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Research paper

Syn-collisional pan-African granite in the northern part Birnin Gwari schist belt in NW Nigeria

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Abstract

Syn-collisional granite in the northern part of the Birnin Gwari schist belt consists dominantly of granite and lesser granodiorite and quartzolite. Petrographic and ge¬ochemical data revealed three granite groups: the biotite-hornblende granite (quartzolite - BHG); the biotite granite (BG) and the biotite-muscovite granite (BMG). The rocks generally have calc-alkaline and high-K calc-alkaline affinities, and calc-alkalic to alkali-calcic, peraluminous and ferroan and magnesian geochemistry. They are characterized by LILE enrichment, high LREE fractionation factor [(La/Yb) (6.74 to 45.14] with weak to moderate negative Eu (Eu/Eu* = 0.38 to 0.62) and strong negative Nb, P and Ti anomalies. Variation in the behavior of lithophile elements (Ba, Sr and Rb) revealed diverse granite trend such as "high and low Ba-Sr"; "normal", "anomalous" "strongly differentiated" and "granodiorite and quartz diorite" granite. Their display of similar trace elements and REE patterns suggest they are cogenetic. Major and trace element data indicate differentiation of a mafic magma and partial melting of crustal components inherited from shale-greywacke and quartzose sedimentary protoliths in volcanic arc and post collisional settings. The field and geochemical characteristics of this granite suggest that they are similar to other granites in schist belts in other parts of Nigeria, forming the lateral continuation of the same Pan-African magmatic belt.

Keywords: *Birnin Gwari; Calc-Alkaline; Granite; Nigeria; Quartzolite.*

1. Introduction

Syn-collision granites in and around Birnin Gwari area constitute one of the three major rock units of the Precambrian Basement Complex rocks north of Birnin Gwari schist belt. The other units are the Migmatite-Gneiss-Quartzite suite represented by dioritic, granodioritic, granitic and granitic gneisses and Birnin Gwari schist belt represented biotite-staurolite quartz schist. Turner, (1983) and Ajibade et al. (2008) described the Birnin Gwari Schist belt and the underlying quartzo-feldspathic rocks of the Zungeru Formation as a simple N-S syncline, 150 km long, forming a single structural unit named Zungeru-Birnin Gwari Schist Belt. The northern part of the belt which is the study area (Fig. 1) is displaced dextrally by a NE-SW transcurrent fault and characterized by conspicuous NNE-SSW trending ridges rising over 100m above the surrounding country, comprising mainly phyllites, mica schists, with which metagreywacke, pebbly schist and metavolcanics are interlayered. The lower part (south of the study area) consists of finely banded phyllites in the west and higher grade biotite-muscovite schists in the east, overlain by the Durimi pebbly schist, a metamorphosed mudstone conglomerate.
Published work on the rocks includes radiometric dating, structures and mineralization. Grant (1978) described the structures in this belt where he recognised a simple N-S structural style, and Rb–Sr whole rock data from the adjacent Zungeru mylonites have yielded ages varying from 600Ma – 700Ma. Radiometric age measurement of Rb – Sr data from Kusheriki granite emplaced across the gneissic envelope gives an age of 500 + 4 Ma. which suggests Pan-African deformation and emplacement of the region (Ajibade et al., 1979; 2008). They described a complex structural sequence from parts of the neighbouring Birnin-Gwari Schist and Ushama Schist Formations and identified four deformation episodes that have affected the rocks in these areas and later define the Zungeru Mylonites. They also confirmed the presence of two types of migmatites and gneisses which are believed to belong to two different ages. Garba (2002) also revealed epigenetic gold-sulphide mineralization hosted by sub-parallel shear zones along isoclinal axes of tightly folded graphitic phyllites near Tsohon Birnin Gwari in the Kushaka schist belt similar to Bin Yauri area (Zuru schist belt) and other areas of Archaean and younger mesothermal gold mineralization in the world.
Previous published work on of the rocks close to the study area especially the Older Granites in Minna and Abuja focused on the geochemistry, geochronology and rare metal pegmatites (Ajibade et al. 2008; Goodenough et al. 2014). Little or no work has been done on the granitoids in this part of the Birnin Gwari schist belt. Geochemical data required for proper classification and characterization of these granitic rocks are generally scarce. In this work, major, trace and rare earth elements (REE) data on eight relatively unknown granitic plutons and four host rock (granite gneiss) have been used to assess their petrogenetic evolution and tectonic setting.

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2. Regional geology

The Nigerian basement complex consists of three major rock units: (1) the Migmatite Gneiss Quartzite Complex (MGQC) dated from Archean to Early Proterozoic (2700-2000 Ma), a heterogeneous assemblage of predominantly amphibolite-facies migmatites, orthogneisses, paragneisses, and minor-basic to ultrabasic rocks; (2) the N-S and NE-SW Schist Belts, believed to overlie the MGQC and consisting mainly of psammitic to pelitic metasediments with interlayered granitoid gneisses and rare amphibolites, interpreted as metavolcanics; and (3) Late Proterozoic to Early Phanerozoic (750-450Ma) Older Granites, intruding both 1 and 2 and composed of tonalitic to granitic plutons and charnockites, strongly foliated to almost unfoliated, and considered to have been emplaced during the Pan-African orogeny (Russ,1957; McCurry, 1976; Fitches, et al.1985; Rahaman 1976; 1988; Olanrewaju, 1988; Turner 1983; Oyinloye and Ojo, 1988; Tubosun et al. 1984).

The "Older Granites" of Nigeria include a wide spectrum of rocks varying in composition from tonalite through granodiorite to granite, syenite and charnokitic rocks. They have been described as calcalkaline, I-type granites (Olarewaju and Rahaman, 1982; Egbuniwe et al., 1985; Fitches et al., 1985). The syenites have mildly alkaline affinities (Egbuniwe et al., 1985). Typical minerals of metasedimentary rocks such as garnet and staurolite are also commonly encountered in some of the granitic rocks which are often weakly foliated. They are characterized by high grade metamorphism, folding, faulting and widespread granite plutonism. They have been dated repeatedly at 750-500Ma (van Breemen, 1977; Rahaman et al., 1983; Fitches, Ajibade, Egbuniwe, 1985; Ferre et al., 1998; Ekwueme & Kroner, 1998) (Table 1). Similar granitic rocks have also been studied in various parts of the Nigerian basement complex, northern Nigeria (Olarewaju & Rahaman, 1982), Jebba area (Okonkwo & Winchester, 2004), Obudu Plateau, southeastern Nigeria (Ukwang & Ekwueme, 2009), Kabba-Lokoja area (Ezepue & Odigi, 1993), among others. Granite magmatism is commonly associated with several tectonic settings and various stages during orogenic evolution (Harris, Pearce & Tindle, 1986; Maniar & Piccoli, 1989).

In NW Nigeria the rocks include syenites and biotite granites. They have been described as calc-alkaline, I-type granites (Olarewaju and Rahaman, 1982; Egbuniwe et al., 1985; Fitches et al., 1985). In north-central Nigeria, they are Al-rich to slightly Al-excess granites, granodiorites, syenites, syenodiorites, and diorites derived through partial melting of crustal rocks (Onyeagocha, 1986; Obiora, 2012). In SW granites are felsic and intermediate alkali rich rocks of peraluminous, ferroan and magnesian character, and of non-oceanic origin, grouped as within plate granites (Igonor and Abimbola, 2016). The south-eastern margin of the southwestern sector in Idofin-Osi-Eruku area, granites are Fe-rich potassic calc-alkaline rock and products of syncollisional volcanic arc magmatism emplaced in the late phase of the Pan-African Orogeny (Odewumi and Olanrewaju, 2013). In the SE, granites are high-K calc-alkaline transalkaline to non-alkaline rock, with alkalic-calcic to alkalic, ferroan and metaluminous character derived from partial melting of hornblende-rich crustal sources in an orogenic (syn- to late/post-collisional) tectonic setting (Obiora, 2012). Other granitic rocks described according to their petrographic affinities are porphyritic granites, fine to medium grained granite, syenite, quartz syenite, quartz hypersthene granite and hypersthene granite as described by Oyawoye (1964; 1972) and Makanjuola (1982).

3. Study area

The study area covers a total area of 1,250 square kilometers and lies in the north western part of Nigeria comprising part of Kushaka and Birnin Gwari schist belts. It falls within 1:100,000 Kushaka Sheet 122 and bounded by latitudes 10^0 30" N and 11^0 00'' N and longitudes 6^0 30''E and 6^0 42'' E (Fig. 1). The area is underlain predominantly by three main lithologies: (i) Migmatite-Gneiss-Quartzite suite represented by dioritic, granodioritic, granitic and granitic gneisses; the schist belts represented by (ii) biotite and staurolite quartz schist and (iii) syn-collision biotite granite (BG) and biotite-muscovite granite (BMG).

4. Materials and methods

Twelve representatives granite (eight in Kushaka pluton and four surrounding granitic gneisses) samples were carefully selected and thin sections were prepared and petrographic studies of different rock types were done using a petrographic research microscope at the Department of Geology, Ahmadu Bello University, Zaria. Modal compositions of the rocks were estimated from thin section studies using the JMicrovision software of Nicholas Roduit version 1.2.7. (2002-2008). Modal analyses of the granitoids are given in Table 1. These twelve samples were also analysed (Table 2). About 1 kg of each sample was broken into pieces with a hammer and crushed into smaller pieces with a jaw-crusher. The samples were thereafter pulverized in a disc mill for about two minutes. Each pulverised sample was thoroughly homogenized to obtain a representative portion. The samples were thereafter sent to laboratories for whole-rock geochemistry in the Department of Lithospheric Research, University of Vienna, Austria, while REE analyses were done at the MSALABS in Langley, British Columbia, Canada.

Rocks were crushed and grounded to the finest powder possible in an agate (or tungsten carbide) swing mill for the whole X-ray-fluorescence analysis. Major elements were determined by the fused bead method on calcined rock powder fused with lithium tetraborate as flux to form a glass bead. Trace elements used the pressed pellet method directly on the crushed and milled rock powder mixed with polyvinyl alcohol as a binding agent. The element analyses are performed on a sequential X-Ray spectrometer PHILIPS PW2404 using a super-sharp end-window tube with a Rh-anode and a programmable 4kW generator (60kV max., 125mA max.; iso-Watt-switching), with accompanying PANalytical software. REE analyses were done using a lithum metaborate/tetraborate flux in a platinum crucible and fused samples poured into a platinum mold to create a homogenous glass disk and then analysed by Xray-flourescence (XRF).

5. Results

5.1. Field characteristics and petrography

The granite plutons intruded both the Migmatite-Gneiss-Quartzite suite represented by dioritic, granodioritic, granitic and granitic gneisses and the Birnin Gwari schist in Gworon Dutse, Mando, Loko, Bagwoma, Birnin Gwari and Kugu. They are further sub-divided into: a) granodiorite (Birnin Gwari/Mando border); b) granite (Gworon Dutse coarse grained biotite and medium grained biotite-muscovite granite; Mando biotite-muscovite granite; Mando/Loko biotite-muscovite granite; Nassarawa Kwona biotite granite, Kugu biotite granite and Bagwoma quartzolite); c) host Gwaska granitic leucosome, Kampani Doka biotite and biotite-muscovite granite gneiss Kungwi biotite migmatitic gneiss). These intrusions form N-S oriented oval and elongated bodies of whaleback with moderate and high

relief on either side of the transcurrent Kalangai fault (Fig. 1). The host granitic gneisses are characterized by gneissose foliation and migmatitic ones shows alternations of light and dark coloured bands. The light bands consist mainly of quartz and feldspars while the dark bands are enriched in biotite and muscovite. They are coarse porphyritic to medium grained rocks and generally devoid of pervasive foliation. The modal composition of granites in the Kushaka Schist Belt is given in Table 2 and Fig. 3.

5.1.1. Granodiorite

Granodiorite along the Birnin Gwari/ Mando axis is restricted to the contact zone between the Birnin Gwari staurolite bearing quartz schist and Mando biotite and muscovite granite. This is a medium grained rock characterized by light grey granitic inclusions in the light-brown coloured rock slightly aligned in the N-S foliation direction. Under the microscope, it is a coarse to medium grained rock consisting of quartz (30%), K-feldspar (30%), plagioclase (15%), biotite (15%), and accessory minerals (5%). The K-feldspars (orthoclase with little microcline) occur as platy subhedral grains with faint albite twinning; plagioclase occurs as platy euhedral to subhedral crystals. K-feldspar and plagioclase minerals are characterized by zoned and dense clay minerals generally ascribed to low-temperature alteration. Anhedral biotite occurs in closely with iron-oxide and titanite and also forms part of the dense materials in the feldspars. Accessory minerals are titanite, magnetite, zircon and apatite.

5.1.2. Granite

Granite occur as N-S trending isolated plutons and low whale back outcrops on the edges of the Birnin Gwari schists in places with sharp contacts with the schists and granitic gneisses (Fig. 1). Granitoids in Goron Dutse consists of four individual closely spaced plutons, with high relief (550m), and intruded the Birnin Gwari metasediments at the northwestern fringes. Two varieties

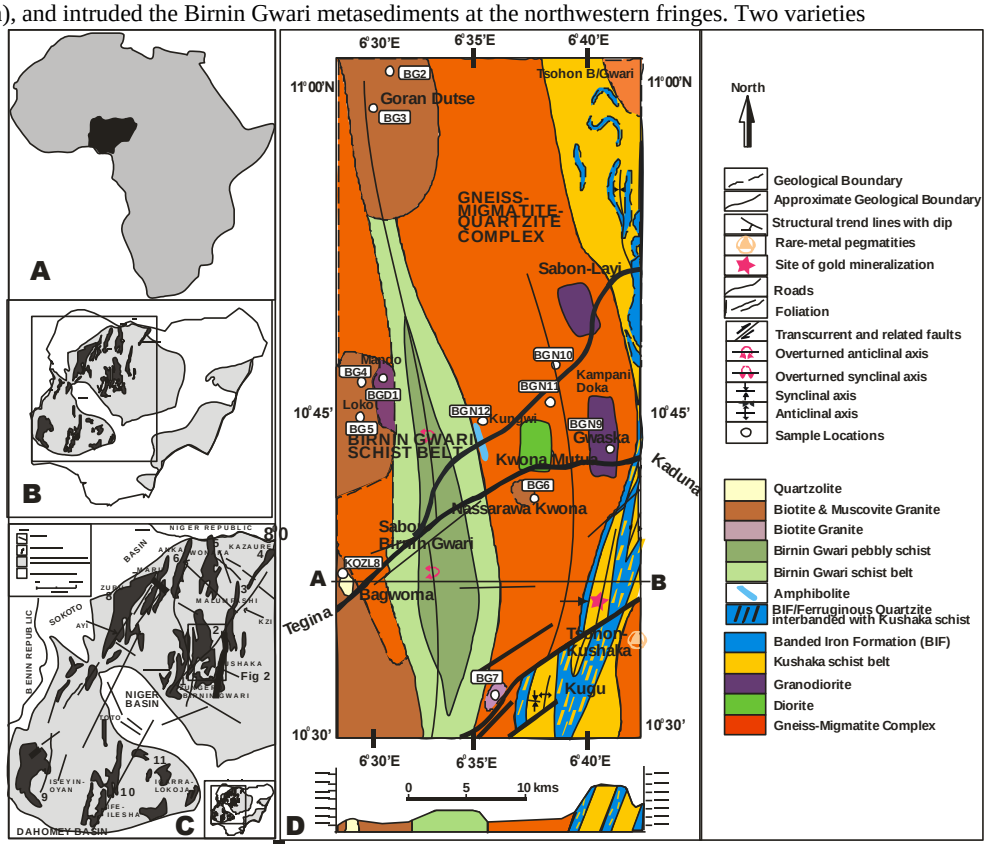


Fig. 1: Geological Map of Northern Part of Birnin Gwari Schist Belt (Sheet 122) Modified After Truswell and Cope, (1963).

are coarse porphyritic and fine- to medium grained equigranular types, occurring closely together and the latter as dykes and veins in the former. The coarse porphyritic types in hand specimen shows grey to light pink feldspar porphyries of 2 – 12 mm in diameter. Mafic minerals are biotite and muscovite, weakly foliated and trending 220^0 NE-SW. Under microscope, these rocks show granitic texture formed by pink K-feldspar phenocryst in quartz and feldspar matrix and associated with flaky and needle-like brown biotite. The coarse porphyritic type occurs as hypidiomorphic rock in which felsic minerals constitutes more than 60%. Quartz forms about 35% and occurs as euhedral prismatic crystals filling the interstices of the orthoclase and stacked against each other. K-feldspar (40%) occurs as orthoclase and microcline with large phenocryst showing micro-perthitic texture and with cracks across the cross hatch twinning. Some of the orthoclase contains dense mass of fine mica and clay minerals as alteration and small tabular muscovite inclusions. The cracks in the feldspars are filled with tiny rounded quartz and fibrous biotite minerals as well as opaque magnetite.

Table 1: Age Data on Some Granite and Migmatite Gneiss Host in the Nigerian Basement Complex

Lithology	Geologic Age	Method	Epoch	Event/Author
Southwest				
Akure gneissic Charnockite	634 Ma	U-Pb age	Pan-African	Metamorphism Tunbosun et al. (1984)
Ikare massive Charnockite	634 Ma	U-Pb age	Pan-African	Intrusion Tunbosun et al.(1984)
Idanre massive charnokite	593Ma	U-Pb	Pan-African	Intrusion Tunbosun et al.(1984)
Northwest				
Kazaure Older Granite	592 + 14	Rb-Sr age	Pan-African	Intrusion Danbatta (2002)
Minna Granodiorite	505 + 12	Rb-Sr	Pan-African	Intrusion Ajibade (2008)

Badiko syntectonic diorite	623Ma	U-Pb	Pan-African	Dada et al. (1993)
Minna Granodiorite	790 – 760 Ma	U-Pb zircon	Pan-African	Goodenough et al., 2014
Southeast				
Granodiorite in banded gneiss from Oban massif (Uwet)	616.9 + 1 Ma	Pb-Pb single zircon evaporation	Pan-African	Intrusion Ekweme and Kroner (1998)
Granite from Mkar Gboko	547 + 33 Ma	Rb-Sr whole rock isochron	Pan-African	Intrusion Umeji and Caen-Vachette (1984)
Northeast				
Toro Bauchite (Quartz fayalite monzonite)	638 Ma	U-Pb age	Pan-African	Dada et al., (1989)
Amp-bi-granite from Soli Hill and Rahama	598 + 11 Ma and 577 + 16 Ma	Pb-Pb single zircon evaporation	Pan-African	Intrusion Ferre et al., (1998)
Metadiorite from Toro	623 + 20 Ma	U-Pb zircon Upper intercept	Pan-African	Metemorphism Lar (1988)
North-central				
Biotite granite from Nassarawa Eggon	539 + 8 Ma	Rb-Sr biotite age	Pan-African	Intrusion Umeji and Caen-Vachette (1984)
Panyam granite	692 + 161 Ma	Rb-Sr isochron age	Pan-African	Van Breemen et al. (1977)
Panyam granite	605 + 10 Ma	U-Pb zircon age	Pan-African	Van Breemen et al. (1977)
Migmatite/Granitic Gneiss				
Kaduna granodiorite gneiss	3.46Ga	U-Pb	Pre-Pan-African Archean	Bruguier et al. (1994)
Kaduna early gneiss	3.1Ga	U-Pb, Rb-Sr	Pre-Pan-African Archean	Dada (1989). Bruguier et al. (1994)
Ife-Ilesha granite gneiss	1.12Ga	Rb-Sr	Pre-Pan-African Eburnean	Grant et al., 1972
Kusheriki banded gneiss	1.2 & 1.3Ga	Rb-Sr	Pre-Pan-African Eburnean	Grant et al., 1972
NW Kaduna migmatite	1.15Ga	Rb-Sr	Pre-Pan-African Kibaran	Grant et al., 1972
Sabon Gayam gneiss	1.2 & 0.7 Ga	Rb-Sr	Pre-Pan-African Kibaran	Grant, 1978

Other minerals are plagioclase (about 5%) occurring as simple twinned crystals. Biotite (about 15%) occurs as anhedral to subhedral needlike mineral, forming rims around the orthoclase and along the cracks with tiny rounded quartz (Plate I). Accessory minerals include magnetite, illmenite, titanite, zircon and apatite. Medium grained variety revealed that it is composed of quartz (35%), K-feldspar (30%), muscovite (15%), biotite (5%), plagioclase (5%) and iron-oxide (5%). Quartz occur as fine to medium euhedral and prismatic crystals closely wedge together showing undulose extinction. Orthoclase occurs as cracked phenocryst with quartz inclusions, dense clay minerals and fibrous muscovite. Phenocrysts of quartz and orthoclase looks like an “eye ball” set and stand out from muscovite groundmass. The acicular muscovites surrounding the phenocryst are strongly aligned in the foliation direction and shows blue, purple, yellow and brown interference colours. Biotite occurs as subhedral to euhedral crystals in the groundmass with magnetite and apatite as accessory minerals.

Granite in Mando and Loko border both the gneisses and Birnin Gwari metasediment. The contact zones with the metasediments are sharp with chilled margins as observed west of Mando village stretching for about 1 km. It is a fairly elevated granite outcrop (443m) in places dissected by River Ikanga. This is medium grained granite and observable minerals include pinkish to milky feldspars, silvery muscovite flakes, and black to brownish biotite, in places slightly weathered and brownish green muscovite (Fig. 2). The contact zone with Birnin Gwari staurolite quartz schist extends hundreds of meters and is characterized by granitic dyke intrusion with chilled margins. Two varieties are recognized in the field; the yellowish green and grey types, both containing pink feldspar, biotite and muscovite. Petrographically, quartz (30%) occur as subhedral phenocryst together with plagioclase (5%), orthoclase (20%) and microcline (20%), as well as medium grain euhedral crystals, closely interlocked with each other and with biotite (10%) and muscovite (10%) forming part of the groundmass. K-feldspar occurs as subhedral phenocryst of orthoclase and micro-perthite and as subhedral to euhedral medium grain crystals in the groundmass occurring with microcline and biotite. The orthoclase in few places shows faint albite twinning and sodic feldspars with typical cross hatch twinning and is surrounded by biotite phenocryst. This shows replacement with the evidenced vermicular growth in the K-feldspar (Fig. 2). Both biotite and white mica occur as fibrous and needle-like crystals, align in and squeezing themselves along the foliation plane. Accessory minerals include zircon, magnetite and apatite.

Granite in Nasarawa Kwona area form low lying outcrops, extending southward along Birnin Gwari – Kaduna road for about 2 km, and intersected by river Faleli and tributaries of Kogi Kusheriki. It is a medium grained, pink coloured rock. Macroscopic observation shows the pink feldspar dominating the grey colour quartz; dark colour biotite and muscovite minerals are visible. The dark biotite minerals marked by planar orientation in foliation direction $N170^0$ (Plate I). The exposure is characterized by quartz veins, fractures and joints cross cutting one another. The outcrop occurs close to extensive NE trending quartzite outcrop. Microscopically, pink K-feldspar phenocryst is in a fine cloudy quartz and feldspar matrix associated with lesser amount of mafic doted and flakey brown biotite (10%) and muscovite (5%) minerals (Fig. 2). Quartz occur as coarse to medium grained subhedral to euhedral prismatic crystals, tightly packed alongside each other, with undulose extinction, constituting 35% of the matrix. K-feldspar (35%) is mainly perthitic orthoclase and some tabular microcline with cross hatch, simple and Carlsbad twinning; one half of a simple twinned crystal shows Carlsbad twinning. Some of the K-feldspar and plagioclase crystals show impurities of dense clay minerals and often zoned. Plagioclase minerals are few (5%) coarse and tabular crystals with albite twinning (An_{30}). The doted anhedral biotite minerals fill the interstices of the orthoclase and quartz crystals. Iron-ore occur as assessory euhedral, subhedral to anhedral mineral dotted in the matrix making up 5% of the rock.

Granite outcrop in Kugu area is a low lying medium grain, weakly foliated rock, showing pink to reddish brown feldspars, grey quartz and dark biotite (Fig. 1). It consists of quartz (25%), K-feldspar (30%), plagioclase (25%), biotite (10%) and iron-ore (5%). Euhedral to

subhedral quartz crystals are welded together and show some fine and dense clay minerals inclusion but still with its characteristics undulose extinction. Plagioclase is euhedral with mica inclusions while biotite occurs as oriented subhedral crystals. Euhedral to subhedral K-feldspars are perthitic, in places masked with faint albite twinning and inclusion of dense mica minerals. Patches of K-feldspar show vermicular intergrowth with quartz.

Quartzolite is an isolated outcrop northwest of Bagwoma dam. It's a light coloured rock with grey, white, milky and reddish brown contrasting colours and coarse grain fibroblastic texture; with preferred mineral banding (360^0NS) of grey fibrous quartz, light brown to reddish brown biotite and hornblende. The exposure is also characterized by crenulation cleavages and well defined schistocity. Petrographically, the rock consists of quartz (60%), K-feldspar (10%), hornblende (15%), and biotite (10%) strongly aligned. Quartz is characterized by spherical and polygonal cracks and intergrowth, with acicular biotite sandwiched between it and K-feldspar. Observable alteration is seritization where K-feldspar is altered to an aggregate of finely divided white mica. Hornblende is anhedral, lathlike and elongated with pale brown & reddish brown crystals (Fig. 2). Biotite occurs as needle-like mineral stacked between the orthoclase polygons. Both hornblende & biotite are similar in occurrence, but the difference is the better cleavage in hornblende. Accessory minerals are opaque minerals as inclusions in the hornblende and plagioclase.

Porphyritic biotite granite in Gwaska occur as porphyritic leucosome that intruded the Gwaska paleosome, comprising mainly felsic minerals such as quartz (40%) and K-feldspar (40%), with biotite (15%) as ferromagnesian mineral. Quartz occurs as euhedral to subhedral medium crystals in between the feldspars and is characterized by myrmekitic intergrowth with orthoclase. K-feldspar subsolvus consisting of orthoclase (perthitic and micro-perthitic) and microcline with cross hatch twinning. The feldspars also contain dense mass of clay and mica minerals as alterations. Biotite crystals are anhedral, scattered in the matrix and along cracks in between the feldspars and enclosed in the orthoclase. Accessory minerals include apatite and magnetite.

5.1.3. Granite gneisses

The granite and migmatitic gneisses occur as prominent outcrops and as low lying whale back exposures along river channels in Kampani Doka and Kungwi areas respectively.

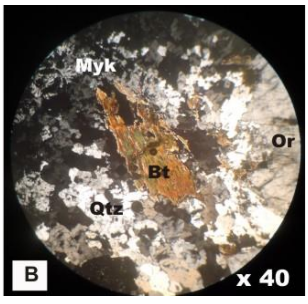
Kampani Doka granitic gneisses occur as prominent outcrop (about 520m high) is fine grained, weakly foliated equigrannular pink to reddish brown rock, being quarried for constructional material. Microscopically, it consists of quartz (30%), orthoclase (25%) muscovite (25%), iron-oxide (10%) and biotite (5%). Quartz forms clusters of polygonal and prismatic crystal intergrowth, and as groundmass with K-feldspars, muscovite iron-oxide and biotite. Muscovite minerals are anhedral but aligned along-side quartz intergrowth. Iron-oxide formed part of the groundmass and medium grain sizes clustered with and sometimes encircling the quartz crystals. Biotite also occurs as accessory along-side the doted iron-oxide. The low lying highly foliated Kampani Doka outcrop is found along the tributaries of Kusheriki river channel. In thin section the rock is composed of phenocryst of quartz (30%), K-feldspar (25%) biotite (25%) epidote (10%) and iron-ore (5%) set in groundmass comprising polygonal quartz, feldspar, biotite and iron-ore. Biotite occurs as platy elongated subhedral crystals dotted between the polygonal intergrowths of quartz crystals. Accessory minerals include zircon, apatite, titanite and magnetite.

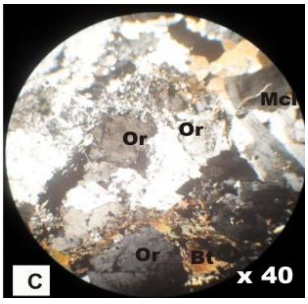
5.2. Geochemistry

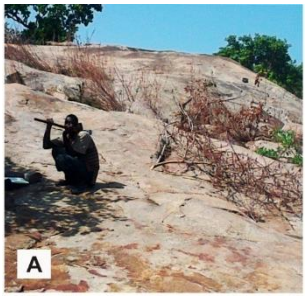
5.2.1. Rock classification

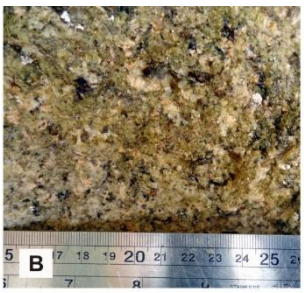
The rocks plot in the field of granite and granodiorites and quartzolite as on the nomenclature of (after Middlemost, 1979) (Fig. 4A and B) and show sub-alkaline affinity in agreement with petrographic characteristics (Fig. 4). The normative Ab-An-Or Feldspar triangle of O'Connor (1965) diagram also shows the rocks plot in granite and granodiorite field; here, granites and weakly foliated biotite granite gneiss (BGn10) straddle between granite and granodiorite field (Fig. 4B). The granodiorite may have resulted from close relationships with and reaction

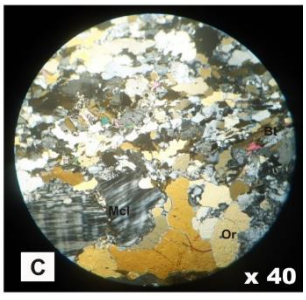












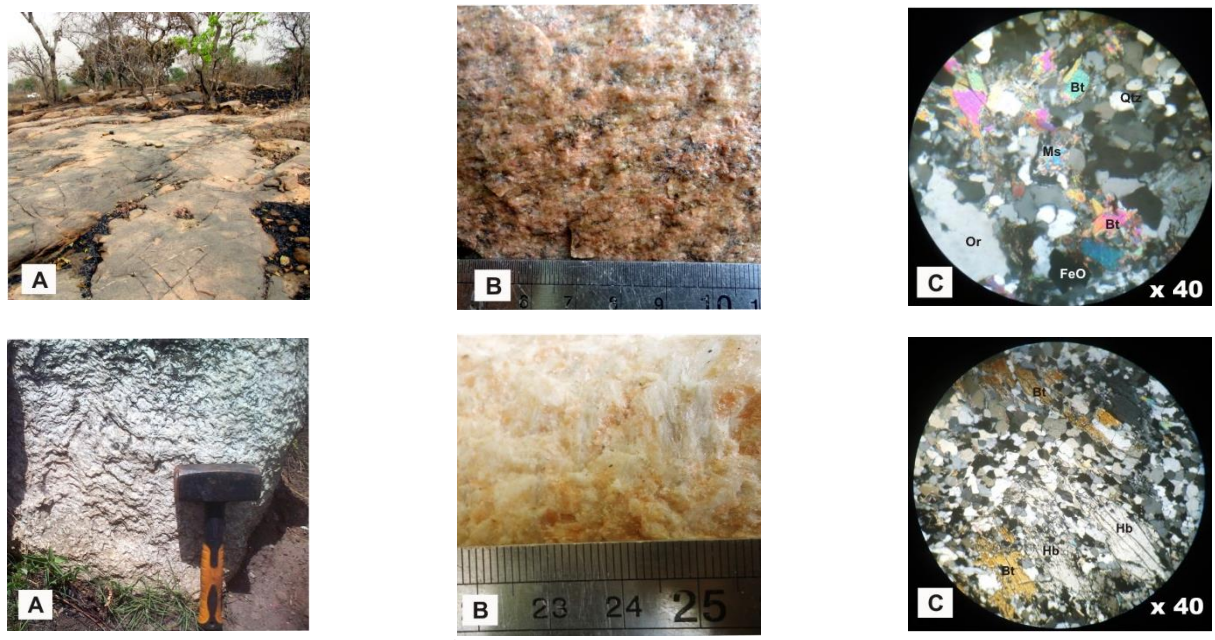


Fig. 2: Outcrops, Hand Specimen and Photomicrograph of Gworon Dutse Biotite Granite; Mando Biotite-Muscovite Granite; Nassarawa Kwona Biotite-White Mica Granite and Bagwoma Quartzolite in the Birnin Gwari Schist Belt.

Table 2: Modal Composition of Granite in the Birnin Gwari Schist Belt

Samples	BGD1	BG2	BG3	BG4	BG5	BG6	BG7	QZL8	BGn9	BGn10	BGn11
Quartz	30	35	35	30	30	35	25	60	40	30	30
Plagioclase	15	5	5	5	5	5	25				
Microcline		20		20	30	15			20		
Orthoclase	30	20	30	20	20	20	30	10	20	25	25
Hornblende								15			
Biotite	15		10	10	10	15	10	10	15	5	25
Muscovite			15	10	10	5				25	
Epidote											10
Iron-oxide	5	5					5			5	5
Accessory	5	5	5	5	5	5	5	5	5	5	5
Total	100	100	100	100	100	100	100	100	100	100	100

LEGEND: BGD1=Birnin Gwari/Mando Biotite Granodiorite. BG2=Goron Dutse coarse porphyritic biotite granite. BG3= Goron Dutse medium grained biotite-muscovite granite. BG4=Mando biotite-muscovite granite. BG5= Mando/Loko biotite-muscovite granite. BG6=Nassarawa Kwona biotite-muscovite granite. BG7=Kugu Biotite Granite. BG8=Bagwoma quartzolite. BG9=Gwaska leucosome (Biotite Granite). BGn10= Kampani Doka biotite-muscovite granite gneiss. BGn11=Kampani Doka biotite granite gneiss. BGn12=Kungwi migmatitic gneiss.

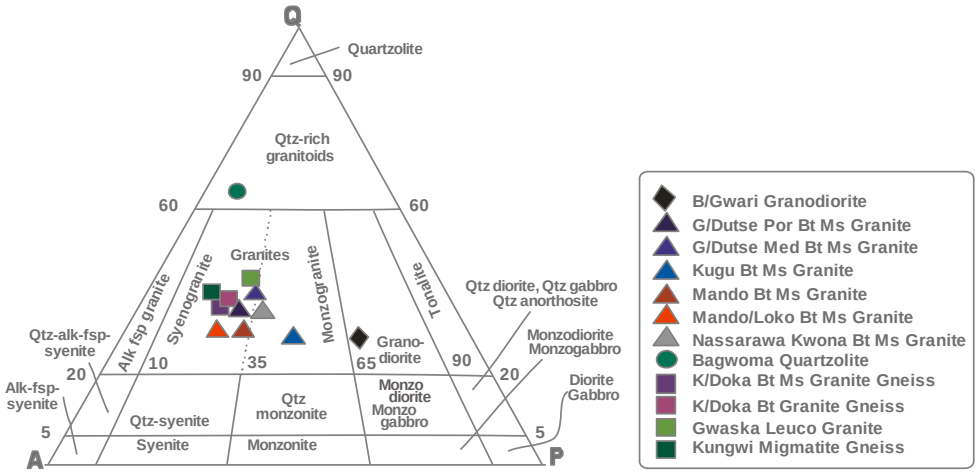


Fig. 3: Modal Classification Diagrams of the Granite in the Birnin Gwari Schist Belt (After Streckeisen, 1976).

between Birnin Gwari schist and Mando biotite-white mica granite, a phenomenon that may be attributed to the mobility of Na and K during hydrothermal alteration (Fig. 1).

5.2.2. Major element characteristics

Birnin Gwari Granitoids exhibits wide range of silica contents (65.24 – 82.42 wt %); granodiorite (65.24 wt %), granite (70.15 – 76.73 wt %) and quartzolite (82.42 wt %). Granites are generally depleted in TiO_2 (0.2 to 0.41 %), Fe_2O_3 (0.36 to 2.41 %), MgO (0.1 to 0.86 %) and CaO (0.04 to 1.94 %) compared to granodiorites with TiO_2 (0.82 %), Fe_2O_3 (5.13 %), MgO (2.31 %) and CaO (3.06 %) (Table

3). The major element composition of the granites, granodiorite and quartzolite as well as granite gneiss plotted on Harker diagram using SiO_2 as an index of differentiation show that TiO_2, Fe_2O_3, MgO, CaO and P_2O_5 are all negatively correlated with SiO_2, generally forming a well-defined linear trend. Al_2O_3 content on the average is high in granodiorite, granite and quartzolite (12.86 – 15.99 wt %). Al_2O_3 and Na_2O shows

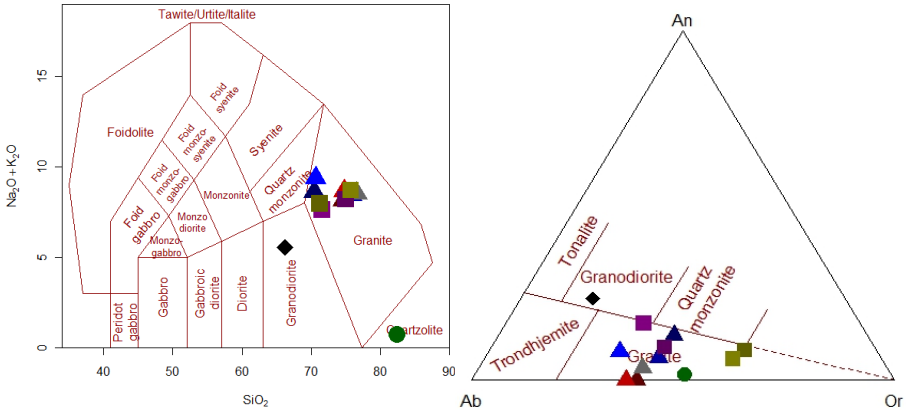


Fig. 4: (A): (A) SiO_2 Vs $Na_2O + K_2O$ Versus Diagram (Middlemost, 1985) With Nomenclature of the Granite As Granites, Grandorites and Quartzolite, Distinguishing Them As Subalkaline Magmatic Series (After Cox et al., 1979) and (B) Normative An-Ab-Or Diagram Showing the Distribution of the Rocks in Granitic to Granodioritic Field (After O'Connor, 1965) of Granite in the Northern Part of Birnin Gwari Schist Belt (Symbols As in Fig. 3).

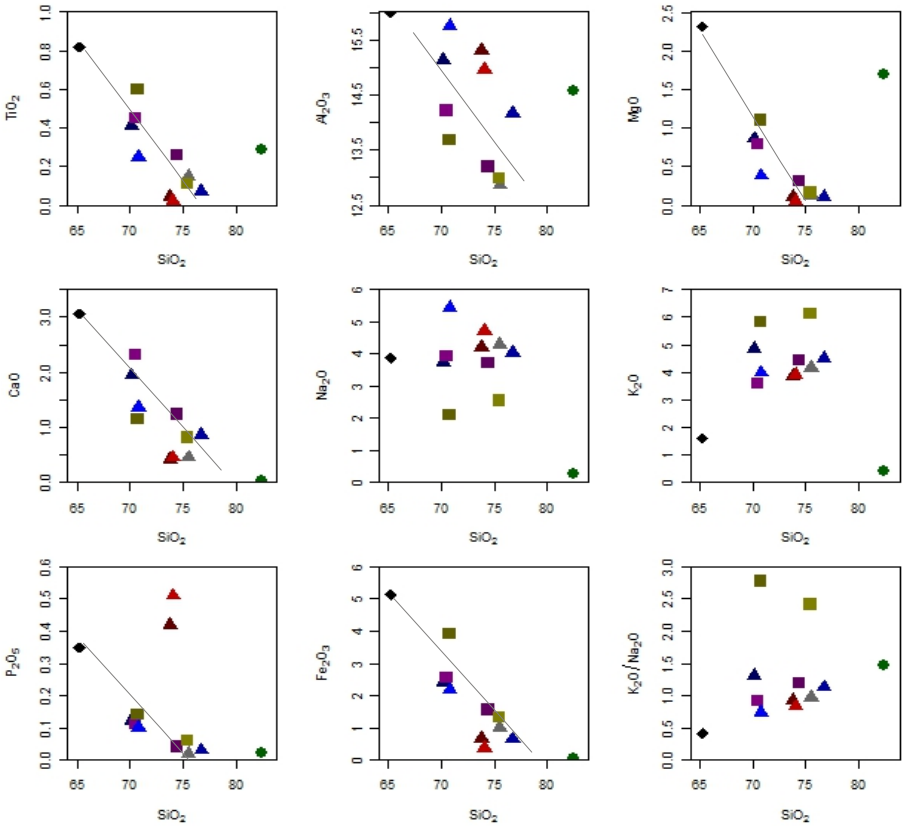


Fig. 5: Harker Variation Diagrams; Silica (SiO_2 Wt %) Plotted Against a Range of Major (in Wt %) Elements in the Granite of Birnin Gwari Schist Belt (Symbols as in Fig. 3).

Table 3: Major Elements (in Wt %) Abundance of Granite and the Host (Granite Gneiss) in the Northern Part of Birnin Gwari Schist Belt

Sample Name	BGD1 G/diorite	BG2 Granite	BG3	BG4	BG5	BG6	BG7	KQZL8 Quartzolite	BGN9 Host Granite Geiss	BGN10	BGN11	BGN12
SiO_2	65.24	70.15	76.73	73.76	74.06	75.5	70.79	82.42	75.44	74.42	70.49	70.74
TiO_2	0.82	0.41	0.07	0.04	0.02	0.15	0.25	0.29	0.11	0.26	0.45	0.6
Al_2O_3	15.99	15.12	14.16	15.3	14.95	12.86	15.74	14.57	12.99	13.2	14.21	13.68
Fe_2O_3	5.13	2.41	0.64	0.66	0.36	0.99	2.17	0.03	1.32	1.55	2.55	3.91
MnO	0.07	0.04	0.01	0.03	0.06	0.08	0.04	0.17	0.03	0.05	0.09	0.04
MgO	2.31	0.86	0.1	0.11	0.06	0.13	0.38	1.7	0.16	0.31	0.79	1.1
CaO	3.06	1.94	0.87	0.41	0.45	0.45	1.35	0.04	0.82	1.24	2.31	1.15
Na_2O	3.87	3.72	4.02	4.2	4.7	4.29	5.42	0.28	2.54	3.71	3.92	2.09
K_2O	1.6	4.86	4.52	3.87	3.89	4.14	3.98	0.41	6.13	4.42	3.6	5.81
P_2O_5	0.35	0.12	0.03	0.42	0.51	0.02	0.1	0.02	0.06	0.04	0.11	0.14
LOI	1.09	0.35	0.42	0.97	0.7	0.51	0.46	0.57	0.27	1.01	0.59	0.56
Total	99.53	99.98	101.5	99.77	99.76	99.12	100.6	100.5	99.87	100.21	100.21	99.82
K_2O/ Na_2O	0.41	1.30	1.12	0.92	0.82	0.96	0.73	1.46	2.41	1.19	0.91	2.77
Fe-number	0.68	0.73	0.98	0.85	0.85	0.88	0.85	0.01	0.89	0.83	0.76	0.78

Table 4: Trace Elements (in Ppm) Abundance of Granite and the Host (Granite Gneiss) in the Northern Part of Birnin Gwari Schist Belt

Sample Name	BGD1 G/diorite	BG2 Granite	BG3	BG4	BG5	BG6	BG7	KQZL8 Quarzolite	BGN9 Granite Geiss	BGN10	BGN11	BGN12
As	2.8	0.7	2.8	4.5	4.3	2.5	2.2	2.5	2.2	2.9	2.5	3.8
Ba	217.5	998	368.9	147.1	41.5	1183	1707	122	104.5	1445.5	1107.8	33.3
Ce	63.1	127.6	27.6	12	0	92.7	79	10.6	44.4	75.9	69.9	13.2
Co	40.9	44.4	49.9	60.5	47.4	102	42.4	55.8	56.7	67.7	48.7	2.4
Cr	89.2	28.5	8.4	6.9	5.8	3.3	13.7	6.8	7.8	3.7	7.4	10.6
Cu	27.7	14.8	5.4	8.7	5.6	4.8	7.1	3.3	6.4	13.7	5.1	209.9
Ga	17.5	21.6	20.7	20.6	16.9	12.7	20.7	2	13.7	11.4	14.3	3.3
La	31.9	77.5	13.7	1.9	0.5	157.2	46.9	<1	25.1	44.4	46.5	0.9
Mo	0.3	0	<1	0.3	0	0.5	<1	<1	0.1	0.3	0.1	<1
Nb	10.4	16.6	10.6	30.5	17.7	9.2	20.3	6.6	7.3	10.3	7.8	<1
Nd	31.9	40.8	11.6	6	0.8	88.7	23.6	6.5	19.4	23.8	31.1	10.5
Ni	29	8.3	0.9	1.5	0.9	1.4	2.7	<1	2	1.2	0.9	1.8
Pb	25.3	33.4	55.9	13.2	15.7	24.1	32.8	0.6	33.9	41.1	41	35.3
Rb	63.7	215.5	180.1	387.5	363	156.1	116	6.5	430.1	140.9	102.6	13.6
Sc	14.6	5.1	2.8	1.7	<1	3.7	3.7	1.8	4.7	1	7.4	<1
Sn	3.8	7.8	5.3	14.6	11.7	7.2	8.3	6.9	10	8.2	5.9	38.6
Sr	324.9	285.3	133.1	38.5	26.3	46.1	1298	8.2	33.4	143.4	230.7	131.2
Ta	<1	1.5	1	8.6	9.3	<1	0	<1	<1	<1	<1	<1
Th	6.6	17.1	8.6	1	0.4	20.6	12.7	1.2	19.9	21.7	14.8	<1
U	2.3	3.4	5.9	9.5	15.7	6.5	8.8	0.1	14.2	5	3.7	0.9
V	114.2	38.8	6.4	1.1	<1	3.8	17.9	6.2	6.7	10.1	20.7	2.6
W	172.5	252.9	293.8	337.3	349	570.4	234.1	341.8	394.8	367.4	254.8	<1
Y	45.3	27.4	9.4	6.1	4.5	60.5	16.4	13.9	41.9	21.5	31.6	3.6
Zn	65.8	45.9	16.1	38.6	21.8	21.4	67.8	0.5	18.8	29.6	54	43.3
Zr	160.9	150.6	64	30	22.4	144.1	219.5	135.3	57.3	175.4	166.4	28.2
Th/U	2.86	5.02	1.45	0.10	0.02	3.1	1.44	12	1.40	4.34	4	1.1
Rb/Sr	0.19	0.75	1.35	10.06	13.8	3.38	0.08	0.79	12.87	0.98	0.44	0.10

negative correlation but with scattered trend, while K_2O shows positive correlation (Table 2; Fig. 5). The contents of Na_2O (3.72 - 4.29 wt %) and K_2O (4.14 – 4.86 wt %) is high in granite except for granodiorite and quartzolite. K_2O/Na_2O ratio in granite is 0.41 – 1.30.

5.2.3. Trace element characteristics

The trace elements of the granitoids plotted on Harker diagram using SiO_2 as an index of differentiation show that Ba, Ce, Cr, La, Sr, Zr and Nb are negatively correlated with SiO_2 generally forming a well-defined linear trend while Rb, U, Th and Y are all negatively correlated, with slightly scattered trend (Fig. 6). The trace elements composition and ratios are presented in Table 4 and primitive mantle-normalized elements contents spider diagrams after Sun and McDonough (1989) are shown in Fig. 7. The normalized abundance patterns permit characterization of the rocks. Granites, granodiorite, quartzolite and granite gneisses show similar spider distribution patterns, but with some deviation; an implication of close genetic relationship but different source materials. Some samples of granite (BG2 and BG3) and granitic gneisses (BGn10 and BGn11) show enrichment of the large ion lithophile elements (LILE: Ba, Rb, K; radioelements Th and U and depletion of the high field strength elements (HFSE: Nb, Ce, P and Ti), while granodiorite (BGD1), granite (BG3, BG4 and BG5) and granitic gneiss samples (BGn9 and BGn12) are depleted in Rb, Ba and La (Fig. 6). Rb is fairly enriched in the granites (116 – 215.5 ppm) and granite gneiss (102 – 430 ppm), slightly depleted in granodiorite (63.7 ppm) and completely depleted in quartzolite (6.5 ppm) compared to the mean crustal average of 90 ppm. Ba content is variable in the rocks; varies in granite (as low as 41.5 and as high as 1707 ppm), granodiorites (217.5 ppm) and very high in granite gneiss (104.5 – 1107.8 ppm). Sr varies in granite (26.3 – 1298 ppm), and granite gneiss (33.4 – 230.7 ppm) and moderately high in granodiorite (324.9 ppm), showing negative correlation with increasing SiO_2; consistent with small plagioclase abundances of this rocks. The ratio Th/U is 0.02 - 1.45 in granite (exceptions are samples BG2 and BG7 with 5.02 and 12 respectively); 1.1 - 1.4 in granite gneiss (exceptions are samples BGn10 and BGn11 with 4.34 and 4 respectively); and 2.86 in granodiorite.

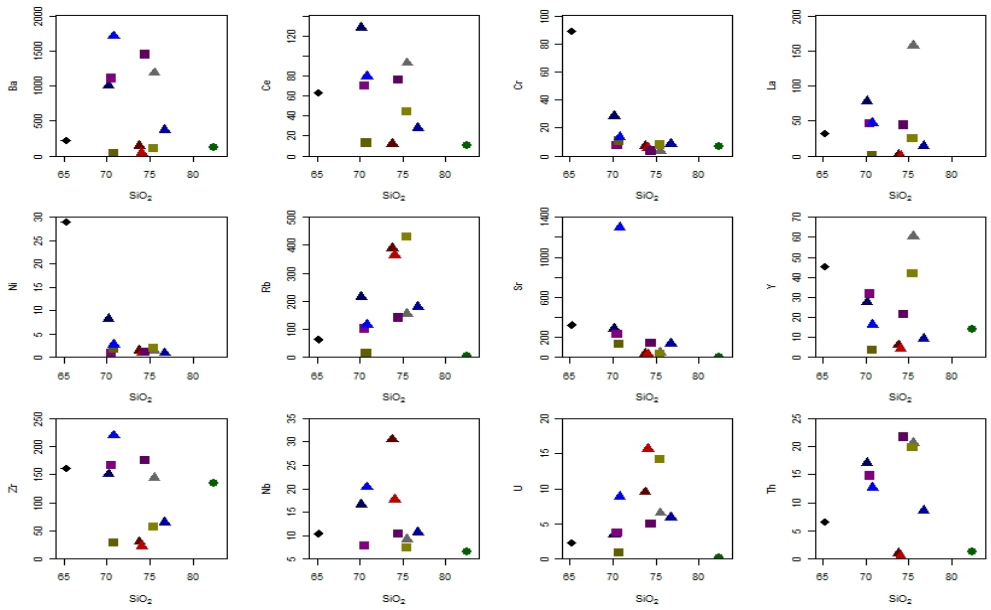


Fig. 6: Harker Variation Diagrams; Silica (SiO_2 Wt %) Plotted Against A Range of Trace (in Ppm) Elements in the Granite of Birnin Gwari Schist Belt (Symbols As in Fig. 3).

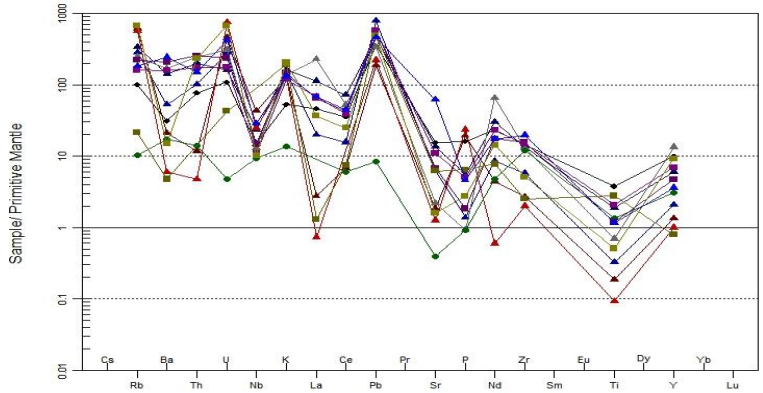


Fig. 7: Mantle-Normalized Multi-Element Diagram of Granite in the Northern Part of Birnin Gwari Schist Belt (Sun and Mcdonough, 1989) (Symbols as in Fig. 3).

5.2.4. Rare earth elements characteristics

Chondrite-normalized REE patterns (Boynton, 1984) are presented in Table 5 and Fig. 8. The Birnin Gwari granite show a Light Rare Earth Elements (LREE) enrichment relatively to Heavy Rare Earth Elements (HREE), low to high fractionation [$(La/Yb)N$ = 6.74 – 45.14] with pronounced negative Eu anomaly with Eu/Eu* values between 0.38 – 0.62. Granite sample (BG4) however exhibit near flat LREE and HREE trend with slight negative Eu anomaly (0.38).

Table 5: REE Data (Ppm) on the Granite in the Northern Part of Birnin Gwari Schist Belt

Sample	BG 2	BG 4
La	61.6	2.9
Ce	111.15	5.87
Pr	12.17	0.79
Nd	38.4	2.8
Sm	5.83	0.78
Eu	0.64	0.16
Gd	4.49	0.80
Tb	0.54	0.14
Dy	2.79	0.82
Ho	0.49	0.13
Er	1.25	0.33
Tm	0.17	0.05
Yb	0.92	0.29
Lu	0.12	0.04
∑REE	240.56	15.90
$(La/Yb)_N$	45.14	6.74
$(Ce/Yb)_N$	31.25	5.24
$(La/Sm)_N$	6.65	2.34
$(Ce/Sm)_N$	4.60	1.82
$(Eu /Yb)_N$	1.98	1.57
Eu/Eu*	0.38	0.62

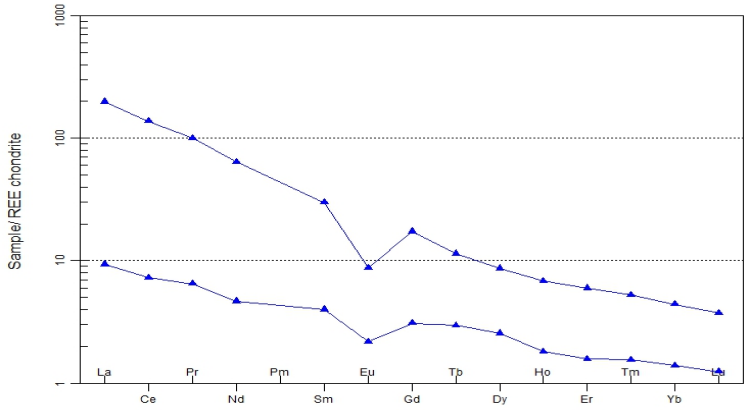


Fig. 8: Chondrite-Normalized Pattern for the Birnin Gwari Schist Belts Granite, Chondrite Normalization Values are from (Boynton, 1984) (Symbols as in Fig. 3).

5.2.5. Magma characterization

The magma types are illustrated by the AFM diagram of Irvine and Baragar (1971) and show calc-alkaline affinity with granite, granodiorite, quartzolite and the host granite gneiss clustering in the calc-alkaline field (Fig. 9). The SiO_2 vs Fe_2O_3/(Fe_2O_3+MgO); SiO_2 vs Na_2O+ K_2O-CaO and ASI vs A/NK diagram (after Frost et al, 2001) distinguish Birnin Gwari granite as magnesian with ferroan character, calc-calcic to alkali calcic and peraluminous (Fig. 10). The granites with higher Fe-number (0.73 - 0.89) are generally ferroan while the grandiorites and granite gneisses with low Fe-number (< 0.76) are magnesian (Table 4; Fig. 10A). The granites and granodiorites can be further classified into calc-alkalic - alkali-calcic and on the Modified Alkali-Lime Index (MALI) plot of Na_2O+ K_2O-CaO versus SiO_2 discrimination diagram (Frost et al., 2001) (Fig. 10B). The granites and granodiorites are peraluminous with the Al saturation index (ASI) ranging from 1.0 to 1.5. However, the Kampani Doka biotite and biotite-muscovite gneiss (BGn10 and BGn11) and the Kugu biotite granite (BG7) straddle between peraluminous and metaluminous (Fig. 10C). The alkali concentration discrimination diagram K_2O vs Na_2O in wt % and SiO_2 vs K_2O of Peccerillo and Taylor (1976) define granites as I-type and of high-K calc-alkaline; granodiorites as calc-alkaline and granite gneiss as shoshonite series, the exceptions being the S-type Gwaska leuco granite (BG10) and the Kungwi migmatite gneiss (BGn12) (Figs. 1 & 11A and B). Using the series of diagrams that employ Ga/Al and Y, Ce, Nb and Zr against various major elements ratios and Zn, Zr and Y, designed by Whalen et al., (1987) to discriminate A-type granites from I- and S-types (Fig. 12), granite in the Birnin Gwari schist belt plot in the field of I- and S- type or close to the boundary of the A-type granite. On the Sr- Rb-Ba ternary diagram after Tarney and Jones (1994) (Fig. 13A), the granitoids shows diverse trend towards high and low Ba-Sr as well as adakite granitoids. The Ba-Rb-Sr ternary diagram (after El Bouseily and El Sokkary, 1975) also shows wide distribution of the granites as "granodiorite and quartz diorite", "anomalous", "normal" and "strongly differentiated"; granodiorite as "diorite" and quartzolite as "normal" granite (Fig. 13B).

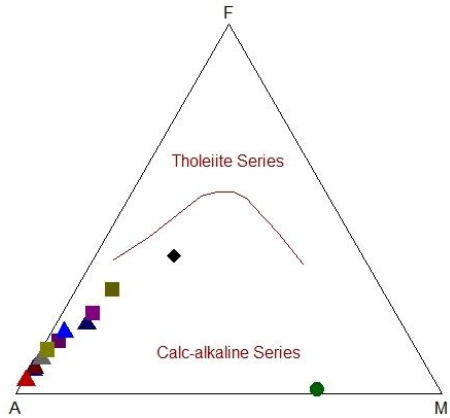


Fig. 9: AFM Diagram (After Irvine and Baragar, 1971) Discriminating Birnin Gwari Granite as Calc-Alkaline Series (Symbols as in Fig. 3).

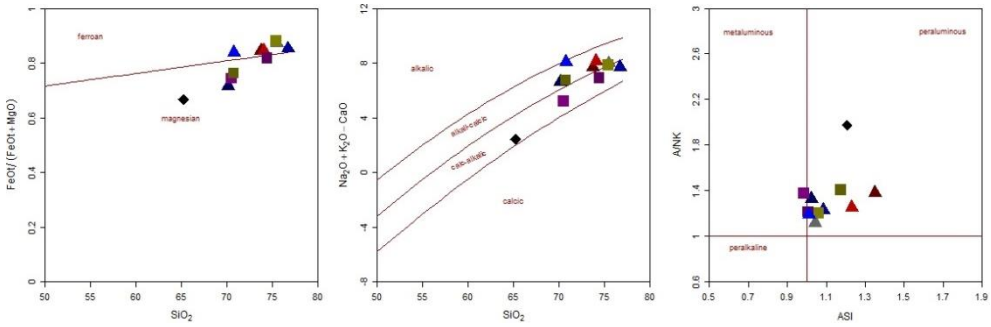


Fig. 10: (A) SiO_2 Vs Fe_2O_3/(Fe2O3+Mgo); (B) Sio_2 Vs Na_2O+ K_2O-Cao and (C) ASI vs. A/NK Diagram (After Frost et al, 2001) Discriminating the Birnin Gwari Granite as Mainly Magnesian, Alkali-Calcic to Alkali and Metaluminous (Symbols as in Fig. 3).

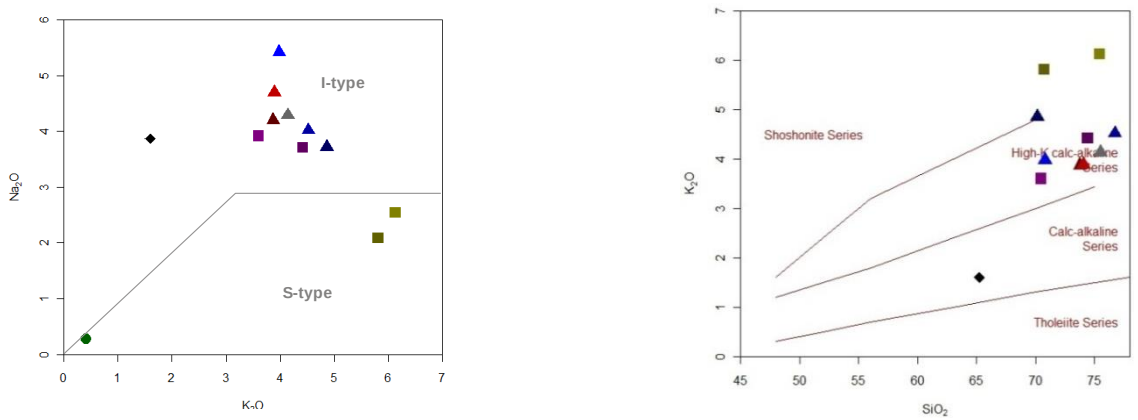


Fig. 11: (A) Alkali Concentration Discrimination Diagram (K_2O Vs Na_2O in Wt %) Defining the I-Type Nature of the Granite And (B) SiO_2 vs. K_2O After Peccerillo and Taylor (1976) Discriminating Granite as Calc-Alkaline, High-K Calc-Alkaline and Shoshonite Series in the Northern Part of the Birnin Gwari Schist Belt (Symbols as in Fig. 3).

5.2.6. Geotectonic setting

On the multicratonic R1-R2 diagram of Batchelor and Bowden (1985), the granite is dominantly of syn-collisional type (Fig. 14A). Also the Zr vs (Nb/Zr) $_N$ diagram of Thiéblemont and Tegyey (1994) with normalization values from Sun and McDonough (1989) delineate the tectonic setting of the granite as subduction-zone magmatic rocks (Fig. 14B). The Y+Nb vs Rb and Y vs Nb geotectonic discrimination diagram (after Pearce et al., 1984) shows granite plot in the volcanic arc and syn-collision granitoid fields (Fig. 15). The SiO_2 vs K_2O; SiO_2 vs $Fe_2O_3/(Fe_2O_3+MgO)$, M/AFM vs F/AFM and C/ACF vs F/ACF tectonic discrimination diagram of Maniar and Piccolli, (1989), plotted in fields of island arc (IAG), continental arc granite (CAG) and continental collision granite (CCG) (Fig. 16).

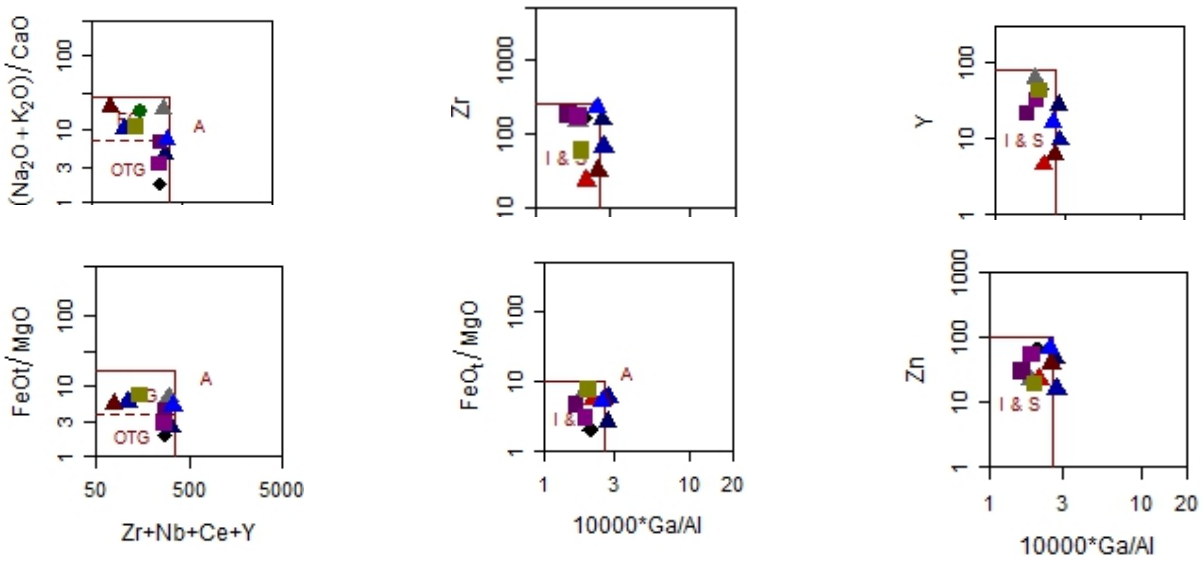


Fig. 12: Set of Binary Plots Zr+Nb+Ce+Y vs. Fe_2O_3/Mgo and (Na_2O+ K_2O)/Cao; 10000*Ga/Al vs. Fe_2O_3/Mgo and K_2O+Mgo; 10000*Ga/Al vs. Y and Ce Proposed by (Whalen et al., 1987) to Distinguish A-Type Granite From I- and S-Type (Major Elements in Wt % and Trace Elements and REE in Ppm) (Symbols as in Fig. 3).

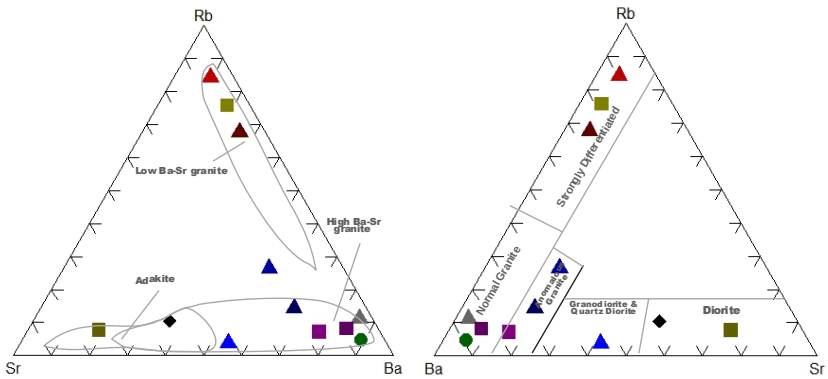


Fig. 13: Sr-Rb-Ba Ternary Diagram After Tarney and Jones (1994) Illustrating the High Ba-Sr Nature and Ba-Rb-Sr Ternary Diagram Showing the Distribution of the Granites and the Granodiorite (After El Bouseily and El Sokkary, 1975) of the Birnin Gwari Schist Belt Granite (Symbols as in Fig. 3).

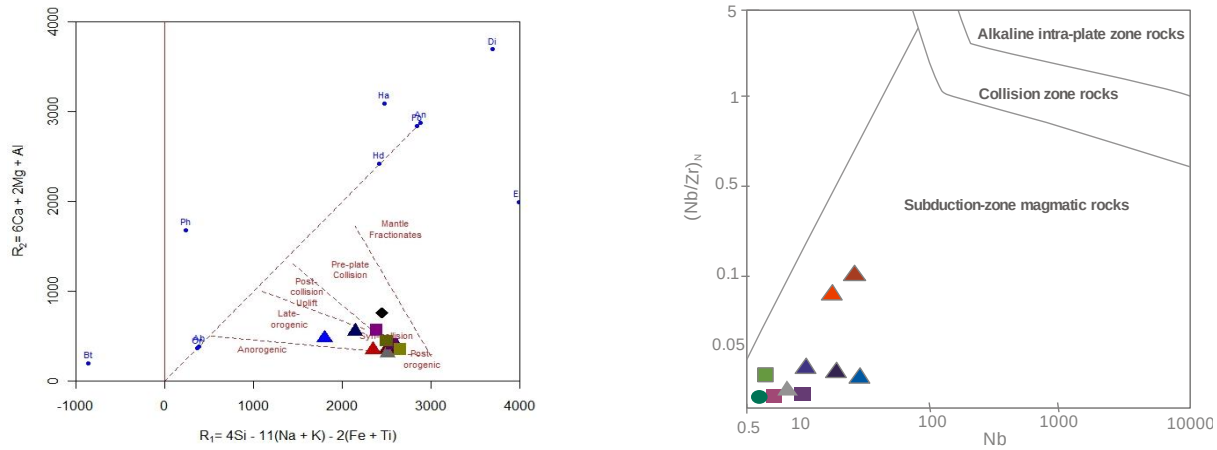


Fig. 14: R1 vs. R2 Diagram of (Batchelor and Bowden, 1985) [R_1=(4Si – 11(Na+K) – 2(Fe+Ti); R_2=(6Ca+2Mg) + Al)]. and Nb vs. $(Nb/Zr)_N$ Diagram of Thiéblemont and Tegyey (1994) [(in the Subduction-Zone Magmatic Rocks, Normalization Values from Sun and Mcdonough (1989)] to Delineate the Tectonic Setting of the Granite in the Northern Birnin Gwari Schist Belt. (Symbol as in Fig. 3)

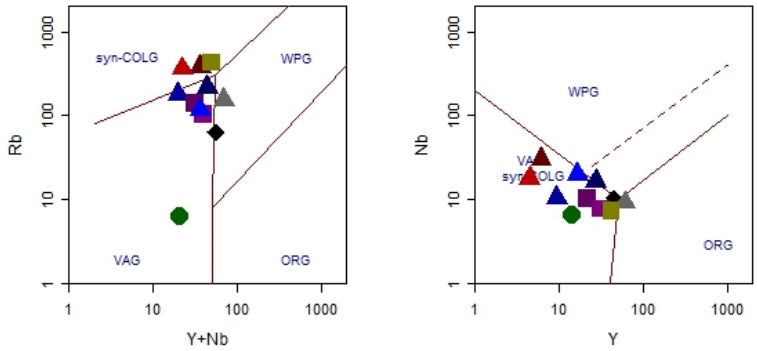


Fig. 15: (A) (Y+Nb) vs. Rb and (B) Y vs. Nb (In Ppm) Geotectonic Discrimination Diagram (After Pearce Et Al., 1984) Of Granite in the Northern Part of Birnin Gwari Schist Belt. ORG=Ocean Ridge Granites, Syn-COLG=Syn-Collisional Granites, VAG=Volcanic Arc Granites, WPG=Within Plate Granites (Symbol as in Fig. 3).

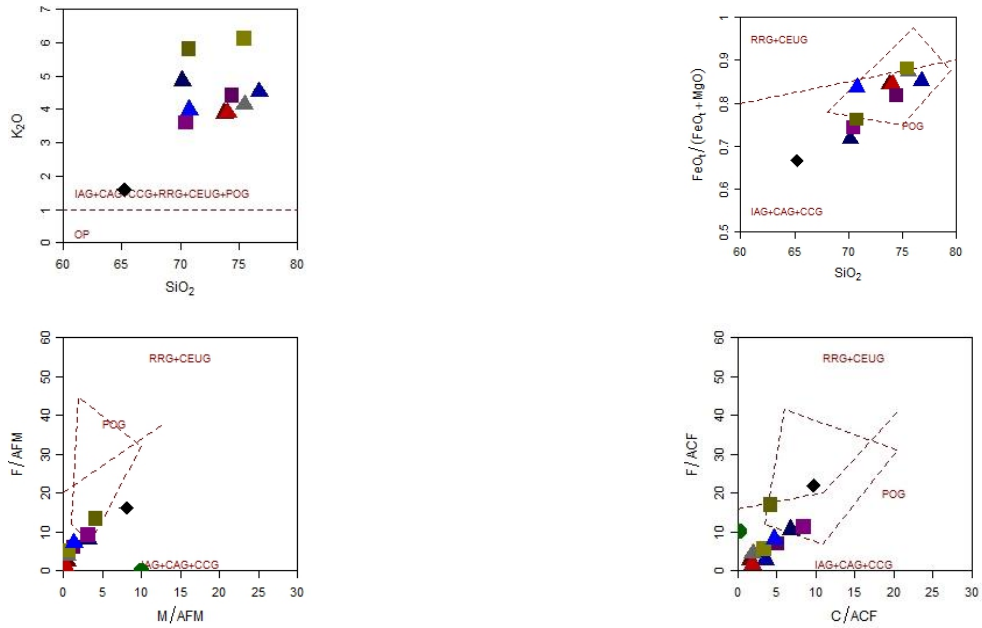


Fig. 16: Major Element Based Geotectonic Classification of Granite in the Northern Part of Birnin Gwari Schist Belt (A) SiO_2 vs. K_2O; (B) M/AFM vs. F/AFM; (C) SiO_2 vs. Fe_2O_3/(Fe_2O_3+Mgo); (D) C/ACF vs. F/ACF (Maniar and Piccoli, 1989). Field IAG=Island Arc Granitoids, CAG=Continental Arc Granitoids, CCG=Continental Collision Granitoids, CEUG=Continental Epeirogenic Uplift Granitoids, OP=Oceanic Plagiogranites (Symbols as in Fig. 3).

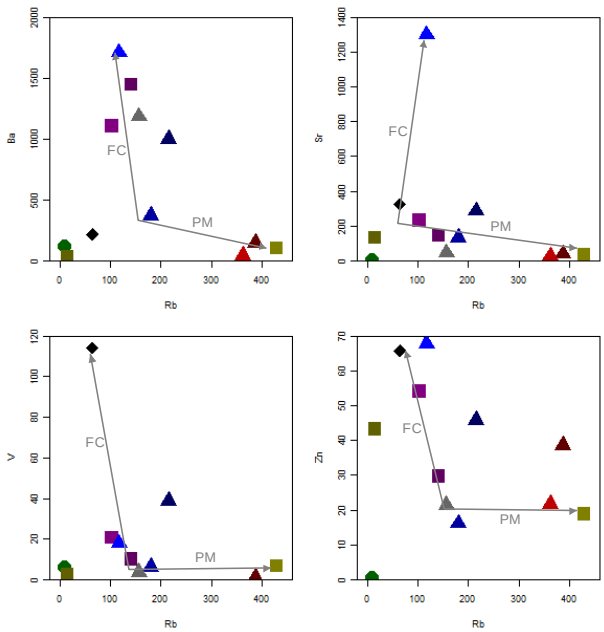


Fig. 17: Plot of Compatible Elements (Ba, Sr, V and Zn) Versus Incompatible Element (Rb) After Zorano et al. (2007) of Granite in the Northern Part of Birnin Gwari Schist Belt (Symbols as in Fig. 3).

6. Discussions

The Birnin Gwari mineral assemblage is quartz + K-feldspar + biotite + muscovite + plagioclase.

Wide variation in SiO_2 content in the Birnin Gwari granite, granodiorite and quartzolite is usually interpreted as fractional crystallization and is characteristic of I-type granite (Azevedo and Nolan, 1998); its well-defined linear trend might be the result of either hybridization or fractionation (Chappell and Stevens, 1988; Hassanen et al., 1996). The positive and negative correlation with increasing SiO_2 and the slightly scattered trend in K_2O, Na_2O and Al_2O_3 suggests different geological processes, such as mixing or even distinct effects that should be investigated (Rollinson, 1993).

The high content of Na_2O means that Na has not been removed from the source rocks (Chappell and White, 1992). Na_2O values of < 3 wt % in the quartzolite and two of the granite gneiss samples are characteristics of S- type granite while Na_2O with > 3 wt % in the granite and granodiorite are of I- type granite. Additionally, negative correlation of P_2O_5 with increasing SiO_2 and low K_2O/Na_2O ratios of granitoids in Birnin Gwari are characteristics of low-temperature I-type granites which may have resulted from fractional crystallization of and partial melting with pre-existing of peraluminous and calc-alkaline Birnin Gwari metasediments inherited from shale-greywacke and quartzose sedimentary protoliths derived from granodioritic and granite-quartz monzonite provenance (Oluyede et al., 2020b). Low temperature I-type granitoids are product of fractional crystallization of and partial melting with pre-existing heterogenous metapellitic-amphibolitic igneous protolith (Chappell et al., 1988; Sun and Chen, 1992, Robert and Clemens, 1993; Ajaji et al., 1998). The high K_2O content in granite (4.14 – 4.86 wt %) is due to presence of large quantities of K-feldspar; typically high K_2O, negative Nb and Ti anomaly reinforces the calc-alkaline character and is characteristic of subduction-related granites in continental margin settings (Whalen et al., 1996; Soesoo, 2000; Ferre et al., 1998; Grigoriev and Pshenichny, 1998, Rottura et al., 1998). High concentration of Large Ion Lithophile Elements (LILE) is an indication of adundance of silicate minerals such as amphibole, biotite and feldspars. The positive Pb anomaly is more pronounced in all the rock types owing to the decay of the high uranium content.

The varied ratio Th/U of 0.02 - 1.45 in some granite and 5.02 and 12 in others and granite gneiss and also 2.86 in granodiorite is an indication of contributions from crustal and mantle materials; rocks derived from the upper crust are characterized by ratio ≥4, whereas ratio <4 has been related to a mantle contribution (Cullers and Podkovyrov, 2002; Roddaz et al., 2006); rocks derived from the upper crust are characterized by ratio ≥4, whereas ratio <4 has been related to a mantle contribution (Cullers and Podkovyrov, 2002; Roddaz et al., 2006). Variation in content and behavior of lithophile elements (Ba, Sr and Rb) is very useful in magmatic evolution controlled dominantly by fractional crystallization, partial melting or more complex processes (Dall Agnol et al 1999). Sr- Rb-Ba and Ba-Rb-Sr ternary diagram revealed diverse granite trend such as high and low Ba-Sr granite (Tarney and Jones, 1994) “granodiorite and quartz diorite”; “normal”, “anomalous” and “strongly differentiated” granite (El Bouseily and El Sokkary, 1975). Strongly differentiated granites are those that are distinctly impoverished in Ba but enriched in Rb. They represent a very late stage of differentiation. “Anomalous granites” are those that have undergone chemical changes (e.g metasomatism) or were not formed by simple mechanism, while “normal granites” are those that are characterize by “normal” distribution of the three index lithophile elements (El Bouseily and El Sokkary 1975).

Birnin Gwari granitoids are also classified as subduction-zone magmatic rocks. For example “arc” magmatism are generated in convergent plate margins during active subduction of oceanic lithosphere, and is accompanied by the generation of basic to intermediate to acidic (basalt/tholeiite–andesite–dacite/rhyolite) plutonism and volcanism (Thiéblemont and Tegyey, 1994); this is supported by post-orogenic plot of Y+Nb vs Rb and Y vs Nb geotectonic discrimination diagram (after Pearce et al., 1984) where granite plot in the volcanic arc and syn-collision granitoid fields (Figs. 43 and 15). The trend and/or process of magmatic evolution of granitoids is seen from log of compatible element (Sr, Ba, Zn and V) versus log of incompatible element (Rb) plot (Fig. 17), where differentiated liquids produced by partial melting will show a sub- horizontal trend whereas fractional crystallization will give rise to a sub-vertical trend (Cocherie, 1986; Zorano et al., 2007). The granitoids may have been derived from fractional crystallization of dioritic and granodioritic mantle material and partial melting and variable mixing pre-existing heterogenous crustally derived peraluminous and calc-alkaline Birnin Gwari metasediments inherited from shale-greywacke and quartzose sedimentary protoliths derived from granodioritic and granite-quartz monzonite provenance. Fractional crystallization, in constrast to partial melting, is a very powerful process to impoverish magmatic liquid in compatible elements. The discrimination between the two mechanisms is based on the behaviour of these elements.

Consequently, it can be deduced that the mechanism of differentiation is fractional crystallization and partial melting of mantle materials and crustally derived metapellitic-amphibolitic igneous protolith in the Birnin Gwari schist belt (Sun and Chen, 1992, Robert and Clemens, 1993; Ajaji et al., 1998; Zorano et al., 2007).

The high-K calc-alkaline, calc-alkalic to alkali-calcic, magnesian to ferroan and peraluminous character of the Birnin Gwari granitoids make them similar to the Caledonian granitoids, otherwise variously known as high-K alkali-calcic granitoids, Post-orogenic granitoids, shoshonitic granitoids and K-rich calc-alkaline granitoids (Frost et al., 2001). A comparison of the geochemical characteristics of the granitic rocks in this study with those from other parts of Nigeria and the world (Table 6) reveal that they are very much similar to those of the Pan-African granitic rocks which occur in other schist belts in the SW, NW, SE and NE together with Jurassic (younger) Granites in the Northern Plateau areas (Obiora, 2012). Collision that resulted in the evolution of Birnin Gwari "subduction-zone magmatic rocks" took place under extensional and compressional regimes, and preceded by subduction of the lithosphere beneath an ancient oceanic crust at the eastern margin of the West African craton underneath the Tuareg shield (Obiora, 2006); this resulted in Eburnean and Pan-African deformations as well as Pan-African intrusion of calc-alkaline granites and volcanics (Danbatta, 2010) supported by the presence of basic to ultrabasic rocks such as extrusive basalt in the neighbouring Kushaka schist belt (Oluyede, 2020a) and calc-alkaline volcanics and hypabyssal rocks in the Anka schist belt (Agunleti et al., 2020) in the Nigerian sector. This has also resulted in characteristic ophiolitic complexes and a high positive gravity anomaly in a narrow zone within the Dahomeyide orogen, located at the southeastern margin of the West African Craton in Togo and Benin Republic (Schluter, 2005). Comparison of geochemical characteristics and ages of the Birnin Gwari granitoids with others Pan-African granitoids in different parts of Nigeria (notably in southwest, southeast, north-central, northwest, and northeast) revealed their similarities and their relation to the Pan-African granites also referred to as Older Granite. All the ages determined from the Pan-African granites showed consistency and correlates well (Table 1 & 6).

7. Conclusions

Petrographic and geochemical data have revealed three granitoids groups in the Biirnin Gwari granitoids: the biotite-hornblende granite and quartzolite (BHG), the biotite granite (BG) and the biotite ± muscovite granite (BMG), with plagioclase, hornblende and biotite fractionation playing an important role during continuous fractional crystallization process. They are high-K calc-alkaline and shoshonitic, calc-alkalic to alkali-calcic, peraluminus and magnesianto ferroan suite of granitoid rocks bearing similarities to the Caledonian granitoids. The granitoids shows diverse trend such as high and low Ba-Sr granite; "granodiorite and quartz diorite"; "normal", "anomalous" and "strongly differentiated" granite based on the behavior of their lithophile elements (Ba, Sr and Rb). The high K_2O (> 2.5 wt %) and Na_2O (>3.0 wt %) and low K_2O/Na_2O ratios have characterized them as I-type granites. Other geochemical features include LILE and radioelement enrichment (some granite samples show depletion of Rb and Ba), negative Nb, P and Ti anomaly and low to high fractionation factor $(La/Yb)_N$ (6.74 – 45.14) which reinforces the calc-alkaline character and geochemical indication of subduction-zone magmatic rocks derived from fractional crystallization of dioritic mantle material and partial melting and variable mixing pre-existing heterogenous crustally derived peraluminous and calc-alkaline Birnin Gwari metasediments inherited from shale-greywacke and quartzose sedimentary protoliths derived from granodioritic and granite-quartz monzonite provenance in syn-collisional orogenic setting during the Pan-African Orogeny.

Table 6: Comparison of Geochemical Characteristics of the Granitic Rocks in Birnin Gwari Schist Belt with Those in other Parts of Nigeria and the World

Geochemical Characteristics	NW Nigeria (1)	NE Nigeria (2)	North Central Nigeria (3a)	(3b)	SE Nigeria (4) (4a)	(4b)	SW Nigeria (5)	Cameroon & Adamawa Massif (6)	Sudan (7)	Poland (8)	NE Turkey (9)	This Study Birnin Gwari
SiO2 wt %	63.5-70.4	62.72-75.09	71.34-73.96	66.61-86.89	63.47-70.91	65.4-69.89	64.17-77.19	64.75-76.27	57.66-72.06	60-76	53 - 85	65.24–82.42
Na_2O – K_2O vs SiO_2	Calc alkaline	Transalkaline to non-alkaline	NA	NA	Calc-alkaline	Calc-alkaline	Calc-alkaline	Calc-alkaline	Calc-alkaline	Alkaline to sub-alkaline	Calc-alkaline	Calc-alkaline
K_2O vs. SiO_2	NA	High K Calc-alkaline	NA	NA	FeO enriched	High K Calc-alkaline, Transalkaline, Non-alkaline	High K Calc-alkaline	High K Calc-alkaline	High K Calc-alkaline	High K Calc-alkaline to shoshonite	Medium to High K Calc-alkaline	High K calc-alkaline
Fe - number	Magnesian	Ferriferous to High Ferriferous	Magnesian	Magnesian	Magnesian	Ferroan	Ferroan	Ferroan & Magnesian	Ferroan & Magnesian	Femic	NA	Ferroan & Magnesian
MALI	Alkalic-calcic	NA	Alkalic - Calcic	Calcic – Alkalic	Alkalic – Calcic to Calcic Alkali	Alkalic – Calcic to Alkali	Alkalic – Calcic to Calcic Alkali	Calcic – Alkalic	Calcic - Alkalic	Alkalic - Calcic	NA	Calc-Alkali to alkali-calcic
ASI	Metaluminous & peralkaline for syenite	Met aluminous	Per-aluminous	NA	Per aluminous	Met aluminous	Met Aluminous	Met aluminous	Met aluminous	NA	Met aluminous	Per aluminous
Eu	NA	Moderate	Pronou	NA	NA	Pronounc		Pronou	Modera	NA	--	Weak

anomaly	Eu anomaly	nce Eu anomaly	e Eu anomaly	nce Eu anomaly	te Eu anomaly	to modera te Eu anomaly

Explanation: No 1: Olanrewaju and Rahaman (1982); Egbuniwe et al., (1985); 2: Rahaman et al., (1998); 3a: Onyegocha (1986); 3b: Obiora and Ukaegbu (2007); 4a:Rahaman et al., (1988); 4b: Obiora, (2012); 5: Okonkwo and Winchester, 2004; 6: Haruna, (2014); 7: Lissan & Bakheit, (2011); 8: Baginski et al., (2007); Karacic et al., (2008). 3a and b were computed by Obiora and Ukaegbu, (2009).

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