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RESEARCH ARTICLE

INTEGRATING AEROMAGNETIC DATA FOR SUBSURFACE CHARACTERIZATION AND RESOURCE EXPLORATION IN THE ILESHA SCHIST BELT, NIGERIA

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ABSTRACT

This review presents a detailed examination of how the aeromagnetic method has been utilized in the Ilesha region of Southwestern Nigeria, which holds considerable geological and economic importance within the Ife-Ilesha Schist Belt. This technique has proved vital for understanding subsurface complexities, especially in mineral exploration such as gold, structural analysis, estimating depths, assessing groundwater potential, and identifying geohazards. Research shows prominent NE-SW structural trends associated with the Pan-African Orogeny, which are critical for the movement of fluids and the formation of minerals. The progression of studies reflects a shift from qualitative analysis to integrated multi-geophysical and remote sensing methods, improving accuracy in mapping and resource identification. The findings underscore the success of methods such as Euler deconvolution and analytical signal in revealing hidden structures and estimating the depths of magnetic sources, which can differ considerably across studies. Despite improvements, there are still gaps in comprehensive petrophysical analysis, understanding the evolution of structures over time, quantitative evaluations of groundwater, and studies on the environmental effects of mining. Future investigations should emphasize integrated 3D modeling, advanced inversion techniques, machine learning implementations, and systematic comparisons of methodologies to enhance geological models and promote sustainable resource management. This review is designed to be a foundational resource for comprehending the aeromagnetic method's significance and implications in this geologically critical area.

KEYWORDS

Aeromagnetic Method, Ilesha Area, Mineral Exploration, Structural Delineation, Pan-African Orogeny

1. INTRODUCTION

The Ilesha area, located within the crystalline basement complex of Southwestern Nigeria, is of notable geological and economic significance. It is part of the Ife-Ilesha Schist Belt, recognized for its abundant mineral resources, particularly gold, and its intricate structural designs shaped by multiple geological events, chiefly the Pan-African Orogeny (Rahaman, 1988; Ocan et al., 2016). Gaining a clear understanding of the subsurface geology in this complex region is essential for effective mineral exploration, groundwater resource management, and geohazard evaluations (Ojo and Akintorinwa, 2013). However, challenges arise from dense vegetation, thick overburden, and limited rock exposures, which often hinder direct geological mapping (Ajakaiye and Ajayi, 1981).

In this scenario, geophysical techniques, specifically the aeromagnetic method, have become crucial tools for unraveling the subsurface complexities of the Ilesha area (Adepelumi et al., 2008). Aeromagnetic surveys consist of measuring the Earth's magnetic field variations that stem from differences in the magnetic characteristics of the underlying rocks (Reeves, 2005). These measurements provide vital insights into the distribution of magnetic minerals, the structure of geological formations, and the depths to magnetic sources (Olade, 1975; Ojo and Akintorinwa, 2013). Due to its non-invasive approach, cost-effectiveness, and capacity for large-area coverage, aeromagnetic surveys are favoured for comprehensive geological investigations (Adepelumi et al., 2008; Reeves, 2005).

This review article seeks to deliver a thorough and organized perspective on the application of the aeromagnetic method in the Ilesha area, Southwestern Nigeria. It compiles findings from several peer-reviewed studies, highlighting the evolution of research themes, notable contributions, and the methodologies applied. The discussion will explore key themes, including structural delineation, mineral exploration, depth estimation, groundwater potential assessment, and geohazard evaluations (Ocan et al., 2016; Ojo and Akintorinwa, 2013). Additionally, it will analyze conflicting perspectives or ongoing debates within existing literature, pinpoint gaps in current research, and offer concrete recommendations for future studies. The aim is to provide a foundational resource for researchers and students, especially those working on thesis introductions related to the geophysics of the Ilesha area, ensuring a solid understanding of the aeromagnetic method's relevance and implications in this geologically important region.

2. GEOLOGICAL SETTING OF THE ILESHA AREA

The Ilesha area is within the Precambrian Basement Complex of Southwestern Nigeria, forming part of the broader West African Craton. The region's geology is primarily characterized by migmatite-gneiss complexes, metasediments, and metavolcanics, intruded by various granitoid formations (Oyinloye 1998; Ayodele 2015; Nuhu, 2023). This area constitutes the Ife-Ilesha Schist Belt, one of Nigeria's several north-south oriented schist belts, believed to be remnants of supracrustal rocks folded into the older migmatite-gneiss complex during the Pan-African Orogeny, which occurred approximately 600 ± 150 million years ago

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(Oyinloye 1098; Nuhu 2023). This orogeny produced intense folding, faulting, and metamorphism, giving rise to intricate structural patterns that influence the distribution of mineral resources (Adeoti and Okonkwo, 2016; Ayodele 2015).

The primary rock types found in the Ilesha area include gneisses, amphibolites, quartzites, schists (such as mica schist and talc schist), and pegmatites (Ayodele 2015; Bolarinwa and Adeleye, 2015). The schist belts carry significant gold deposits, typically linked to quartz veins and shear zones. The area's structural characteristics, including faults, fractures, and shear zones, are vital for controlling hydrothermal fluid migration and mineral localization. The dominant structural trend in the area is generally NE-SW, indicative of the Pan-African Orogeny’s influence, although E-W and N-S trends are also noted, often representing subsequent deformation or localized stress fields.

Understanding the intricate geological framework of the Ilesha area is essential for accurate aeromagnetic data interpretation, as magnetic susceptibility variations are directly linked to the distribution of rock types and their structural modifications. For example, mafic and ultramafic rocks (e.g., amphibolites) typically display higher magnetic susceptibilities than felsic lithologies such as granites and gneisses (Bolarinwa and Adeleye, 2015; Ohiom et al., 2019), while zones of intense fracturing or alteration may exhibit distinct magnetic anomalies due to the redistribution or depletion of magnetic minerals. This complex geological interplay highlights the utility of aeromagnetic methods in subsurface exploration, enabling the delineation of lithological contrasts, structural discontinuities, and potential mineralization zones within the study region.

3. Principles Of The Aeromagnetic Method

The aeromagnetic method is a passive geophysical technique that measures the variations in the Earth's magnetic field caused by the differing magnetic properties of subsurface rocks. These variations, referred to as magnetic anomalies, are generated by magnetometers towed by an aircraft, usually at a constant height above the ground. The core principle of this method is based on the fact that distinct rock types display different concentrations of magnetic minerals, predominantly magnetite, which affects their magnetic susceptibility. As a result, geological formations with varying magnetic susceptibilities result in measurable anomalies in the Earth's magnetic field (Burger et al., 2006; Nabighian, 1972).

3.1. Magnetic Properties of Rocks

The magnetic characteristics of rocks are determined by the presence and concentration of ferromagnetic minerals, with magnetite ($Fe3O4$) being the most prominent. Other magnetic minerals, such as maghemite, hematite, and pyrrhotite, make smaller contributions. The magnetic susceptibility of a rock indicates its capacity to become magnetized in an external magnetic field. Generally, igneous and metamorphic rocks that are rich in mafic minerals tend to have higher magnetic susceptibilities compared to sedimentary rocks. For instance, basalts and gabbros exhibit strong magnetic responses, whereas limestones and sandstones are typically weakly magnetic. Variations in magnetic susceptibility underground create anomalies that can be detected and mapped (Burger et al., 2006)

3.2. Data Acquisition and Processing

Gathering aeromagnetic data involves flying an aircraft fitted with a magnetometer over several parallel lines, usually organized in a grid layout, with tie-lines flown perpendicular to the primary survey lines for quality assurance and leveling purposes (Reid et al., 1990; Nabighian et al., 2005). The total magnetic intensity (TMI) data collected undergo several processing steps to isolate anomalies indicating subsurface geological variations. These steps typically include:

Diurnal Correction: To adjust for temporal fluctuations in the Earth's magnetic field caused by solar activity (Blakely, 1995).

International Geomagnetic Reference Field (IGRF) Removal: To remove the regional magnetic field, isolating only the residual anomalies from local geological sources (Maus et al., 2005).

Leveling: To account for variations in aircraft altitude and maintain consistency throughout observation lines (Reid et al., 1990).

Reduction to the Pole (RTP) or Equator (RTE): These procedures transform magnetic anomalies to represent how they would appear with a vertical (RTP) or horizontal (RTE) magnetic field, simplifying interpretation by placing anomalies directly above their sources, especially in areas like Nigeria with significant magnetic inclination (Nabighian and Hansen, 2001; Salem et al., 2012).

3.3 Interpretation Techniques

Interpreting aeromagnetic data can generally be divided into qualitative and quantitative methods:

- **Qualitative Interpretation**: This involves reviewing magnetic anomaly maps to detect patterns, trends, and features corresponding to geological structures. Linear anomalies may indicate faults, dykes, or lithological contacts, while circular or elliptical anomalies might suggest the presence of intrusive bodies or domes. The shape, amplitude, and gradient of anomalies can reveal information about the causative sources' characteristics and depths (Blakely, 1995; Salem et al., 2012).
- **Quantitative Interpretation**: This employs mathematical and computational techniques to extract specific data regarding subsurface sources. Common quantitative methods include:
  - **Analytical Signal**: This method yields anomaly maps that are unaffected by the Earth's magnetic field direction or the source's magnetization direction, making it effective for delineating magnetic source boundaries (Nabighian, 1972).
  - **Total Horizontal Derivative (THDR):** This highlights the horizontal gradients of magnetic anomalies, effectively marking the boundaries of magnetic bodies (Blakely, 1995).
  - **First Vertical Derivative (FVD):** This method enhances shallow features and refines anomalies, facilitating the identification of subtle geological structures (Reid et al., 1990).
  - **Euler Deconvolution**: A potent technique used to determine the depth and structural index of magnetic sources, particularly useful for defining geological contacts, faults, and intrusive structures (Reid et al., 1990; Thompson, 1982).
  - **Source Parameter Imaging (SPI):** This provides estimates of depth to magnetic sources through the analysis of the local wavenumber of the magnetic field (Salem et al., 2012).
  - **Radially Averaged Power Spectrum**: Utilized to estimate the average depths to magnetic sources, often distinguishing between shallow and deep sources (Spector & Grant, 1970).
  - **Peters' Half-Slope Method**: A graphical technique for estimating the depth to the top of a magnetic source by measuring the slope of the magnetic anomaly profile (Peters, 1949).

These interpretation techniques, when systematically applied, enable geophysicists to build detailed subsurface models, define geological structures, and pinpoint potential targets for further exploration. The progress of these methods, particularly with the emergence of advanced computational tools, has notably improved the precision and reliability of aeromagnetic interpretations in the complex geological environment of the Ilesha area (Salem et al., 2012; Ajakaiye and Burke, 1975).

4. Research Themes And Their Evolution In The Ilesha Area

The application of the aeromagnetic method in the Ilesha area has consistently revolved around several key research themes, each evolving in complexity and integration over time. These themes reflect the primary geological and economic questions pertinent to the region.

4.1. Structural Delineation and Tectonic Framework

Historically, structural delineation has been a fundamental aspect of aeromagnetic studies in the Ilesha area. Initial investigations largely focused on identifying significant linear features suggestive of faults, fractures, and lithological contacts through qualitative interpretations of magnetic anomaly maps. As data processing methods evolved, more sophisticated techniques, such as analytical signal, total horizontal derivative, and first vertical derivative, became standard for enhancing and delineating these structures (Akinlalu et al., 2018). The introduction of 3D Euler deconvolution further improved structural mapping by providing depth estimates for these features, facilitating a more thorough understanding of their subsurface geometry.

The findings show that research consistently indicates a dominant NE-SW structural trend, characteristic of the Pan-African Orogeny that shaped the regional geology (Odeyemi, 2006). These structures are significant as they often act as pathways for mineralizing fluids and govern the placement of various rock units. Some studies also recognize E-W and NNE-SSW trends, indicating secondary structural modifications or specific shear zones like the Ifewara shear zone (Elueze, 1988). The capacity to map these features, even when they are obscured, provides invaluable insights into Ilesha's tectonic history and crustal framework, contributing to a better understanding of geodynamic processes and potential geohazards such as earthquakes.

4.2 Mineral Exploration and Prospectivity Mapping

The Ilesha area, renowned for its gold mineralization, has seen extensive use of aeromagnetic surveys in mineral exploration, initially focusing on identifying magnetic highs or lows associated with known mineral occurrences or host rocks (Elueze, 1986). Over time, the methodology has evolved to integrate aeromagnetic data with complementary geophysical datasets, such as electrical resistivity and radiometric data, enhancing the development of more accurate mineral prospectivity maps (Olaleye et al., 2022). Further advancements include the application of sophisticated modeling techniques like Multi-Criteria Decision Analysis (MCDA) and the SWARA model, which incorporate diverse geological and geophysical parameters to systematically classify regions into zones of varying mineralization potential (Faruwa et al., 2021).

Aeromagnetic data has proven highly effective in delineating magnetic anomalies associated with mineralized zones, host rocks (e.g., granitoids), and structural controls on mineralization, with studies consistently identifying lineament density, lithology, and hydrothermal alterations as critical factors influencing gold mineralization, particularly emphasizing the importance of NE-SW trending structures in facilitating fluid movement (Carranza and Hale, 2002; Holden et al., 2008). The integration of aeromagnetic data with radiometric and remote sensing datasets significantly enhances the identification of hydrothermally altered zones, which are key indicators of gold mineralization (Abdelkareem et al., 2020; Eldosouky et al., 2021). Validation efforts using known mining sites and geochemical analyses have demonstrated the robustness of these prospectivity models, with high success rates in predicting high-potential gold exploration targets (Nyabeze et al., 2017; Osinowo et al., 2018), thereby reinforcing the reliability of aeromagnetic methods in mineral exploration.

4.3 Depth Estimation of Magnetic Sources

Estimating the depth to magnetic sources and basement topography is critical for understanding the Ilesha area's subsurface architecture. However, the widespread use of Euler deconvolution and spectral analysis has considerably enhanced the accuracy and dependability of depth estimates, thereby revealing the thermal structures and geothermal potential (Adegbuyi and Abimbola, 1997). These techniques are capable of determining the depths to the top of magnetic sources, including the crystalline basement and various geological interfaces, thus offering a three-dimensional perspective on the subsurface.

Recent research employs advanced methods like source parameter imaging (SPI) and 3D Euler deconvolution to estimate depths ranging from 0.3 to 5.48 km, indicating both shallow and deep magnetic sources (Reid et al., 1990; Ozebo et al., 2015). These advancements have improved the resolution of basement topography models (Thompson, 1982; Reid et al., 1990). Observations from studies in the Ilesha area describe a range of depths to magnetic sources, reflecting the varying depths of geological features (Oladapo et al., 2013). For example, depths to sources located within shear zones have been estimated between 90 m and 200 m, while overall magnetic source depths can range from as shallow as 12.6 m to as deep as 600 m for geological contacts (Oladapo et al., 2013). These depth variations are influenced by the specific geological features studied and the resolution of the data (Reid et al., 1990). The consistent application of these methods has resulted in a clearer representation of subsurface geometry, aiding in the identification of shallow, accessible mineral targets and mapping deeper basement structures (Ozebo et al., 2015; Thompson, 1982).

4.4 Groundwater Potential Assessment

Although often not the primary focus, aeromagnetic data have increasingly been acknowledged for their indirect contributions to groundwater exploration. The evolution in this area involves connecting magnetic patterns to features that control groundwater movement, such as fractured zones and weathered basement. Recent studies underscore the importance of integrating aeromagnetic results with direct electrical methods to validate groundwater potential (Okpoli and Akinbulejo, 2022). Additionally, spectral analysis of aeromagnetic data has identified Curie point depths (e.g., 15.1 km at Ikogosi Warm Spring), suggesting geothermal potential linked to radioactive heat production (Ademeso et al., 2014).

Findings show that Aeromagnetic surveys can efficiently outline structural discontinuities like faults and fractures, which often serve as key channels and reservoirs for groundwater. The NE-SW trending lineaments associated with the Pan-African Orogeny have been suggested to correlate with areas of high-yield groundwater aquifers. However, it is consistently recommended that these findings be confirmed and further explored through electrical methods to determine the exact groundwater potential and the stability of the underlying basement.

5. Case Studies

This study while primarily a ground magnetic survey, provides fundamental insights into magnetic data interpretation applicable to aeromagnetic studies (Kayode et al., 2013). The research focused on the eastern part of Ilesa town, aiming to delineate subsurface geological structures for mineral potential. They employed a proton precision geometric magnetometer to record total field magnetic data along fifteen traverses. Qualitative and quantitative interpretations were performed. Key findings include residual magnetic values ranging from 80 nT to -330 nT. The Peters half-slope method was used to estimate the maximum depth to the basement at approximately 160 m. The analytical signal was utilized to estimate the lateral extent of interpreted lithologies. The study concluded that the generated results were effective in delineating geological structures and identifying areas with mineral potential and further highlights the utility of magnetic methods in mapping subsurface features and estimating depths, which are directly applicable to aeromagnetic data analysis (Kayode et al., 2013).

The researcher specifically focused on the interpretation of high-resolution airborne magnetic data (HRAMD) of Ilesha and its environs (Olurin et al., 2017). The study area, delimited by geographic latitudes 7°30′-8°00′N and longitudes 4°30′-5°00′E, falls within the basement complex of Southwestern Nigeria. The digitized airborne magnetic data, acquired in 2009, were obtained from the Nigerian Geological Survey Agency (NGSA). The research applied Euler deconvolution on filtered and enhanced magnetic data to delineate geological structures and estimate depths (Olurin, 2017). The total magnetic intensity distribution ranged from -77.7 nT to 60.9 nT. The residual magnetic intensity map revealed distinct magnetic highs and lows, indicating variations in magnetic susceptibilities. A significant finding was that the depths to magnetic sources, determined by Euler deconvolution, varied from 12.6 m to 110.7 m. The study also identified predominant structural trends in the NE-SW and NW-SE directions, consistent with the regional Pan-African orogeny. The study further emphasized the effectiveness of HRAMD and Euler deconvolution in mapping complex geological structures for mineral exploration.

The analysis provided new insights into the Ife-Ilesha schist belt by integrating satellite, aeromagnetic, and radiometric data (Salawu et al., 2021). The objective was to evaluate structural features and identify potential economic mineral zones. They enhanced Shuttle Radar Topographic Mission (SRTM) digital elevation data using hill-shading and superimposed total gradient amplitude lineaments on a 3-D Euler deconvolution map. The study revealed major structural trends including NE–SW, NNE–SSW, E–W, and minor N–S directions, with the Ifewara shear zone trending NNE–SSW. Depths to the top of sources within the shear zone were estimated to vary from 90 m to 200 m. Complementary analysis of airborne radiometric data showed that the Ifewara shear zone and adjacent areas are characterized by radiometric anomalies, indicating regional mineralization alteration zones. The study concluded that there is a strong correlation between the satellite, radiometric, and aeromagnetic maps, providing valuable insights and re-evaluation of structural features relevant to gold mineralization.

investigated the mode of occurrence of mineral deposits in Iperindo and its environs, all in the Ilesha area, using integrated geophysical techniques, including magnetic and electrical methods (Olomo et al., 2021). For the magnetic data, the total magnetic intensity map was enhanced using reduction to the equator, magnetic susceptibility, and analytic signal filters to suppress noise and accentuate magnetic bodies. 3-D Euler deconvolution and radial spectral analysis were applied to locate and estimate the depth to magnetic anomalous bodies, which were suspected to host mineral deposits. The study found that magnetic deposits have varying depths from 20 m to 300 m. Delineated magnetic anomalies predominantly trend in the northeast–southwest direction, implying geological structures formed during the Pan-African orogeny, which are often impregnated with mineralized bodies. The integration with electrical resistivity and induced polarization data further highlighted areas with disseminated mineral deposits within fault/fracture zones.

The analysis focused on assessing the mineralization potential in part of the Ilesha Schist belt using a multi-criteria decision analysis (MCDA) approach within the analytical hierarchy process (Akinlalu et al., 2021). They identified three key parameters from aeromagnetic, electrical resistivity, and geological data that favor gold mineralization: lineament density, lithology, and electrically derived coefficient of anisotropy. Data enhancement techniques, including total horizontal derivative, 3-D Euler deconvolution, and source edge detection, were applied to aeromagnetic data to produce a lineament map. The aeromagnetic results showed predominantly NE-SW trending structures, characteristic of the Pan-African orogenic events, with some E-W trending lineaments indicating secondary alteration. Euler deconvolution solutions estimated geological contacts at depths of 94-600 m. The study successfully developed a reliable mineralisation potential model (MPM) with high validation success rates, confirming the importance of integrated geophysical and geological parameters for gold exploration.

Th study interpreted the aeromagnetic dataset of Ilesha, southwestern Nigeria, with a dual objective: to reveal possible future earthquake hazards and establish groundwater potential (Olafisoye et al., 2022). They applied various edge detection methods, including analytical signal amplitude, total horizontal derivative, first vertical derivative, and 3D Euler deconvolution, to residual magnetic intensity anomalies to identify linear structural discontinuities. Upward continuation filtering and depth estimation procedures (Source Parameter Imaging and radially averaged power spectrum) were also used to map geological structures and determine the depth to crystalline basement rocks. The study found that lineaments predominantly trend NE-SW, indicative of the Pan-African Orogeny, and suggested these areas as possible high-yield groundwater aquifer zones. Deep-lying faults extending beyond 2 km were identified. 3D Euler deconvolution and spectral analysis revealed magnetic source depths ranging from 55 m to 345 m and 13 m to 250 m, respectively. The delineated structural discontinuities showed a stress history similar to the Ifewara-Zungeru fault network, suggesting potential future earthquake occurrences.

The study employed the stepwise weight assessment ratio analysis (SWARA) model for gold prospectivity mapping in parts of the Ilesa Schist belt (Akinlalu et al., 2024). They utilized aeromagnetic, aero-radiometric, and ASTER (remote sensing) datasets. Data enhancement techniques were applied to aeromagnetic data to produce lineament maps, and analyses of radiometric and ASTER data delineated hydrothermally altered zones. The study identified lithology, lineament density, hydrothermal alteration, and slope as key factors influencing gold mineralization, with hydrothermal alteration being the most important. They confirmed that NE-SW trending structures facilitate the transportation of hydrothermal and mineralizing fluids, and gold mineralization is primarily associated with granitoids. The produced gold mineralization map classified the study area into five potential zones, with high to very high potential in the southern, western, and northwestern axes. Qualitative and quantitative validations showed high success rates (73 % and 74 % respectively), substantiating the model's reliability (Akinlalu et al., 2024). These studies collectively demonstrate the versatility and increasing sophistication of the aeromagnetic method in understanding the complex geology and resource potential of the Ilesha area. They highlight a clear trend towards integrated approaches, advanced data processing, and quantitative modeling to address various geological and economic questions.

The researcher Other important studies include who integrated aeromagnetic and vertical electrical sounding data to assess groundwater potential around Ijano, identifying fractured zones with NE-SW trends as favorable for groundwater exploration (Okpoli and Akinbulejo, 2022). To study combined aeromagnetic and radiometric data to map mesothermal alteration zones in the western Ilesha Schist Belt, finding that potassium-enriched zones correlate with gold deposits, as validated by existing mining pits (Olaleye et al., 2022). Applied geostatistical methods (variogram and kriging) to aeromagnetic data, demonstrating that kriging enhances the delineation of magnetic anomalies for mineral exploration, particularly in distinguishing zones of strong and weak gold mineralization (Olowofela et al., 2024). The investigated the petrology and gold mineralization of the Ilesha Schist Belt, using aeromagnetic data to link gold mineralization with NE-SW trending shear zones and magnetic anomalies associated with amphibolite belts (Elueze, 1986). Estimated Curie point depths in the Ikogosi Warm Spring area using aeromagnetic data, reporting an average depth of 15.1 km and attributing geothermal potential to radioactive heat production from thorium-bearing quartzite (Adegbuyi and Abimbola, 1997). That analyzed the Ifewara Fault Zone's relationship with regional fracture systems through aeromagnetic profiles, concluding that the fault zone serves as a major structural control influencing both mineralization and seismic activity (Odeyemi, 2006).

6. Conflicting Viewpoints Or Ongoing Debates

While the body of researchers on the aeromagnetic method in the Ilesha area generally converges on several key understandings, certain aspects present subtle differences, varying interpretations, or areas that warrant further discussion and potential debate. These points often arise from the inherent complexities of geophysical data interpretation, the use of diverse methodologies, and the multifaceted nature of the geological setting.

6.1 Variability in Depth Estimates

One of the most notable areas of variation among studies is the reported range of depths to magnetic sources and geological contacts. The analysis reported depths to magnetic sources ranging from 12.6 m to 110.7 m using Euler deconvolution (Olurin, 2017). That research found magnetic source depths ranging from 13 m to 345 m (from spectral analysis) and 55 m to 345 m (from D Euler deconvolution) (Olafisoye et al., 2022). To study estimated depths to magnetic anomalous bodies between 20 m and 300 m (Olomo et al., 2021). Estimated fracture depths of 6–38 m using Euler deconvolution, while reported deeper sources (0.478–5.48 km) using horizontal gradient and local wavenumber methods (Okpoli et al., 2021; Olowofela et al., 2024). That study reported estimated depths of geological contacts ranging from 94 m to 600 m using Euler deconvolution solutions (Akinlalu et al., 2021). This variability, while seemingly disparate, can be attributed to several factors. Firstly, different studies may be targeting different types of magnetic sources (e.g., shallow mineralization, deep basement structures, or specific lithological contacts), each with its characteristic depth range. Secondly, the resolution of the aeromagnetic data (e.g., flight height, line spacing) can significantly influence the detectability and accurate depth estimation of sources. Higher resolution data might resolve shallower, more subtle features, while lower resolution data might only capture deeper, larger anomalies. Thirdly, the specific interpretation algorithms and their parameters (e.g., structural index in Euler deconvolution) can yield different results. Finally, the inherent assumptions of each depth estimation technique play a role; for example, spectral analysis provides average depths over a broader area, while Euler deconvolution provides point-by-point estimates. A direct comparative study systematically applying various depth estimation techniques to the same high-resolution dataset, coupled with ground-truthing (e.g., borehole data), could help reconcile these differences and provide a more unified understanding of the subsurface depth architecture.

6.2 Relative Importance and Interplay of Structural Trends

There is a consensus that NE-SW trending structures are dominant in the Ilesha area, reflecting the pervasive influence of the Pan-African Orogeny (Salawu et al., 2021; Olomo et al., 2021; Akinlalu et al., 2021; Olafisoye et al., 2022; Akinlalu et al., 2024; Akinlalu et al., 2018). However, the emphasis and interpretation of other structural trends sometimes vary: noted the presence of E-W trending lineaments as imprints of secondary structural alteration, distinct from the dominant NE-SW trends (Akinlalu et al., 2021). The study highlighted NNE-SSW trends, particularly associated with the Ifewara shear zone, alongside NE-SW and E-W trends (Salawu et al., 2021). The analysis identified NW-SE trends as characteristic of the Pan-African orogeny (Faruwa et al., 2021; Olurin, 2017).

It is not necessarily about the existence of these trends but rather their relative importance in controlling geological processes, particularly mineralization. Further research could involve detailed structural analysis combining aeromagnetic data with field mapping and microstructural studies to understand the kinematics and timing of these different structural sets and their precise role in fluid flow and mineral deposition. This would help to resolve whether these are truly conflicting viewpoints or simply different levels of detail and focus in interpretation.

6.3 Integration of Methods vs. Single-method Aeromagnetic Interpretation

The increasing integration of aeromagnetic data with other geophysical methods (e.g., electrical resistivity, radiometrics) and remote sensing datasets reflects a paradigm shift toward more comprehensive subsurface evaluations (Salawu et al., 2021; Olomo et al., 2021; Akinlalu et al., 2021, 2024). While aeromagnetic surveys provide valuable structural and lithological insights, their limitations in characterizing certain geological features, such as conductive mineralization or fluid-bearing structures, necessitate complementary approaches. For example, identified groundwater potential zones using aeromagnetics but emphasized the need for electrical resistivity verification, while demonstrated ERT's superior capability in delineating gold-associated sulfide mineralization, underscoring the method-dependent nature of target detection Olafisoye et al., 2022; Osinowo et al., 2020). This highlights the importance of tailored, multi-method strategies over reliance on any single dataset.

Future studies should quantitatively evaluate the diagnostic improvements offered by combined methods compared to aeromagnetic-only interpretations, particularly in complex terrains like the Ilesha Schist Belt. Such analyses would provide empirical guidelines for balancing geological resolution with cost-effectiveness, addressing a critical gap in exploration geophysics. The challenge remains in developing standardized frameworks to assess when multi-method approaches are justified versus when aeromagnetics alone may suffice, ensuring both scientific rigor and economic viability in resource exploration.

7. Detailed Petrophysical Characterization Of Rock Units

While studies interpret magnetic anomalies based on inferred lithologies and structures, there is a general lack of detailed petrophysical characterization of the various rock units in the Ilesha area. Understanding the precise magnetic susceptibility, density, and other physical properties of different rock types (e.g., gneisses, schists, granitoids, mineralized zones) through laboratory measurements on representative rock samples is crucial. Such data would significantly improve the accuracy and confidence of quantitative interpretations of aeromagnetic data, allowing for more precise lithological mapping and differentiation of magnetic sources. Without robust petrophysical constraints, interpretations often rely on generalized assumptions, which can introduce ambiguities.

7.1 Temporal Evolution of Structural Features and Mineralization

Most aeromagnetic studies in the Ilesha area focus on delineating the current structural framework and its relationship to mineralization. However, there is a gap in research that investigates the temporal evolution of these structures and their influence on geological processes over different geological epochs. Understanding the sequence of deformational events, the timing of fluid flow, and the episodic nature of mineralization in relation to the development of specific structural features would provide a deeper, four-dimensional understanding of the region's geodynamic history. This could involve integrating aeromagnetic interpretations with geochronological data and detailed structural geology studies.

7.2 Quantitative Assessment of Groundwater Potential

While aeromagnetic data have been used to identify structural features that may host groundwater a significant gap exists in the quantitative assessment of groundwater potential. Current studies primarily focus on delineating potential zones based on structural controls. However, for effective groundwater resource management, it is crucial to quantify aquifer parameters such as transmissivity, storage coefficient, and hydraulic conductivity (Olafisoye et al., 2022). This would require integrating aeromagnetic interpretations with direct hydrogeological investigations, including pumping tests, borehole logging, and more extensive electrical resistivity or electromagnetic surveys specifically designed for hydrogeological characterization. Developing integrated geophysical and hydrogeological models would provide a more robust framework for sustainable groundwater exploitation.

7.3 Environmental Impact Assessment of Mining Activities

The Ilesha area has a long history of mining, including significant artisanal and small-scale mining activities (Adekiya et al., 2024). Despite this, there is a notable gap in studies that integrate aeromagnetic data with environmental geophysics to assess the impact of these mining activities on the subsurface and groundwater systems (Abubakar et al., 2024). Aeromagnetic data, combined with other geophysical methods, could be used to map subsurface disturbances, delineate contaminant plumes (if associated with magnetic minerals or their alteration products), and monitor changes in groundwater levels or quality. Such research is vital for addressing environmental concerns, land degradation, and public health issues associated with mining.

7.4 Application of More Advanced 3D Inversion Techniques

While Euler deconvolution and spectral analysis are widely applied for depth estimation and structural interpretation, the literature shows limited application of more advanced 3D inversion techniques to aeromagnetic data in the Ilesha area. Full 3D inversion can provide more accurate and detailed subsurface models, especially in areas with complex geological structures and overlapping anomalies (Li and Oldenburg, 1998; Farquharson and Oldenburg, 2004). These techniques can resolve ambiguities inherent in 2D or simpler 3D methods by simultaneously fitting the observed magnetic field to a 3D distribution of magnetic susceptibility (Kwan and Fedi, 2003). Implementing such advanced techniques could lead to a more precise understanding of the geometry and distribution of magnetic sources, improving targeting for exploration (Thurston and Smith, 1997; MacLeod et al., 1993).

8. Suggestions For Future Research

Building upon the identified gaps in the current literature, the following suggestions outline promising avenues for future research utilizing the aeromagnetic method in the Ilesha area, Southwestern Nigeria. These recommendations aim to enhance the precision, comprehensiveness, and practical applicability of geophysical investigations in the region.

8.1 Integrated 3D Geological and Geophysical Modeling

Future research should prioritize the development of 3D geological and geophysical models of the Ilesha area. This involves integrating high-resolution aeromagnetic data with other complementary datasets, such as:

Seismic Data: While challenging in basement terrains, targeted seismic reflection or refraction surveys could provide high-resolution structural information, especially on deeper crustal features and fault geometries, which can constrain aeromagnetic interpretations.

Electrical Resistivity and Electromagnetic (EM) Data: As highlighted electrical methods are crucial for delineating conductive features associated with mineralization (e.g., sulfides, graphite) and groundwater by (Osinowo et al., 2020; Olomo et al., 2021). Integrating these with aeromagnetic data in a 3D modeling environment would provide a more complete picture of subsurface conductivity and magnetic susceptibility distributions.

Borehole and Well Data: Existing and future borehole logs, core samples, and well completion reports provide invaluable ground-truth information on lithology, alteration, and fluid presence. Incorporating these into 3D models would significantly reduce ambiguity in geophysical interpretations.

Geological Mapping and Remote Sensing: Detailed geological maps, structural measurements, and advanced remote sensing products (e.g., hyperspectral data for alteration mapping) should be integrated to provide surface constraints and validate subsurface models. The study demonstrates the power of such integration (Salawu et al., 2021; Akinlalu et al., 2024).

Such integrated 3D models would allow for more accurate characterization of subsurface structures, precise targeting for mineral and groundwater resources, and a better understanding of the overall geological framework.

8.2 Environmental Geophysics and Mining Impact Assessment

Given the prevalence of mining activities in the Ilesha area, future research should focus on the environmental applications of aeromagnetic and integrated geophysical methods:

Mapping Subsurface Contamination: Investigate the use of aeromagnetic data, possibly in conjunction with electrical resistivity or electromagnetic methods, to map subsurface contamination plumes associated with mining activities, especially if these plumes contain or react with magnetic minerals.

Assessing Ground Stability: Utilize geophysical methods to assess ground stability in areas affected by mining, identifying potential subsidence zones or unstable ground conditions.

Groundwater Monitoring: Implement time-lapse geophysical surveys to monitor changes in groundwater levels and quality in response to mining operations, providing crucial data for environmental management and remediation efforts.

9. Conclusion

The aeromagnetic method has become indispensable in deciphering the geological framework and resource potential of the Ilesha area, Southwestern Nigeria. This review consolidates findings from multiple peer-reviewed studies, highlighting the method's efficacy in mapping subsurface structures such as faults, shear zones, and mineralized corridors, particularly for gold exploration, despite challenges posed by dense vegetation and thick overburden. Beyond structural delineation, aeromagnetic surveys have enabled depth-to-source estimations, groundwater prospectivity assessments, and preliminary geohazard evaluations, offering a foundational understanding of the region's subsurface architecture. Recent research in Ilesha reflects a transition from qualitative interpretations to advanced quantitative analyses and integrated multi-geophysical approaches, as demonstrated by studies combining aeromagnetic, radiometric, and remote sensing data. Despite progress, gaps persist in petrophysical characterization, structural evolution, and environmental impact studies related to mining. Future efforts should prioritize 3D modeling, machine learning-enhanced interpretations, and environmental geophysics to refine resource targeting and promote sustainable exploration practices in this geologically complex region.

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