding mineral exploration efforts. We hope to provide insights into the structural controls on mineral deposition, which would be essential for resource evaluation and sustainable extraction planning.

1.1 Geological Setting

The study area lies within the Southern Benue Trough of the Anambra Basin, South-eastern Nigeria. The Early Cretaceous witnessed the separation of the South American and African continents, forming the Benue Trough Sedimentary basin. According to Murat (1972), three major tectonic cycles were identified within the South-eastern Nigeria. During the Aptian-Early Campanian period, the initial phase of the tectonic setting was marked by the onset of rifting and the opening of the Benue Trough. Subsequently, in the Santonian-Early Campanian period, compression tectonics led to the folding and uplift of the Abakaliki Anticlinorium, the formation of the Anambra Basin, and the development of the complementary Afikpo Syncline (Figure 2).

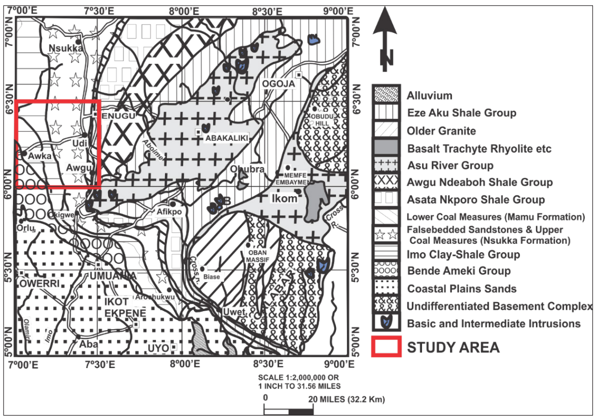

Figure 2. Geologic map of the study area (modified from Abraham et al., 2018)

During the Late Campanian to Eocene, the third phase of the tectonic setting led to alternating periods of rapid uplift and subsidence, followed by the progradation of a delta and the subsequent deposition of sedimentary infill in the Anambra Basin. The Cretaceous depocenter of Anambra Basin received sedimentary fill during the Campanian-Tertiary age. The sedimentary formation of the Anambra Basin is abridged in (Nwajide, 2013). Freshwater sandstones were deposited till the north and west onto the Precambrian Basement. Sedimentation was entirely nonmarine until the deposition of the Nsukka Formation, in which marine intercalations indicate a gradual encroachment of the sea and mark the end of deposition in the Anambra Basin. The Udi region is characterized by the Nsukka Formation, the Bende Ameki group, the Imo clay-shale group, and part of the Mamu Formation (Figure 2).

1.2 Mineral Resources Map of the Study Area

The Udi region's mineral resources map (Figure 3) was extracted from the Mineral Resources Map of Nigeria as published by the Geological Survey of Nigeria Agency (GSNA) in 2004. Figure 3 reveals a mineral-rich region within the Cretaceous sedimentary basin of south-eastern Nigeria. The mineral emplacements also hint at the possible presence of associated mineral deposits that may not have been identified at the time.

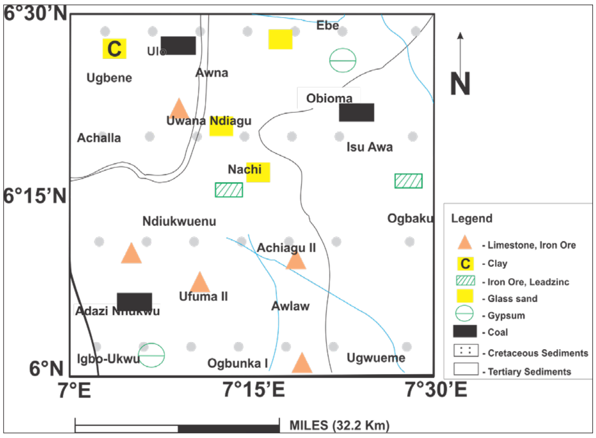

Figure 3. Mineral map of the study area (Extracted from Nigeria Geological Survey Agency (NGSA): Mineral Resources map of Nigeria, 2004)

Notable minerals in the region include the calcite and aragonites domiciled in the vast accumulation of limestone in the southern and northwestern (NW) regions. Other minerals include dolomite, siderite, and lead-zinc (galena and sphalerite) in the central and eastern regions. Gypsum dominates the NE and SE regions, and the earlier coal deposits were discovered in the NW, NE, and SE regions. Some significant clay and glass sand depositions have also been recorded in the northern region of the study area.

2. Methodology

A high-resolution aeromagnetic data was used for this study. The data was acquired from the Nigerian Geological Survey Agency (NGSA), which had acquired the digital data for the entire country between years 2005 and 2009. The airborne survey was conducted by Fugro Airways Services. The surveys were flown at 500m line spacing with an average flight elevation of 80 m along NW – SE directions, and data published in the form of grids of by map sheets. The regional field and diurnal magnetic effects were eliminated from the data. We then applied the Reduction to Equator (RTE) correction, following the methodology outlined by Abraham et al. (2024a), Ganguli et al. (2021), Abraham et al.

(2018), Jain (1988), and Leu (1981). This correction assumed a magnetic declination of -2.15° and an inclination of -13.91° for the study area, utilizing the fast Fourier transform operator. Figure 4 displays the resulting aeromagnetic map of the Udi region.

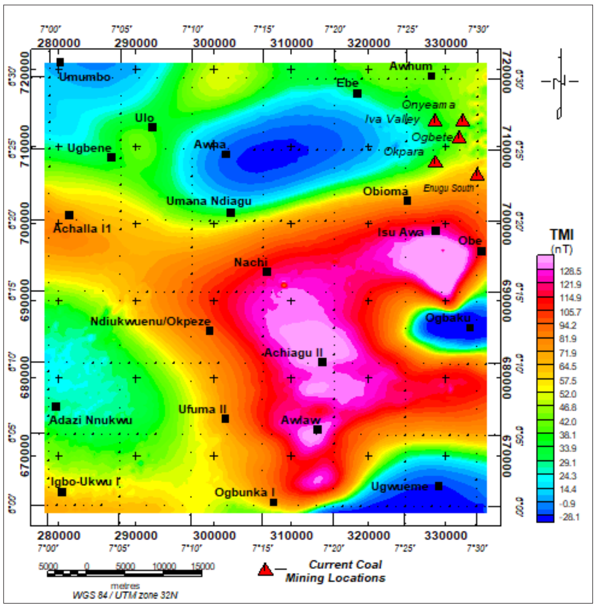

Figure 4. Residual Magnetic Anomaly Map of Udi.

The map revealed significant fluctuations in magnetic strengths, indicating diverse magnetic characteristics. At Awlaw, Achiagu II, Nachi, Isu Awa, Oba, and certain areas of the Ndiukwuenu – Achalla regions, there are noticeable positive irregularities with values ranging from 71 to 140 nT. These irregularities indicate the possible presence of high magnetic minerals within the subsurface at these locations. The mixture of positive (38 – 57 nT) and negative (-25 – 29 nT) magnetic anomalies at Onyeama and Iva Valley, Ulo, and Adazi locations could be signals from the coal deposits embedded in the region. The magnetic susceptibility of coal is a mixture of diamagnetic, paramagnetic, and ferromagnetic (Seferinoglu and Duzenlf, 2022).

2.1 Source Edge Detection (SED)

The Source Edge Detection (SED) technique would be used to locate edges (i.e., geological contacts) or peaks from magnetic field data by analyzing the local gradients. The SED function estimates the location of abrupt lateral changes in magnetization or mass density of upper crustal rocks following the procedure of identifying maxima on a grid of horizontal gradient magnitudes. Using the technique of Cordell and Grauch (1982), a database of source edge locations was derived from the grid of the total magnetic field. A map is produced with ⫞ symbols representing locations and gradient directions of magnetic field anomalies (Figure 5).

2.2 Analytic signal (AS)

The AS processing technique was used to enhance the resolution and interpretability of magnetic data anomalies. With the AS computations, information on the amplitude and phase of anomalies were extracted to aid in identifying subtle magnetic anomalies associated with geological boundaries and lithological variations. The analysis of magnetic anomalies presents unique challenges due to the phenomenon of spatial offset between the observed anomalies and their underlying sources. This displacement, often called skewness and the non-vertical nature of the Earth's magnetic field and the induced magnetization within geological bodies. In this context, the Analytic Signal (AS) function emerges as a particularly valuable tool for interpretation despite not being a directly measurable parameter. Its key advantage lies in its independence from both the magnetization direction and the orientation of the inducing field. This property ensures that geological bodies with identical geometries produce identical analytic signals, regardless of their magnetic characteristics or geographical location. Another notable feature of the AS function is the symmetry of its peaks. These peaks align precisely with the edges of broad geological structures and centrally over narrow features. This predictable behavior significantly enhances the accuracy of source localization and geometric interpretation in magnetic surveys. By leveraging these properties, the AS function overcomes many ambiguities associated with traditional magnetic anomaly interpretation, offering a more direct and reliable method for delineating subsurface structures and geological boundaries (Abraham et al., 2024a).

The Analytic Signal is given by Equation (1):

$$A(x,y) = \sqrt{\left(\frac{\partial T}{\partial x}\right)^2 + \left(\frac{\partial T}{\partial y}\right)^2 + \left(\frac{\partial T}{\partial z}\right)^2} \quad (1)$$

where T is the observed field at x and y.

The Analytic Signal (AS) method offers a practical approach to estimating the depth of magnetic sources, particularly when assuming these sources are vertical contacts. This technique employs a straightforward amplitude half-width rule, which typically yields depth estimations with an accuracy of around 70%. A significant advantage of the AS method is its ability to circumvent the challenges often encountered in traditional reduction-to-pole processes. These conventional methods can be problematic when the effects of natural remanent magnetization on the source's overall magnetization are not well understood or quantified. Figure 6 provides a visual display of the AS results. This approach proves especially valuable in situations where the magnetic properties of subsurface structures are complex or poorly constrained. By focusing on the geometry of the anomaly rather than its absolute magnetic properties, the AS method provides a more robust and versatile tool for magnetic data interpretation.

2.3 Source Parameter Imaging (SPI)

The Source Parameter Imaging (SPI) technique is an automated method for determining the depths of magnetic sources from gridded magnetic data. A key advantage of this approach is its independence from magnetic inclination and declination, eliminating the need for pole-reduced input grids in the analysis process. Empirical studies involving real-world datasets with drillhole verification have demonstrated the reliability of SPI, with depth estimates typically falling within a ±20% margin of error. This level of accuracy is comparable to that achieved by Euler deconvolution, another widely used technique in magnetic data interpretation. However, SPI offers distinct benefits over Euler deconvolution. Notably, it generates a more comprehensive and coherent set of solution points, providing a fuller picture of the subsurface structure.

SPI assumes a step-type source model (Thurston and Smith, 1997; Blakely and Simpson, 1986).). For a step, the following formula holds:

$$\text{Depth} = 1/K_{max}, \quad (2)$$

where is the peak value of the local wavenumber K over the step source.

$$K = \sqrt{\left(\frac{dA}{dx}\right)^2 + \left(\frac{dA}{dy}\right)^2}, \quad (3)$$

where

$$\text{Tilt derivative } A = \tan^{-1}\left\{[dM/dz]/\left(\sqrt{\left(\frac{dA}{dx}\right)^2 + \left(\frac{dA}{dy}\right)^2}\right)\right\}, \quad (4)$$

and, M = the total magnetic field anomaly grid.

The result of the SPI computations for this study area is presented in Figure 7.

2.4 Euler Deconvolution

Euler deconvolution was applied to the residual magnetic data to estimate the depth and location of magnetic sources contributing to observed anomalies. By analyzing the second vertical derivative of the magnetic field, this method facilitated the identification and delineation of isolated magnetic sources, including faults, dykes, and mineralized zones.

The Standard 3D form of Euler's equation can be defined (Reid et al., 1990) as:

$$x\frac{\partial T}{\partial x} + y\frac{\partial T}{\partial y} + z\frac{\partial T}{\partial z} + \eta T = x_o\frac{\partial T}{\partial x} + y_o\frac{\partial T}{\partial y} + z_o\frac{\partial T}{\partial z} + \eta b \quad (5)$$

Where x, y, and z are the coordinates of a measuring point, x_o, y_o, z_o and are the coordinates of the source location whose total field is detected at x, y, and z, b is a base level, and η is a structural index (SI). The SI represents an exponential factor that correlates with the field decay rate over distance for a source with a specific geometry. The value of the SI is contingent upon the type of source body under investigation (Whitehead and Musselman, 2005). For instance, η = 0 denotes a contact, η = 1 signifies the top of a vertical dyke or the edge of a sill, η = 2 corresponds to the center of a horizontal or vertical cylinder, and η = 3 represents the center of a magnetic sphere or dipole (Thompson, 1982; Reid et al., 1990). The implementation of Euler deconvolution is depicted in Figure 8 (a and b) for structural indexes of 0 and 1.

2.5 3D Modeling of Susceptibility Contrast

The processed magnetic data were integrated into three-dimensional (3D) geological models to visualize and interpret subsurface geological structures of mineralized interests. Incorporating information on magnetic susceptibility contrast, these models enabled the quantification of magnetic properties and characterization of geological features in three dimensions, facilitating the identification of potential mineralization targets and the assessment of structural extents. The 3D modeling results are displayed in Figure 9.

Pilkington (2009) applied the Cauchy norm described by Sacchi and Ulrych (1995) to address the 3D magnetic inverse problem. This approach aimed to generate sparse models, characterized by minimizing the number of non-zero values that adequately fit the observed data. The resulting inversion technique is classified as geologically unconstrained (Abraham et al., 2024a). This classification distinguishes it from constrained inversion methods incorporating specific geological information. Constrained inversions typically integrate hard geological data, such as information from drill hole intersections, to guide the inversion process. By contrast, the unconstrained approach developed by Pilkington relies solely on magnetic data and mathematical principles to produce a solution. This method offers flexibility in scenarios where detailed geological constraints are unavailable or when an unbiased interpretation of the magnetic data is desired. However, the lack of geological constraints may result in solutions that, while mathematically sound, might not fully align with known geological structures or properties in some cases.

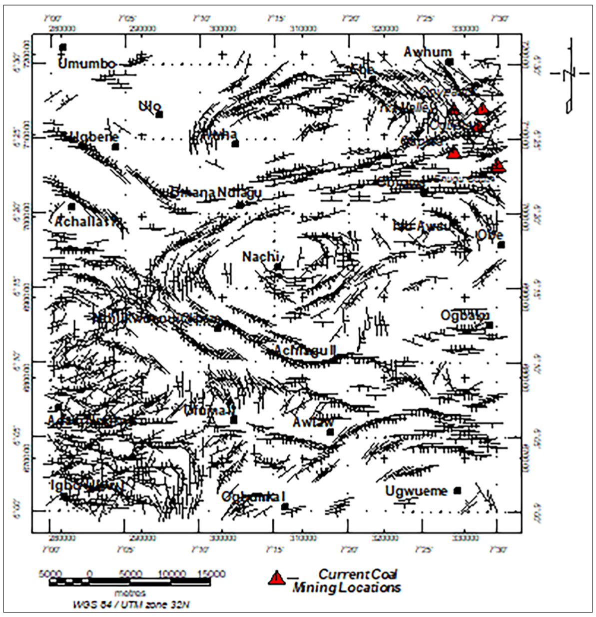

Figure 5. Source Edge Detection in 2 peak directions showing location and gradient direction of potential field anomalies.

The choice of methods, particularly SPI and Euler Deconvolution, was based on the specific requirements of this study and the nature of the geological formations in the Udi region. SPI was selected for its ability to provide depth estimates without requiring detailed prior geological constraints. This is particularly important in underexplored areas where detailed geological mapping is scarce. SPI has been successfully applied in similar sedimentary environments (Büyüksaraç et al., 1998; Abraham et al., 2024a, 2024b), where it has proven effective in estimating the depth to magnetic sources, particularly in regions with complex magnetic anomalies. On the other hand, Euler Deconvolution was chosen for its ability to identify subsurface structural lineaments such as faults and fractures. Given the presence of known mineral deposits associated with fault systems in the Udi region, Euler Deconvolution was particularly useful in identifying these structural features and estimating their depths. Compared to alternative methods, such as spectral analysis or tilt-depth methods, Euler Deconvolution provides a more direct approach to delineating vertical and horizontal discontinuities in the magnetic data (Abraham et al., 2024b; Abraham and Alile, 2019). Combining these methods enhances this study's robustness by providing complementary information on the depth and structural characteristics of the mineralized zones.

3. Results and Discussion

The magnetic anomalies in the Udi region exhibit significant highs (29–135 nT) and lows (-28.1 to -0.9 nT) (Figure 4). High anomalies are concentrated in regions with recorded mineral signatures, particularly at Achiagu II (limestone and iron ore), Nachi (Pb-Zn and glass sand), Uwana Ndiagu (limestone and iron ore), and the Isu Awa–Obe axis (Pb-Zn and iron ore). In contrast, the magnetic lows show no direct correlation with surface mineral occurrences, except in Umumbo, where documented clay deposits are present. This investigation suggests that anomalous subsurface structures may be mineralized but remain unexposed at the surface.

The observed anomaly values (-28.1 to 135 nT) align with previously reported values in south-eastern Nigeria (Nwankwo and Ene, 2020; Abraham et al., 2022, 2024a; Ugodulunwa et al., 2021). Similar anomaly ranges (-30 to 120 nT) were noted in the Enugu coal basin and Ajao area (Nwankwo et al., 2020; Ugodulunwa et al., 2021), supporting our interpretation that the Udi region is highly prospective for mineralization. The stronger magnetic responses at Achiagu II and Isu Awa (up to 135 nT) suggest higher concentrations of ferromagnetic minerals such as iron ores and Pb-Zn sulfides. Additionally, the negative anomalies associated with coal deposits at Ulo and Adazi Nnukwu are consistent with Usman et al. (2024a), further validating this methodology.

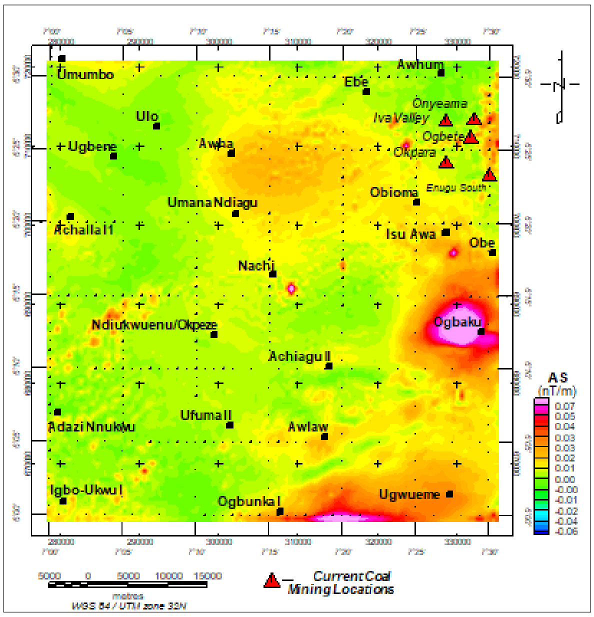

Figure 6. Result of Analytic Signal computations on the magnetic anomalies. Some isolated anomalous structures could be identified from the map.

The source edge detection (SED) analysis (Figure 5) highlights steep magnetic gradient changes at Obioma, Ndiukwuenu, and Adazi Nnukwu. These correspond to sharp anomaly variations and may indicate shifts in the magnetic mineral properties of the underlying formations. The gradient changes at Nachi, Isu Awa, and Awlaw coincide with magnetic highs, suggesting variations in the distribution of magnetized subsurface structures. These results reinforce the role of fault and fracture systems in controlling mineral emplacement.

The analytic signal (AS) response (Figure 6) reveals maxima over magnetization contrasts, particularly at Ndiukwu, Nachi, Ogbaku, Ogbunka-I, Awna, and Obe. These maxima indicate significant subsurface sources corroborated by other geophysical analyses. The AS amplitudes suggest proximity to mineralized structures, such as Pb-Zn mineralization at Ogbaku–Isu Awa and limestone and iron ore deposits at Uwana Ndiagu, Ndiukwuenu, and Ogbunka-I. A comparison of this method with results from Abraham et al. (2024b) confirms the effectiveness of the AS method in delineating Pb-Zn mineralization structures.

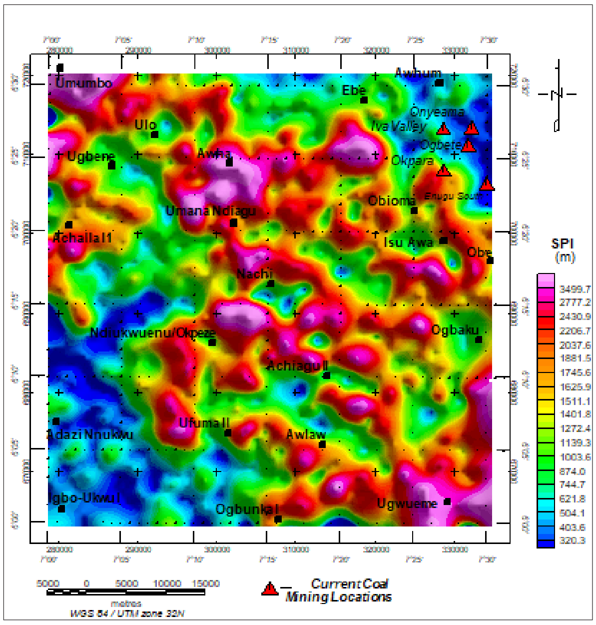

Figure 7. Depths result from SPI computations on the magnetic data.

The SPI method (Figure 7) estimates magnetic source depths ranging from 280 to 3600 m, with deeper anomalies observed in the central study area and shallower sources in the NE and SW. The revealed depths align with known mineralized zones (Figure 3), providing depth estimates for target structures. For instance, the Pb-Zn and iron ore deposits at Nachi are inferred to be within 600–1000 m, while the Isu Awa–Ogbaku mineralization extends to depths of 1200–1500 m. Similarly, limestone and iron ore formations at Ufuma-II, Ogbunka-I, Achiagu-II, and Uwana are estimated at 700–2100 m depths.

Euler deconvolution (Figure 8) further corroborates these depth estimates and identifies subsurface faults trending EW and NW-SE with depths of 10–2300 m. These fault systems likely facilitated the emplacement of Pb-Zn sulfides at Ogbaku and influenced coal deposition at Ulo through sedimentary basin subsidence. Nwankwo and Ene (2020) had achieved similar deductions in the region using gravity and Landsat datasets. Additionally, clusters of Euler solutions indicate possible dykes and sills at depths of 300–3400 m. These intrusive structures may have contributed to metasomatism, influencing Pb-Zn formation at IsuAwa–Ogbaku and Nachi. Intrusive heat sources around Ebe and Igbo-Ukwu may have driven gypsum precipitation in the Cretaceous basin. Similar observations and conclusions have been drawn by Abubakar et al. (2023) on the ability of magnetic data to map subsurface geological structures in southwestern Nigeria. Table 1 summarizes the key mineralized zones identified in this study, highlighting their corresponding magnetic anomaly ranges, depth estimates, associated minerals, and structural controls. The observed variations in magnetic signatures reinforce the influence of fault and fracture systems on mineralization. For instance, the higher magnetic anomalies at Achiagu II and Isu Awa–Obe align with known iron ore and Pb-Zn deposits. In contrast, the negative anomalies at Onyeama and Adazi Nnukwu correspond to coal-rich zones. These findings provide further validation of the geophysical methods used in this study.

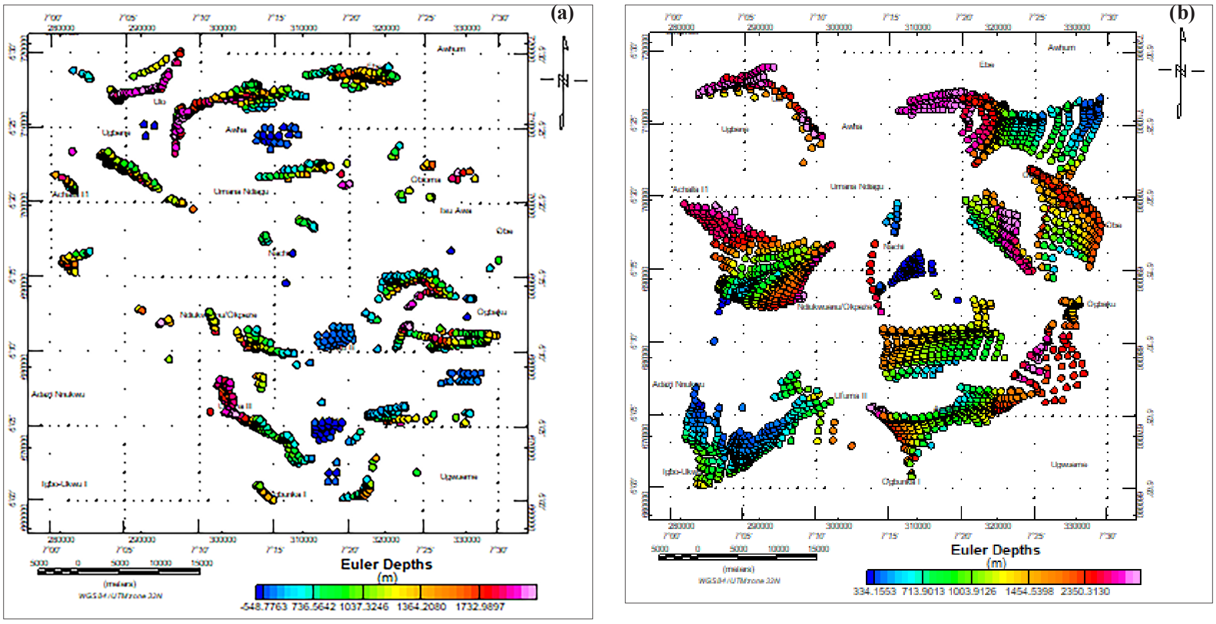

Figure 8. Euler depth solutions map. **(a)** SI=0 for geologic contacts. **(b)** SI=1 for the top of a vertical dyke or the edge of a sill identification in the region.

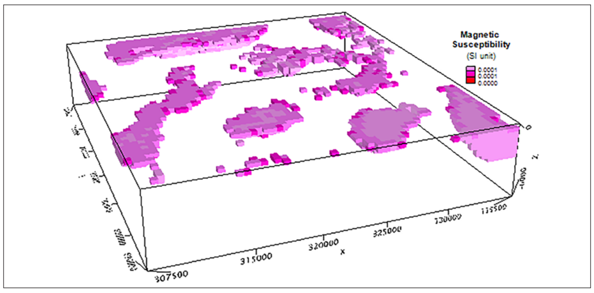

Figure 9. 3D inversion result for the study region obtained from clipping susceptibilities lower than 0.0001 SI.

The 3D magnetic inversion results (Figure 9) delineate subsurface structures with varying magnetic susceptibilities, supporting the presence of mineralized bodies. The successful mapping of known coal deposits in the NE confirms the reliability of this approach and suggests that other identified anomalies are likely indicative of mineralized zones.

Table 1. Summarizes the key mineralized zones and their respective magnetic properties.

Mineralized Zone	Magnetic Anomaly Range (nT)	Depth Range (m)	Associated Minerals	Structural Control
Achiagu II	71 to 140	700 – 2100	Limestone, Iron ore	Fault-controlled
Nachi	71 to 140	600 – 1000	Pb-Zn (Galena, Sphalerite), Glass Sand	Fault zone
Isu Awa – Obe	71 to 135	1200 – 1500	Pb-Zn, Iron ore	Fracture zone
Uwana Ndiagu, Ndiukwuenu	71 to 120	700 – 2100	Limestone, Iron ore	Structural zones
Onyeama, Ogbete	38 to 57	< 300	Coal	Basin margin structures
Adazi Nnukwu	-25 to -29	< 300	Coal	Fault-controlled

4. Conclusion

This comprehensive magnetic study of the Udi region in southeast Nigeria has yielded valuable insights into the region's mineral potential and subsurface structures. The integration of multiple magnetic data analysis techniques, including magnetic anomaly mapping, source edge detection (SED), analytic signal (AS), source parameter imaging (SPI), Euler deconvolution, and 3D inversion, has proven highly effective in characterizing the region's geology and mineralization.

Key findings of this study include:

- Significant magnetic anomalies (ranging from -28.1 to 135 nT) correlate well with known mineral deposits, including limestone, iron ore, lead-zinc (Pb-Zn) sulfides, and coal.
- Depth estimates of potential mineral sources ranging from 280 to 3600 m provide crucial information for future exploration efforts.
- Identification of linear trends suggests faults and fractures, which likely played a vital role in mineral emplacement and formation.
- Successful mapping of subsurface structures with contrasting magnetic susceptibilities through 3D inversion modelscorroborates other analytical results.
- Confirmation of known mineralization sites and identification of new prospective areas for further investigation.

The study demonstrates the power of integrating multiple magnetic data analysis techniques in mineral exploration, particularly in sedimentary basin environments. The results validate this approach's effectiveness and provide a solid foundation for future targeted exploration efforts in the Udi region. This research contributes significantly to understanding of the area's geological structures and mineral potential, offering valuable guidance for resource development in Nigeria. Further work, including ground-based geophysical surveys and drilling programs, is recommended to expand upon these findings. This study is a model for similar investigations in other sedimentary basins with potential mineral resources.

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