Geology and Petrography of the Basement Complex Rocks of Tsauni and Environs, North Central Nigeria

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***Abstract*—Detailed geological mapping and petrographic study of the rocks in Tsauni area and environs situated within Gwagwalada in Abuja Federal Capital Territory have been carried out to establish the geology relative to the rock types, texture, mineralogy, and mineralization. The area is part of the Basement Complex of North Central Nigeria and a newly discovered skarn environment with preserved basement metagranitoids of the migmatite-gneiss complex and lower grade metasedimentary schist belts. Major rock types identified include migmatite and various types of gneisses. Subordinate rocks include calc-silicate (skarn) rocks, ultramafic relicts and fine to medium grained granite all crosscut by younger Pan African granite, diorite, pegmatites, and quartzo-feldspathic veins. Two types of skarn; A and B were distinguished petrographically being the first mention of skarn occurrence in Nigeria. Petrographic study of selected rocks under plane and crossed polarized light alongside Back Scattered Electron (BSE) images from microprobe analysis showed the mineral suites to include quartz, feldspar (mostly plagioclase and subordinate alkali feldspar), biotite, minor amphibole, pyroxene, calcite and muscovite with accessory epidote, allanite, zircon, titanite, apatite and opaque minerals which selectively occur in both metagranitoids and skarn. Opaque minerals include magnetite, ilmenite± rutile, galena, pyrite sphalerite, and chalcopyrite. Structural features include foliation, joints, xenoliths and pendant (flame) textures, veins, and veinlets which are all aligned in the NE-SW, NW-SE, and minor N-S and E-W directions suggesting control from some deep-seated sources.**

***Keywords*—basement complex, Tsauni, geology, petrography, migmatite, gneisses, Nigeria**

I. INTRODUCTION

Detailed field mapping and petrographic studies are key to appraising the geology of important geologic terrains to establish the rock types, mineral contents, alteration products, contact, textural and geometrical relationships, and the identification of associated useful structures such as veins, dykes, and sills that could host mineralization. Such studies have proven to be useful in both the exploration and discovery of potential and economically viable basement rocks and minerals locked up in certain "hidden" geologic terrains across the globe like Turkey [1, 2], China [3], Greece [4], Ethiopia [5], and Iran [6]. Studies on the geology and petrography of some parts of the Basement Complex of Nigeria have been carried out by workers such as Abdullahi *et al.* [7], Adamu *et al.* [8], Elnafaty [9], Ekeleme *et al.* [10], and Oshiliki *et al.* [11]. Elnafaty in his work related the geology and petrography of the area studied with barite and copper mineralization occurrence in the rocks.

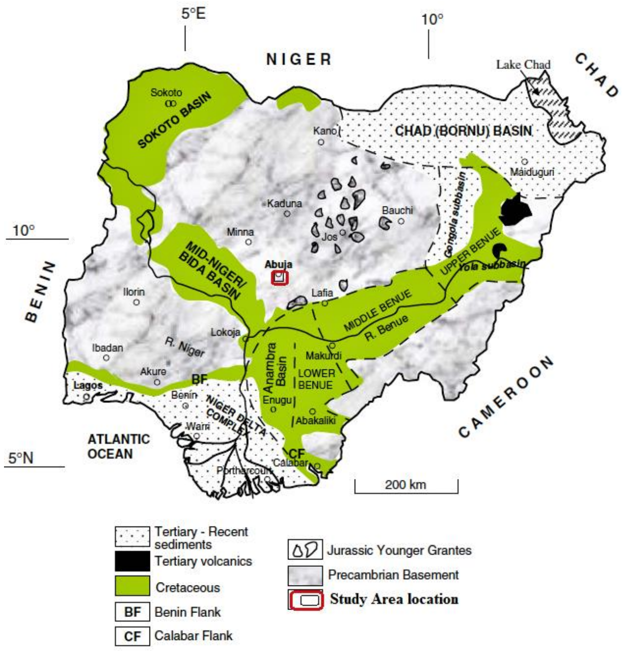

Fig. 1. Outline geological map of Nigeria with the study area (modified after Obaje [32]).

The study area is an important part of the Precambrian basement which is composed of the migmatite-gneiss complex and extension of the schist belts of north central Nigeria (Fig. 1). This is due to its rich geology and polymetallic Pb-Zn, Fe, Au and associated mineralization as well as the collection of such resources since the

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precolonial era till the recent times. Although the area is well known to artisanal and small-scale company miners, it has received relatively little attention from geologists and explorationists despite its relevance on the tectonism of the Pan African mobile belt of Nigeria. Rocks of North Central Nigeria to which the study area is an integral part have been described on a regional scale by several workers such as Grant [12], Oyawoye [13], McCurry [14], Turner [15], Dada *et al.* [16], Obiora and Ukaegbu [17], and Ekwueme and Kalsbeek [18] who centered on geology, petrology, geochemistry, and geochronology of rocks in the areas of study. However, none of these works was directly carried out in the study area.

II. Literature Review

Earlier works carried out in relation to the area include those of Russ [19] and Truswell and Cope [20] who studied the area using reconnaissance survey method. Huntings [21] carried out Airborne Geophysical Surveys across Nigeria under the Geological Survey of Nigeria with the area inclusive. Woakes and Bafor [22] studied some aspects of gold mineralization within the schist belts including the area of study and parts of the present Niger state. Okunola *et al.* [23] studied the Pb-Zn mineralization in the area using integrated geological and geophysical methods to identify and describe the potential mineralization zones based on gravity and VLF-EM anomalies produced. The Nigerian Geological Survey Agency as reported by the Ministry of Solid Minerals and Development Agency (MMSD) [24] carried out exploration for solid minerals across North Western Nigeria which included part of the study area. They recorded that Babban Tsauni is one of the prominent Pb-Zn mineralization areas within the crystalline Basement Complex of Nigeria having significant lead, gold, and silver deposits whose rock suite consists of pegmatized migmatite, migmatitic gneisses, amphibolites, ultramafites, pegmatite and silicified rocks and quartzo-feldspathic veins with multiple deformations and joint systems, intruded by pegmatites and granites of the Pan African orogeny. No petrographic study of the rocks and ore minerals or mention of calc-silicate rocks (skarn) and skarn deposits were recorded. Detailed geological field mapping and petrographic study of the representative rock samples as studied in the present work will help to shed light on the area thereby establishing the geology relative to the rock types, texture, mineralogy, and mineralization of each individual "barren" and mineralized rocks and nature of the mineralization.

III. Regional Geology

A. The Nigerian Basement Complex

The Precambrian Basement Complex of Nigeria is a part of the Pan-African mobile belt which lies between the West African craton, the Congo craton, and the southern part of the Tuareg shield (Fig. 2). It covers about 50% of the entire country and consists of:

- Migmatites/migmatitic gneisses including augen-gneisses, foliated and slightly foliated hornblende, biotite and quartzo-feldspathic gneisses, and granodiorites.
- The Schist belts composed of mica-schists, tremolite/hornblende/actinolite schists, graphite schists, occasional marbles, and dolomites, phyllites calc-silicate rocks quartzites, metaconglomerates and Banded Iron Formation (BIF) with occasional manganese in some places.
- Precambrian (Pan African) granites including porphyritic/porphyroblastic muscovite granites, non-porphyritic and non porphyroblastic granites, biotite granites, hornblende-biotite granites, aplites, granodiorites, diorites, quartz diorites, gabbros, quartz gabbros and dolerites, syenites and hypersthene granites (charnockites) [25–32].

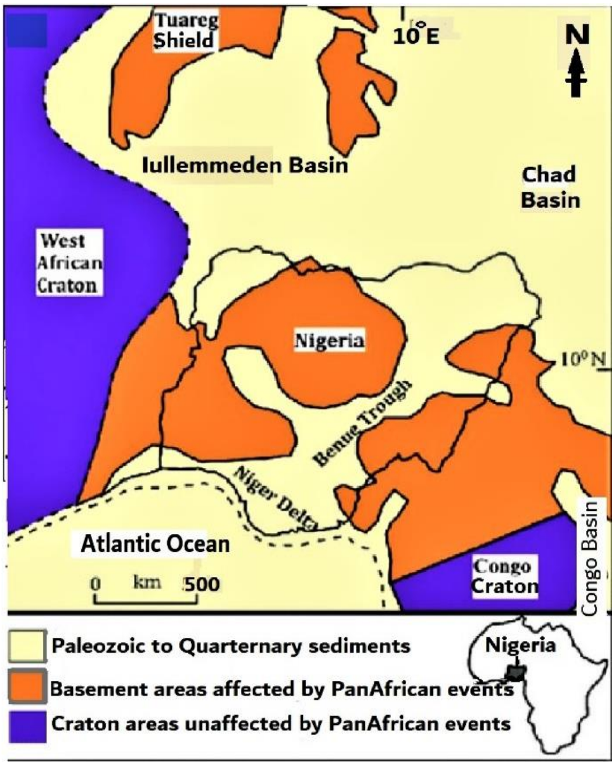


Fig. 2. The location of the Precambrian basement complex of Nigeria between the West African craton, the Congo craton and the southern part of the Taureg Shield (modified after Akingboye and Osazuwa [33]).

The Precambrian ages of the basement rocks in Nigeria are generally related to the Pan African thermotectonic/orogenic event (900–450 Ma) which was believed to have reactivated and obliterated the entire crust. Few imprints of older events such as the Liberian (3000–2400 Ma), Eburnean (2400–1600 Ma), and Kibaran (1600–900 Ma) indicating relict ages have been recorded in some places [31, 34]. Predominant acid volcano-plutonic sequence of Jurassic age known as the Younger Granites and numerous basaltic and rhyolitic dykes including quartzo-feldspathic veins, veinlets, and pegmatites occur as intrusions within the Basement Complex.

IV. MATERIALS AND METHODS

- **Field Mapping:** This involved the systematic method of sampling along profiles and rock contacts aided by the Geographical Positioning System (GPS) to record positions, field coordinates, and outcrop elevations. Structural measurements were made using the compass clinometer. Samples of fresh rocks were collected with the use of sledge and geological hammers, labeled and stored for laboratory use. Hydrochloric (HCl) and nitric (HNO_3) acids were used to test for gold and carbonates respectively.
- **Desk Work:** Landsat imagery of Paiko Sheet 185 obtained from the National Centre for Remote Sensing (NCRS), Jos was digitized to produce lineament map of the study area using the Integrated Land and Water Information System (ILWIS) package and also to produce the rose diagrams.
- **Petrographic Study**: Fifteen (15) selected rock samples were cut into chips using a cutting machine and subsequently polished using carborundum to obtain the required thickness of about 0.03µm and a perfect smooth surface. Each cut and polished rock sample was mounted on a clean glass slide using adhesive. The prepared slides were examined under plane and cross polarized light using the petrological microscope at the Geology Department of the University of Jos.
- **Microprobe Study**: Eight (8) selected rock samples were prepared into doubly-polished thin sections used for electron probe micro analysis. The mineral components from the doubly polished thin sections were scanned in plane polarized (pp) and cross polarized (xp) light using Canon Cano scan 9000F flatbed. The Electron Microprobe Analysis (EPMA) was performed using the JEOL JXA-8230 Super probe Electron probe Microanalyzer at the Chevron Geomaterials Characterization Laboratory, Department of Geology and Geophysics, Louisiana State University, Baton Rouge, U.S.A. Felspars were analyzed using a defocused beam with an accelerating potential of 10 kV with a beam current of 10 nA and a spot size of 5µm. All other silicates (biotite, amphibole, muscovite, calcite, and chlorite) were conducted using a defocused beam with an accelerating potential of 15 kV with a beam current of 20 nA and a spot size of 5µm. Analyses were processed using the φpZ-XPP matrix correction procedure in the JEOL software. Data obtained is presented in subsequent articles.

V. RESULTS AND DISCUSSION

A. Field Geology

The study area is bounded by latitude 9°8'.20"N to 9°11'24.0"N and longitude 6°55'45.0" to 6°59'24.0"E of Paiko sheet 185 SE. It covers an area of about 40 square kilometers ($40km^2$) with villages such as Babban Tsauni Kassa, Tsauni Tsama, and Gwoi. Tsauni area and environs form an important part of the Basement Complex of north central Nigeria due to its composition of major rock groups that make up the complex (Fig. 3). These rock groups include the Migmatite-gneiss complex, the Schist belts, and the Pan African Older Granites.

Classified as the older metasediments by Oyawoye [25], the migmatite gneisses appear to be the oldest rocks in the study area. Field and contact relationships between the various rock units including structural elements such as ptygmatic folds, zenoliths and pendant (flame) structures, grain recrystallization and crystal elongation suggest poly metamorphism by anatexis and some degree of granitization (Fig. 4a–c). Such features are more pronounced at the contacts between the migmatite-gneiss and granites and between the migmatite-gneisses and mafic metagabbro / hornblende gneiss exposed to the northwestern and southeastern parts of the study area respectively. Quartz crystal elongation characterizes the contact between the granite intrusion and the migmatized calc silicate gneiss at the northeastern side (Fig. 23).

Important rock types distinguished in the field are slight to well foliated gneiss, biotite, migmatized calcic and amphibolite bearing gneisses, augen gneiss, migmatite, calc-silicate/skarn with subordinate fine to medium grained granite/granodiorite, pegmatite and granitic dykes, minor diorite and quatrzo-feldspathic veins/veinlets. Fragments of migmatized ultramafic rocks also occur on the eastern side but were not sampled. The rocks are generally metagranitoids and basement intrusives of probably pre to post Pan African ages. Although most skarns are generally considered a product of contact metamorphism /metasomatism as a result of a magmatic (mostly granitic) intrusion adjacent to a carbonate or calc silicate rock, they may form in almost any rock type including shale, sandstone, granite, iron formation, basalt, gneiss and schist [35]. Skarns are either exoskarns (of sedimentary protolith) or endoskarns (of igneous protolith). The calc-silicate/skarn recorded in the study area for the first time, is an endoskarn of amphibolite bearing and quartzo-feldspathic gneiss composition with only some small carbonate-rich intercalations mostly entirely obliterated except for the effervescence observed with dilute HNO_3.

The basement migmatite and gneisses are most likely produced from a regional metamorphism of both prograde and retrograde nature that occurred in the upper greenschist facies into the upper amphibolite facies.

This opinion is based on the occurrence of diopsidic-hedenbergite rich pyroxene and feldspars of plagioclase (albite to andesine-An_{3-41}) composition in some parts of the study area [36]. Tourmaline and wollastonite in the skarn are indicative of high temperature contact metamorphism. Also, the occurrence of minerals like epidote, chlorite, and actinolite in some of the metagranitoids and skarn are suggestive of retrograde metamorphism. The pegmatite and granite intruded these basement rocks (Fig. 3).

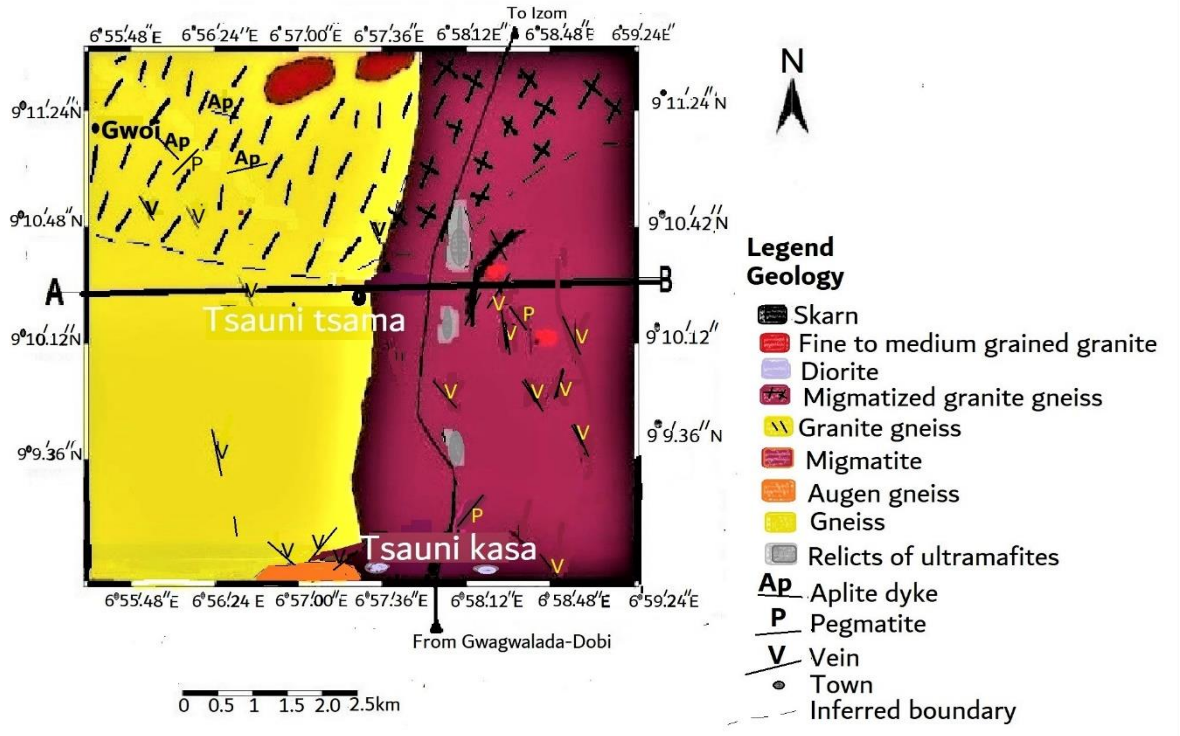


Fig. 3. Geological map of Tsauni and environs.

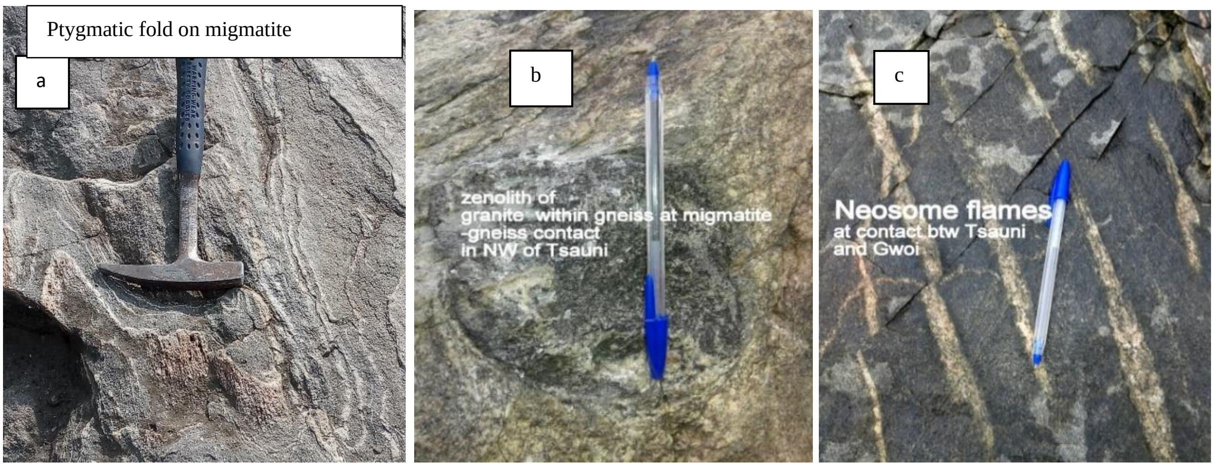


Fig. 4. Photographs of (a) ptygmatic fold on migmatite @SE (b) zenolith of granite on migmatite gneiss (c) flame (pendant) structure on migmatite at contact between migmatite gneiss and granite. Both (b) and (c) occur between Tsauni and Gwoi settlements in the NW part of the study area.

Migmatite:

The migmatite of the study area are mostly exposed to the eastern half cut across from north to south by the minor road through which the area is accessed. Migmatites characterize medium to high-grade metamorphic environments and are highly deformed [37]. Migmatites are generally dark colored rocks whose topography consists of undulating low to high hills in the study area. Elevation reaches 300m above sea level. Migmatite in the study area mostly appears as pockets of migmatized foliated calcic and amphibolite bearing gneisses and pure migmatite. Intense folding and folding of fold axes (ptygmatic folds), joints, quartzo-feldspathic and quartz veins, pegmatite dykes, flame structures, and zenoliths characterize the contacts between the migmatite and gneisses particularly at the south eastern and north western side (Fig. 4a–c).

Foliation bands of leucocratic and melanocratic minerals are common with tightly folded features of ptygmatic folds exposed in some places. Paleosomes and neosomes are also common in the migmatite, especially at the contact with gneiss (Fig. 5b–c). Whereas the paleosome represents the unmodified remnant of the metamorphic parent rock from partial melting, the neosome (new rock), represents component exsolved by partial melting and has a pegmatitic, aplitic, granitic or generally plutonic appearance [17]. The neosome occurs as flames in some exposed outcrops. The flame neosome structures are considered to indicate slow cooling in pulses during anatexis/ and or fractional crystallization.

The rocks appear to have formed under moderate to extreme temperature and pressure conditions during prograde metamorphism of the pre-existing gnessic/ granitic rocks. Evidence of this is seen in the xenoliths of granite and xenoblasts of gneiss within the migmatite-gneiss at the contact between the two rocks (migmatite-gneiss) and fine-medium grained granite towards Gwoi at the northwestern part of the study area. Field evidence, therefore, shows that the granite is probably older than the migmatite (Fig. 4b). Several veins cross cut the migmatite, especially to the north and south east. Relicts of migmatized ultramafic rocks were also observed in some places (Fig. 3). Strike of rocks / foliation trends are generally in the NE-SW, NW-SE, and minor N-S directions.

The migmatite gneisses (migmatized amphibolite bearing gneiss and pure migmatite, augen and calcic gneisses) of the study area host the epithermal style vein mineralization which includes late magmatic-hydrothermal magnetite and subordinate sulphides of lead, zinc, copper, iron and associated gold and barite.

Gneisses:

The study area is underlain by gneissic rocks to the western side which covers about 60% of the entire area. The rocks are generally elongated rugged ridges and massive conical hills. They include slightly foliated/ foliated biotite gneiss, amphibolite-bearing gneiss, augen gneiss, granitic gneiss, calcic (calcite rich), and calc-silicate gneiss (Fig. 3 and 6a–f). Macroscopically, the gneisses are light grey in colour with medium to coarse texture and composed of quartz, feldspar, biotite, subordinate pyroxene, amphibole, calcite, and muscovite. The mineral grains in most of the rocks generally appear as porphyroblasts embedded in a groundmass of mainly quartz and feldspar. Accessory minerals were only identified in thin sections. Several quartz veins occur as intrusions in the rocks. The slightly foliated gneiss is less deformed and contains smaller quartz veins than the porphyroblastic (augen) gneiss which is also highly weathered probably due to the fractures caused by abundant joints and mineralized veins present on the rock. The augen gneiss contains large porphyroblasts of feldspar embedded in a fine matrix of quartz, feldspar, and biotite (Fig. 6d). The quartz veins in the augen gneiss range between 1cm to about 8 meters in thickness with the latter hosting the major polymetallic Pb-Zn, Fe-Cu-Ba- Au mineralization in the southwestern part of Tsauni town. Most of the veins trend in the NE-SW and NNW-SSE directions with minor N-S and E-W trends. Elevation of the gneiss is generally about 350m but the augen gneiss are lower hummocky hills whose elevation averagely stand at 200m (Fig. 3).

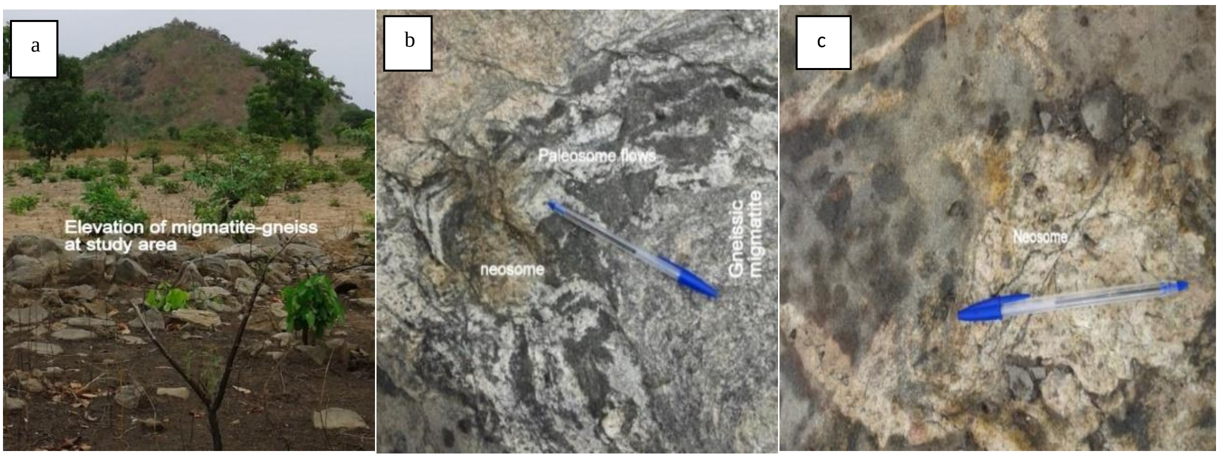


Fig. 5. Photographs of (a) Typical migmatite-gneiss elevation (b) Paleosome on migmatite (c) Neosome on migmatite in the study area.

Metasedimentary rocks:

The metasedimentary schist belt of the study area is composed of migmatized amphibolite bearing gneiss, quartzo feldspathic and calc-silicate gneiss with carbonate-rich intercalations which appear to be tightly infolded into the older migmatite-gneiss complex associated with them and generally trend NNW-SSE direction (Fig. 7a). Contact relationship to the older migmatite-gneisses is gradational. The rocks are commonly medium to coarse grain in texture. Whereas the gneissic varieties are light grey in colour with lighter bands, the calc-silicate rocks are very dark with altered types showing the usual skarn-like weathering dark colours and lighter bands.

Calc-silicate rocks (Skarn):

Rocks produced by metasomatic alteration of existing rocks in which "calc-silicate" minerals (calcium-iron-magnesium-manganese-aluminum silicates) such as diopside, garnet, epidote, wollastonite, calcite and amphiboles are formed are referred to as skarn. Tourmaline is also present in some skarns. Skarns are generally dark-coloured and coarse grain in texture. Skarns can form during regional or contact metamorphism and from a variety of metasomatic processes involving fluids of magmatic, metamorphic, meteoric and or marine origin [35]. Skarns may be barren or contain metals and other minerals of economic value. Skarn deposits are important sources of base and precious metals as well as tin, tungsten, and iron. Majority of the world's major skarn deposits are considered to be related to hydrothermal systems. They are found adjacent to plutons along faults and major shear zones, in shallow geothermal systems, on the bottom of the sea floor, and at lower crustal depths in deeply buried metamorphic terrains [38, 39].

The link between these diverse environments and what defines a rock as skarn is the mineralogy which includes a wide variety of calc-silicate and associated minerals but usually is dominated by garnet and pyroxene. However, important skarns composed of pyroxene-amphibole, amphibole-epidote, magnetite-epidote, boron dominated, feldspar dominated, and pyroxene dominated with abundant or minor calcite / or wollastonite and magnetite have been studied extensively across the world in the past and recent times [39–47].

The Skarn of the study area is exposed to the north eastern part. It is a dark colored coarse-grained rock inter grown with the host migmatite and migmatized quartzo feldspathic and amphibolite-bearing gneisses. Two types of skarn were identified in the study area as A-pyroxenamphibole dominated and B-Biotite-apatite, and monazite dominated.

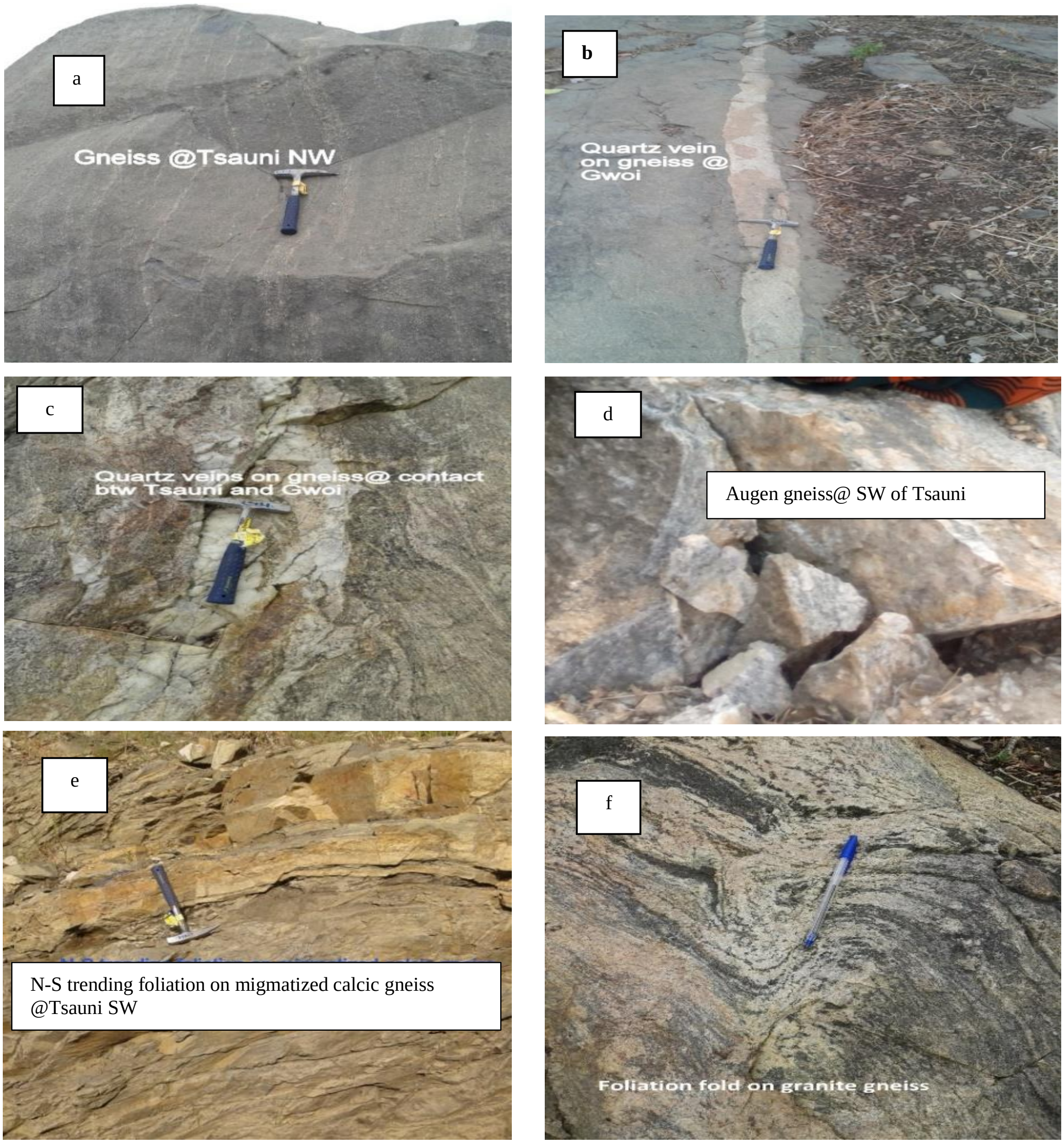


Fig. 6. Photographs of (a) Slightly foliated gneiss (b) Quartz vein on gneiss (c) Quartz vein on granite gneiss/ gneiss contact (d) Augen gneiss € Migmatized calcic gneiss (f) Foliated granitic gneiss in the study area.

The skarn of the study area has endoskarn polymetallic features with an imprint of both calcic-Fe and magnesian-Fe mineralogy that should be confirmed through microprobe ore mineral chemistry. Alteration zones are common in the calc-silicate (skarn) rocks with evident color and mineralogical changes Pegmatite intrusions, granitic and aplite dykes and several veins cut across the rocks and trend mostly NE-SW and N-S (Fig. 7b–f). Polymetamorphism in the area produced both prograde and retrograde minerals such as clinopyroxene, wollastonite, hornblende and epidote, actinolite, chlorite respectively in the skarn. Macroscopic petrography shows coarse grain texture and includes major amphibole, pyroxene, epidote, calcite, quartz, minor biotite and muscovite in skarn type A, abundant biotite, calcite, quartz and > 0.1% accessory apatite, titanite and monazite in skarn type B. Pb – Zn – Fe-Cu (sulphides) and Fe-oxide mineralization associated with minor gold, silver, and barite are common.

Fig. 7. Photographs of (a) Outcrop of migmatized calc silicate gneiss, biotite and amphibolite bearing gneisses (b) Vein intrusion with visible alteration haloes on quartzo-feldspathic gneiss (c) Altered skarn (d) migmatized calc silicate rock with carbonate-rich intercalation (e) Pegmatite outcrop on gneiss (f) Granitic dyke intrusion trending NE-SW. All (except e) are exposed at the NE part of the study area. Coordinates: (Latitude N9°10'30.1" Longitude E6°58'.13").

Pegmatite and Granitic Dykes:

These are common rocks that intruded the older basement and meta-sedimentary rocks of the study area, especially at the mineralized zones in the south and northern sides of Tsauni town (Fig. 3). The rock unit represents the youngest rocks of the study area and consists mainly of granites-muscovite and biotite granite, granitic and aplite dykes, quartz veins/ veinlets, quartzo-feldspathic veins, and pegmatite. The rocks are generally felsic and occur as intrusions within the migmatite-gneiss and the metasedimentary rocks (Fig. 7e and f). Field relationships indicate that the hydrothermal activity that accompanied the granitic rock intrusion(s) was probably responsible for triggering the contact metamorphism that produced the skarn at the igneous/metamorphic fronts to the northeastern part of the study area. The pegmatites are associated with the Pan African events that affected most of the Nigerian migmatite-gneiss complex and meta-sedimentary rocks accompanied by intense deformation and magmatism represented by folding, faulting, metamorphism and a series of hydrothermal activities that probably yielded mineralization in the affected rocks [34]. The last two are probably responsible for the vein-dyke and skarn mineralization in the study area. The granitic dykes and pegmatites generally trend in the NE-SW and N-S with minor E-W directions.

B. Petrography

Under the microscope, the gneisses, migmatite, pegmatite, granite, and skarn of the study area displayed consistent mineralogy and almost similar texture across individual similar rock units. The slight differences in mineralogy/ and or textures were only observed in the mineralized varieties.

Gneisses:

The gneisses which include augen, foliated biotite and amphibolite-bearing and slightly foliated varieties are generally composed of porphyroblasts of quartz, feldspar (plagioclase-oligoclase and minor albite, orthoclase and minor microcline) and biotite set in a finer grained matrix. Subordinate pyroxene, amphibole, and muscovite are common features. (Figs. 8 and 9) Opaque minerals are common and were revealed in the microprobe mineralogical analysis to be mostly iron oxides of magnetite and ilmenite composition (Figs. 8–14). Rutile needles were also identified in one sample.

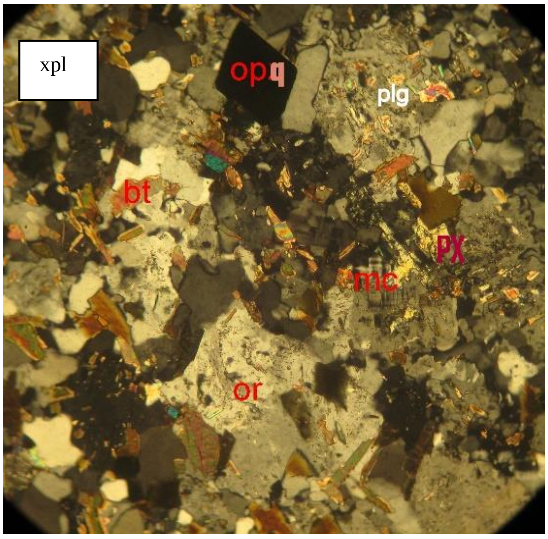


Fig. 8. Photomicrograph of gneiss (IF2) (X40) from the south western side of the study area. or = orthoclase, bt = biotite, plg = plagioclase, mc = microcline, Px = pyroxene, opq = opaque mineral. Note the alteration of pyroxene and sericitization of plagioclase at the right side of field of view.

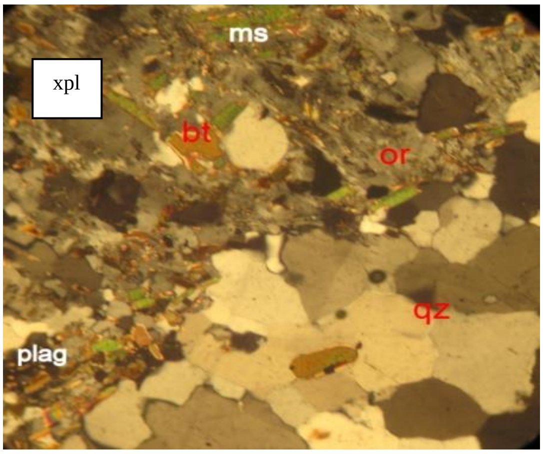


Fig. 9. Photomicrograph of migmatized-gneiss (IF 3b) in xpl (X40), bt = biotite, or = orthoclase, qz = quartz, pl = plagioclase, ms = muscovite. Note the elongation of some quartz grains at the centre of field view.

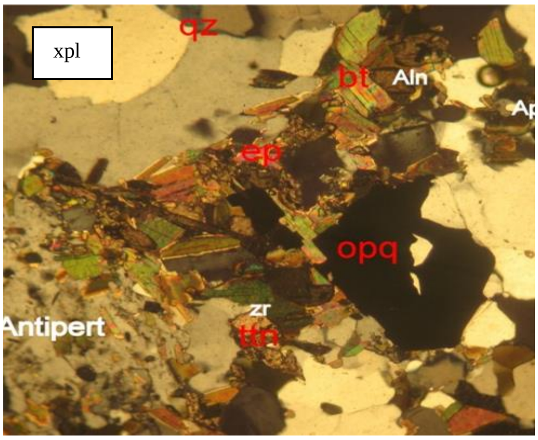


Fig. 10. Photomicrograph of augen gneiss (IF 15b) in xpl(X40), bt = biotite, qz = quartz, opq = opaque mineral, ttn = titanite, Aln = allanite, zr = zircon, Ap = apatite, Antipert = Antiperthite, Ep = epidote.

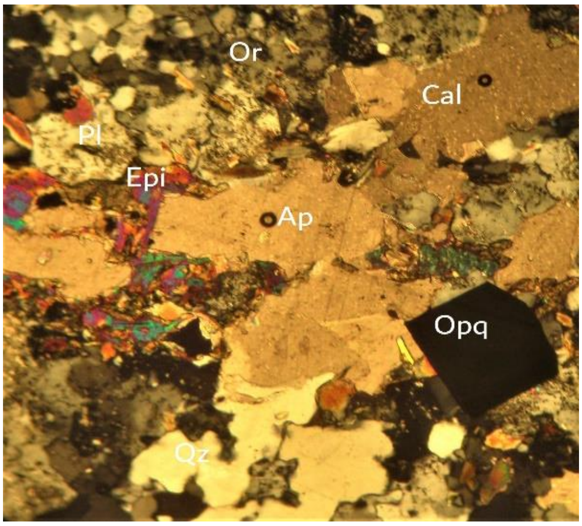


Fig. 11. Photomicrograph of migmatized calcic gneiss (IF1) (X40) in Tsauni southwest. orth = Orthoclase cal = calcite, qz = quartz, epi = epidote, opq = opaque. Note the alteration of calcite by epidote at centre left.

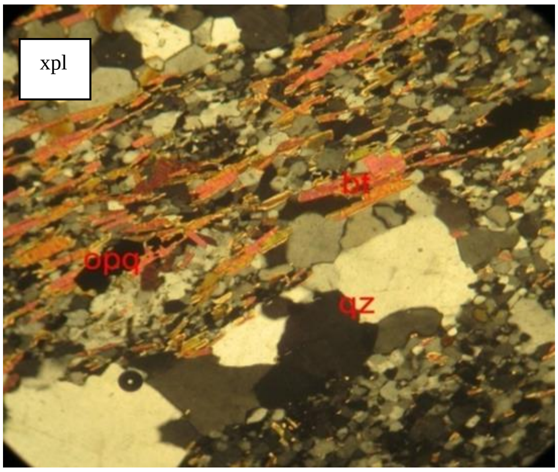


Fig. 12. Photomicrograph of migmatized biotite gneiss (IF 44) in xpl (x40), qz = quartz, bt = biotite, opq = opaque. Note the foliation of biotite and quartz.

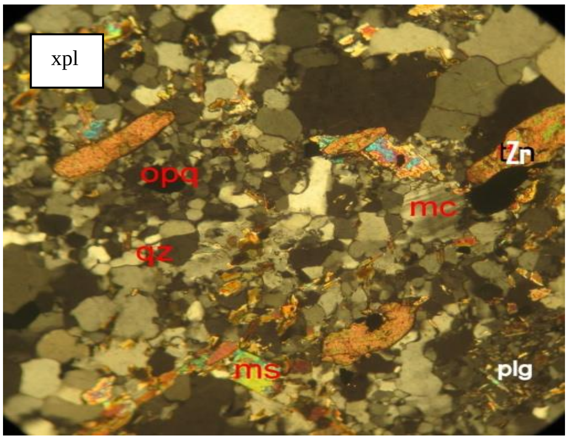


Fig. 13. Photomicrograph of unmineralized gneiss (IF 48) (X40) in Tsauni northwest in xpl with porphyroblasts of zircon grains. bt = biotite, qz = quartz, plg = plagoclase, zr = zircon, ms = muscovite, mc = microcline.

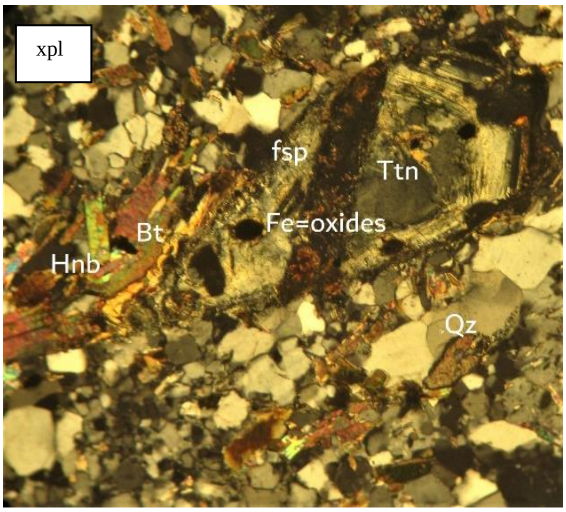


Fig. 14. Photomicrograph of amphibolite bearing gneiss (IF 48) (X40) in Tsauni north west in xpl showing a porphyroblast of altered sphene (titanite) now entirely replaced by feldspars, hornblende, biotite, and iron oxide. bt = biotite, qz = quartz, hnb = hornblende, ttn = titanite, or = orthoclase.

The Augen gneiss shows large porphyroblasts of feldspars that are generally aligned in a parallel orientation embedded in a fine-grained matrix of quartz, feldspar, and biotite. Antiperthites commonly occur in the augen gneiss (Fig. 10). Samples of migmatized augen gneiss collected at the mineralized zones and contacts are mostly pyroxene prone with the pyroxene highly altered, feldspar mostly sericitized and quartz intensely fractured. These features are consistent with the tectonism/ magmatic and hydrothermal activities that yielded alteration and mineralization within the rock. Feldspars in the rock as revealed from both microscopic thin section observation and microprobe analysis include mainly oligoclase, orthoclase, minor albite, and microcline. Quartz is generally sub-anhedral, white to light grey in colour showing undulose extinction. Biotite here are generally seen as small- moderate greenish brown "needles"/ lamellae mostly clustered as overgrowths on quartz and feldspar. Strong relief on ppl is common. Allanite and apatite occur as accessory minerals. The presence of microcline in association with plagioclase (oligoclase) is suggestive of retrograde metamorphism [48, 49] since both minerals (of low grade and higher-grade metamorphism respectively), rarely occur together.

The mineralized migmatized calcic gneiss consists of abundant secondary calcite overgrowths and epidote alteration at calcites boundary in addition to the usual gneissic mineralogy (Fig. 11). The calcites are probably hydrothermal calcites related to the mineralization. Pinkish buff is common with no visible lamellae twinning. Epidote appears as sub-euhedral small greenish yellow crystals with weak pleochroism and zero extinction. Birefringence is high up to 3rd order yellowish-pink and bluish purple.

The biotite and amphibolite bearing gneisses contain abundant biotite and moderate amphiboles respectively. Calcite, muscovite, epidote, zircon, monazite, and sphene occur in some samples with the last three being more common among the less mineralized zones. Biotite generally defines the foliation bands common in the rocks and forms nucleation centers for most of the opaque minerals (Figs. 12 and 13).

Most of the migmatized amphibolite bearing gneiss exposed at Tsauni northwest that contain magnetite generally appear as a cumulate gneiss (with mineralogy of plagioclase, quartz, hornblende, biotite, subordinate microcline, and muscovite and > 0.1% overgrowths of zircon and titanite). One large pseudomorph porphyroblast of sphene (titanite) has been almost completely altered and infilled by crystals of feldspar, hornblende, biotite ± chlorites, and iron oxides leaving only the diamond shape behind (Fig. 14). This probably corroborates with an early magmatic/ cumulate origin (and subsequent secondary events) for the magnetite and ilmenite revealed by microprobe analysis in the same rock of the study area.

Migmatite:

The migmatite mineralogy is somewhat similar to that of the gneiss except for the fewer calcite grains which mostly appear as early formed contrary to the late formed calcite overgrowths on earlier biotites and feldspars characteristic of the migmatized calcic gneisses (Figs. 15 and 16). Major mineralogical constituents of the migmatite include biotite, feldspar, and quartz with subordinate pyroxene and amphibole. Muscovite, calcite and apatite are accessory. Opaque minerals are common. As in the gneisses, the biotites define the foliation trend and form nucleation sites for opaque minerals.

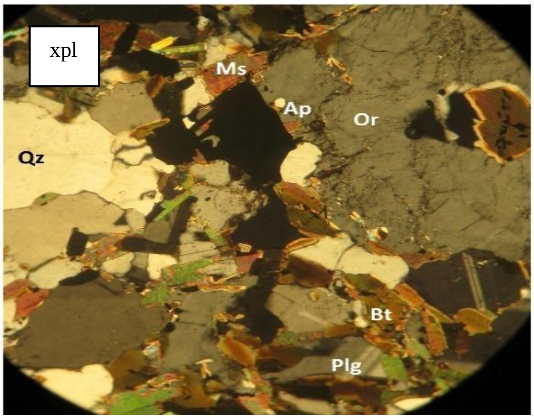


Fig. 15. Photomicrograph of migmatite exposed at Tsauni northeast (IF 42b) in xpl (x40), qz = quartz, bt = biotite, opq = opaque, pl = plagioclase, ap = apatite. Note the porphyroblast of orthoclase that totally replaced the "atoll" plagioclase to the right and biotite foliation.

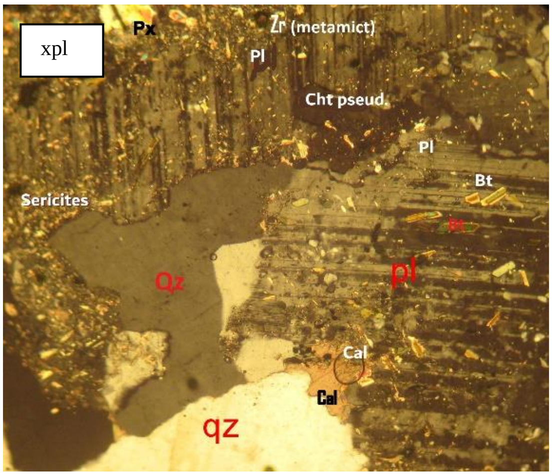


Fig. 16. Photomicrograph of migmatite exposed at Tsauni southeast (IF 5a) in the study area showing pophyroblasts of plagioclase and quartz in xpl (x40), qz = quartz, bt = biotite, cal = calcite, pl = plagioclase. Note the interstitial calcite between plagioclase and quartz at lower right of field of view.

Calc silicate rocks (skarn):

Mineralogy is generally zoned in the skarn. Major minerals identified in skarn type A (IF 39A, IF 41A, IF 41B, and IF 45B) include quartz, pyroxene, amphibole, calcite, epidote, subordinate biotite, wollastonite, tourmaline and accessory opaque minerals ± allanite, apatite and titanite (Figs. 17–19). Calcite in the skarn appears to have occurred in two generations of both primary and secondary nature. It shows the characteristic pink buff with twin lamellae and moderate relief. Pyroxene and amphiboles are mostly clinopyroxene of diopsidic-hedenbergiteand magnesio-hornblende compositions respectively [37] and represent minerals of the progade metamorphism. Tourmaline and wollastonite are also important. Wollastonite is whitish to cream colour in thin sections with two directional cleavages longer at the x-axis. It has moderate relief. Tourmaline occurs as elongated crystal prisms of brownish red to bluish purple colours with uneven – conchoidal fractures. Pleochroism is moderate to strong with moderately strong relief. Microscopic evidence indicates that both tourmaline and wollastonite are older than calcite which generally occurs as overgrowths and at the boundaries of both (Fig. 18). The retrograde skarn is represented by actinolite, eoidote, and chlorite.

Skarn type B on the contrary consists of abundant biotite, calcite, quartz and accessory feldspar, opaque minerals, > 1% apatite, titanite, and monazite (Figs. 20 and 21) Field relationship shows that skarn type A is very close to the hydrothermal veins as wall rocks while type B like the other metagranitoids, is far from the veins which may have resulted to the differences in especially the accessory "secondary" minerals like apatite, allanite and monazite (concentrated in type B) probably protracted from secondary hydrothermal processes [50]. The near absence to accessory nature of feldspar in the skarn may also be a result of hydrothermal alteration from metasomatic induced mobility that led to alkali and alumina losses.

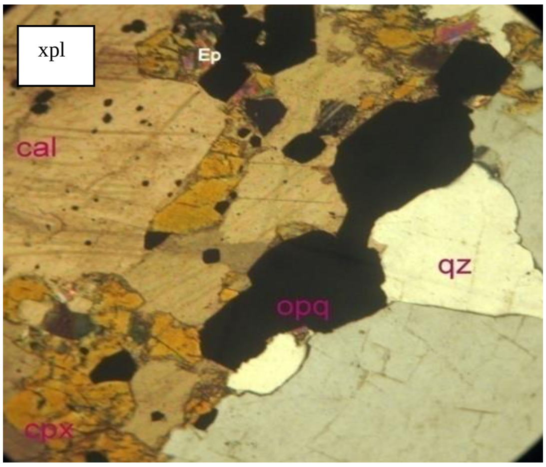


Fig. 17. Photomicrograph of skarn (IF 39 A) in xpl (x40), qz = quartz, cal = calcite, cpx = clinopyroxene, Ep = epidote. Note the primary calcite and zonation of the minerals in the skarn.

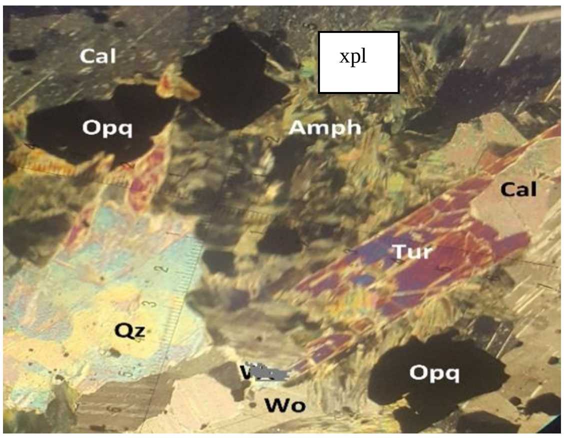


Fig. 18. Photomicrograph of skarn type A (IF 41A) in xpl (x40), qz = quartz, cal = calcite, amph = amphibole, bt = biotite, Tur = Tourmaline, Wo = wollastonite, Opq = opaque mineral.

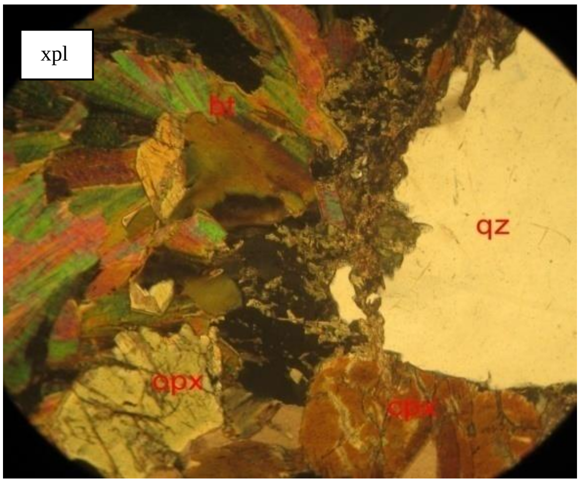


Fig. 19. Photomicrograph of skarn type A (IF 45 B-1) in xpl (x40), qz = quartz, bt = biotite, cpx = clinopyroxene, Amph-amphibole, Ap = apatite, cal = calcite.

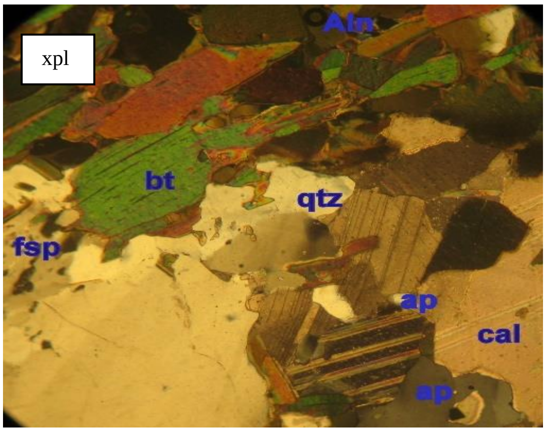


Fig. 20. Photomicrograph of skarn type B in xpl (x40), bt = biotite, qz = quartz, cal = calcite, fsp = feldspar, ap = apatite, Aln = allanite.

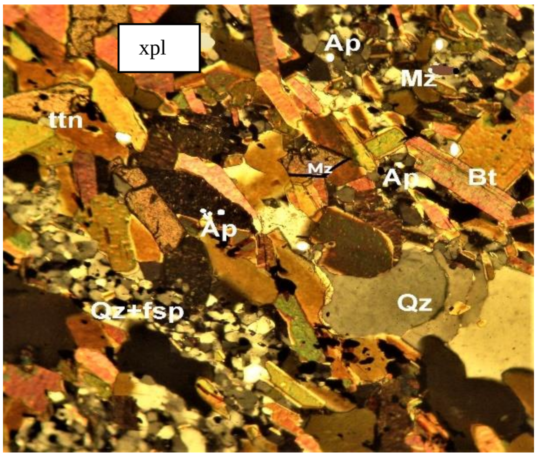


Fig. 21. Photomicrograph of skarn type B (IF 41B-2) in xpl (x40), qz = quartz, fsp = feldspar, bt = biotite, ttn = titanite, mz = monazite, Ap = apatite. Opaque minerals are disseminated.

Granite:

The constituent minerals of the granite include quartz, feldspar, muscovite and subordinate biotite, and hornblende (Fig. 22). The rock is generally medium grained. Muscovite occurs as phenocrysts in some and shows the characteristic basal cleavage in one direction. The granite is intrusive into the migmatite and calc-silicate/amphibolite bearing gneiss adjacent to the skarn deposit. Some samples contain crystals of calcite and/or wollastonite, pyroxene, and amphibole probably inherited from the host rocks. The granite at contact with gneiss shows distinct quartz elongation and fractures indicating deformation (Fig. 23).

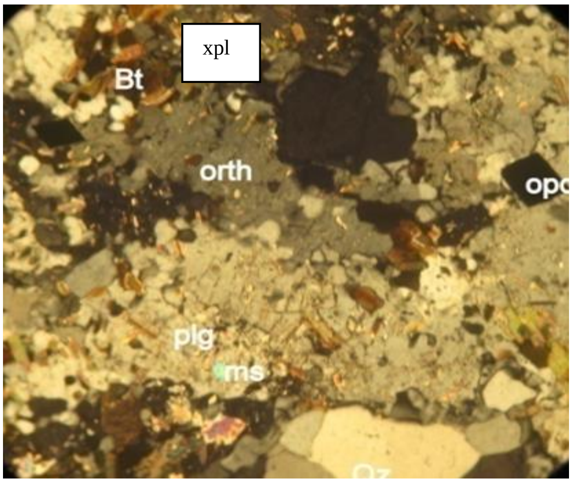


Fig. 22. Photomicrograph of granite (IF25-2) in XPL (x40), musc = muscovite, qz = quartz, plg = plagioclase, fsp = feldspar, bt = biotite, hnb = hornblende, opq = opaque mineral, orth = orthoclase.

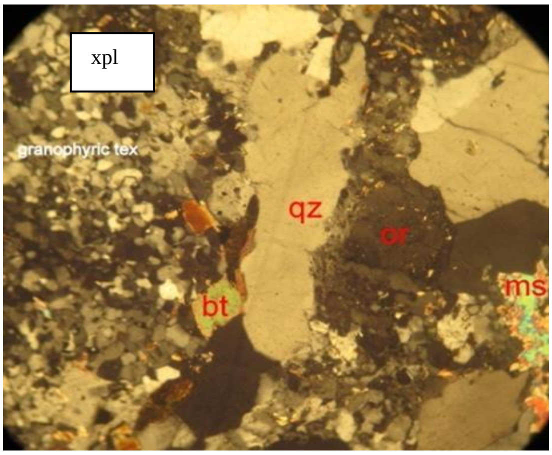


Fig. 23. Photomicrograph of granite-gneiss contact in Tsauni north east (IF 46C) in XPL(x40). Note the elongated quartz porphyroblast at the center between granite and gneiss and the fractured quartz at the right side of the field of view. The granite shows granophyric texture. qz = quartz, bt = biotite, ms = muscovite, or = orthoclase.

Pegmatite:

The pegmatite of the study area is composed of large crystals of quartz, plagioclase, microcline, and minor biotite. Muscovite is also important (Fig. 24). The quartz crystals are highly fractured and sericites are common among the plagioclase which also displays polysynthetic twinning. Accessory zircon, sphene, and opaque minerals are rare. Microcline shows the characteristic cross-hatch texture with low relief while quartz shows undulose extinction. Muscovite is intensely birefringent with pinkish blue-purple colours. The characteristic bird's eye/ mottled extinction is common with moderate to high relief.

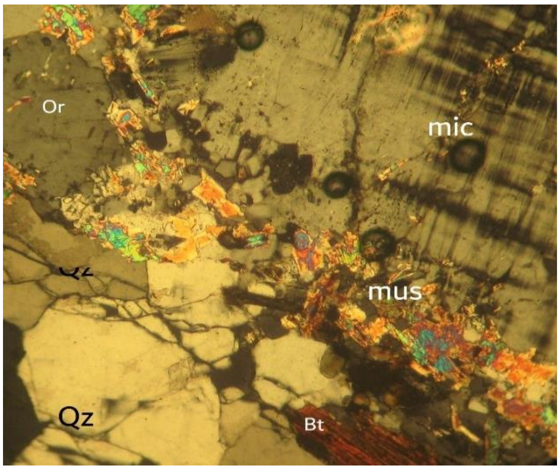


Fig. 24. Photomicrograph of pegmatite (IF36A) in xpl (x40), qz = quartz, bt = biotite, or = orthoclase, mc = microcline, ms = muscovite.

Mineralogy of some silicates and ore minerals from EPMA analysis:

Silicates and some ore minerals from the various rock types in the study area were identified using the Back Scattered Electron (BSE) images. Analysis from microprobe imaging. across the metagranitoids revealed the mineralogy to include plagioclase, k-feldspar, quartz, biotite and accessory calcite, epidote, zircon, apatite, allanite, and titanite. The skarn generally includes major calcite, biotite, amphibole, pyroxene, some quartz, epidote and subordinate accessory feldspar ± apatite, allanite, and zircon. Ore minerals include sub-euhedral magnetite and subordinate galena, pyrite, chalcopyrite among others (Figs. 25–27). Mineralogy of the rocks confirms the petrographic study carried out using thin sections. Silicates identified from individual rock types such as the augen gneiss display the characteristic porphyroblastic mineralogy of feldspars generally embedded in a finer matrix. Such porphyroblasts generally host the biotites and some accessory minerals as overgrowths (Fig. 26a–b). The typical skarn mineralogy in the study area includes calcite, pyroxene, amphibole, quartz, biotite and accessory, epidote, chlorite etc. (Fig. 27).

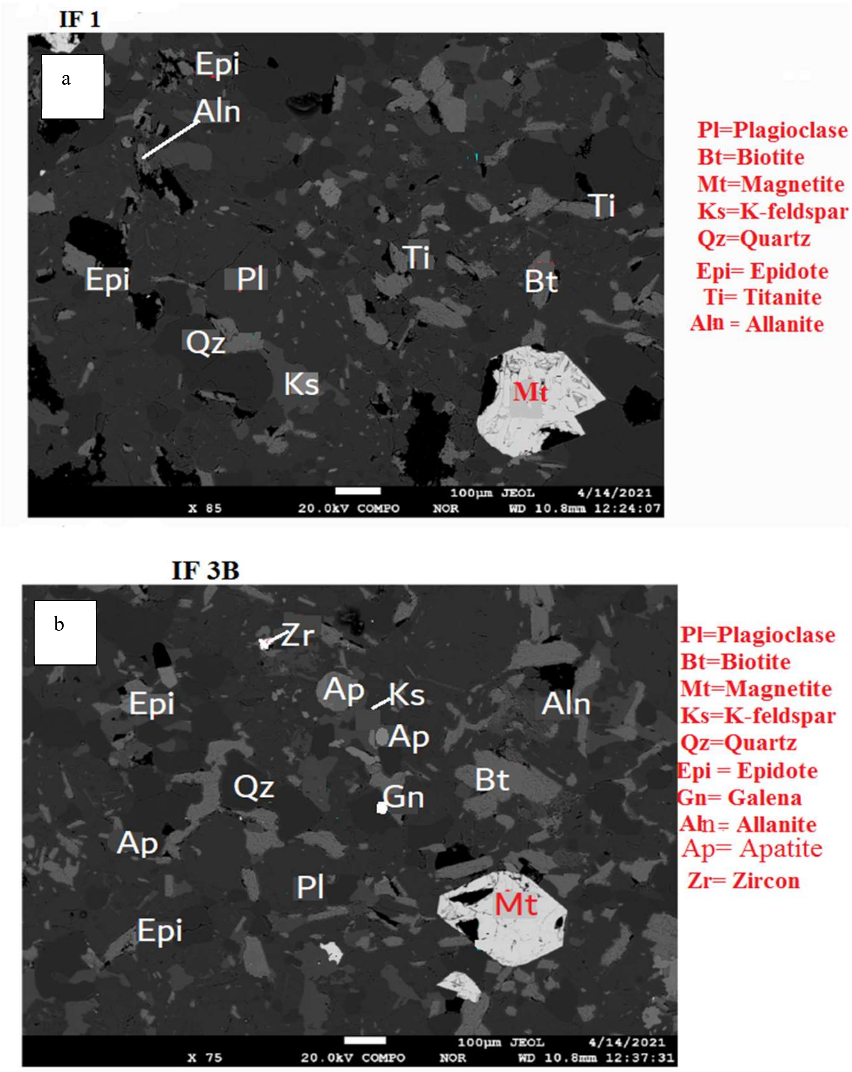


Fig. 25. a–b: BSE images of selected migmatite-gneisses from the study area. Note the sub-euhedral magnetite grains and galena blebs overgrowths on the main mineralogy.

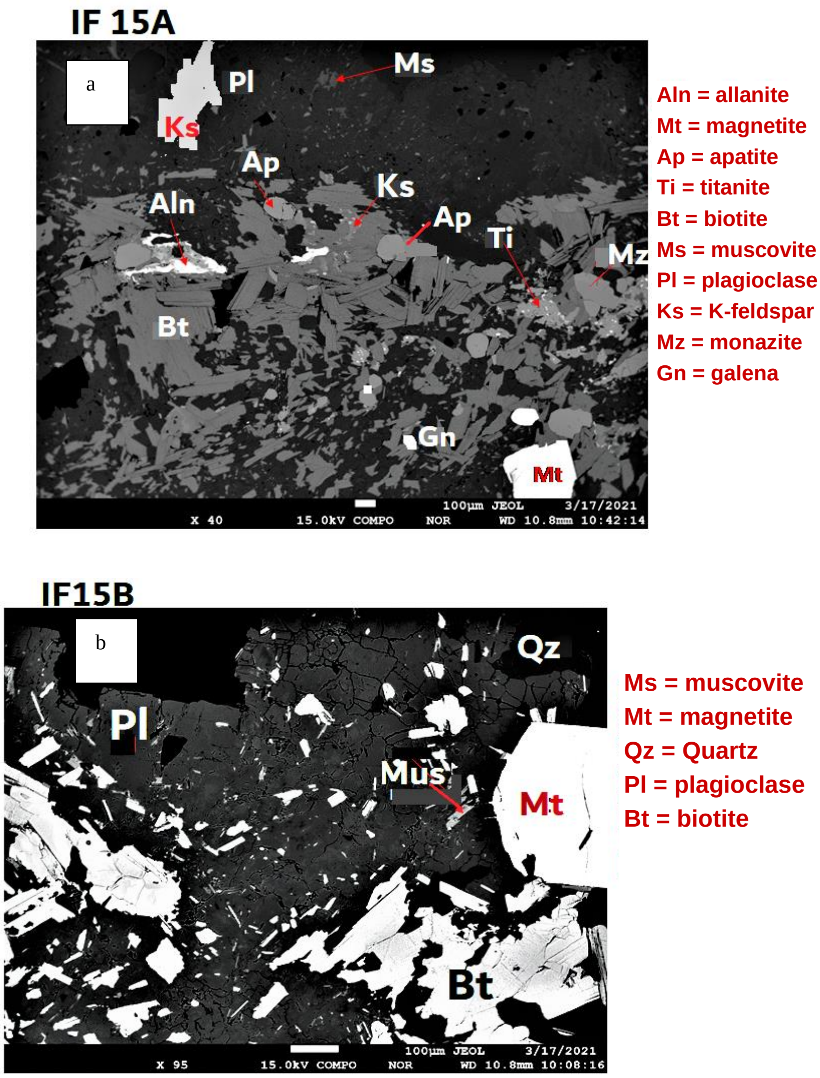
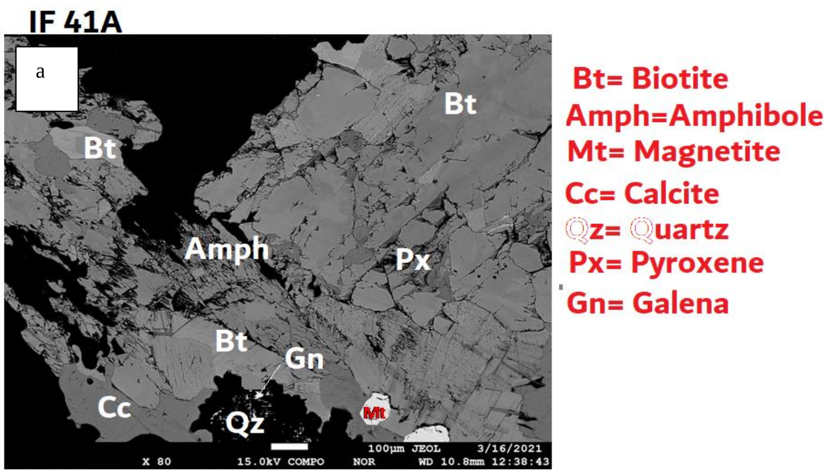


Fig. 26. a–b: BSE images of a typical augen gneiss in the study area. Note the antiperthitic texture of plagioclase hosting k-feldspar at left side of field of view in a. Feldspar crystals generally host biotite and other accessory mineral overgrowths. Quartz intergrowth with feldspar is evident at upper right of the image in b. Zoning in biotite is also evident at the left central side of the same image.



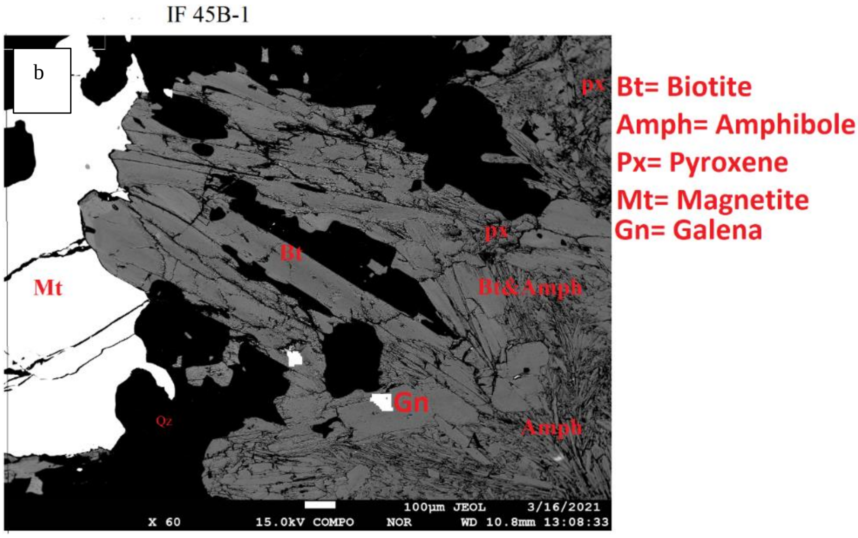
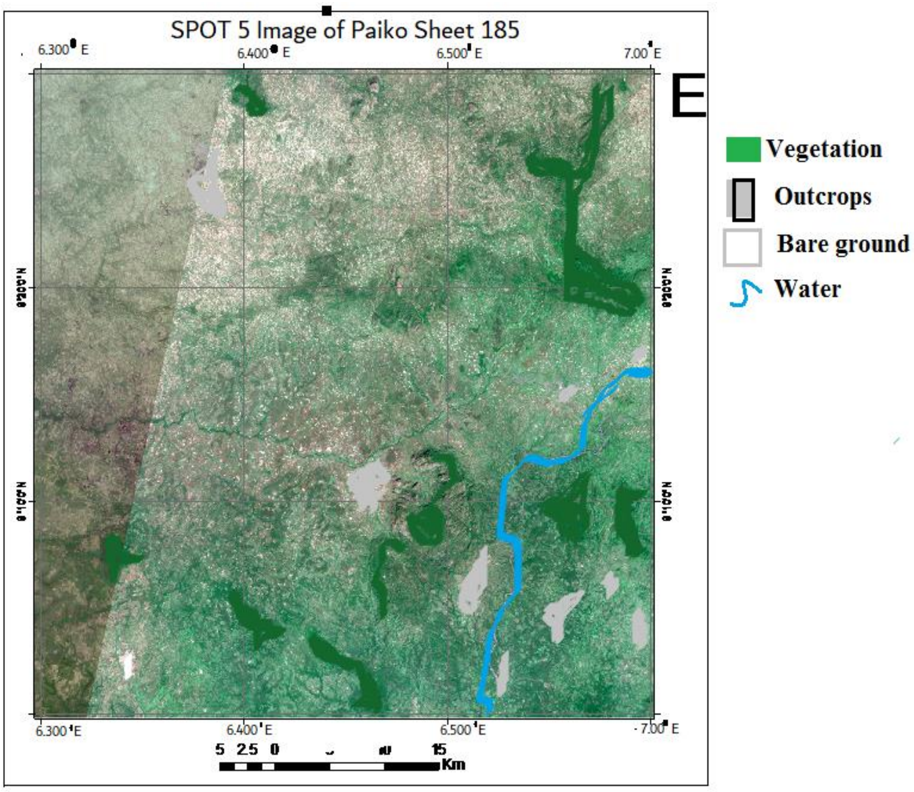


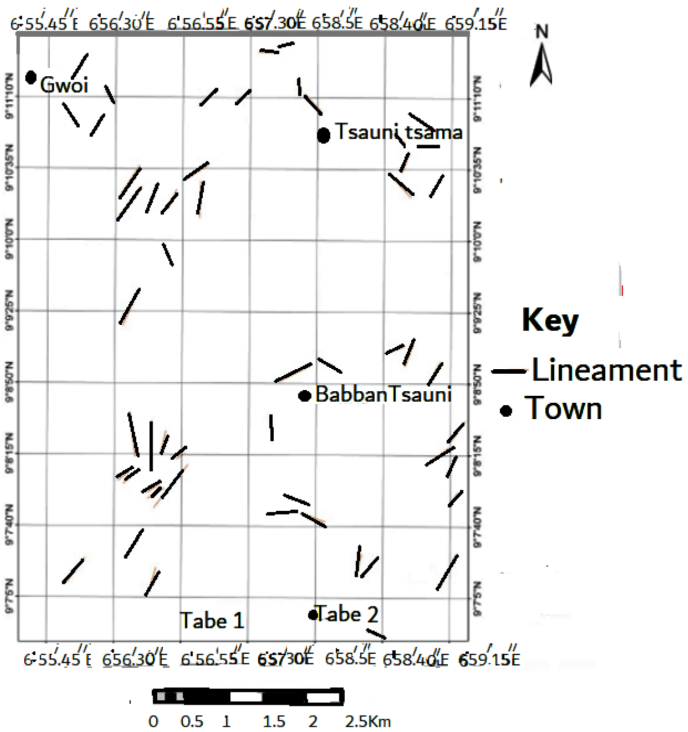
Fig. 27. a–b: BSE images of the typical mineralogy of skarn in the study area.

VI. Structural Features

Geologic structures reflect the type of stress that rocks have undergone or are undergoing and the reaction of such rocks to the applied stress. Such reactions are interpreted as strain resulting to structural features produced on the rocks. The study of structures during field mapping utilizes the measurements of present-day rock geometries to uncover information about the history of deformation (strain) in the rocks [51]. Such study has proven to be an invaluable tool in economic geology, petrology, mining, and other geosciences fields. Generally, the nature and extent of geologic structures depend on the duration and intensity of the deformation. Most structural elements of the study area include joints, veins, dykes, folds and foliations and dominantly trend in the NE-SW, NW-SE, and minor E-W directions as shown on the lineament map produced from the satellite imagery of Paiko sheet 185 (Figs. 28a–b). Rose diagrams produced from structural features of representative rocks of the study area also depict similar trends (Figs. 29a–c). These trends seem to correspond with the major structural trends in the Nigerian Basement Complex.



a

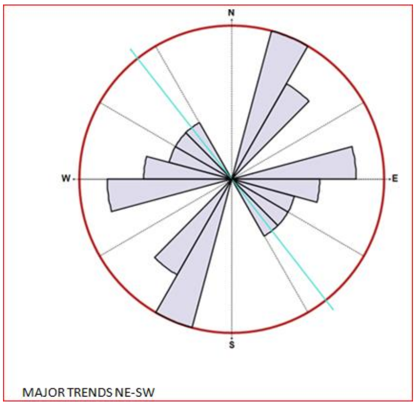


b

Fig. 28. a: Satellite imagery of Paiko sheet 185 covering the study area [modified after National Centre for Remote Sensing (NCRS), Jos]; b: Lineament map of the study area. Source: National Centre for Remote Sensing (NCRS), Jos.

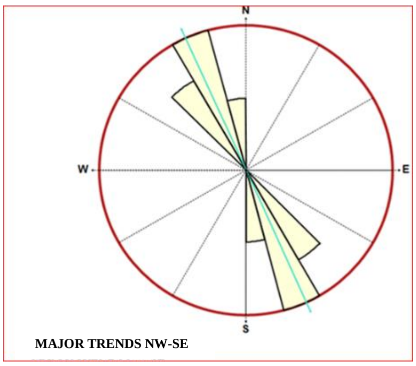
a

S/n	Strike of joints (°) on Migmatite	S/n	Strike of joints (°) on Migmatite
1	32	11	150
2	40	12	122
3	282	13	38
4	260	14	20
5	20	15	28
6	26	16	270
7	280	17	265
8	18	18	260



b

S/n	Strike(°) of joint on Gneiss (PORPHYROBLASTIC)
1	158
2	160
3	148
4	150
5	166
6	152
7	156



c

S/n (calcic gneiss)	Strike of foliation (º)
1	368
2	290
3	280
4	340
5	348
6	110
7	136
8	340

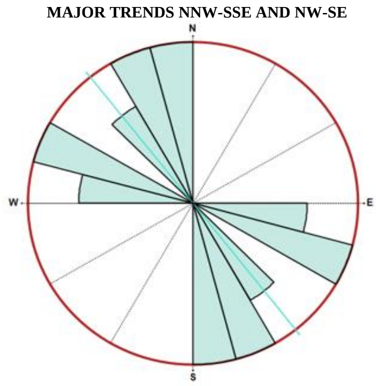


Fig. 29. a–c: Rose diagrams of foliation and joints on selected rocks from the study area.

VII. Conclusion

Tsauni area and environs are underlain by the crystalline Basement Complex and metasedimentary rocks of migmatite – gneisses and calc-silicate composition whose origin most likely includes a regional metamorphism of both prograde and retrograde nature that occurred in the upper greenschist facies into the upper amphibolite facies. This opinion is based on the occurrence of diopsidic-hedenbergite rich pyroxene and feldspars of plagioclase (albite to andesine – An_{3-41}) composition in some parts of the study area. Ultramafic fragments that could represent higher grade metamorphism were not sampled in this study. The occurrence of wollastonite and tourmaline in the skarn also suggests contact metamorphism at high temperature.

The Pan African granites and pegmatites that intruded the migmatite gneiss and metasedimentary rocks were accompanied by series of deformations, intense metamorphism, faulting, folding, and hydrothermal activities. These activities had re-activated and also "remobilized" most parts of the older crust. One product of the metamorphism and hydrothermal activities is seen in the metasomatism that produced the skarn deposits. The area is mineralized with sulphides of Pb-Zn, Fe, Cu, and oxides of magnetite/ilmenite and associated Au, Ag ± Ba within the metagranitoids of migmatite, migmatized calcic, biotite, amphibolite bearing, and augen gneisses composition and skarn.

Petrographic study as a basic tool for the identification of rock types, texture, and mineralogy compares well with the microprobe images presented here, relative to the mineralogy of both silicates and ore minerals studied. Geochemical analyses of the rocks and ore minerals are suggested.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

This work is part of Ifeoma A. Ekeleme's PhD study. Ifeoma A. Ekeleme conducted the field work and wrote the article; Ahmad I. Haruna supervised the PhD research and made contributions to edit the article; Ayodeji E. Olorunyomi produced the geological and lineament maps; Job G. Chollom prepared the thin sections/photomicrographs and Isaac E. Ochiba edited the article; all authors had approved the final version.

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References

[1] S. Sonmez and S. G. Sayili, "Geology, petrography and precious metal mineralization of Altintepe and Çilektepe sectors of karşiyaka ore occurrences, Izmir, Turkey," *Bull. Miner. Res. Expl.*, vol. 121, pp. 33–49, 1999.

[2] E. Yigitbas, "Preliminary results on the geology and petrography of the Camtica Metamorphics in the Biga Peninsula, NW Turkey," in *Proc Int. Symposium on the Geodynamics of Eastern Mediterranean-Active Tectonics in the Acgean*, Istanbul, Turkiye, 2005.

[3] Y.-S. Geng, Q.-H. Shen, and X.-S. Hui, "Metamorphic petrology and geology in China: A review," *China Geol.*, vol. 1, pp. 137–157, 2018. https://doi.org/10.31035/cg2018012

[4] M. Constantinos, N. Arvanitidis, G. Gaal, and K. Papavassilliou, "Orogenic mineralizations: A new exploration target for gold-polymetallic ore deposits in Greece," presented at the 36th Int. Geol. Conf., Brisbain, Australia, 2012.

[5] K. Bheemalingeswara and N. Tadesse, "Petrographic and geochemical study of low-grade metamorphic rocks around Negash; with reference to base metal mineralization and groundwater, Tigray, Northern Ethiopia," *MEJS*, vol. 1, no. 2, pp. 106–132, 2009.

[6] E. Safarzadeh, J. Hassanzadeh, F. Masoud, and M Pourmoafi, "Precambrian basement in Sirjan, Southern Iran," *Tectonophysics*, vol. 451, pp. 71–96, 2008.

[7] M. Abdullahi, M. A. Adediran, and N. Abdullahi, "Geology and petrography of basement rocks around Tsauni, Northwestern Nigeria," *Int. Journ. of Adv. in Sci.*, pp. 28–38, 2019.

[8] L. W. Adamu, A. O. Umar, T. S. Ereosun, *et al.*, "Petrogenetic studies of the basement complex rocks in Jimgbe and Environs, Northcentral Nigeria," *Nig. Journ. of Bas. Appl. Sci.*, vol. 29, no. 2, pp. 46–68, 2021.

[9] J. M. El-Nafaty, "Geology and petrography of the rocks around Gulani Area, Northeastern Nigeria," *Journ. Geol. Min. Res*., vol. 7, 5, pp. 41–57, 2015.

[10] I. A. Ekeleme, M. U. Uzoegbu, I. E. Abalaka, and A. E. Olorunyomi, "Petrographic evaluation of rocks around Arikya and its Environs, North Central Nigeria," *Int. Journ, Geol. Min*., vol. 3, no. 1, pp. 103–109, 2017.

[11] I. B. Oshiliki, A. I. Haruna, and J. J. Onuorah, "Petrographic and structural characteristics of the basement units in Kura Area

Northeastern Nigeria," *Int. Journ. of Adv. Res. Publ*., vol. 3, no. 3, pp. 53–57, 2019.
[12] N. K. Grant, "Geochronology of Precambrian basement rocks from Ibadan, South-Western Nigeria," *Earth Planet Sci. Lett.*, vol. 10, pp. 19–38, 1970.
[13] M. O. Oyawoye, "The basement complex of Nigeria," in *African Geology*, T. F. J. Dessanvagie and A. J. Whiteman, Eds., Ibadan: Ibadan University Press, 1972, pp. 66–102.
[14] P. McCurry, "The geology of the Precambrian to lower Paleozoic Rocks of Nigeria," in *Geology of Nigeria*, C. A. Kogbe, Ed., Lagos, Nigeria: Elizabethan Press, 1976.
[15] D. C. Turner, "Upper proterozoic schist belts in Nigerian sector of the Pan-African Province of the West Africa," *Precamb. Res*., vol. 21, pp. 55–78, 1983.
[16] S. S. Dada, U. L. Brique, U. Harms, *et al.*, "Charnockitic and monzonitic Pan African series from north central Nigeria. Trace element and Nd, Sr, Pb isotope constraints on their petrogenesis," *Chemical Geology (Isotope Geosc*.), vol. 124, pp. 233–252, 1995.
[17] S. C. Obiora and V. Ukaegbu, "Petrology and geochemical characteristics of pre cambrian-granitic basement complex rocks in the Southernmost part of north central Nigeria," *Chinese Journ. of Geochemistry*, vol. 28, pp. 377–385, 2009.
[18] B. N. Ekwueme and F. Kalsbeek, "U-Pb geochronology of metasedimentary schists in Akwanga Area of North central Nigeria and its implications for the evolution of the Nigerian basement complex," *Global Journ. of Geol. Sci.*, vol. 12, pp. 21–30, 2013.
[19] W. Russ, "The geology of parts of Nigeria; Zaria and Sokoto Provinces," *Geological Survey of Nigeria Bulletin*, no. 27, p. 43, 1957.
[20] J. F. Truswell and R. N. Cope, "The geology of parts of Niger and Zaria Provinces," *Geological Survey of Nigeria Bulletin*, no. 29, p. 53, 1963.
[21] Huntings (Geology and Geophysics Ltd.), "Airborne magnetometer and Gamma-Ray spectrometer survey over Central Northern Nigeria (Katsina-Jos)," 1975.
[22] M. Woakes and B. E. Bafor, "Primary gold mineralization in Nigeria," in *Geology, Geochemistry and Genesis of Gold Deposits*, R. P. Foster, Ed., 1984, pp. 661–871, 1984.
[23] O. A. Okunola, M. A Qladunjoye, and O. O. Osinowo, "Geological setting and integrated geophysical exploration for Pb-Zn sulphide mineralization in Babban Tsauni area, Federal Capital Territory Abuja, Central Nigeria, Euro," *Journ. of Scientific Research*, vol. 18, no. 3, pp. 369–388, 2007. https://www.researchgate.net/publication/259008535
[24] Ministry of Mines and Steel Development. (September 2010). Nigerian geological survey agency report. On "Lead-zinc exploration opportunities in Nigeria". [Online]. Available: https://searchworks.stanford.edu/view/9162731
[25] M. O. Oyawoye, "The geology of the Nigerian basement complex – A survey of our present knowledge of them," *Nigerian Mining (Geological and Metallurgical Society)*, vol. 1, pp. 87–102, 1964.
[26] M. A. Rahman, "Review of basement geology of SW Nigeria," in *Geology of Nigeria*, C. A. Kogbe, Ed., Elizabethan Press, 1976, pp. 41–57.
[27] A. C. Ajibade, M. A. Rahman, and A. E. Ogezi, "The Precambrian geology of Nigeria. A geochronological summary," in *Geology of Nigeria*, 2nd edition, C. A. Kogbe, Ed., Jos: Elizabethan Publisher (Nig.) Ltd., 1982, pp. 191–205, 1982.
[28] A. C. Onyeagocha, "Petrology and geologic history of NW Akwanga Area in Northern Nigeria," *Journ. Afr. Earth Sci*., vol. 2, pp. 41–50, 1984.
[29] B. N. Ekwueme, "Structural orientation and Precambrian deformational episode in Uwet Area, Oban Massif, S.E. Nigeria," *Precambrian Research*, vol. 34, pp. 269–289, 1987.
[30] S. S. Dada, "Proterozoic evolution of Nigeria," in *The Basement Complex of Nigeria and Its Mineral Resources*, O. Oshi, Ed., Ibadan: Akin Jinad and Co., 2006, pp. 29–44.
[31] S. C. Obiora, *Field Description of Hard Rocks: With Examples from the Nigerian Basement Complex*, Enugu: SNAAP Press (Nig.) Ltd., 2005, p. 44.
[32] N. G. Obaje, "The basement complex," in *Geology and Mineral Resources of Nigeria*, Berlin: Springer, 2009, vol. 120.
[33] A. S. Akingboye and I. B. Osazuwa, "Subsurface geological, hydrogeophysical and engineering characterization of Etioro-Akoko, Southwestern Nigeria, using electrical resistivity tomography," *NRIAG Journal of Astronomy and Geophysics*, vol. 10, no. 1, pp. 43–57, 2021. https://doi.org/10.1080/20909977.2020.1868659
[34] J. B. Wright, D. A. Hastings, W. B. Jones, and H. R. Williams, "The Pan African of West Africa – The eastern domain," in *Geology and Mineral Resources of West Africa*, London, UK: George Allen and Unwin Publ., 1985, pp. 56–69.
[35] S. S. Dada, A. Onema, R. Adisa, and G. Ibrahim, "Lead reservoirs and metallization in Nigeria: Example of contrasting geological terrains," *Journal of Geosciences and Geomatics*, vol. 3, no. 2, pp. 26–28, 2015.
[36] L. D. Meinert, "All about skarns," in *Proc. Symposium for Mining/Exploration Skills*, Smith College Northampton, 1992, p. 37.
[37] I. A. Ekeleme, "Geology and petrogenesis of the polymetallic Pb-Zn, Fe and associated mineralization in the metagranitoids and skarn of Tsauni Area and Environs, North Central Nigeria," PhD thesis, Department of Applied Geology, Abubakar Tafawa Balewa University, Bauchi, 2023.
[38] I. V. Haruna, "Review of the basement geology of the mineral belts of Nigeria," *Journ. of Appl. Geology and Geophysics*, vol. 5, no. 1, pp. 37–45, 2017.
[39] M. T. Einaudi, L. D. Meinert, and R. J. Newsberry, "Skarn deposits," *Economic Geology, 75th Anniversary*, vol. 3, pp. 317–391, 1981.
[40] D. Burianek, S. Houzar, L. Krmicek, and J. Smerda, "Origin of the pegmatite veins within the skarn body at Vevcice near Znojmo (Gfõhl Unit, Moldanubian Zone)," *Journal of Geosciences*, vol. 62, pp. l–23, 2017.
[41] P. Drahota, Z. Pertold, and M. Pudilova, "Three types of skarn in the Northern Part of the Moldanubian Zone, Bohemian Massif-implications for their origin," *J. Czech. Geol. Soc.*, vol. 50, pp. 19–33, 2005.
[42] F. Ivarsson, "Characterization of Fe-rich skarns and fluorapatite-bearing magnetite occurrences at the Zinkgruvan Zn-Pb-Ag and Cu Deposit, Bergslagen, Sweden," M.Sc. thesis, Dept. of Geology, Lulea University of Technology, 2019.
[43] I. Kuscu, "Geochemistry and mineralogy of the skarns in the Celebi District, Kirikkale, Turkey," *Turkish Journ. of Earth Sci*., vol. 10, 12132, 2001.
[44] A. G. Mueller, "Copper-Gold Endoskarns and High-Mg Monzodiorite-Tonalite intrusions at Mt. Shea, Kalgoorlie, Australia: Implications for the origin of Gold- Pyrite- Tennantite mineralization in the Golden Mine," *Mineralum Deposita*, vol. 42, no. 7, 2017.
[45] S. S. Palinkaš, Z. Peltekovaski., G. Tasev, *et al.*, "The role of magmatic and hydrothermal fluids in the formation of Sasa Pb- Zn-Ag Skarn Deposit, Republic of Macedonia," *Geosciences*, vol. 8, no. 12, 444, 2018. doi:10.3390/geosciences8120444
[46] T. Shoji, "Formation of Feldspar – Bearing skarn from the assemblage, Calcite-Biotite- Quartz in H_2O-CO_2 Mixtures," *Mining Geology*, vol. 30, no. 159, pp. 19–26, 1980.
[47] M. Stefan and D. G. Dumitras, "Contrasting types of Boron – Bearing deposits in Magnesian skarns from Romania," *Ore Geology Reviews*, vol. 112, 102952, 2019. https://doi.org/10.1016/j.orgeorev.2019.102952
[48] R. A. Howie, J. Zussman, and W. Deer, "An introduction to the rock forming minerals," *Longman Edition*, p. 696, 1992.
[49] J. D. Winter, *An Introduction to Igneous and Metamorphic Petrology*, New York: Prentice Hall, 2010, p. 58.
[50] T. Mikael, M. M. Olga, D. Henrik, *et al.*, "Fractionation of REEs in greisen and hydrothermal veins related to A-type magmatism," *Geofluids*, article ID45233214, p. 20, 2019. https://doi.org/10.1155/2019/4523214
[51] S. A. Olusoji, "Geology and structure of the Precambrian rocks in Iworoko, Are and Afao Area, Southwestern Nigeria," *Int. Res. Journ. Natural Sci*., vol. 1, no. 1, pp. 14–29, 2003.