

ORIGINAL RESEARCH ARTICLE

Geology and Economic Potential of Manawaji and Environs, Gulani Area, Upper Benue Trough, Nigeria

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ABSTRACT

Understanding the geology of an area is vital for assessing its economic potential. This study evaluates the lithology and economic significance of rocks around Manawaji, Upper Benue Trough, northeastern Nigeria. Field mapping and petrographic examination of representative samples identified Bima Formation sandstones, fossiliferous Pindiga limestones, crystalline limestone, mylonite, and columnar basalts in the area. The sandstones are medium- to coarse-grained, quartz-dominated, and cemented by hematite with minor microcline feldspar. The Pindiga limestones contain ammonite assemblages, whereas the crystalline limestone shows a microcrystalline calcite with fine-grained texture and absence of twinning, suggesting formation under low-stress, non-metamorphic, hydrothermal conditions. The mylonite occurs as boulder-like outcrops showing grain-size reduction, oriented quartz and biotite, and depletion of feldspar and muscovite in thin section, consistent with a quartz–biotite mylonite type. Columnar basalts consist mainly of olivine, pyroxene, and opaque minerals that are possibly titanomagnetite or ilmenite. Collectively, these lithologies record a tectonomagmatic evolution involving Pan-African crustal reworking, Mesozoic rifting and sedimentation, Tertiary volcanism, and post-magmatic hydrothermal alteration. The rocks exhibit economic potential as sources of construction aggregate, basalt fiber, dimension stone, gemstones, and groundwater reservoirs, with possible metal enrichment in sedimentary units. Future studies should incorporate geochemical mapping, geophysical surveys, and advanced analytical techniques (XRF, XRD, SEM, LA-ICP-MS) to confirm the rocks classification, delineate enrichment zones and evaluate the extractive viability of the identified resources.

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INTRODUCTION

The study of geology of an area play a key role in defining the economic potential of rocks in the area because mineralization processes are largely governed by tectonic factors (which determine the evolution of the host rock, source of the ore constituents and fluid that deposit the ore as well as the conditions in which the mineralization is formed) and the mineralogy of host rocks (Guilbert & Park, 1986; Ridley, 2013; Robb, 2021; Thomas & MacAlister, 1909). Rocks are formed by multiple geological processes, including magmatic differentiation, metamorphism, and sedimentary deposition, all of which are influenced by tectonic activity (Plummer et al., 2016).

Different tectonic environments, such as convergent margins, rift zones, and cratonic basins, provide unique pressure-temperature conditions that induce

mineralization, culminating in the creation of economically significant deposits (Ridley, 2013; Robb, 2021). Subduction zones, for example, are often found to be associated with porphyry copper deposits (Park et al., 2021; Sun et al., 2017) and epithermal gold deposits (Groves et al., 2020b) due to magmatic-hydrothermal activity caused by the subducting slab. Orogenic belts are associated with structurally controlled gold (Groves et al., 2022a) and base metal (Leng et al., 2019) mineralization. Similarly, sedimentary basins provide suitable environment for coal, evaporite formation, and Mississippi Valley-type (MVT) lead-zinc deposits (Akinoyemi et al., 2022; Galyamov et al., 2020; Lv et al., 2017; Morris et al., 2024; Nyakuma et al., 2021; Xiong et al., 2021). Rift-related magmatism typical of continental

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intraplate settings is associated with the mineralization of rare earth elements (Magnin et al., 2023). The influence of plate tectonics on hydrothermal fluid circulation further enhances the potential for economically valuable mineralization, such as volcanogenic massive sulfide (VMS) and skarn deposits (Denisová & Piercey, 2023; Domínguez-Carretero et al., 2022; Drummond et al., 2020; Liu et al., 2023; Rajabpour et al., 2023; Sharman et al., 2015; Shu et al., 2017; Tashi et al., 2021; Xu et al., 2024; Zheng et al., 2024).

Nigeria is rich in mineral resources, many of which are underexplored or underused (Ahmed, 2022). This means that, studies are needed to fully elucidate its geology for proper harnessing of the minerals. Recently, the geology of Nigeria has been updated in a number of studies covering various topics such as sedimentary basins stratigraphy (Akpan et al., 2020; Aliyu et al., 2024; Anudu et al., 2025; Daniel et al., 2024; Igwe & Okoro, 2016; Okey, 2024; Okoro & Igwe, 2018; Onuigbo et al., 2020; Onyekuru et al., 2024; Ozulu, G.U. et al., 2024; Rufai et al., 2024; Toyin et al., 2016), geochemical characterization of rocks (Abubakar et al., 2021; Ahmad et al., 2022; Bute et al., 2020, 2022; Kariya et al., 2024a; Kariya et al., 2024b; Omietimi et al., 2022; Oshilike & Haruna, 2021; Oyebamiji et al., 2024; Wada et al., 2024; Zailani et al., 2021), structural geology (Ekwok et al., 2024; Eldosouky et al., 2022; Falebita et al., 2020; Kamaunji et al., 2022; Kitha et al., 2022; Kolawole et al., 2024; Osagie et al., 2021; Salawu, 2021; Salawu et al., 2020, 2021; Ubit et al., 2022), and economic mineral potential (Adebisi et al., 2024; Adewumi & Salako, 2018; Bute et al., 2020; Dalha et al., 2024; Daya et al., 2021; Ekeleme et al., 2023; Girei et al., 2022; Matheis & Caen-Vachette, 1983; Okon et al., 2022; Popoola et al., 2021; Vincent et al., 2021a). New data from these studies have advanced the understanding of the petrogenesis of igneous and metamorphic rocks, sedimentary basin evolution, and the tectonic framework of various areas. Advancements such as the works of Ekwueme et al. (1991), Okonkwo et al. (2024), Dickina et al. (1991), Adetunji et al. (2016), Elatikpo et al. (2022), Kamaunji et al. (2023), and Halilu et al. (2025) have provided more understanding of the geochronology and isotope geochemistry, shedding more light on geological time and the spatial distribution of resources in Nigeria.

However, more work needs to be done to fully elucidate the geological framework of Nigeria. For example, the Migmatite Gneiss Complex (MGCs) of Eburnian to Archean ages, once thought to constitute about 60% of the Nigerian land mass, has recently been discovered to occur only as relict (Dada et al., 2024; Ominigbo, 2022). The migmatite that occurs as outcrops and constitutes a greater portion of the Nigerian crust is Pan-African in age (Halilu et al., 2025). These findings show the evolving understanding of the geology of Nigeria and show the need for further geologic investigations across the country.

The Upper Benue Trough has received increased attention due to its diverse lithologies, complex tectonic history, and mineral potential (Abodunrin et al., 2024; Abubakar et al., 2024; Daspan et al., 2023). Gulani area of Yobe State is

part of this structurally controlled sedimentary basin. It comprises of Tertiary/Quaternary basalts from the Biu plateau, Cretaceous sediments, and rocks from the Precambrian Basement Complex of Nigeria (Ayok, 2016b, 2016a, 2016c; El Nafaty, 2015; Wanah & Kore, 2020). Baryte-copper mineralizations that are epigenetic occur in some places (El-Nafaty, 2015; EL-Nafaty, 2017; Wanah & Kore, 2020), diatomite has been reported around Bularafa (Adam et al., 2024) and the basalts have been reported to host sapphire (Obiefuna & Nggada, 2014). Hence, the area offers a unique setting to investigate the interactions between tectonics and mineralization.

Despite the increasing number of geological studies in northeastern Nigeria, there is no research on the geology of Manawaji, which is part of the Mutwe SE sheet. This study therefore aims to fill that gap by carrying out detailed field mapping and petrographic examination of rocks around Manawaji to identify and classify the lithological units (rocks) in this area, determine their mineralogical composition, infer their tectonic setting of formation, and assess their potential for economic mineralization.

MATERIAL AND METHODS

Study Area

The study was carried out in an area located between latitudes 11°02'21.67"N and 11°05'08.33"N and longitudes 11°50'08.33"E and 11°52'55"E (Figure 1). This area is within the uppermost part of the the Gongola Sub Basin of the Upper Benue Trough as it transitions into the Chad Basin. The Manawaji is a small settlement near Bularafa in Gulani Local Government, Yobe State, Northeastern Nigeria. The area is accessible via narrow rural access routes. The area has a tropical climate and has two seasons: a rainy season between May and October and a dry season between November and April (WWO, n.d.) Rainfall is 25 mm to 300 mm a year, and the temperature is approximately 30°C (WWO, n.d.) The study area vegetation is typically Sahel-Savannah and is composed of trees, shrubs, and grasses that are adapted to a semi-arid environment (Bukar & Abba, 2022). Dominant plants in the study area include species of Fabaceae, Combretaceae, Mimosaceae, and Rhamnaceae. Some common tree species are the Sodom apple, Doum palm, Guiera tree, Desert date, and Thorn Acacia (Bukar & Abba, 2022). The relief of the study area is characterised by low-lying hills of sandstone, very high elevated outcrops of columnar basalt, and flat terrains (Figure 2). The elevated hills and outcrops dominate the northwest, southwest, and southeast parts of the study area. The flat terrains are interspersed with smaller hills and valleys. This topography affects the surrounding drainage system, which is predominantly dendritic, with dendritic ephemeral streams and rivers branching out across the terrain.

Geological mapping

Field investigations to observe rock outcrops were conducted. A topographic map of Mutwe SE was obtained from the Yobe Geographic Information System Unit, Damaturu, Yobe State, Nigeria.

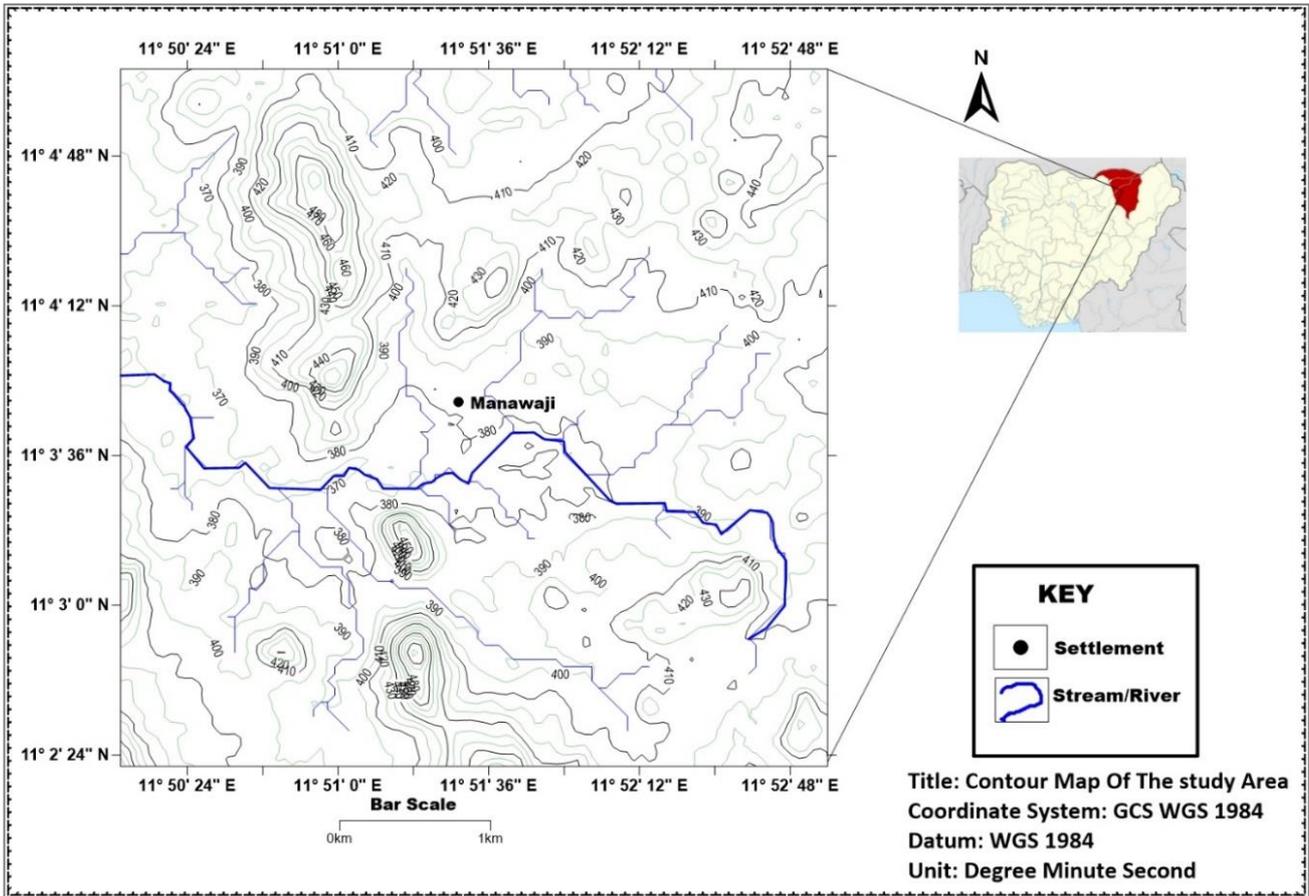


Figure 1: Location Map of the Study Area

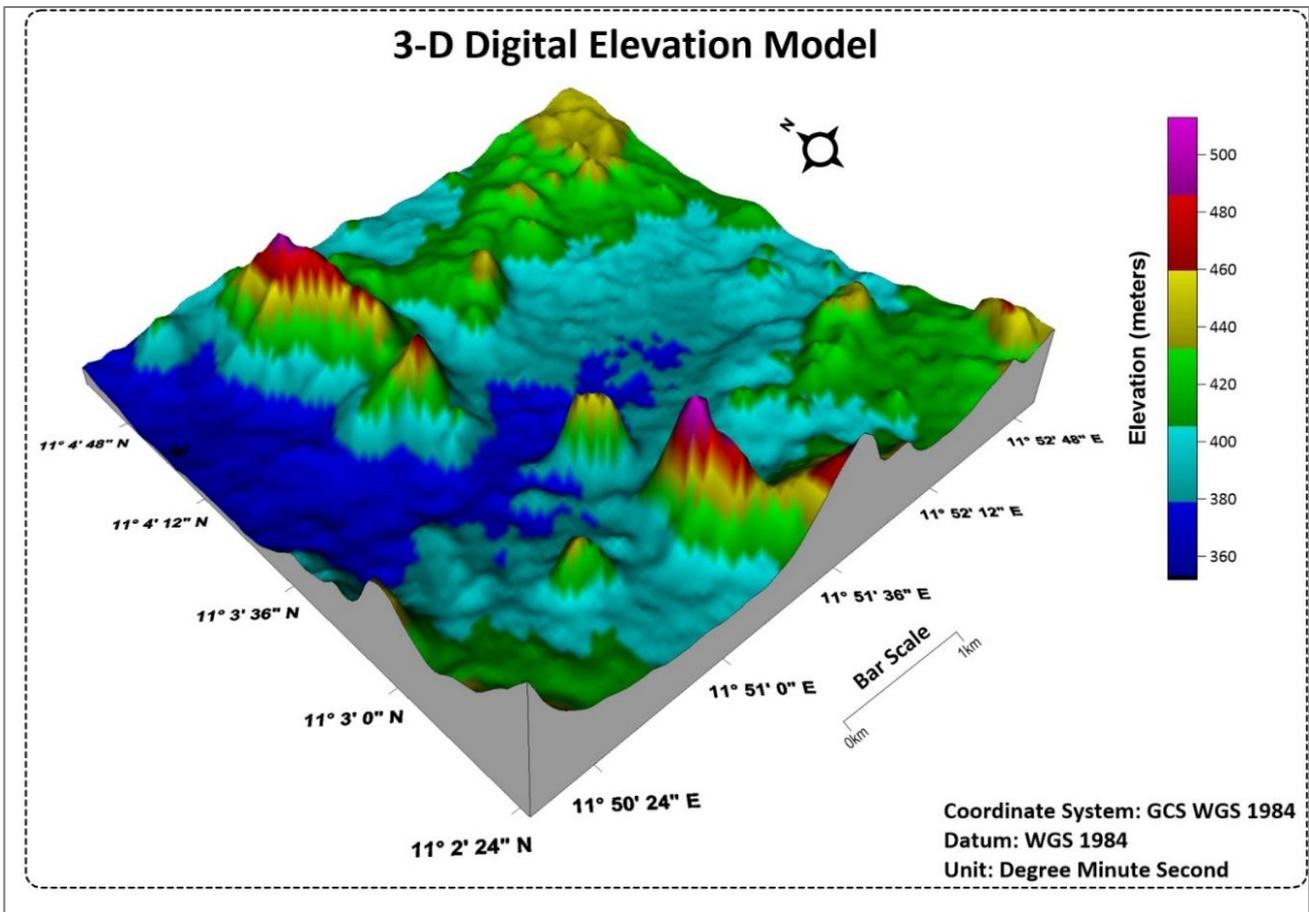


Figure 2: Digital Elevation Model showing the Relief of the Study Area

The study area was carefully outlined with Manawaji at the centre (Figure 1). The bounding coordinates were then calculated and extracted manually from the topographic base map. Using Google Earth Pro, the study area boundary was delineated with the polygon tool and exported as a KML file, then converted into a comma-delimited text (CSV) file containing longitude (X), latitude (Y), and elevation (Z) values in decimal degrees. The dataset was imported into Golden Software Surfer (version 25.2.259) for gridding and surface generation. A Digital Elevation Model (DEM) was produced (Figure 2), after which a contour map (Figure 1) was generated. All coordinates were referenced to the WGS 1984 datum. Then the contour map was printed, gridded and analyzed to define physiographic features, accessways, and possible outcrop areas. Geological traverses were planned based on the area's structures and geomorphology (Coe, 2010). Observations were made on lithological and structural features. The mapping exercise was systematic to minimise sampling bias (Coe, 2010; Freeman, 2009). Materials used include a topographic map, GPS, compass, clinometer, geological hammer, measuring tape, masking tape, HCl, and a sampling bag.

Thin section preparation procedure

Thin section preparation was performed according to standard protocols. A representative piece of the rock sample was first cut with a diamond saw to obtain an appropriate chip suitable for thin section preparation. Then, a carborundum powder was used to grind and polish the piece of rock obtained in order to provide a smooth surface. A glass slide was then marked with the sample code using a diamond pen. Then, heating both the rock chip and glass slide for around 5 minutes was carried out to facilitate adhesion. Next, a mixture of Araldite adhesive was used to bond the rock chip onto the marked slide. Air bubbles were removed from the thin section slide by pressing with forceps and reheating until properly fixed. The thin section prepared was allowed to dry for 5–10 minutes before being taken for grinding. The sample was ground to a standard thickness of 30 microns using a precision grinding machine. Then, the thin section was polished and cleaned with a detergent diluted with a methylated spirit to get rid of any stuck grain particles. A cover slip was finally affixed using Canada balsam, and care was taken to remove any trapped air bubbles. The prepared slides were then left to cure for a period of two days prior to petrographic analysis (Reed & Mergner, 1953).

Optical microscopy technique

An optical microscope was used to conduct a detailed petrographic examination of thin sections prepared from representative rock samples. The analysis was carried out using a polarizing microscope under both plane-polarized light (PPL) and cross-polarized light (XPL) to examine the optical properties of the constituent minerals. Key

petrographic attributes were recorded under PPL, which include crystal shape, mineral habit, and color, with particular attention to any pleochroism. Additionally, under PPL, the presence and orientation of cleavage planes as well as relief of the minerals, were noted to assist in mineral identification. Under XPL, interference colors were carefully assessed to determine the maximum birefringence exhibited by each mineral phase, while the extinction angles were examined in relation to cleavage directions and crystal faces to infer crystallographic orientations. Additionally, under XPL, features such as crystal twinning, zoning, and alteration textures were also examined to provide further insights into the mineralogical and thermal history of the rocks (MacKenzie et al., 2017).

Geologic Map of the Study Area

After the fieldwork and petrographic analyses, the results were integrated and used to produce a geological map (Figure 3) of the study area using Golden Software Surfer (version 25.2.259). The mapped lithological units and structural data were digitized and spatially referenced within the software environment to produce a detailed geologic map that shows the distribution of rock types and structural features in the study area.

RESULTS AND DISCUSSION

The different rock types encountered in the study area will be discussed in terms of their field occurrence and petrographic examination to assess their economic potential. Five lithologies were observed in the study area, which are Bima Formation sandstones, fossiliferous Pindiga limestones, crystalline limestone, mylonite, and columnar basalts (Figure 3).

Sandstone

The sandstone is the most prominent rock in the study area. Field observations indicate that the sandstone is light grey to reddish-brown, suggesting varying concentrations of iron oxide. It is also moderately to well-indurated that is predominantly medium- to coarse-grained with minor intercalations of clays and siltstones in some locations. Petrographic analysis reveals a quartz-dominated framework and feldspar (microcline) with occasional iron oxide occurrence. (Plate 1). The cementing material is primarily silica and iron oxides.

The sandstone also exhibits evidence of hydrothermal activity in the form of quartz-dominated veins (Plate 2a) that appear to be more resistant to weathering than the surrounding sandstone, which cuts across the primary bedding planes. In some sections, the sandstone extends several meters upward along the margins of the basalt (Plate 2b), which is indicative of interactions between sedimentary deposition and subsequent emplacement of the volcanics. At location 11° 2' 59.1" N, 110° 1' 59" E, the sandstone appears to be hard, consolidated, and light to dark green in color (Plate 2c), with some micaceous flakes (Plate 2d); hence, it is tentatively classified as metasomatized sandstone.

The minor intercalations of clays and siltstones suggest fluvial to deltaic depositional processes (Scholle & Spearing, 1982). The presence of hydrothermal features suggests that the sandstone, which is part of the Bima Formation of the Gongola Arm of Benue Trough (El Nafaty, 2015; EL-Nafaty, 2017) in this area may have been influenced by localized tectonic or magmatic events,

possibly related to the nearby basalt emplacement. This alteration could have affected the diagenetic history of the sandstone. The greenish coloration in the metasomatized unit may be associated with secondary alteration due to hydrothermal fluids containing sericite, epidote, or other green-colored alteration minerals (Fulignati, 2020).

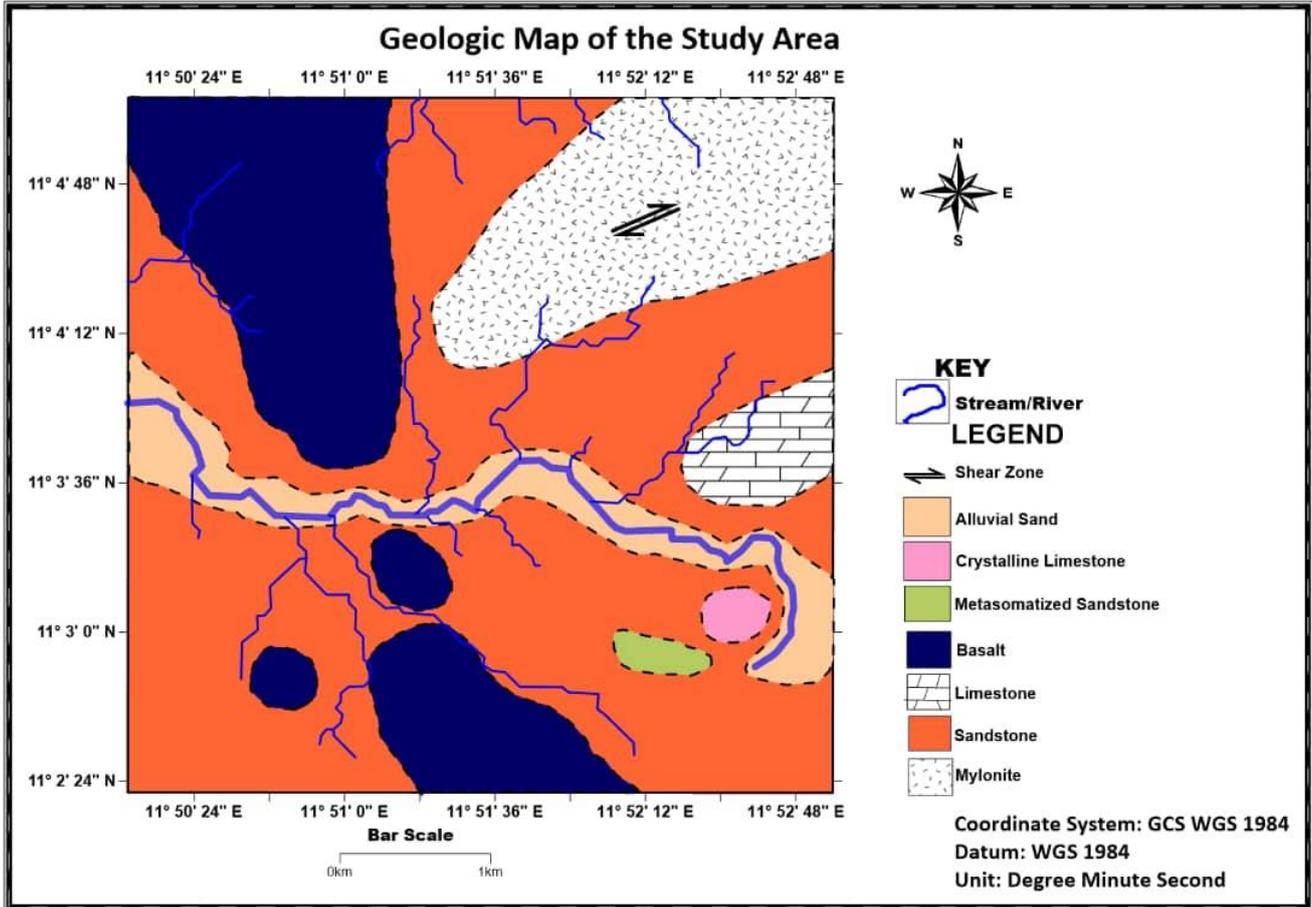


Figure 3: Geologic Map of the Study Area

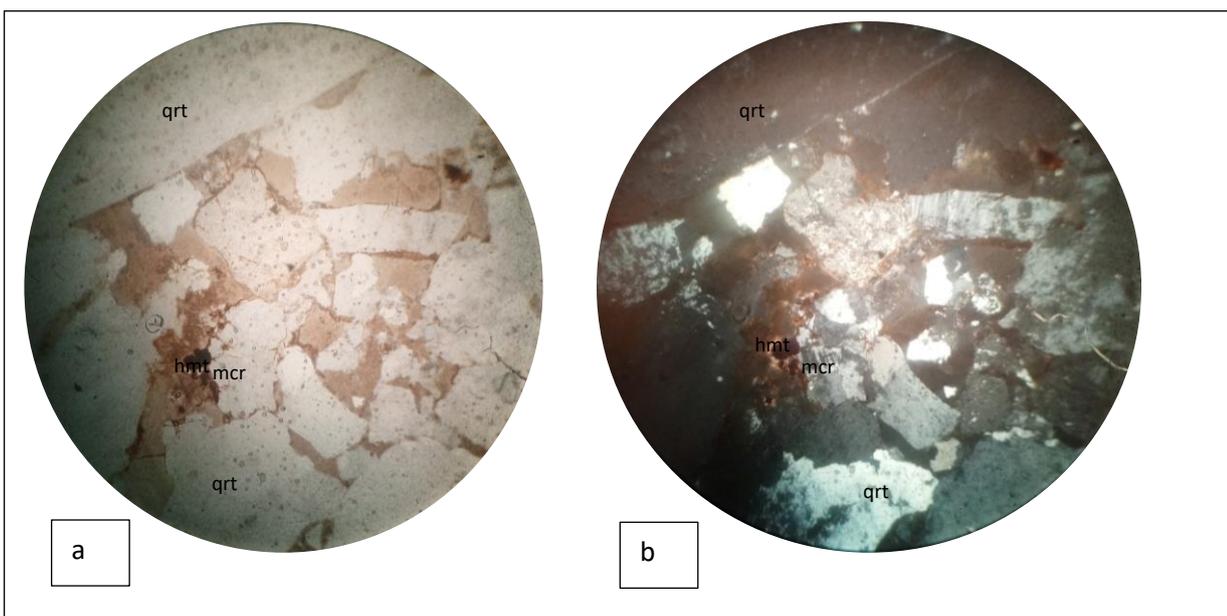


Plate 1: Photomicrograph (a: PPL and b: XPL) of the Highly Indurated Sandstone (sample ABTA) in the area (qrt: quartz; mcr: microcline; hmt: hematite), Magnification x400.



Plate 2: Bima Sandstone in the Study Area (a) Resistant Hydrothermal Veins in the Sandstone; (b) The sandstone extends several meters upward along the margins of the basalt; (c and d) Metasomatized sandstone (tentative).

These fluids could have moved through the pre-existing fractures and faults and altered sandstones in this area, which resulted in the introduction of minerals that generate the rocks' greenish colors and increase their silica content (Berger, 1998; Browne, 1978; Goldschmidt, 1922; Lindgren, 1925; Pirajno, 1992; Putnis & Austrheim, 2013). The Bima Formation is an Albian continental sedimentary unit that unconformably overlies the Basement of the

Upper Benue Trough, which is known for its fluvio-deltaic depositional environment and post-depositional modification (Kamale et al., 2019).

Limestone

A well-consolidated limestone containing ammonite fossils (Plate 3b) was exposed at location N11° 3' 46.3"

E11° 52' 39.7" 397 m within the study area in a terrain dominated by dark humus-rich soil, likely derived from weathering of shale. The limestone occurs as disjointed, angular to sub-rounded blocks (Plate 3a), suggesting in-situ weathering and disintegration. The surrounding soil, perhaps a remnant of a more shale lithology, seems to

have been affected by preferential erosion. This results in the more resistant limestone remaining. Thus, the exposure has exhibited a differential weathering and fossil preservation, indicating that the carbonate-rich limestone is more resistant to chemical and physical weathering than the shale (Bland & Rolls, 2016; Earle & Panchuk, 2019).



Plate 3: Limestone in the Study Area (a) disjointed, angular to sub-rounded blocks of the limestone; (b) Ammonites collected at the location

The Ammonites preserved indicate a marine depositional environment (Kennedy & Cobban, 1976). Ammonites are commonly known as index fossils of Mesozoic marine deposits, especially those of the Jurassic and Cretaceous (Lehmann, 2015; Levin & King, 2017). Their occurrence favors interpretation of deposition of the limestone in shallow, low-energy conditions (epicontinental sea) with dominance of carbonate sedimentation (Flügel, 2004). Such depositional environments were prevalent and widely distributed in parts of northern Nigeria during the early to mid-Cretaceous within the Yolde and Pindiga formation of Upper Benue Trough and their extensions (Aigbadon et al., 2024; Naibi et al., 2024; Obaje, 2009; Sarki Yandoka et al., 2015; Waziri et al., 2020).

Collumnar Basalt.

These rocks are encountered in several locations in the study area; [N11° 2' 43.5", E11° 51' 39.7"], [N11° 4' 15.2", E11° 52' 41.6"], [N11° 3' 54.4", E11° 50' 58.2"], [N11° 3' 11.3", E11° 51' 18.9"], [N11° 3' 39.1", E11° 50' 53.8"] and [N11° 3' 47.6", E11° 49' 18.6"]. They occur as well-developed, vertically oriented, polygonal jointed rock columns (Plate 4). They are also tall (405 – 545m above sea level) and form extensive ridges with a rugged, fragmented surface due to weathering and erosion. The

columns are prominent at [N11° 2' 45", E11° 51' 18.6"] Plate 4. The thin section (Plate 5) of the columnar basalt shows olivine, pyroxene and numerous opaque minerals which might be titanomagnetite or ilmenite. The columnar joints in the basalts are indicative of extrusive igneous activity, where basaltic lava, upon cooling and contracting, formed polygonal joints due to tensile stresses (Phillips et al., 2013). The vertical orientation and geometric regularity of the joints are classical features of columnar basalt that indicate emplacement and cooling in relatively horizontal lava flows (Das et al., 2025; Li & Liu, 2020; Mondal et al., 2022; Udinmwun et al., 2016).

The rocks represent a significant volcanic event linked to the Tertiary to Recent magmatic activities that affected parts of northern Nigeria (Fitton, 1980). They are similar to other basalts reported in the Benue Trough, such as those of the Biu, Awe and Yola areas (Adekeye & Ntekim, 2007; Lekmang et al., 2020; Obiefuna & Nggada, 2014). Hence, the basalts in the study area are part of rocks that are typically associated with post-Cretaceous continental rift-related volcanism, especially within the tectonic framework of the Benue Trough and the broader West and Central African Rift System (WCARS) (Auwalu et al., 2023; Moreau et al., 1987; Obiefuna & Nggada, 2014).

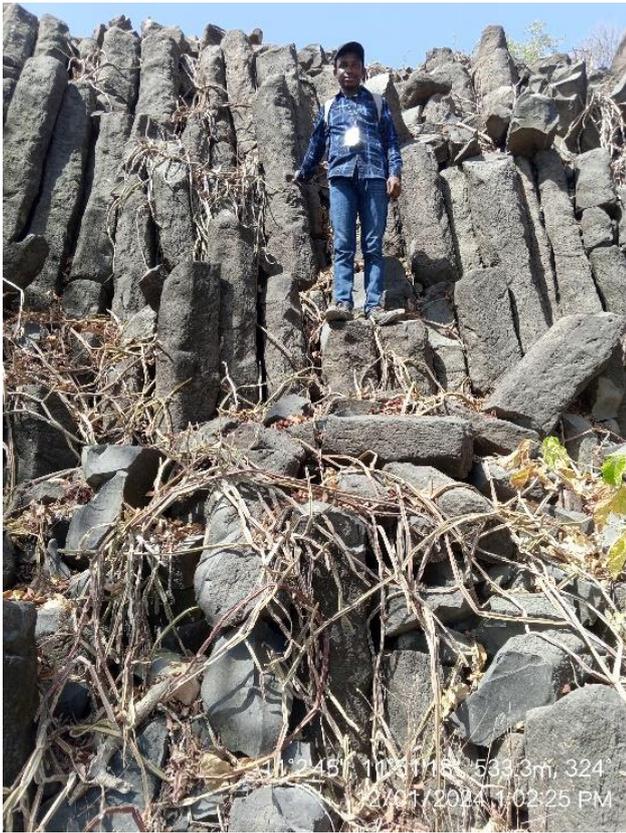


Plate 4: Collumnar Basalt in the Study Area

Mylonite

In the study area, the mylonite occurs as an inlier characterized by boulder-like, rounded to sub-rounded weathered blocks (Plate 6), forming a rugged terrain surrounded by a valley-like depression. The rock mass is strongly disintegrated and is striking roughly N50°E. Also, *Adansonia digitata* and *Ficus platyphylla* have grown on the outcrops which is a supplementary geomorphic and ecological evidence of deep-seated fracturing. These species are all deep-rooted perennial plants (Katende et al., 1995; Rahul et al., 2015) indicating a deep-seated aquiferous fault.

The boulders' orientation along a dominant N50°E fracture trend suggests structural control likely inherited from regional tectonic processes, possibly linked to the Pan-African orogeny (Darko et al., 2019; Udinnwen, 2017). The presence of a valley-like depression encircling the mylonite outcrop is consistent with differential erosion, where the mylonite's relative resistance to weathering has left it standing in high relief, while adjacent, more weatherable lithologies such as the sandstone, shale, and Limestone have been preferentially removed (Bland & Rolls, 2016; Earle & Panchuk, 2019). The thin-section petrography of the mylonite reveals an atypical assemblage dominated by quartz and biotite, with no recognisable primary feldspar (Plate 7).

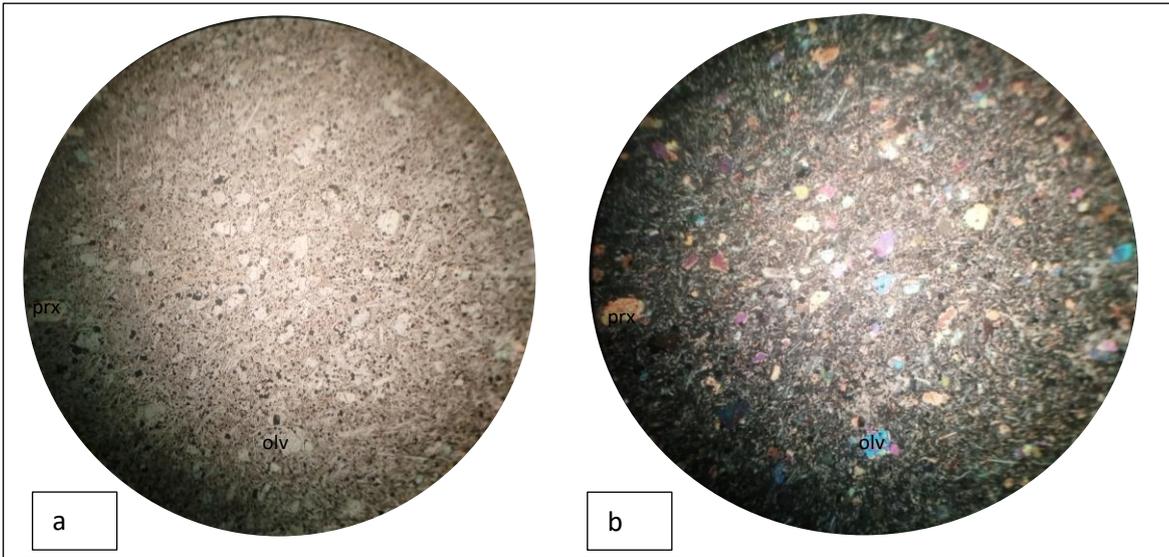


Plate 5: Photomicrograph of the Columnar Basalt; a: PPL view of sample ABDB, b: XPL view of sample ABDB; (olv: olivine; prx: pyroxene); Magnification x400.

As seen in the thin sections, feldspars appear either absent or completely altered to a fine-grained matrix (beyond recognition). Texturally, some samples of the rock show pronounced grain-size reduction and is largely composed of a fine to very fine-grained matrix (Plate 7e and f). Grain shapes are elongated and commonly show a preferred orientation (Plate 7e and f) defining a strong planar fabric (mylonitic foliation?). Collectively, these petrographic characteristics, which are, grain-size reduction, oriented quartz and biotite, and feldspar depletion, are all indications that the rock is a mylonite. Finally, based on

the petrographic mineral assemblages the mylonite in the study area is suggested a name: quartz–biotite mylonite as it has compositional affinity similar to the quartz–biotite mylonite reported by McCaig & Miller (1986) in the Mérens fault zone of the central Pyrenees.

The quartz–biotite mylonite in the study area records a progressive deformational history that began with the reworking of Pan-African granitoid suites (“Older Granites”), which are Neoproterozoic to early Paleozoic (600–500 Ma) medium- to coarse-grained, equigranular to porphyritic plutonic bodies of the Nigerian Basement

Complex (Dada, 2008; Ferré et al., 2002; Hamdja Ngoniri et al., 2021; McCurry, 1971; Obaje, 2009), and their subsequent transformation into mylonite during the Pan-African Orogeny. Intense ductile shearing within deep crustal shear zones produced grain-size reduction, dynamic recrystallization, and a mylonitic foliation (Haldar, 2020). Feldspars depletion is most likely due to its conversion into muscovite and quartz represented by the reaction: $3\text{KAlSi}_3\text{O}_8 + 2\text{H}^+ \rightarrow \text{KAl}_3\text{Si}_3\text{O}_{10}(\text{OH})_2 + 6\text{SiO}_2 + 2\text{K}^+$, that is possible during mylonitization as reported by O'Hara (1988). However, the absence of muscovite in the thin section suggests not only feldspar breakdown but also subsequent removal of newly formed mica due to extensive fluid–rock interaction and volume loss during mylonitization. For example, Newman & Mitra (1993) reported ~73–75% mass loss dominated by SiO_2 , Al_2O_3 , K_2O and Na_2O within a mylonite zone in Linville Falls of North Carolina. Such intense mass loss implies that hydrous phases like muscovite can dissolve under differential stress, with their components transported and reprecipitated elsewhere along fluid pathways (Putnis & Austrheim, 2013).

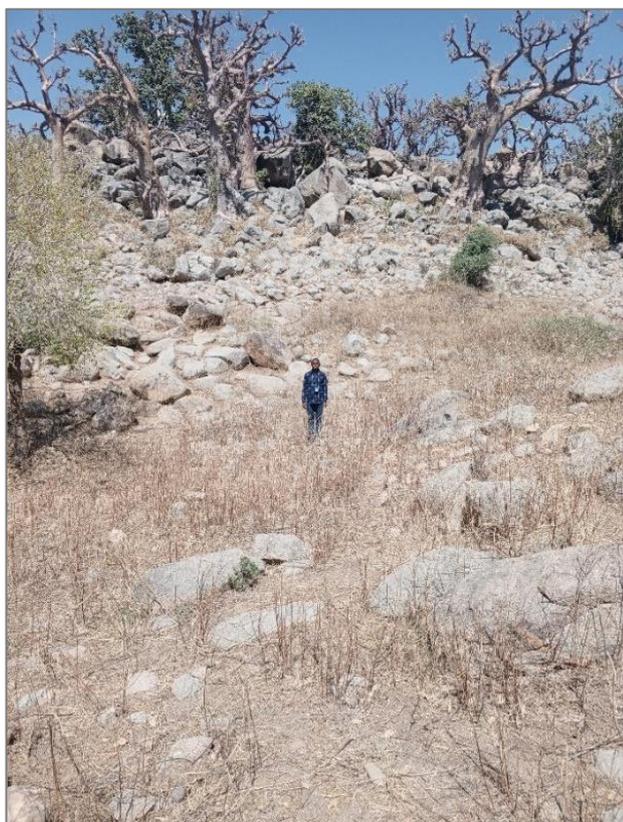


Plate 6: Mylonite in the Study Area

Exhumation transported these rocks to shallower crustal levels (Fernie et al., 2018; Ring et al., 1999), where brittle processes overprinted most of the earlier ductile structures. Brecciation and fracturing observed in the outcrops are most likely linked to any, combination, or all of the subsequent major tectono-magmatic events, including the opening of the Benue Trough during

Gondwana breakup (Fernie et al., 2018), emplacement of Tertiary volcanic suites along Pan-African fault systems (Moreau et al., 1987), and episodic reactivation of Pan-African shear zones (Attoh et al., 2005; Legre et al., 2024; Skobelev et al., 2004; Viola et al., 2012).

Mylonitization is a process that involve intense ductile deformation along shear zones, producing fine-grained, foliated rocks characterized by dynamic recrystallization and progressive grain-size reduction (Higgins, 1971). A unique attribute of this process is its ability to generate rocks with unusual mineralogical compositions, depending on protolith type, deformation conditions, and fluid activity (Sun & Dong, 2023). Under mylonitization conditions, different mineral assemblages may develop, leading to the formation of feldspar-rich (Prior & Wheeler, 1999), feldspar-poor (Newman & Mitra, 1993), mica-rich (Newman & Mitra, 1993), or quartz-dominated (Chakraborty et al., 2020) mylonites.

The Pan-African Orogeny ($\sim 600 \pm 50$ Ma) was an important Neoproterozoic event driven by the amalgamation of Gondwana that involved widespread crustal reworking, metamorphism, mylonitization, partial melting, and magmatic activities (Ajibade et al., 1987; Dada, 2008; B. Ekwueme & Kalsbeek, 2015; Halilu et al., 2025; Okpoli et al., 2022; Ugwuonah et al., 2017). The mylonite in the study area is possibly a reworked Pan African granite. Although several studies have documented the occurrence of Pan-African Orogenic mylonites in several places including, USA (Rast & Skehan, 1995), Zimbabwe (Carney et al., 1991), Mali (Lancelot et al., 1983) and Southwestern Nigeria (Adeoti & Okonkwo, 2017; Okpoli et al., 2022), this study is the first to report the occurrence of Pan-African mylonite in Northeastern Nigeria.

Crystalline limestone

The crystalline limestone occurred at location N11 3'10", E11 52' 6.3" as fine-grained, massive rocks exhibiting varying degrees of coloration (Plate 8a). Its color ranges from whitish to reddish-brown, and brownish with greenish to bluish hues (Plate 8b).

Plate 9 shows thin-section photomicrographs of the crystalline limestone. In plane-polarized light, thin-section of the crystalline limestone appears colorless with very low relief, and individual grains are not discernible, indicating a microcrystalline texture (Plate 9a, c & e). It shows a uniform appearance with no visible rhombohedral cleavage or distinct crystal boundaries due to the fine-grained nature of the rock. Under cross-polarized light, it exhibits low first-order gray interference colors, straight extinction, and an absence of twinning (Plate 9b, d & f). Numerous opaque minerals occur as disseminations in

some of the samples (Plate 9a and b). The rocks are interpreted as predominantly composed of calcite. The absence of twinning as well as straight extinction exhibited by the calcite suggests that it does not experience

deformation due to tectonic stress or metamorphic conditions, indicating precipitation under hydrothermal conditions.

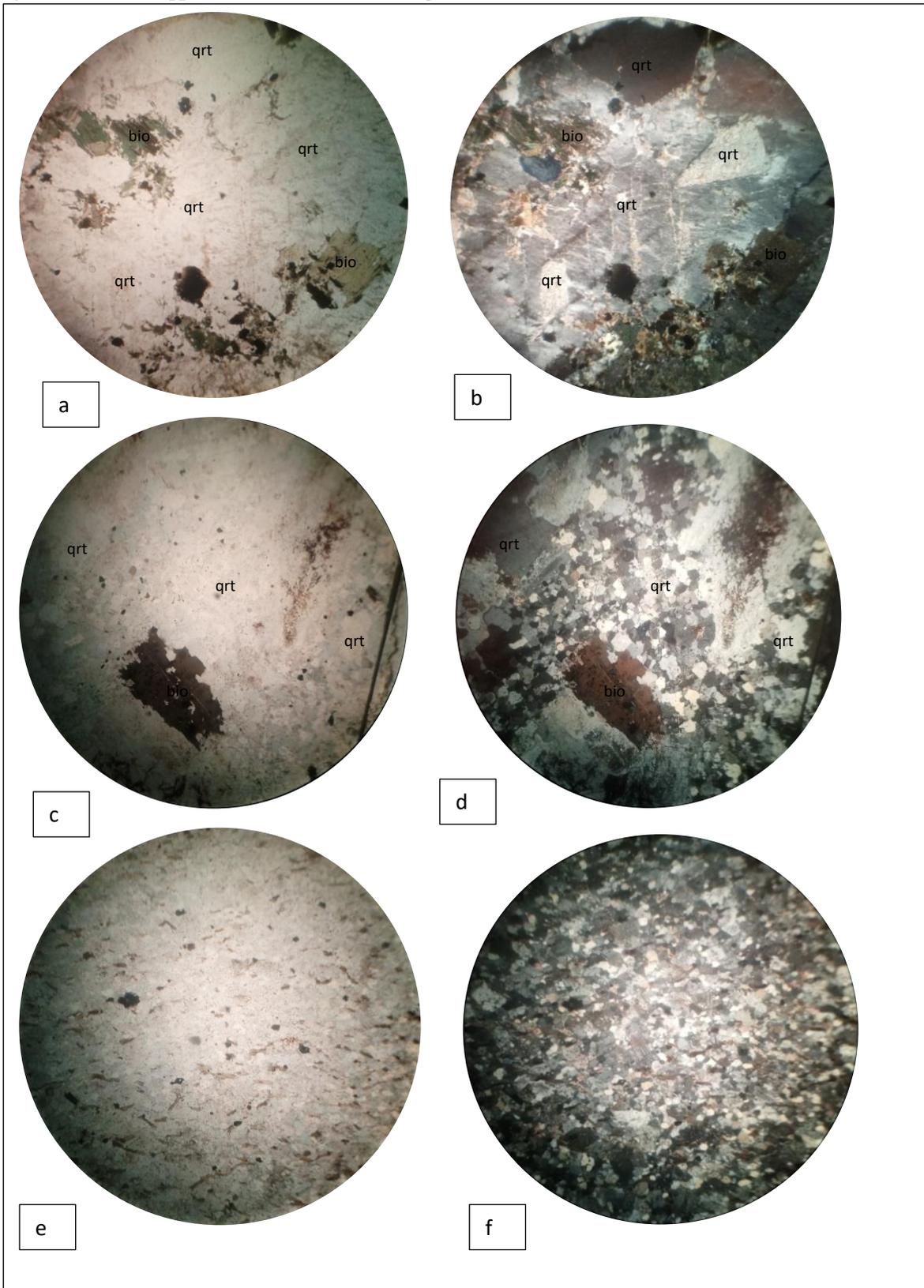


Plate 7: Photomicrograph of the Mylonite in the Study Area; a, c and e are PPL view of three samples of mylonite from three locations and b, d and f are the corresponding XPL views, respectively; (qrt: quartz; bio: biotite). Magnification x 400.



Plate 8: crystalline limestone in the Study Area (a) Massive white (b) reddish-brown with greenish to bluish hues

The field association of the crystalline limestone with columnar basalts indicates that Tertiary magmatism might be the source of the thermal and hydrothermal conditions necessary for carbonate mobilization and reprecipitation (Bute et al., 2024; Vincent et al., 2021b). The crystalline limestone may also have formed through hydrothermal processes associated with Mesozoic magmatism that occurred throughout the Benue Trough, where heated connate brines dissolved the Cretaceous limestones of the basin and subsequently precipitated calcite (Akande et al., 1989; Akande et al., 1988). Naibi et al. (2024) also reported the occurrence of crystalline limestone in the middle Benue Trough within the Cretaceous limestone of the Awgu Formation.

ECONOMIC POTENTIAL OF THE STUDY AREA

The diverse lithological and structural characteristics of the Manawaji area indicate considerable economic potential. Below are the economic potential areas:

Industrial applications of basalt

From a construction application point of view, basalt is an important construction aggregate. This is due to its good compressive strength, resistance to abrasion, and chemical inertness (unreactive at environmental conditions) (Karasin et al., 2022). These features make it suitable for the production of road base materials, railway ballast, concrete aggregate, clay brick, and asphalt mixtures (Apaydın & Yılmaz, 2021; Bell, 2007; Li et al., 2021; Sanad et al., 2021; Wu, 2012). It is also highly suitable as a dimension stone for building cladding and other

architectural uses due to its low porosity and physical durability (Alaimo et al., 2016; Osband et al., 2024; Saudi et al., 2024). Additionally, basalt may be processed to produce a high-performance material called basalt fiber that exhibits superior tensile strength, thermal stability, and resistance to corrosion and is environmental friendly (Chowdhury et al., 2022). Basalt fiber is increasingly used in construction, both for concrete reinforcement, composite rebar, as well as fire-resistant insulation panels and fabrics (Bhat et al., 2015; Branston et al., 2016; Lopresto et al., 2011).

Gemstone potential

The Manawaji area holds the potential to host gemstone (sapphire) mineralization (gem-quality corundum) as the basalts in the area share similar characteristics with those reported to host sapphire from the Biu Plateau, northeastern Nigeria by Obiefuna & Nggada (2014). Sapphire is commonly regarded to be associated with alkali-rich basalts and their weathering products, which is a relationship well established in gem-producing areas such as Southeast Asia, Madagascar, Southern Vietnam, and some areas in Australia (Rakotondrazafy et al., 2008; Sutherland et al., 2015; Vu et al., 2021; Wong et al., 2017). The basalts in the Manawaji area offer a favorable geological environment for the mineralization of such gemstones (Aseeva & Kislov, 2021; Sun et al., 2024; Wang et al., 2022a).

The conditions needed to form sapphires are aluminum-rich, silica-undersaturated, high-temperature environments, conditions feasible either during basaltic

magmatism or later in hydrothermal environments or both (Sorokina et al., 2019; Vu et al., 2021). As these basalts experience tropical weathering, corundum crystals

can be released and concentrated further into eluvial or alluvial deposits in the soil. This process is confirmed by the locals residing in and around the Manawaji area.

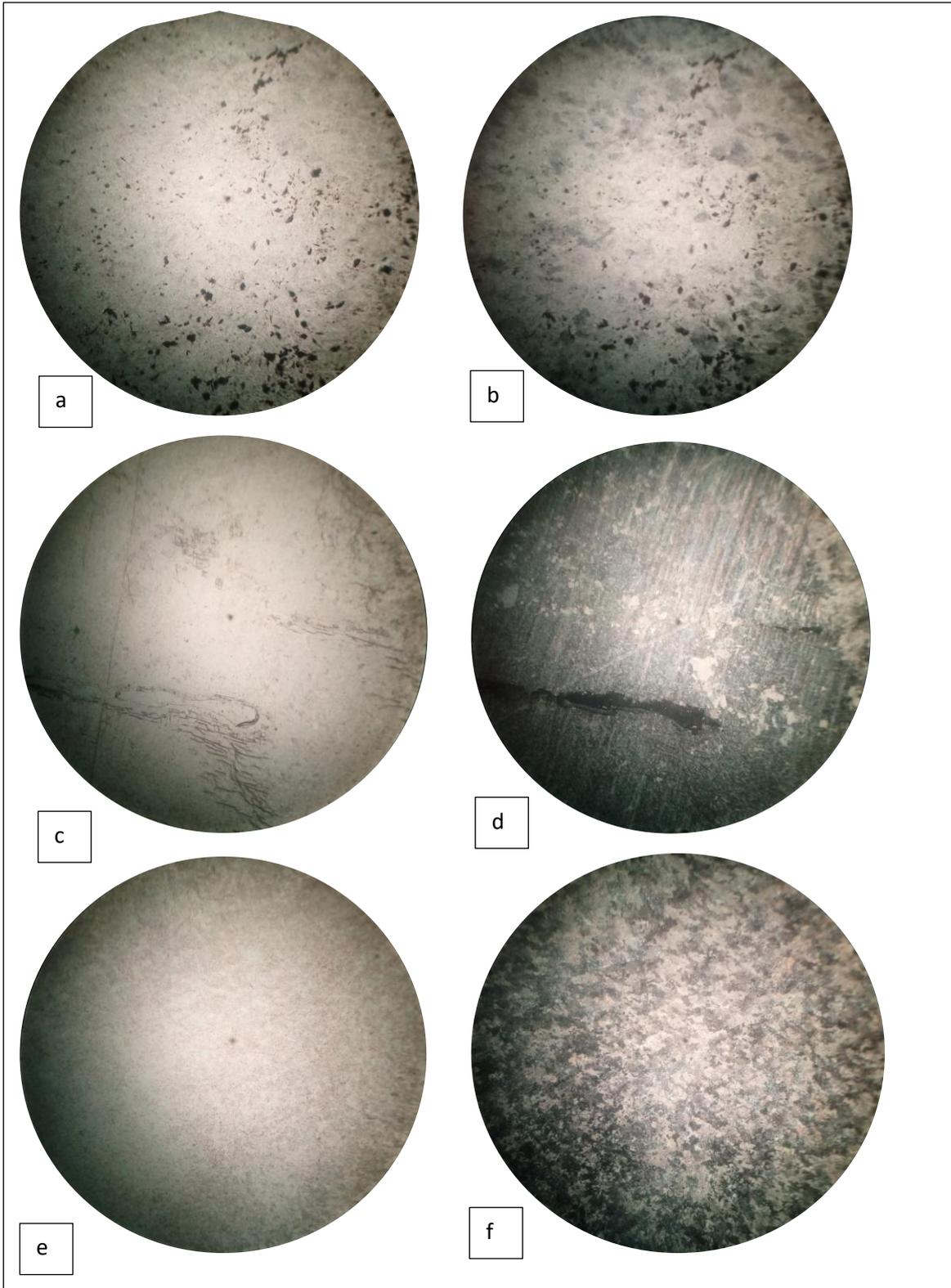


Plate 9: Photomicrograph of the Crystalline Limestone in the Study Area; a, c and e are PPL view of three samples and b, d and f are their corresponding XPL views respectively. Mag. X 400.

During the course of the fieldwork, community members reported recovering sapphire crystals from soils around the basaltic rocks after episodes of heavy rain. This phenomenon is in agreement with the process of formation of secondary sapphire placers (Aseeva & <https://scientifica.umyu.edu.ng/>

Kislov, 2021; Kislov et al., 2022; Schmetzer et al., 2016; Yui et al., 2006). If subsequent mineralogical and geophysical surveys confirm economic quantity of sapphire in Manawaji, the area could play an important role in Nigeria’s existing plans to diversify the economy

through solid minerals development (Kojo et al., 2019; Ujah, 2025).

Geological tourism and geoheritage development

The study area exhibits a great potential for geological tourism and geoheritage. The columnar basalts are a stunning natural phenomenon of volcanic origin (Singtuen & Anumart, 2022). Due to their aesthetic value, educational importance, and close relationship with volcanic activity, columnar jointing (Plate 4) is globally recognized as a geoheritage feature (Mc Keever & Zouros, 2005). Iconic examples, like the Giant's Causeway in Northern Ireland and the Basaltic Monogenetic Volcanic Field of the Bakony–Balaton in Hungary, have been designated as international geosites and UNESCO World Heritage areas attracting thousands of geotourists each year (Crawford, 2016; Harangi & Korbély, 2023; Tomkieleff, 1940). Besides the columnar basalts, crystalline limestone in the Manawaji area could provide further scientific and geoeducational significance by serving as a real-world natural laboratory for students and researchers (Poulson & White, 1969).

Geotourism has been successfully incorporated into regional development strategies worldwide (Carrillo-Hernández et al., 2024; Dowling, 2011; Newsome, 2010; Newsome & Dowling, 2018; Ólafsdóttir, 2019). In turn, in geologically rich regions of Africa, areas such as the Vredefort Dome in South Africa and the Ngorongoro Crater in Tanzania, key geotourism centers have been developed. This has promoted conservation, scientific education, and economic activity (Greffrath & Roux, 2011; Zaba & Gaidzik, 2011). In Nigeria, such programs are gradually gaining recognition in places such as the Zuma Rock and Idanre Hills (Anifowose & Kolawole, 2014; Mshelia et al., 2024). Therefore, developing a geopark or geotourism project in the Manawaji area will be vital for the diversification of the local economy, geoeducation advancement, and conservation of unique geological treasures for future generations.

Rare metal and strategic mineral potentials

Metasomatic enrichment of metals in sedimentary rocks that are in contact with basalts, although not yet confirmed economically, is reported by Stanienda-Pilecki (2025) in the area of St. Anne's Mountain, Opole Voivodeship, Strzelce Opolskie, Leśnica, Poland. Additionally, Deymar et al. (2018) describe alkali metasomatism as a process of Ti–REE–Y–U–Th mineralization. Key elements like Ti, Cr, V, Zr, Cu, Mo and Zn, could be enriched in the sedimentary rocks of the Manawaji area which are vital for capacitors, battery technologies, high-performance alloys, and aerospace systems (Grohol & Veeh, 2023; USGS, 2023). If this is verified through geophysical surveys and mineralogical (further geochemical exploration) studies, then Manawaji has the potential to become a strategic exploration area for rare metals.

Groundwater resources and hydrogeological potential

The groundwater potential of the Manawaji area is another important economic asset that should be of great consideration. The fluvio-deltaic Bima Formation has been reported as a very good aquifer because it has natural porosity and permeability (Bello et al., 2022). Sandstone aquifers have been widely utilized in arid and semi-arid settings for domestic water supply, irrigation, and livestock farming, owing to their ability to store and transmit water effectively (Domenico & Schwartz, 1998; Medici et al., 2016).

Beyond domestic use, such as agricultural activities and accessibility to clean drinking water, groundwater development in Manawaji could have broader economic implications, including industrial-scale bottling and international water exportation. The global demand for premium natural groundwater, especially in water-stressed nations such as Singapore, the UAE, and parts of Asia, has fostered a burgeoning global market for packaged natural water, valued at over \$300 billion annually (IBWA, 2023; Shahin & Salem, 2015). High-purity groundwater, if discovered in this area, tested for quality, and properly branded, could be used as a marketable water resource. Other global countries such as France, China, and Italy have since launched bottled water export initiatives targeting increasing demand for naturally sourced water on international markets (Turkish Goods, 2023).

A thorough hydrogeological survey (i.e., electrical resistivity tomography, pumping tests, borehole lithology) should be undertaken to identify aquifer limits, thicknesses, recharge areas, and sustainable yield. If done in a sustainable manner, this project could diversify Nigeria's export profile beyond oil while improving the water security of communities around Manawaji.

CONCLUSION

This study evaluates the economic resource potentials of the rocks in Manawaji, Upper Benue Trough, Gulani, Nigeria. The interdisciplinary approach employed, integrating fieldwork with Thin section analysis, provides extensive support towards achieving the goal of assessing the economic potentials of the area. The area has five major lithologies (fluvio-deltaic sandstones of the Bima Formation, fossiliferous limestones of the Pindiga Formation, columnar basalts, mylonite, and crystalline limestone) and has five economic potentials (i) columnar basalt suitable for dimension stone and as raw material for basalt fiber production; (ii) gemstones (sapphire) potentials; (iii) high-purity groundwater potentials; (iv) geotourism and natural laboratory potentials; and (v) prospective sources of critical metals. Subsequent work can combine geophysical surveys, geochemical exploration (e.g., XRF, SEM-EDS, LA-ICP-MS) fluid inclusion analyses, and further mineralogical and beneficiation studies to confirm the rocks classification, assess subsurface alteration zones and the extractive potential of highlighted resources in this area.

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