

Advanced Integration of Aeromagnetic, Radiometric, and Multispectral Remote Sensing Data for Structural Characterization, Hydrothermal Alteration Mapping, and Mineral Prospectivity Modeling of Lithium–Cesium–Tantalum Pegmatites and Orogenic Gold in the Borgu Basement Terrain, Northwestern Nigeria

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Abstract

This study employs an integrated geospatial and geophysical framework to assess the mineral prospectivity of the Borgu Area, Niger State, northwestern Nigeria, with particular emphasis on rare-metal pegmatites (lithium, beryl, and tourmaline) and orogenic gold systems. The study area is situated within the Nigerian Basement Complex of the Pan-African Mobile Belt and is predominantly underlain by granitic gneiss. Interpretation of aeromagnetic datasets reveals a well-defined NE–SW structural fabric characterized by faults, fractures, and lithological boundaries, which are interpreted as key controls on fluid migration and mineral emplacement. The Total Magnetic Intensity response is dominated by low-amplitude anomalies, indicative of magnetite-depleted felsic lithologies typically associated with Lithium–Cesium–Tantalum (LCT) pegmatite systems. Source Parameter Imaging further constrains the depth to magnetic sources to approximately 120–180 m, suggesting relatively shallow subsurface conditions favorable for exploration. Radiometric analysis delineates zones enriched in potassium and thorium, reflecting highly evolved granitic systems with potential for rare-metal mineralization. Complementary remote sensing analysis based on Landsat imagery identifies diagnostic hydrothermal alteration signatures, including iron oxide staining, clay mineral development, and silica enrichment. The integration of geophysical, radiometric, and spectral datasets within a GIS-based analytical framework enabled the systematic delineation of ten high-priority exploration targets. The combined results highlight the strong influence of lithological composition, structural architecture, and hydrothermal processes on mineralization within the Borgu basement terrain. These findings underscore the exploration potential of the area and provide a robust basis for subsequent field validation, including detailed geological mapping, geochemical surveys, and targeted ground geophysical investigations.

Keywords: *Remote sensing; aeromagnetic data; mineral prospectivity; LCT pegmatites; lithium mineralization; orogenic gold; Nigerian Basement Complex; Borgu area*

1. Introduction

Nigeria is endowed with substantial solid mineral resources, including economically strategic metals and gemstones such as lithium, beryl, tourmaline, and gold, all of which have become increasingly important due to their applications in renewable energy technologies, electronics manufacturing, and the gemstone industry (Goodenough et al., 2014; Küster, 1990). Among these resources, lithium has gained exceptional global significance as a critical component in rechargeable battery systems, particularly for electric vehicles and energy storage technologies. Gold, on the other hand, commonly occurs in structurally controlled quartz veins and hydrothermal systems within crystalline basement terrains, where deformation structures provide favorable pathways for mineralizing fluids (Groves et al., 1998; Goldfarb et al., 2001). Within Nigeria, lithium-bearing pegmatites are extensively developed across the Basement Complex, notably in Nasarawa, Kogi, Oyo, Kwara, and Niger States, where they are closely associated with Pan-African granitoids and metasedimentary belts. In the same geological framework, gold mineralization is widely reported within the schist belts of northwestern and north-central Nigeria, where faults, fractures, and shear zones exert significant structural control on ore deposition. These mineral occurrences emphasize the important role of tectonic deformation, magmatic evolution, and hydrothermal activity in concentrating economically viable mineral deposits within the Nigerian Basement Complex. The Nigerian Basement Complex

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constitutes part of the Pan-African Mobile Belt and records extensive tectono-metamorphic reworking during the Pan-African Orogeny ($\sim 600 \pm 150$ Ma). It is composed predominantly of Precambrian migmatites, gneisses, schists, and granitoids that have experienced multiple episodes of deformation, metamorphism, and magmatic intrusion (Akingboye and Osazua, 2016; Ekeleme et al., 2024). These geological processes generated an extensive network of structural features such as folds, fractures, faults, and shear zones that not only influenced crustal evolution but also created favorable conduits and traps for hydrothermal fluids, thereby exerting a strong control on mineral localization. The Borgu area, situated in northwestern Niger State within the north-central segment of the Nigerian Basement Complex, is underlain by a suite of metamorphic and igneous rocks, including gneisses, schists, and granitic intrusions. The occurrence of pegmatite veins, quartz lodes, and hydrothermal alteration features within this terrain indicates a geologically favorable environment for both rare-metal pegmatite mineralization and structurally controlled gold deposition (NGSA, 2022). Despite these favorable geological indicators, the mineral potential of the area remains underexplored, and there is limited documentation of integrated studies utilizing both remote sensing and airborne geophysical datasets for systematic mineral prospectivity evaluation.

Accordingly, this study adopts an integrated mineral exploration framework that combines remote sensing techniques with geophysical data interpretation to delineate prospective zones for rare-metal pegmatites and orogenic gold within the Borgu Basement terrain. The approach incorporates lithological discrimination, structural and lineament analysis, hydrothermal alteration mapping, and subsurface geophysical characterization to identify mineralization targets. By integrating these complementary datasets, the study aims to improve the reliability of target delineation and provide a geospatial basis for future exploration activities in the area.

2. Study Area

2.1 Location and Accessibility

The study area is situated within Exploration License EL-054003 in Borgu Area, Niger State, northwestern Nigeria (Figure 1). It encompasses portions of New Bussa, Lemu, Kainji, and adjoining settlements, and is geographically bounded between longitudes $4^{\circ}16'$ – $4^{\circ}18'E$ and latitudes $10^{\circ}03'$ – $10^{\circ}04'N$.

Accessibility to the area is generally favorable, facilitated by an interconnected network of primary and secondary roads linking the major settlements. In addition, a series of unpaved access routes, including lateritic roads, farm tracks, and footpaths, provide entry into the interior sections of the license area for detailed field investigations. The terrain is characterized by gently undulating topography, comprising low-relief surfaces with occasional isolated hills. These physiographic conditions permit relatively efficient mobility during geological mapping and mineral exploration activities.

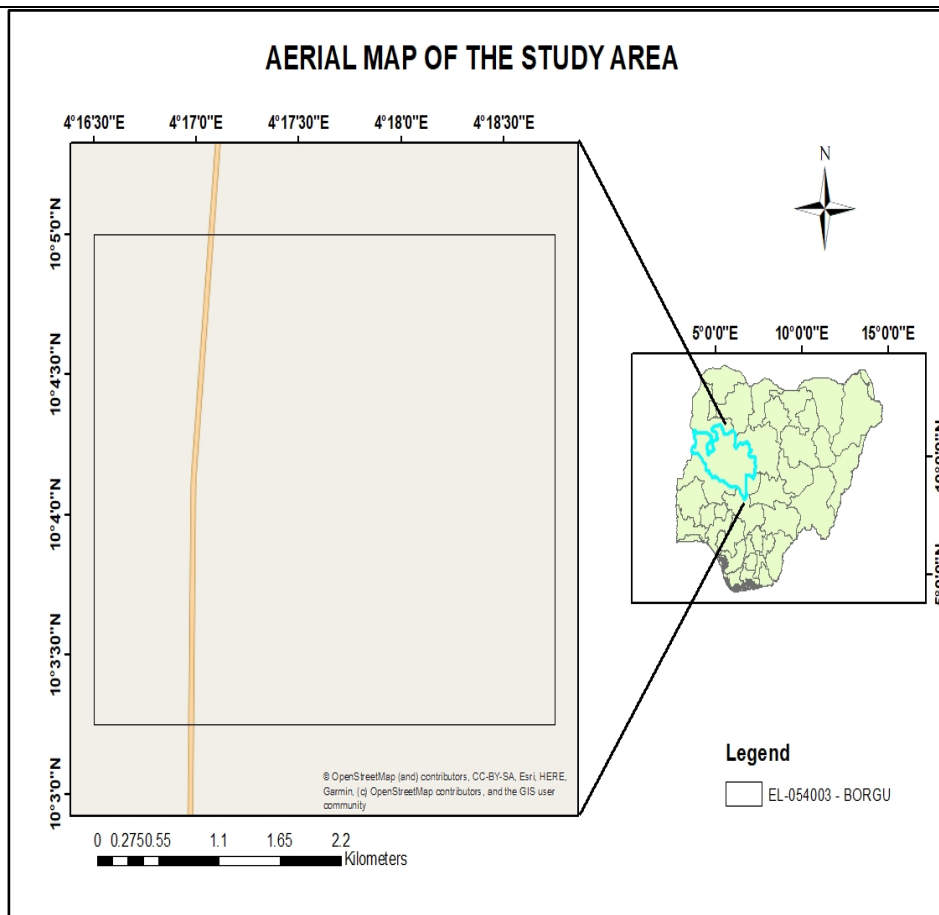


Figure 1: Aerial Map of the Study Area

2.2 Climate and Vegetation

The study area falls within the Guinea Savannah ecological zone of northwestern Nigeria and experiences a tropical climate marked by well-defined wet and dry seasons (Figure 2). The wet season extends from May to October, whereas the dry season spans November to April and is strongly influenced by the Harmattan, a dry and dust-laden northeasterly wind. Mean annual temperatures typically range between 25 °C and 35 °C, reflecting the region's generally warm climatic conditions. Vegetation within the area is dominated by savannah grasslands interspersed with shrubs and sparsely distributed trees, alongside cultivated farmlands where crops such as maize, millet, sorghum, and yam are grown. The landscape also includes seasonal drainage channels and localized woodland patches. These vegetation characteristics, together with seasonal climatic variability, exert a significant influence on field accessibility, degree of bedrock exposure, and the reliability of spectral signatures during remote sensing analysis.

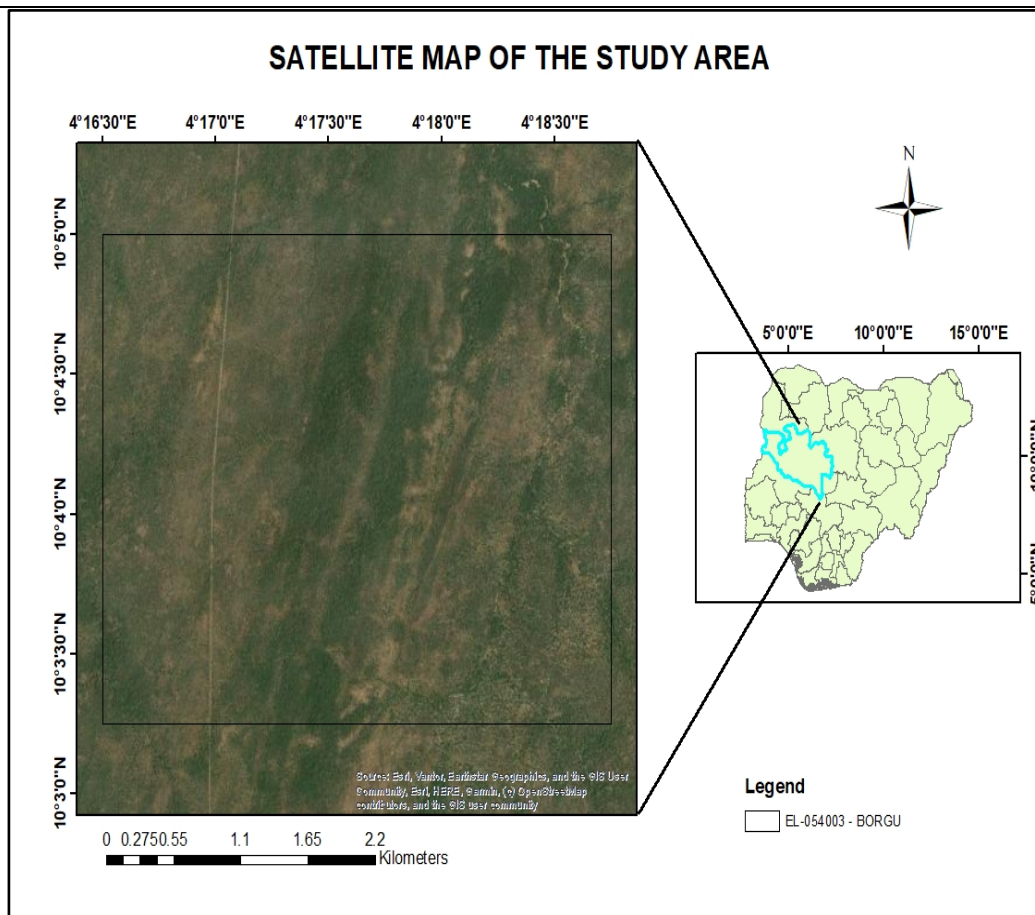


Figure 2: Satellite Map of the Study Area

2.3 Topography and Drainage

The study area is characterized by a gently undulating landscape comprising low hills, subdued slopes, and shallow valleys, which collectively facilitate relatively easy access for geological field investigations (Figure 3). The absence of pronounced escarpments or rugged terrain further enhances its suitability for both remote sensing analysis and ground-based exploration activities. Digital Elevation Model (DEM) analysis indicates elevation values ranging from approximately 224 m to 232 m above mean sea level, confirming the overall low-relief morphology of the terrain. Relatively lower elevations are concentrated in the northern and northeastern sectors, where they likely function as natural drainage pathways and potential sites for secondary mineral accumulation. In contrast, the slightly elevated southern and southwestern portions may correspond to zones of enhanced bedrock exposure, providing favorable conditions for the identification of primary mineralization. The drainage network is predominantly controlled by seasonal streams exhibiting a dendritic pattern, reflecting homogeneous lithological conditions and structural simplicity. Drainage development is largely rainfall-dependent, with the general south-to-north regional gradient governing surface runoff, erosional processes, and sediment transport across the license area.

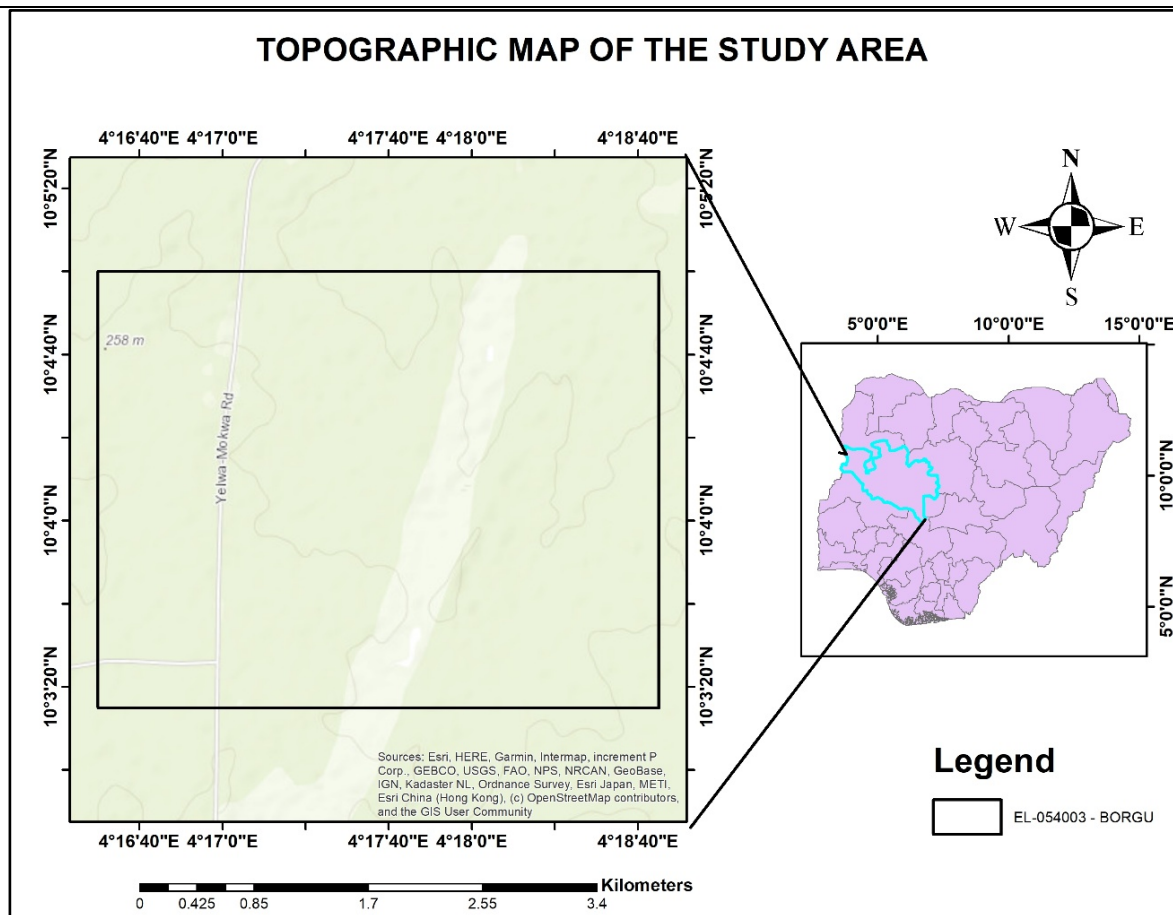


Figure 3: Topographic Map of the Study Area

3. Geological Setting

3.1 Regional Geology

The study area is situated within Borgu Area of Niger State, Nigeria, and forms part of the Nigerian Basement Complex within the Pan-African Mobile Belt (Figure 4). This geological terrain underwent extensive tectono-metamorphic reworking during the Pan-African Orogeny ($\sim 600 \pm 150$ Ma) and is predominantly composed of Precambrian crystalline rocks, including migmatites, gneisses, schists, and granitoids. These lithological units have been subjected to multiple phases of deformation, metamorphism, and magmatic emplacement, resulting in a structurally complex basement framework (Akingboye and Osazua, 2016; Ekeleme et al., 2024). The Nigerian Basement Complex is conventionally subdivided into three principal lithotectonic units: the Migmatite–Gneiss Complex, the Schist Belts, and the Pan-African Older Granite suite (Oyawoye, 1972; Rahaman, 1988). These units collectively record a prolonged history of tectono-metamorphic evolution and are spatially associated with granitoid intrusions and pegmatitic bodies, which play a critical role in the localization of economically significant mineralization. At the regional scale, the Borgu area is dominated by migmatite–gneiss assemblages and Pan-African granitoids, which are intruded by pegmatite bodies and quartz veins. These pegmatites are recognized as important hosts for rare-metal mineralization, particularly lithium-bearing minerals, as well as beryl and tourmaline, reflecting their association with highly fractionated granitic systems (Küster, 1990; Chukwu and Obiora, 2021).

3.2 Local Geology

The local geology of the study area is primarily characterized by granite gneiss (Figure 4), a high-grade metamorphic rock of granitic protolith distinguished by well-developed gneissic foliation. This foliation is defined by compositional banding, typically consisting of alternating quartz–feldspar-rich layers and ferromagnesian mineral bands. The granite gneiss constitutes the basement host rock for subsequent pegmatite and quartz vein intrusions, which represent key exploration targets for rare-metal mineralization, including lithium, beryl, and tourmaline. Structural discontinuities within the gneiss, such as fractures, joints, and shear zones, serve as preferential conduits

for hydrothermal fluid migration. These structures are therefore critical in controlling the emplacement of pegmatitic bodies as well as the formation of quartz vein-hosted orogenic gold mineralization.

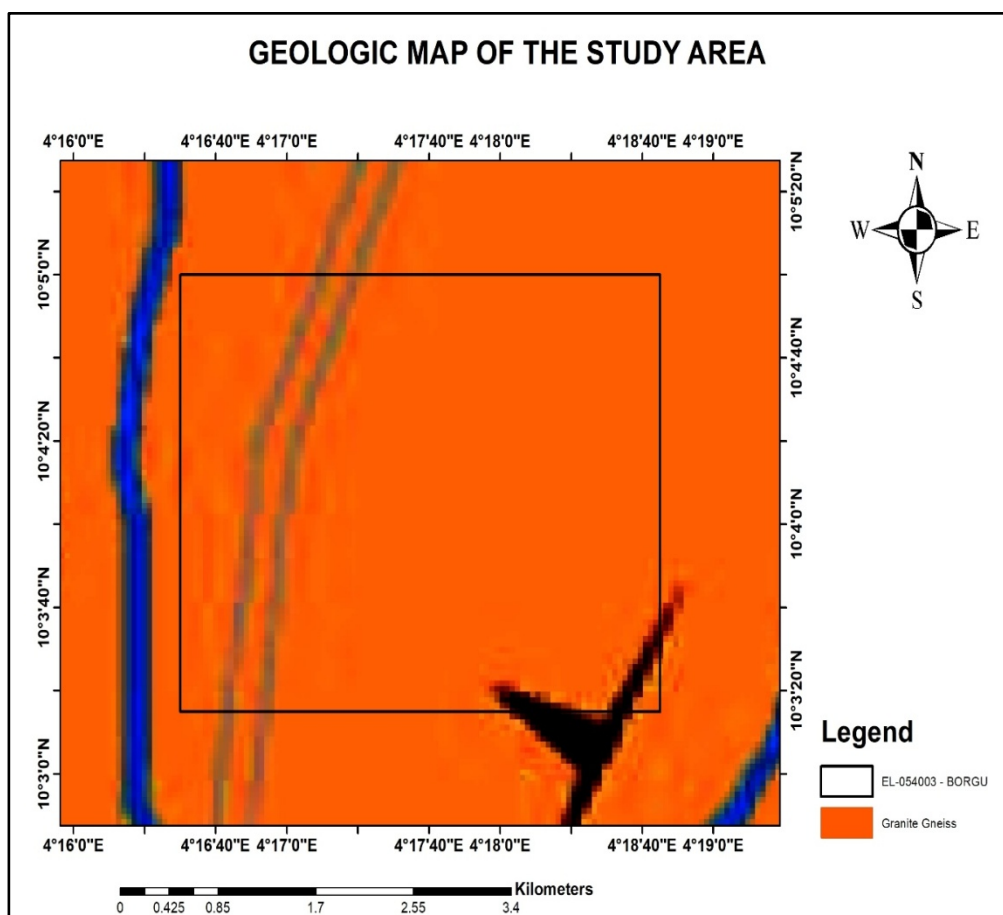


Figure 4: Geologic map of the study area showing the dominant Granite Genesis.

3.3 Mineralization Controls

Mineralization within the study area is primarily governed by the interplay between structural deformation and magmatic evolution. Rare-metal pegmatites are preferentially emplaced along pre-existing structural discontinuities, including fractures, joints, and shear zones, which function as effective conduits for the migration and concentration of mineralizing fluids (Cerny and Ercit, 2005; London, 2008). In a comparable manner, gold mineralization in crystalline basement terrains is predominantly structurally controlled and is typically localized within quartz veins and deformation-induced fracture networks associated with shear zone systems (Groves et al., 1998; Goldfarb et al., 2001). Collectively, these geological attributes indicate a high potential for both rare-metal pegmatite formation and structurally controlled orogenic gold mineralization within the Borgu area. In particular, the Lithium–Cesium–Tantalum (LCT) pegmatite family—commonly enriched in lithium, beryl, and tourmaline—is characteristically linked to highly evolved S-type granitic systems. These pegmatites are generally associated with low magnetic responses, reflecting magnetite depletion during advanced stages of magmatic differentiation (Cerny and Ercit, 2005).

4. Methodology

4.1 Data Acquisition

This study adopts a desktop-based mineral exploration framework utilizing multi-source geoscientific datasets to evaluate the mineral prospectivity of the Borgu exploration license area in Niger State, Nigeria. The datasets employed include airborne geophysical data (aeromagnetic and radiometric), multispectral Landsat satellite imagery, Digital Elevation Model (DEM) data, and regional geological maps, supplemented by relevant published literature. The integration of these datasets provides a comprehensive basis for lithological discrimination, structural analysis, and hydrothermal alteration mapping.

4.2 Aeromagnetic Data Processing

Aeromagnetic data were processed using a suite of filtering and enhancement techniques designed to extract both shallow and deep structural information. The Total Magnetic Intensity (TMI) dataset was initially analyzed to characterize spatial variations in subsurface magnetic susceptibility and to delineate lithological boundaries as well as intrusive bodies (Figure 5). To enhance structural interpretation, derivative-based filters were applied. The First Vertical Derivative (1VD) was utilized to emphasize near-surface magnetic anomalies and sharpen lithological contacts (Figure 6), whereas the Second Vertical Derivative (2VD) provided improved resolution of shallow discontinuities, including fractures and localized structural features (Figure 7). Depth estimation of magnetic sources was performed using Source Parameter Imaging (SPI), which provides rapid and reliable approximations of source depths based on local wave number analysis (Figure 8). The Analytical Signal (AS) was computed to delineate magnetic source edges independent of magnetization direction, thereby improving the detection of subsurface contacts (Figure 10). In addition, the Tilt Derivative (TDR) was applied to enhance both weak and strong magnetic anomalies simultaneously, facilitating the identification of fault geometries and structural trends (Figure 11).

4.3 Remote Sensing Analysis

Multispectral Landsat imagery was processed using band ratioing and image enhancement techniques to discriminate lithological units and identify hydrothermal alteration zones. Several diagnostic spectral indices were derived to map mineralogical variations. The Iron Oxide Index (Band 4/Band 2) was used to highlight ferric iron minerals such as hematite and goethite (Figure 13), while the Clay Mineral Index (Band 6/Band 7) targeted hydroxyl-bearing minerals indicative of argillic alteration (Figure 14). The Ferric Iron Index was employed to assess oxidation intensity (Figure 15), and the Ferrous Mineral Index (Band 6/Band 5) was used to detect ferrous-bearing minerals associated with mafic or altered lithologies. In addition, a Quartz Index was generated to delineate silicified zones, which are commonly associated with both pegmatitic and hydrothermal systems. The Normalized Difference Vegetation Index (NDVI) was calculated to evaluate vegetation cover and its potential masking effect on spectral signatures (Figure 18), thereby improving the reliability of lithological and alteration mapping.

4.4 GIS Integration and Target Delineation

The processed aeromagnetic, radiometric, remote sensing, and DEM datasets were integrated within a Geographic Information System (GIS) platform to facilitate multi-criteria spatial analysis. The integration involved the overlay and comparative assessment of key exploration parameters, including structural lineaments, lithological boundaries, elevation variations, and hydrothermal alteration indicators. Zones exhibiting spatial coincidence of favorable geological, structural, and geochemical proxies were identified through this integrated analysis as prospective targets for mineralization. These areas were subsequently delineated as priority exploration zones, reflecting their potential to host rare-metal pegmatites and structurally controlled gold deposits.

5. Results

5.1 Aeromagnetic Interpretation

5.1.1 Total Magnetic Intensity (TMI)

The Total Magnetic Intensity (TMI) map of the study area (Figure 5) is characterized by a relatively subdued magnetic signature within the exploration license, in contrast to the higher-amplitude anomalies observed toward the northwestern and southeastern margins. This pronounced magnetic low suggests that the license area is underlain by lithologies with low magnetic susceptibility, most plausibly metasedimentary units such as schists and phyllites, or highly evolved, magnetite-depleted felsic intrusions, including S-type granites. Such low magnetic responses are widely recognized as indicative of favorable host environments for Lithium–Cesium–Tantalum (LCT) pegmatite systems, as these highly fractionated melts are typically depleted in ferromagnetic minerals, particularly magnetite. From an orogenic gold exploration perspective, the positioning of the license area within a magnetic low corridor is also significant. These magnetic depressions are commonly associated with major crustal-scale shear zones, where hydrothermal alteration processes may have resulted in magnetite destruction, thereby reducing the overall magnetic signature. Consequently, the observed magnetic low is interpreted as a potential indicator of structurally controlled fluid pathways and enhanced mineralization potential within the study area.

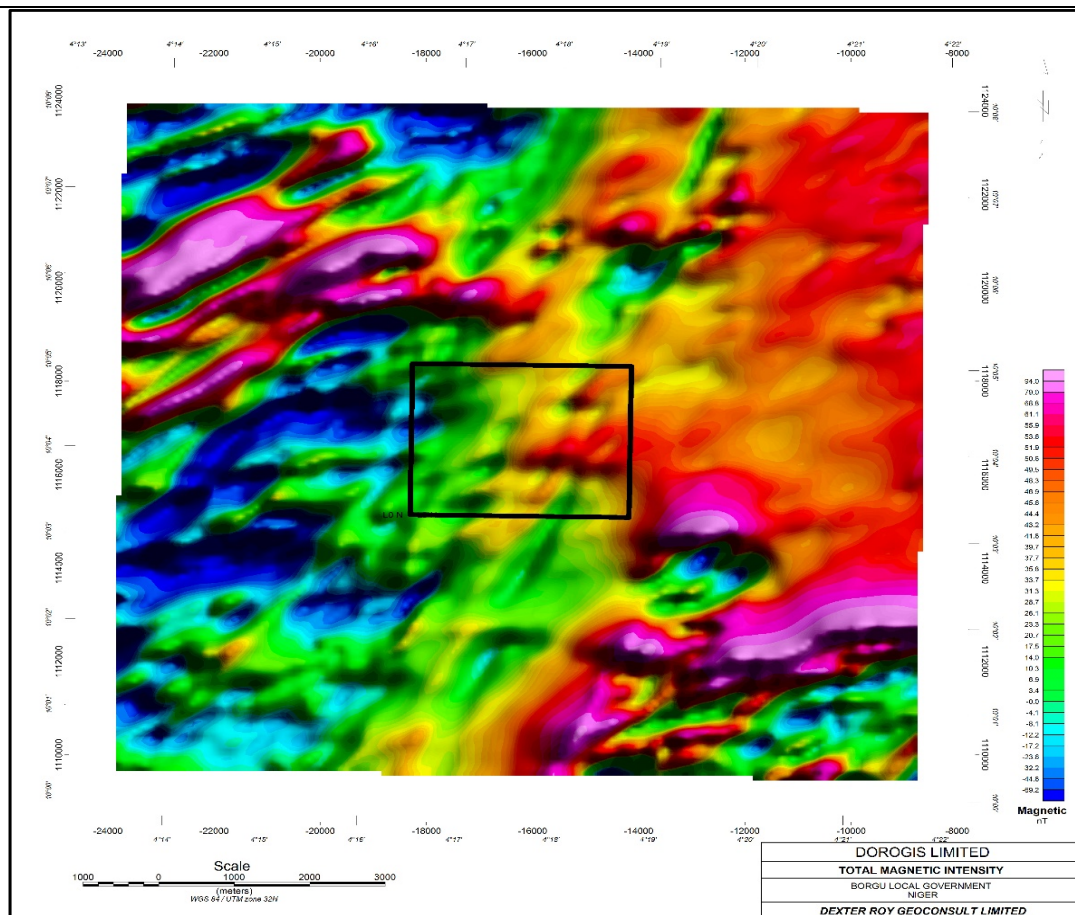


Figure 5: Total Magnetic Intensity

5.1.2 Vertical Derivative Analysis

The First Vertical Derivative (1VD) map (Figure 6) delineates a well-defined network of NE–SW trending linear features, interpreted as lithological contacts and major fault systems that control the structural framework of the basement terrain. The application of the 1VD filter enhances short-wavelength anomalies, thereby improving the resolution of near-surface structures and enabling more precise mapping of these lineaments. Such structurally controlled features are particularly significant for pegmatite exploration, as pegmatitic intrusions are commonly emplaced along pre-existing zones of weak structural weakness aligned with regional tectonic trends. The Second Vertical Derivative (2VD) map (Figure 7) further refines the structural interpretation by resolving finer-scale discontinuities within the dominant NE–SW corridor. The results indicate that this primary structural zone comprises a series of closely spaced, sub-parallel fractures and minor shear zones. This high density of structural features suggests an intensively deformed regime, which is highly favorable for orogenic gold mineralization. In such settings, secondary and tertiary fracture networks enhance permeability and fluid–rock interaction, thereby facilitating the circulation, focusing, and precipitation of hydrothermal fluids responsible for gold deposition.

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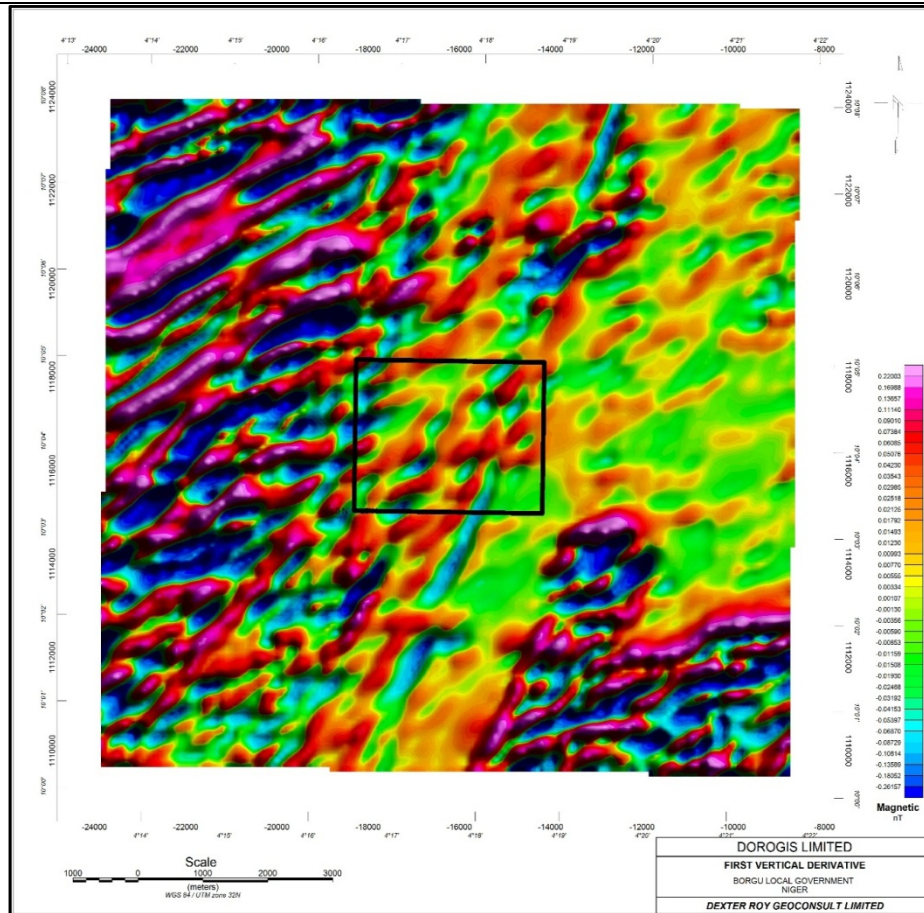


Figure 6: First Vertical Derivatives

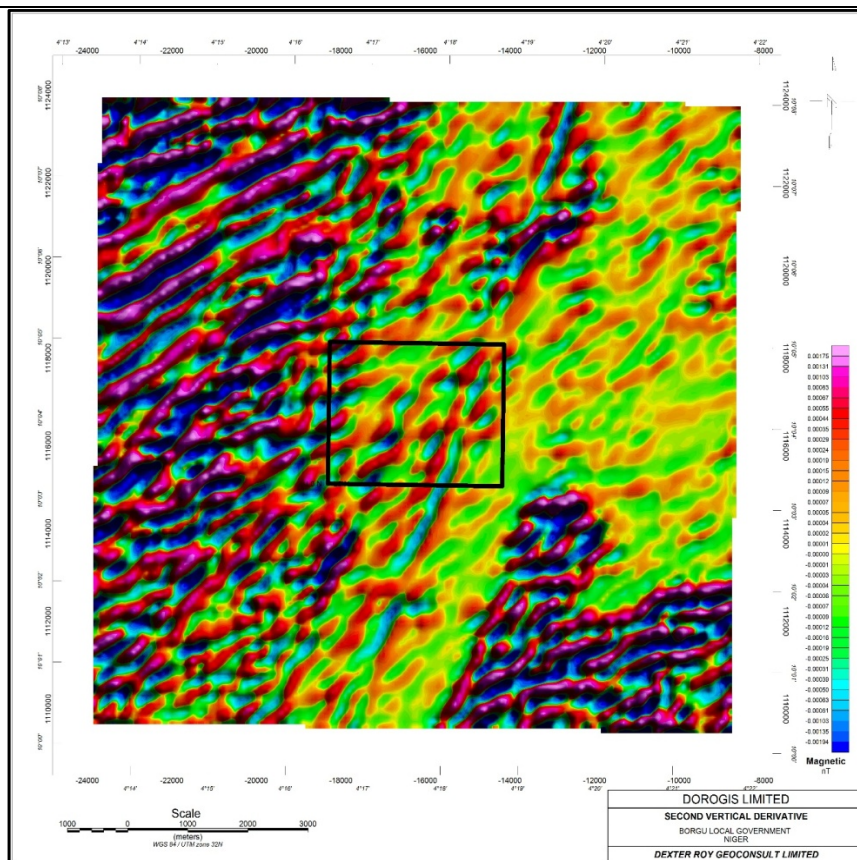


Figure 7: Second Vertical Derivatives

5.1.3 Source Parameter Imaging (SPI)

The Source Parameter Imaging (SPI) results (Figure 8) provide quantitative estimates of the depth to magnetic sources across the study area, offering valuable constraints on subsurface geometry. The analysis indicates that the magnetic basement is relatively shallow, with depth estimates ranging from approximately 120 m to 180 m. Such shallow depth conditions are significant from an exploration perspective, as they imply that mineralization associated with the basement–cover interface or shallow-seated intrusive bodies is potentially accessible through conventional exploration techniques, including drilling. Spatially, the shallowest magnetic source depths are predominantly concentrated along the western flank of the exploration license. These zones are interpreted to represent areas of reduced overburden thickness and possible proximity to bedrock exposures. Consequently, they constitute high-priority targets for preliminary exploration activities such as trenching and pitting, where subsurface mineralization may be more readily accessible for direct investigation.

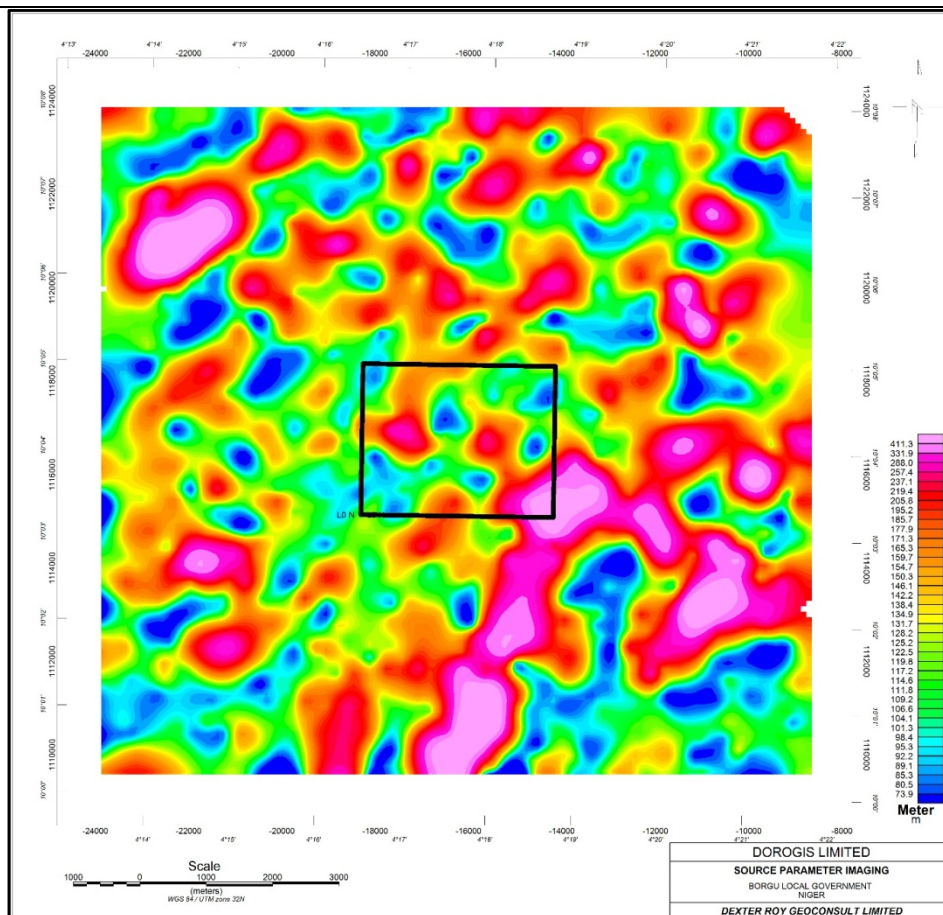


Figure 8: Source Parameter Imaging

5.1.4 Radiometric Data

Radiometric data analysis provides important insights into the geochemical characteristics of the study area and its potential for rare-metal mineralization. The K–Th–U ternary map (Figure 9) is predominantly characterized by cyan-to-white color responses, indicative of significant enrichment in potassium (K) and thorium (Th). Such radiometric signatures are commonly associated with highly evolved granitic systems within the Nigerian Basement Complex, particularly those linked to pegmatitic intrusions emplaced within metasedimentary host rocks. The spatial distribution of white zones on the ternary map, representing the coincident enrichment of potassium, thorium, and uranium (U), is especially significant. These anomalous regions are interpreted to reflect advanced stages of magmatic differentiation, which are typically conducive to the formation of highly fractionated pegmatites. Consequently, these radiometric anomalies constitute key exploration indicators for lithium- and beryl-bearing pegmatitic systems within the study area.

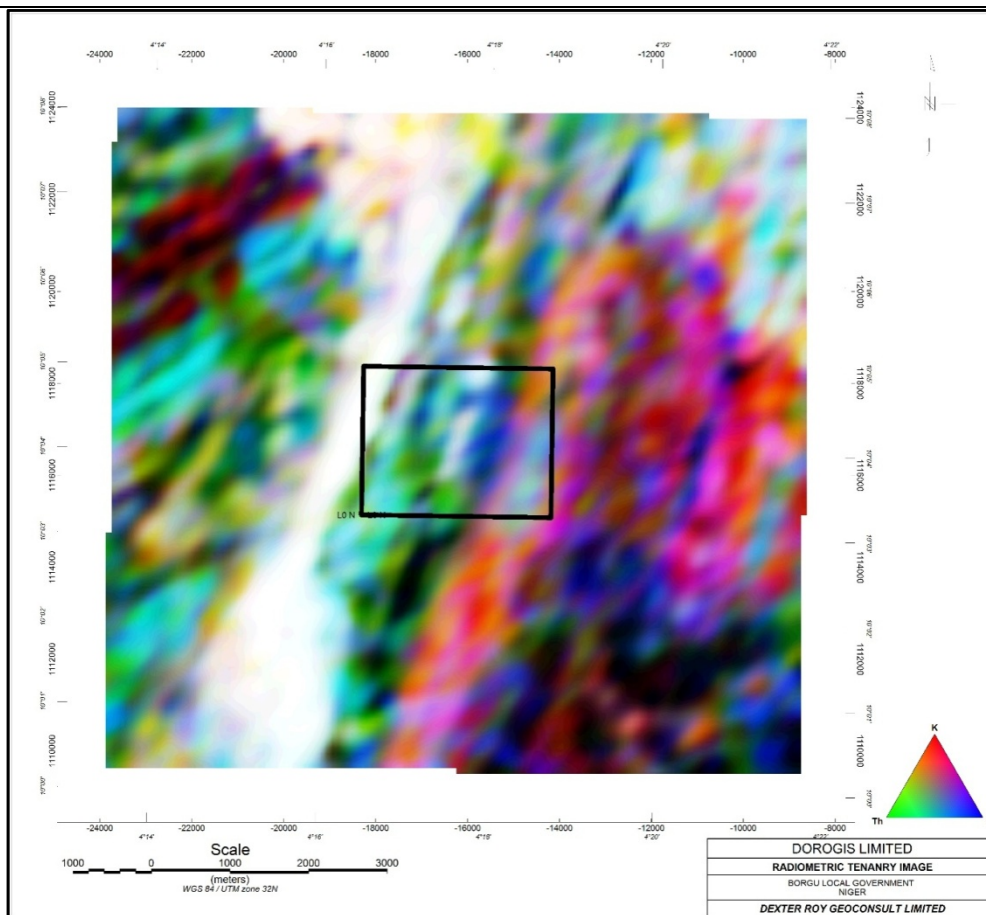


Figure 9: Radiometric Tenanry Image

5.1.5 Analytical Signal (AS) Map

The Analytical Signal (AS) map (Figure 10) further corroborates the dominance of low-amplitude magnetic responses within the exploration license, confirming that the area is characterized by a magnetically subdued regime relative to the surrounding basement. This signature is consistent with the presence of magnetite-depleted felsic lithologies and supports the inferred potential for Lithium–Cesium–Tantalum (LCT) pegmatite mineralization, as such systems are typically associated with weak magnetic expressions due to the absence of significant ferromagnetic mineral content. Notwithstanding the generally low magnetic intensity, the AS map reveals localized, discrete high-amplitude anomalies along the western margin of the license area. These features are interpreted as deeper-seated magnetic sources or small, concealed mafic intrusions, such as dyke-like bodies. The juxtaposition of these relatively competent, magnetically responsive units against surrounding less competent metasedimentary rocks likely generates rheological contrasts within the crust. Such contrasts are critical in focusing deformation and localizing strain, thereby creating favorable structural traps for hydrothermal fluid accumulation and subsequent gold mineralization.

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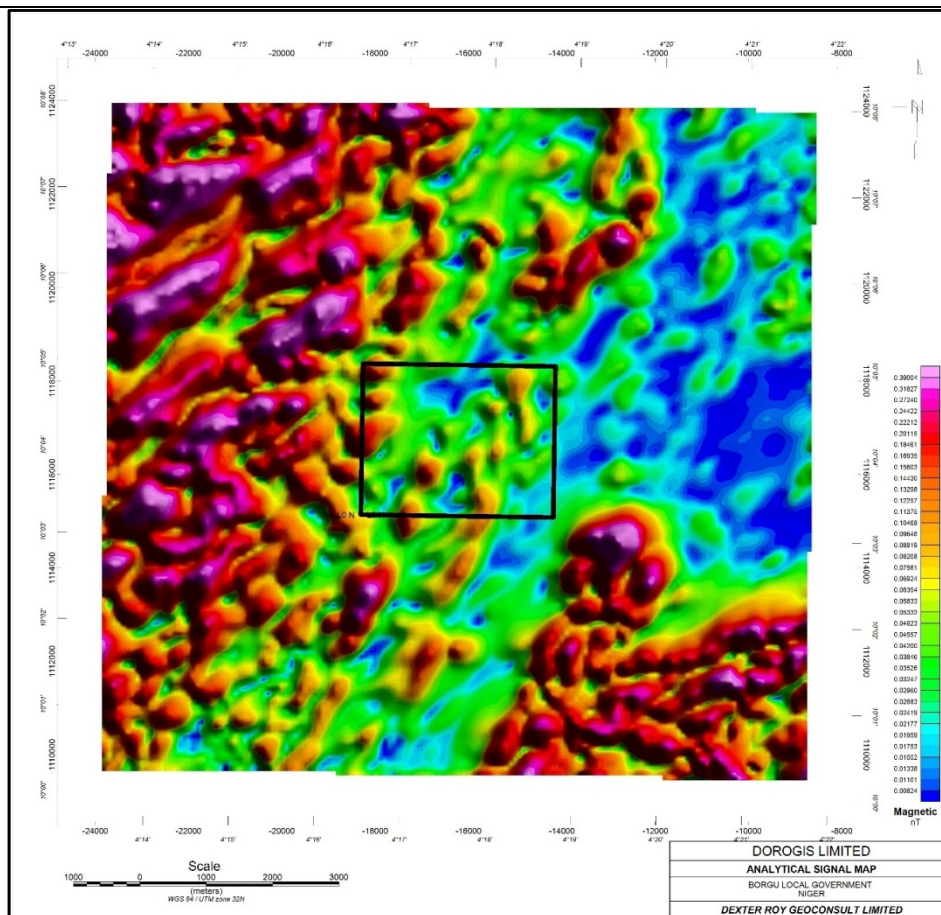


Figure 10: Analytical Signal Map

5.1.6 Tilt Derivative (TDR) Map

The Tilt Derivative (TDR) transformation enhances both shallow and deep magnetic sources by normalizing amplitude variations, thereby improving the continuity and interpretability of structural features across the study area. The TDR map (Figure 11) reveals a distinct structural inflection within the central portion of the exploration license, expressed as a localized kink or bend along the dominant NE–SW structural trend. This geometric anomaly is interpreted as a zone of structural complexity, likely representing a dilatational site formed through minor rotation or offset along intersecting fault segments. Such zones are characterized by localized extensional conditions and reduced confining pressure, which are favorable for the ingress and concentration of hydrothermal fluids. In the context of orogenic gold systems, these structural configurations are considered highly prospective, as they facilitate fluid focusing, enhanced permeability, and subsequent mineral precipitation. Accordingly, the identified structural inflection zone within the central part of the license area constitutes a priority exploration target. It is recommended for detailed ground verification, including structural mapping and geochemical sampling, to evaluate its potential for hosting gold and associated mineralization.

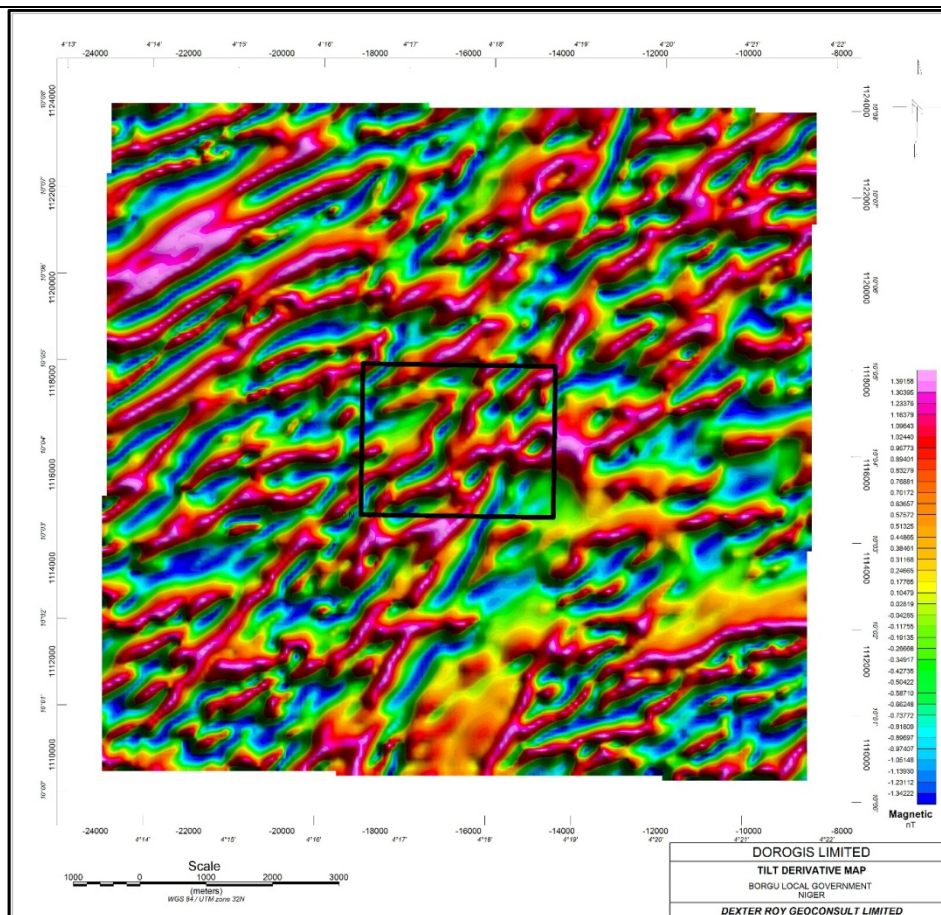


Figure 11: TILT Derivatives Map

5.1.7 Lineament Map

The lineament map of the study area (Figure 12) delineates a dominant NE–SW-oriented structural grain, reflecting the regional tectonic fabric of the basement terrain. Although the exploration license area is characterized by relatively low magnetic contrast, integration with derivative-based products, particularly the First Vertical Derivative (1VD) and Tilt Derivative (TDR), confirms the continuity of these structural features across the license boundary. This structural coherence indicates that the license area is situated within a regionally extensive deformation corridor. Notably, the observed convergence and apparent pinching of lineaments toward the southern portion of the license suggest localized zones of strain concentration. Such structural configurations are typically associated with enhanced deformation intensity, leading to the development of dense fracture networks and increased rock permeability. From an exploration standpoint, these high-strain zones are considered highly prospective for orogenic gold mineralization, as they facilitate large-scale hydrothermal fluid flow and promote efficient fluid–rock interaction, ultimately enhancing the potential for gold deposition.

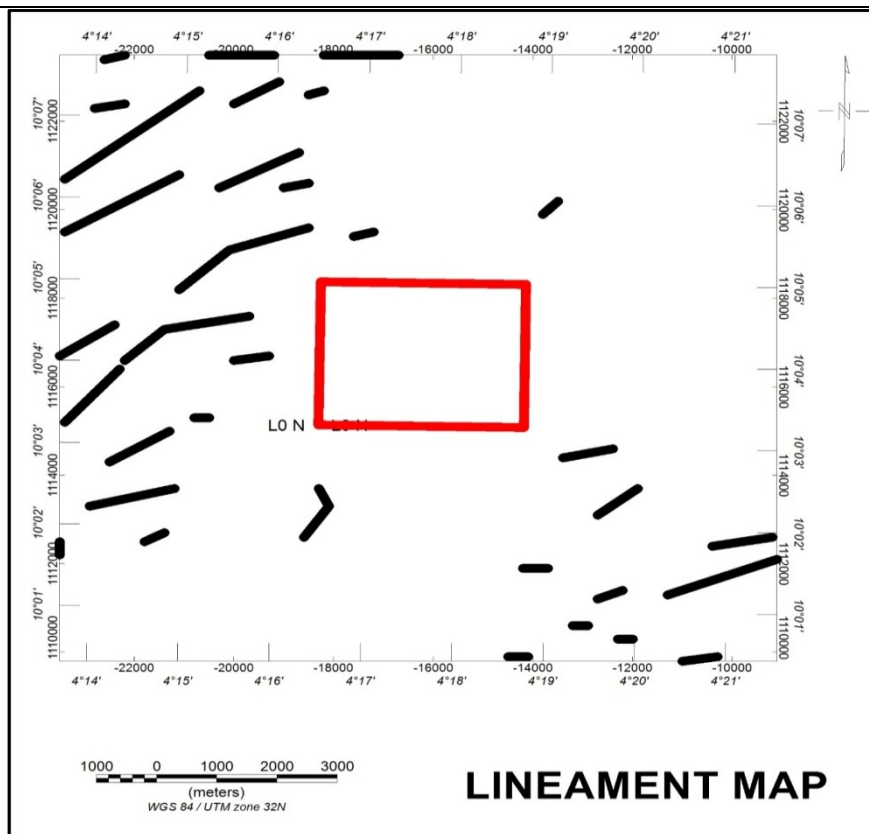


Figure 12: Lineament Map

5.2 Remote Sensing Results

5.2.1 Alteration Indices

Remote sensing analysis based on Landsat multispectral imagery reveals the presence of significant hydrothermal alteration signatures across the study area. The Iron Oxide Index (Band ratio 4/2) was employed to delineate zones enriched in ferric iron minerals, particularly hematite and goethite (Figure 13). These minerals commonly develop as oxidation products of sulfide-bearing lithologies and are frequently expressed at the surface as gossans or ferruginous caps overlying mineralized zones. Elevated values of the Iron Oxide Index are interpreted to reflect areas of intense oxidation, potentially associated with the weathering of sulfide minerals such as pyrite and arsenopyrite, which are commonly linked to gold-bearing hydrothermal systems. The spatial distribution of these anomalies is therefore considered indicative of near-surface expressions of mineralization. Consequently, iron oxide-rich zones identified in this analysis represent high-priority targets for field verification, as they are often spatially associated with the margins or upper levels of hydrothermal alteration systems.

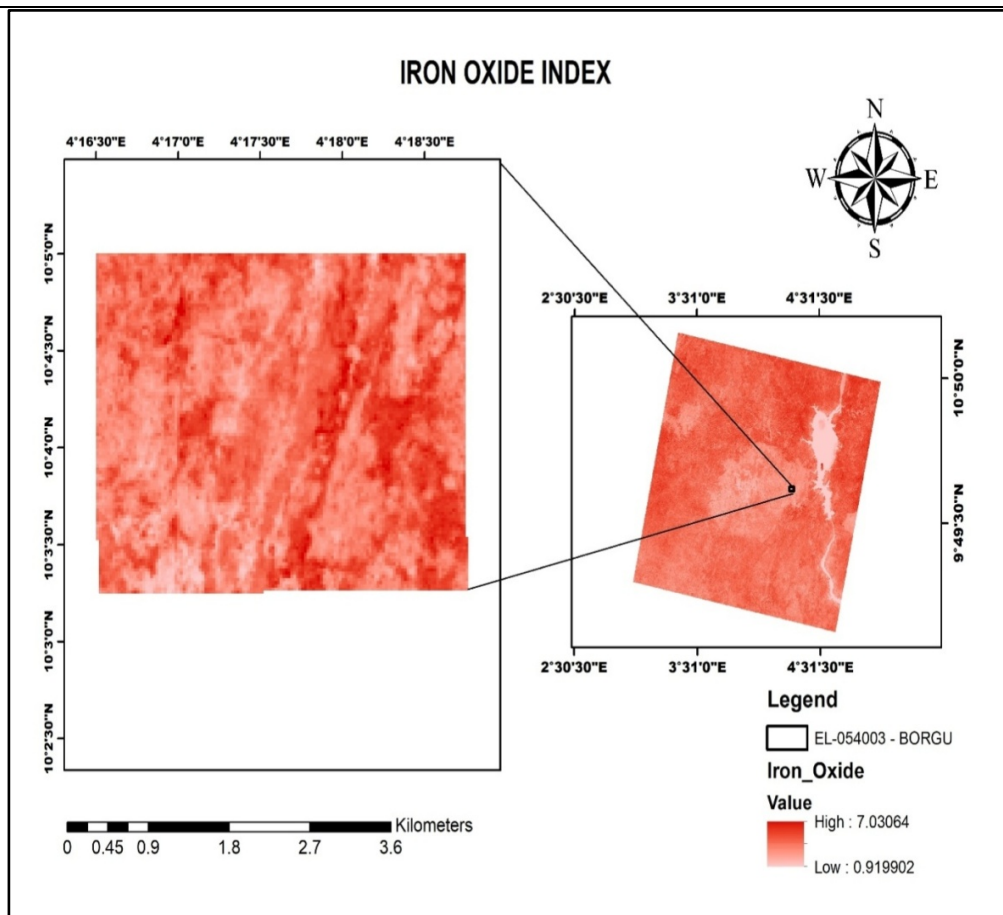


Figure 13: Iron Oxide Index

The Clay Mineral Index (Band ratio 6/7) was applied to delineate hydroxyl-bearing minerals, primarily kaolinite, illite, and muscovite, which exhibit diagnostic absorption features in the shortwave infrared (SWIR) region (Figure 14). These minerals are commonly associated with hydrothermal alteration processes and therefore serve as important indicators in mineral exploration. Elevated clay index responses are interpreted to represent zones of argillic alteration, which are frequently developed in association with hydrothermal systems. In the context of gold exploration, such anomalies are indicative of alteration halos surrounding quartz vein systems, reflecting fluid–rock interaction during mineralization. For lithium exploration, high clay responses may correspond to the weathered surfaces of pegmatite bodies or the presence of mica-rich phases such as muscovite and lepidolite, which are characteristic of highly fractionated granitic and pegmatitic systems. Accordingly, the spatial distribution of clay-rich anomalies provides a valuable proxy for identifying prospective zones of hydrothermal alteration and rare-metal enrichment within the study area.

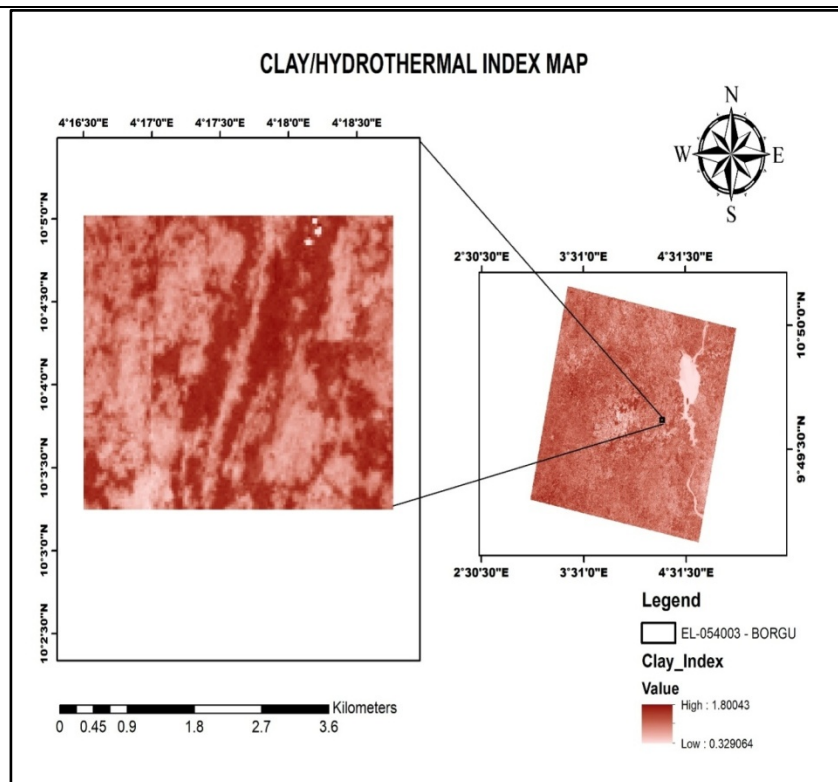


Figure 14: Clay Index

The Ferric Iron Index (Figure 15) delineates zones of intense surface oxidation, commonly associated with lateritic weathering profiles and the enrichment of ferric iron minerals such as hematite and goethite. These oxidized surfaces typically represent advanced stages of chemical weathering and may correspond to the supergene expression of underlying mineralized systems. In contrast, the Ferrous Mineral Index (Band ratio 6/5) is effective in identifying ferrous iron-bearing minerals, including chlorite and biotite, which are commonly associated with less oxidized lithologies and hydrothermal alteration zones. Elevated ferrous responses within metasedimentary units are interpreted as indicators of propylitic alteration, which generally forms the distal alteration halo surrounding hydrothermal mineralization, particularly in orogenic gold systems. The spatial relationship between ferrous- and ferric-dominated zones provides important insights into both alteration zoning and weathering intensity. Specifically, transitions from ferrous-rich to ferric-rich signatures may reflect progressive oxidation and the development of a paleo-weathering profile, thereby aiding in the delineation of alteration gradients and enhancing the interpretation of subsurface mineralization potential.

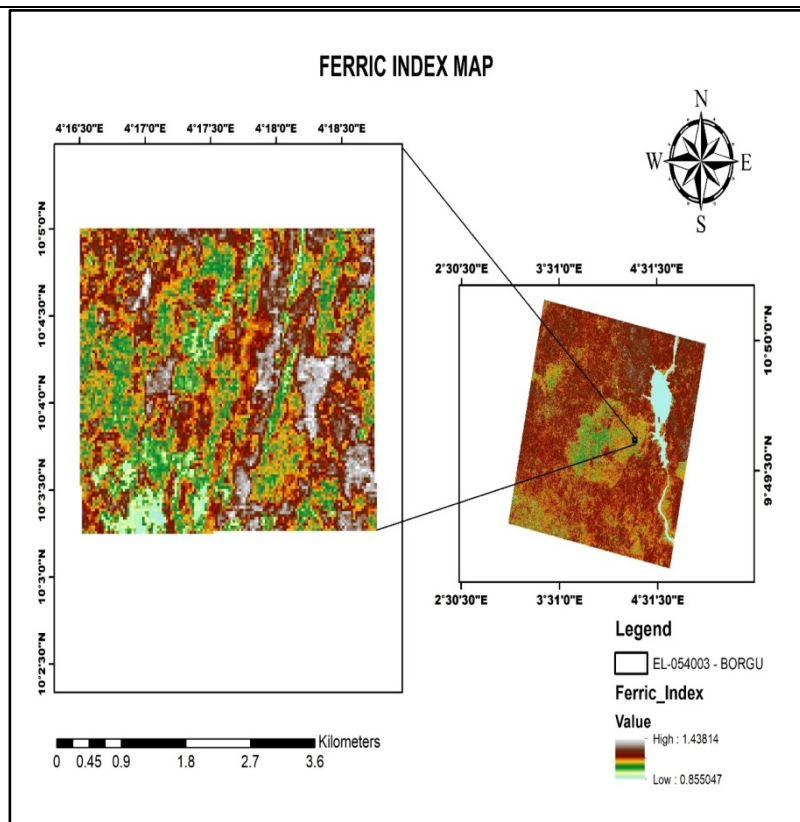


Figure 15: Ferric Iron Index

5.2.2 Quartz Index and False Color Composite

The Quartz Index map (Figure 16), derived from Shortwave Infrared (SWIR) band ratios, is designed to enhance the spectral response of silica-rich materials and effectively delineate zones of silicification and quartz vein development. This index highlights areas where quartz enrichment is pronounced, providing a key indicator of hydrothermal alteration and silica-saturated systems. Given that both Lithium–Cesium–Tantalum (LCT) pegmatites and orogenic gold deposits are typically associated with silica-rich environments, the high-intensity anomalies identified on the Quartz Index map are interpreted as zones of elevated exploration potential. The presence of NNE-trending linear quartz anomalies suggests structurally controlled silicification, which may correspond to auriferous quartz vein systems or extensive pegmatitic intrusions emplaced along lithological contacts, particularly at schist–gneiss boundaries. These linear features are therefore considered significant exploration targets, as they likely represent pathways of focused fluid flow and sites of enhanced mineral deposition within the study area.

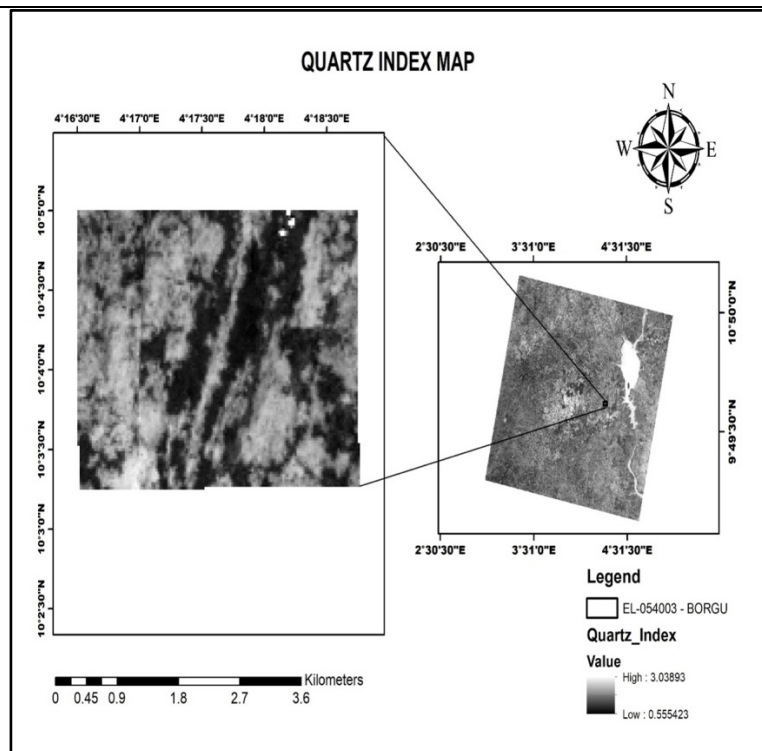


Figure 16: Quartz Index

The False Color Composite (FCC) image (Figure 17) constitutes a fundamental litho-structural framework for the study area. By integrating Shortwave Infrared (SWIR) and Near-Infrared (NIR) spectral bands within the RGB channels, the composite enhances lithological discrimination and emphasizes structural features through improved spectral contrast. The FCC imagery reveals a dominant NNE–SSW to NE–SW structural orientation, consistent with the regional tectonic grain of the Nigerian schist belts. Distinct tonal variations, ranging from cyan to brown hues, facilitate the differentiation of lithological units, with more competent granitic and gneissic bodies exhibiting contrasting spectral responses relative to the comparatively less resistant schistose units. Linear features extracted from the FCC image are interpreted as shear zones and brittle–ductile fault systems, which likely exert a primary control on the emplacement of pegmatitic intrusions and quartz vein systems. These structures are considered critical components of the mineralizing framework, as they act as conduits for hydrothermal fluid flow and localization of mineral deposition within the study area.

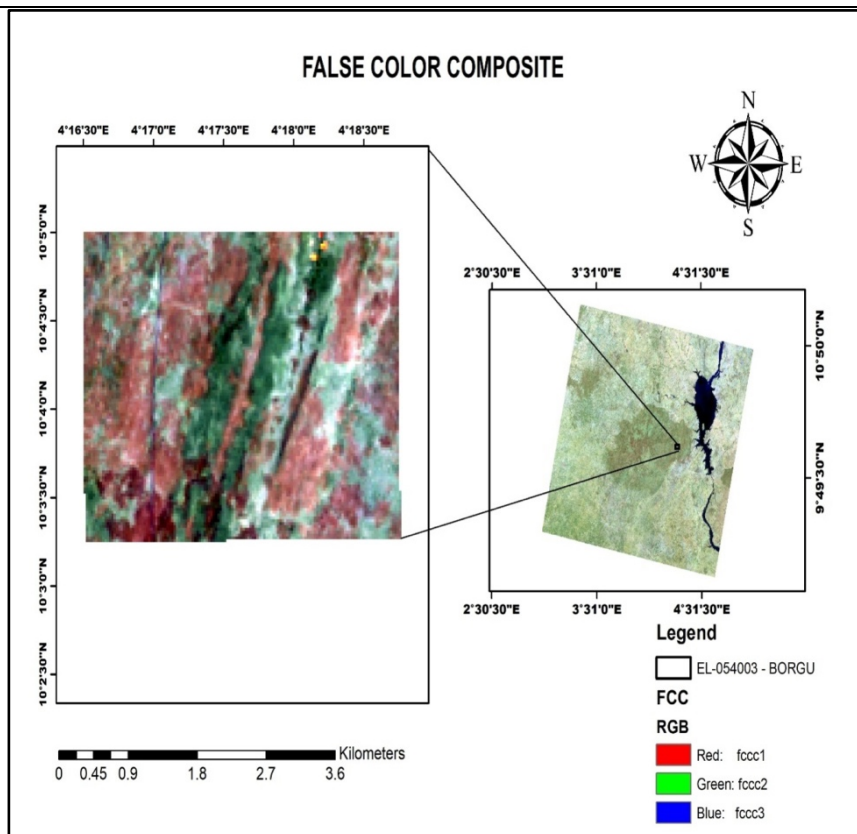


Figure 17: False Color Composite

5.2.3 NDVI Analysis

The Normalized Difference Vegetation Index (NDVI) was employed as a spectral constraint to evaluate the reliability of lithological and alteration signatures derived from multispectral analysis. The NDVI map (Figure 18) indicates predominantly low-to-moderate values across the central and western sectors of the exploration license, suggesting limited vegetation cover and the presence of exposed or shallowly buried bedrock. These conditions are favorable for direct spectral detection of lithological and hydrothermal alteration features. In contrast, zones exhibiting high NDVI values are largely confined to riparian corridors associated with seasonal drainage systems, where dense vegetation cover may obscure underlying geological signatures. Such areas require cautious interpretation, as vegetative masking can reduce the accuracy of spectral indices used in mineral exploration. From an exploration perspective, regions characterized by low NDVI values are considered priority targets for surface-based investigations, including geochemical sampling and field mapping, as they provide improved exposure and more reliable geospatial correlation with alteration anomalies.

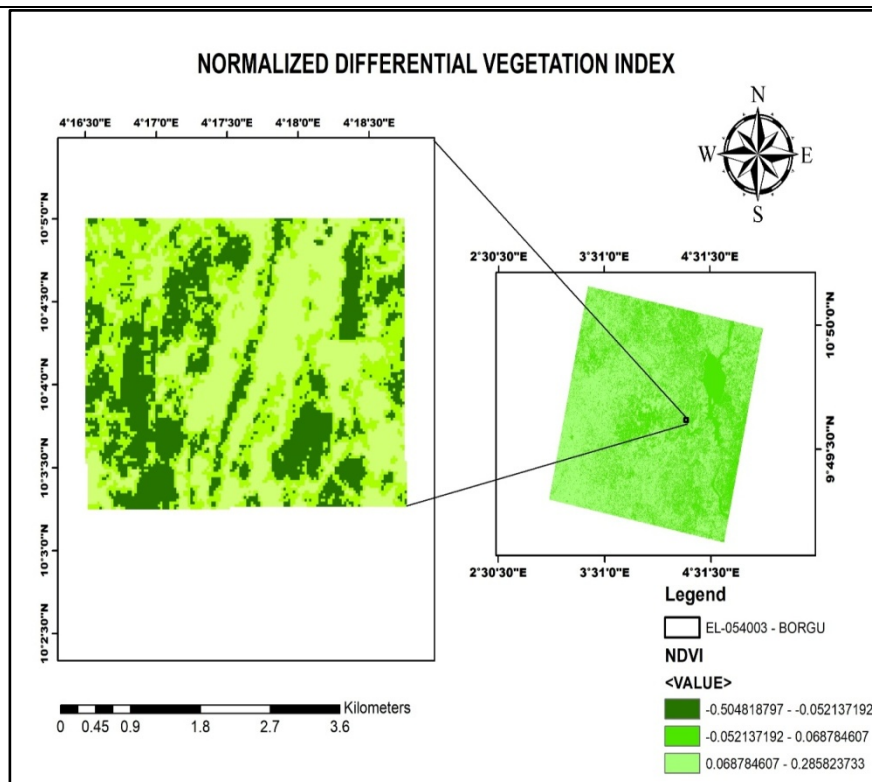


Figure 18: Normalized Differential Vegetation Index

5.3 Prospectivity Mapping

Integration of the processed geophysical, remote sensing, and topographic datasets facilitated the generation of mineral-specific prospectivity models within a GIS-based analytical framework. The gold prospectivity map (Figure 19) was produced using a weighted overlay approach that incorporates key exploration indicators, including the Clay Mineral Index, Iron Oxide Index, Ferric Iron Index, and NDVI. This multi-criteria integration highlights zones where hydrothermal alteration signatures—expressed by elevated clay mineral content, iron oxide enrichment, and ferric iron anomalies—spatially coincide with areas of low vegetation cover, thereby minimizing spectral masking effects. Such zones are interpreted as representing favorable conditions for near-surface expression of hydrothermal systems associated with orogenic gold mineralization. The resulting prospectivity distribution delineates discrete high-potential targets, reflecting areas where alteration intensity, geochemical proxies, and surface exposure collectively enhance the likelihood of gold occurrence. These zones constitute priority targets for follow-up exploration, including detailed geochemical sampling and structural field validation.

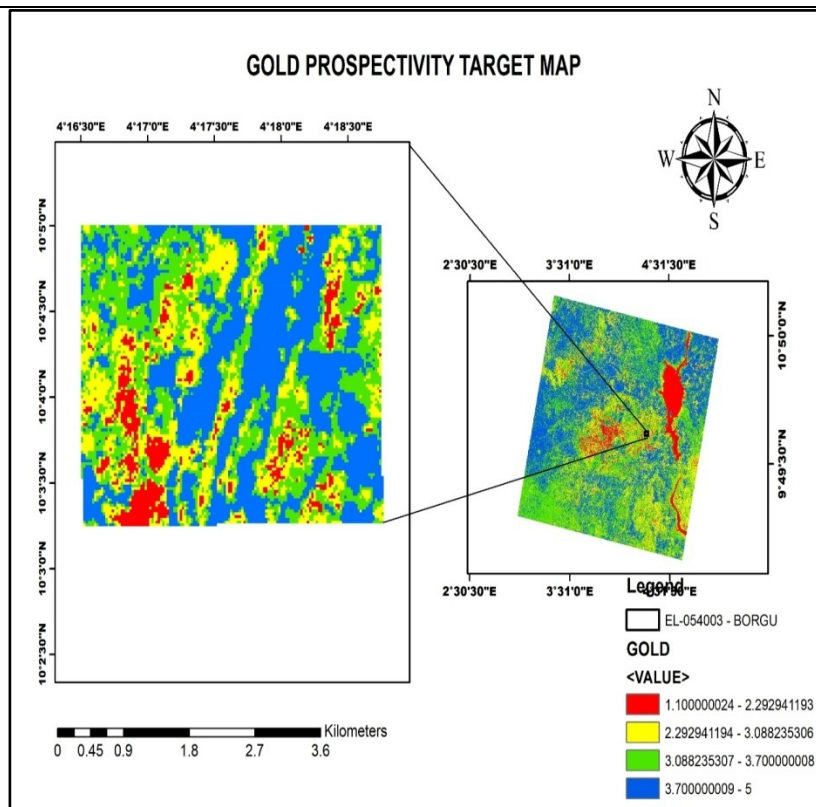


Figure 19: Gold prospectivity map

The beryl prospectivity map (Figure 20) was generated through a multi-criteria weighted overlay of key spectral indicators, including the Quartz (Silica) Index, Clay Mineral Index, Ferrous Mineral Index, and NDVI. This integration targets diagnostic signatures associated with pegmatitic systems, particularly silica enrichment, mica-related alteration, and ferrous mineral assemblages commonly linked to evolved granitic environments. Zones of elevated prospectivity are defined by the spatial coincidence of strong silica responses, enhanced clay mineral signatures, and moderate to high ferrous mineral anomalies within areas characterized by low vegetation cover. The inclusion of NDVI ensures that only regions with minimal spectral interference from vegetation are emphasized, thereby improving the reliability of the mapped anomalies. These high-potential zones are interpreted as prospective sites for beryl-bearing pegmatites, where silicification, mica development (e.g., muscovite), and associated ferrous phases reflect the geochemical evolution of fractionated granitic systems. Consequently, the delineated targets provide a focused basis for follow-up exploration, including detailed field mapping and geochemical verification.

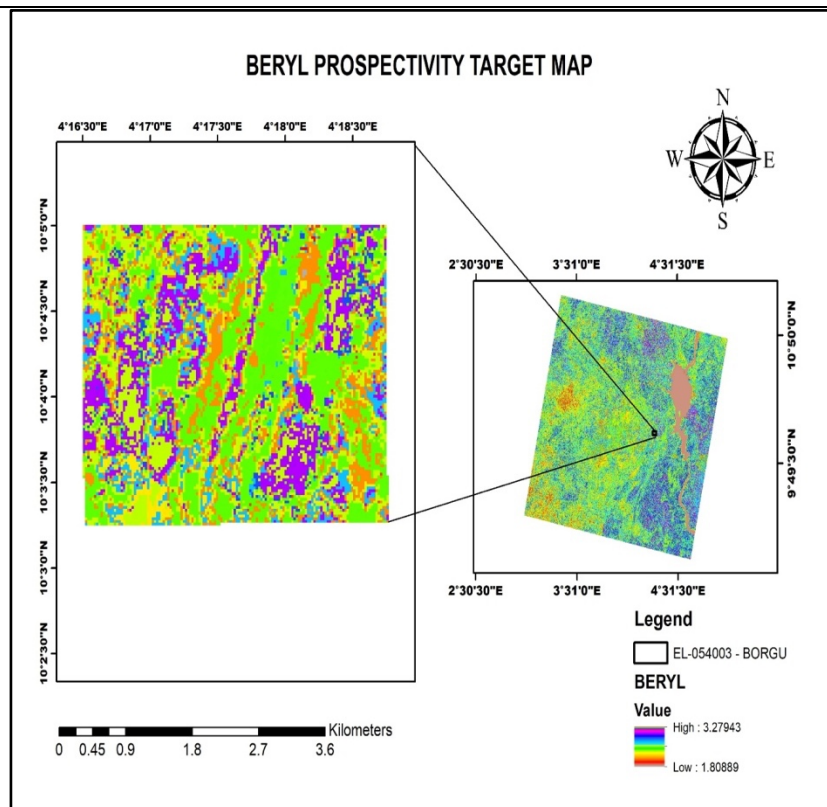


Figure 20: Beryl prospectivity map

The tourmaline prospectivity map (Figure 21) was developed using a multi-criteria weighted overlay of the Quartz (Silica) Index, Clay Mineral Index, Iron Oxide Index, Ferrous Mineral Index, and NDVI. This combination of spectral parameters is designed to capture key geochemical and alteration signatures associated with boron-rich pegmatitic and hydrothermal systems in which tourmaline commonly forms. Zones of highest prospectivity are delineated by the spatial convergence of strong silica enrichment, pronounced clay alteration, and elevated iron oxide responses, together with moderate ferrous mineral signatures, within areas of low vegetation cover. These integrated anomalies are indicative of complex hydrothermal alteration environments, where silicification, oxidation, and mica-related processes collectively reflect fluid evolution and mineral precipitation. The presence of iron oxide enrichment in conjunction with silica and clay alteration further suggests potential oxidation of primary mineral phases and the development of alteration halos surrounding pegmatitic intrusions. Consequently, these zones are interpreted as favorable targets for tourmaline-bearing mineralization and may also represent broader rare-metal-enriched systems associated with highly fractionated granitic sources.

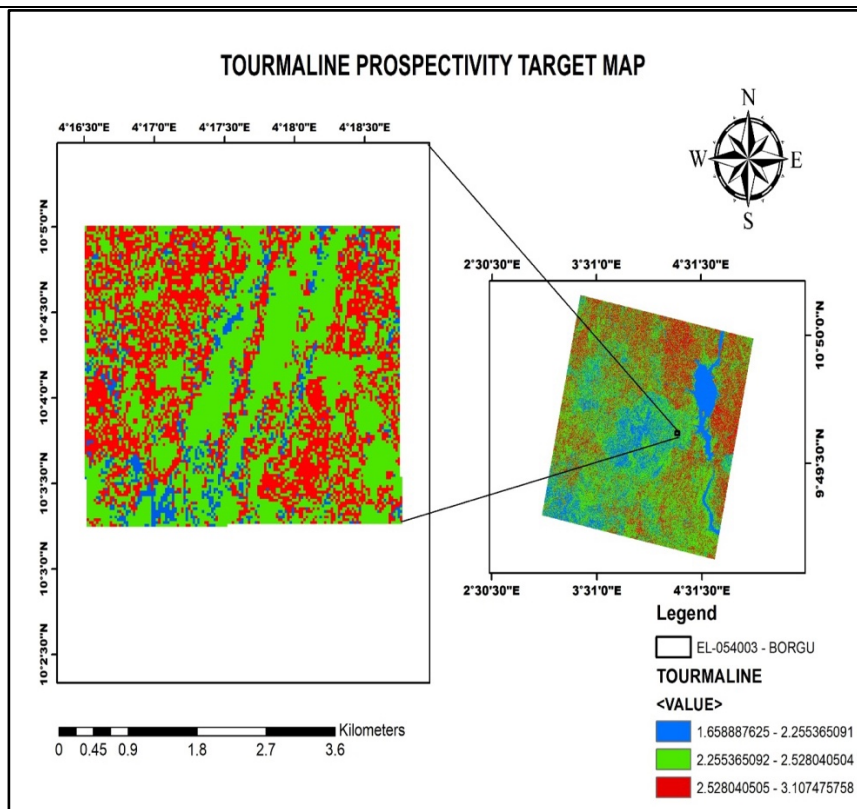


Figure 21: Tourmaline prospectivity map

The lithium prospectivity map (Figure 22) delineates distinct high-anomaly zones predominantly concentrated in the southwestern and eastern sectors of the study area, with prospectivity values ranging from 2.05 to 3.65. These elevated responses are interpreted as indicative of zones with enhanced potential for lithium mineralization, likely associated with pegmatitic intrusions and structurally controlled emplacement within the basement terrain. The spatial clustering of high-value anomalies suggests localized zones of mineral enrichment, potentially corresponding to Lithium–Cesium–Tantalum (LCT) pegmatite bodies emplaced along favorable structural corridors. In contrast, moderate prospectivity zones are more diffusely distributed around the high-anomaly cores and are interpreted as dispersion halos. These halos may reflect secondary geochemical redistribution processes, including weathering and lateral migration of lithium-bearing components away from primary source zones. The observed spatial pattern—characterized by well-defined anomaly cores surrounded by moderate-intensity zones—provides a coherent exploration model, wherein high-value zones represent primary targets, while the surrounding moderate anomalies can be used to guide vectoring toward the center of mineralization. Consequently, the southwestern and eastern anomaly clusters are identified as priority targets for detailed field investigation, including geochemical sampling and subsurface validation.

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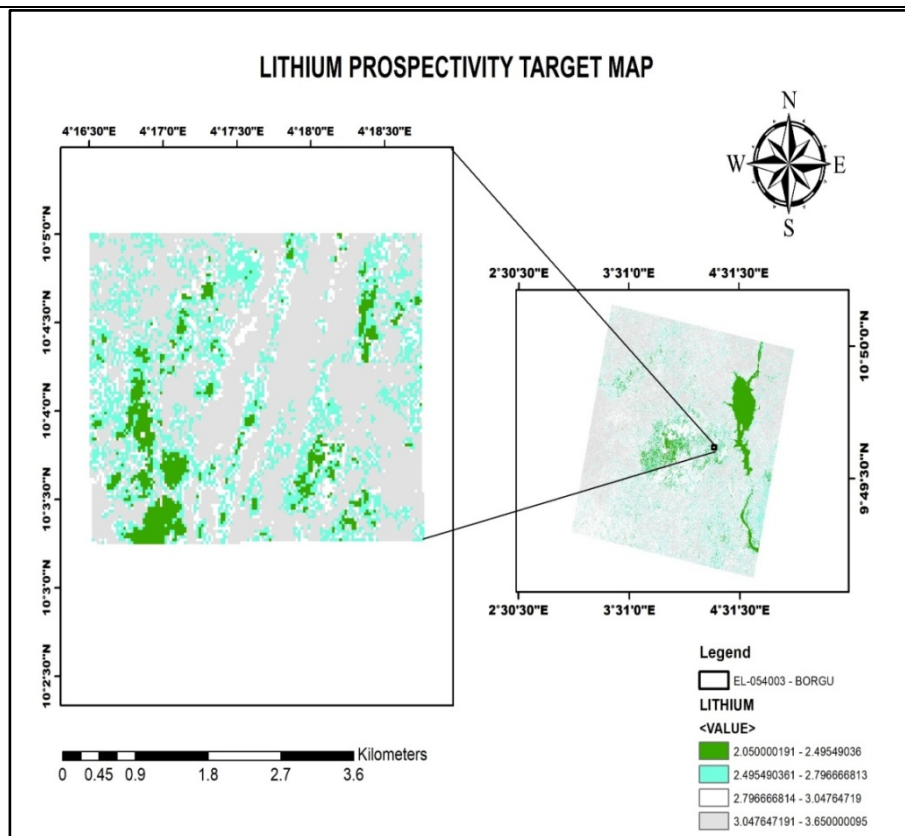


Figure 22: Lithium prospectivity map

Target ID	Longitude	Latitude	Primary Target
1	4° 16' 45"	10° 04' 00"	Gold
2	4° 17' 15"	10° 03' 45"	Gold
3	4° 17' 00"	10° 03' 15"	Gold
4	4° 17' 30"	10° 04' 30"	Beryl
5	4° 18' 00"	10° 03' 30"	Beryl
6	4° 17' 12"	10° 04' 00"	Beryl
7	4° 17' 00"	10° 03' 30"	Tourmaline
8	4° 16' 30"	10° 03' 30"	Lithium/Tourmaline
9	4° 18' 00"	10° 03' 45"	Lithium
10	4° 17' 00"	10° 03' 25"	Lithium

Table 1: Summary of identified exploration targets

6. Discussion

6.1 Structural Controls on Mineralization

The dominant NE–SW structural orientation identified in this study is consistent with the regional tectonic framework of the Nigerian Basement Complex within the Pan-African Mobile Belt (Feybesse and Milési, 1994; Perrouty et al., 2012). These structures are interpreted as products of Pan-African transpressional deformation and are widely recognized as fundamental controls on mineralization across the West African region. In particular, the intersection of NE–SW and subordinate NW–SE structural trends, as delineated from the 2VD analysis, represents zones of enhanced structural complexity. Such intersections are commonly associated with localized dilation and increased permeability, thereby facilitating hydrothermal fluid focusing and subsequent gold deposition (Robert and Poulsen, 2001). The occurrence of magnetic low anomalies within the TMI dataset is characteristic of magnetite-depleted lithologies typically associated with Lithium–Cesium–Tantalum (LCT) pegmatite systems. Comparable magnetic signatures have been documented in established pegmatite provinces across Namibia, Senegal, and other segments of the West African Craton (Miller et al., 2009; Lambert-Smith et al., 2016). The spatial coincidence of these magnetic lows with radiometric anomalies enriched in potassium and thorium further substantiates the presence of highly evolved granitic systems, which are conducive to rare-metal mineralization.

6.2 Comparison with Regional Studies

The results obtained in this study are in strong agreement with previous investigations of mineralization within the Nigerian Basement Complex. Comparable structural controls have been reported by Ekeleme et al. (2024), who identified shear zones and pegmatite intrusions within migmatite–gneiss terrains as key hosts for Pb–Zn–Fe–Au mineralization in north-central Nigeria. Similarly, the radiometric signatures observed in the Borgu area are consistent with those documented in other Nigerian pegmatite provinces, where elevated potassium and thorium responses are indicative of evolved granitic and pegmatitic systems (Akoh et al., 2015; Chukwu and Obiora, 2021). Furthermore, the inferred potential for orogenic gold mineralization aligns well with established metallogenic models for the West African Craton. Orogenic gold systems, typically formed under mesothermal conditions (Groves et al., 1998), are compatible with the metamorphic and structural evolution of the Nigerian Basement Complex. The structural architecture observed in the Borgu area—characterized by major shear zones, subsidiary fracture networks, and competent host lithologies—bears strong resemblance to the geological settings of significant gold deposits in Mali and Burkina Faso, thereby reinforcing the regional exploration significance of the study area.

6.3 Implications for Exploration

The integration of aeromagnetic, radiometric, and remote sensing datasets demonstrates a robust and cost-effective framework for mineral prospectivity assessment within the Borgu Basement terrain. The relatively shallow depth to magnetic sources (120–180 m), as estimated from SPI analysis, indicates that potential mineralized zones are accessible using preliminary exploration techniques such as trenching and pitting prior to drilling. The ten priority targets delineated in this study provide a structured basis for subsequent exploration activities. In particular, zones exhibiting coincident lithium prospectivity, favorable structural settings, and well-defined hydrothermal alteration signatures—especially within the southwestern and eastern sectors of the study area—should be prioritized for detailed field validation. Additionally, structurally controlled gold targets located at lineament intersections and associated with strong alteration anomalies represent key sites for focused geochemical sampling and subsurface investigation.

7. Conclusions and Recommendations

7.1 Conclusions

This study demonstrates the effectiveness of an integrated geophysical and remote sensing approach for mineral prospectivity assessment within the Borgu Basement terrain, northwestern Nigeria. The geological framework, dominated by granite gneiss of the Nigerian Basement Complex, provides a structurally and lithologically favorable setting for both rare-metal pegmatite mineralization and structurally controlled orogenic gold systems. Aeromagnetic interpretation reveals a dominant NE–SW structural architecture, interpreted as a major control on fluid migration and the emplacement of pegmatitic intrusions. The identification of extensive magnetic low zones is consistent with magnetite-depleted felsic lithologies typical of Lithium–Cesium–Tantalum (LCT) pegmatite environments. Radiometric data further support this interpretation, with potassium and thorium enrichment indicating the presence of highly evolved granitic systems associated with rare-metal mineralization.

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Complementary remote sensing analysis delineates significant hydrothermal alteration signatures, including iron oxide enrichment, argillic alteration, and silicification, all of which are diagnostic of mineralized systems. The integration of structural, radiometric, and spectral datasets enabled the systematic delineation of ten priority exploration targets across the study area. Furthermore, the relatively shallow depth to magnetic sources (120–180 m), as derived from Source Parameter Imaging, suggests that potential mineralized zones are accessible for near-surface exploration and preliminary economic evaluation. Overall, the results emphasize the critical role of lithological composition, structural architecture, and hydrothermal processes in controlling mineralization within the Borgu area, and highlight its significant exploration potential within the Nigerian Basement Complex.

7.2 Recommendations

To validate and refine the mineral prospectivity model developed in this study, targeted field-based investigations are essential. Detailed geological mapping should be conducted within the delineated priority zones to confirm lithological relationships, structural controls, and the occurrence of pegmatitic and quartz vein systems. Ground verification of remotely identified alteration anomalies is also necessary to establish their direct association with mineralization. Systematic geochemical surveys, including soil, stream sediment, and rock sampling, are recommended, particularly along major structural corridors identified from aeromagnetic interpretation. These surveys will provide critical geochemical constraints for refining target selection. In addition, detailed petrographic and mineralogical characterization of pegmatite bodies should be undertaken to evaluate their degree of fractionation and rare-metal potential. Follow-up ground geophysical investigations—such as high-resolution magnetic surveys, electrical resistivity tomography (ERT), and induced polarization (IP)—are required to enhance subsurface resolution and constrain the geometry of mineralized structures. In areas where structural, geochemical, and radiometric anomalies coincide, shallow trenching and pitting are recommended to directly expose and sample mineralized zones. Finally, where integrated datasets continue to indicate significant mineralization potential, a phased exploration drilling program should be implemented to assess depth continuity, grade distribution, and the overall economic viability of the identified targets.

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