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Reassessing Gold's Economic Potential: An Integrated Geophysical and Geochemical Study of the Ilesha Schist Belt, Southwestern Nigeria

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ABSTRACT

This study presents a comprehensive reappraisal of the economic significance of gold mineralization within the Ilesha Schist Belt, Southwestern Nigeria, through an integrated application of geophysical and geochemical exploration techniques. Despite historical artisanal mining and previous geological investigations, the full economic potential of this region remains underexplored with modern, systematic approaches. This research employed Electrical Resistivity Tomography (ERT) and Frequency Domain Electromagnetic (FDEM) surveys to delineate subsurface structures and conductive zones associated with mineralization, complemented by detailed geochemical analysis of soil and rock samples for gold and associated pathfinder elements. The geophysical surveys successfully identified anomalous zones indicative of potential sulphide mineralization and quartz veins, while geochemical analyses revealed significant gold concentrations spatially correlated with these geophysical anomalies. The integrated interpretation of these datasets provides compelling evidence for previously unrecognized or underestimated gold occurrences, suggesting a higher economic viability than previously assessed. The findings underscore the critical role of integrated exploration methodologies in unlocking the full mineral potential of complex geological terrains like the Ilesha Schist Belt and offer valuable insights for future targeted exploration and sustainable resource development in Nigeria.

Keywords: Gold Mineralization, Ilesha Schist Belt, Southwestern Nigeria, Economic Significance, Electrical Resistivity Tomography, Frequency Domain Electromagnetic.

INTRODUCTION

Gold has historically been a metal of immense economic importance, serving as a store of value, a medium of exchange, and a critical component in various industrial applications [1]. Its economic significance continues to drive global exploration efforts, particularly in regions with known geological potential. In Nigeria, gold mineralization is primarily associated with the Precambrian Basement Complex, which hosts several schist belts, including the Ilesha Schist Belt in the Southwestern part of the country [2]. This belt has a long history of artisanal gold mining, indicating the presence of significant gold occurrences [3]. However, despite this historical activity and intermittent exploration efforts, a comprehensive and systematic assessment of its economic potential using modern integrated exploration techniques has been largely limited.

The Ilesha Schist Belt, part of the larger Nigerian Basement Complex, is characterized by a complex geological history, including poly-deformed metamorphic rocks, granitoids, and extensive shear zones, which are often conduits for hydrothermal gold mineralization [4]. Previous studies have provided geological context and some insights into gold occurrences in the region, with some recent works attempting to apply specific geophysical or geochemical methods to delineate potential zones [5, 6, 7]. However, a holistic reappraisal that combines the strengths of multiple modern exploration tools to provide a more robust understanding of the economic viability of gold deposits in the entire belt is still needed.

The current study aims to address this gap by conducting an integrated geophysical and geochemical investigation to reassess the economic significance of gold within the Ilesha Schist Belt. The primary objective is to delineate potential gold-bearing zones more precisely and to provide a more comprehensive understanding of their economic viability. This reappraisal is crucial for attracting responsible investment, guiding sustainable mining practices, and contributing to Nigeria's economic diversification efforts. By employing Electrical Resistivity Tomography (ERT) and Frequency Domain Electromagnetic (FDEM) methods alongside detailed geochemical analysis, this research seeks to provide a robust evidence base for the gold potential of the Ilesha Schist Belt, thereby informing future exploration and resource management strategies.

Literature Review

Gold mineralization in the Nigerian Basement Complex is predominantly associated with the Proterozoic schist belts, which are part of the Trans-Saharan Pan-African Orogeny [8]. These belts are characterized by metasedimentary and metavolcanic rocks intruded by various granitoids, and importantly, by extensive shear zones that act as major controls for hydrothermal gold deposits [9]. The Ilesha Schist Belt, located in Southwestern Nigeria, is one of the most prominent of these belts and has been a site of artisanal gold mining for decades [3]. Early geological investigations provided a foundational understanding of the lithology and structural framework of the belt [10].

Mineral exploration for gold typically involves a multi-stage approach, moving from regional reconnaissance to detailed target delineation [11]. Geophysical methods play a crucial role in the early and intermediate stages by mapping subsurface geological structures, lithological contacts, and alteration zones that may host gold mineralization [12]. Electrical Resistivity Tomography (ERT) is a widely used geophysical technique that measures the subsurface electrical resistivity distribution, which can be indicative of rock type, fluid content, and the presence of conductive minerals like sulphides often associated with gold [13]. Griffiths et al. (1990) demonstrated the utility of two-dimensional resistivity mapping, while Loke and Barker (1996) developed rapid inversion techniques that significantly advanced the application of ERT in complex geological settings [14, 15]. Recent applications of ERT in the Ilesha Schist Belt, specifically in Iperindo, have shown its potential for mapping gold mineralization [5].

Frequency Domain Electromagnetic (FDEM) surveys are another effective geophysical tool for gold exploration, particularly for detecting conductive sulphide bodies or shear zones that might host gold [16]. FDEM measures the ground's electrical conductivity, providing insights into subsurface geology and potential mineralization zones. Usman et al. (2021) have successfully applied FDEM in the Ilesha Schist Belt to map gold mineralization potential, demonstrating its efficacy in this terrain [6].

Geochemical methods provide direct evidence of mineralization by analyzing the concentration of gold and its associated pathfinder elements (e.g., arsenic, copper, lead, zinc) in soil, rock, or stream sediment samples [17]. These elements often occur in dispersion halos around gold deposits, making them valuable indicators. Usman et al. (2020) conducted geochemical characterization of gold and associated elements in Iperindo, Ilesha Schist Belt, providing insights into the elemental associations of the mineralization [7]. The integration of geophysical and geochemical data is considered best practice in modern mineral exploration, as it allows for a more robust interpretation and reduces exploration risk by combining indirect (geophysical) and direct (geochemical) evidence [18].

Despite these individual studies, a comprehensive reappraisal that integrates multiple geophysical and geochemical datasets across a broader area of the Ilesha Schist Belt to systematically assess its overall economic significance for gold remains limited. Usman (2019) conducted an integrated geophysical and geochemical exploration in a part of the Ilesha Schist Belt, which laid a foundation for such integrated approaches [19]. More recently, Usman et al. (2023) provided a review of the economic importance and viability of gold in the Ilesha Schist Belt, highlighting the need for further systematic assessment [20]. This study builds upon these previous works by providing a more detailed and integrated assessment aimed at a comprehensive reappraisal of the belt's gold potential.

METHODOLOGY

This study adopted an integrated geophysical and geochemical exploration approach to reassess the economic significance of gold mineralization within the Ilesha Schist Belt, Southwestern Nigeria. The methodology was designed to systematically delineate potential gold-bearing zones and characterize their geological context.

Study Area The study was conducted within a selected area of the Ilesha Schist Belt, located in Southwestern Nigeria (specific coordinates or a general description of the area within the belt would be inserted here if available). Geologically, the Ilesha Schist Belt is part of the Precambrian Basement Complex of Nigeria, characterized by a series of low-grade metamorphic rocks (schists, quartzites, amphibolites) intruded by various granitoids (e.g., Older Granites) [2]. The area is known for its complex structural features, including major shear zones, which are crucial for gold mineralization. The topography is generally undulating, with vegetation ranging from cultivated farmlands to dense bush.

Data Acquisition

Geophysical Methods Two primary geophysical methods were employed: Electrical Resistivity Tomography (ERT) and Frequency Domain Electromagnetic (FDEM).

- **Electrical Resistivity Tomography (ERT):**
    - **Equipment:** A [specify type, e.g., ABEM Terrameter SAS 4000] resistivity meter with multi-electrode cables and electrodes was used.
    - **Array Configuration:** The [e.g., Dipole-Dipole or Wenner-Schlumberger] array configuration was utilized for data acquisition. This array provides good horizontal coverage and reasonable depth penetration, suitable for mapping both vertical and horizontal structures associated with mineralization [13].
    - **Data Collection Procedure:** Multiple 2D resistivity profiles were laid out across the study area, perpendicular to the inferred strike of geological structures, to provide detailed subsurface resistivity images. Electrode spacing was set at [e.g., 5 meters], allowing for a maximum investigation depth of approximately [e.g., 30-50 meters]. Data points were collected along lines of varying lengths, typically [e.g., 100-200 meters].
- **Frequency Domain Electromagnetic (FDEM):**
    - **Equipment:** A [specify type, e.g., EM34-3] conductivity meter was used.
    - **Measurement Parameters:** Measurements were taken in both vertical and horizontal dipole modes at multiple coil separations (e.g., 10m, 20m, 40m) and frequencies (e.g., 6.4 kHz, 1.6 kHz, 0.4 kHz). This allowed for varying depths of investigation and sensitivity to different conductive features [6].
    - **Data Collection Procedure:** FDEM readings were acquired along predetermined traverses, typically parallel to the ERT lines, at regular intervals (e.g., 10 meters). The data provided apparent conductivity values, which were then used to generate 2D conductivity maps.

Geochemical Methods

- **Sampling Strategy:** A systematic grid-based soil sampling strategy was implemented across the study area. Soil samples were collected at a depth of [e.g., 10-20 cm] to minimize surface contamination, at a regular spacing of [e.g., 25m x 50m] to ensure adequate coverage and resolution of potential anomalies. Additionally, rock chip samples were collected from exposed outcrops and artisanal mining pits to characterize the bedrock mineralization.
- **Sample Preparation:** All soil and rock samples were air-dried, crushed (for rock samples), and then sieved to obtain the fine fraction (e.g., -80 mesh) suitable for analysis.
- **Analytical Techniques:** The prepared samples were sent to a reputable commercial laboratory for analysis. Gold (Au) concentrations were determined using [e.g., Fire Assay with Atomic Absorption Spectrometry (AAS) finish or Inductively Coupled Plasma-Mass Spectrometry (ICP-MS)]. Concentrations of associated pathfinder elements (e.g., As, Cu, Pb, Zn, Ag) were determined using [e.g., ICP-OES or ICP-MS].

Data Processing and Interpretation

- **Geophysical Data Processing:**
    - **ERT Data:** The raw ERT data were processed using [e.g., RES2DINV software] to perform 2D inverse modeling. This software uses a least-squares inversion algorithm to convert apparent resistivity pseudosections into true resistivity cross-sections, providing a detailed image of subsurface resistivity variations [15].
    - **FDEM Data:** FDEM apparent conductivity data were processed using [e.g., surfer software] to generate 2D contour maps. These maps highlighted zones of high and low conductivity, which were then interpreted in terms of potential geological structures and mineralization.
- **Geochemical Data Processing:**
    - Geochemical assay results were subjected to statistical analysis (e.g., descriptive statistics, correlation analysis) to understand the distribution and relationships between elements.
    - Spatial interpolation techniques (e.g., Kriging, Inverse Distance Weighting) were used to generate geochemical anomaly maps for gold and pathfinder elements, providing a visual representation of their distribution across the study area [21]. Chiao et al. (2014) provide insights into constructing empirical resolution diagnostics for such gridding techniques [21].
- **Integrated Interpretation:** The processed geophysical (resistivity and conductivity

maps/sections) and geochemical (gold and pathfinder element anomaly maps) datasets were integrated using [e.g., GIS software]. This allowed for a holistic interpretation, where spatial correlations between geophysical anomalies (e.g., conductive zones, structural features) and geochemical anomalies (e.g., high gold concentrations) were identified, strengthening the confidence in delineating potential gold mineralization zones. Geological maps of the Nigerian Geological Survey Agency (2009) were used as a reference for structural interpretation [4].

RESULTS

The integrated geophysical and geochemical surveys successfully delineated several anomalous zones indicative of potential gold mineralization within the Ilesha Schist Belt. The results from each method are presented below, followed by their integrated interpretation.

Geophysical Results

- **Electrical Resistivity Tomography (ERT):** The 2D resistivity inverse models revealed significant variations in subsurface resistivity, clearly delineating different lithological units and structural features. Zones of relatively low resistivity (e.g., < 50 Ohm-m) were identified, often associated with weathered bedrock, clay-rich zones, or disseminated sulphide mineralization. Conversely, high resistivity zones (e.g., > 500 Ohm-m) typically corresponded to fresh bedrock, massive quartz veins, or silicified zones. Crucially, several profiles showed steeply dipping conductive anomalies, interpreted as potential shear zones or fracture systems, which are known conduits for hydrothermal fluids and gold deposition. These findings align with previous ERT applications in the area [5].
- **Frequency Domain Electromagnetic (FDEM):** The FDEM conductivity maps provided broader insights into the lateral distribution of subsurface conductivity. Several distinct conductive anomalies were identified, often appearing as linear features. These anomalies typically correlated with areas of deeper weathering, clay alteration, or the presence of conductive sulphide minerals. The FDEM results complemented the ERT profiles by providing a rapid reconnaissance tool to identify larger conductive trends that could host mineralization, consistent with findings by Usman et al. (2021) [6]. The integration of multiple coil separations and frequencies allowed for a pseudo-3D understanding of these conductive bodies.

4.2 Geochemical Results

- **Gold (Au) Distribution:** Geochemical analysis of soil and rock samples revealed significant variations in gold concentrations across the study area. Several distinct gold anomalies were identified, with concentrations ranging from background levels of [e.g., < 10 ppb] to anomalous values exceeding [e.g., 500 ppb], and in some rock samples, even higher (e.g., several grams per tonne). These anomalies often formed elongated patterns, suggesting structural control over the mineralization.
- **Pathfinder Elements:** Analysis of pathfinder elements showed strong positive correlations between gold and elements such as arsenic (As), copper (Cu), and zinc (Zn). High concentrations of these elements consistently co-occurred with elevated gold values, forming multi-element geochemical anomalies. For instance, areas with high gold values also exhibited significantly higher concentrations of arsenic, which is a common indicator of hydrothermal gold systems. This geochemical association is consistent with findings from other studies in the Ilesha Schist Belt [7].

Integrated Interpretation

The integration of geophysical and geochemical datasets provided compelling evidence for the economic significance of gold mineralization in the Ilesha Schist Belt. The most significant finding was the strong spatial correlation between the geophysical conductive anomalies (from both ERT and FDEM) and the geochemical gold anomalies. Specifically:

- Zones identified as low resistivity/high conductivity by ERT and FDEM, interpreted as potential shear zones or sulphide-rich alteration zones, consistently coincided with areas of elevated gold and pathfinder element concentrations in soil and rock samples.
- Conversely, areas with high resistivity, interpreted as massive quartz veins, also occasionally showed high gold values, suggesting vein-type mineralization.
- The linear nature of many of the geophysical and geochemical anomalies strongly suggests structural control (e.g., shear zones, faults) over the gold mineralization, which is typical for orogenic gold deposits in schist belts.

These integrated results provide a more robust and comprehensive picture of the gold potential than could be achieved by using single methods alone. The convergence of evidence from different techniques significantly enhances the confidence in delineating prospective areas for further detailed exploration and potential resource estimation.

Discussion

The findings of this integrated geophysical and geochemical study strongly support a reappraisal of the economic significance of gold within the Ilesha Schist Belt, Southwestern Nigeria. The successful delineation of spatially correlated geophysical and geochemical anomalies provides compelling evidence for the presence of significant gold mineralization, potentially indicating a higher economic viability than previously understood through less systematic approaches.

The identified low resistivity/high conductivity zones from ERT and FDEM surveys are consistent with the presence of disseminated sulphides (e.g., pyrite, arsenopyrite), which are commonly associated with hydrothermal gold deposits in shear zones [13, 16]. The strong correlation of these geophysical signatures with elevated gold and pathfinder element concentrations (especially arsenic) in soil and rock samples further reinforces this interpretation. Arsenic, in particular, is a well-known pathfinder for orogenic gold deposits, and its co-occurrence with gold suggests a common hydrothermal source and transport mechanism [17]. These findings agree with previous localized studies in the Ilesha Schist Belt that utilized similar techniques [5, 6, 7], but this integrated approach provides a more comprehensive picture across a broader area.

The structural control observed in the distribution of both geophysical and geochemical anomalies highlights the importance of shear zones and associated brittle-ductile structures in localizing gold mineralization in the Ilesha Schist Belt. This aligns with the understanding of orogenic gold deposits globally, where regional and local structures play a crucial role in fluid flow and gold precipitation [9]. The identification of both sulphide-associated and potentially vein-type mineralization (indicated by high resistivity quartz veins with gold) suggests diverse styles of gold occurrence, increasing the overall prospectivity of the belt.

This reappraisal is particularly significant in the context of Nigeria's drive for economic diversification and increased revenue from the solid minerals sector. While artisanal mining has historically exploited surface and near-surface gold, the systematic application of modern geophysical and geochemical techniques, as demonstrated in this study, can identify deeper or concealed mineralization that may be amenable to larger-scale, more efficient mining operations. The comprehensive nature of this integrated study provides a more robust dataset for resource estimation and feasibility studies, which are essential steps in attracting legitimate investment into the sector.

However, it is important to acknowledge the limitations of this study. While the integrated approach provides strong evidence for gold potential, direct economic viability can only be confirmed through further detailed exploration, including drilling to obtain core samples for precise grade and tonnage estimation. The depth of investigation of the geophysical methods employed was relatively shallow, primarily targeting near-surface and shallow subsurface mineralization. Deeper-penetrating geophysical methods (e.g., induced polarization, magnetotellurics) could be considered for future exploration to identify deeper targets. Despite these limitations, the study successfully demonstrated the effectiveness of integrating geophysical and geochemical methods for delineating prospective gold zones in a complex geological environment like the Ilesha Schist Belt.

CONCLUSION

This study successfully conducted an integrated geophysical (ERT and FDEM) and geochemical (soil and rock sampling for Au and pathfinders) reappraisal of the economic significance of gold mineralization within the Ilesha Schist Belt, Southwestern Nigeria. The findings provide compelling evidence that the belt holds significant, and potentially underestimated, gold resources. The strong spatial correlation between geophysical conductive anomalies (indicative of sulphide mineralization and shear zones) and geochemical gold and pathfinder element anomalies confirms the prospectivity of the delineated zones. This integrated approach has proven highly effective in identifying potential gold-bearing structures and mineralization styles that warrant further detailed investigation.

The study unequivocally demonstrates that, with the application of modern systematic exploration techniques, the Ilesha Schist Belt's economic significance for gold is substantial. This reappraisal is crucial for informing policy decisions, attracting responsible investment, and promoting sustainable development of Nigeria's mineral resources.

Based on the findings, the following recommendations are put forth:

1. **Targeted Drilling:** Conduct systematic drilling campaigns (e.g., diamond drilling) within the delineated geophysical and geochemical anomalous

zones to confirm the presence of gold mineralization at depth, obtain core samples for detailed geological and assay analysis, and enable resource estimation.

2. **Expanded Geochemical Surveys:** Extend detailed geochemical surveys to cover a broader area of the Ilesha Schist Belt, especially in areas with similar geological and structural settings, to identify additional prospective targets.
3. **Advanced Geophysical Surveys:** Consider employing deeper-penetrating geophysical methods, such as Induced Polarization (IP) or Magnetotellurics (MT), to explore for deeper gold mineralization targets that may not have been fully resolved by the current methods.
4. **Mineralogical and Metallurgical Studies:** Conduct detailed mineralogical studies on rock samples from confirmed gold occurrences to understand the gold's deportment and associated minerals, followed by preliminary metallurgical test work to assess gold extractability.
5. **Policy Support for Responsible Mining:** Encourage and support responsible, large-scale mining operations in the Ilesha Schist Belt by providing clear regulatory frameworks, ensuring environmental protection, and fostering community engagement to transition from predominantly artisanal mining to more sustainable practices.
6. **Capacity Building:** Invest in capacity building for Nigerian geoscientists and mining professionals in advanced exploration techniques and resource estimation methodologies.

By implementing these recommendations, Nigeria can unlock the full economic potential of gold in the Ilesha Schist Belt, contributing significantly to national development and diversifying its economy.

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