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Geological mapping and structural analysis from satellite imagery of a section of the Adamawa Massif: Implications for mineralization

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Abstract

This study provides a comprehensive geological mapping and structural analysis of lithological units within a portion of the Adamawa Massif in northeastern Nigeria, emphasizing their implications for mineralization. Using a scale of 1:50,000, we identified ten distinct lithological units, predominantly belonging to the Older Granites suite, which reflect the Pan-African Orogeny. Lineament density was quantified as the number of lineaments per grid-unit area and classified into nine spectral bands ranging from 0 to 4. The 214 km^2 study area was divided into 15 equal grid cells. Four of these cells, located in the northwestern mountain ranges, exhibit high lineament density and encompass 57.08 km^2 (26.7 % of the total area). In contrast, the remaining eleven cells, characterized by low lineament density, cover 156.97 km^2 (73.3 %). The highest-density category (Band 7) occupies only 14.27 km^2, amounting to 10 % of the study area. Structural trends in the region are primarily NNW–SSE and NNE–SSW within the banded gneiss, and NNW–SSE and N–S within the medium-grained granite. These joint systems serve as potential conduits for mineralizing fluids, underscoring the area's prospective mineral resources.

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1. Introduction

Exploration geologists have long relied on ground geologic mapping as a foundational tool for understanding subsurface structures, lithologies, and the spatial distribution of mineral resources [1]. This traditional approach, characterized by field-based observations and detailed mapping, provides critical insights into the geological framework of an area, thereby guiding subsequent exploration activities [2]. However, the advent of remote sensing technologies has revolutionized the field, offering new dimensions of analysis that complement and enhance ground-based methods. Remote sensing, encompassing a range of technologies such as satellite imagery, aerial photography, and geophysical surveys, allows for the acquisition of high-resolution data over large and often inaccessible areas [3].

These techniques enable the detection of surface anomalies, structural features, and mineralogical compositions that might be overlooked in conventional field mapping. The integration of ground geologic mapping with remote sensing provides a

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synergistic approach, leveraging the strengths of each method to yield a more comprehensive and accurate understanding of geological settings [3]. This article explores the combined application of ground geologic mapping and remote sensing in the context of minerals. This study aims to demonstrate the enhanced efficacy and precision in identifying and characterizing mineral deposits, ultimately contributing to more efficient and successful exploration strategies.

In certain instances, lineaments have been seen to be structurally regulated mineralized zones [4] or areas with possible mineralization and shallow water sources; this is more likely to occur when surface vegetation aligns with lineaments. A lineament's surface features can be tonal, created by contrast variations, geomorphological, or generated by relief. Lineaments are typically expressed geomorphologically as straight stream/river valleys and aligned portions of valleys [5]. A straight-line dividing sections of tone contrast can be considered a tonal lineament. The majority of tonal differences are caused by variations in vegetation, moisture content, and soil or rock composition [6].

Generally speaking, edges are identified by minute variations in image brightness and can be challenging to identify from linear features. Lineaments can occur wherever on Earth as: (1) straight streams, rivers, and valleys; (2) aligned surface depressions; (3) soil tonal changes; (4) vegetation alignments; (5) variations in vegetation kind and height; or (6) abrupt topographic changes. Geologic features that cause deformation, such as faults, joint sets, folds, cracks, or fractures, may be the cause of all of these mineral concentration processes, including the creation of structural traps, the formation of mineralized veins, the localization of ore deposits, and the enhancement of permeability pathways for hydrothermal fluids, which are critical in the exploration and discovery of economically viable mineral resources. Because many geological lineaments are old, they are typically covered by younger sediments [7]. Arrays of brittle structures are exposed on the surface topography when these structures reactivate. Similar to this, a wide zone of distinct lineaments may represent the surface representation of a deep-seated lineament [8].

1.1. Location of the study area

The study area is located between latitudes 8°48′N to 8°58′N and longitudes 12°30′E to 12°38′E (Figure 1) in Fufore LGA, Adamawa State. The area is roughly 214 km^2 in total land area. About 80% of the region is below 300 meters above sea level, and the remaining 20% is made up of hills and mountains, making the area considered low-lying [9]. Its borders are as follows: Yola City to the west, Fufore Town to the north, Toungo and Jada Towns to the south, and the Cameroon Republic to the east. The Chamba, Verre, and Fulani speaking tribes live in the region, which is known for its rural landscapes. Along with smaller rivers like Mayo-Ine, the region is mostly drained by the River Benue and Lakes Pariya, Gobako, Gerwedi, and Kapo.

The primary means of subsistence for the populace is agriculture, with maize, guinea corn and groundnuts being the main crops farmed. Other pursuits include fishing and raising animals. The locals get their water from surface sources like lakes, ponds, and streams, and from subsurface sources such as shallow boreholes and hand-dug wells [10]. Seasonal variations in temperature and humidity are seen in the area, with distinct dry and rainy seasons. April through October is considered the wet season, with 750–1000 mm of yearly precipitation on average. The region experiences dry, dusty, and foggy northeast trade winds that originate in the Sahara Desert during the dry season, which runs from December to March [11].

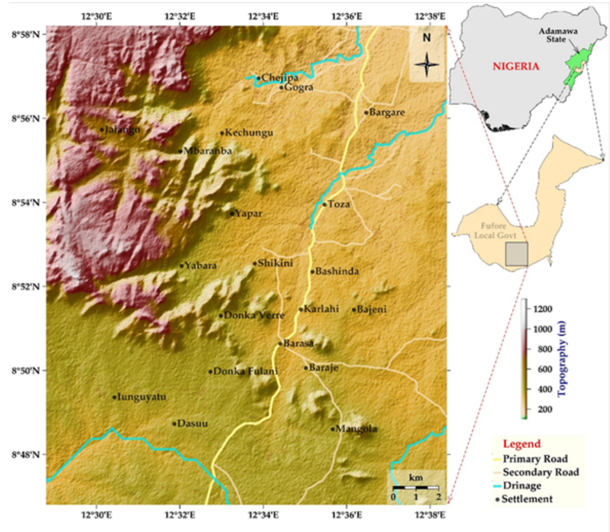

Figure 1. Topographic map of study area in Fufore LGA of Adamawa state

Accessibility in the area is fairly good. It is accessible through the Yola-Gurin major road, where it branches off to the right at Wuro Ardo community towards Karlahi ward. A motorable road passes from Wutire (the northern part) through Toza, Bunto, Karlahi, and Rajiya (the eastern half) and goes westwards to Turpa in the southwestern part respectively (Figure 1).

1.2. Topography

The general elevation of the study area shows that the northwest, west, and part of the southeast consist of craggy tors and ridges with high elevation (Figure 1), while the east and northeastern as well as parts of the southwest, are dominated by lowlying landmass. The elevations range from about 243.84m to 914.4m above sea level. The areas around Baraja, Bunto, Toza, Kila Sakra Lugunyatu, Gogra, and Wuromati constitute the lowland areas, while areas around Mamlaipa, Barki Pa, Baraje, Sabon Gari Koma, Kila Sakra and Donka Fulani constitute the high-elevation places respectively.

2. Materials and Methods

The materials used for the geological fieldwork were a GPS, a Clinometer, a Marker, a Hammer, Satellite imagery (SPOT 5 and SAT-X), and a Topographic Map of the Study Area. Others were software for interpretations, the ARC GIS 10. The research work followed a series of systematic approaches to the various activities that were carried out as follows: field mapping to identify various rock types and units and acquisition/interpretation of satellite imagery data over the study area.

2.1. Geologic mapping

The geologic field work started with a reconnaissance survey of the study area to be familiar with the people, and terrain and to establish suitable mapping method(s). In the end, three methods of traverses were applied. These were; road traversing, river/Stream traversing, and compass traversing [12]. Detailed geologic fieldwork was done and different rock units were delineated, geologic structures and their orientations were measured, and careful observation of rock exposures in the study area. The area being a basement terrain, the emphasis was on lithologic differences to establish different lithologic units and appropriate/inferred geologic boundaries. Exposures of different rock types were mapped along river channels, road cuts as well as the base and top of the hills. Description of different lithological units, sampling, and photographs of features were orderly and recorded appropriately in the field notebooks [13]. Fresh representative rock samples from different lithological units were collected and labelled accordingly. Similarly, major and minor structures were mapped appropriate measurements were recorded for analysis. The systematic traverse mapping method of observing geologic structures in the study area which covers approximately 214 km^2 by using the base map of the area as a guide [14]. Equipment used is the base map, Brunton-type compass clinometers for recording directions and measuring the angle joints and fractures, geologic hammer for chipping of rock samples, sample bag, field notebook/pen and pencil for recording observations, and marker for labelling and measuring tape for measuring linear structures. At the end, a detailed geologic map of the study area was produced using the ARC GIS 10 software.

2.2. Satellite imagery data

Satellite imagery data over the study area was acquired from the Nigeria Centre for Remote Sensing, Jos, Plateau State. Data from two different satellite imageries were used the SPOT-5 and Nigeria SAT-X with a resolution of 22 meters to enhance and improve the visibility of the lineaments over the study area. To improve the understanding of the linear characteristics, processing procedures including histogram equalisation and filtering were applied to the satellite imagery using ArcMap 10.3, a part of ARC GIS. To improve the perception of the lines that trend in different directions filters such as the line horizontal, line vertical, line diagonal right, and line diagonal left were applied.

It is important to use caution when critically analysing an image to distinguish between geological and artificial structures when mapping important lineaments for groundwater and mineral prospecting [15]. With Digital Elevation Models (DEM), an accurate representation of relief may be plotted together with extensive topographic analysis for geological features and rock boundaries that exhibit a correlation with relief. Geological, hydrological, and mineral research is increasingly employing digital elevation models for terrain analysis [16]. Distinct features are created from linear features that are not visible on traditional maps. In geological and geomorphological research, three-dimensional representations of the Earth's surface and their analysis at various lighting angles and orientations are helpful [17].

A 30 m resolution DEM was employed for this investigation. The lack of vegetation and the majority of man-made structures within DEM contribute to its utility in allowing the delineation of geological formations, rock boundaries, and drainage patterns inside densely vegetated and built-up areas. The spatial resolution of the images has a significant impact on the derived lineaments' correctness. A lineament map with greater resolution images has better quality.

In structural mapping, disparate data sets with the same spatial reference were integrated using ArcMap to extract shared or unique information between the sets. ArcMap exhibited all the different data sets, such as the Nigeria Sat-X and Spot 5 pictures, curvature, drainage, and shaded terrain maps. Mapping was done by examining each layer separately and contrasting it with other layers in the GIS environment. The geological map was helpful since it indicated that the majority of the study area's rock types were distributed on the surface in the northwest. Examining geographically referenced features is one benefit of working in a GIS environment with many data sources. In a GIS setting, it is possible to study a feature that is more prominent in one data set than it is in another. A shapefile was made in ArcCatalog and assigned to the same coordinate system and spatial reference as the other data sets to begin digitising the lineaments. The lineaments seen from the various data sets were then mapped out on the screen using the digitising tool.

3. Results and discussion

3.1. Geological mapping

Geologic mapping of the area was done on a scale of 1:50,000 revealing that the area was underlain by ten (10) lithological units (Table 1). Most of these lithological units are demarcated by topographic forms, which in most cases reflect the geology of the underlying rocks. The Older Granites suite which constitutes about 60% of outcrops (Figure 2) in the area is the most obvious manifestation of the Pan-African Orogeny in this part of Nigeria and West Africa [18]. The formation of these features results in boulders, rugged tors with steep sides, sub-elliptical plutons, and masses with batholithic dimensions (Figure 3a). These features are found in and around the areas of Korkai, Lugga Chamba, Karlahi Chamba, Mamlaipa, Donrupa, Bongladi, and Begni. Low-lying and occasionally flat outcrops of banded gneisses, quartz dyke, and amphibolite are found in certain areas (Figure 3b), particularly in the vicinity of Baraje, Belwa Gite, Donkan Vera, Sabon Gari Koma, and Kila Sarka. These lithological units are grouped into two.

The major rock unit consists of mappable lithologic units, which consist of three (3) lithologies, namely, banded gneiss,

Table 1. Generalized list of Basement Complex rocks in the study area.

Age		Rock units
Lower Paleozoic	Intrusive	Pegmatite
		Aplite
		Quartz-veins
		Dolerites
		Fault rocks
		Quartz dyke
	Older Granites	Coarse-grained
		Medium grained
Pre-Cambrian	Metamorphic Complex	Banded gneiss
		Amphibolite

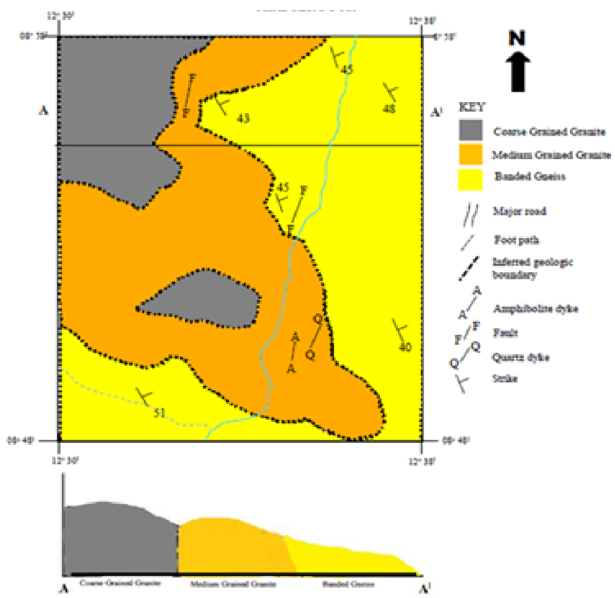

Figure 2. Geological map of the study area

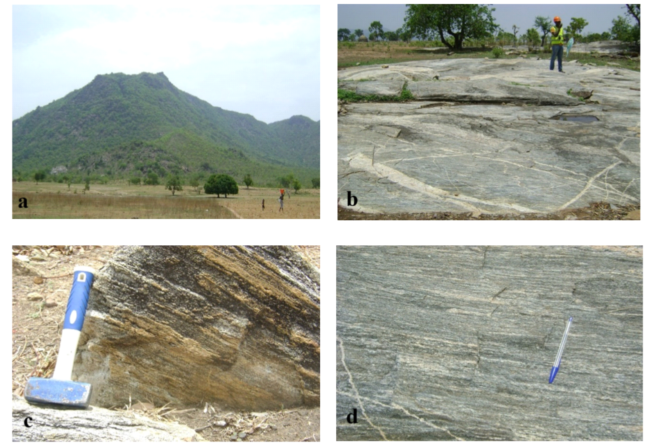

Figure 3. (a) Craggy tors at Donrupa, (b) Low-lying exposures of banded gneiss north of Kila Sakra (c) Banded gneiss at Wuromanti (d) Banded gneiss at Rajiya

medium-grained granite, and coarse-grained granite. Approximately 40% of the rock formations in the region are made up of huge, low-lying, and short ridges composed of banded gneiss. A few boulders with a radius of roughly one to three meters were also seen strewn throughout the medium-grained granite foundation north of the localities of Jakada, Balwa Gite, Kila-Sakra, and Rajiya, respectively. Two varieties of the rock are exposed in the study area. The first variety outcropped in the northeastern and eastern parts of the mapped area in places such as Bargare, Wuromati, and Bahausa. These varieties are short ridges, medium to coarse-grained with almost consistent thickness and length of alternating leucocratic and melanocratic bands (mafic and felsic components) that are mostly contoured and filled in some places with coarse quartzofeldspathic materials that nearly deflected the gneissosity of the rock (Figure 3c).

The bands are regular, sometimes discontinuous, and cross-cutting along shear planes. The alternating bands range on average from about 2 to 3 cm (with few variations) across and are generally conformable with the regional structural trend. There also occur other bands in which the distinction with the enclosing gneisses is more lithological than mineralogical It consists of abundant quartz and feldspar minerals. They also exhibit varying degrees and trends of weak foliations marked by varied sizes, amounts, and orientations of feldspar porphyroblasts. The second variety outcropped in the southern and southwestern parts of the map at Rajiya, Belwa Gite, Kila-Sakra, and Turpa respectively. The exposure occurred low-lying and massively at the base of medium-grained granite. It consists of regularly layered dark-grey bands alternating with layers of light bands (Figure 3d).

More commonly, however, the leucocratic bands are subordinate to the dark grey, show well-defined boundaries, and form strings of 2 and 3 cm depending on the outcrop. The persistence of individual bands is variable and may locally be such that they maintain their identity for considerable distances within an outcrop. Banded gneiss in shear zones may host sulfide mineralization, as fluids migrate along fractures during deformation. Gold deposits often occur in association with gneissic terrains, especially where quartz veins or shear zones intersect them, and can contain mica, feldspar, or garnet, which are valuable for industrial applications.

It is strongly jointed, with joint directions averaging N-S (1700), and has weakly developed foliations with medium dip and mineral lineation angles. The dip attitudes are irregular, and the azimuth varies over short distances. The dips range from 250 to 400 southeast. Other cross-cutting features observed on the rock units are micro faults, micro folds, pegmatite veins, quartz veins, and dolerites. The exposures are adversely affected by weathering in some places, especially along the river channels. The outcrop has a gradational boundary with the surrounding rock units.

The medium-grained granite, constituting approximately 40% of the study area, is a significant component of the neosomes within the banded gneiss complex. This granite outcrops predominantly as craggy tors in the central and northern parts of the study area, particularly around Donka Verre, Karlahi, Yapar, Bashinda, Bongladi, Dongi, and Gogra. These outcrops are observed as concordant or discordant intrusive bodies of varying widths and as sub-rounded to rounded boulders of diverse sizes. Their colouration ranges from light to dark hues, with some weak foliation and noticeable fractures (Figure 4a).

Petrographic analysis reveals a composition primarily of feldspar, biotite, and quartz, with the latter two constituting the dominant minerals. These minerals display interlocking grain textures. Despite relative homogeneity across the study area, minor variations in colour and mineral composition are noted. Associated structural features include quartz veins, joints, pegmatites, and xenoliths of banded gneiss. The medium-grained granite's mineralogical and structural attributes highlight its potential for hosting mineral deposits, particularly quartz-related minerals and pegmatite-hosted resources. Coarse-grained granite forms about 20% of the lithological units in the study area. These granites occur as in-situ boulders, ranging from 1 to 10 meters in radius, and are found primarily in high ridges and craggy tors in the northwestern regions, including Mbaranba Hills, Shikini Hills, and Bongladi (Figure 4b). The rock is predominantly light to greyish in colour, coarse-grained, and composed of quartz, biotite, hornblende, and feldspar phenocrysts that exhibit a whitish to creamy hue.

The coarse-grained granite shows weak foliation, defined by the orientation of mafic minerals, and is extensively affected by spheroidal weathering. Notable structural features include quartz veins, pegmatites, dolerites, joints, and aplites. These characteristics make the coarse-grained granite a potential target for mineral exploration, particularly for feldspar, mica, and hornblende, which are economically valuable in industrial applications.

The study area also contains eight minor lithological units, including amphibolite, quartz dykes, quartz veins, pegmatite, aplite, dolerite, and fault rocks. These units, although unmappable on a large scale, play a crucial role in understanding the region's mineral potential.

Figure 4. (a) Medium-grained Granite at Yapar (b) Coarse-grained granite at Bongladi (c) Amphibolite dyke at Baraji (d) Fault rock at River Longmiri

3.2. Amphibolite

This unit is exposed as massive, low-lying dykes intruding medium-grained granite and, occasionally, banded gneisses. In the Baraje area and southeast of Karlahi, the amphibolite exhibits a dark-gray to greenish-black hue with textures ranging from fine- to coarse-grained. It is composed predominantly of hornblende, with subordinate quartz, feldspar, and epidote. These dykes strike north–south (50°) and measure between 2.5 and 3 meters in thickness. Their sharp contacts with the host rocks, together with associated fractures, enhance the exploration potential for amphibole minerals (Figure 4c).

3.3. Fault Rocks

Fault rocks, observed at Bongladi, River Yasipa, River Toza, and River Longmiri, display fractured, fragmented, and brecciated textures. They contain angular to sub-angular clasts and show evidence of differential grain movement within the pre-existing lithologies (Figure 4d). The coloration varies from creamy white to pinkish, often with distinct banding. Most fault zones trend north–south (350°), with subordinate orientations in the NE–SW and NW–SE directions. These zones act as seasonal waterways, reflecting structurally controlled drainage patterns and potentially serving as conduits for mineral-bearing fluids. The brecciated matrix and sharp contacts with the country rocks underscore their significance for hydrothermal mineral exploration.

The lithological units in the study area are bounded by both gradational and abrupt contacts. Structural elements—such as fractures, joints, and veins—provide pathways for fluid migration and mineral deposition, highlighting the region's potential to host economically significant mineral deposits. The interplay between rock-unit characteristics and structural controls emphasizes this geological setting's suitability for targeted mineral exploration activities.

Quartz dykes in the study area are observed as low-lying silicified boulders of various sizes and shapes, predominantly located east of Karlahi (Figure 5a). These dykes are composed mainly of sutured hexagonal quartz crystals, indicative of pegmatitic or hydrothermal origins within the medium-grained granite suite. The boulders typically measure an average of 30 cm by 70 cm or larger in diameter. Their colouration ranges from dirty brown to dirty white, although fresh samples appear white to milky white. Scattered poorly developed quartz crystals were also observed around the outcrops. Mineralogically, these dykes consist predominantly of quartz with minor muscovite flakes, suggesting potential mineralization zones of interest for quartz and associated mica resources.

Quartz veins and lenses are widespread, cross-cutting the basement rocks, particularly the Older Granites. These veins exhibit considerable variation in thickness, ranging from a few centimetres to about a meter, and occur across all rock units in the area (Figure 5b). The irregularities in their morphology likely reflect diverse formation processes. In some locations, the veins thin out, widen or change orientation. Large quartz veins are often associated with muscovite plates and, occasionally, biotite. Some veins exhibit concordant relationships with

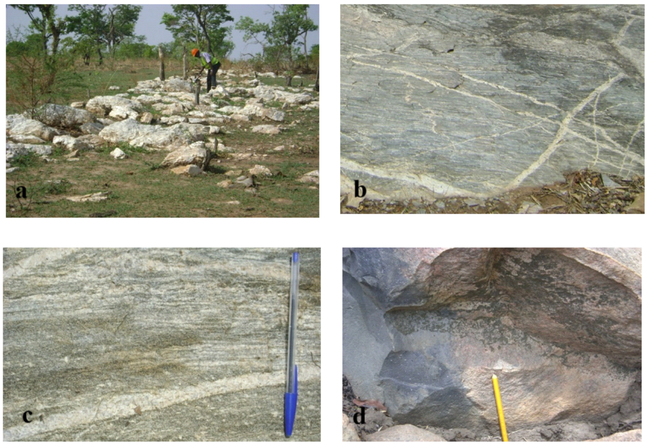

Figure 5. (a) Quartz dyke east of Karlahi (b) Quartz veins between Turpa and Kila-Sakra (c) Aplite in banded gneiss at Kila-Sakra (d) Dolerite dyke (left of pencil) at Bangere

their host rocks, showing deformation consistent with tectonic events affecting the host. In contrast, most veins are structureless and discordant, indicating multiple episodes of quartz emplacement. The structural and mineralogical features of these veins underscore their significance in mineral exploration, particularly for quartz and mica deposits.

Aplite rocks are conspicuous as granitic intrusions and veins composed predominantly of quartz, with subordinate feldspar (Figure 5c). These rocks are fine-grained, light-coloured, and granitic in composition. Aplites often occur in association with pegmatites, as observed north of Kila-Sakra. The thickness of these veins ranges from 15 cm to 50 cm, and they frequently display pinch-and-swell structures. These characteristics make aplite rocks an important consideration in exploring quartz-rich and feldspar-bearing lithologies.

Dolerite occurs as tabular, unmetamorphosed bodies intruding gneisses and Older Granites, cross-cutting the foliation in the host rocks. These dykes are fragmented into irregular sizes and shapes and exhibit linear fabrics (Figure 5d). The dolerites are typically black and fine-grained, consisting predominantly of augite and feldspar, with occasional pale green spots of olivine visible in hand specimens. The rocks display a diabasic texture, and the contact with the country rocks is sharp and chilled. The observed dolerite dykes generally trend N-S, with variations in NE-SW orientations that align with the regional structural trend of the basement complex. The thickness of these dykes ranges from a few centimetres to several meters. Their intrusion represents a late-stage event in the evolutionary history of the basement complex and provides valuable insights into the region's magmatic and tectonic history. The dolerite's mineralogical composition and structural relationships make it a potential exploration target for mafic mineral deposits.

Pegmatitic rocks are widespread throughout the study area and are found associated with all the lithologic units. They consist mostly of plagioclase microcline feldspars and quartz. The pegmatites in the gneisses are conformable but are more commonly cross-cutting with highly irregular forms. In the Older Granites, they are regular tabular bodies with a fairly constant strike and dip and invariably cross-cutting. Most are simple pegmatite veins with central quartz bounded by feldspar. They mostly trend N-S, aligning themselves with the structural trend of the Basement Complex rocks. They are coarse-grained pinkish to creamy white, and vary in size from veinlets to a few centimetres wide and several meters long (Figure 6a). They develop pinch and swell structures occurring side by side with an aplitic body in some outcrops. The contact between the pegmatite vein and the country rock is mostly sharp, but transitional in some places because some remnants of country rock can still be traced continuously across the pegmatite veins. Pegmatites represent the last and most hydrous portion of magma to crystallize and hence contain high concentrations of minerals present only in trace amounts in granitic rocks.

3.4. Structures

The rock units in the study area were affected by uplifting during the Pan-African Orogeny in the Precambrian times and continued into the lower Palaeozoic times [19]. These events led to the development of major as well as minor structures. Major faults were mapped in the area, most especially within the Older Granite series, based on the occurrence of major fault rocks (cataclasites). Massive occurrences of cataclasites were observed within medium-grained granites and gneisses at Bangladi and River Toza. It forms a brecciated/shear zone that is about 50 meters wide and several kilometres long, trending 3300 (Figure 6b). Cross-cutting joints also characterize it.

3.5. Minor faults

Several minor faults resulting in dextral and sinistral displacement occur conspicuously, mostly within the banded gneiss, with few in low-lying granitic bodies. The amount of displacement is often within the range of a few centimetres (Figure 6c). A normal (dextral) fault was observed in banded gneiss with fault planes trending N-S (1900).

Foliations: The area is dominated by weakly developed foliations across all the lithological units. In the banded gneisses, the most conspicuous surface is marked by parallel layers consisting of alternating platy dark and light minerals as well as lithological banding on the other hand. In some places, the bands can be peeled off along micaceous laminae parallel to the lithologic banding. It is also similar to parallel foliation as a result of colour banding observed in some outcrops. They strike 070 and dip 650 E (Figure 6d). The granites display weakly developed foliations which are mostly trending N-S direction. The banding is in the ratio of 2–4 mm to 1–5 cm for felsic and mafic respectively. Generally, over most of the mapped area, the regional strike of the foliation is roughly constant in the N-S direction with variation between NW-SE and NE-SW directions respectively.

Folds are widespread features in the banded gneiss. Most interlimb angles of the folds are 950, a dip of the axial plane is 170, and the plunge is 0350 on average. The forms are variable from open to near isoclinals, and the fold axes maintain a

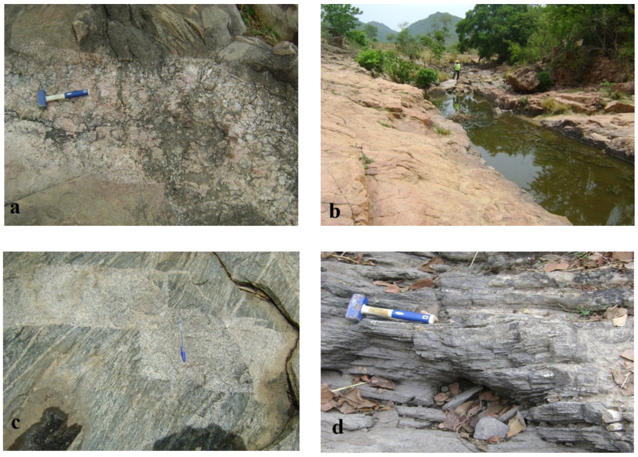

Figure 6. (a) Pegmatite at Mijiyawa (b) Major fault zone at River Bangladi (c) Minor fault at Toza (d) Foliations in banded gneiss at Wuromanti

Figure 7. (a) Folding in banded gneiss at Kila Sakra, (b) Joints in Mylonite at River Bangladi

constant N-S direction with few trending E-W and NW-SE. In some places, the folds tend to be tight with an interlimb angle of about 230, a dip of the axial plane 80 and a plunge of 200 on average. Similarly, the folds tend to be ptymatic and isoclinal in some outcrops (Figure 7a).

Joints were very common in all the lithologies mapped in the area, with dominant ones in the banded gneisses and fault rocks. The joints are mostly parallel to each other except in a few cases where they cross-cut one another (Figure 7b). The joint systems in the study area exhibit three distinct orientations across different lithological units, reflecting the region's structural complexity. In the banded gneiss, joints predominantly trend NNW–SSE, NNE–SSW, and N–S (Figure 8a). Fault rocks exhibit a dominant NW–SE joint trend (Figure 8b), while the medium-grained granites primarily display NNW–SSE and N–S joint orientations (Figure 9).

These joint systems act as potential conduits for fluid flow, facilitating the emplacement of hydrothermal minerals. The variation in joint orientations across lithologies highlights tectonic influences and stress regimes that may control mineral deposition. The NW–SE trend in fault rocks, in particular, suggests structural reactivation zones favourable for mineralization. Understanding these joint patterns is essential for delineating areas with enhanced mineral exploration potential, especially for hydrothermal deposits and structurally controlled mineral systems.

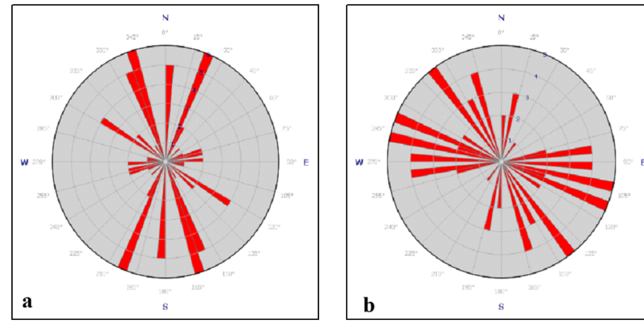

Figure 8. (a) Rose diagram showing joint directions in migmatite banded gneiss at Jakada (b) Rose diagram showing the joint direction in fault rock at River Yasipa

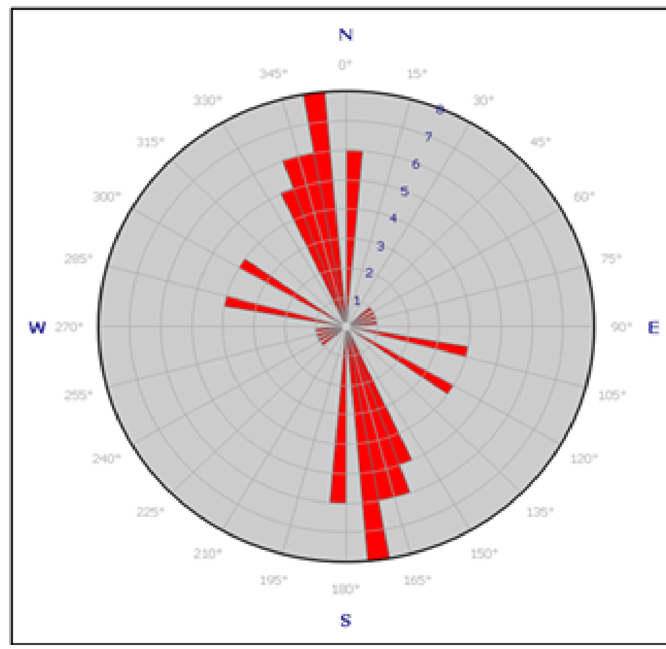

Figure 9. Rose diagram showing the joint direction in medium-grained granite at Yapar

The satellite image (Figure 10) is a georeferenced map that includes geographical coordinates, key landmarks, and areas of interest, particularly labelled settlements or locations. The red-toned colouration suggests a false-colour composite or a processed image designed to highlight geological or vegetation features. The distinct linear and curvilinear features visible in the image may represent geological lineaments such as faults, fractures, or lithological boundaries. These lineaments are crucial as they can act as conduits for hydrothermal fluids, leading to mineralization. The major settlements (e.g., Karlahi, Yasipa, Donruba) appear near regions of high lineament density, which could indicate structurally controlled mineral deposits.

The predominant red hues suggest areas with high reflectance, likely due to exposed soil, barren land, or specific rock types. Areas with lighter tones may correspond to lithological units such as quartz veins, granites, or other silicified rocks. Darker zones could indicate vegetation cover or specific

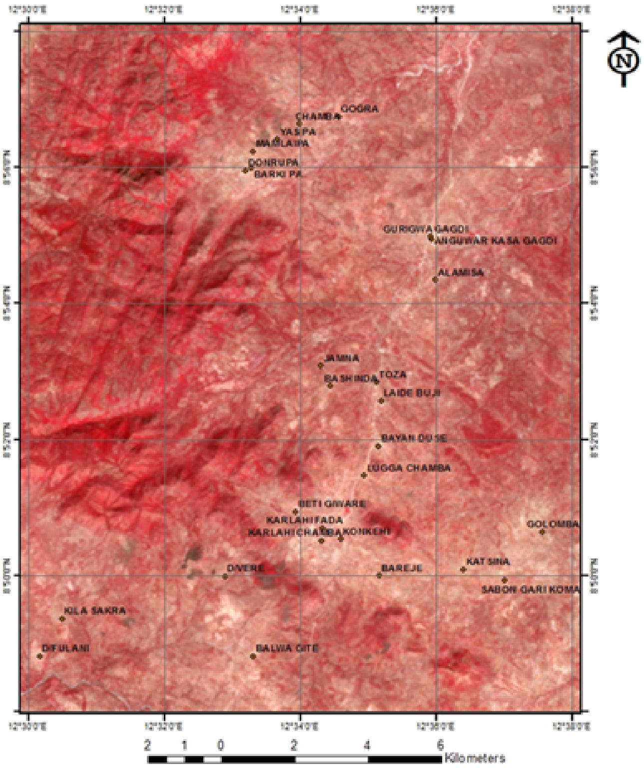

Figure 10. Satellite image of SAT-X of the study area

lithologies with lower reflectance, such as mafic rocks or fault zones. The craggy, rugged appearance in certain areas (e.g., Gogra, Mbaranba Hills) indicates possible rocky outcrops, tors, or ridges. Such features are associated with granite intrusions and other resistant lithologies. These elevated areas may serve as exploration targets for mineral-rich veins (e.g., quartz, pegmatite) or localized mineralization related to igneous activity.

The structural trends visible in the image correspond to the general NNW-SSE, NNE-SSW, and NW-SE joint and fault systems described in the area. These trends are key to targeting potential mineralized zones, particularly for quartz veins, pegmatites, and hydrothermal deposits. Fault intersections and densely fractured zones around Karlahi and Toza could represent enhanced permeability zones for fluid flow and subsequent mineral deposition. Areas near Karlahi, Gogra, and Toza should be prioritized for field investigation based on their structural significance and proximity to mapped geological features like medium-grained granites and fault zones. The lighter-toned regions may indicate quartz-rich lithologies or pegmatites, which are prospective for minerals like feldspar, mica, and rare earth elements. River systems in structurally controlled areas (e.g., River Yasipa, River Toza) could serve as secondary exploration targets for placer deposits or alluvial mineralization.

The SPOT-5 satellite image (Figure 11) showcases a detailed false-colour composite with clear topographic and structural features. The resolution and visual data in the image make it particularly useful for identifying geological features relevant to mineral exploration. The image reveals prominent lineaments, particularly trending NW-SE and NNW-SSE. These structures may represent fault zones or fracture systems, which are critical for mineral exploration as they can serve as conduits for mineralizing fluids. Areas such as Karlahi, Bongladi, and Toza show dense clusters of these lineaments, suggesting potential zones for hydrothermal mineralization. The river systems (e.g., River Yasipa and River Toza) appear to follow structural trends, indicating structural control. These regions could host secondary mineral deposits, such as placer gold or heavy mineral sands. Differences in tonal contrasts across the image may correspond to variations in lithological units.

Lighter-toned areas, particularly around Karlahi, Beti Giware, and Donruba, could represent granitic outcrops or quartz-rich lithologies. These are often associated with rare metal deposits (e.g., tungsten, tin, or lithium). Darker zones, such as those around Kila Sakra and Golomba, may indicate denser rock types like amphibolites or mafic intrusions, which could host base metal mineralization (e.g., nickel or copper). Rugged topographies, such as those near Mbaranba Hills, suggest areas of exposed bedrock, potentially granites or quartz veins. These regions are prime targets for pegmatitic mineral exploration. The reddish tones in the image may indicate zones of hydrothermal alteration or weathered surfaces. Alteration minerals such as hematite, limonite, or kaolinite are common in mineralized zones. Specific areas, such as Karlahi Fada, may warrant geochemical sampling to confirm the presence of alteration minerals. Locations like Bareje and Sabon Gari Koma are positioned in regions where quartz veins and associated pegmatites have been reported. These areas could host metallic ores such as gold, silver, or tin.

The density of lineaments can be expressed in various ways; in this study, it is expressed as the number of lineaments per grid unit area (Figure 12). The map reveals that the density is divided into 9 spectral bands of lineament density distribution with an assigned band value of 0 – 4. The study area of 214 km^2 was divided into 15 grid areas, each covering approximately 14.27 km^2. Four grid areas, which are located along the mountain ranges in the Northwestern portion of the study area, are relatively covered by lineaments representing 57.08 km^2 or 26.7%. Eleven grid areas characterized by low density of lineament distribution covered most of the study with an area of 156.97 km^2 or 73.3% of the total study area. In addition, the highest lineament density range is Band 7, which occupies only 14.27 km^2 or 10% of the study area. This area is inhabited due to high mountain ranges, and the area is heavily forested. The area with a high percentage of interconnectivity of the lineaments is shown in grids 7, 11 & 13, covering an area of 42.81 km^2 or 20% of the study area. The area with the highest density in band value of 0-4 representing lineaments alone is 25% of the total lineaments observed in the study area. The major part of Karlahi is characterized by the absence of lineaments to low lineament density. Figure 13 shows the lineament density map of the study area, which describes the concentration of the lineaments.

The present study is aimed at delineating mineral potential zones using ground geological mapping and remote sensing data. The geology of the study area consists of coarse-grained

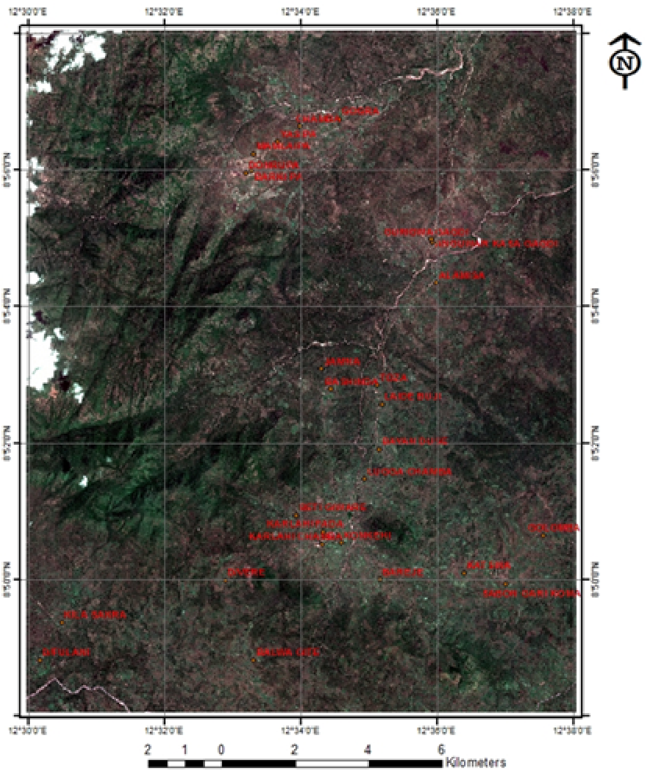

Figure 11. Spot 5 satellite image of study area

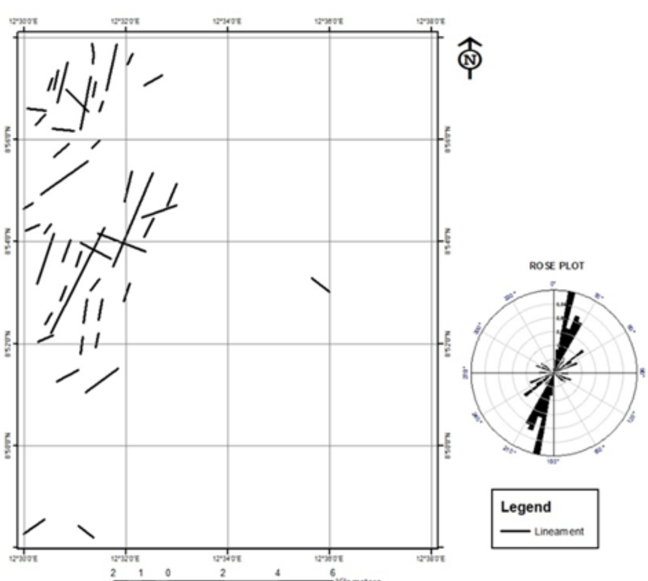

Figure 12. Lineament map of the study area

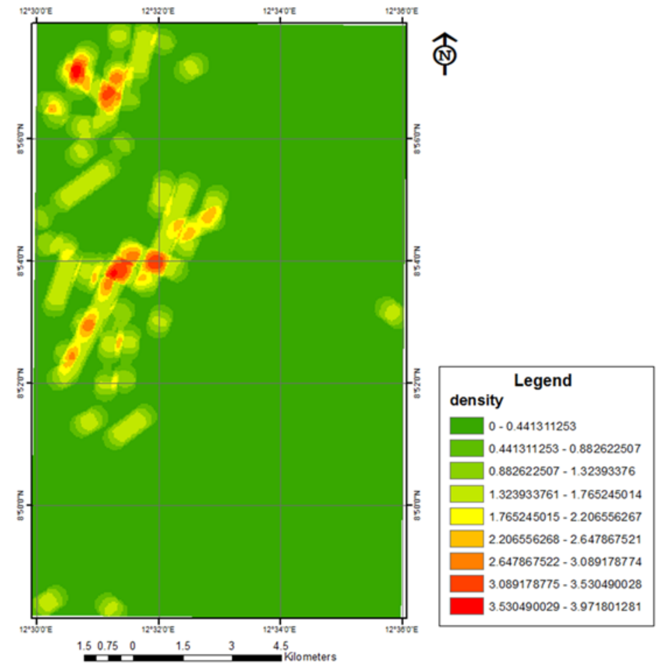

Figure 13. Lineament density map of the study area

granite mostly occurring at the northwestern and central part of the study area, medium-grained granite occurring at the central area, and banded gneiss around the eastern part and southern part of the study area this conforms with the Adamawa massifs consisting of largely granitoid and migmatite gneisses complex. Making up the basement complex rocks and the most obvious [20, 21]. Joints are very common and generally trend NNW-SSE, NNE-SSW and N-S in the banded gneiss, while in the medium-grained granite, they generally trend NNW-SSE and N-S. These joints generally act as conduits to groundwater recharge, movement and mineral occurrence in the area. Major faults correspond with the general trend of the fractures in the Nigerian Basement Complex [22]. Recent work in different parts of Nigeria's basement shows that the pan-African granites are light-level intrusions-emplaced by stopping a diapiric process [23]. The lineaments mapping revealed a low presence of lineaments concentrated in the northwestern part of the area. The interconnectivity of these lineaments serves as conduits to groundwater movement and as recharge zones of the groundwater system in the area and potential areas for mineralization.

4. Conclusion

The comprehensive geological mapping of the study area at a 1:50,000 scale has elucidated the complex lithological and structural characteristics of the region, which is underlain by ten distinct lithological units. The predominance of the Older Granites suite, constituting approximately 60% of the outcrops, serves as a significant indicator of the Pan-African Orogeny and highlights the intricate geological history of the area. These granites, along with banded gneiss and medium to coarse-grained granites, form the major rock units, while a variety of minor rock units including amphibolite, quartz dykes, and pegmatites also contribute to the geological diversity.

The study reveals that the banded gneiss, a significant rock unit, exhibits notable structural features such as weak foliations, folds, and joints which are prevalent throughout the area. The medium-grained and coarse-grained granites display distinct textural and compositional attributes, with the medium-grained granite forming prominent craggy tors and the coarse-grained granite forming in-situ boulders. Additionally, the study identifies various intrusive and fault rocks, indicating significant tectonic activity and the influence of the Pan-African Orogeny.

Structural analyses through GIS techniques and satellite imagery have provided insights into the lineament density and distribution, revealing that the northwestern part of the area is relatively rich in lineaments. These lineaments, primarily trending NNW-SSE, NNE-SSW, and N-S, serve as conduits for groundwater recharge and are potential zones for mineralization. The connectivity and density of these lineaments underscore their importance in hydrogeological and mineral exploration studies. Overall, the geological mapping and structural analysis have not only provided a detailed understanding of the lithological units and their spatial distribution but also highlighted the significant structural features that influence groundwater movement and mineral potential in the area. This study contributes valuable data that can inform future geological and hydrogeological investigations, aiding in the exploration and sustainable management of natural resources in the region.

Data availability

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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