

PETROGENESIS, TECTONIC SETTING AND MINERAL POTENTIAL OF IGNEOUS ROCKS FROM THE GAMPU AREA AND ENVIRONS, ZING, NORTHEASTERN NIGERIA: CONSTRAINTS FROM FIELD GEOLOGY AND GEOCHEMISTRY

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ABSTRACT

The Gampu area of Zing, northeastern Nigeria, located approximately between 8°43'–8°49'N and 11°35'–11°45'E, forms part of the northern Adamawa Massif and exposes a diverse assemblage of Precambrian basement and intrusive igneous rocks. The geology tectonic setting and mineral potential of Gampu and its environs is poorly constrained. This study aims to investigate the petrogenesis, tectonic setting and mineral potential of the igneous rocks in the area using integrated field geology, petrography and whole-rock major- and trace-element geochemistry. Geological mapping identified gneisses, granites, granodiorites, tonalites, quartz syenites, quartz monzonites and minor mafic intrusions, including doleritic dykes. Petrographic observations reveal mineral assemblages dominated by quartz, plagioclase, alkali feldspar, biotite and amphibole, with accessory phases including zircon, allanite, titanite, apatite and opaque minerals. Whole-rock geochemical analysis reveals intermediate to felsic compositions, with SiO₂ contents ranging from 49.1 to 70.2 wt.% in the analysed igneous rocks. Major-element classification and alumina-saturation characteristics indicate diverse granitoid compositions ranging from metaluminous to peraluminous. Harker variation trends indicate that fractional crystallization, involving the progressive removal of mafic minerals, feldspar and accessory phases, played an important role in magma evolution, although the compositional diversity suggests contributions from more than one parental magma. The granites and granodiorites exhibit geochemical characteristics compatible with crustally influenced, syn-collisional magmatism, whereas the tonalites, quartz monzonites and quartz syenites show affinities with late- to post-collisional magmatism. The latter association is interpreted to reflect mantle-influenced magmatism followed by fractional crystallization and variable interaction with continental crust. The coexistence of contrasting magmatic affinities suggests that the Gampu area records multiple stages of Pan-African tectono-magmatic evolution, from crustal melting and syn-collisional granitoid emplacement to late- and post-collisional magmatism and progressive differentiation. Trace-element enrichment, particularly in Rb, Zr, Y and Nb, indicates substantial magmatic differentiation and suggests potential for rare-metal mineralization. The anomalously high Nb and Ta concentrations recorded in sample GM01 warrant further analytical and mineralogical verification, while the elevated Cr and Ni contents of the dolerite indicate a mafic component that merits further investigation. Overall, the Gampu area represents a compositionally and tectonically diverse magmatic domain whose mineralization potential is closely related to magmatic differentiation and late-stage tectono-magmatic processes. Further geochronological, isotopic and mineral-chemical investigations are recommended to establish the timing, magma sources and economic significance of the observed geochemical anomalies.

Keywords: Adamawa Massif; Gampu; Zing; granitoids; petrogenesis; Pan-African magmatism; tectonic setting; fractional crystallization; geochemistry; mineral potential.

1 INTRODUCTION

The Nigerian Basement Complex forms part of the Pan-African mobile belt that extends between the West African and Congo cratons [1]. It consists predominantly of migmatite-gneiss complexes, schist belts and granitoid intrusions that record a complex history of crustal evolution and Pan-African tectono-thermal events. Northeastern Nigeria contains extensive exposures of crystalline basement rocks that constitute part of the Adamawa Massif and are closely associated with the geological evolution of the Cameroon Highlands and the Benue Trough [2]. The study area is located in Gampu and its environs, Zing Local Government Area of northeastern Nigeria (Figure 1). It lies between longitudes $11^{\circ}35'00''$ and $11^{\circ}45'00''$ E and latitudes $8^{\circ}43'00''$ and $8^{\circ}50'00''$ N within the northern sector of the Adamawa Massif (Figures 1 & 2). The area is bounded by the Gongola and Yola arms of the Benue Trough to the west and south, respectively, while the Chad Basin occurs farther north. The Adamawa Massif has been considered an extension of the Bamenda Massif and forms part of the broader geological province associated with the Cameroon Highlands and the Cameroon Volcanic Line [2]. The region is characterized predominantly by Precambrian igneous and metamorphic rocks, including gneisses, migmatites and granitoids. Previous geological investigations in and around the study area have largely been regional in scope and have documented the occurrence of gneisses, migmatites, granites and granodiorites, [3, 4]. However, detailed investigations integrating field relationships, petrography and whole-rock geochemistry are necessary to better constrain the petrogenesis, tectonic setting and possible mineralization associated with the igneous rocks. Therefore, this study is aimed to characterize and classify the lithological units in the area, determine their geochemistry and constrain the petrogenesis and tectonic setting of the igneous rocks and assess their possible mineral potential.

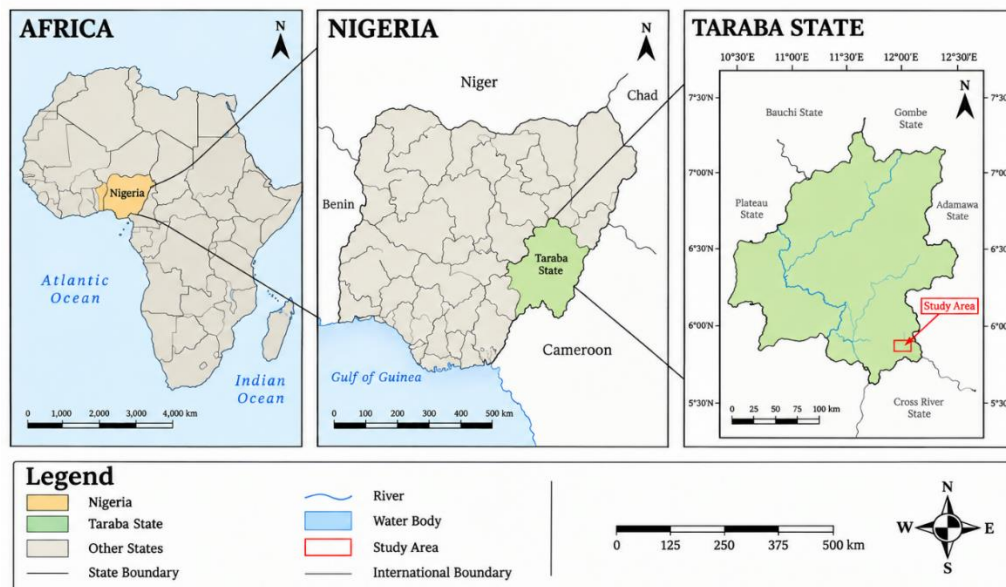


Figure 1 Map showing the location of the study area.

2 REGIONAL GEOLOGICAL SETTING

Nigeria is situated within the broader Pan-African mobile belt of West and Central Africa and comprises extensive Precambrian basement rocks together with younger sedimentary basins and localized volcanic and intrusive rocks. The Nigerian Basement Complex is dominated by high-grade metamorphic rocks, including migmatite-gneiss assemblages, schist belts and granitoid suites, which record multiple episodes of crustal development, metamorphism, deformation and reworking. The modern geological framework of Nigeria recognizes several basement domains and sub-domains together with major Phanerozoic basins, including the Benue Trough. The recently compiled 1:2,000,000 Litho-Structural Map of Nigeria integrates geological information with national airborne magnetic and radiometric datasets to better constrain the country's regional lithological and structural architecture [5]. The Nigerian Basement Complex forms part of the larger Neoproterozoic Pan-African

orogenic system and preserves evidence of interaction between older continental crust and later tectono-magmatic events. In the eastern and northeastern parts of the country, the basement is structurally connected with the geological domains extending into Cameroon. These relationships are particularly important around the Adamawa Massif, where Precambrian basement rocks were affected by Pan-African deformation and granitoid emplacement [5, 6].

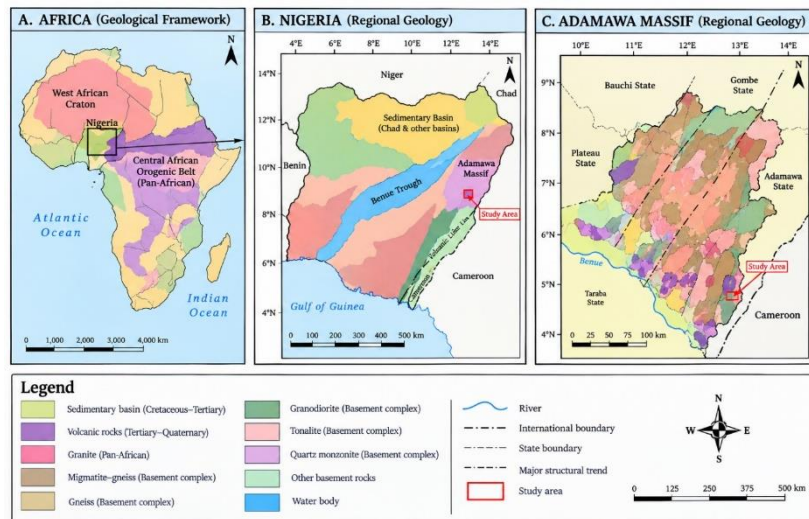


Figure 2. Regional geological Map of the Study Area [5, 6]

2.1 Adamawa Massif

The Adamawa Massif, located in northeastern Nigeria, constitutes an important segment of the eastern Nigerian Basement Complex and continues structurally toward the Adamawa–Yadé domain of Cameroon. The massif is characterized predominantly by crystalline basement rocks, including granite-gneiss, banded gneiss, migmatitic rocks and granitoids, with extensive emplacement of Older Granites during the Pan-African orogeny [7]. Geological and geophysical investigations indicate that the Adamawa Massif has a complex polycyclic history. Granite-gneisses are interpreted as among the older lithological components and were subsequently intruded by syn- to late- and post-collisional granitoids. Integrated Landsat, airborne geophysical and field studies have identified granite-gneiss, banded gneiss, amphibolite, Older Granites, volcanic rocks and superficial alluvial/proluvial deposits within different parts of the massif [2, 7]. The wider Adamawa–Yadé domain provides important evidence for the polycyclic evolution of the basement. Geochronological studies in Cameroon have identified Archean crustal components, with some tonalite–trondhjemite–granodiorite (TTG) protoliths dated at approximately 2.98–2.55 Ga, followed by Paleoproterozoic reworking at approximately 2.08–2.07 Ga. These older crustal components were subsequently affected by major Pan-African magmatic and metamorphic events between approximately 640 and 610 Ma [6]. The Pan-African event was particularly important in shaping the present architecture of the Adamawa Massif. Granitoid emplacement was accompanied by deformation, fracturing and the development or reactivation of basement structures. In the Nigerian Adamawa Massif, mapped structural trends include NE–SW, NW–SE, NNE–SSW and ENE–WSW, while detailed mapping of parts of the massif has also documented NNW–SSE, NNE–SSW and N–S trends (Kamaunji et al, 2019; [2, 7]. These structural features are important to the geological evolution and mineralization of the massif because fractures, joints and lineaments can provide pathways for hydrothermal fluids and influence the emplacement and alteration of mineralized rocks. [7] for example, documented significant lineament concentrations in parts of the Adamawa Massif and interpreted the associated joint systems as potential conduits for mineralizing fluids. Regionally, the Adamawa Massif is therefore interpreted as a polycyclic Precambrian crystalline basement terrain that records Archean/Paleoproterozoic crustal components and significant Neoproterozoic Pan-African magmatism, metamorphism and deformation. Its geological relationship with the Adamawa–Yadé domain of Cameroon indicates that the basement architecture extends across the Nigeria–Cameroon region and forms part of the broader Central African Pan-African orogenic system [6]. The combination of diverse metamorphic and granitoid lithologies, multiple generations of deformation and extensive structural development make the Adamawa Massif an important area for

understanding the Precambrian evolution of northeastern Nigeria and for investigating structurally controlled mineralization [6, 7].

2.2 Geological Setting of the Study Area

The Gampu area is situated within the northern part of the Adamawa Massif in northeastern Nigeria. The Adamawa Massif constitutes part of the Nigerian Basement Complex and is characterized by a complex assemblage of metamorphic and igneous rocks. The regional geology of the area is influenced by the Pan-African tectono-thermal event, which resulted in widespread deformation, metamorphism, granitoid magmatism and crustal reworking across the Nigerian Basement Complex [1, 8]. The proximity of the study area to the Benue Trough and Cameroon Highlands further makes it important for understanding the relationship between Precambrian basement evolution and subsequent tectono-magmatic events. Field mapping indicates that the major lithological units exposed in the study area include gneisses, fine- to medium-grained granites, granodiorites, tonalites, quartz syenites, quartz monzonites and minor mafic intrusions, including doleritic dikes.

3 MATERIALS AND METHODS

3.1 Field Investigation

Detailed geological field mapping was carried out across the study area. The investigation involved systematic traverses, identification of lithological contacts, description of rock textures and structures, and documentation of outcrop relationships. Representative fresh rock samples were collected from the different lithological units for petrographic and geochemical investigations. Geographic positions of selected outcrops were recorded during the field investigation and subsequently used in the preparation of the geological map (Figure 3).

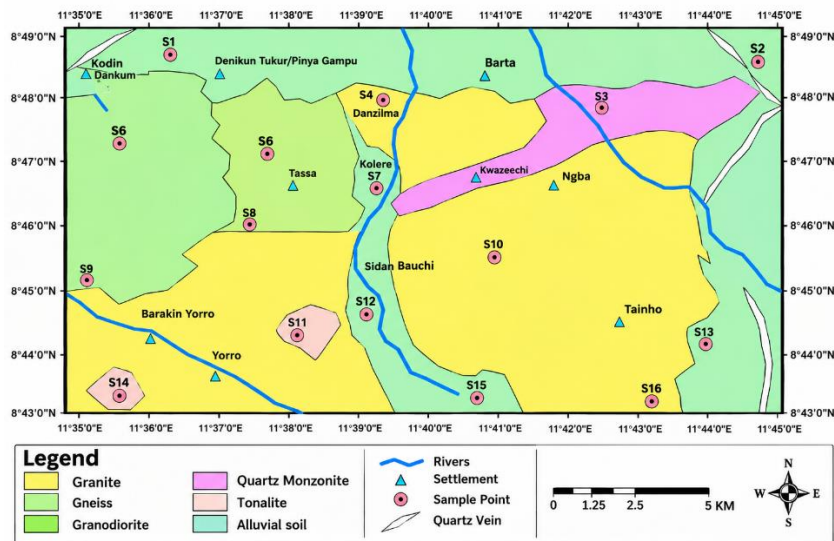


Figure 3. Geological Map of the study area

3.2 Petrographic investigation and Structural Geology

Representative rock samples were prepared as thin sections and examined under a polarizing petrographic microscope. Thin sections were prepared in the petrological laboratory of the Geology Department, Modibbo Adama University, Yola. Preparation involved cutting, lapping, frosting, mounting, trimming, grinding and final thinning to approximately 30 μ m. Seven representative thin sections were examined under plane-polarized and cross-polarized light for mineral identification and textural relationships. Joints, veins, fractures and faults were recorded throughout the mapped area. Jointing is widespread, with particularly extensive joint development found in the northeastern and southwestern sectors of the study area. Granite, pegmatite and dolerite dykes show diverse orientations. The dominant structural trends are NE–SW and subordinate NW–SE. These structures can be interpreted as evidence of polyphase deformation associated with the tectono-magmatic evolution of the Pan-African basement [9].

3.3 Whole-Rock Geochemical Analysis

Representative rock samples were analyzed for major and trace elements using X-ray fluorescence spectrometry (XRF) at Gombe State University Department of Geology Laboratory. The major oxide data were used for rock classification, evaluation of magmatic differentiation and determination of alumina saturation characteristics. Trace element data were further employed in evaluating magma evolution, petrogenetic processes, mineral potential and tectonic setting using established geochemical discrimination diagrams.

4 RESULTS AND DISCUSSION

4.1 Field Relationships and Lithology

The Gampu area is characterized by diverse crystalline rock assemblages comprising both metamorphic and intrusive igneous rocks. The principal lithological units identified include gneisses, granites, granodiorites, tonalites, quartz syenites and quartz monzonites. The granites are generally fine- to medium-grained and occur as relatively massive bodies. Granodiorites and tonalites represent intermediate to felsic intrusive phases, while quartz syenites and quartz monzonites constitute more alkaline and evolved lithologies. The occurrence of different intrusive rock types within the study area suggests multiple episodes of magmatism and emplacement under changing tectonic conditions.

4.2 Petrography

Representative rock samples were prepared as thin sections and examined under a polarizing petrographic microscope. Quartz syenite contains quartz, alkali feldspar and biotite. Quartz is commonly anhedral, colourless in plane-polarized light and exhibits low first-order interference colours and, locally, undulose extinction. Feldspar displays twinning including Carlsbad-type features. Quartz monzonite contains quartz, plagioclase, feldspar, biotite and amphibole. Tonalite contains plagioclase, microcline, biotite, amphibole and pyroxene, with chlorite and muscovite as secondary minerals, while allanite, zircon, titanite, apatite and opaque minerals as accessories. Granodiorite is characterized by quartz and potassium- and sodium-bearing feldspars. Dolerite contains phenocrystic to microcrystalline clinopyroxene, amphibole, plagioclase, alkali feldspar and Fe–Ti oxides. The petrographic assemblage broadly supports the field identification of a compositionally varied granitoid suite, ranging from quartz-rich felsic rocks to relatively mafic tonalitic and doleritic rocks.

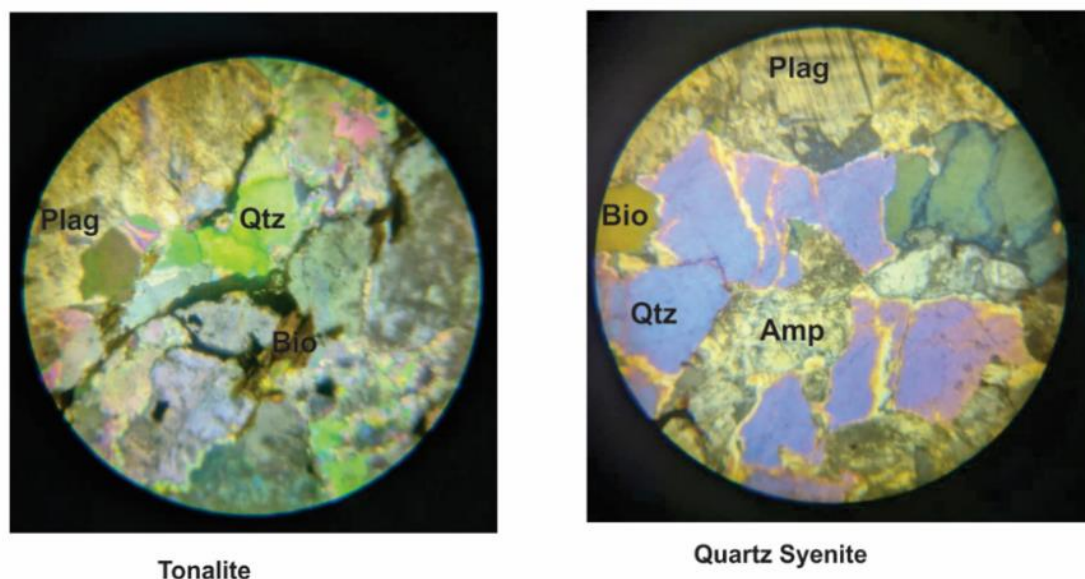


Figure 4. Showing microphotograph of quartz syenite and tonalite under cross polarized light

4.3 Geochemical Classification

Whole-rock geochemical data (Table 1) demonstrate considerable compositional variations among the investigated rock types. The silica contents indicate the occurrence of intermediate to felsic compositions, with the more evolved granitoids displaying relatively high SiO₂ contents.

Table 1. Showing the result of geochemical analysis Major Oxides

Sample No. Composition (Wt.%)/Rock Name	GM01 Quartz Syenite	GM02 Quartz Monzonite	GM03 Granite	GM04 Granite	GM05 Tonalite	GM06 Granodiorite	GM07 Granite	GM08 Tonalite	GM09 Dolerite	GM10 Quartz
SiO ₂	66.1	62.2	69.6	69.1	61.2	70.2	69.3	64.8	49.1	95.4
Al ₂ O ₃	10.4	10.3	10.5	10	11.2	10	9.89	10.6	9.16	0.665
K ₂ O	10.9	8.43	8.36	9.23	6.11	6.41	8.53	6.05	1.08	0.349
Fe ₂ O ₃	3.98	7	2.81	4.14	8.78	4.17	4.95	6.41	18.4	1.48
Na ₂ O	1.68	1.72	1.6	1.64	2.1	1.82	1.62	1.92	1.89	ND
CaO	2.95	4.5	3.12	2.58	5.18	3.76	2.57	5.38	13.9	0.215
MnO	0.143	0.184	0.104	0.148	0.268	0.158	0.171	0.204	0.383	0.196
MgO	ND	0.59	0.156	0.178	0.972	0.264	0.183	0.676	2.59	ND
TiO ₂	0.765	1.87	0.481	0.389	1.2	0.572	0.408	1.01	1.13	ND
P ₂ O ₅	1.8	2	1.71	1.62	1.98	1.76	1.61	1.87	1.48	1.45
Trace elements composition (ppm)										
S	851	873	ND	ND	789	776	ND	803	808	ND
Ar	2200	2130	3220	3020	1200	3620	2150	3280	1700	ND
V	126	457	498	263	268	125	251	182	396	ND
Cr	ND	176	84.3	71.5	92.7	93.2	97.2	99.6	248	112
Ni	ND	46.6	11	22.3	43.6	32.3	28.8	27.1	235	30.5
Cu	23	70.7	26.6	36.9	35.2	34.6	32	103	19.6	28
Zn	46.2	115	49.1	52.6	165	77.8	51.6	126	170	2.16
Ga	14.8	43.1	32.1	35	46.5	38.4	30.7	45.6	32.1	2.16
Rb	640	608	478	587	741	460	555	579	24.7	7.11
Sr	2180	2180	3130	1500	2310	1000	1460	2100	1070	13
Zr	394	918	476	471	748	346	485	545	265	5.61
Y	37.9	114	24.4	38	121	104	35.2	93.3	91	ND
Nb	490	80.9	ND	14.4	73.8	24.2	17	37.8	340	4.79
Ag	8.79	ND	7.66	ND	11.6	10.9	ND	ND	17.5	9.16
Sn	ND	ND	ND	ND	2.74	ND	ND	ND	10.2	ND
Ba	3750	3080	6420	2320	1990	846	2040	1600	202	ND
Ta	489	ND	ND	ND	ND	11.3	ND	ND	301	ND
Pb	86.6	83.4	52.8	38.3	58.6	56.4	58.1	70.8	31	ND
Nd	ND	76.5	ND	ND	86.1	ND	63.6	104	ND	ND

The samples were classified using major-element-based discrimination diagrams, including the R_1 – R_2 classification scheme [10]. The results distinguish quartz syenite, quartz monzonite, tonalite, granodiorite and granite compositions. The alumina saturation index was evaluated using the A/CNK relationship [11]. The investigated samples occupy predominantly metaluminous to peraluminous compositional fields (Figure 5.), suggesting variations in magma source and differentiation processes. In addition, the granites in the study area are classified as I-type granite (Figure 6).

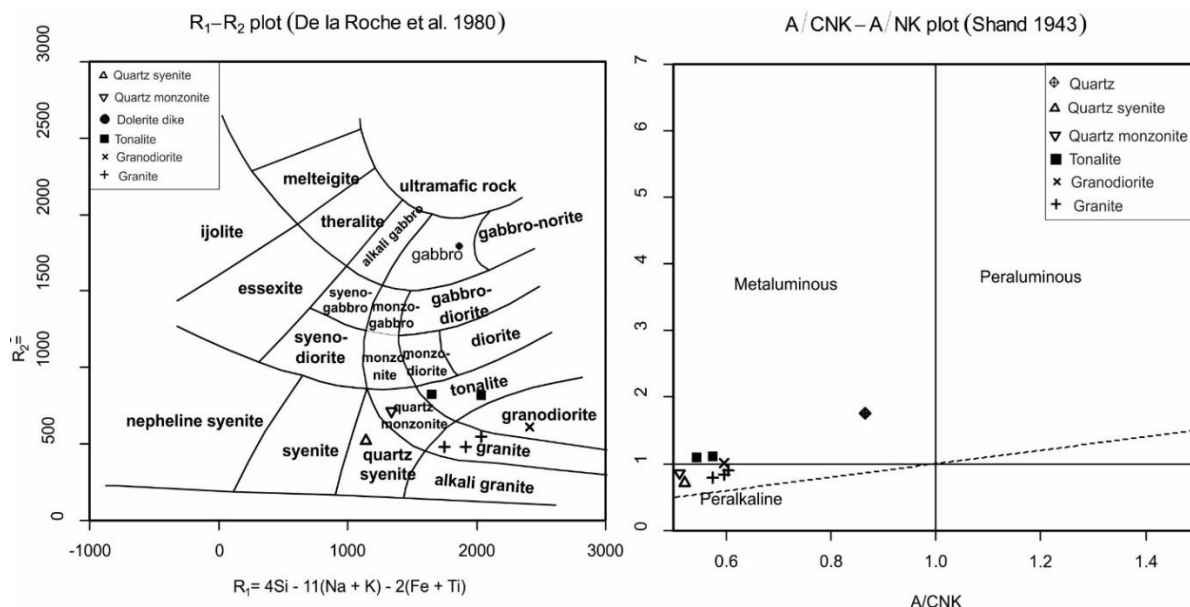


Figure 5: a) TAS diagram showing rock classification in the study. b) A/CNK Plot

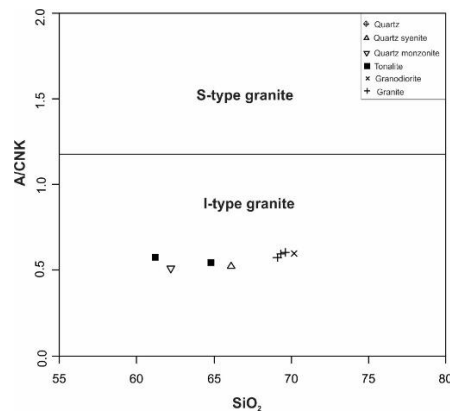


Figure 6. A/CNK versus SiO_2 indicating granite type

4.4 Major Element Variations

Harker variation diagrams were constructed by plotting SiO_2 against major oxides. The observed variations reflect progressive magmatic differentiation among the investigated rock units. The relationships between SiO_2 and major oxides suggest that fractional crystallization played an important role in the evolution of some of the magmas. Variations in CaO , MgO , FeO , TiO_2 and P_2O_5 relative to SiO_2 are particularly useful in assessing the removal or fractionation of mafic minerals, plagioclase and accessory phases during magma evolution [12]. The compositional spread of the samples also suggests that the rocks may not have been derived from a single homogeneous parental magma.

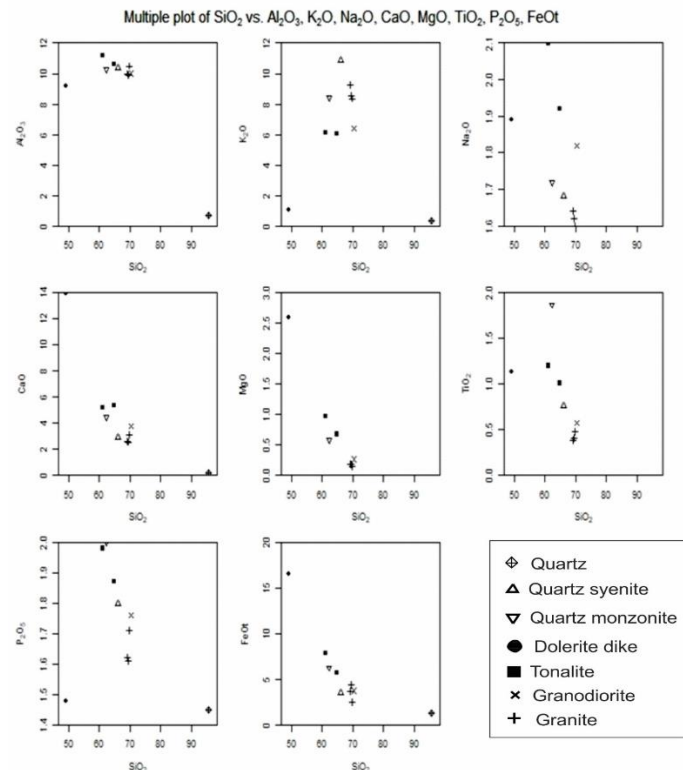


Figure 7. Harker variation plots of SiO_2 against the major element

4.5 Petrogenesis of the Igneous Rocks

The field, petrographic and geochemical data suggest that the igneous rocks of the Gampu area and its environs were generated through more than one petrogenetic process. The original Harker plots show generally decreasing concentrations of several major oxides with increasing SiO_2 , while P_2O_5 displays a contrasting trend (Figure 6). These relationships can be interpreted as evidence for removal of high-temperature minerals, particularly plagioclase, during crystallization and progressive magmatic fractionation [12]. The granites and granodiorites display characteristics consistent with derivation from

relatively evolved crustal sources (Figure 8). Their occurrence within the basement terrain and their inferred tectonic affinity suggest that partial melting of pre-existing continental crust may have contributed significantly to their generation [8,21]. The tonalites, quartz syenites and quartz monzonites, on the other hand, appear to represent a distinct magmatic association. Their compositional characteristics and trace element relationships suggest involvement of mantle-derived magmas followed by varying degrees of fractional crystallization and crustal interaction. The origin of syenitic magmas has been widely debated [12]. Previous studies have argued that syenitic magmas are difficult to generate solely through partial melting of sialic continental crust [12, 13]. Peralkaline granites and syenites characterized by elevated alkali contents have been associated with fractional crystallization of potassium-rich basaltic or andesitic parental magmas with limited crustal contribution [8, 14]. The geochemical characteristics of the Gampu syenitic rocks and tonalite are consistent with an important role for fractional crystallization during their evolution (Figure 8). The compositional relationship between the more mafic and more evolved rocks further supports magmatic differentiation as an important petrogenetic process.

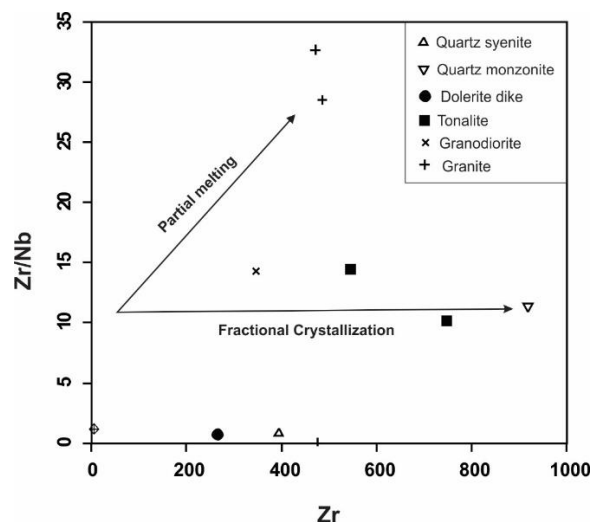


Figure 8. Zr/Nb versus Zr diagram for the rocks in the study area after [8]

4.6 Magma Source Characteristics

The investigated rocks display variations from relatively felsic granitoids to intermediate and alkaline compositions. This diversity suggests differences in source composition and/or melting conditions. The granitic and granodioritic rocks are interpreted to have significant crustal contributions [15, 16], whereas the tonalitic and syenitic rocks may have evolved from relatively more mantle-influenced parental magmas, possibly involving mantle-derived melts. Such mantle-derived or mantle-influenced parental magmas may subsequently have undergone fractional crystallization and variable interaction with continental crust [17, 18]. The coexistence of crustally derived and mantle-influenced magmas within the same geological terrain may reflect a multi-stage tectono-magmatic evolution, involving crustal melting during syn-collisional deformation and subsequent emplacement of mantle-derived magmas during late-orogenic magmatism [8, 19], and this is consistent with the tectono-magmatic evolution of the eastern Nigeria basement rocks [20].

4.7 Tectonic Setting

Tectonic discrimination diagrams were used to evaluate the tectonic affinities of the investigated rocks (Figures 9 and 10). The granitic rocks plot predominantly within the syn-collisional field, suggesting emplacement in a convergent tectonic regime associated with continental collision and crustal reworking. Syn-collisional granitoids are commonly linked to crustal melting during crustal thickening and tectonic convergence [21, 22]. This interpretation is consistent with the occurrence of granitic to granodioritic rocks in the Zing–Monkin area, where their geochemical characteristics have previously been interpreted in terms of syn- to late-orogenic magmatism [4, 19]. In contrast, the tonalites, quartz syenites and quartz monzonites display affinities with post-collisional to late-orogenic fields. Such signatures are characteristic of magmatism developed during the later stages of an orogenic

cycle, following the principal collisional event and associated with tectonic adjustment and lithospheric re-equilibration [21]. The R_1 – R_2 discrimination diagram further indicates the presence of contrasting tectono-magmatic affinities among the investigated rocks, with samples occupying syn-collisional and late-orogenic fields. The coexistence of these affinities suggests that the Gampu-Zing granitoids record more than one stage of Pan-African magmatic evolution, consistent with the previously proposed syn- to late-orogenic tectonic evolution of the Zing–Monkin granitoids [3, 4, 19].

Granite tectonic discrimination – Pearce et al. (1984)

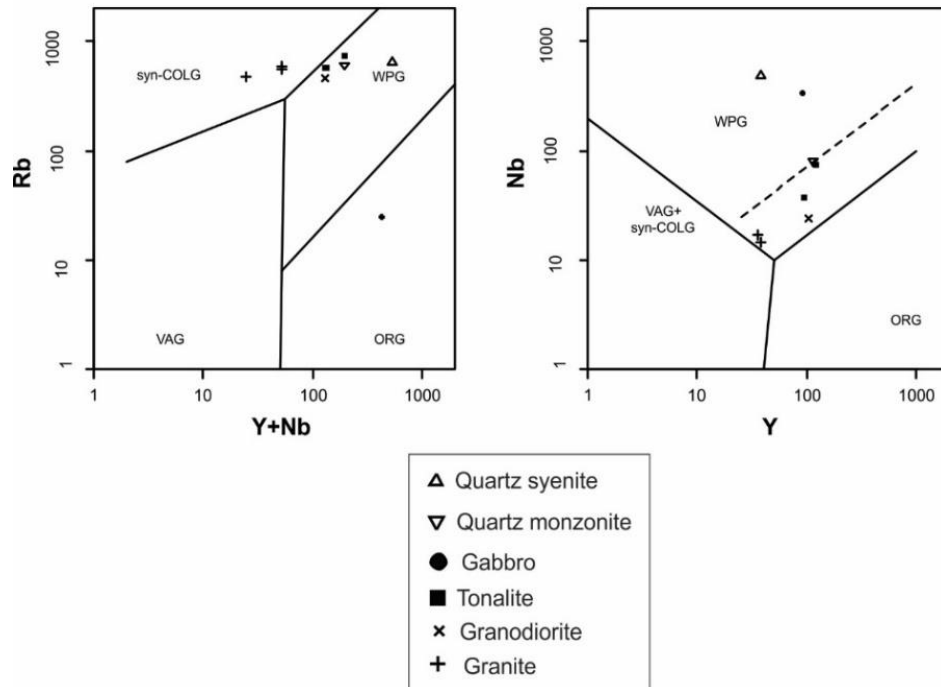


Figure 9. Rb versus Y + Nb diagram after [22], b Nb versus Y diagram after [22]

R_1 – R_2 (Batchelor + Bowden 1985)

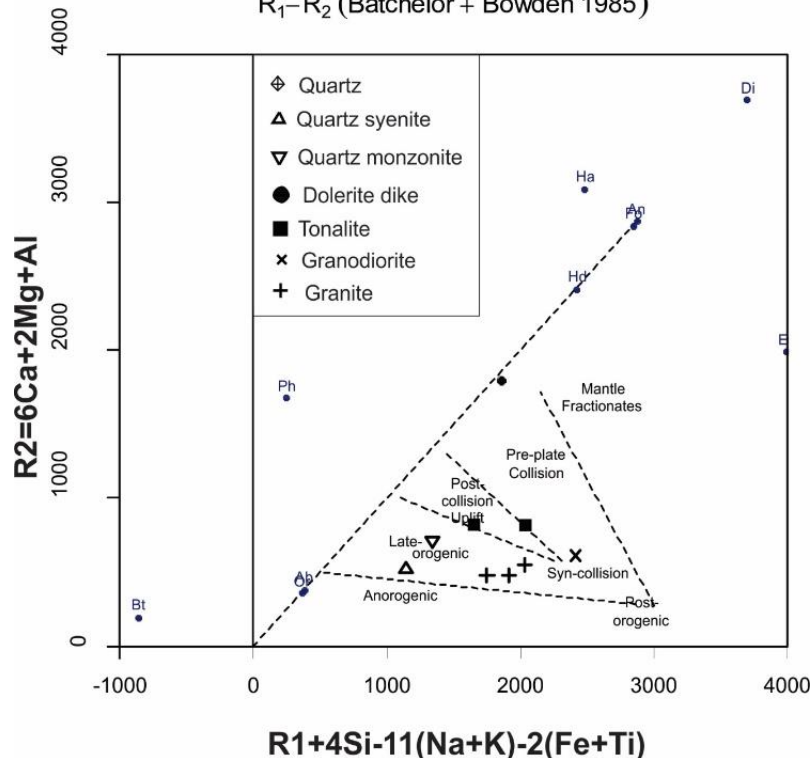


Figure 10. R_1 – R_2 tectonic diagram after [21]

4.8 Proposed Tectono-Magmatic Evolution

Based on the geological, petrographic and geochemical characteristics of the investigated rocks, a three-stage tectono-magmatic model is proposed for the Gampu-Zing area. The model involves an initial phase of crustal melting and syn-collisional granitoid emplacement, followed by late- to post-collisional magmatism and subsequent magmatic differentiation. This interpretation is consistent with the regional evolution of the Adamawa Massif, where older basement rocks were subsequently intruded by syn- to post-collisional Pan-African granitoids [19].

4.8.1 Stage I: Crustal Thickening and Syn-Collisional Magmatism

The earliest intrusive phase in the area is represented by the granitic and granodioritic rocks. Their syn-collisional affinity suggests emplacement during a period of active continental convergence and crustal thickening. Such tectonic conditions can promote partial melting of pre-existing continental crust and generation of felsic magmas, particularly where heat is supplied by crustal thickening, mantle-derived magmatic input, or underplating. The occurrence of syn-collisional granitoids within the Adamawa Massif is consistent with the broader Pan-African tectono-magmatic evolution of the region, which involved emplacement of granitoids into an older remobilized basement [19, 23].

4.8.2 Stage II: Late- to Post-Collisional Magmatism

Following the principal collisional phase, the tectonic regime evolved toward late- to post-collisional conditions. The tonalitic, quartz monzonitic and quartz syenitic rocks, which display affinities with these tectonic fields, may therefore represent magmatism during the later stages of the orogenic cycle. Their compositions could have developed through interaction between mantle-derived and crustal melts, followed by variable fractional crystallization. A similar association of late- to post-collisional granitoids has been documented elsewhere in the Adamawa Massif, where Pan-African magmatism is interpreted to have occurred during progressive tectonic adjustment following collision [4, 19].

4.8.3 Stage III: Magmatic Differentiation and Late-Stage Hydrothermal Processes

Continued fractional crystallization and differentiation of the parental magmas produced the observed compositional diversity among the intrusive rocks. The development of progressively evolved compositions may have been accompanied by late-stage volatile-rich fluids and hydrothermal processes, potentially accounting for the enrichment of incompatible elements in the most evolved lithologies. Such differentiation is consistent with the systematic geochemical variation documented among granitoids of the Zing–Monkin sector, where decreasing concentrations of several trace elements from granodiorite toward granite and increasing Rb contents were interpreted as evidence of fractional crystallization from a related parental magma [19]. In general, the proposed model indicates that the Gampu intrusive suite records multiple stages of Pan-African tectono-magmatic evolution, beginning with crustally influenced syn-collisional magmatism and progressing toward late- to post-collisional magmatism and magmatic differentiation. The coexistence of these tectonic affinities is consistent with the polycyclic nature of the Nigerian Basement Complex and the documented syn- to post-collisional evolution of the Adamawa Massif [4, 19].

4.9 Mineral Potential

The geochemical data indicate that the Gampu area and environs possesses potential for several styles of mineralization, particularly Nb–Ta–rare-metal mineralization. The granitoid samples display enrichment in incompatible elements such as Rb, Zr, Y and Nb (Table 1), reflecting substantial magmatic differentiation and the capacity of the evolved melts to concentrate incompatible elements. This is consistent with the documented geochemical evolution of granitoids in the northern Adamawa Massif, where progressive fractional crystallization resulted in enrichment of Rb and depletion of Sr, Ba and compatible elements [19]. The exceptionally high Nb (490 ppm) and reported Ta (489 ppm) contents of the quartz syenite (GM01) further indicate a potential Nb–Ta enrichment zone, although these anomalous concentrations require analytical verification and mineralogical confirmation before being interpreted as evidence of ore mineralization. The association of Ta–Nb mineralization with evolved granites and pegmatites is well established in African rare-metal provinces [24]. The dolerite

(GM09), characterized by relatively elevated Cr (248 ppm), Ni (235 ppm) and MgO (2.59 wt.%), represents a distinct mafic component and may warrant investigation for Cu–Ni–Cr mineralization; however, the present whole-rock data alone are insufficient to establish an economic sulfide accumulation.

5 CONCLUSIONS

Integrated geological mapping, petrographic observations and whole-rock geochemical data demonstrate that the Gampu area and its environs comprises a diverse assemblage of metamorphic and intrusive igneous rocks, including gneisses, granites, granodiorites, tonalites, quartz syenites and quartz monzonites, with subordinate mafic intrusive rocks. The lithological and geochemical characteristics indicate a complex tectono-magmatic history involving contrasting crustal and mantle-influenced magmatic processes. The granitic and granodioritic rocks exhibit geochemical characteristics consistent with syn-collisional granitoids, suggesting emplacement within a convergent tectonic regime. Their relatively evolved compositions and incompatible-element enrichment are compatible with significant crustal involvement and magmatic differentiation. This interpretation is consistent with the documented occurrence of syn- to post-collisional Pan-African granitoids within the Adamawa Massif and with previous geochemical studies of the Zing–Monkin granitoids, which identified syn- to late-orogenic affinities and systematic compositional variation attributable to fractional crystallization. The tonalites, quartz syenites and quartz monzonites display comparatively more evolved late- to post-collisional tectonic affinities. Their compositional characteristics are consistent with magmatic differentiation involving variable mantle–crust interaction, although the available whole-rock data do not uniquely constrain the relative contributions of mantle-derived and crustal components. The occurrence of these contrasting magmatic affinities suggests that the Gampu intrusive suite records more than one stage of Pan-African tectono-magmatic evolution, consistent with the broader polycyclic history documented for the Adamawa Massif. The systematic variation in major and trace elements further indicates significant fractional crystallization during magma evolution. In particular, enrichment of incompatible elements in some of the felsic rocks points to progressive differentiation and concentration of elements that may be relevant to rare-metal mineralization. Generally, the results suggest that the Gampu area and its environs records a multi-stage Pan-African tectono-magmatic evolution involving crustally influenced syn-collisional magmatism, subsequent late- to post-collisional magmatism, and progressive magmatic differentiation. However, the precise temporal relationships, magma-source characteristics and extent of mantle–crust interaction remain unresolved. Hence, it is recommended that high-precision geochronology, Sr–Nd–Pb isotopic studies, zircon Hf–O isotopes and targeted mineral-chemical investigations would therefore provide important constraints on the petrogenesis and tectonic evolution of the Gampu magmatic suite. Detailed mineralogical and geochemical exploration is also required to evaluate the significance of the observed incompatible-element enrichment and establish whether these anomalies represent localized mineralization.

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