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ORIGINAL RESEARCH ARTICLE

Geophysical Investigation of the Subsurface Geological Structures at Alex Ekwueme Federal University Ndufu-Alike Ikwo (AE-FUNAI) in Southeastern Nigeria

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ABSTRACT

This research comprehensively investigates the subsurface geological structures at Alex Ekwueme Federal University Ndufu-Alike Ikwo (AE-FUNAI) in southeastern Nigeria. This area is located near regions where significant lead-zinc (Pb-Zn) mineralization and salts have been discovered. The geological setting of the region is complex, involving the intersection of the West African Craton, Benue Trough, and Anambra Basin, providing a unique opportunity to study various rock types and structural features. We applied integrated geophysical data processing methods of Analytic Signal (AS), Euler Deconvolution (ED), and 3D modelling of susceptibility contrast to delineate mineralized structures at the region. Subsurface intrusions of dyke-like structures at average depths of 25 – 125 m were identified and mapped. Major N-S and E-W trending fault systems were also delineated, which could serve as conduits for mineral-rich fluids. Generally, results indicate the presence of significant magnetic anomalies related to subsurface geologic intrusions with potential mineral deposits. Findings from this study will guide decision-making processes on siting building projects, future mineral exploration, and land-use planning in the study area.

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INTRODUCTION

Assessing structural integrity and geological hazards is crucial for ensuring safe and sustainable development practices, particularly in areas subject to mineral exploration and extraction activities. The existence of mineral-bearing structures within the subsurface can influence the stability of a region. Alex Ekwueme Federal University Ndufu-Alike Ikwo (AEFUNAI) campus may be sitting on clusters of mineral deposits and a vast accumulation of salt resources. This hypothesis is built on the premise that AEFUNAI is located in a region known to harbor sizable mineral deposits ranging from lead-zinc (Pb-Zn) to salts. Some of these deposits are mined locally and industrially (Abraham et al., 2023, 2018b; Obassi et al., 2015; Nwachukwu, 2004). Applying the magnetic geophysical method for these probes presents a detailed, cost-effective procedure for generating a picture of the subsurface at AEFUNAI. The method has long been recognized as a powerful geophysical tool for investigating subsurface geological structures, offering valuable insights into the composition, geometry, and tectonic evolution of Earth's crust (Usman et al., 2024; Abraham et al., 2024; Abraham et al., 2018b). The area of coverage by this study is located within geographic latitudes 6.11^o and 6.13^oN and geographic longitudes 8.13^o and 8.16^oE within the sedimentary terrain of southeastern Nigeria (Figure 1). Magnetic surveys have emerged as invaluable tools for regional geological investigations, particularly in areas characterized by complex geological settings and significant mineral potential (Ugodulunwa et al., 2021). This methodology has proven especially relevant in southeastern Nigeria, where diverse geological features and substantial mineral deposits present unique opportunities for geophysical exploration (Usman et al., 2024; C; Abraham et al., 2018b; Amigun et al., 2015). The Alex Ekwueme Federal University Ndufu-Alike (AE-FUNAI) region, situated within the lower Abakaliki Basin, exemplifies such geological complexity. The area is characterized by epigenetic fracture-controlled vein deposits, predominantly within gently dipping carbonaceous black shales. These mineral outcrops, exposed through road cuts, agricultural activities, mining

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operations, and fluvial channels, encompass approximately 54.56 km² (Bate et al., 2024; Abraham et al., 2023).

The geological framework comprises the Cretaceous sequence of the lower Benue Trough (Figure 1), consisting of minor intrusions, limestone, shale, and pyroclastics, classified under the Albian-age Asu River geological group (Rock et al., 2022; Ugodulunwa et al., 2021; Ekwe et al., 2020). Lead-zinc mineralization in the Abakaliki region, formed through hydrothermal processes at approximately 140°C, manifests in four primary lodes: Ishiagu, Enyigba, Ameri, and Ameka (Abraham et al., 2023). Evidence suggests that a significant portion of the Enyigba lode extends into the AE-FUNAI periphery (Ugodulunwa et al., 2021). The southeastern region of Nigeria, including the vicinity of AE-FUNAI, is characterized by complex geological formations associated with the West African Craton, Benue Trough, and Anambra Basin. The region's geological evolution has been influenced by tectonic processes, including rifting, sedimentation, and magmatism, resulting in diverse lithologies and structural features. Moreover, mineralized zones, such as lead-zinc deposits in the Abakaliki area and coal seams in the Afikpo Basin, underscore the economic importance of understanding the region's subsurface geology. The Nigeria-Benue trough took shape after a sequence of tectonic events and repeated sedimentation during the Cretaceous period. The separation of the continents led to the sudden formation of a rift (aulacogen) filled with transgressive and regressive sedimentary deposits (Ugwu and Alasi, 2016). The lower Benue trough is supported below by a thick sedimentary succession set down in the Cretaceous era. The Abakaliki Anticlinorium is characterized by four geological formations: the Nkporo Shale (Campanian), the Awgu Shale (Caniacian), the Asu River Group (Albian), and the Eze-Aku Shale (Turonian) (Figure 2). These sedimentary deposits were shaped by significant tectonic events occurring in two stages, resulting in the folding of the sediments. The Cenomanian and Santonian deformations substantially impacted the area (Ezema et al., 2014; Olade, 1975; Nwachukwu, 1972). Multiple intrusive bodies due to magmatism that affected the Eze-Aku and Asu River Group are found within the shale formation. The majority of these intrusions have been obscured by the shale formation, which constitutes the predominant superficial geology of the region. Intermediate intrusions are visible on the surface and are observable in certain areas of the study area, such as Abakaliki town. These intrusions manifest as sills (Ezema et al., 2014; Ofoegbu, 1985; Eze and Mamah, 1985). The Asu River Group is primarily composed of shale, with occasional occurrences of siltstone, limestone, sandstone, and intercalations.

Recent geological assessments have identified critical challenges in the region, including the formation of sinkholes and widespread structural damage to buildings. These phenomena are attributed to subsurface instability caused by the dissolution of mineral-bearing formations and subsequent cavity development (Chibuogwu et al., 2023). The combination of unauthorized mining activities and naturally occurring geological processes has heightened concerns about ground stability and regional structural integrity (Usman et al., 2023; Rock et al., 2017; Ako et al., 2014). This investigation aims to delineate subsurface structures within the AE-FUNAI vicinity, focusing on identifying mineral-bearing formations and potential geohazards. The research holds significant implications for infrastructure development and mineral resource management, contributing to our understanding of southeastern Nigeria's subsurface geological architecture.

Quantitative interpretation of potential field data involves analyzing parameters such as depth, horizontal positioning, source geometry, and variations in physical properties (Abraham et al., 2023; Aboud et al., 2023; Alqahtani et al., 2022; Essa and Abo-Ezz, 2021; Essa et al., 2021; Ganguli et al., 2021; Eshaghzadeh et al., 2020; Abraham and Alile, 2019; Aboud et al., 2018; Srivastava and Agarwal, 2010; Abdelrahman et al., 2003; Büyüksaraç et al., 2005). Numerous geophysical studies have been conducted in the vicinity of Abakaliki and surrounding areas. These investigations include the use of Vertical Electrical Sounding (VES) to evaluate aquifer characteristics (Ugwu and Alasi, 2016), determining the depth to magnetic sources near Abakaliki and estimating Curie Point Depth (CPD) (Abraham et al., 2018b), and using aeromagnetic data for hydrocarbon and mineral exploration prospects (Ugodulunwa et al., 2021; Ezema et al., 2014). Additionally, seismic refraction and VES techniques have been employed to examine the sedimentary sequence deposition in the region (Agha and Arua, 2014).

Recent advancements include the work by Abraham et al. (2024, and 2023), which applied magnetic inversion techniques to explore the spatial extent and geometry of magnetic structures and their role in mineralization processes in southeastern Nigeria. Their methodology incorporated 3D magnetic data inversion, Euler deconvolution, analytic signal analysis, Enhanced Local Wavenumber (ELW) technique, and Particle Swarm Optimization (PSO) to determine source characteristics. Their findings revealed magnetic bodies with susceptibilities exceeding 0.00188 SI, extending to depths of nearly 5.5 km and spanning approximately 18 km in the EW direction at the Ngbo–Ekerigwe area. However, no ground magnetic survey has been conducted in the entire region, which could have confirmed some potential areas and improved the resolution of identified anomalies. Given the vast expanse of southeastern Nigeria, more investigations are still needed in this direction. Inversion of magnetic survey data can offer restrictions on subsurface susceptibility allotments (Büyüksaraç et al., 2005; Lelievre, 2003).

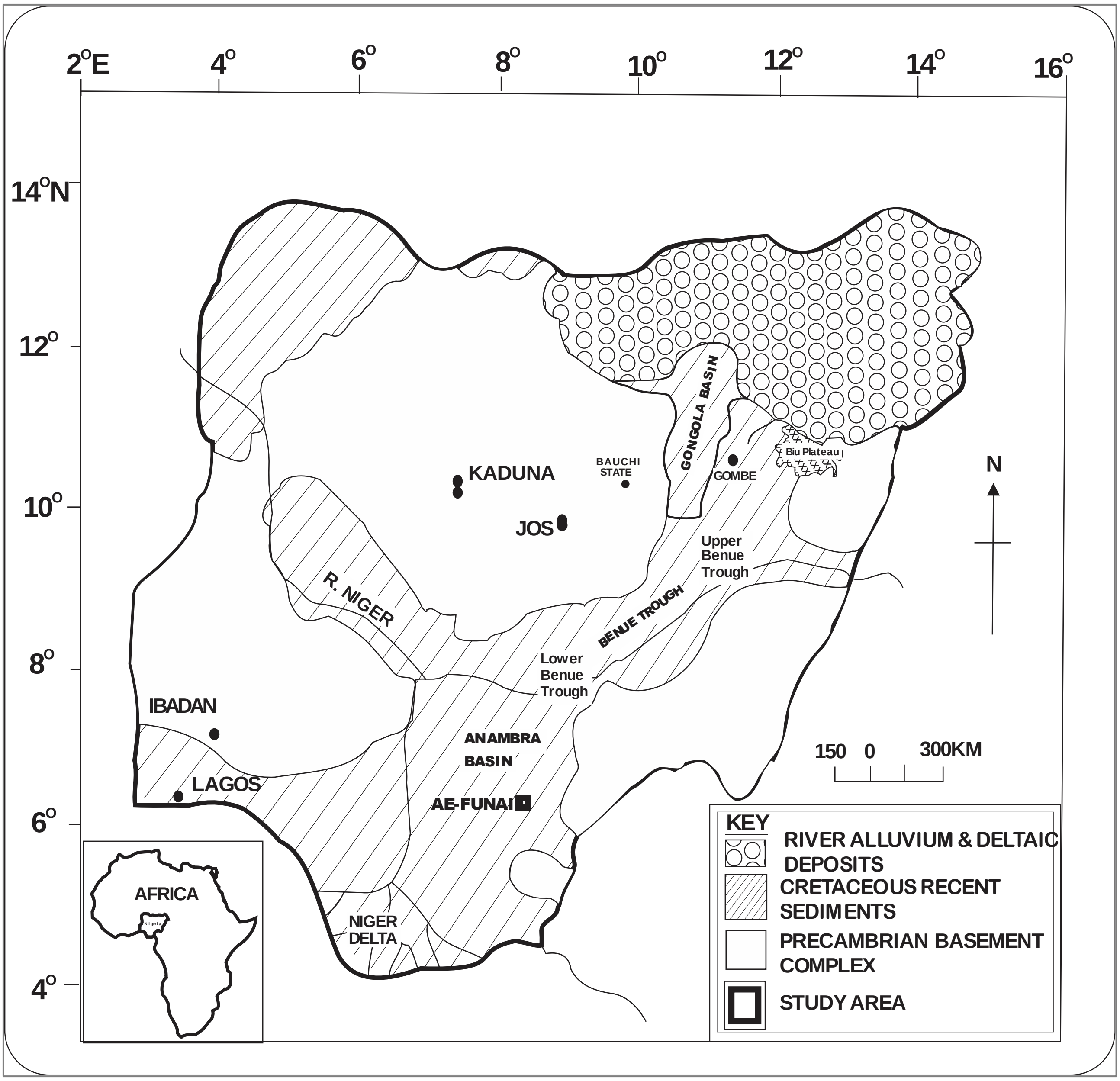


Figure 1. Map of Nigeria showing the general geology (modified from Abraham et al., 2018a). The location of the study is inserted.

The Abakaliki region is recognized as a highly mineralized zone, with substantial deposits of lead, zinc, sodium chloride, silver, and limestone, as reported in various studies (Abraham et al., 2018a; Ugwu and Alasi, 2016; Ezema et al., 2014). These resources are evidenced by the area's prevalence of local and small-scale mining activities. Magnetic susceptibility correlates directly with the concentration of magnetic minerals such as iron oxides, pyrrhotite, cobalt, nickel, and metallic iron is a key parameter in exploring economically valuable mineral deposits. Therefore, The magnetic survey data analysis can provide critical insights for identifying potential drilling locations (Lelievre, 2003). 2D and 3D inversion modeling have significantly contributed to the availability of robust datasets for mineral exploration (Büyüksaraç et al., 2005). Local magnetic anomalies and 3D voxel-based modeling techniques are now indispensable tools in modern exploration targeting (MacLeod and Ellis, 2013). Magnetic inversion delineates magnetic bodies rich in magnetite and other magnetic minerals and provides structural insights into mineralized zones (Couto et al., 2017). These techniques are instrumental in interpreting complex ore bodies, with magnetic data playing a crucial role in characterizing their geometry and distribution (Leâo-Santos et al., 2015).

MATERIALS AND METHODS

The magnetic method measures Earth's magnetic field variations caused by subsurface geological structures, including faults, fractures, igneous intrusions, and mineral deposits. These variations are influenced by the magnetic properties of the underlying rocks and minerals, providing indirect but valuable information about the subsurface geology. For this study, the master plan of AEFUNAI was obtained and reproduced into grids and sub-grids.

The realized sub-grids were assigned regions of approximately 1000 x 1000 m, which were used for various study phases. This research covers phase one as stipulated on the grid. The GPS and magnetic compass gadgets were utilized to locate the various grid points on the map to ensure comprehensive spatial coverage and data density. High-resolution geomagnetic data of the AEFUNAI region was collected using the ground-based Geometrics G-856AX portable proton precession magnetometer. Data was acquired using 100 m line spacing. The raw magnetic data underwent corrections for diurnal variations, cultural noise, and instrumental drift. Data were gridded to a uniform grid spacing of 18.5 m (Figure 2) to facilitate subsequent analysis. The International Geomagnetic Reference Field (IGRF) (2020 model) was subtracted from the data. The polynomial fitting technique was employed to separate the regional and residual components of the magnetic field. This separation allowed for removing long-wavelength variations associated with deep-seated geological structures, revealing shorter-wavelength anomalies indicative of near-surface geological features. Figure 3 shows the resulting residual magnetic field anomalies for the coverage region.

Analytic signal (AS):

The analytic signal (AS) processing technique was employed as it combines both amplitude and phase information from magnetic anomalies, facilitating the identification of subtle magnetic signatures associated with geological boundaries and lithological variations (Usman et al., 2024; Rajagopalan, 2003). The AS technique has proven especially valuable in complex geological terrains where traditional magnetic interpretation methods may be limited by interference effects and varying magnetization directions (Abraham et al., 2024; Nabighian et al., 2005). The interpretation of magnetic anomalies presents significant challenges due to the complex relationship between observed signals and their geological sources. Magnetic data interpretation is particularly complicated by horizontal displacements of anomalies relative to their sources (skewness), which occurs because geomagnetic field vectors and induced magnetization directions typically deviate from vertical orientations (Roest et al., 1992; Nabighian, 1972). The analytic signal (AS) function, although not a directly measurable physical property, plays a crucial role in geophysical interpretation due to its independence from both the magnetization direction and the inducing field orientation. This unique characteristic ensures that bodies of similar geometry produce identical analytic signal responses. Additionally, the AS peaks are symmetric and are positioned directly above the edges of broader bodies or over the centres of narrower ones, providing valuable spatial information about subsurface structures (Cooper and Cowan, 2006).

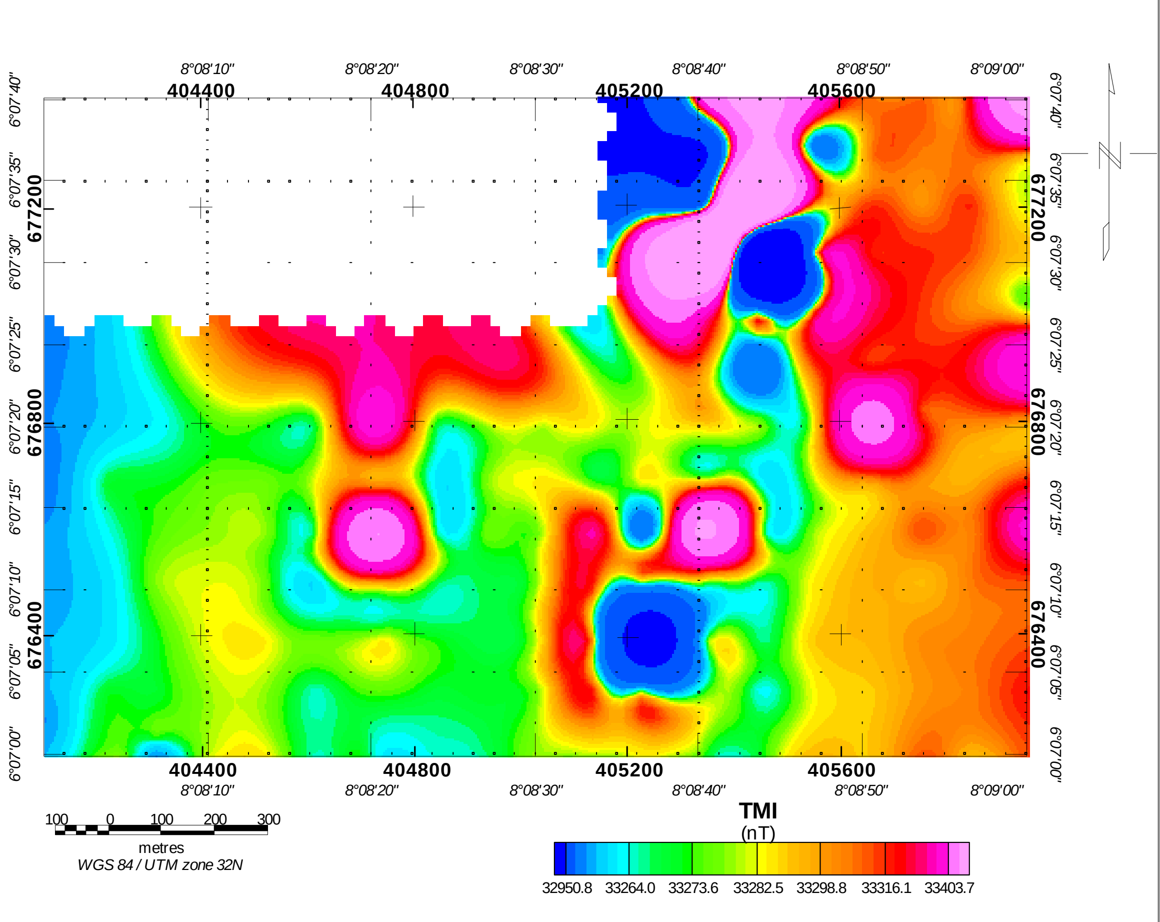


Figure 2. Total Magnetic Intensity field map. This shows the resulting gridded data acquired from the study area.

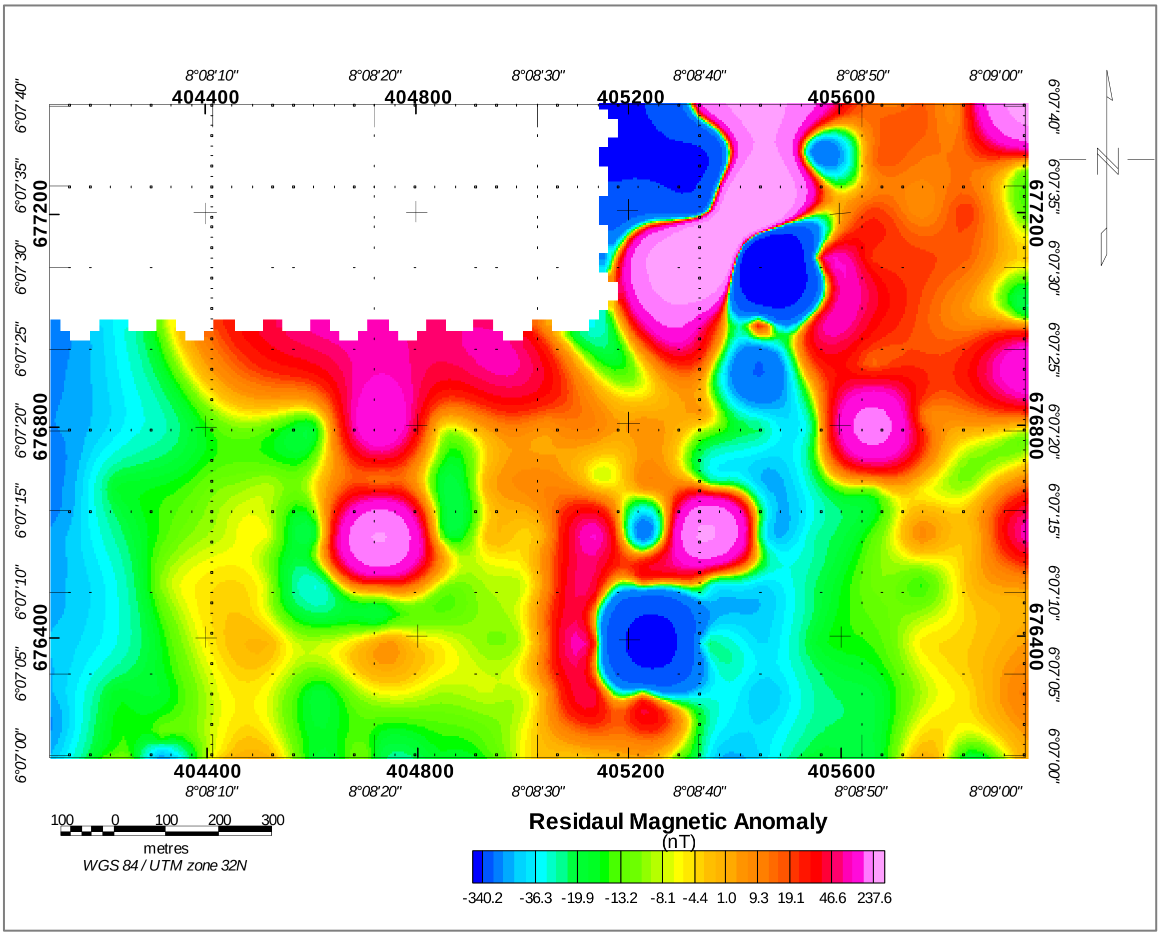


Figure 3. Residual Magnetic Anomaly Map. This plot is the resulting residual map after the regional-residual anomalies separation.

The Analytic Signal is given by Equation (1):

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

where T is the observed field at x and y.

Assuming the anomalies result from vertical contacts, the Analytic Signal (AS) can provide an estimate of source depth using a straightforward amplitude half-width approach, achieving depth accuracy of approximately 30%. This method circumvents challenges commonly associated with the traditional reduction-to-pole process for ∂T, particularly when the influence of natural remanent magnetization on source magnetization distribution is uncertain (Riedel, 2008). Figure 4 illustrates the calculation of AS, demonstrating how it facilitates the determination of source characteristics without requiring assumptions about the magnetization direction of the source body. Processing was realized with Geosoft software.

Euler Deconvolution: We applied Euler deconvolution techniques to analyze the residual magnetic field, facilitating depth estimation and spatial localization of magnetic sources. By examining the second vertical derivative signatures, this methodology revealed distinct magnetic features, including structural discontinuities, intrusive bodies, and mineralized structures.

The Standard 3D form of Euler's equation can be defined (Reid et al., 1990) as Equation (2):

$$x\frac{\partial T}{\partial x} + y\frac{\partial T}{\partial y} + z\frac{\partial T}{\partial z} + \eta T = x_o\frac{\partial T}{\partial x} + y_o\frac{\partial T}{\partial y} + z_o\frac{\partial T}{\partial z} + \eta b \qquad (2)$$

Where x, y, and z are the coordinates of a measuring point, x_0, y_0, and z_0 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 Structural Index (SI) is an exponential parameter that reflects how the magnetic field diminishes with distance based on the geometry of the source body. The specific value of the SI depends on the nature of the source being analyzed (Whitehead and Musselman, 2005). For example, an SI value of $\eta = 0$ indicates a geological contact, $\eta = 1$ corresponds to the top of a vertical dyke or the boundary of a sill, $\eta = 2$ represents the centre of a horizontal or vertical cylinder, and $\eta = 3$ is associated with the centre of a magnetic sphere or dipole (Thompson, 1982; Reid et al., 1990). The implementation of Euler deconvolution is depicted in Figure 5 (a and b) for structural indexes of 0 and 1.

3D Modeling of Susceptibility Contrast: We constructed three-dimensional (3D) geological models by integrating the processed magnetic data, enabling comprehensive spatial visualization of subsurface structures. The models incorporated analytic signalderived magnetic susceptibility contrasts, providing quantitative insights into magnetic properties and facilitating three-dimensional characterization of geological features for mineralization targeting and structural analysis. Three windows were taken on the four isolated anomaly structures in Figure 4. The 3D modeling results are displayed in Figure 6 (a, b, c) respectively.

RESULTS AND DISCUSSION

Analysis of the magnetic anomalies revealed significant subsurface structures and their potential implications for mineral exploration and geologic stability. Results from this study successfully delineate four distinct anomalous zones (locations A, B, C, and D) within the study area (Figure 4). These zones, characterized by varying magnetic intensities and structural depths, suggest the presence of mineralized geologic features, including intrusions and fault-controlled systems (Figure 5). The results provide critical insights into these structures' spatial distribution, geometry, and depth, which were further validated by comparative evaluations of depth solutions and 3D models (Figure 6). The discussion in this section presents a detailed interpretation of the identified anomalies, focusing on their geophysical signatures, potential geological implications, and relevance to mineral exploration and environmental considerations.

Initial assessment of the residual magnetic anomalies (Figure 3) reveals the presence of anomalous magnetic source bodies within the subsurface, mostly in the study area's central, northern and eastern regions. Positive anomalies ranging between 46-240 nT are observed in the north and central areas and could represent anomalous intrusions within the subsurface of the general shale geology. Negative anomalies (-4- -340 nT) could also be seen southwards, northwards, and westwards of the study area. While these could also represent a magnetic response of the shale geology in the region, the presence of other magnetic source bodies within the shale formation could cause the anomalies.

To confirm if the magnetic anomalies within the region were caused by crustal thinning or intrusions, we applied the analytic signal (AS) technique to the magnetic anomalies (Figure 4). Locations of the AS maxima determine the outlines of magnetic sources (Abraham et al., 2022; Obande et al., 2014; Roest et al., 1992).

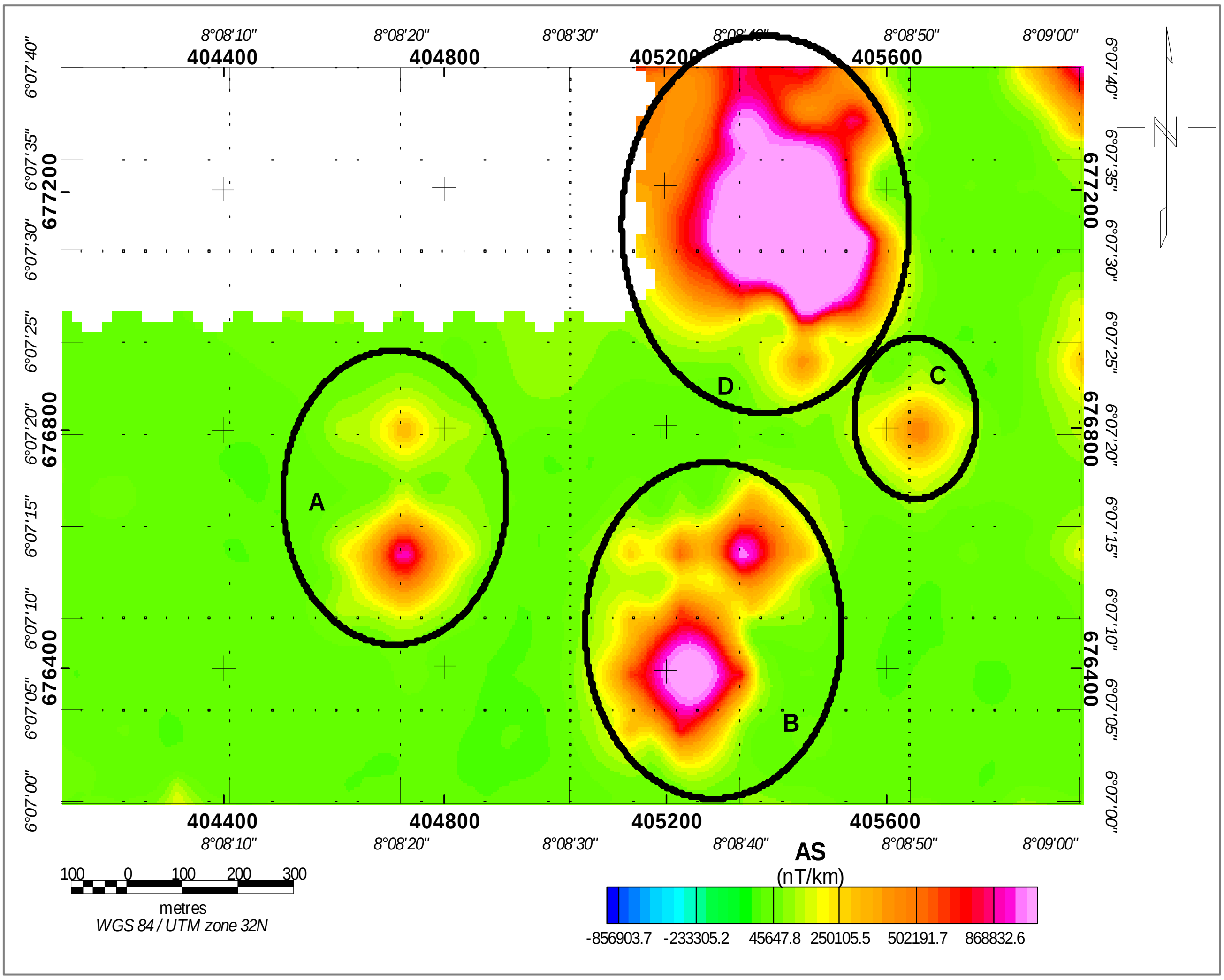


Figure 4. Result of Analytic Signal computations on the magnetic anomalies. Four isolated anomalous structures have been identified from the computations (circles A, B, C, and D).

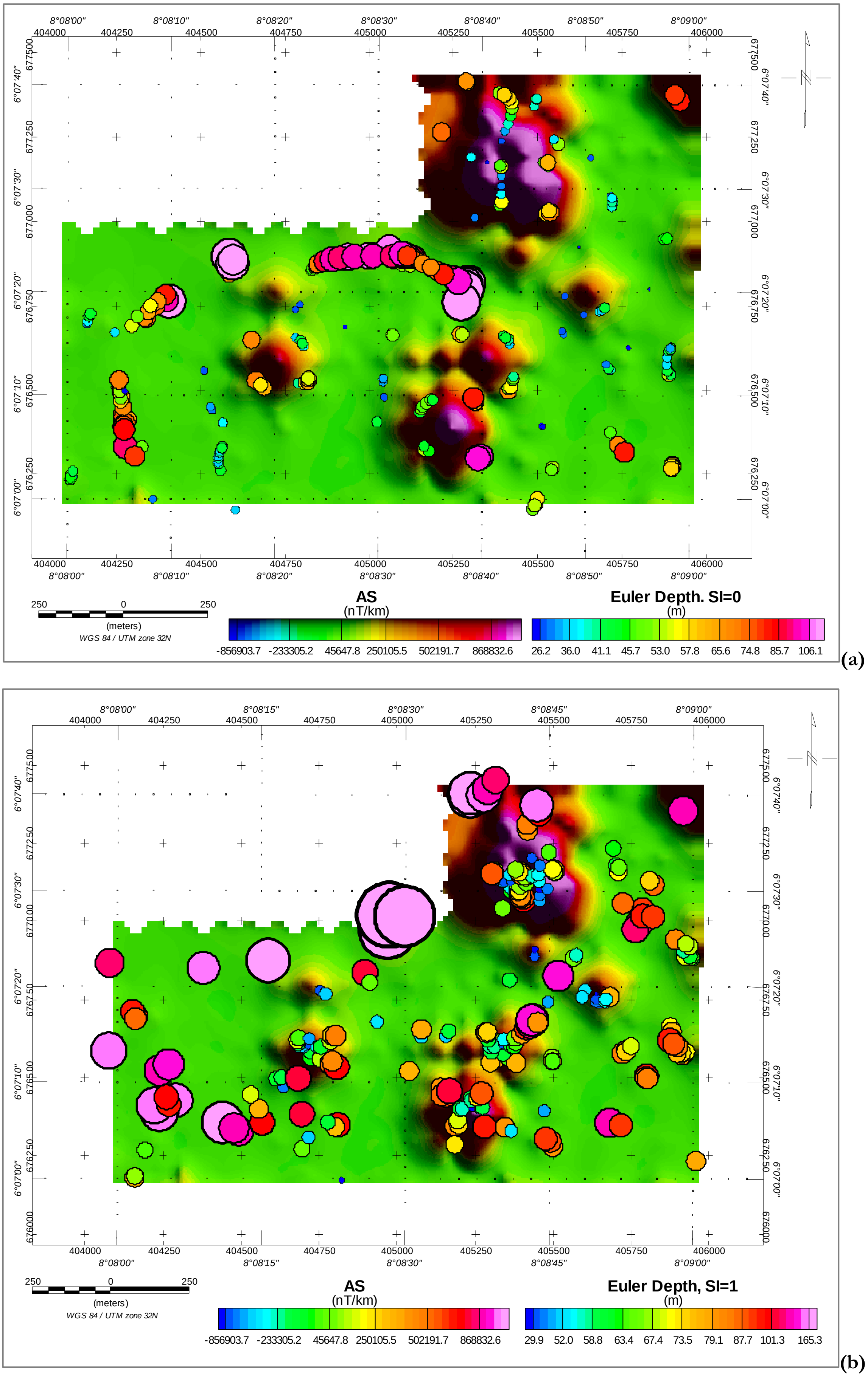
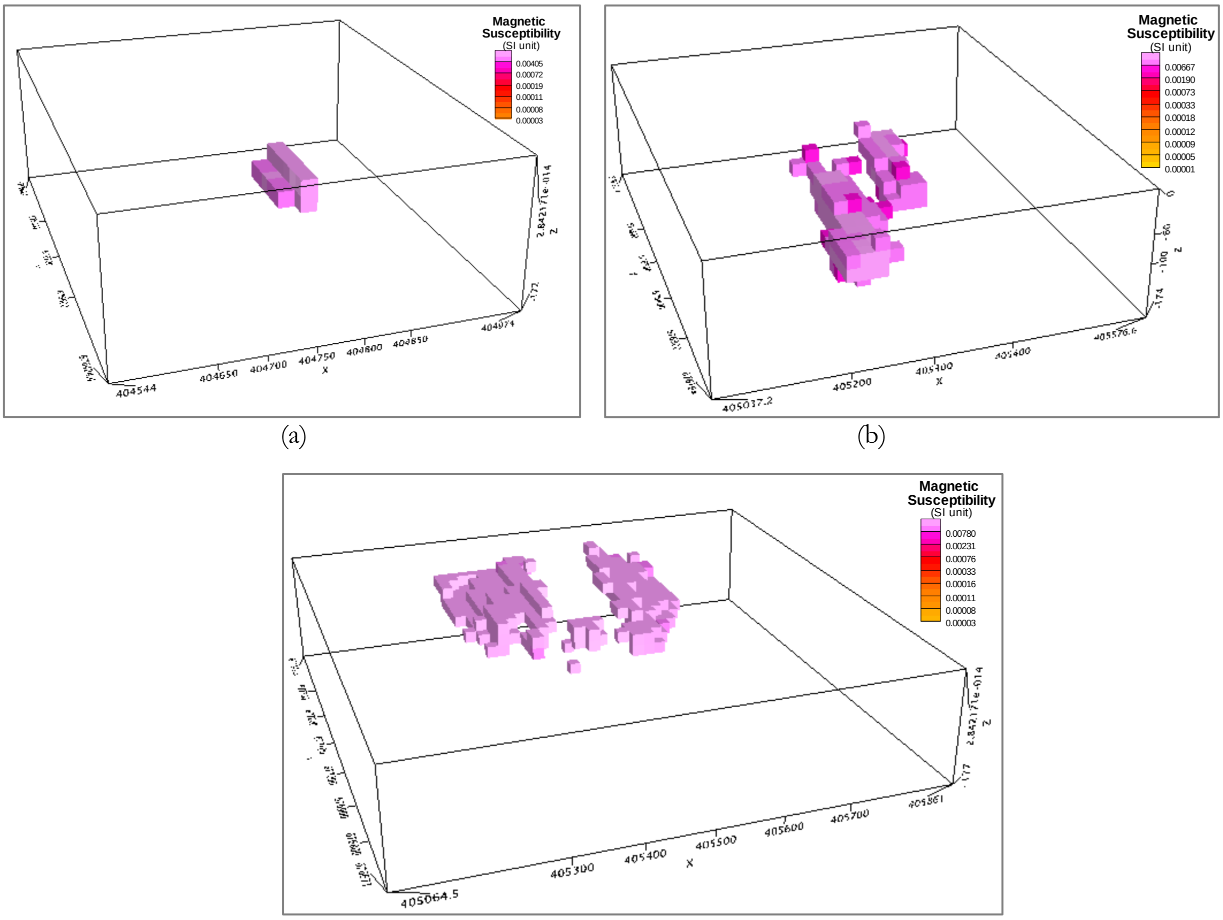


Figure 5. Euler depth solutions plotted on Analytic Signal map. (a) SI=0 for geologic contacts. (b) SI=1 for top of a vertical dyke or the edge of a sill investigation.



(a) (b)

(c)

Figure 6. 3D inversion result for computed windows. (a) Window A result obtained from clipping susceptibilities lower than 0.007 SI. (b) Window B result obtained from clipping susceptibilities lower than 0.006 SI. (c) Windows CD results obtained from clipping susceptibilities lower than 0.006 SI.

A distinct isolation of subsurface anomalous structure could be observed (A, B, C, D) with a high positive response rate >8600 nT/km. The isolated structures are considered mineralized geologic structures intruding on the subsurface at these locations. These contrasting geologic structures within the subsurface, as exposed from the AS computations, are significant for this study. Abraham et al. (2018a, 2022 and 2023) submitted that some of the locations within southeastern Nigeria had notable intrusions within the subsurface, which was responsible for most of the mineralization in the region. Structure D appears larger and could well be extensive within the subsurface. This structure and environment's location would be more stable than its counterparts in A and C. This is due to the larger diameter and extensive spread of the anomalous structure within the area. Our study has identified significant magnetic anomalies corresponding to intrusions, particularly at locations A, B, C, and D. However, while the previous works (Abraham et al., 2024, 2023; Ugodulunwa et al., 2021; Ekwe et al., 2020; Ugwu et al., 2016; Ezema et al., 2014; Eze and Mamah, 1985) reported mineralization primarily associated with granitic intrusions, this study suggests that the anomalies may also relate to fault-controlled structures within a shale-dominated geological setting. Structure D, for instance, is interpreted as a dyke or sill with a larger extent and higher mineralization potential than previously documented features (Nwachukwu, 2004; Nwachukwu, 1972) in similar settings. Consequently, we would advise possible sitting of building structures at location D against similar actions at locations A and C. Locations A and C may not be very stable or give way in the long run if the geologic structure within these locations is unstable or bear soluble minerals.

We computed the Euler deconvolution of the magnetic field to further examine these structures and estimate their possible depths. Figure 5 (structural index, SI = 0) shows a plot of Euler solutions superimposed on the AS map. Figure 5 (a) indicated that the identified subsurface anomalous structures were not principally affected by geologic contacts in the study area. A notable clustering of Euler solutions at the central region (E - W), having depths ranging from 85 – 110 m, is not directly connected to any identified structures and could represent a fracture. Similar trending Euler solution clusters (N – S (depths ranging 50 – 120 m), NE – SW (depths ranging 57 – 125 m)) could be seen in the western region, and a N – S trending (depths ranging 25 – 57 m) on the structure at location C (Figure 5 (a)). This structure could represent a geologic fault system at the location. This hypothesis is drawn from observation noticed on the 3D model computations on structure D location. Figure 5 (b) (SI =

1) shows direct agreement of the Euler solutions clustering on identified structures. Given the structural index chosen for Figure 5 (b), the alignment of Euler solutions confirms the presence of structures earlier identified. Structures at locations A, B, and C could be interpreted as dyke structures intruding the subsurface at this location. The structure at location D could represent a dyke or sill structure, depending on further investigations. The respective depths of the interpreted dyke structures indicate depths ranging from 25 – 120 m (structure A), 29 – 125 m (structure B), 25 – 75 m (structure C), and 25 – 100 m (structure D). The estimated depths of these structures promise possible mineral exploration, especially at locations A, B, and C at localized scale and structure at locations D and industrialized scale. Similar techniques applied in other parts of the world (Aboud et al., 2023; MacLeod and Ellis, 2013; Riedel, 2008; Roest et al., 1992) have revealed subsurface dykes and mineralized structures associated with tectonic activities. The clustering of Euler solutions observed in our study, particularly for structures at location D, mirrors findings from these works, which identified fault-controlled mineralization at comparable depths. However, the amplitudes and lateral extents of anomalies reported in this study, especially at structure D, exceed those typically documented in other geological studies, suggesting a unique mineralization environment.

A 3D evaluation of these structures (Figure 6) presents a possible nature of these anomalous structures within the subsurface. While a minimal structural ensemble is observed from the model result at location A, a significant subsurface structure is observed at locations B, C, and D. The possible N – S geologic fault trending (Figure 5 (a) structure D) is confirmed in the 3D model result. Further evaluation of identified locations is advised to enable possible mineral exploitation. We also advise caution or outright avoidance of establishing high-rising building structures or heavy constructional edifices at locations A and B as these locations could be unstable to bear such weights, or there may be a future need for immediate exploration and exploitation of the identified structures for minerals.

CONCLUSION

A successful geophysical assessment of the AE-FUNAI vicinity using a land-based magnetic survey method has been conducted. AE-FUNAI environs host compelling isolated subsurface geologic structures whose depths, locations, nature, and expanse have been estimated. This was achieved using residual magnetic anomaly analysis, the analytic signal (AS) technique, Euler deconvolution, and 3D modeling. The findings revealed significant magnetic anomalies, primarily in the central, northern, and eastern regions, indicative of subsurface intrusions and potential mineralized structures within the shale-dominated geology. Positive magnetic anomalies (46–240 nT) were observed in the northern and central regions, suggesting the presence of intrusions, while negative anomalies (-4 to -340 nT) in the southern, northern, and western regions may represent a combination of shale responses and magnetic source bodies. The AS analysis identified four key anomalous structures (A, B, C, and D) with high response rates (>8600 nT/km), interpreted as mineralized intrusions. Structure D, characterized by its extensive spread and larger diameter, is likely the most stable and suitable for industrial-scale mineral exploration. In contrast, structures A, B, and C, with depths ranging from 25 to 125 meters, are recommended for localized exploration. Euler deconvolution results confirmed these structures' depths and highlighted additional fault-controlled features, particularly a north-south trending fault associated with structure D. 3D modeling validated the geometry and extent of the identified anomalies, confirming the potential for significant mineralization at structures A, B, C, and D. While structure D appears to be the most promising target for large-scale exploitation, structures A and B are less stable and unsuitable for heavy construction, requiring further evaluation to mitigate risks of instability or future mineral extraction activities. While we recommend further investigations at identified sites, we advise caution in setting up heavy buildings or construction structures at these locations. Some of the identified structure locations could pose safety issues or conflicting economic interests in the near future.

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