Petrology, Geochemical Characteristics and Iron Mineralization Potential of the Precambrian Granitoids in Tabe (Pagadna) Area and Environs, North Central Nigeria

Ifeoma. A. Ekeleme*, Murtala S. Adamu, Ayodeji E. Olorunyomi, and Job G. Chollom

Department of Geology, University of Jos, Jos, Nigeria
Email: ekelemei@unijos.edu.ng (I.A.E.); murtalams@gmail.com (M.S.A.); ayodeji27@gmail.com (A.E.O.); daguson@gmail.com (J.G.C.)
*Corresponding author

***Abstract*—The Precambrian granitoids in Tabe (Pagadna) area located within the Federal Capital Territory (FCT) Abuja, Nigeria is underlain by migmatite, banded gneisses of hornblende and biotite—rich varieties, subordinate amphibolite, Pan African granitic intrusions, and dykes of diorite, pegmatite, and hydrothermal quartz veins/ veinlets. The rocks are generally mafic to intermediate with minor felsic compositions. The aim of this research is to determine the geochemical characteristics of the rocks relative to their iron-deposit potentials and make suggestion on the origin. Field evidence and geochemical analysis of major oxides from fifteen representative samples using Inductively Coupled Plasma Emission Spectrometric method (ICPES) reveal that the granitoids are generally metagranitoids which have been subjected to high- grade regional metamorphism that reached the upper amphibolite facies based on the presence of hypersthene and plagioclase of andesine composition in some of the rocks. Anatectic melting and fractional crystallization may have resulted to the occurrence of ptygmatic folds, folded gneissose foliation, abundant quartzo-feldspathic veins, and lenses/inclusions of very dark-coloured metavolcanics on the rocks. The rocks have a magnesian, calc-alkalic and mildly peraluminous geochemical characteristics. The general characteristics is suggestive that the rocks were derived from (fractional) partial melting of an original basaltic rock from the upper mantle / lower crust which progressed to partially melt an overlying pelitic and felsic crustal rocks during the high-grade regional metamorphism of probably the Pan African orogeny. The formation of iron mineralization within the metagranitoids is considered to be a product of late magmatic and intense hydrothermal activities that prevailed during the crustal reactivation of the Pan African orogenic event.**

***Keywords*—Precambrian granitoids, high-grade regional metamorphism, fractional crystallization, mineralization, Tabe (Pagadna), North central Nigeria**

I. INTRODUCTION

The study area is a metamorphic terrain that is a component of the Basement Complex in north central Nigeria (Fig. 1). Situated between the Congo and West African cratons, the Nigerian Basement Complex is a component of the Pan African mobile belt, which is made up of reactivated Dahomeyan rocks. The Pan African mobile belt, which extends into the northeastern Brazilian province of Boborema, is made up of the metasedimentary and metavolcanic schist belts, the migmatite-gneiss complex, and a series of polycyclic metamorphisms, tectonic movements, and magmatic deformations that led to the emplacement of igneous rocks known as the Pan African Older Granites of Nigeria [1, 2].

These earlier granites are intrusive into the migmatite gneiss and schist belts; however, they are widely thought to be post-tectonic with the Pan African event [3]. These rocks collectively comprise the Precambrian to Lower Palaeozoic Basement Complex. The research area is located in the southern section of the North Central Nigerian Basement Complex. Several workers, such as [4–10], have previously studied and described several aspects and axes of the Nigerian Basement Complex, which is dominated by metamorphic and igneous rocks with minor pegmatite and granitic intrusions. Others, such as [11–25], have recently studied and classified the majority of the axes of the Nigerian Basement Complex.

Onyeagocha [26, 27] and Obiora and Ukaegbu [28] have both investigated some aspects of the geology and geochemistry of the basement rocks of north central Nigeria.

II. LITERATURE REVIEW

The study area is situated at the southeastern part of Gwagwalada in Abuja Area council and forms an integral part of the north central Nigerian Basement Complex within sheet 185 (Paiko). The area has received little or no attention in the general literature of the Nigerian basement rocks. Existing records on the geology of Abuja area and environs occur in the form of Geological maps_produced and updated by the Nigerian Geological Survey Agency

---

Manuscript received November 18, 2024; revised December 20, 2024; accepted February 17, 2025; published February 27, 2025.

doi: 10.18178/ijges.11.1.7-16

(NGSA) [29] in the early millennium where the Basement Complex was referred to as "Undifferentiated". However, a few studies have been carried out in the adjacent area known as Babban Tsauni and its environs. Okunola, *et al.* [30] carried out an integrated geological and geophysical investigation for Pb-Zn mineralization in Babban Tsauni which is the adjoining northern part of the study area, described the geology and made useful suggestions on the distinct Pb-Zn mineralized zones within the area. The NGSA also embarked on an exploration drive in search of potential mineralized areas in northwestern Nigeria at the beginning of the millennium and recorded the general geology, base metal sulphides and gold mineralization in Babban Tsauni and Ledi (southeast of Tabe town) [31])

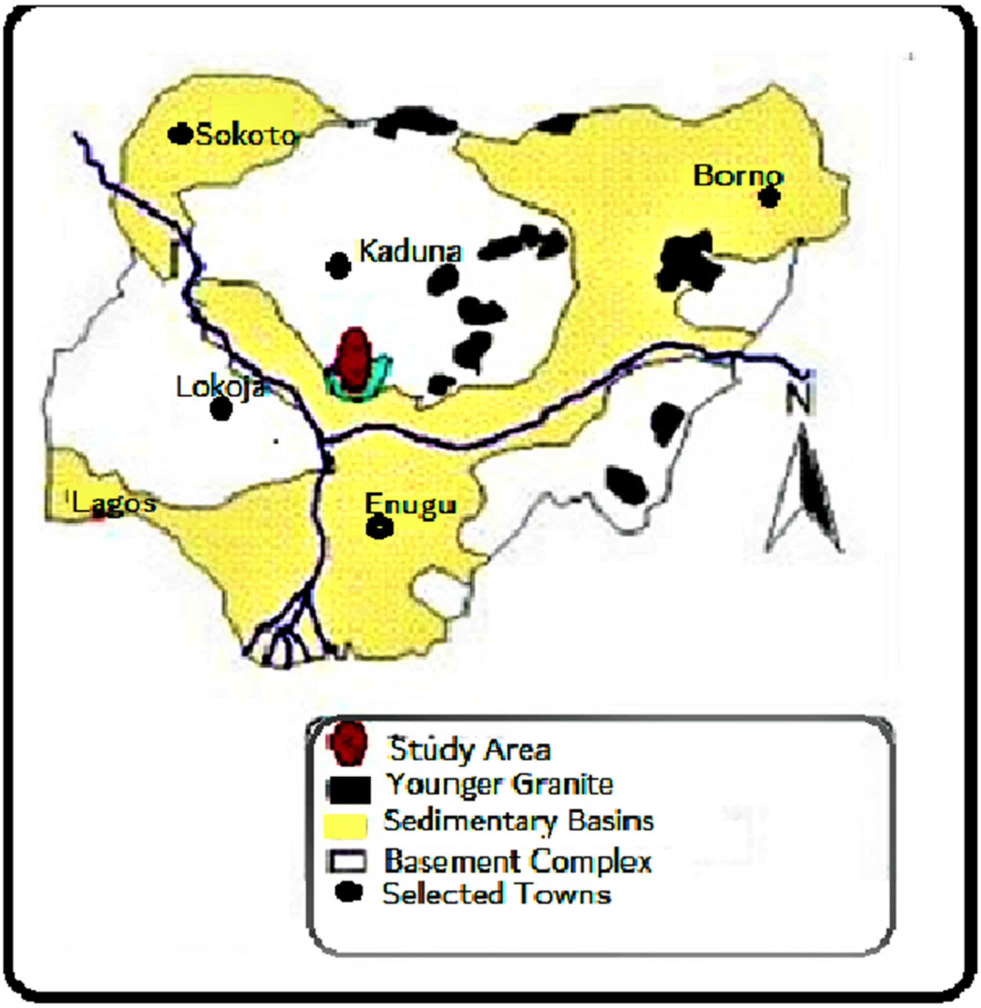


Fig. 1. Geological map of Nigeria showing the study area (modified after Okunola *et al.* [30]).

The most recent work carried out in Tabe (Pagadna) area described the geology and petrography of the rocks in details, making mention of the iron mineralization [32]. However, no record exists on the geochemical characteristics of the granitoids relative to the iron mineralization which this present paper attempts to address.

III. GEOLOGIC SETTING AND METHODOLOGY

The rocks of the study area consist of gneisses (slightly foliated to foliated) migmatite, subordinate fine to medium grained granites, metagabbro, metadiorite pegmatitic and granitic intrusions (Fig. 2). Field relation shows that diorite, pegmatite, and granitic dykes postdate the migmatite and gneissic rocks. Contact relationship between the migmatite and gneiss is gradational from north to south (Fig. 2) while the contact between the hornblende gneiss/ metagabbro and migmatite at the eastern side is sharp and characterized by intense foliations, folds and folding of fold axes, ptygmatic folds, pegmatite, and vein intrusions. The area is easily accessed through the minor road linking Gwagwalada town to Dobi in Gwagwalada Local Government Area. It is about 10km from Gwagwalada and covers Tables I and II (Pagadna) to the south, part of Tsauni to the north and old Ledi to the east (Fig. 2). The area forms the southern part of Babban Tsauni where prominent Pb-Zn, Fe (Au, Cu, Ag) mineralization has been recorded in the crystalline basement and calc silicate rocks (skarn) [30, 31, 33].

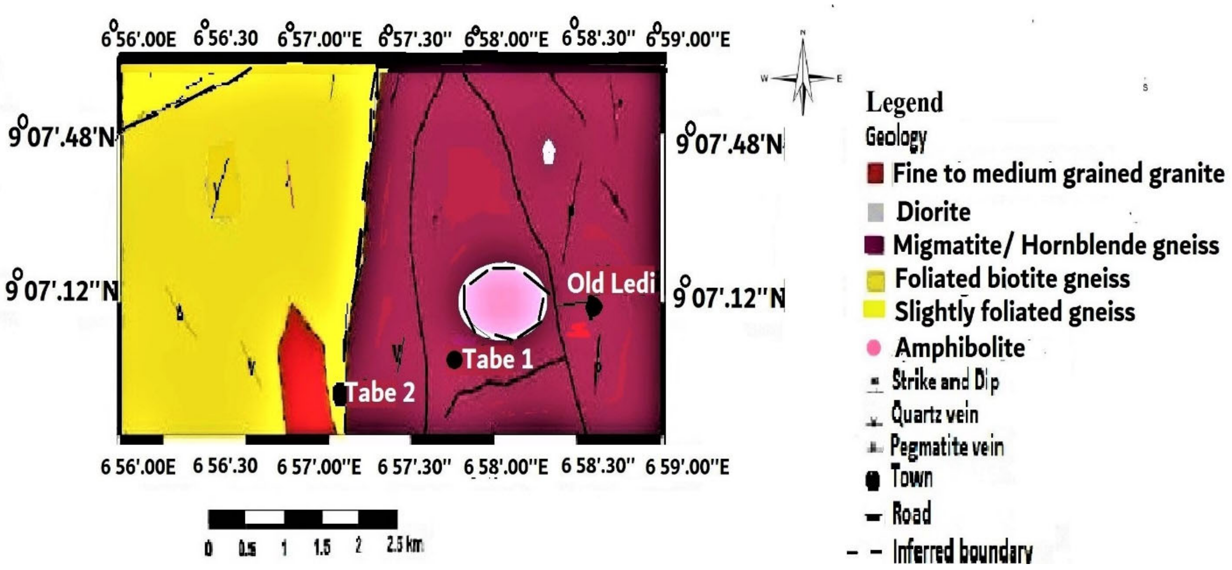


Fig. 2. Geological map of Tabe (Pagadna) area.

TABLE I. MAJOR OXIDES DATA, FE-NUMBER, MALI, ASI AND CIPW NORMS FOR THE GRANITOIDS IN TABE AREA AND ENVIRONS

Sample ID	**IF1**	**IF3**	**IF7**	**IF33**	**IF5**	**1F15**	**IF10**	**IF2**	**IF36A**	**IF36**	**IF37**	**IF6**	**IF34**	**IF4**	**IF4B**
Rock type	*MD*	*MD*	*MD*	*MD*	*Gn*	*Gn*	*Peg*	*Peg*	*Peg*	*Hgn*	*Hgn*	*Leugn*	*MG*	*MG*	*MG*
SiO_2	58.00	57.30	58.60	58.94	69.60	69.80	97.80	86.50	88.43	60.94	61.04	72.30	50.53	48.30	**48.10**
Al_2O_3	14.60	14	15.1	17.16	13.45	13.87	0.52	6.61	7.00	14.5	14.53	13.10	14.48	14.51	**12.86**
Fe_2O_3	13.57	12.54	12.45	6.75	5.07	7.32	0.24	1	0.52	9.39	9.22	5.01	14.60	16.78	**2330**
MgO	1.87	2.57	1.04	2.31	2.04	0.75	Nd	0.24	0.05	3.68	3.68	1.04	4.21	4.00	**0.23**
CaO	3.34	5.1	4.88	4.21	4.15	2.34	Nd	0.54	0.13	2.53	2.54	2.14	7.17	7.87	**0.66**
K_2O	1.04	1.05	1.02	3.51	0.64	1.87	Nd	1.42	0.8	2.76	2.77	0.75	3.26	1.54	**1.37**
Na_2O	2.50	1.67	1.54	3.78	1.66	2.50	Nd	2.3	2.44	2.97	2.98	1.53	1.18	1.20	**3.10**
TiO_2	1.87	3.06	3.18	1.43	1.78	1.85	0.05	0.35	0.03	1.51	1.51	2.35	2.67	3.12	**0.22**
P_2O_5	0.79	0.59	0.54	0.57	0.61	0.48	Nd	0.03	0.06	0.22	0.21	0.21	0.57	0.70	**0.80**
MnO	0.18	0.17	0.18	0.05	0.11	0.17	0.02	0.14	0.01	0.14	0.14	0.07	0.27	0.31	**0.55**
LOI	2.24	1.34	1.47	0.6	1.5	0.52	0.72	0.87	0.40	0.70	0.70	1.2	0.70	1.67	**1.57**
Total	99.21	100	100	99.64	99.61	99.55	99.43	99.97	99.93	99.73	99.59	100.21	99.73	100	**99.78**
Fe*	0.88	0.83	0.92	0.75	0.71	0.91	Nd	0.81	0.91	0.72	0.71	0.82	0.78	0.72	**0.71**
N+K−Ca	0.2	−2.38	−2.32	3.08	−1.85	2.03	Nd	3.18	3.11	3.2	3.21	−0.86	−2.73	−5.13	**−5.14**
A/CNK	1.01	1.00	1.03	1.01	1.03	1.01	Nd	1.33	1.39	1.13	1.18	1.11	0.81	0.78	**0.76**
Q	31.77	30.48	35.26	12.67	47.29	43.33	Nd	66.27	71	22.82	22.77	52.85	12.73	13.62	**13/53**
C	5.18	2.26	3.88	0.85	3.94	4.63	Nd	0.38	2.03	2.55	2.51	3.56	0	0	**0**
Or	6.15	6.21	6.03	20.74	3.78	11.05	Nd	8.39	4.73	16.31	16.37	4.43	19.27	15.10	**15.21**
Ab	21.15	14.13	13.03	31.99	14.05	21.15	Nd	19.46	20.65	25.13	25.22	12.95	9.98	8.15	**8.80**
An	11.41	21.45	20.68	17.16	16.6	8.47	Nd	2.48	0.25	11.11	11.23	14.21	24.58	29.66	**29.28**
Di	0	0	0	0	0	0	Nd	0	0	0	0	0	0	0	**0**
Hy	4.66	6.4	2.59	5.75	5.08	1.87	Nd	0.6	0.12	9.17	9.17	2.59	10.49	9.96	**9.87**
Ol	0	0	0	0	0	0	Nd	0	0	0	0	0	0	0	**0**
Il	0.39	0.36	0.39	0.11	0.24	0.36	Nd	0.3	0.02	0.3	0.3	0.15	0.58	0.66	**0.65**
Hm	13.57	12.54	12.45	6.75	5.07	7.32	Nd	1	0.52	9.39	9.22	5.01	14.6	16.78	**16.80**
Tn	0	0	0	0	0	0	Nd	0	0	0	0	0	5.12	3.39	**3.50**
Ru	1.67	2.87	2.98	1.37	1.66	1.66	Nd	0.19	0.02	1.35	1.35	2.27	0.28	1.39	**1.48**
Ap	1.87	1.4	1.28	1.35	1.44	1.14	Nd	0.07	0.14	0.52	0.5	0.5	1.35	1.66	**1,55**
Sum	97.81	98.09	98.57	98.75	99.15	100.99	Nd	99.14	99.48	98.66	98.64	98.52	98.98	98.38	**98.85**

MD = metadiorite   MG = Metagabbro   HG = Hornblend gneiss   Mg = Migmatite   LG = Leucogneiss   Peg = Pegmatite

TABLE II. SUMMARY OF GEOCHEMICAL CHARACTERISTICS FOR GRANITOIDS FROM OTHER PARTS OF THE PRECAMBRIAN BASEMENT COMPLEX OF NIGERIA

Location	**SAMPLE**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**
From [28], North-central Nigeria	Fe*	0.79	0.76	0.76	0.8	0.88	0.79	0.79	0.75	0.87	0.84	0.95	
	N+K–Ca	3.78	5.27	2.71	6.72	7.45	4.99	6.09	2.66	7.34	2.43	3.4	
	A/CNK	1.03	1.06	1.15	1.06	1.27	1.01	1	0.98	1.25	2.93	2.86	
From [39], South-western Nigeria	Fe*	0.87	0.62	0.72	0.77	0.85	0.76	0.72					
	N+K–Ca	7.15	0.2	0.51	6.57	7.16	6.81	5.04					
	A/CNK	0.93	0.92	0.83	0.96	0.97	1	0.97					

From [38], North-western Nigeria	Fe*	0.69	0.65	0.78	0.79	0.84							
	N+K–Ca	7.99	6.63	8.95	5.02	7.15							
	A/CNK	0.95	0.75	0.93	0.71	0.94							
From [8], Oban Massif, South-eastern Nigeria)	Fe*	0.6	0.62	0.57	0.49	0.6	0.59	0.59	0.57	0.56	0.55	0.55	0.55
	N+K–Ca	4.87	4.75	2.73	2.43	5.49	5.65	5.73	4.51	5.27	5.08	2.11	3.38
	A/CNK	1.02	1.06	0.98	1.02	1.05	1.05	1.04	1	1.01	1	0.95	0.94

A. *Materials*

The materials used to carry out this work include the following: Literature for reviews, Topo map, satellite image, compass clinometer, Global Positioning System (GPS), Geological and sledge hammers and chisel for sample collection, measuring tape used to measure veins, dykes and foliation length and thicknesses, hand lens for magnification, HCl and HNO_3 solutions used for the identification of carbonate (especially calcite) minerals in rocks. Digital camera for taking photographs of outcrops and structural exposures, field notebook, biro, pencil, masking tape, and pen markers for notes and sample labelling.

B. *Analytical Methods*

Geochemical Analysis:

Fifteen samples representative of the different rock types were analyzed using the ICPES method at the Acme Analytical Laboratories Limited, Vancouver, Canada.

The method was used to analyze for major oxides (SiO_2, Fe_2O_{3tot}, CaO, MgO, Na_2O, K_2O, TiO_2, MnO and P_2O_5). Each of the prepared rock pulp was mixed with Lithium metaborate or tetraborate ($LiBO_2$ / $Li_2B_4O_7$) flux, put in crucibles and fused in a furnace. Dissolution of the cooled bead was achieved by the use of nitric acid (HNO_3) and then subsequently analyzed. Loss on Ignition (LOI) was determined by igniting each sample powder split in a weighed crucible at 1000 ^oC, and then measuring the weight loss by determining the difference in weight before and after heating.

C. *Microprobe Study*

Six (6) 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. Quantitative analysis on the larger sample numbers will be presented in subsequent papers.

IV. RESULT

Geochemical data of major elements analyzed from the fifteen selected rock samples, with three variables used for granitoids classification proposed by Frost *et al.* [34], namely, Fe- number (Fe*), Modified Alkali Lime Index (MALI or N+K-Ca), Aluminum Saturation Index (ASI or A/CNK) and Chris, Iddings, Pearson and White (CIPW) norm values calculated for the rocks are presented in Table I. The result shows that the granitoids are generally weakly to moderately corundum normative with the metagabbro having zero corundum values. Modal muscovite is moderate in some of the migmatite and gneisses but abundant in the diorite and granite. Normative hypersthene and anorthite are also high in the mafic metagabbro, intermediate diorite and hornblende gneiss. Plot of Fe- number [FeO_{tot} / (FeO_{tot} +MgO)] versus SiO_2(wt%) indicates that the rocks have a predominant magnesian characteristics (Fig. 3). MALI (Na_2O+K_2O-CaO) versus SiO_2(wt%) plot shows that the rocks are predominantly calc- alkalic (Fig. 4). The plot of Shand [35] place most of them as peraluminous rocks but at values below 1.1 while the plot of Chappel and White, [36] shows that the rocks are generally mildly peraluminous (Fig. 5) while the plot of]. The metagabbro are notably metaluminous (Fig. 6). The oxide variation (Harker) plots show a general negative relationship of, Al_2O_3 MgO, CaO, Fe_2O_3, TiO_2, and $P_2O_5$with respect to SiO_2 increase (Fig. 7a–h). The Feldspar Ab-An-Or diagram of O'Connor [37], Fig. 8 place the rocks as granodiorites, and tonalites with minor trondhjemites. The same variables proposed by Frost *et al.* [34], were used for data obtained on granitoids from other parts of the Precambrian Basement Complex of Nigeria by Rahman *et al.*, Obiora and Ukaegbu, Egbuniwe et.al and Olarewaju [8, 28, 38, 39]. The data plotted also show that the rocks are generally magnesian. However, the rocks studied by them show slight contrast by being predominantly alkali calcic to calc-alkalc (Figs. 9 and 10). These agree with the differences between their ASI (defined as molecular Al/ (Ca-1.67+N+K) with higher values than that of the present study area whose range is between 0.78–1.39 (at an average of 0.98) suggesting a generally moderate peraluminous rocks. However, the granitoids in the works of Rahman *et al.* [8] and Obiora and Ukaegbu [28] are peraluminous which compare well with the mildly peraluminous rocks in the study area (Figs. 9 and 10 and Tables II and III).

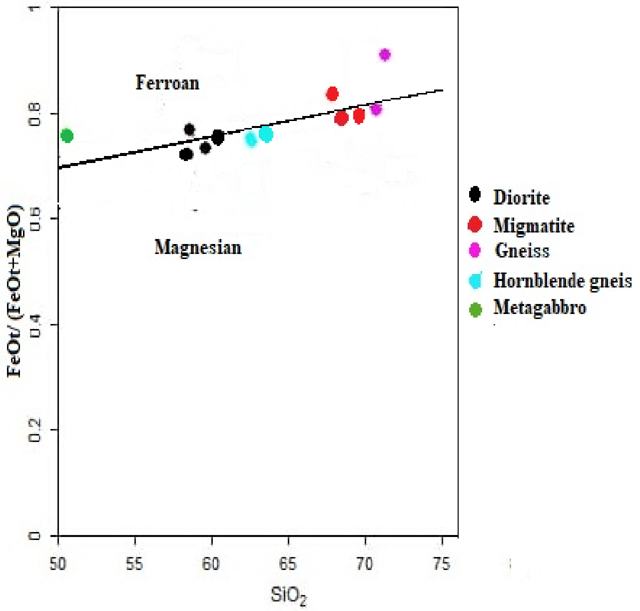


Fig. 3. FeO ^{tot} / (FeO ^{tot}+ MgO)] versus SiO_2 diagram (modified after 34).

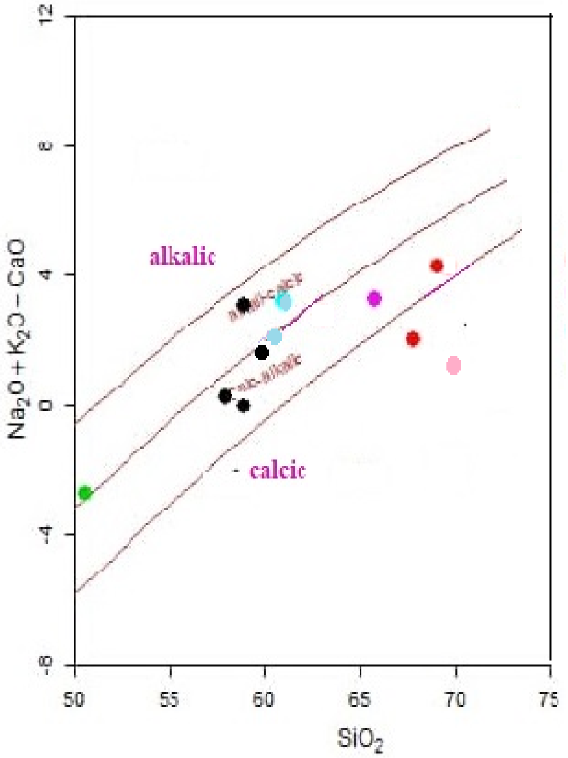


Fig. 4. Na_2O+K_2O-CaO versus SiO_2 diagram (after [36]) Legend is the same as in Fig. 3.

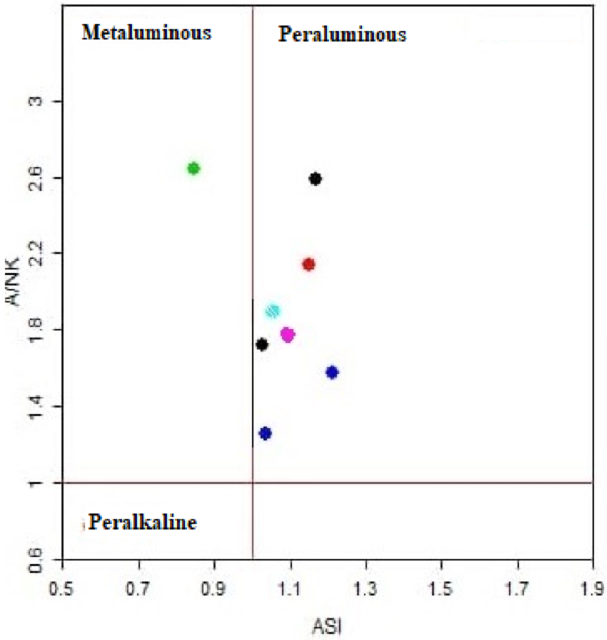


Fig. 5. Plot of ASI vs SiO_2 for Tabe granitoids. (modified after [35]).

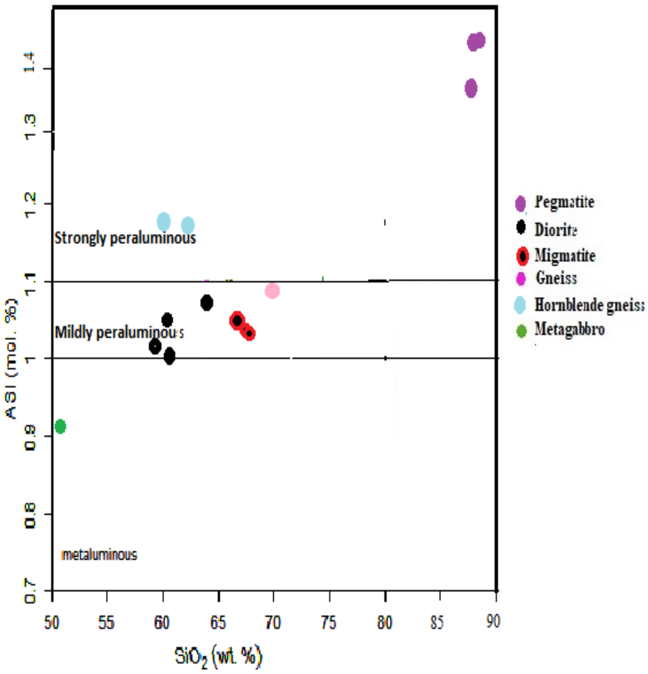


Fig.6. Plot of ANK vs ASI (modified after [36]) Legend is the same as in Fig. 5.

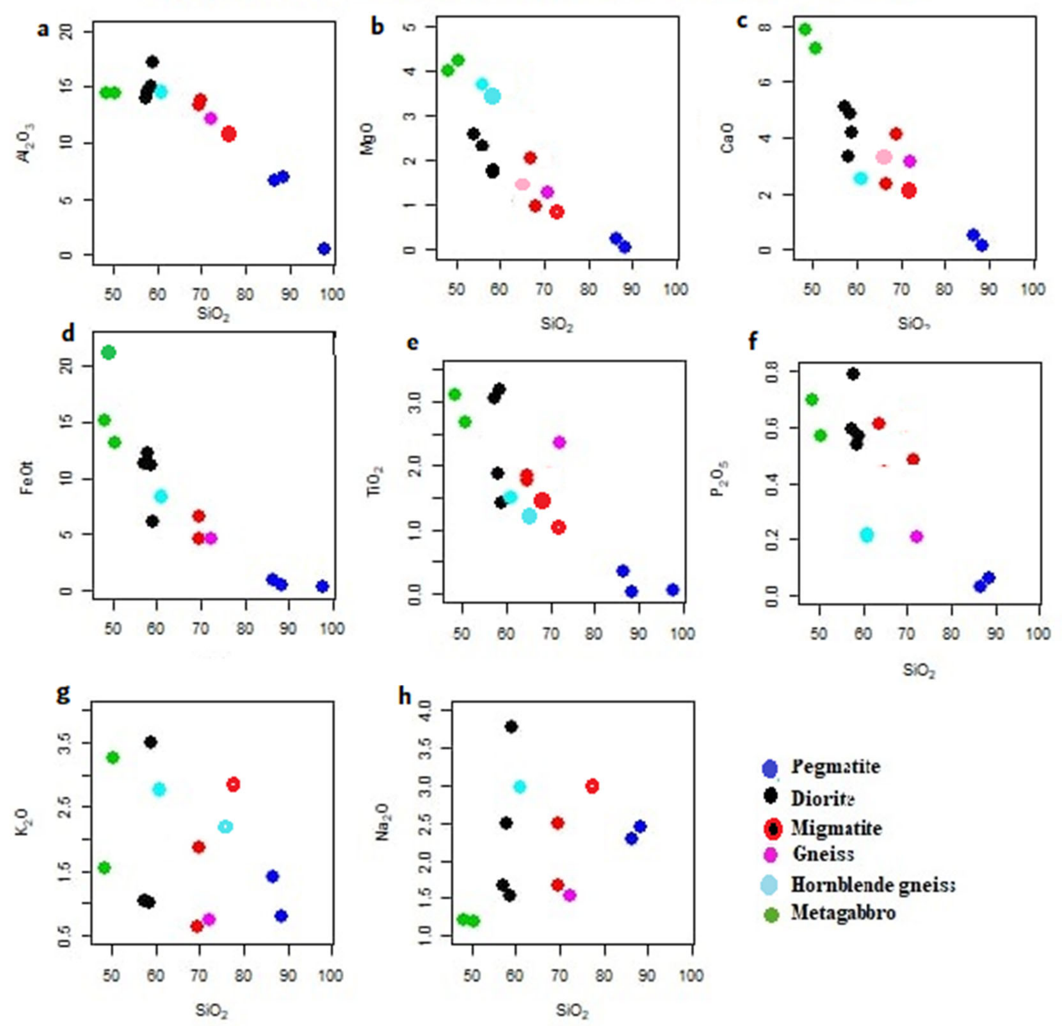


Fig.7. a–h: Harker plots for representative granitoids in Tabe (Pagadna) area.

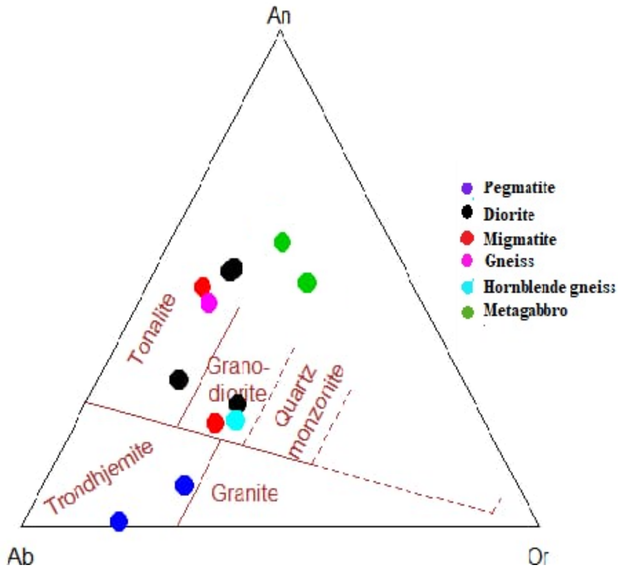
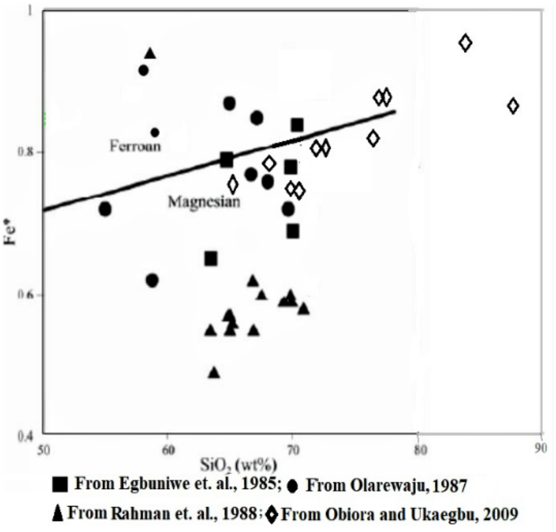


Fig. 8. Ab-An-Or plot of representative granitoids from the study.



area.(modified after 38)

Fig. 9. $FeO^{tot}/FeO^{tot}+ MgO$ versus SiO_2 diagram for granitoids from other parts of the Precambrian Basement Complex of Nigeria (modified after [28]).

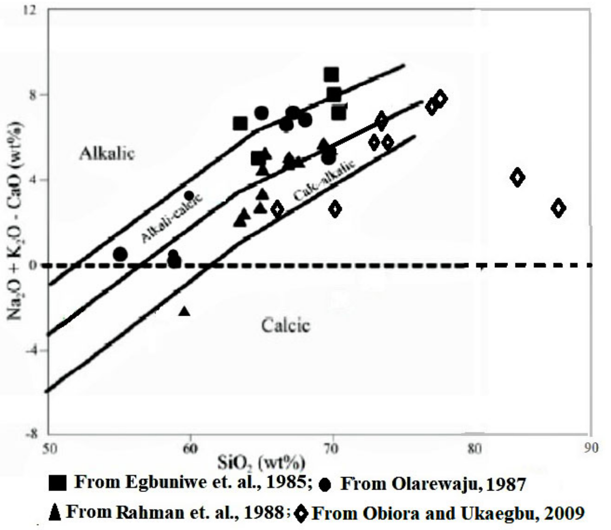


Fig. 10. Na_2O+ K_2O-CaO versus SiO_2 diagram for granitoids from other parts of the Precambrian Basement Complex of Nigeria (modification is the same as in Fig. 9).

TABLE III. SUMMARY OF SELECTED ROCK-TYPES AND GEOCHEMICAL CHARACTERISTICS FOR GRANITOIDS FROM OTHER PARTS OF THE PRECAMBRIAN BASEMENT COMPLEX OF NIGERIA

Rock-type/Location	**Geochemical characteristics**		
	Fe*	**MALI**	**ASI**
Granitic basement rocks, North-Central Nigeria	Magnesian	Calc-alkalic	Peraluminous
Syenite and granite pluton; north-western Nigeria	Magnesian	Alkali-calcic	Metaluminous
Granitoid; south-eastern Nigeria	Magnesian	Alkali-calcic to calc-alkalic	Peraluminous
Metagranitoids -Tabe Northcentral Nigeria (Present work)	Magnesian	Calc - alkalic	Mildly Peraluminous

V. IRON-RICH MINERALIZATION

Ore minerals of magnetite, ilmenite and accessory rutile compositions are associated with the metagabbro, hornblende gneiss and metadiorite of the study area (Table I, Fig. 11). These ores of iron and titanium are also rich in chromium, vanadium and manganese which are suggestive of a magmatic-hydrothermal origin related to the Pan African orogenic events. The minerals also show some degree of remobilization and metamorphism after their formation [40]. A more detailed exploration of the vanadiferous and chromium -rich iron ores may help unravel their extent, reserve value and viability. Vanadiferous, titaniferous and chromium- rich iron deposits have been a major source of critical metals like vanadium, titanium and chromium in countries like South Africa, U.S. and Australia as they have been employed in a wide range of industrial activities [32, 33, 41]

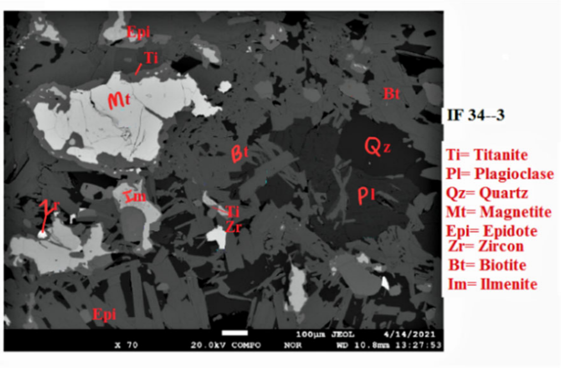


Fig. 11a: BSE Image of a magnetite-ilmenite-titanite bearing metagabbro in the study area.

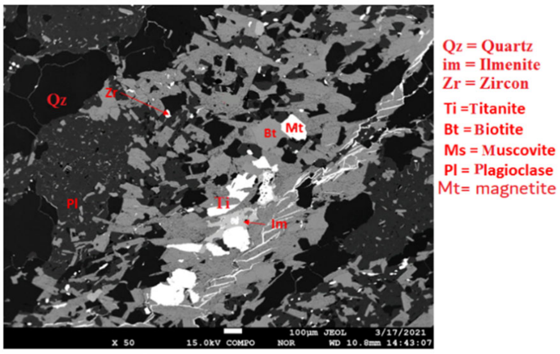


Fig. 11b: BSE image of amphibolite gneiss in the study area showing magnetite and ilmenite.

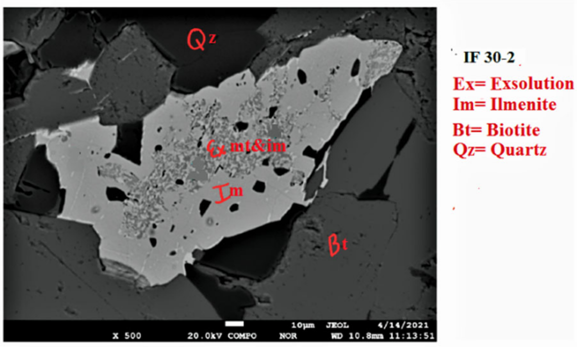


Fig. 11c: BSE image of exsolution texture of ilmenite and magnetite in a large ilmenite grain.

VI. DISCUSSION

The metagabbro and hornblende/biotite gneisses consist of plagioclase with anorthite compositions of andesine, and together with normative hypersthene, indicate regional metamorphism of the high grade that reached the upper amphibolite facies [28, 32, 42]. The high-grade regional metamorphism that produced the rocks was accompanied by plastic deformation and anatexis of an original mafic rock (probably gabbro) which later partially melted a more felsic crustal material. The abundance of quartzo- feldspathic veins, ptygmatic folds and intense folding of gneissose foliations are evidence of this opinion.

Lenses and inclusions of melanocratic to mesocratic rocks in some of the migmatite exposed around the study area described elsewhere in Ekeleme *et al.* [33] are most likely remnants of the anatectically melted protolith. Whereas biotite is more abundant in the gneisses (less in the metagabbro), muscovite occurrence in the metadiorite and leucogneiss with the presence of corundum in the CIPW norm are probably responsible for the general mildly peraluminous feature of the rocks. Frost *et al.* [34] described the occurrence of muscovite in the mode and corundum in the norm of granitoids as characteristic features for strongly peraluminous rocks. However, Chappel and White [36] separated the mildly peraluminous from strongly peraluminous granitoids based on the ASI values as shown in Fig. 5.

The rocks with high ASI or ACNK values of >1.1 constitute the strongly peraluminous granitoids while those with values <1.1 belong to mildly peraluminous granitoids. The general magnesian character of the granitoids suggests silica enrichment with only minimal iron-enrichment relative to magnesium during differentiation. Such features have been described to occur during a relatively oxidizing condition due to early crystallization of magnetite [34, 42]. This situation must have played out as the iron enriched metagabbro must have fractionated at the earlier stage. The presence of abundant magmatic magnetite mineralization in the metagabbro and amphibolitic migmatite gneisses of the study area support this opinion [40]. Granitoids with magnesian characteristics are considered as products of subduction settings. Increasing water pressure during melting leads to a decrease in MALI (N+K-Ca) and may be responsible for the low-moderate values of MALI in the studied granitoids. Hence, producing the calc-alkalic characteristics in the rocks. This condition of increasing water pressure involves a moderate increase in the melting of plagioclase during fractionation processes [2, 28]. Slight evidence of magma mixing from the melts that yielded the rocks during fractionation is presented by the few points which cross the trend lines (Fig. 4). The mildly peraluminous nature of the granitoids is probably suggestive of the partial melting of a basaltic rock (in this case a gabbro) or an orthogneiss with metaluminous characteristics (containing calcic phases like hornblende and augite) which later mixed with pelitic or semi-pelitic meta sedimentary rocks or gneisses (with abundant muscovite) during the high-grade regional metamorphism that affected the area. The occurrence of muscovite-bearing high-silica leucogneisses and granitic gneisses in some places around the study area is considered an evidence to support the above opinion.

The possibility of formation by partial melting of basaltic rocks at the base of the crust which further triggered the partial melting of an overlying pelitic silica-rich material to cause assimilation or mixing is supported by Anderson and Cullers [43] and Frost *et al.* [44]. The granitoids of the study area have an average ASI value of 0.98 which falls below 1. Values of 1 and above have been described as strongly peraluminous rocks by Frost *et al.* [34] and Shand [35]. The rocks of the study area are most likely a part of the special I and S type described elsewhere by Chappel and White [45] which include mildly peraluminous rocks as an indication of the combination of both ortho and paragneiss progenitors in the study area. Such events may have occurred in a semi anhydrous to hydrous, relatively oxidizing melt conditions related to subduction zones. The negative trends in differentiation of Al_2O_3 MgO, CaO, Fe_2O_3, TiO_2, and $P_2O_5$with respect to SiO_2 increase shown on Harker plots suggest a co-genetic source. However, Na_2O and K_2O versus SiO_2 plots show scatter trends considered to be characteristic of intense hydrothermal activities that accompanied mineralization during the evolution or reactivation of the rocks [28, 46]. The slight clouds of “duplicated” trends shown on the MgO, CaO and P_2O_5 versus SiO_2 plots are as a result of a later assimilation or mixing during the rocks’ evolution in the area and environs [46]. The Feldspar Ab-An-Or diagram of O’Connor, [37] which places the granitoids as tonalites and granodiorites is in agreement with the general composition of quartz (>10%), feldspars of mostly plagioclase (oligoclase, andesine, minor albite) and subordinate K feldspar (orthoclase/ minor microcline) in the rocks [46].

The granitoids are then considered as magnesian, calc-alkalic and mildly peraluminous rocks that may be affiliated to moderately hydrous, oxidizing melts and source regions commonly found in subduction zone settings. They fit in with the calc-alkaline I- type and S-type metaluminous to peraluminous Cordilleran granitoids of North America that are typified by tonalite and granodiorite -granite or gabbro whose origin was by partial melting of mantle-derived mafic underplate and crustal contribution. Melting mechanism was by subduction-related energy transfer of fluids upwards from slab to wedge [44, 47, 48]. The Pan African orogeny about 600Ma may have culminated in a collision between two continental margins; an active one of the Tuareg shield and a passive West African craton type that led to the subduction responsible for the granitoids evolution [28]. High- grade regional metamorphism and anatectic melting of surrounding mafic rocks, schists and gneisses associated with widespread occurrence of K-metasomatism that brought about the rejuvenation or reactivation and remobiliza6on of the basement rocks form the popular view for the origin of the Basement Complex granitoids of Nigeria [8, 28, 46]. Evidence from field, petrographic and geochemical studies of rocks in the study area, also sustain similar opinion to some logical extent. Iron mineralization that is associated with the migmatized metagabbro, hornblende gneiss and metadiorite include magnetite, titanite and accessory rutile whose origin are considered to be from late magmatic-hydrothermal processes [32, 33, 46].

VII. CONCLUSION

The study area is underlain by migmatite, migmatized metagabbro, banded gneisses of hornblende and biotite-rich varieties, amphibolite, Pan African granitic intrusions, and dykes of diorite, pegmatite, and hydrothermal quartz veins/ veinlets. Iron deposits of magnetite, ilmenite and accessory rutile compositions are associated with the metagabbro, hornblende gneiss and metadiorite whose origin appear to be late magmatic-hydrothrmal. The occurrence of hypersthene in the norm and plagioclase of andesine composition in the metagabbro and gneisses are evidence that the high-grade metamorphism which produced the rocks probably reached the upper amphibolite facies. Features of plastic deformation, ptygmatic folds, and partially melted inclusions of mafic and few mesocractic "parent rocks" are evidence for anatectic melting in the study area. The presence of moderate muscovite and normative corundum in some of the rocks coupled with Aluminum Saturation Index (ASI) values generally <1.1 (0.98 on the average) place the rocks as mildly peraluminous granitoids. The inverse relationship of plots of Fe_2O_3, CaO, Al_2O_3, TiO_2, MgO and P_2O_5 with slight "cloudy" duplicate trends in CaO and MgO plots versus SiO_2 indicate "cogenesis" that involved partial melting and fractional crystallization of an originally mafic (I-type/ metaluminous) rock from the upper mantle/ lower crust which also partially melted an overlying more felsic pelitic (S-type) rocks probably during the high-grade regional metamorphism of the Pan African orogeny.

Magma mixing may have resulted from the above condition as evidenced by the "duplicated" trends shown on MgO, CaO and TiO_2 versus SiO_2. The magnesian calc-alkalic and mildly per-aluminous characteristics of the rocks are suggestive of a moderately hydrous, oxidizing melt sourced from a subduction-related setting. The granitoids of the study area generally compare relatively well with those in other parts of the Precambrian Basement Complex of Nigeria with respect to their magnesian character and peraluminous features. They also fit in with the calc-alkaline I and S-type metaluminous to peraluminous subduction- related Cordilleran granitoids of North America.

CONFLICT OF INTEREST

The authors declare no conflict of interest.

AUTHORS' CONTRIBUTIONS

This work is part of Ifeoma Ekeleme's PhD study. She conducted the field work and wrote the article. Ayodeji Olorunyomi prepared the geological map and diagrams used for geochemical interpretation. Adamu Murtala gave directions and useful advice for the field mapping exercise and Job Chollom worked in the laboratory. All authors had approved the final version.

ACKNOWLEDGMENT

The Authors are grateful to the University of Jos who gave study leave and paid the tuition fees of the first author for her to pursue and complete her PhD. Dr. Susie Woo of the Acme Labs, Vancouver, Canada is acknowledged for the geochemical analysis.

REFERENCES

[1] S. S. Dada, U. L. Brique, and U. Harms *et al.*, "Charnockitic and monzonitic pan African series from Northcentral Nigeria. Trace element and Nd, Sr, Pb isotope constraints on their petrogenesis," *Chemical Geology (Isotope Geosc.)*, vol. 124, pp. 233–252, 1995.

[2] J. B. Wright, D. A. Hastings, W. B. Jones, and H. R. Williams, "The pan African of west Africa—The eastern domain," *Geology and Mineral Resources of West Africa*, pp. 56–69, 1985.

[3] W. R. Fitches, A. C. Ajibade, and I. G. Egbuniwe *et al.*, "Late Proterozoic schist belts and plutonism in NW Nigeria," *Jour. Geol. Soc. London*, vol. 142, pp. 319–337, 1985.

[4] 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.

[5] P. M. Curry, "The geology of the Precambrian to lower paleozoic rocks of Northern Nigeria—A review," in *Geology of Nigeria*, Elizabethan Publishers, Lagos, 1976, pp. 15–39.

[6] M. A. Rahman, "Review of basement geology of SW Nigeria," in *Geology of Nigeria*, Elizabethan Press, Lagos, 1976a, pp. 41–57.

[7] E. A. Annor, "A structural classification of the Precambrian basement complex of Nigeria," *Journal of Mining and Geology*, vol. 7, no. 2, pp. 42–57, 1986.

[8] M. A. Rahma, "Recent advances in the study of the basement complex of Nigeria," *Precambrian Geology of Nigeria*, pp. 11–41, 1988.

[9] B. N. Ekwueme, "Tectonothermal evolution of Oban massif, Nigeria," *Proceed. 28th Int. Geol. Congress*, Washigton D.C. 1989, pp. 439–440.

[10] S. S. Dada, "Geochemistry and petrogenesis of the reworked archaean gneissic complex of Northcentral Nigeria: Major and trace element studies on Kaduna amphibolites and migmatitic gneisses," *Global Journ. Pure and Applied Sci.*, vol. 5, pp. 535–543, 1999.

[11] A. O. Oyinloye, "Geochemical characteristics of some granite gneisses in Ilesha area Southwestern Nigeria: Implication on evolution of Ilesha schist belt, south western, Nigeria," *Trends in Geochemistry India*, vol. 2, pp. 59–71, 2002.

[12] A. O. Oyinloye, "Geology and geochemistry of some cystalline basement rocks in Ilesha area Southwestern Nigeria: Implication on provenance and evolution," *Journal of Science and Industrial Research*, vol. 50, no. 4, 2007.

[13] A. O. Oyinloye, "Geology and geotectoniic setting of the basement complex rocks in Southwestern Nigeria: Implications on provenance and evolution," *Earth and Environmental Sciences*, 2011.

[14] S. C. Obiora, "Petrology and geotectonic setting of basement complex rocks around Ogoja, Southeastern Nigeria," *Ghana Journal of Sciences,* vol. 46, pp. 13–25, 2006.

[15] S. S. Dada, "Proterozoic evolution of Nigeria. In Oshi, O.(ed.), The basement complex of Nigeria and its mineral resources," *Akin Jinad and Co. Ibadan*, pp. 29–44, 2006.

[16] N. J. Obaje, "The basement complex," in *Geology and Mineral Resources of Nigeria, Lecture Notes in Earth Sciences*, Berlin: Springer-Heidelberg, vol. 120, 2006.

[17] O. O. Akindele. (2011). Geology and geotectonic setting of the basement complex rocks in Southwestern Nigeria: Implication on provenance and evolution. earth and environmental sciences. [Online]. Available: https//: www. Intechopen.com/books/earth-and environmental –sciences/geology and geotech. setting

[18] K. D. Opara, Y. E. Obiora, and S. O. Onyekuru *et al.*, "Petrology and geochemistry of basement complex rock in Okompita, Oban Massif, Southeastern Nigeria," vol. 5, no. 4, pp. 1–14, 2014.

[19] O. S. Ayodele, "The geology, geochemistry and petrogenetic studies of the precambrian basement rocks around Iworoko, are and Afao area, Southwestern Nigeria," *Journal of Environment and Earth Science*, vol. 5, no. 3, pp. 58–66, 2015.

[20] B. Adeoti and C. T. Okonkwo, "Structural geology of the basement complex rocks in Iwaraja area, Southwestern Nigeria," *International Letters of Natural Sciences*, vol. 58, pp. 12–22, 2016.

[21] I. V. Haruna, "Review of the basement geology of the mineral belts of Nigeria," *Journal of Applied Geology and Geophysics*, vol. 5, no. 1, pp. 37–45, 2017.

[22] M. S. Lawal, A. J. Ojero, and O. A. Muhammad *et al.*, "Integrated geology and geochemical analysis of Eruku basement complex,

Southwestern Nigeria," *Nigerian Journal of Basic and Applied Sciences*, vol. 25, no. 1, pp. 63–72, 2017.

[23] S. B. Muhammad and R. Saad, "Regional structural architecture of parts of Northern Nigeria basement complex inferred from upward continuation of magmatic field intensity data," *International Conference of Solid States Science and Technology*, July 2018. doi: 10.1088/1742-6596/1083/1/012057

[24] N. E. Bassey and E. Udinmwen, "Structural and tectonic setting of hong hills in Hawai precambrian basement complex, Northeast Nigeria," *Journal of Geology and Mining Research*, vol. 11, no. 4, pp. 48–58, 2019.

[25] M. Abdulkarim, H. A. Ibrahim, H. M. Grema, and A. Yunusa, "Petrological and structural evolution of basement rocks around Guga, Katsina State, Northwestern Nigeria," *Science World Journal*, vol. 16, no. 2, pp. 145–151, 2021.

[26] A. C. Onyeagocha, "Petrology and geologic history of NW Akwanga Area in Northern Nigeria," *Jour. Afr. Earth Sci.*, vol. 2, pp. 41–50, 1984.

[27] A. C. Onyeagocha, "Geochemistry of basement granitic rocks from Northcentral Nigeria," *Jour. Afr. Earth Sci.*, vol. 5, pp. 651–657, 1986.

[28] S. C. Obiora and V. Ukaegbu, "Petrology and geochemical characteristics of pre cambrian-granitic basement complex rocks in the southernmost part of Northcentral Nigeria," *Chinese Journ. of Geochemistry*, vol. 28, pp. 377–385, 2009.

[29] S. Malomo, "Geological map of Nigeria (digitized 1:2000000)," *Nigerian Geological Survey Agency publ.*, 2004.

[30] 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.

[31] Nigerian Geological Survey Agency. (2010). Report on investigation of Izom lead/ zinc mineralization. [Online]. Available: https://ngsa.gov.ng

[32] I. A. Ekeleme, M. U. Uzoegbu, A. I. Haruna, and I. E. Ochiba, "Geology and petrography of the basement complex rocks at Pagadna (Tabe) area, North central Nigeria," *Int. Journ. Innovative Envi. Studies. Res.*, vol. 11, no. 2, pp. 84–101, 2023.

[33] I. A. Ekeleme, A. I. Haruna, M. U. Uzoegbu, and I. E. Ochiba, "The geology and polymetallic Pb-Zn, Fe and associated mineralization in parts of Tsauni and environs, Northcentral Nigeria," *Int. Journal of Innovative Environmental Studies Research*, vol. 4, no. 2, pp. 12–24, 2023.

[34] B. R. Frost, C. G. Barnes, W. J. Collins, R. J. Arculus, D. J. Ellis, and C. D. Frost, "A geochemical classification of granitic rocks," *Journal of Petrology*, vol. 42, pp. 2022–2048, 2001.

[35] S. J. Shand, *Eruptive Rocks, Their Genesis, Composition, Classification and Their Relation to Ore Deposits with a Chapter on Meteorite*, New York: John Wiley and Sons, 1943, chp.2.

[36] B. W. Chappel and A. J. R. White, "Two contrasting granite types," *Pacific Geology*, vol. 8, pp. 173–174, 1974.

[37] J. T. O. Connor, "A classification of quartz-rich igneous rocks based on feldspar ratios," *United States Geological Surveys,* vol. 2, pp. 79–84, 1965.

[38] I. Egbuniwe, W. Fitches, M. Bentley, and. N. Snelling, "Late pan African syenite-granite plutons from North Western Nigeria," *Journal of African Earth LSciences*, vol. 3, pp. 427–435, 1985.

[39] V. Olarewaju, "Charnockite-granite association in SW Nigeria: Rapakivi granite type and charnockite plutonism in Nigeria," *Journal of Afr. Earth Sci.*, vol. 6, pp. 67–77, 1987.

[40] I. A. Ekeleme, A. I. Haruna, M. U. Uzoegbu, I. E. Ochiba, and J. G. Chollom, "Ore petrography and structural lineaments of the migmatite-gneisses at Tsauni-Pagadna (Tabe) area, North central Nigeria African," *Jour. of Innovative Studies.*, vol. 4, no. 3, pp. 33–59, 2023.

[41] Encyclopaedia Britannica, Magmatic Cumulates. 2007. [Online]. Available: https://www.britannica.com/science/mineral-deposit/immiscible-melts

[42] 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.

[43] J. L. Anderson and R. L. Cullers, "Crust-enriched, mantle-derived tonalities in the early proterozoic, Penokean Orogen of Winsconsin," *J. Geology*, vol. 95, pp. 139–154, 1987.

[44] C. D. Frost, B. R. Frost, R. Kirkwood, and K. R. Chamberlain, "The Tonalite-Trondhjemite-Granodiorite (TTG) to Granodiorite-Granite (GG) transition in the late Archean plutonic rocks of central Wyoming Province," *Can. J. Earth Sci.*, vol. 43, pp. 1419–1444.

[45] B. W. Chappel and A. J. R. White, "I and S-types granites in the Lachian fold belt," *Transaction Royal Society Edinburg. Earth Sci.*, vol. 83, pp. 1–26, 1992.

[46] 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 dissertation, Department of Applied Geology, Abubakar Tafawa Balewa University, Bauchi, Nigeria, 2023.

[47] A. R. Pitcher, "A classification of granitoid rocks based on tectonic setting," *Mountain Building Processes*, London-Academic Press, 1983.

[48] J. D. Winter, *An Introduction to Igneous and Metamorphic Petrology*, New York—Prentice Hall (Ed.), 2010, p. 518.