GEOLOGY, GEOCHEMISTRY AND PETROGENESIS OF BIRNIN KUDU YOUNGER GRANITE COMPLEX, NW NIGERIA

BY

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DECLARATION

I, ABUBAKAR Usman, with registration number P13SCGL8046 hereby declare that the work in this dissertation entitled **"Geology, Geochemistry and Petrogenesis of Birnin Kudu Younger Granite Complex, Northwestern Nigeria"** has been carried out by me in the Department of Geology, Ahmadu Bello University, Zaria. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at this or any other institution.

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CERTIFICATION

This work entitled **"Geology, Geochemistry and Petrogenesis of the Birnin Kudu Younger Granite Complex, Northwestern Nigeria"** by ABUBAKAR Usman meets the regulations governing the award of the degree of Masters of Science in Geology (Mineral Exploration) of Ahmadu Bello University, Zaria and is approved for its contribution to knowledge and the literary presentation.

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DEDICATION

This work is dedicated to the almighty Allah, the supreme and majestic, and for the benefit of humanity.

ACKNOWLEDGEMENT

I am most grateful to almighty Allah for whom I owe my life, breath, existence, survival, sustenance, providence and my being for granting me the courage, strength and wisdom for carrying out this research.

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ABSTRACT

The distinctive petrological, mineralogical and geochemical features of theBirnin Kudu Complex are of great economic values which makes them attractive targets for petrological research. The study area lies between latitude 11^{0}24'56" and 11^{0}27'30" N, longitude 9^{0}26'30" and 9^{0}30'46" E was mapped in detail and a geological map produced on a scale of 1:25, 000. The rocks in the study area are post-orogenic granite emplaced within plate.Fifteen rock samples were used for both petrographic and geochemical analyses. Petrographic and field studies revealed that the area is underlain by three major rock types namely: granophyre (35%), rhyolite (40%) and crystal-rich ignimbrite (25%)all of which are surrounded by hornblende biotite granite. Petrographic studies revealed that quartz and K-feldspars are the dominant constituent minerals of these rocks. The rocks of the Birnin Kudu Complex are relatively enriched in LREE and depleted in HREE. Furthermore, the REE patternsexhibit prominent negative Eu-anomaly.The constituent rocks of the Birnin Kudu Complex are metaluminous, which is a characteristic feature of A-type granites. Discrimination on the basis of Fe-index indicates that the rocks are ferroan, with typical A-type signatures.The rhyolites can be interpreted to be derived from magma sourced from the enriched mantle, this enrichment may have occurred during an earlier period of subduction. The granophyres and the crystal-rich ignimbrites were interpreted to be derived from the interaction of earlier derived magma with the crust, leading to the continental margin trace element signatures.

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CHAPTER ONE

GENERAL INTRODUCTION

1.1 BACKGROUND

Petrogenetic studies of igneous rocks generally involvescharacterisation of the source regions of the magmas, determination of the conditions of partial melting and subsequent modification of primary mantle derived magmas during transport, and storage at high levels (Wilson,2007). Such studies must be based on sound field observations, involving careful mapping and a comprehensive knowledge of the petrography, major, minor and trace elements and radiogenic and stable isotope geochemistry of the rock units (Wilson, 2007). Geochemistry is a very important tool used for petrogenetic studies.

Geochemistry utilizes the principles of chemistry to explain the mechanism regulating the working past and present,of major geologic systems such as Earth's mantle, its crust, ocean and atmosphere. Geochemistry has made significant contribution to the understanding of many terrestrial and planetary processes such as mantle convection, the formation of planets, the origin of granite and basalts, sedimentation changes in the oceans and climates, origin of mineral deposits etc. (Albarede, 2003).

Geochemistry of rocks can also be used to determine their provenances and to identify the various geologic processes to which different rock suites have been subjected. All these can be achieved with the aid of major and trace elements (Rollinson, 1993).

Rare earth elements (REEs) are very useful for petrogenetic interpretations because they preserve the chemistry of the parent material from which they are derived. The degree of enrichment for a particular REE relative to chondritic abundances is a function of the initial concentration of that element in the source and the degree of partial melting, and subsequent fractional crystallization (White, 2005).

The Birnin Kudu Complex is divided into two parts; a N-S trending curve of isolated exposures of pink, altered granite porphyry and an E-W line of volcanic hills rising up to 100 m above the surrounding plains, (Bennett *et al.*, 1984).

1.2 STATEMENT OF RESEARCH PROBLEM

The petrogenesisand nature of A-type granite is an active research area, globally. The distinctive petrological, mineralogical and geochemical features and great economic importance of these granites continue to make them attractive targets for petrological research (Collins *et al.*, 1982).

Out of the 52 complexes documented in the Nigerian Younger Granite Province, there are complexes that have not been mapped in sufficient detail to allow for petrogeneticcharacterisation (Bennett*et al.*, 1984, Kinnaird, 1985).

1.3 LOCATION AND ACCESSIBILITY

The study area is located in the northwestern part of Nigeria.It lies within Birnin Kudu sheet 105 NE and Gwaramsheet 106 NW, between latitude 11^{0}24'56" and 11^{0}27'30" N, longitude 9^{0}26'30" and 9^{0}30'46" E.It is accessible through a major road from the state capital (Dutse), and also through another major road from Gwaram in Jigawa state and Misau in Bauchi state. Several other minor roads and footpaths exist, linking some other minor settlements.

1.4 CLIMATE AND VEGETATION

The climate of the studied area is characterised by alternate dry and rainy seasons with their commencement periods, usually around October to April and May to September respectively. The dry season is usually cold with low temperature especially at night while the rainy season is characterised by relatively high temperature. Birnin Kudu has a tropical climate. In the dry season, there is much less rainfall than in rainy season. According to (Köppen and Geiger, 2006),this climate is classified as Aw. The annual temperature here averages 26.4 °C. Annual rainfall is in the range of 500 to 800 mm. Most precipitation falls in August.

The studied area falls within the Sudan Savannah where the vegetation is generally sparse, characterised by shrubs, grasses and fairly tall trees. The majorityof trees found are date palms (Phoenix dactylyfera) and mango (Mangiferaindica) trees.

1.5 RELIEF AND DRAINAGE

The northeast, northwest and southwestern parts of the studied area are basically flat-lying while the southeastern part and part of the northeastern area are essentially elevated due to the concentration of outcrops.

The highest elevation inthe studied area is 457 m above sea levelin the northeastern to southeastern parts and the lowest is 427 m in the southwestern part. The area is drained by seasonal streams and rivers. River Dogwalois the main river in this area. During the period of this study, the streams were dry. Their pattern is however dendritic, with tributaries.

1.6 PEOPLE AND LAND USE

The studied area is sparsely populated with majority of this population being Hausas, with some Fulanis.

The main occupation of the people in the area is agriculture in the form of staple crop farming and cattle rearing. Animals reared here include; cow, goats and sheep, while crops grown here include; maize, guava, cashew, date and groundnuts.

Farming activities in the studied area is not restricted to rain-fed farming as the presence of a dam referred to as Dogwalodam (by the locals), which take its source from river Dogwalo allows for a certain level of irrigation farming.

1.7 SCOPE OF PRESENT WORK

This study examined the geology, geochemistry and as well the origin of the Birnin Kudu Complex. In as much as the map of the study area covers a total area of 770 Km^2, the research gave preference to the Birnin Kudu Complex alone, with little consideration to the surrounding basement rocks.

1.8 AIM AND OBJECTIVES

The aim of this research work is to investigate the petrogenesis and nature of the magma from which the Birnin Kudu Complex was formed, this was achieved through the following;

(i) Produce geological map at a scale of 1:25,000.

(ii) Generate major oxides and trace elements including the rare earth elements data on the various constituent rocks of the Birnin Kudu Complex.

(iii) Undertake petrographic description of the various rock units that make up the Birnin Kudu Complex.

(iv) Constrain the tectonic setting and environment of magma generation.

(v) Assess the economic mineralization potentials of the Birnin Kudu Complex.

1.9 JUSTIFICATION

Based on the available information, (Bennett *et al*, 1984, Kinnard*et al*, 1984) there is no detail study devoted solely to determination of the petrogenesis of the Birnin Kudu Complex. The only detailed work published on the area is on speleological studies by (Szentes, 2008).

Apart from the fact that only limited information about individual complexes are available, there is no general consensus about the petrogenesis of Younger Granites Province as a whole. This situation argues for accumulation of comprehensive geochemical data which will aid the detailed study of the Birnin Kudu Complex.

CHAPTER TWO

LITERATURE REVIEW

2.1 BACKGROUND

Nigeria lies west of the West African Craton in the region of the late Precambrian to early Paleozoic Orogenesis (Olusiji, 2013). The geology of Nigeria is dominated by crystalline and sedimentary rocks both occurring approximately in equal proportions (Woakes*et al*., 1987).

2.2 PREAMBLE

The geology of Nigeria is made up of three geological components (Wrights, 1985)

i Crystalline Basement Complex rocks (Pan-African and older).

ii Alkaline Ring Complexes : Jurassic (200-145 million years).

iii Tertiaryvolcanics.

iv Sedimentary, Cretaceous to Recent mostly clastic rocks.

This review will lay more emphasis on the Alkaline Ring Complexes.

2.2.1 Alkaline Ring Complexes (Younger Granite Complexes)

In Nigeria and Niger, over 80 anorogenic centers representing the eroded roots of volcanoes form an extensive chain of syenite-granite ring complexes extending for about 1,300 km (Bowden and Turner, 1974). In Nigeria, the Jos Plateau have received more attention due to its economic potentials. The province decreases in age from Ordovician in northern Niger to late Jurassic in central Nigeria (Karche and Varchette, 1976;Karche, 1978).

Two distinct groups of granite, which differ considerably in age, structure, mineralogy, chemistry and origin have been recognized in the northern Nigeria as the 'Older and Younger' Granite (Falconer, 1911).

By contrast, the Younger Granite are a petrologically distinctive series of alkali feldspar granite, associated with rhyolites and minor gabbros and syenites, which occur as ring dykes and related annular and cylindrical intrusions (Abaa, 1985; Bennett *et al.*, 1984). Often several cycles of intrusion occur within the one complex and the large size of many of the complexes is due to the overlapping and superposition of separate intrusive cycles.

Geological studies were undertaken on some of the complexes, such as Ririwai, Banke, Kudaru (Jacobson, 1947), Tibchi (Ike, 1979), Mada (Abaa, 1985), Buji (Ashano and Umeji(2010),and GeshereComplex(Magaji*et al.*, 2011). The peak of these studies led to the production of the 1:500,000 geological map of the Province by (Bowden *et al.*,1984). Despite these studies, many of the Nigerian anorogenic complexes have not been studied in sufficient detail to give room for the full understanding of the petrogenesis of these magmatic complexes. In addition, for many of these anorogenic complexes, little or no compositional data on whole rocks and minerals exist to allow for a petrogenetic characterization (e.g. Bennett *et al.*, 1984, Mucke, 2003).

Chemically, two groups of granitic rocks have been identified in the Younger Granite Province. These are peralkaline (rocks, in which the molecular proportion of alumina is less than that of soda and potash combined) and subalkalinegranite, which is predominantly biotite granite. The Younger Granite ring-complexes of Nigeria are over 45% subalkaline types of granite, which are mineralized with rich deposits of cassiterite, columbite, sphalerite, wolframite and galena, consequent to fluid interaction in the cupolas. The peralkaline granite, in addition to more common rock-forming minerals, contain in accessory amounts the rare minerals astrophyllite and pyrochlore, along with cryolite, zircon, topaz, thorite and occasional themosenolite (Jacobson *et al*., 1958, Jacobson and Macleod, 1977).

Fifteen of the complexes have been isotopically dated and a perceptible trend in the north from 213±7 Ma (Dutse), 186 ± 15 Ma (Zaranda) and 183 ± 7 Ma (Ningi-Burra) to those in the south at 151 ± 4 Ma (Pankshin), 145 ± 4 Ma (Mada), and 141 ± 2 Ma (Afu) is discernable. This progressive change in age, and the fact that similar alkali granite ring complexes in southern Niger and further north in Air are Carboniferous, Devonian and Ordovician in age has prompted authors (e.g. Bowden *et al*., 1976) to advocate a sequential age trend covering some 500 Ma over a distance of more than 2,000 km. (Rahaman*et al*.,1984) and (Bowden and Kinnaird, 1984) have provided further isotopic evidence of this age progression.

2.2.2 Birnin Kudu Complex

Birnin Kudu administrative center is 130 km ESE of Kano town, northwestern Nigeria. Geologically, the study area consists of an Older Granite plateau with residual monolithic granite boulders, which slopes gently south-wards to a small river. The eastern region consist of ridges of rhyolites(Szentes, 2008).

The Birnin Kudu Complex consists of a north-south trending group of isolated exposures of granite porphyry, the arc-like form suggests they may be part of a ring-dyke with a diameter of 7 km, and east-west line of hills of volcanic rocks covering 8 km^2, which would imply a hidden surface area of 36 km^2(Bennett *et al*., 1984).

2.3 PETROGRAPHY AND PETROLOGY

Petrographic descriptions of the rocks of Younger Granitehave been provided by many authors amongst which are Buchanan *et al*., (1971),Rocci(1960), Jacobson *et al*., (1958)and Borley, (1963); 1976.

From a chemical viewpoint, the mafic minerals are Fe-rich (e.g. fayalite and hedenbergite) in keeping with the low Mg content of the rocks. The most comprehensive study of any mineral group is for the amphiboles, in which a range of composition from 'hastingsite' to 'riebeckitic-arfvedsonite' has been described (Borley, 1963;Mucke, 2003;Magaji*et al*., 2011).

Alkali feldspar from the granite and syenites has a range in structural state from orthoclase to maximum microcline representing increasing degree of post-magmatic modification by aqueous fluids (Badejoko, 1977; Martin and Bowden, 1981;Abaa, 1985;Sakoma and Martin, 2011).

The province is also characterised by a wide range of accessory minerals reflecting the abundance of many trace elements. These accessory minerals include zircon, monazite, thorite, xenotime, apatite, fluorite, columbite, cryolite, allanite, thomsenolite and fergusonite (Jacobson *et al*., 1958), astrophyllite and amblygonite (Macleod *et al*., 1971), and narsarsukite (Jeremine and Michel-levy, 1961). It should be pointed out however, that some of these minerals may be secondary, and most of the identifications are optical only. A summary of the chief mineral associations is given by (Jacobson *et al*., 1958).

2.4 GEOCHEMISTRY

A geochemical characterization of the province has listed such features such as low Mg and Ca, and high total Fe, F, Li, Rb, Y, Nb, Hf, U and Th (Jacobson *et al*., 1958, Macleod *et al*., 1971, Jacobson and Macleod, 1977;Batchelor, 1987;Ashano and Umeji, 2010). Additional trace elements data has been published by Bowden, (1964); 1966a;1966b.

Frost *et al.*, 2001 had earlier introduced a geochemical classification of granitic rocks. This classification scheme suggests that granitic rocks could be classified using three compositional variables, FeO/(FeO+MgO) (or Fe-index), Na_2O+K_2O-CaO (or the modified alkali- lime index, MALI), and the aluminum-saturation index [ASI; molecular Al/(Ca - 1.67P+Na+K)]. Based on this scheme, the rocks of the Younger GraniteProvince of Nigeria belong to the ferroan class.

Ike *et al.*, (1983) proposed that the low content of magnesium and extreme enrichment of Fe in rocks and minerals of the intermediate and felsic range are the result of low fugacity of oxygen prevailing during the initial stages of fractionation.

Ike *et al.*, (1983) also indicated that the initial conditions were of low, fixed oxygen content, which enabled iron enrichment to take place while magnesium was continuously being removed from the system by crystallization and removal of magnesium-rich mafic phases.Alkaline rocks were excluded in the original granite classification scheme of (Frost *et al.*, 2001). However, (Frost *et al.*, 2008) revised the scheme and classified various types of alkaline rocks using two geochemical indices: the alkalinity index (AI) and the feldspathoid silica-saturation index (FSSI).

Rare earth elements concentration has been determined and like many of the trace elements mentioned earlier, found to be relatively abundant, with the exception of Eu which may often be markedly depleted (Aleksiyev, 1970; Bowden and Van Breemen, 1972). Other geochemical features of the province has been summarized in several publications (Macleod *et al.*, 1971; Bowden and Turner, 1974; Jacobson and Macleod, 1977).

2.5 PETROGENESIS

Wide variation of initial strontium isotopes in the Nigerian Younger Granites Province has been used as an argument in favour of a significant contribution by crustal rocks in the genesis of the anorogenic rocks (Bowden and Van Breemen, 1972; Van Breemen*et al*., 1975). In many parts of the world however, unlike Nigeria, there is no connection between initial strontium isotope ratios and rock type, for example, Marangudzi (Foland and Henderson, 1976). Thus, whereas in Niger-Nigeria province, rocks such as syenites with low initial ratios have commonly been ascribed a mantle source, it is not necessarily the case that the highly trace-element-enriched peralkaline granite for example, with high initial ratios, have had any extensive involvement with the crust. Limited stable isotopic evidence support this view, for example the oxygen isotopic composition of the Ririwaialbitearfvedsonite granite, which has an initial strontium isotopic ratio of 0.752 (Van Breemen*et al*., 1975), does not indicate any significant crustal input via a hydrothermal circulatory system in the cooling magma chamber (Borley*et al*., 1976).

Jacobson *et al*., (1958) is of the opinion that the peralkaline, aluminous or peraluminousgranite had been derived by divergent paths of differentiation from a common mafic parent. Likewise, evidence obtained from the field in Air, Niger Republic by (Black, 1965) suggested a tholeiitic basaltic magma to be the parental magma. This however, depends on the development of anorthositeat an initial stage, capable of depleting the gabbroic liquid in aluminium, which on subsequent fractionation yielded a peralkaline felsic residium. Black (1965) added that the non-peralkaline granite may also have been a separate product of differentiation of the same tholeiitic magma.

Again, when considering a comparatively limited portion of the province, particularly the well-studied Jos Plateau region, the scarcity of intermediate and basic rocks has been used as an argument against a mantle-derived origin for the granite (e.g. Macleod *et al.*, 1971). However, there are a number of cases, particularly in oceanic areas, where a model for the derivation of granitic liquids from a basaltic parent has been proposed, despite a scarcity of intermediate rocks. For example, the dearth of intermediate rocks can be attributed to variation in the viscosity withcomposition (Jones, 1979) or the level of erosion reached within a volcanic (or possibly subvolcanic) structure (Gas and Mallick, 1968). Therefore, the relative volumes of basic, intermediate and acid rocks can be shown in certain areas to have little if any bearing on petrogenesis (Wilkison, 1966).

Bowden and Turner (1974) suggested that non-peralkaline granite may have developed in the lower crust as a result of arching of the crust, volatile concentrations and heat focusing, but that peralkaline granite could also be of crustal origin developed by contact anatexis during the limited phases of basaltic magma eruption.

Martin, (2006) considered the A-type granite to be of crustal origin resulting from fenitisation in an extensional environment, whilst (Bonin, 2007) regarded the A-type granite as originating from the mantle as transitional-alkaline mafic to intermediate magma compositions.

Even with all the efforts made so far, petrogenetic studies of the Nigerian Younger Granite remain a fertile research area (e.g.Mucke, 2003; Martin, 2006;Magaji*et al.*, 2011; Frost 2011 and Sakoma and Martin, 2011).

CHAPTER THREE

MATERIALS AND METHODS

3.1 METHODOLOGY

The methodology adopted for the research work comprises of desk study, satellite image interpretation, field mapping, and laboratoryanalysis of collected samples, data analysis, interpretation and compilation of the overall findings in a thesis.

3.2 DESK STUDY

The desk study involved an intensive search and review of published and unpublished materials relevant to the research and the study area. These include journal, articles, geological maps, conference proceedings, reports, theses and dissertations.

3.3 FIELD METHODS

Field work which lasted for about four weeks all together was carried out and a total of 60samples were collected, out of which15 samples were taken used for both geochemical and petrographic studies. Sample sites were recorded using Global Positioning System (GPS), while dip and strike of planar and trend of linear structures were measured using a compass clinometer. Photographs of outcrops were also taken and description of field observations documented. Systematic geological mapping on a scale of 1:25,000 was carried out along with sampling, establishing boundaries of the rock types.

3.4 LABORATORY ANALYSES

Laboratory work carried out during this study is divided into petrographic and geochemical analysis.

3.4.1 Petrographic Methods

Fresh samples were selected from the different rock types and thin sections were prepared in the thin section laboratory of the Geology Department, Ahmadu Bello University, Zaria.

i A thin slice of each rock specimen was cut on the diamond saw and trimmed to fit onto glass microscope slide.

ii The slice was glued to the microscope slide with clear epoxy.

iii The slide was mounted in a special holder and ground on a diamond slap until it is translucent. Finally, it was hand finished with 600 grit silicon carbide on a glass lap.

iv When the thickness of 0.03 mm was attained, the section is complete and ready for examination under the petrographic microscope. The thickness of the section was measured with a digital micrometer.

v A cover slip was placed on the mount to protect the specimen.

The prepared slides were examined under the petrological microscope to identify the constituent minerals at a magnification of 10X/0.25mm. The properties of these minerals as seen in polarized light, crystal form and mutual interference between crystals were clearly stated.

3.4.2 Sample Preparation for Geochemical Analysis

Geochemical analysis commenced with the pulverisation of the Fifteen (15) selected whole rock samples for geochemical analysis were pulverized to200µ mesh size at the Activation laboratory, Ontario Canada. The pulverisationof the samples was undertaken with the aid of Retsch Planetary Ball Mill 400. Rock chips were loaded into the planetary ball mill and a time interval of 15 minutes was allowed for complete pulverisation. After pulverisation of each sample, the equipment was cleaned using acetone. Pulverisation was later followed by weighing 15 grams of each sample using an electronic weighing balance. Samples were then sealed, labeled. The samples were analysed for major, trace and rare earth elements using the 4 lithos package inductively-coupled plasma mass spectrometry (ICP-MS).

3.4.3 Analytical Techniques

The major elements were analysedby inductively couple plasma atomic emission spectrometry following a lithium borate fusion and dilute acid digestion while trace and REE were analysed by inductively-coupled plasma mass spectrometry (ICP-MS)following a multi-acid digestion method. Details of the analytical procedures adopted has been discussed in the work of (Maja *et al.*, 2011). As a means of dissolving the mineral constituents, theanalytical procedure involved addition of 5 ml each of perchloric acid ($HClO_4$), trioxonitrate (V) HNO_3 and 15 ml Hydrofluoric acid (HF) to 0.5 g of sample. The solution was stirred properly and allowed to evaporate to dryness after it was warmed at a low temperature for some hours. Four (4) ml of hydrochloric acid (HCl) was then added to the cooled solution and warmed to dissolve the salts. The solution was cooled; and then diluted to 50 ml with distilled water. The solution was then introduced into the ICP torch as aqueous - aerosol. The emitted light by the ions in the ICP was converted to an electrical signal by a photo multiplier in the spectrometer, the intensity of the electrical signal produced by emitted light from the ions were compared to a standard (a previously measured intensity of a known concentration of the elements) and the concentrations were then computed. Analytical precisions vary from 0.1% to 0.04% for major elements.

Trace elements were analyzed by Inductively- Coupled Plasma Mass Spectrometry (ICP-MS) from pulps after 0.2 g of rock powder was fused with 1.5 g $LiBO_2$ and then dissolved in 10 ml of trioxonitrate (V) (HNO_3). The REE (rare earth element) contents were determined by ICP-MS from pulps after 0.25 g rock-powder was dissolved with 5 ml of perchloric acid ($HClO_4$) and trioxonitrate (V) HNO_3, and 15 ml of hydrofluoric acid (HF). Analytical precisions vary from 0.1 to 0.5 ppm for trace elements and from 0.01 to 0.5 ppm for rare earth elements.

Using this method, the following elements were analysed; Ba, Be, Co, Cs, Ga, Hf, Nb, Rb, Sn, Sr, Ta, Th, U, V, W, Zr, Y, La, Ce, Pr, Nd, Sm, Eu, Gd, Tb, Dy, Ho, Er, Tm, Yb, Lu, Mo, Cu, Pb, Zn, Ni, As, Cd, Sb, Bi, Ag, Au, Hg, Tl and Se.The major oxides SiO_2, Fe_2O_3 (T), Al_2O_3, MgO, MnO, CaO, Na_2O, K_2O, TiO_2 and P_2O_5 were also analysed with ICP-MS.

3.5 DATA ANALYSIS

Data obtained from geochemical analysis of the rocks were used to plot various classification and discrimination diagrams which aided the interpretation of the geochemical characteristics of the rock types in the Birnin Kudu Complex.

CHAPTER FOUR

RESULTS

4.1 BACKGROUND

The results obtained from field relationship, structures, petrography and geochemistry of rock samples from the study area are presented in this chapter. A table of modal composition is presented in Table 1. The analytical data of the rocks are presented in Table 2, for major oxides, trace and rare earth elements respectively, whilethe spatial distribution of the different rock units encountered is presented in (Figure 1). Plates I, III, V and VII are photographs of granophyre, rhyolite, crystal-rich ignimbrite and biotite hornblende granite respectively, taken from the field, while plates IIa and b, IVa and b, VIa and b and VIIIa and b are photomicrographs of granophyre, rhyolite, crystal-rich ignimbrite and hornblende granite biotite respectively, taken under microscope.

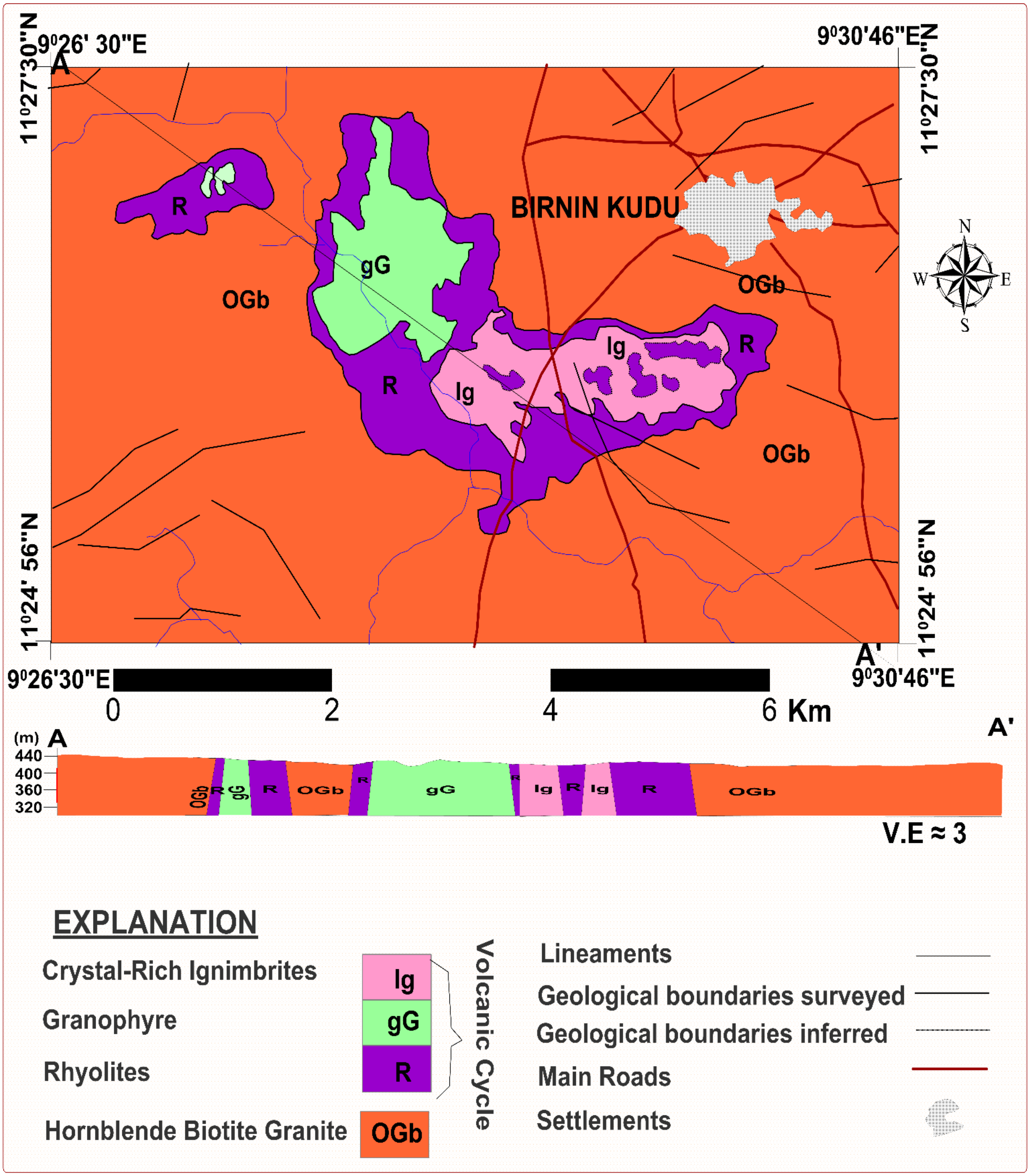


Figure 1. Geologic Map of the Birnin Kudu Complex.

Table 1: Modal composition (based on point counting, using JMicrovision software) of the rocks from the study area. All values are in percentage (%).

Rock types/Minerals	G G	R H	I G	H B G
Quartz	26	13.66	12.27	21.38
Sanidine		12.2		
Hornblende				15.17
Quartz/Feldspar	36			6.21
Opaque		3.41	3.68	4.14
Orthoclase Feldspar	38		22.7	13.1
Plagioclase			2	12.41
Biotite				27.59
Augite			14.11	
Groundmass		70.73	47.2	
Total	100	100	101.96	100

Where: GG: Granophyre, RH: Rhyolite, IG: Ignimbrite, HBG: Hornblende biotite granite

4.2 GRANOPHYRE

4.2.1 Field Relationships

Outcrop of this rock typewas encounteredat the northwestern portion of the Complex, north of the volcanic ridge.In composition, granophyre is just a typical granite, but it is the texture that is remarkable. Granite porphyry has the same phenocrysts of quartz and feldspar as granophyre, but the groundmass is just ordinary fine-grained granite in fact, it often grades into granophyre. They occur in form of boulders, isolated and N-S trending exposures of pinkish to whitish, granitic rocks.The contact of this with the rhyolite was recorded (Plate I). This granite covers about35% of the study area, and it is the dominant rock type inside the town of Birnin-Kudu. In the northwestern and southwestern part of the study area, the rock is quarried as aggregate and dimension stones for construction purpose. Thesegranite form some kind of rock shelters as studied by (Szentes, 2008). This can be seen in the photographs captured (Plate I). They occur like sub-volcanic intrusion.

Plate I: Photograph of Granophyre at $11^0$27'31"N and $09^0$29'12"E, showing mode of occurrence.

4.2.2 Petrography of Granophyre

In thin section, the granophyre contain quartz, orthoclase and myrmekite (Plate IIa and b). Quartz occurs as polycrystalline mineral and display undulose extinction. It is colourless, lacks cleavage and non pleochroic, and exhibits first order interference colour of grey-white, with low birefringence.

Orthoclase is also colourless and non pleochroic like quartz, with very low relief distinguished from quartz by cloudy patches on individual crystals in plain polarized light which indicate weathering of the crystal along cleavage planes.

The mineral grains areanhedral with few euhedral orthoclase grains seen. Some of the minerals are coarse grained. The orientation of the minerals is random and they are holocrystalline that is, phaneritic. The potassium feldspars are largely being altered to calcite and sericite. In terms ofcomposition, the dominant minerals are potassium feldspars (orthoclase) making up to 38% of the total composition, followed by quartz/feldspar (myrmekite) which is about 36% and quartz 26%, the lowest is in terms of percentage composition are the secondary minerals (opaque minerals, zircon and calcite) about 2%. The myrmekitic (wormy) texture is typical of granophyre.

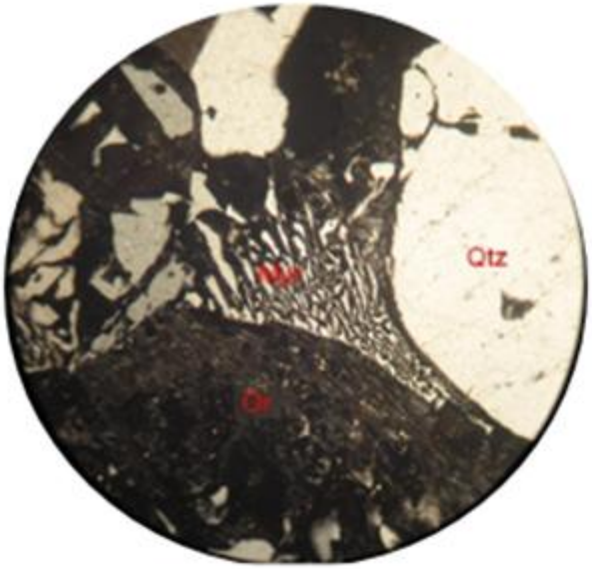


Plate IIa: Photomicrograph of Granophyre in XPL. Qtz = Quartz, Or = Orthoclase, and Myr = Myrmekite. Mag.0.25mmX10.

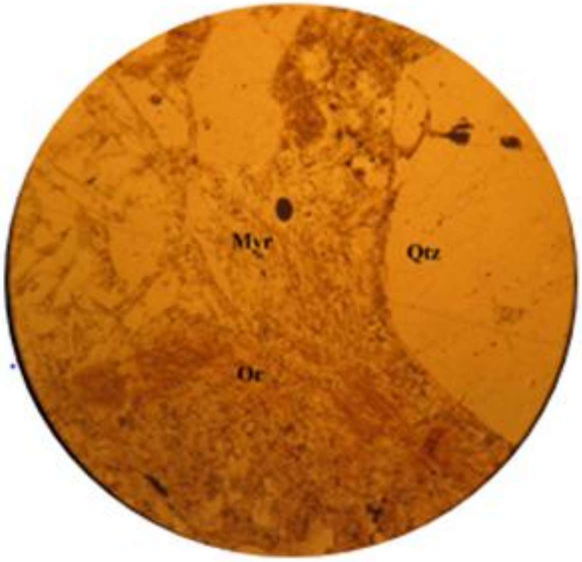


Plate IIb: Photomicrograph of Granophyre inPPL. Qtz = Quartz, Or = Orthoclase, and Myr = Myrmekite. Mag.0.25mmX10.

4.3 RHYOLITE

4.3.1 Field Relationships

This is the dominant rock type of the Birnin Kudu Complex. The field occurrence is similar in the different locations with highly intensive jointing all over the exposure (Plate III). The rhyolite occurs in form of isolated hills which are aligned in E-W direction in the central to the eastern part of the Complex. The joints show a dominant trend in the east-west direction and a few others in different directions. The rockis dark to greyish in colour with poorly formed crystals.The contact between the rhyolites and both the alkali granite and the crystal-rich ignimbritesis visible in different places.

Plate III: Photograph of rhyolite, showing multiple joints at 11^{0}26'44"N and 09^{0}29'30"E4.3.2.

4.3.2 Petrography of Rhyolite

The rhyolite is composed of quartzphenocrystsand sanidineembedded ina glassy groundmass. Thegroundmass (glassy) is mostly devitrified glass composed ofopaques, biotite, quartz and feldspars without distinctive shapes (Plate IVa and b).Apart from the quartz and sanidine, most of the other minerals are very fine grained. The quartz shows an inclusion of the groundmass (melt inclusion) within its crystals.

The sanidine shows very good cleavage and exhibits Carlsbad twinning, it is colourless in thin section also shows parallel extinction.The mineral grains are randomly oriented, and are thereforehypocrystalline. In terms of modal composition, the groundmassconsisting of tiny opaques, biotite, quartz and feldspars composed of about 70.73% of the rock, whilequartz composed of about 13.66%, and sanidine 12.2% of the total composition.

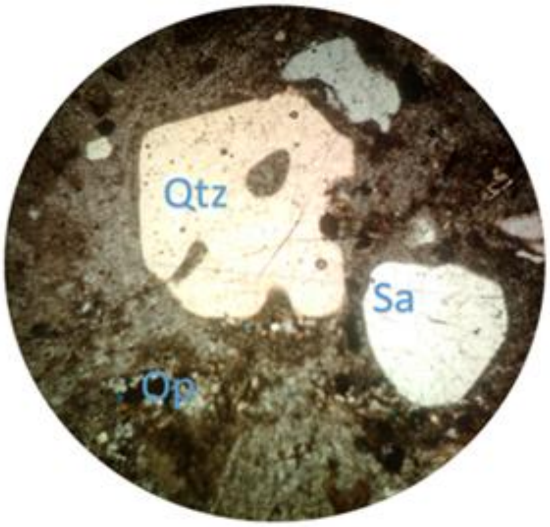


Plate IVa: Photomicrograph of Rhyolite; in XPL.
Qtz = Quartz, Sa = Sanidine, and Op = Opaque.
Mag.0.25mmX10.

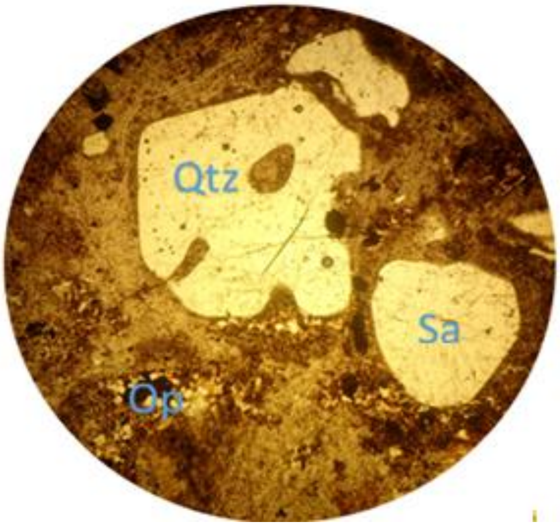


Plate IVb: Photomicrograph of Rhyolite; in PPL.
Qtz = Quartz, Sa= Sanidine, and Op= Opaque.
Mag.0.25mmX10.

4.4 CRYSTAL-RICH IGNIMBRITE

4.4.1 Field Relationships

The crystal-rich ignimbrite is similar to rhyolite, but with larger crystals of constituent mineralsthan the rhyolite (Plate V). This rock is characterized by the preponderance of lithic fragments of different colours, mostly different shades of grey and black, corresponding to earlier volcanic rocks in the stratigraphical succession. The groundmass is dark blue/green in colour and in it fragmental phenocrysts of alkali feldspar and quartz are sparsely distributed.Compared to the rhyolite, absence of flow-bands in the crystal-rich ignimbrite is also a striking difference. Furthermore, crystal-rich ignimbrite occuras isolated hills of higher elevation as the rhyolite, e.g. elevation of 499 meters was recorded at location 24 (N11˚26’ 34.5” and E09˚ 29’ 32.9”). The crystal-rich ignimbrites and the rhyolites are commonly separated by lowland which represents the contact between the rock units.In terms of volume, the crystal-rich ignimbrite is the smallest rock unit of the Birnin Kudu Complex.

Plate V: Photograph of Crystal-rich Ignimbrite at $11^0$26'40"N and $09^0$29'18"E, showing moderately flattened pumice fragments.

4.4.2Petrography of Crystal-rich Ignimbrite

The groundmass consist of quartz, and opaque minerals which are not probably alteration product of pyroxene (Plate VIa and b).Alkali feldspar and quartz occur as fragmental phenocrysts while the groundmass consists mainly of glass shards. The bulk of the phenocrysts around the groundmass are made up of orthoclase feldspars and quartz, with the orthoclase showing Carlsbad twinning (Plate VIa).Quartz is generally medium grainedsubhedral crystals, fragmental phenocrysts of quartz are visible. The mineralis randomly oriented and it is hypocrystalline. In terms of modal composition, quartz is about 12.27%, orthoclase 22.7% and clinopyroxenes(14.11% augite), the groundmass consisting of quartz and opaque minerals makes about 50.88% of the total composition.

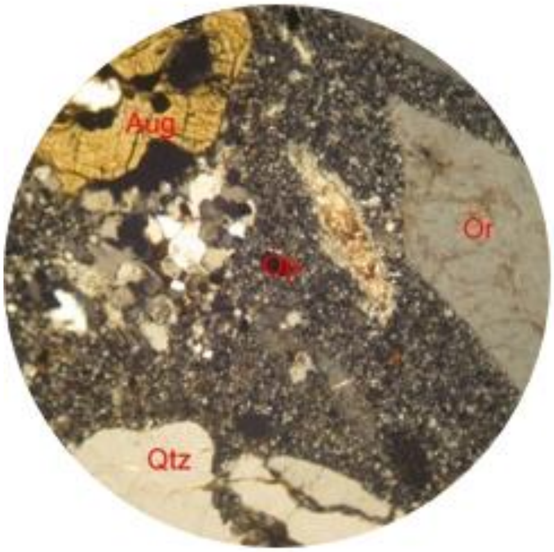


Plate Va: Photomicrograph of Crystal-rich Ignimbrite; in XPL. Qtz = Quartz, Or = Orthoclase, Op = Opaque mineral, Aug = Augite Mag.0.25mmX10.

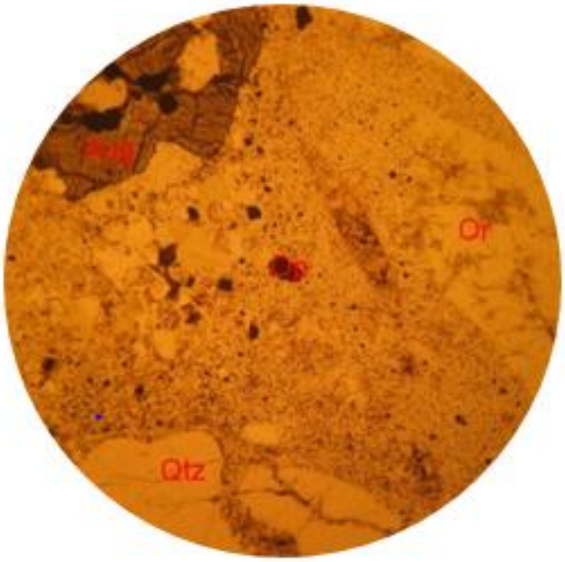


Plate Vb: Photomicrograph of Crystal-rich Ignimbrite; in PPL. Qtz = Quartz, Or = Orthoclase, Op = Opaque mineral, Aug = Augite Mag.0.25mmX10.

4.5 HORNBLENDE BIOTITE GRANITE

4.5.1 Field Relationships

This rock type occurs as low lying outcrops forming a boundary with the rhyolite. It is part of the basement and virtually surrounds theBirnin Kudu Complex, (Figure 1). The structural features in the rock are open joints and fracture-filled veins, with the longest vein measuring up to 31.5 meters in length. On the basis of texture, the rock can be classified as medium to coarse grained granite.

Plate VII: Hornblende Biotite Granite at $11^{0}25'19''$N and $09^{0}30'41''$ showing open joint.

4.5.2 Petrography of HornblendeBiotiteGranite

This hornblende biotite granite has large quartz crystals (Plate VIIIa and b), in PPL colourless, pleochroic white to grey. Lacks cleavage but has cracks on the crystal surface and low relief. In XPL quartz exhibits undulatory extinction and has low birefringence. Orthoclase is cloudy in PPL with low relief, non pleochroic. The presence of cloudy patches which indicates alteration on individual crystals helps distinguish orthoclase from quartz. In XPL it exhibits inclined extinction, interference colour from first order grey and white, and lacks twinning.

Plagioclase in PPL has low relief, with clear cleavage (PlateVIIIb). In XPL plagioclase has grey to white interference colours, slightly lower than quartz, has albite twinning as its most distinctive feature (Plate VIIIa). In PPL Hornblende is pleochroic in various shades of green and brown (PlateVIIIb), with high relief.In XPL it goes through unduolus extinction, has simple twinning (PlateVIIIa), displayssecond and third interference colours; the strong colour of the mineral masks its interference colours.

Biotite (Plate VIIIa and b) has well-developed crystals, anhedral to subhedral in form, with perfect cleavage. The mineral in PPL is pleochroicfrom light to dark brown and has moderate relief. The interference colours of biotite are of a bit lower order and more subdued,interference colour from brown to pink, because of biotite's colouration.

The minerals are largely coarse grained with biotite having few medium grains andphenocrysts of feldspar. The minerals are generally subhedral. The grains show random orientation of minerals.They are holocrystalline. In terms of percentage composition, quartz is the highest with about 21.38% of the total composition, followed by feldspars (plagioclase, orthoclase and myrmekite) representing 31.72%, 27.59% biotite, 15.17% hornblende and about 4.14% opaque minerals.

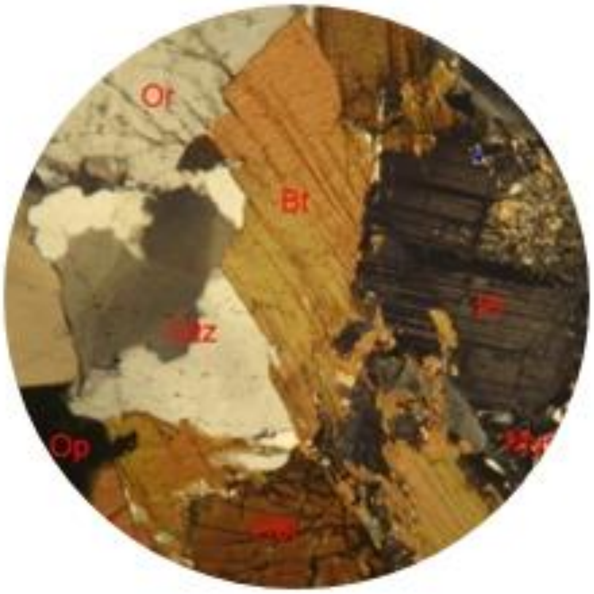


Plate VIa: Photomicrograph of Hornblende Biotite Granite; in XPL. Qtz = Quartz, Or = Orthoclase, Bt= Biotite, Hbl = Hornblende, Op = Opaque mineral, Pl= Plagioclase and Myr = Myrmekite Mag.0.25mmX10.

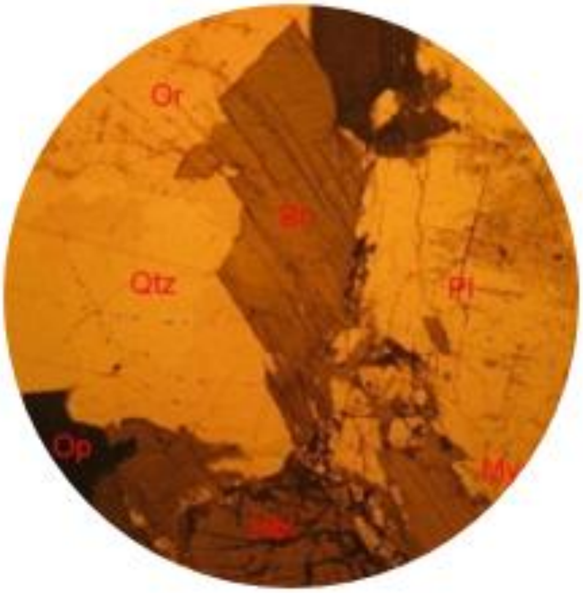


Plate VIb: Photomicrograph of Hornblende Biotite Granite; in PPL. Qtz = Quartz, Or = Orthoclase, Bt= Biotite, Hbl = Hornblende, Op = Opaque mineral, Pl= Plagioclase and Myr = Myrmekite Mag.0.25mmX10.

4.6 Whole Rock Geochemistry

A total of fifteen whole rock samples were analysedfor theirmajor oxides, trace and rare earth element (REE) composition. These comprise of two representative samples of the (basement) hornblende biotite granite, two representative samples of crystal-rich ignimbrite, five representative samples of the granophyre and six representative samples of the rhyolite. Summary of the analytical dataof major elements grouped according to rock suites is presented in Table 2.

4.6.1 Major Elements Geochemistry

The major element composition of the granophyre, rhyolite, ignimbrite, biotite hornblende graniteof the study area are plotted on Harker diagram using SiO_2 as an index of differentiation. SiO_2 is chosen as abscissa because it displays a wide range of variation within the rock suite. The SiO_2 content of the rocks of the Birnin Kudu Complex ranges from 74.59-77.04 wt% while that of the basement rocks, specifically the biotite hornblende granite which is in contact with the Complex ranges from 59.19-68.92 wt%. The variation trend plotted on Harker diagrams presented as (Figure 2) and have already noted that rocks with high total alkalis are deficient in MgO, CaO and Fe_2O_3 hence they display a negative correlation with SiO_2. The rocks from the study area show similar behavior and fall together as SiO_2 rises. By contrast however, K_2O and Na_2O in the same rocks rise with SiO_2.

Al_2O_3concentration in the rocks of the complex does not show strong variation as they cluster close to each other indicating a co-magmatic relationship between the rocks (Figure 2). Aluminiumis present in feldspars, especially plagioclase into which it partitions during the early stages of fractionation. This may explain the decrease in $Al_2O_3$with increasing silica content (Tate *et al.,* 1997). The rocks of the complex have a lower Al_2O_3 concentration compared to the biotite hornblende granites which has concentrations of up to 15.63 wt %.

The concentration of CaO in the rocks of the study area show a negative correlation with SiO_2 (Figure 2). The Concentration of CaO is higher in the biotite hornblende granites than those of the Birnin Kudu Complex, with values of up to (4.9 wt %) in the biotite hornblende granite whereas value as low as (0.12 wt %) recorded outside the Complex. Calcium is strongly fractionated by plagioclase, this may account for the possible positive correlation of the plagioclase rich biotite hornblende granites (Figure 2). Fractionation of calcic phases and their decrease with increasing silica content probably accounts for the inverse trend of CaO displayed amongst the Younger Granite rocks of the Birnin Kudu Complex.

Concentration of MgO is higher in the hornblende biotite granite compared to the rocks of the Birnin Kudu Complex (Figure 2). This trend is reflected in the modal mineralogy of the rocks with the biotite hornblende granite having higher proportion of the mafic phases. Fractionation of ferromagnesian minerals would produce the observed inverse trend.

Concentration of $P_2O_5$is relatively higher in the hornblende biotite granite than in the Younger Granites of the Birnin Kudu Complex (Figure 2).

Concentration of Fe_2O_3 is also higher in the hornblende biotite granite than in the granitoids of the Birnin Kudu Complex (Figure 2). Fe_2O_3 has a negative correlation with SiO_2 in the rocks of the study area. The stability of iron-bearing minerals in a system is dependent on the oxygen fugacity $f(O_2)$ and therefore, oxygen fugacity exert some control on the fractionation (Maaloe, 1985). The decrease in total iron with increase in silica suggests early crystallisation and removal of iron oxides (Wilson, 2007 and Hughes, 1982).

Hornblende Biotite Granite | Granophyre | Rhyolite | Crystal-rich Ignimbrite

	Hornblende Biotite Granite		Granophyre					Rhyolite						Crystal-rich Ignimbrite	
Sample	B27	B28	B4	B6	B43	B47	B55	B8	B19	B29	B42	B45	B20	49A	49B
SiO_2	59.19	68.92	75.79	74.59	77.04	74.88	75.77	75.16	75.41	76.13	76.15	76.18	76.04	76.31	76.74
Fe_2O_3(T)	8.9	4.29	2.74	2.86	2.5	2.73	2.44	2.44	2.28	2.09	2.39	2.31	2.25	2.64	2.63
Al_2O_3	15.63	14.11	11.18	11.94	11.62	12.46	11.92	11.8	11.59	12.04	11.52	12.04	11.84	11.8	11.65
MgO	1.86	0.71	0.03	0.06	0.03	0..07	0.04	0.02	0.02	0.02	0.03	0.02	0.05	0.06	0.02
MnO	0.121	0.059	0.046	0.051	0.026	0.038	0.042	0.023	0.025	0.009	0.03	0.02	0.015	0.035	0.041
CaO	4.9	2.07	0.76	0.73	0.12	0.36	0.32	0.5	0.43	0.54	0.41	0.42	0.56	0.35	0.51
Na_2O	3.68	3.23	3.51	3.42	2.47	3.35	3.56	3.8	3.76	3.74	3.7	3.95	3.84	3.16	3.68
K_2O	3.09	5.17	4.98	5	5.26	5.37	5.04	4.75	4.45	4.78	4.69	4.78	4.57	4.77	4.91
TiO_2	1.603	0.666	0.167	0.183	0.175	0.186	0.139	0.097	0.099	0.103	0.117	0.111	0.085	0.179	0.155
P_2O_5	0.51	0.2	<0.01	0.01	<0.01	.0.08	0.01	0.01	<01.01	<0.01	<0.01	<0.01	<0.01	<0.014	0.01
LOI	0.67	0.42	1	1.23	1.11	0.76	0.8	0.67	0.83	0.54	0.58	0.33	0.72	0.99	0.19
Total	100.2	99.84	100.2	100.1	100.3	100.3	100.1	99.26	98.9	99.98	99.63	100.2	99.99	1.3	100.5

Table 2. Summary of Major Oxides, Trace and Rare Earth ElementsComposition of Rocks from the Birnin-Kudu Complex.

Sample	B27	B28	B4	B6	B43	B47	B55	B8	B19	B29	B42	B45	B20	49A	49B
Be	2	3	4	4	4	3	8	4	7	3	9	10	10	4	5
Ba	1569	972	112	120	85	143	110	33	50	33	36	17	80	92	40
Sr	491	225	13	19	9	21	17	26	7	18	12	3	55	15	6
Y	55	33	118	125	99	124	121	194	169	220	178	249	227	146	164
Zr	563	391	420	470	437	459	358	443	440	454	422	480	400	442	426
Co	53	52	98	63	56	65	76	50	64	43	60	91	52	38	85
Zn	120	70	110	110	90	110	90	180	140	140	160	200	170	130	130
Ga	24	23	31	33	32	33	34	44	43	44	38	43	48	34	34
Ge	1	1	2	2	2	2	2	2	2	2	2	2	23	2	2
Rb	14	215	108	109	129	112	161	324	293	351	248	289	431	138	141
Nb	25	25	42	53	58	51	62	213	218	222	134	181	194	82	70
Mo	<2	<2	5	11	5	5	3	4	4	2	3	4	4	6	7
Ag	1.4	1	1.1	1.2	1	1.2	0.9	1.2	1.2	1.1	0.9	1.2	1	1.1	1.2
Sn	4	2	5	4	5	4	8	18	16	16	13	15	26	7	7
Hf	12.8	9.5	11.3	13.5	12.3	12.7	11.5	18	17.8	18	15.7	18.4	17.8	13.1	12.6

Ratios

Sample	B27	B28	B4	B6	B43	B47	B55	B8	B19	B20	B29	B42	B45	49A	49B
Rb/Sr	0.30	0.96	8.3	5.74	14.3	5.33	9.47	12.46	41.86	7.84	19.50	20.67	96.33	9.2	23.50
Eb/Ba	0.09	0.22	1.0.	0.91	1.52	0.78	1.46	9.82	5.86	5.39	10.64	6.89	17.00	1.50	3.53
K/Rb	174.5	199.6	383	380.79	338.49	398.01	259.87	121.7	126.16	88.02	113.04	156.99	137.30	286.9	298.1
Eu/Eu*	0.65	0.47	0.1	0.09	0.13	0.08	0.09	0.02	0.02	0.07	0.02	0.03	0.01	.0.06	0.04
Gd/N	54.71	36.23	89.3	92.75	46.74	98.55	76.81	48.19	36.59	57..97	53.26	77.17	81.16	89.9	101.1
Yb/N	12.27	12.27	49.1	53.18	50.45	50.00	53.18	98.18	91.82	101.36	108.64	83.19	111.36	60.9	65.5

Trace Elements (ppm)

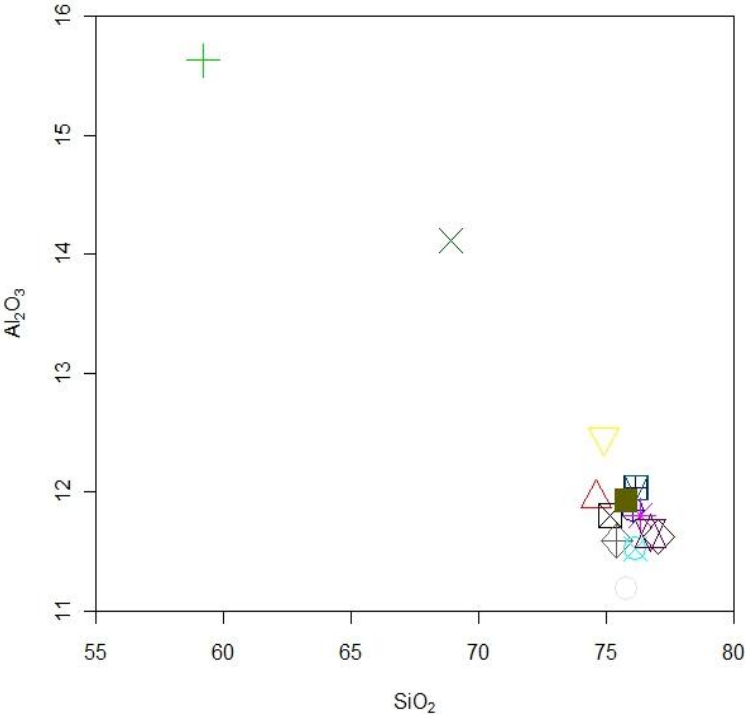
Rare Earth Elements (ppm)

	Hornblende Biotite Granite		Granophyre					Rhyolite						Crystal-rich Ignimbrite	
Sample	B27	B28	B4	B6	B43	B47	B55	B8	B19	B20	B29	B42	B45	49A	49B
La	102	111	105	122	45.9	116	86.9	73.4	63.7	104	83.1	81.3	85.7	88.7	93.5
Ce	195	212	221	251	104	230	183	132	112	147	139	164	152	186	199
Pr	23.6	22	26	29.3	13.3	29	21.3	12.9	10.8	17.4	14.1	17.9	17.2	21.2	23.4
Nd	87.4	72.1	96.4	107	48.4	108	78.7	37.8	31.9	52.3	42.6	61.2	54.6	80.2	88.3
Sm	17	12.7	23.2	24.6	11.8	26.1	19.2	10.5	8.3	13.9	11.7	17.2	17	20.8	24.2
Eu	3.4	1.73	0.77	0.73	0.52	0.68	0.58	0.06	0.07	0.36	0.08	0.16	0.07	0.45	0.36
Gd	15.1	10	24.6	25.65	12.9	27.2	21.2	13.3	10.1	16	14.7	21.3	22.4	24.8	27.9
Tb	2.1	1.4	4.2	4.3	2.6	4.6	3.7	3.3	2.6	3.6	3.6	4.4	5.1	4.5	5.1
Dy	11.5	7.4	25.7	26.1	18.5	27	23.4	25.4	22.8	25.6	27.8	29.9	37.4	27.8	31.6
Ho	2.1	1.3	5	5	4	5.1	4.7	5.9	5.5	5.7	6.4	6.5	8.3	5.5	6.3
Er	5.7	3.4	13.3	13.9	11.8	13.5	13.2	19.5	19	18.7	21.2	19.5	25.7	15.5	17.3
Tm	0.76	0.46	1.79	1.88	1.76	1.81	1.91	3.27	3.11	3.27	3.62	2.89	3.91	2.17	2.42
Yb	4.7	2.7	10.8	11.7	11.1	11	11.7	21.6	20.2	22.3	23.9	18.3	24.5	13.4	14.4
Lu	0.67	0.37	1.57	1.69	1.58	1.59	1.72	2.91	2.75	3.1	3.29	2.51	3.22	1.89	1.91
∑REE	471.03	458.6	559.3	624.9	288.2	601.6	471.2	361.8	312.8	433.2	395.1	447.1	457.1	492.9	535.7

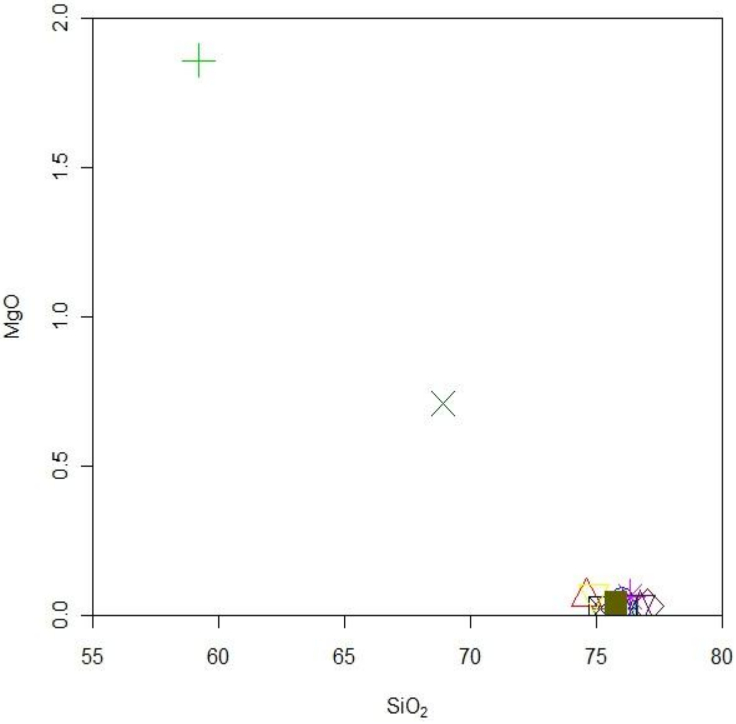
A linear trend is exhibited byNa_2O and K_2O with SiO_2suggesting a co-genetic evolutionary trend for these major oxides in the Birnin Kudu Complex, the trend suggests that the variation in the concentration of Na_2O and K_2O is significantly independent of SiO_2 concentration. This can be interpreted as the physical parameters such as temperature and pressure exerting a stronger control on the variation of Na_2O and K_2O. Therhyolites has the strongest positive correlation of $Na_2O$with SiO_2 followed by the granophyres and then the crystal-rich ignimbrites (Figure 2). The hornblende biotite granite also show a positive correlation of $Na_2O$with SiO_2 but fall off the trend with the Younger Granite rocks showing a compositional gap between the different granitic rocks. Sodium is also partitioned into Fe-Mg minerals in minor amounts. Plagioclase contains far more Na than K but owing to the fact that the major rock constitute of more K-feldspars (microcline and orthoclase), K_2O shows a positive correlation with SiO_2 than Na_2O(Figure 2).

Concentration of K_2O in the constituent rocks of the Birnin Kudu Complex is also similar to those of the hornblende biotite granite just like in Na_2O. K_2O is a major chemical constituent of the mineral mica and feldspars.

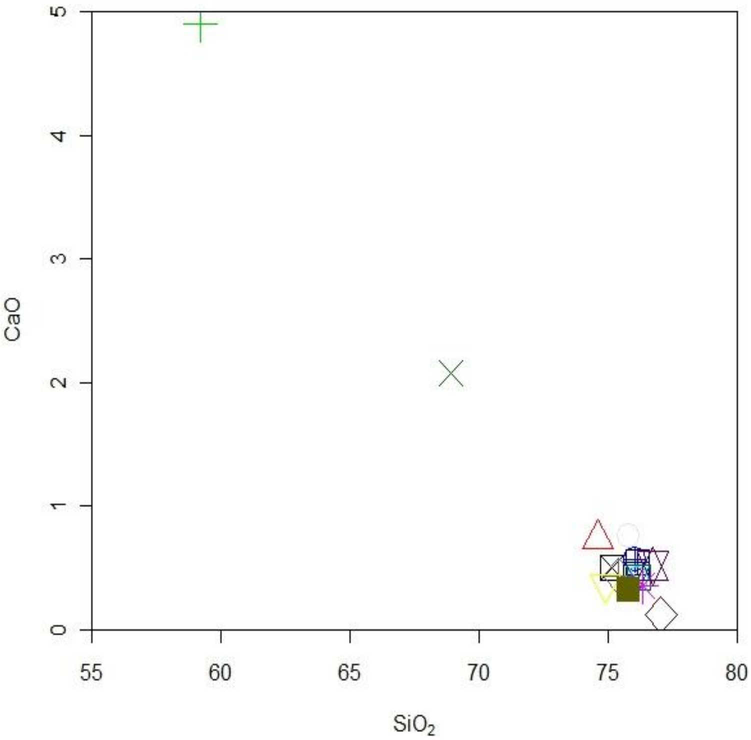
TiO_2 content is relatively higher in the hornblende biotite granite compared to the actual rocks of the Birnin Kudu Complex (Figure 2). Titanium is mainly partitioned into iron oxides (Wilson, 2007). It may also substitute for Fe^{2+} or Mg^{2+} in amphiboles and micas. Titanite is an important carrier of titanium in the felsic rocks.



Al2O3
16
15
14
13
12
11
SiO2
55
60
65
70
75
80



MgO
2.0
1.5
1.0
0.5
0.0
SiO2
55
60
65
70
75
80



CaO
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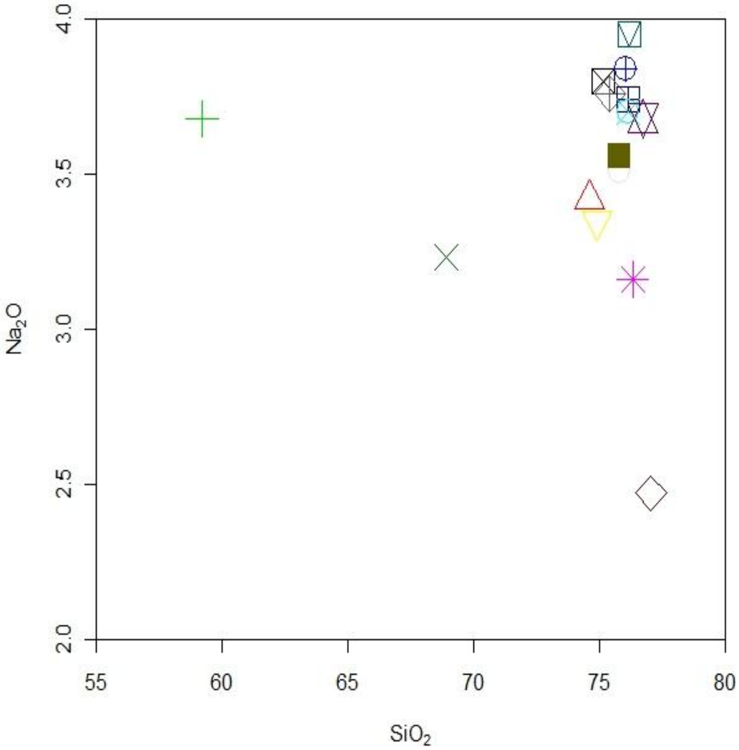
4
3
2
1
0
SiO2
55
60
65
70
75
80



Na2O
4.0
3.5
3.0
2.5
2.0
SiO2
55
60
65
70
75
80

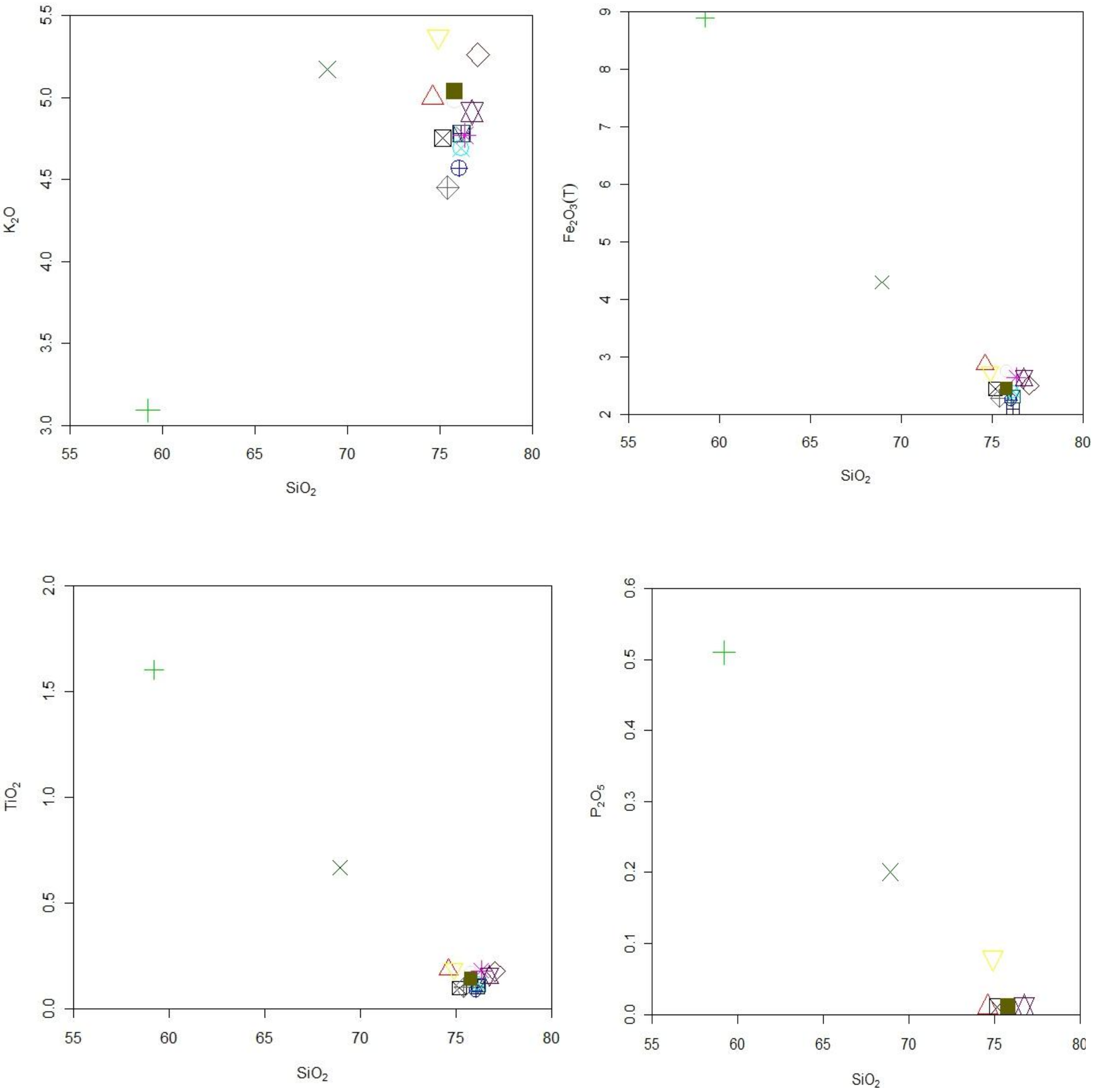


Figure 2. Major elements (wt %) versus SiO$_2$variation diagram of the rocks of the Birnin Kudu area.

Pearce *et al.*, (1984) have also proposed a tectonic classification (Figure 8) of granite based on the Rb, Y, Nb, Yb, and Ta content of the rock.

Whalen, 1987 believes that plots of Ga/Al against major elements ratios and Zr, Nb, Ce and Y (Figure 3) or Zr+Nb+Ce+Y versus major element ratios more clearly differentiates A-type granites.In combination with the plots of (Pearce *et al.*, 1984) they should help to clarify the tectonic setting and classification of granitic rocks.

High Ga/Al values in thegranitoids of the Birnin Kudu Complex appears to be particularly diagnostic of A-type granite from M-I- and S-type granite composition, although a plot of agpaitic index against Ga/Al (Figure 3) indicates that this distinctive character is most pronouncedin strongly alkaline to peralkaline rocks and less so in thesubalkalinerock suites,(Whalen, 1987).

Eby (1990; 1992) subdivided A-type granitoids into two groups on the basis of trace element abundances, particularly the Y/Nb ratio. The group with lower Y/Nb ratios (group A1, with Y/Nbb1.2) includes felsic rocks from oceanic islands and continental rifts; these granitoids were suggested to form from an oceanic island basalt source in an intraplate or rift setting. The group with higher Y/Nb (group A2, with Y/Nb>1.2) was proposed to form by a number of different mechanisms: from an island arc or continental margin basalt source, or from crustal sources such as tonalite or granodiorite, or by partial melting of crust from which a melt was previously extracted (Eby, 1992). In addition, crustal contamination of A1 group granitic magmas may increase Y/Nb such that they plot in the A2 field (Eby, 1992). A1 granitoids are ferroan and metaluminous, and are dominantly alkalic and alkali-calcic. Of Loiselle and Wones' examples, the White Mountain and Nigerian Younger granites belong to the A1 group, as do the sodic series of Pikes Peak granites and some Gardar granites (Eby, 1990; Goodenough et al., 2000; Smith et al., 1999). A2 granitoids include a greater diversity of compositions, from metaluminous to peraluminous to peralkaline, and from alkalic to calc-alkalic. The potassic series of Pikes Peak granites and some Gardar granites belong to group A2 (Marks et al., 2003; Smith et al., 1999).A ternary plot of Nb, Y and Ce was used to discriminate thegranitoids of the Birnin Kudu Complex into A1 and A2 granites. Most of the rhyolites plot as A1, while all the crystal-rich ignimbrites and granophyres plot as A2 (Figure 5). The first, (A1) is characterized by element ratios similar to those observed for oceanic-island basalts. The second class (A2) is characterized by ratios that vary from those observed for continental crust to those observed for island-arc basalts. It is proposed that these two types have very different sources and tectonic settings.

The A1 class represents differentiates of magmas derived from oceanic-island basalts but emplaced in continental rifts or during intra-continental plate magmatism. The A2 class represent magmas derived from continental crust or under-plated crust that has been through a cycle of continent-continent collision or island-arc magmatism (Whalen, 1987).

Numerous workers have used iron enrichment to distinguish between granitoids from different tectonic environments. In particular, suites with A-type characteristics are distinctly more iron enriched than non-A-type granitoids(Frost *et al*., 2001). Fe-number (FeO_{tot}/ (FeO_{tot}+MgO=Fe*) distinguishes ferroangranite, which manifest strong iron enrichment, relative tomagnesiangranite (Frost *et al.,* 2001).

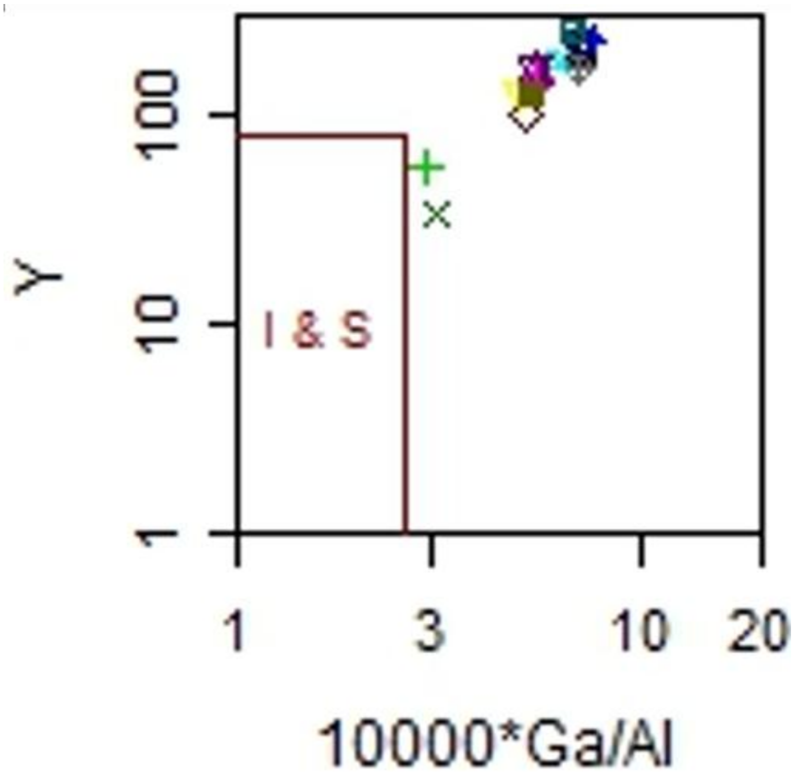
Plot of the granite on FeO_{tot}/ (FeO_{tot}+MgO versus SiO_2 discrimination diagram (Figure 3) after (Frost *et al*., 2001) shows that theBirnin Kudugranitoidsall plots within the ferroans field. This further reinforces the unique attributes of the Birnin Kudu Complex and the Nigerian Younger Granites as a whole earlier reported.This is in line with thegeochemical characterization of the province indicating features such as low Mg and high totalFe (Jacobson *et al*., 1958; Macleod *et al*., 1971, Jacobson and Macleod, 1977;Batchelor,1987; andAshano and Umeji, 2010).Ike *et al*., (1983) proposed that the low content of magnesium, and extreme enrichment of Fe in rocks and minerals of the intermediate and felsic range are the result of low fugacity of oxygen prevailing during the initial stages of fractionation.

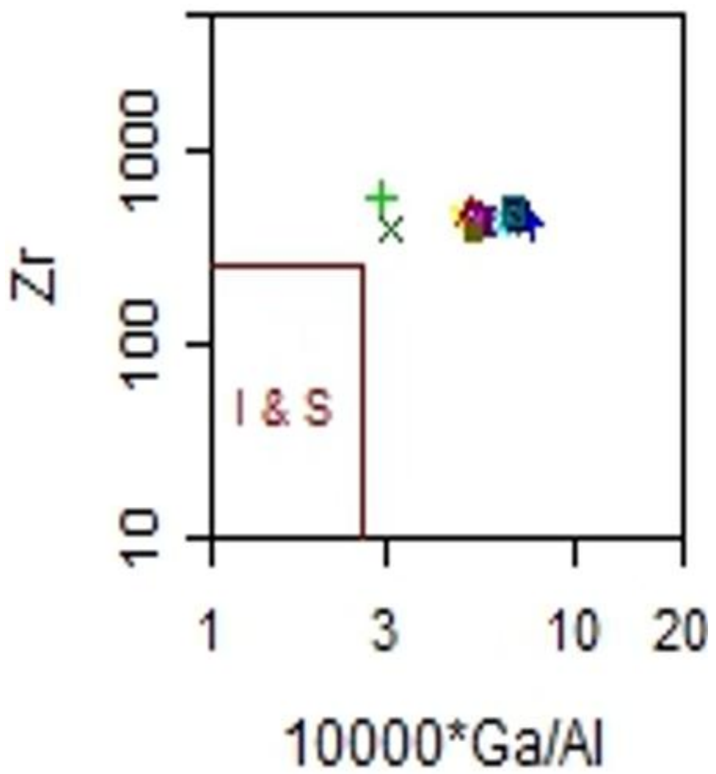
4.6.2 Trace Elements Geochemistry

Trace elements play significant roles in revealing the petrogenetic and evolutionary history of rocks. It has been observed that major element composition in rocks tend towards uniformity and it is only their trace element compositions and ratios that provide clues to their unique differences and petrogenesis (Butler *et al*., 1962; Baba 1990).

Trace elements rarely form minerals in their own right and usually substitute for the major elements in minerals. They are incorporated or excluded from rock forming minerals more selectively than major elements and are therefore regarded as sensitive indicators of igneous processes (Blake *et al*., 1990;Rollinson, 1993). Plots of various trace-element concentration versus SiO_2 are shown in (Figures 6). Majority of the SiO_2 versus trace element variation plots do not show clear and pronounced trends.

Whalen (1987) has reported that Rb/Sr and Rb/Ba ratios of 0.45-0.70 and 0.07-13.8 respectively and marked Eu-anomaly are indicators of feldspar fractionation in granites. The rocks from the study area have an average Rb/Sr and Rb/Ba ratio of 18.38 and 4.44 respectively.


Y
100
10
1
I & S
1
3
10
20
10000*Ga/Al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I & S
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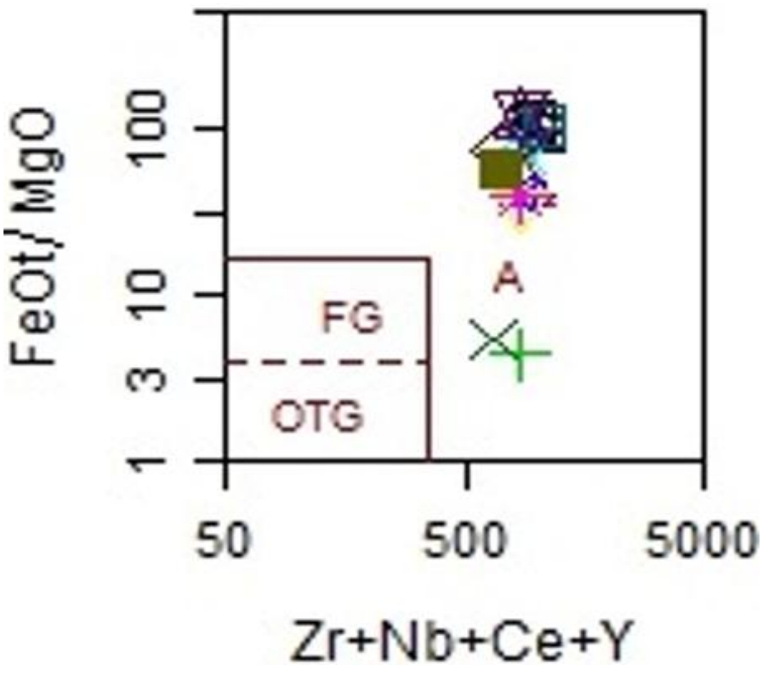
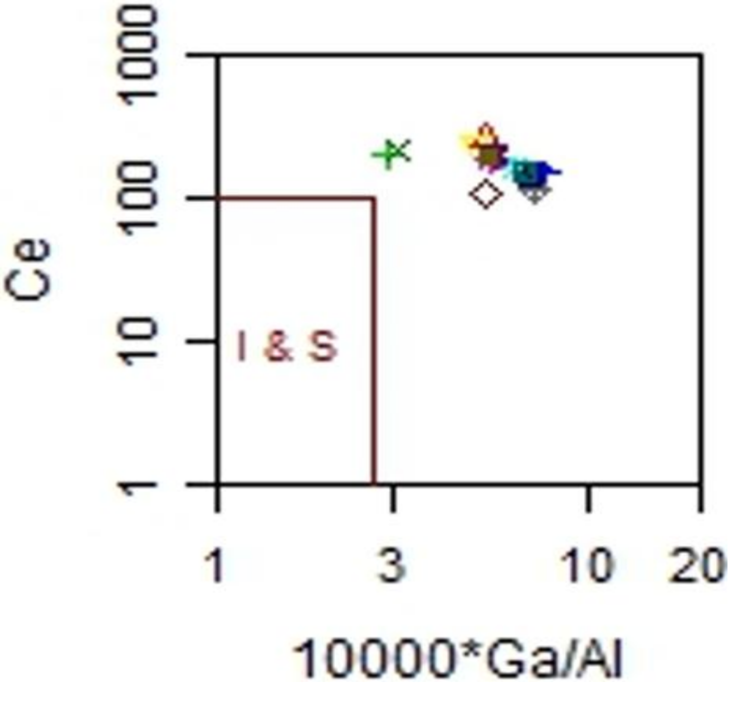
10000*Ga/Al


FeOt/ MgO
100
10
3
1
A
FG
OTG
50
500
5000
Zr+Nb+Ce+Y


Ce
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100
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1
I & S
1
3
10
20
10000*Ga/Al

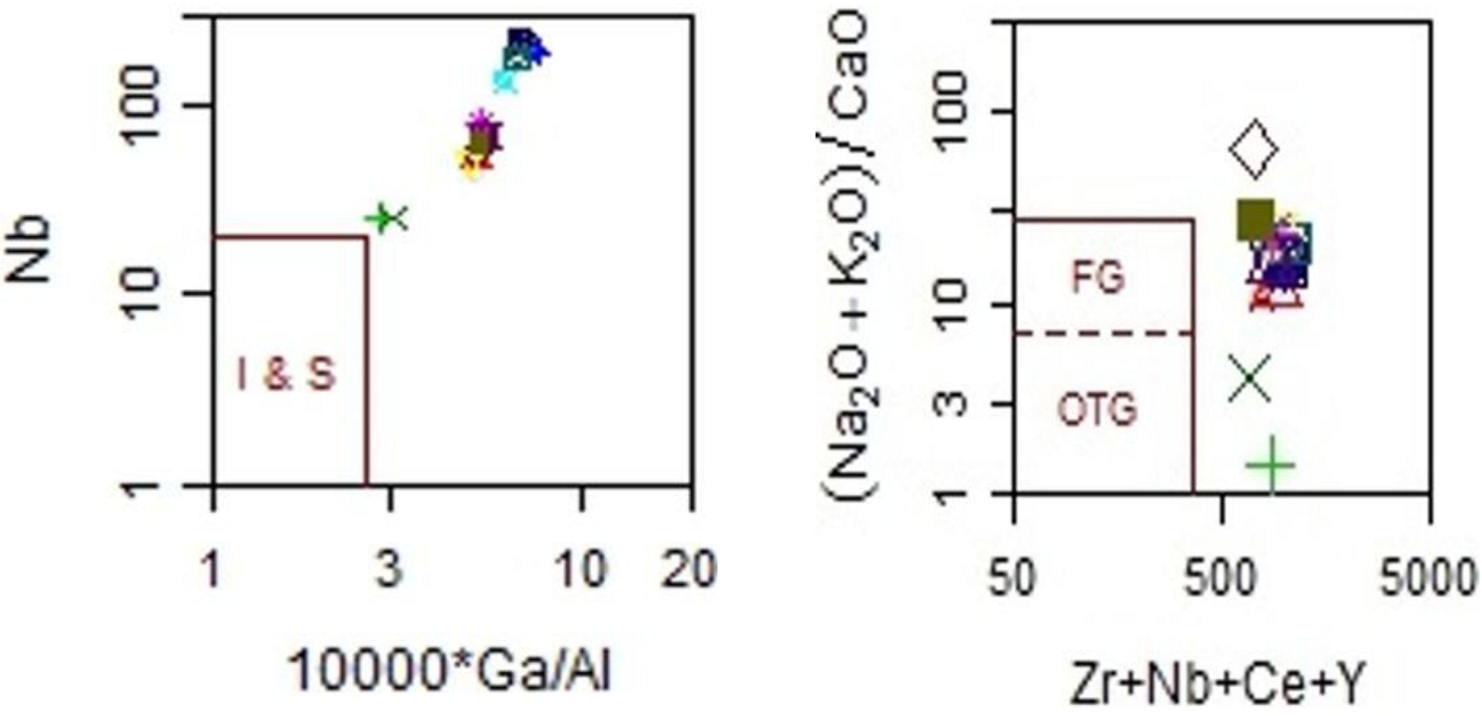


Figure 3. Zr vs 10000*Ga/Al, Y vs 10000*Ga/Al, FeOt/MgO vs Zr+Nb+Ce+Y, Ce vs 10000*Ga/Al, Nb vs 10000*Ga/Al, $(Na_2O+K_2O)/CaO$ vs Zr+Nb+Ce+Y variation diagrams (after Whalen et al., 1987) FG and OGT are the fields for fractionated felsic granites and unfractionated M-, I- and S-type granites respectively.

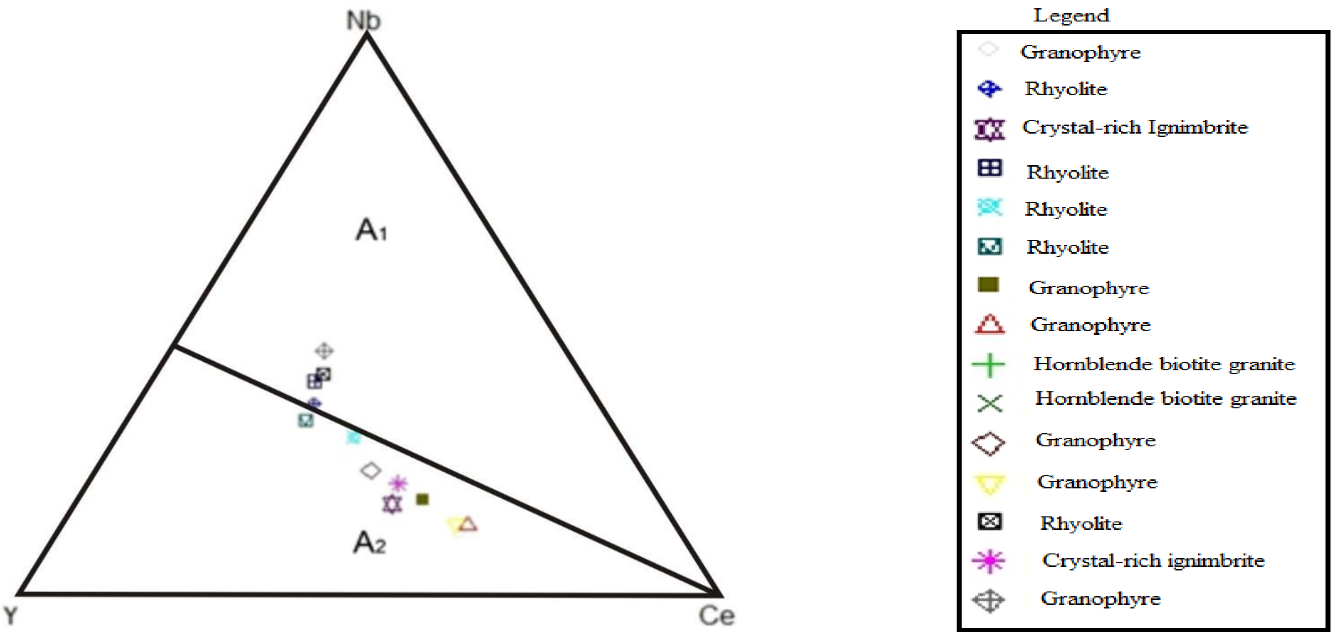


Figure 4. Plots ofNb, Y, Ce of the Birnin Kudu Complex, after (Eby, 1992).

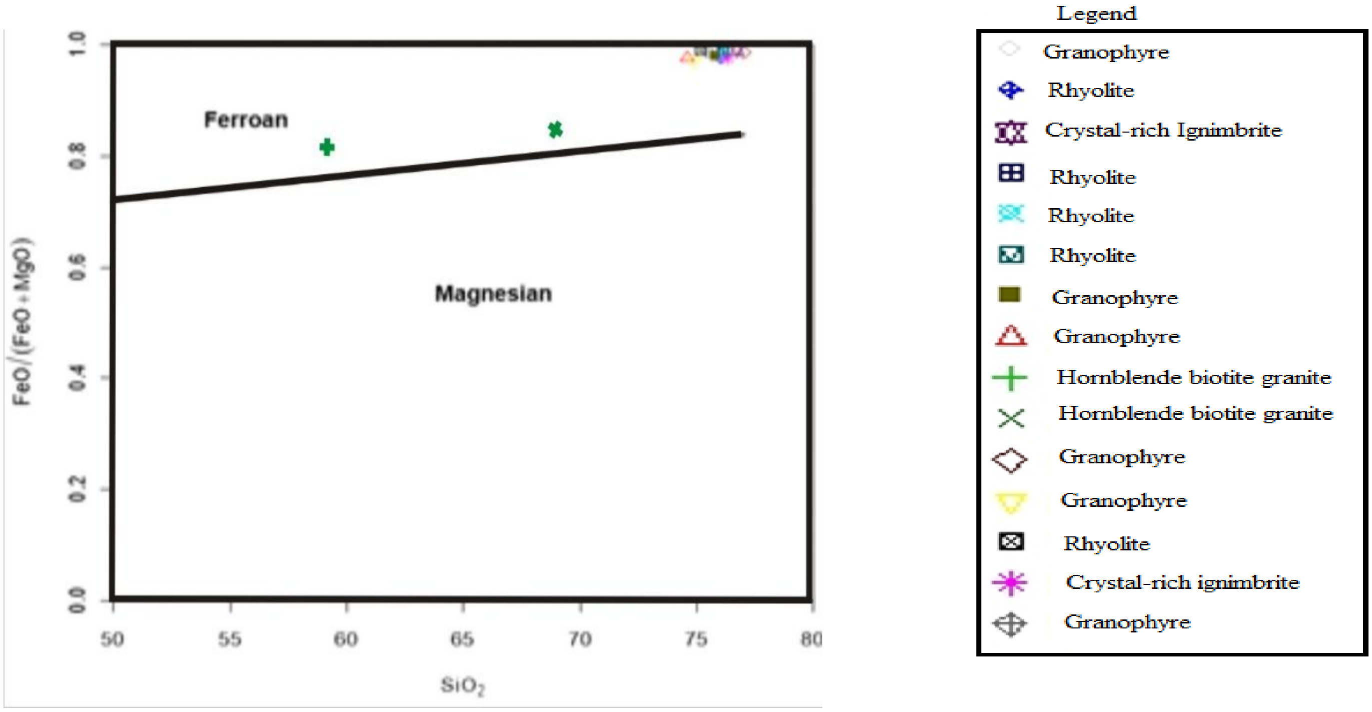


Figure 5. FeO$_{tot}$/ (FeO$_{tot}$+MgO Vs SiO$_2$ discrimination diagram after (Frost *et al*.,2001), for the rocks of the Study Area.

4.6.2.1 Large Ion Lithophile Elements Behaviour (LILE)

Thelarge ion lithophileelements area group of elements having large ionic radii and low charge, and will therefore preferentially concentrate in the liquid until a particular phase with large enough crystallographic sites to accommodate them begin to crystallise. According to Winter, (2014) these elements are largely incompatible with respect to mantle phases (olivine, orthopyroxene, clinopyroxene, garnet etc.). The elements include the following; Cs, Ba, Rb, Sr, Pb and Eu. According to (Dall 'Agnol*et al.*, 1999) the variation in Ba, Sr and Rbcontent is very useful in determining whether magmatic evolution was controlled dominantly by fractional crystallization, partial melting or more complex processes. All the elements that fractionate into plagioclase recorded high values in the rocks of the biotite hornblende granite, with values as high as 1569 ppm recorded for barium (sample B27). This is attributed to the high amount of plagioclase (about 20%) in the rock as revealed by modal analysis (Table 1).

Rubidium is highly enriched in rhyolites, and crystal-rich ignimbrites but relatively lower in both the granophyric and hornblende biotite granite. This can be attributed to the fact that Rb substitutes for K in K-feldspars (Green, 1980) and the rhyolites and crystal-rich ignimbrites are enriched in K-feldspars. Values as high as 431 ppm was recorded in the rhyolites, in contrast to low value (108 ppm) recorded in the granophyre, and the crustal average of 90 ppm for granite.

Strontium and vanadium are much higher in the biotite hornblende granite than in any of the constituent rocks of the Birnin Kudu Complex. Strontium substitute for Ca in plagioclase and to a lesser extent for K in K-feldspars giving rise to strong correlation of Sr with SiO_2 in the hornblende biotite granite and the weak correlation in the rocks of the Birnin Kudu Complex (Figure 7). Sr behaves as a compatible element at low pressure when plagioclase forms early during fractional crystallization of magma (Hanson, 1980).

Strontium decreases steadily with increasing silica content.Strontium decreases readily during the course of fractional crystallisation since it replaces Ca in plagioclase as well as K in K-feldspars. The collinear decrease inSr with decrease in SiO_2 indicates the similarity of the rocks to A-typegranite and that they are products of extensive crystal fractionation. Large variation in the distribution of these lithophile elements in the granite suggests that fractional crystallization was probably responsible for their evolution.

Barium displays considerable scatterin the rocks of the Birnin Kudu Complex andthe host rock (hornblende biotite granite). Furthermore, much higher concentration of barium has been recorded in the hornblende biotite granite than those of the Birnin Kudu Complex (Figure 6).

This trend is attributed to crustal contamination or magma mixing (Wilson, 2007). Barium also replaces K in K-feldspars and hence it decreases during the course of fractional crystallization (El Bouseily and El Sokkary, 1975).Lanthanum and cerium display scattered trend in most of the plots.

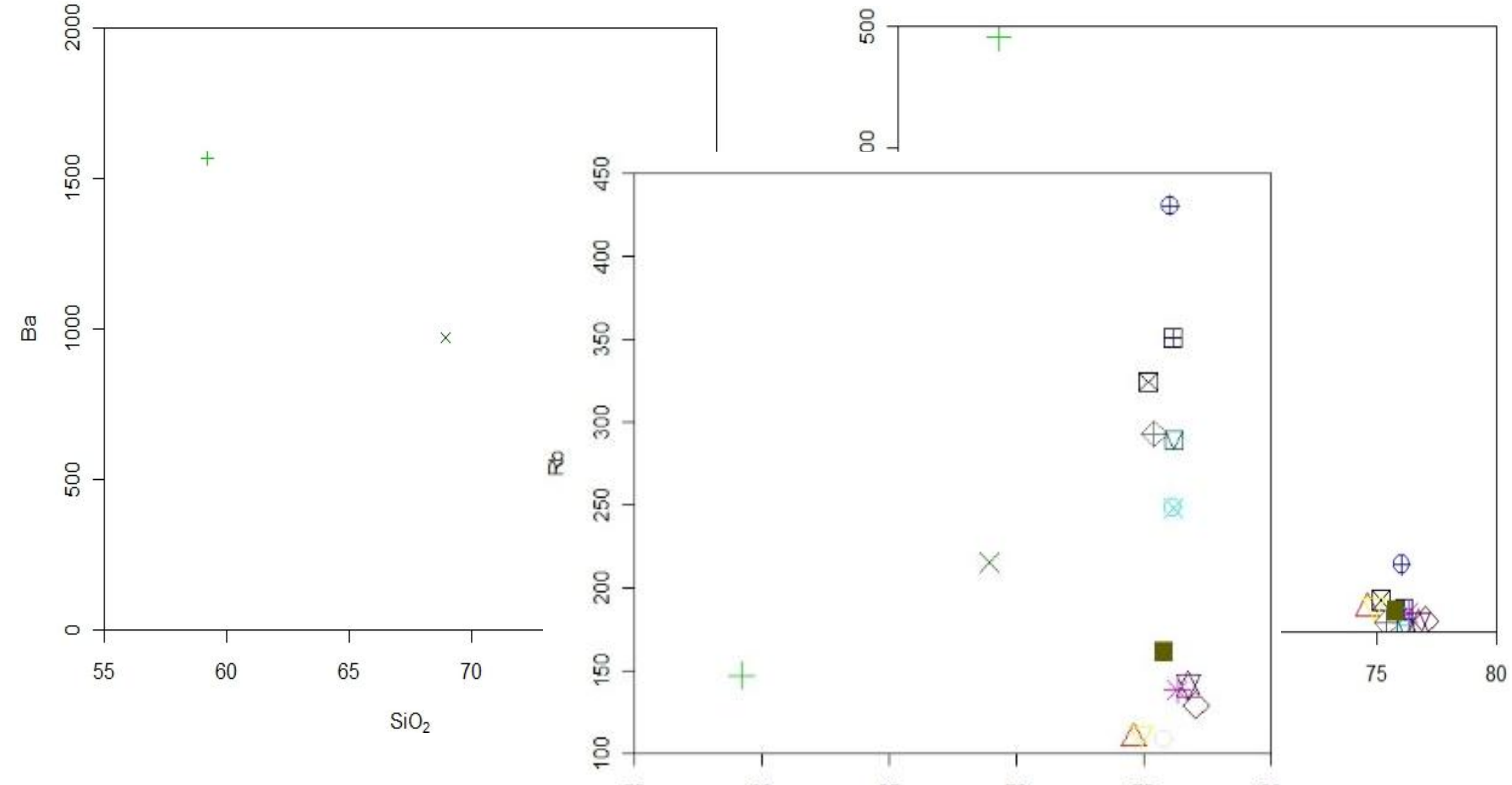
4.6.2.2 High Field Strength Elements (HFSE)

The high field strength elementsare a group of elements with large cation and high charge. Due to difficulty in achieving charge balance, they are commonly excluded from the mantle phases and concentrated in residual liquids. Examples of these elements areTi, Zr, Hf, Nb, Ta, Th and U. Hafnium and Zr are moderately incompatible elements while Nb and Ta are highly incompatible (White, 2005).

Niobium contentin the rocks from the study area ranges from 25 to 222 ppm with the highest value recorded in the rhyolitesand the lowest in thehornblende biotite granite (Figure 6). Niobiumshows positive variation trend in the felsic rocks, with rocks of the biotite hornblende granite having relatively lower concentrations.

Yittriumcomposition ranges from 33 to 249 ppm in the study area (Figure 6). The rocks of the Birnin Kudu Complex contain more (Y > 98 ppm), with the rhyolites in particular having the highest concentrations of >168 ppm. Generally, Y shows similar trend to niobium.

Zirconium concentration is relatively high ranging from 358 to 563 ppm (Figure 6). Zirconium is a classic incompatible element not readily substituting in major mantle phases. It exhibits some scatter and its increase may be attributed to contamination by crustal material and differentiation processes. Zirconiumshows a positive trend with increasing SiO_2. Zirconium is high in both the hornblende biotite granite and as well in the granitoidsof the Birnin Kudu Complex.


Ba
SiO2
Rb
55
60
65
70
75
80
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1000
1500
2000
100
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200
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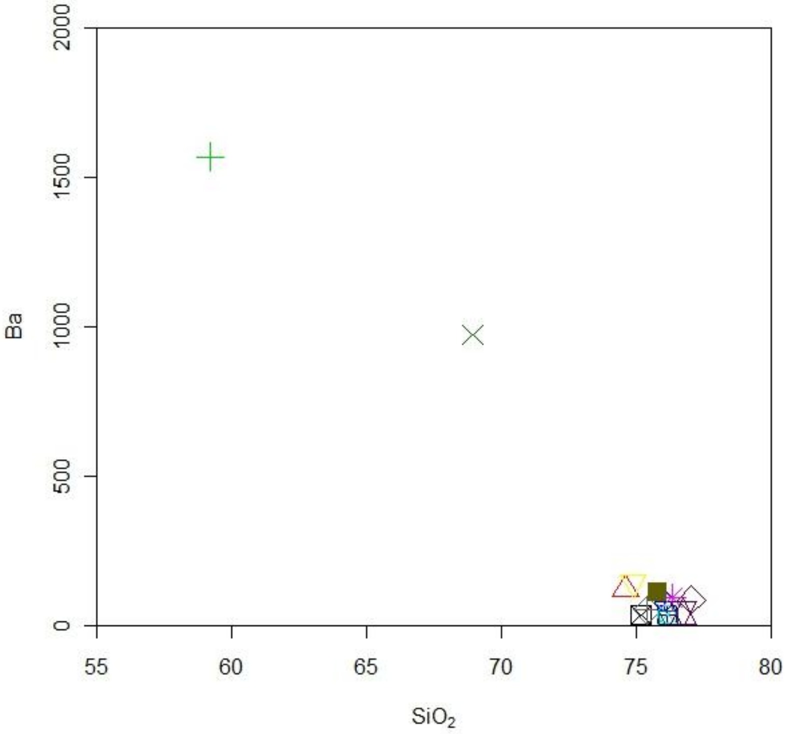
400
450
500


Ba
SiO2
0
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2000
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75
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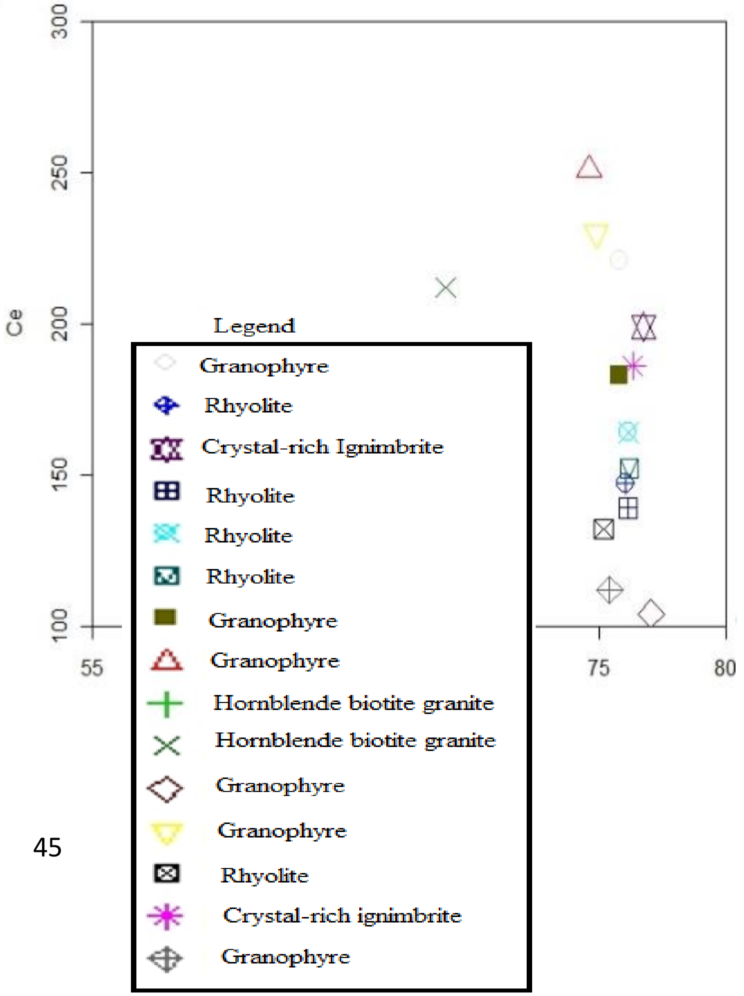
Ce
100
150
200
250
300
55
75
80
Legend
Granophyre
Rhyolite
Crystal-rich Ignimbrite
Rhyolite
Rhyolite
Rhyolite
Granophyre
Granophyre
Hornblende biotite granite
Hornblende biotite granite
Granophyre
Granophyre
Rhyolite
Crystal-rich ignimbrite
Granophyre

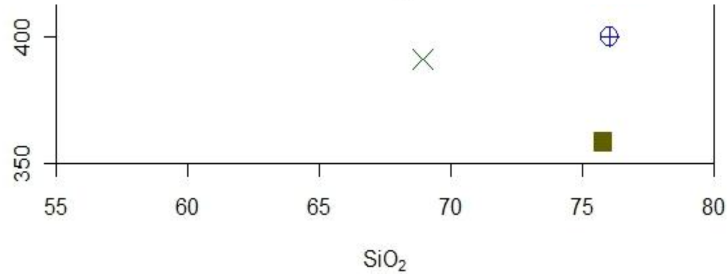
350
400
55
60
65
70
75
80
SiO2

Figure 6. Trace elements content (ppm) versus SiO_2content in the Rocks of the Birnin Kudu Complex.

Tectonic Discrimination

On tectonic discrimination diagrams after (Pearce *et al.*, 1984), all the rocks plot in within plate field, indicating that they are anorogenic (Figure 8). In the first two plots (Rb vs Y+Nb and Nb vs Y), all the rocks plots exactly in the within plate field, while in the last two (Rb vs Ta+Yband T vs Yb), all the rocks of the Birnin Kudu Complex plotin within plate field, in contrast to the basement rocks (hornblende biotite granite) which plots in the syn collisional and on the border line between the within plate and the syn collisional field.

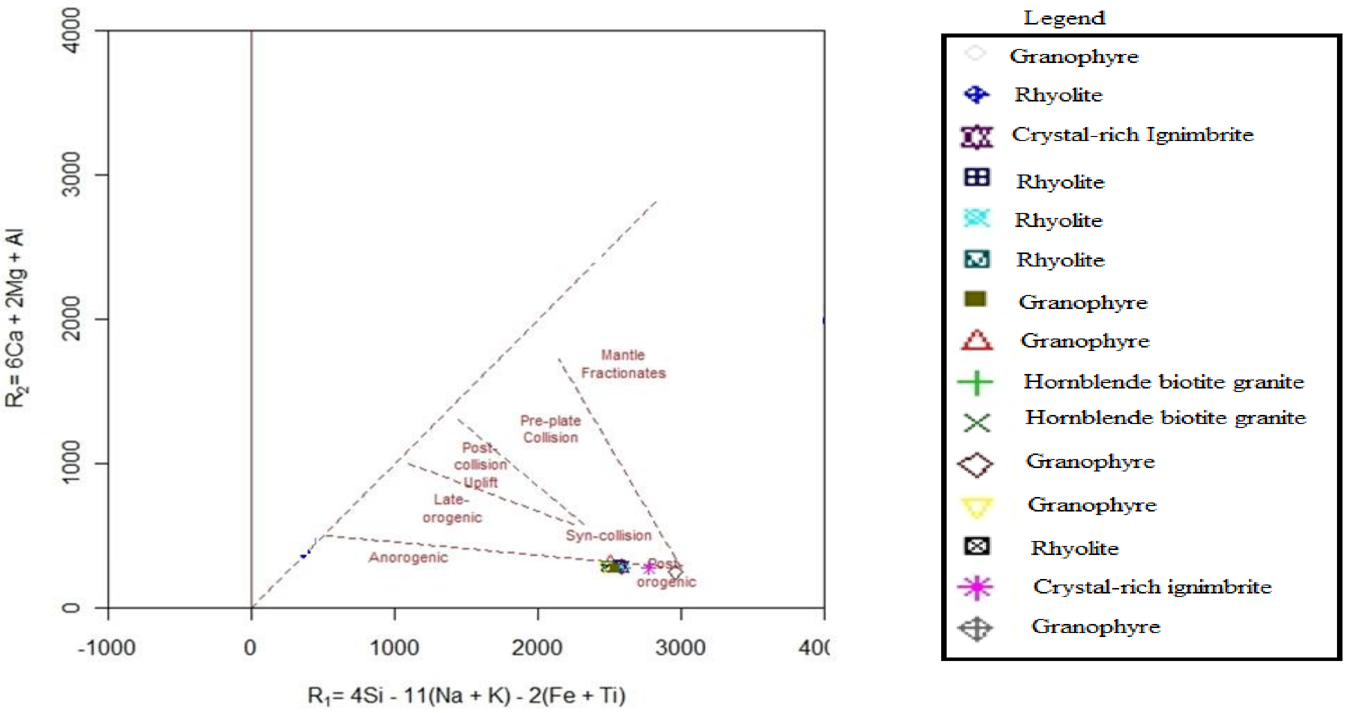

Figure 7. Discrimination plot of the rocks of the Birnin Kudu Complex, after Batchelor and Bowden, 1985.

Aluminium Saturation Index plot for the rocks of the study area, after (Shand, 1943) shows the rocks of the study area plots withinthe metaluminousregions of the plot, this is also in line with the characteristic features of the province(Figure 9).

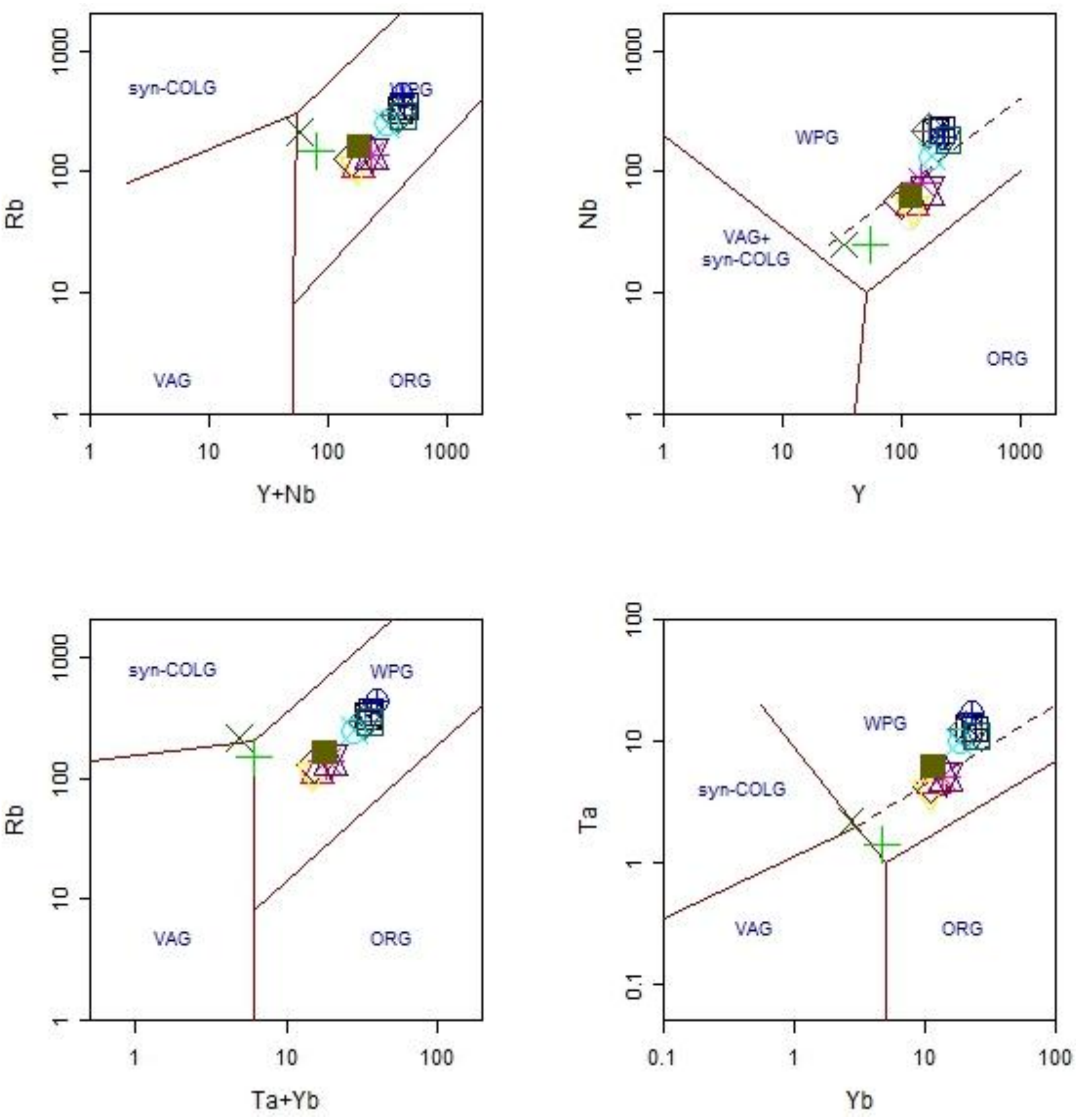

Figure 8. Tectonic discrimination plot of Granitoids of the Birnin Kudu Complex, after (Pearce, 1984)

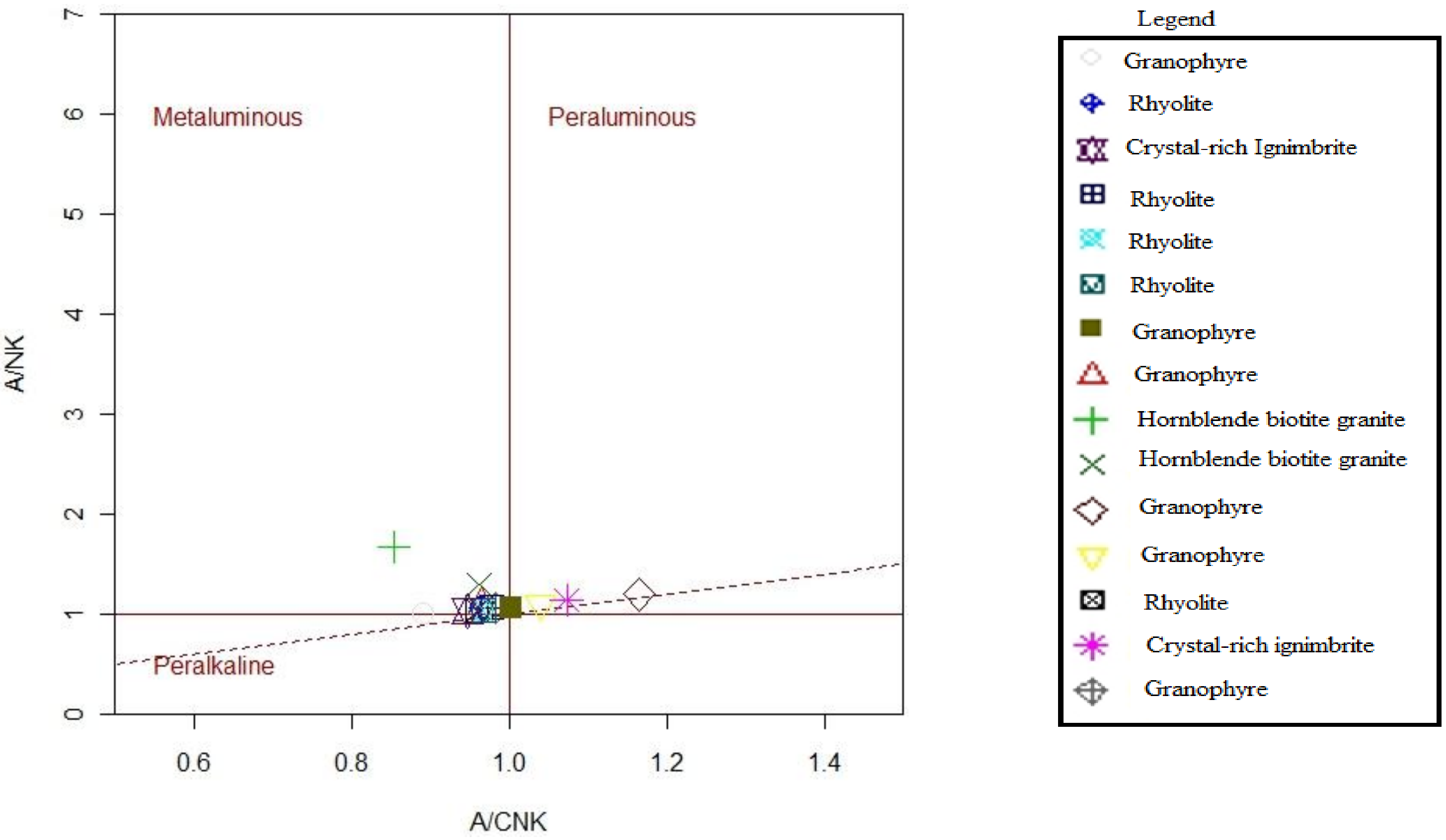

Figure 9. Aluminium Saturation Index plots for the rocks of the Birnin Kudu Complex, after (Shand, 1943).

Plot of Nb/Y against Zr/Ti modified after Perace, (1996)shows that all the rocks of the Birnin Kudu Complex plotted within the field of rhyolite(Figure 10) this cannot be unconnected to the fact that the rocks of the Complex are co-genetic, this is a characteristic feature of A-type granites.

Only the rocks of the basement plotted in the trachyte and basaltic andesite field.

Discrimination plot by Batchelor and Bowden, 1985 (Figure 7) shows clearly that all the rocks of the Birnin Kudu Complex plots within the post-orogenic field, typical of A-type granites.

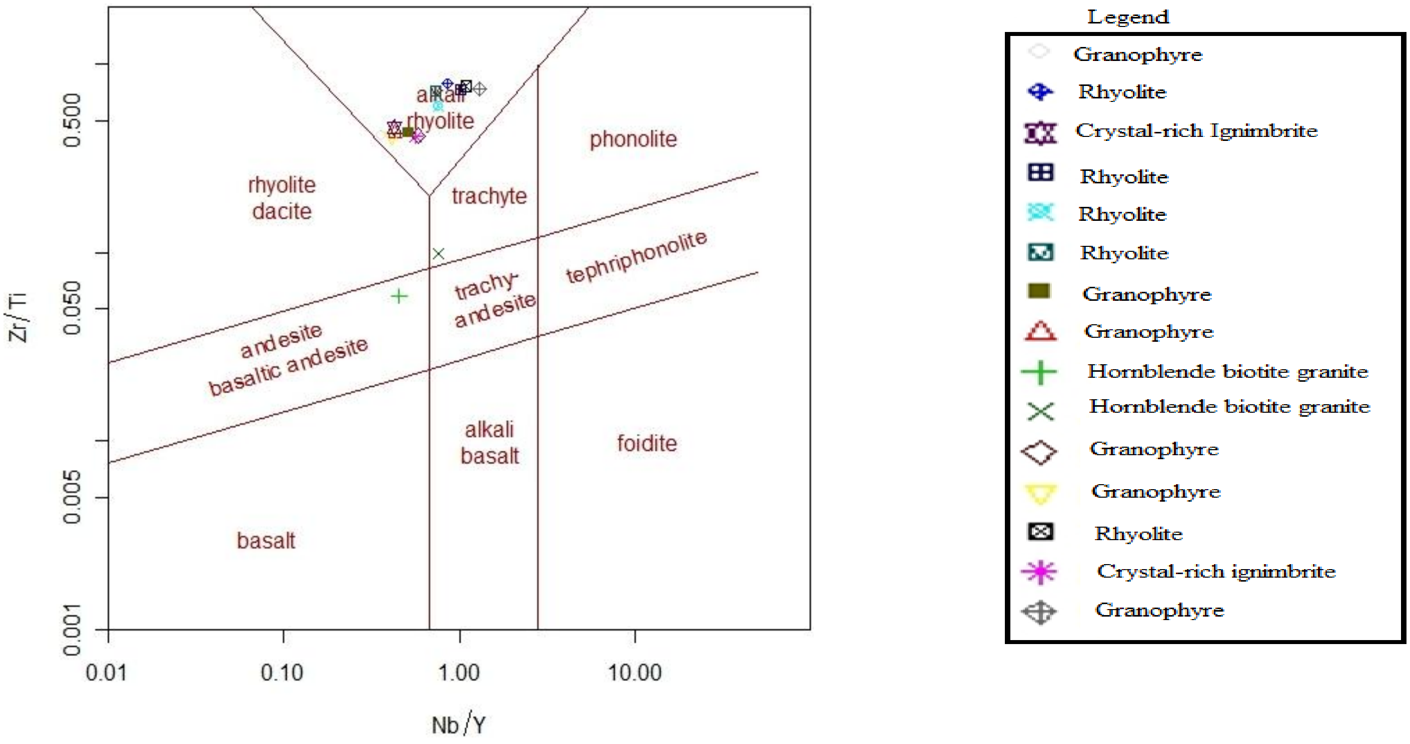

Figure 10. Plot of Nb/Y against Zr/Tifor the rocks of the study area, modified after Perace, 1996.

4.6.3 Rare Earth Elements (REEs) Distribution Pattern

The REEs are a group of 17 elements with atomic numbers from 57 (La) to 72 (Lu). The elements are characterized by relatively large ionic radii, andvalences of either +2 or +3. Their ionic radiusdecreases progressively from La^{3+} (115 pm) to Lu^{3+} (93 pm), and thus the characteristics that governs their relative behaviour (White, 2005). They are further subdivided into Light REEs (La-Gd) and Heavy REEs (Tb-Lu). Y is generally included among the HREEs because its ionic radius is very similar to that of the HREE. The HREEs are more incompatible than the LREEs. The REEs are very useful for petrogenetic investigation.

The hornblende biotite granite is relatively more enriched high in the HREEs but depleted in the LREEs (Figure 12). The ∑REE is lower in the hornblende biotite granite compared to the rocks of the Birnin Kudu Complex.

The concentration of the REEs of an igneous rock are usually normalized against their concentration in standard (e.g. Chondrites) in order to smooth out large differences in concentration between one REE and the others.The rare earth elements (REE) data is presented in Table 2, and the REE spider diagram is presented in (Figures 12, 13 and 14). Europium exhibits distinct different behavior from the general trend of the REE. This is referred to as the europium anomaly and any value above 1.0 indicates a positive anomaly while concentrations less than 1.0 are regarded as negative anomaly. Europium anomalies are chiefly controlled by feldspars, particularly in felsic magmas, for Eu (present in the divalent state) is compatible in plagioclase and K-feldspars, in contrast to the trivalent REE which are incompatible. The degree of enrichment for a particular REE relative to chondritic abundances is a function of the initial concentration of that element in the source and the degree of partial melting, and subsequent fractional crystallisation (White, 2005).

Generally, the REE patterns follows a gentle downward sloping pattern with a marked abrupt downward spike, indicative of negative Eu-anomaly. Thegranitoids of the Birnin Kudu Complex show relatively higher REE concentrations than those of the basement surrounding the Complex (Figure 11). The granitic rocks of the Birnin Kudu Complex are enriched in LREEs compared to the basement rock (hornblendebiotite granite). All of the rocks displayed negative Eu-anomalies(Eu/Eu*) relative to chondritic values (Nakamura, 1974), which is a characteristic feature of all alkaline A-type granites the world over (Anderson 2001; Schitt*et al* 2000), the largest negative Eu is observed in the rhyolites and the ignimbrites. There is a more extensive negative Eu-anomaly signature in the Birnin Kudu Complex compared to those of the surrounding basement rocks (biotite hornblende granite). The Eu-anomaly is most pronounced in the rhyolites (Figure 13). This can be interpreted as the K-feldspars in the alkaline rich rocks of the ring Complex showing a stronger control on the Eu-anomaly compared to the plagioclase in the rocks of the surrounding basement. The depletion in Eu is in line with the works of (Aleksiyev, 1970; Bowden and Van Breemen, 1972; Bowden and Whitely, 1974).

Chondrite normalization plot of the rare earth elements shows high LREE values and low HREE values for the hornblende biotite granites. The granophyres indicates lower degree of partial melting, this is reflected in the higher concentrations of the LREEs (Figure 11).

A-type granite characteristically have enriched relatively flat to somewhat HREE depleted chondrite normalized REE pattern with significant Eu-anomalies (Collins, *et al* 1982) as seen in (Figure 11).

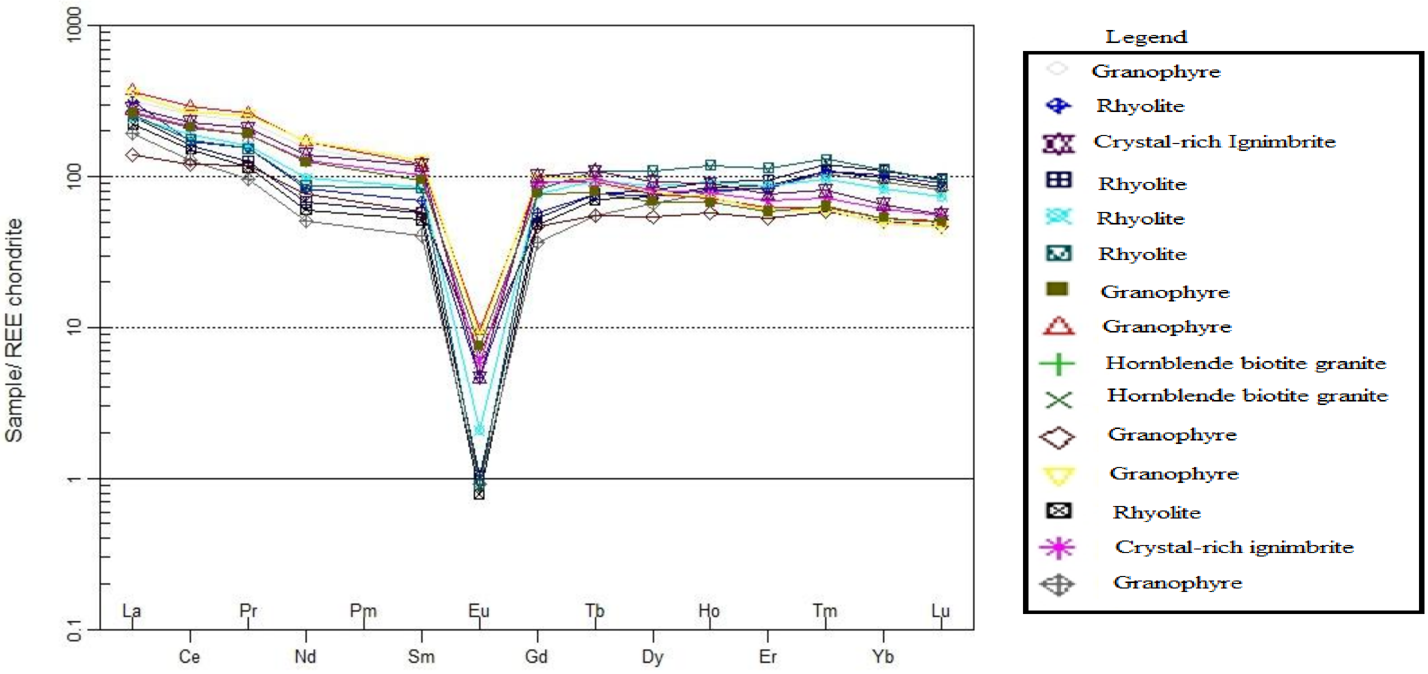

Figure 11. Chondrite Normalised plot of theGranitoids of the Birnin Kudu Complex. Normalising values are those of Nakamura, 1974.

Figure 12 is a chondrite normalized plot of the surrounding basement (hornblende biotite granite) while figure 13 is a combination of all the rocks in the study area including the surrounding basement. Comparing the Eu-anomaly in the plots, those of figure 12 do not show significant Eu-anomalies.

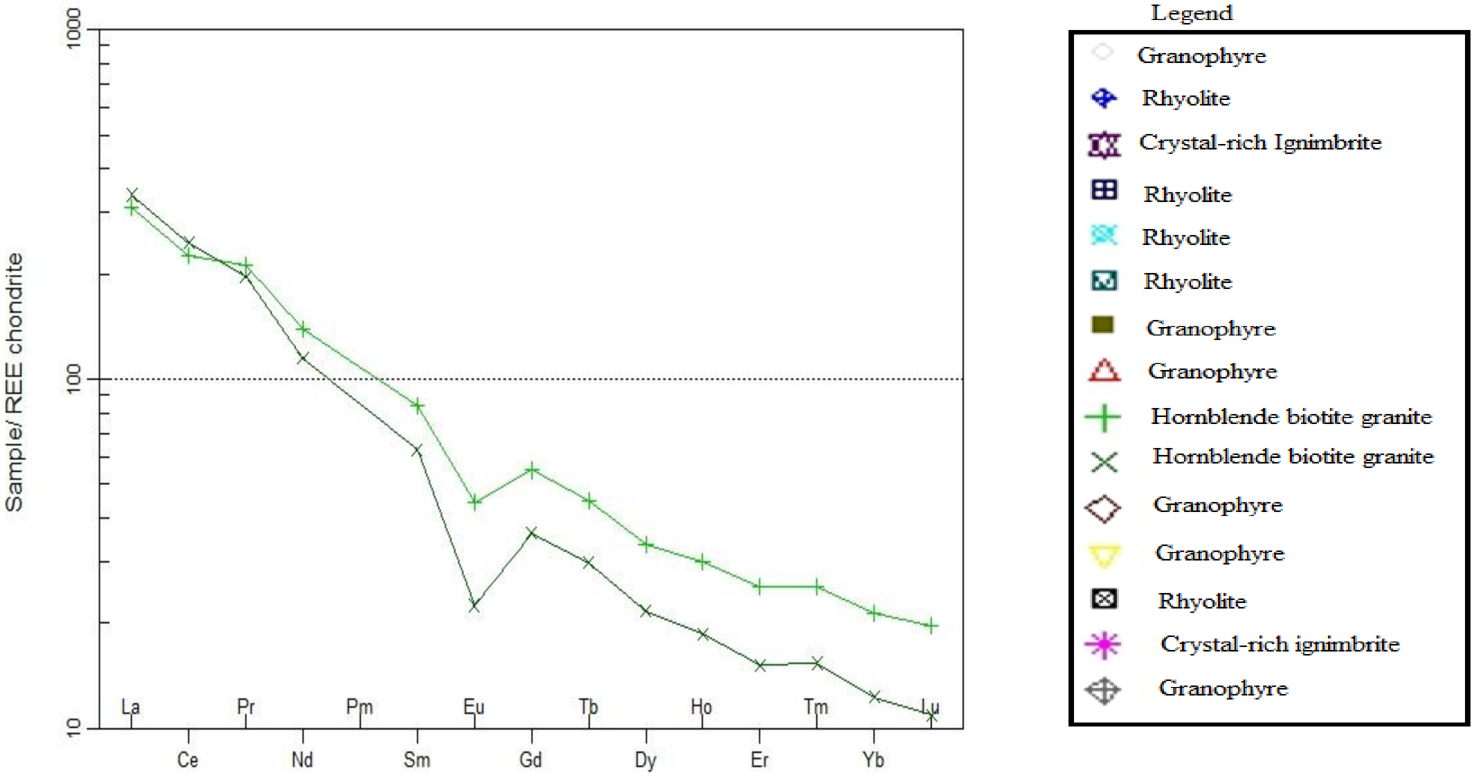

Figure 12. Chondrite Normalised plot of theSorrounding Basement (Hornblende Biotite Granites) of the Birnin Kudu Complex. Normalising values are those of Nakamura, 1974.

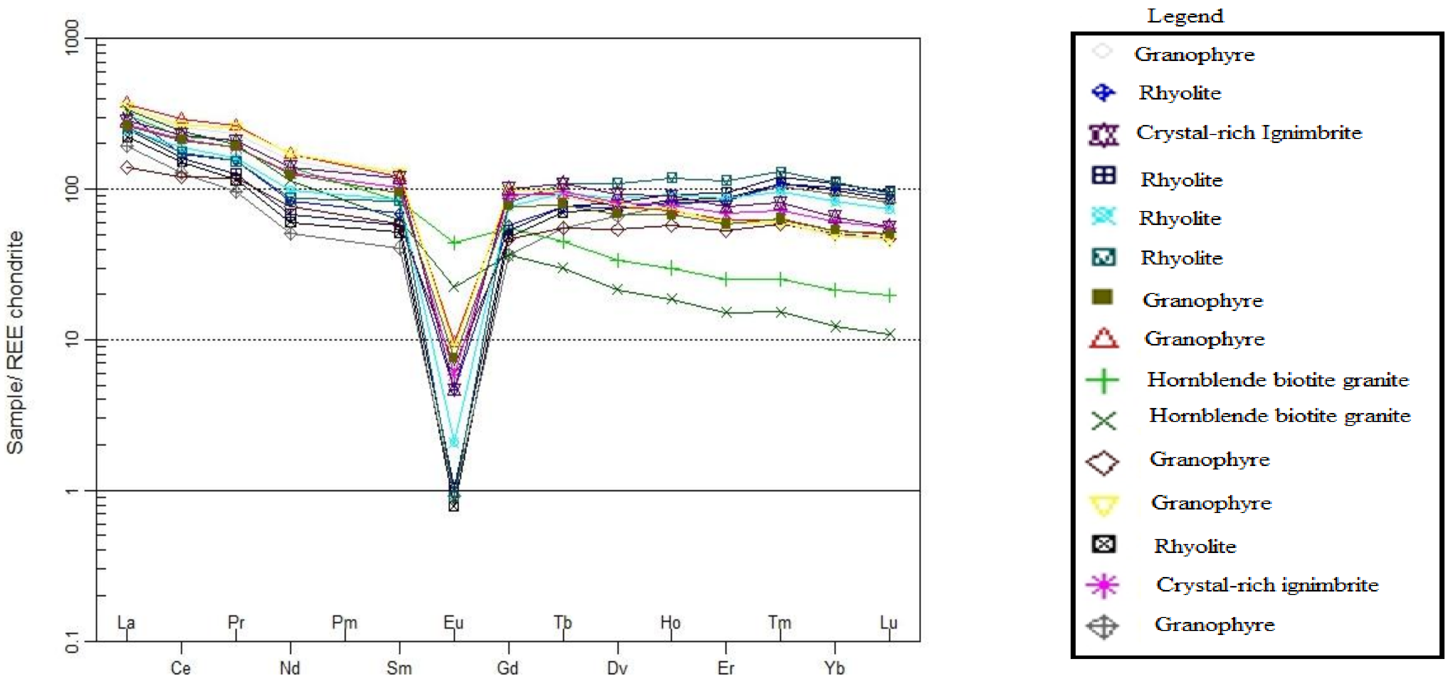

Figure 13: Chondrite Normalised plot of all the rocks within the study areaicluding the hornblende biotite granite. Normalising values are those of Nakamura, 1974.

4.7 STRUCTURAL GEOLOGY

The Birnin Kudu Complex is simple in terms of structures and distribution of major rock-types. In some complexes, such as Amo, a close approach is seen to the ideal pattern of concentric intrusion controlled by successive cauldron subsidence. In others, such as Jos-Bukuru and Kwandonkaya, the pattern of granite intrusion is too intricate and irregular to permit a ready interpretation of the structures. The area is part of the Nigerian Younger Granite Province which is generally anorogenic or post-collisional therefore, there are little or no evidencies of tectonic activities recorded within the study area, exceptfor the rhyolites which are highly jointed (Plate III), this can be attributed to the rapid cooling of the magma as it crystallizes on the surface. The direction of strike for this joints were recorded and a general E-W trend is dominat with a N-S stress direction.

The Birnin Kudu Complex was emplaced as a shallow dipping cupola since there are no evidencies of circular ring fractures in the Birnin kudu Complex. This shallow dipping cupolas is what (Bowden and Kinnaird 1978) refer to as the terminal phase of magmatic activityrelated to the evolution of a Complex.

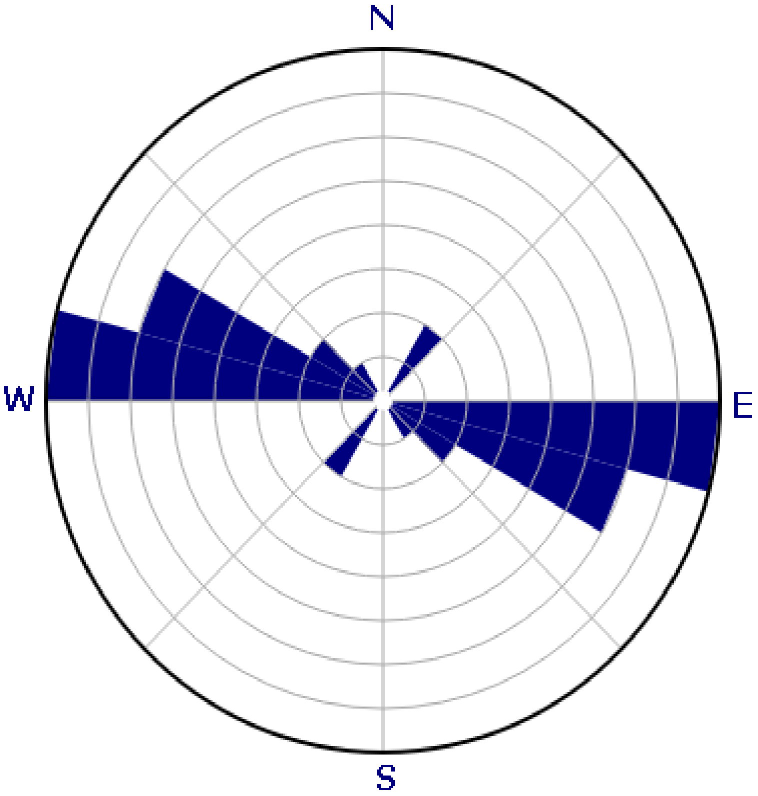

Figure 14: Rose diagram showing the dominant trend in the highly jointed rhyolite in the Complex.

CHAPTER FIVE

DISCUSSION OF RESULTS

5.1 BACKGROUND

Field observations, petrography and geochemical data were integrated and analysedin order to decipher the magmatic processes that resulted in the formation of the Birnin Kudu Complex. On the basis of the field observations, it can be said that magmatism began with a thrusting forward phase (protrusive), now preserved as range of ridges of rhyolites and crystal-rich ignimbrites, withboulders of granophyres. The rocks of the Birnin Kudu Complex are similar to other Complexes in the Nigerian Younger Granite Province, but in the Birnin Kudu Complex, there is no concentric arrangement of the rock units.

5.2 FIELD RELATIONSHIPS

Two contrasting modes of granite emplacement exist in the Nigerian Younger Granite Province, steep-sided units emplaced along polygonal or circular ring fractures or shallow outward dipping cupolas. Emplacement as shallow dipping cupola is the case at the Brinin Kudu Complex. Bowden and Kinnard (1978) referred to this as the terminal phase of the magmatic activity related to the evolution of a complex. The emplacement of the Birnin Kudu Complex without any evidence of ring-dykes and cauldron subsidence. Field studies on the Birnin Kudu Complex revealed that the granophyric zones of the alkali feldspar granite represents the manifestation of sub-volcanic nature of the rocks and metasomatism associated with the roof and margin of the pluton in contact with a colder basement rock.

5.3 PETROGRAPHIC STUDY

Petrographic studies revealed that quartz and K-feldspars arethe dominant mineral in the rocks of the Birnin Kudu Complex

The rapid cooling, diffusion and nucleation within felsic magma usually lead to the situation where time may not be enough forcrystallisationto take place, resulting in the formation of glassy component in the rocks as observed in the Birnin Kudu Complex. This occurs more readily if the magma system is highly polymerised as evidenced by the greater abundance of rhyolitic glass relative to basaltic glass in nature. Once thermal agitation is sufficiently reduced, molecules will bond to their immediate neighbours. Thus, the liquid structure is retained and the solid state is attained simultaneously. This stage is indicative of rapidly cooled, water-saturated magma and alkalis loss due to degassing in near surface environments (Shelly, 1992; Vernon, 2004).

5.4 GEOCHEMICAL VARIATION TRENDS

Based on geochemical data, major oxides distribution shows that the rocks of the Birnin Kudu Complex are metaluminous. In addition, the rocks also show a distinctive REE pattern characterized by prominent Eu-anomaly.

Enrichment in the high field strength elements (HFSE), which are typically hosted in accessory phases, is a characteristic feature of A-type granite in general (Dall' Angol and Ramo 2009, Frost *et al*. 2002). The granophyre exhibit the highest concentration of Rb, Nb, and Y compared to the granite of the Basement Complex.

In the study area, enrichment of Zr and Nbin the granite and rhyolites of the Birnin Kudu Complex probably reflect the formation of alkali zirconosilicate and niobosilicate complexes (such as Na_2ZrF_6 and Na_2Nbf_7) in the melt (e.g. Watson, 1979, Collins *et al.*, 1982). This in turn, may prevent early saturation of the melt in zircon. Watson (1979) has reported that the solubility of zircon increases with the increase in alkalinity index.

The depletion in REE in the biotite hornblende granite of the basement complex relative to the rocks of the Birnin Kudu Complex is pronounced. The sum of REE (∑REE) in most of the granite is quite low when compared to average REE content of 250 ppm in granite as reported by (Emmermann*et al.*, 1975). Chondrite normalized plot of the rare earth elements shows high LREE enrichment relative to the HREEin the biotite hornblende granite. This suggests that the melts from which these rocks were formed equilibrated with residual garnet which is the principal reservoir of HREE, and may also contain high concentration of zircon which is also responsible for HREE retention (Compton, 1978). Moreover enrichment in LREE is the hallmark of crustal and calc-alkaline rocks in general (O'Nions and Pankhurst, 1974) and the depletion in HREE in most of the rocks is due to their concentration in garnet in the residual rock.

5.5 TECTONIC EVOLUTION OF THE COMPLEX

The alkaline character of the rocks, hypersolvus nature of the granites and rhyolites indicates that they conform to the mineralogical and geochemical traits of typical within-plate A-type suites. Looking at the tectonic discrimination diagrams (Pearce et al. 1984), it indicates that the rocks of the Birnin Kudu Complex plot in the within-plate granite (Figure 8) and in the A-type granite field of Whalen, et al. (1987). These observations indicate that the complex was emplaced in an extensional tectonic regime, during cooling, relaxation, fracturing and crustal attenuation, which followed the termination of the Pan-African orogeny.

5.6 PETROGENESIS

Field relationships, petrographic and geochemical studies are the basic criteria for elucidating the petrogenesis of rocks. Based on field relationships, the rocks ofthe Birnin Kudu Complex with the exception of the granophyres which is sub-volcanic, were found to be volcanic and exhibiting typical A-type signatures.

The origin of A-type felsic parental melts is the topic of ongoing debate (Frost *et al.*, 2010, Dall'Agnol, 2012). For example, (Martin,2006) considered the A-type graniteto be of crustal origin resulting from fenitization in an extensional environment whilst (Bonin, 2007) regardedthe A-type granite as originating from the mantle as transitional-alkaline mafic to intermediate magma compositions. Suggested examples of a suitable crustal protolith, as summarised by Poitrasson*et al.*, (1995) includetonalitic rocks (Sylvesteer, 1989; Creaser, 1991), felsic rocks that are already melt depleted during a previous anatectic event (Collins *et al.*, 1982), highly metamorphosed crustal rocks that have been partially hydroxylated and F-enriched (Skjerlie and Johnston, 1992) and crustal rocks metasomatised by a mantle-related volatile-rich phase (Martin, 2006).

Distinctsource-rocks of A-type granitecan be identified with sufficient geochronological data as done by (Anderson *et al.*,2009) where they determined the distinct source-rocks of A-type granite in southwestern Fennoscandia by recording Lu-Hf systematics of inherited domains in zircon crystals.Bowden and Turner (1974) suggested that non-peralkaline granite may have developed in the lower crust as a result of arching of the crust, volatile concentrations and heat focusing, but that peralkaline granite could also be of crustal origin developed by contact anatexis during the limited phases of basaltic magma eruption.

Based on certain trace element (Nb, Ce and Y) distributions by (Eby, 1992) the A type granitoids were further separated in two groups, A1 and A2 (Figure 5). The rhyolites almost entirely plot in the

A1 field while the granophyres and the crystal-rich ignimbrites all plot in the A2 field. The rhyolites in the A1group were interpreted as differentiates of basalt magma derived from an Oceanic Island Basalt (IOB)-like source whilethe granophyres and the crystal-rich ignimbrites that plot in the A2group were derived from the subcontinental lithosphere or lower crust. The rhyolites invariably are associated with true anorogenic (within plate) settings while the granophyres and the crystal-rich ignimbriteswere emplaced in post-collisonal, post-orogenicsettings (Figure 8). The rhyolites can be interpreted to be derived from magma sourced from the enriched mantle, this enrichment may have occurred during an earlier period of subduction. The granophyres and the crystal-rich ignimbrites were interpreted to be derived from the interaction of earlier derived magma with the crust, leading to the continental margin trace element signatures.

The large variation in lithophile elements shows that fractional crystallisation is responsible for the formation of the rocks of the Birnin Kudu Complex. The rocks of the Complex were formed within plate(Figure 8). This indicates that they aregranitoids with typical A-type signatures(Perace, 1996).

Similar trace and REEs suggest that the rhyolite and crystal-rich ignimbrite are co-magmatic with the alkali granite but only represent the extrusive equivalent of the granite. Also, the clustering in most of the plots (Figures: 2 and 7etc.) may be an indication of similar origin and less magmatic differentiation.

The general alkaline character of the granitoids of the Birnin Kudu Complex points to the fact that they conform to the mineralogical and geochemical traits of typical within-plate A-type suites (Frost and Frost 2013). From the tectonic discrimination diagrams (Perace*et al.*, 1984) the Birnin Kudu granitoids plots within the field of within-plate granite, and in the A-type granite field of (Whalen *et al.*, 1987*).*This observations indicates that the Complex was emplaced in an extensional tectonic regime, during cooling, relaxation, fracturing and crustal attenuation, which followed the termination of the Pan African Orogeny.The rocks of the Complex have a pronounced negative Eu-anomaly especially the rhyolites and the crystal-rich ignimbrites indicating a plagioclase bearing melt source.

5.7 VOLCANIC VENT MODEL FOR THE BIRNIN KUDU COMPLEX

The Birnin-Kudu Complex is a typical ring complex and it is part of the Nigerian Younger Granites Province. Volcanic eruptions may have taken place from dispersed vents, above pipes and fissures. There were no evidence of cauldron subsidence structures and ring-dykes and the rhyolites do not appear to be related to cauldron subsidence. The volcanics in the Birnin Kudu Complex are extrusive in nature, there were no vents mapped in the area.

The Birnin Kudu Complex does not show a supposedly complete cycle of the Nigerian Younger Granite magmatic activity as illustrated elsewhere by Macleod *et al*., (1971) and Jacobson and Macleod (1977), this may account for the missing units in the suits of rocks expected in a typical Nigerian Younger Granite Complex or perhaps, much of the earlier volcanic felsic lavas and associated pyroclastic units have been removed by erosion, rock units were not documented.

Eruption of crystal-poor rhyolite from shallow magma chamber may have caused degassing, which forced undercooling and consequent granophyric crystallization of some of the magma remaining in the intrusion.

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The Birnin Kudu Complex was mapped in detail and a geological map produced on a scale of 1:25, 000. The Complex comprises about 40% rhyolite, 35% granophyre, and 25%crystal-rich ignimbrite. The rocks in the study areaare post-orogenic graniteemplaced within plate. They showmetaluminouscharacteristics typical A-type granite signatures. The Complex was emplaced in the biotite hornblende granite.

Petrographic studies showthat major mineral constituentsare quartz, orthoclase, plagioclase, microcline, augite, biotite, hornblende, sanidine and few opaque minerals. The rhyolite outcrops are massive and occur in form of ridges. The basement rock is the "oldest rock" unit in the study area.

The constituent rocks of the Birnin Kudu Complex exhibit trace and REEs distribution patternsthat suggestthat they areco-magmatic. They are moderately enriched in LREE relative to the HREE. They exhibit pronounced negative Eu-anomaly. However, these rocks arecharacterised by the presence of large-ion lithophile elements Cs, Rb, Nb, Th, U, Sm, Y, and low content of Ba, Sr, Ti, and P. Texturally, the A-typegranite are fine-grained indicating near surface crystallisation as hypabyssal intrusive. Similar trace and REEs patternssuggested that the rhyoliteis co-magmatic with alkali granite and represents the extrusive equivalent of the granite.

The hornblende biotite granite displayed high concentrations of LREE compared to low concentrations of HREE and very slight negative Eu-anomaly as against those of the

Complex. Their overall geochemical features indicate the constituent rocks of the Birnin Kudu Complex were formed from partial melting of hornblende-rich crustal source in an orogenic (sync-to post collision) tectonic setting. Also, enrichment in the LREEs relative to the HREEs could be as result of the presence of hornblende (Rollinson, 1993).

6.2 MINERALIZATION

Mineralization commonly associated with A-type granites include Sn, Mo, Ba, Nb, W, Ta, F, Be, Li, and REEs (Eby, 1990). Uranium and Th recorded significant concentrations in the rocks of the study area. Concentrations as high as 8.9 ppm and 29.3 respectively were recorded, which are relatively high in comparison with the average crustal abundance of 4 ppm for U and 18 pp for Th in granites (Rogers and Adams, 1969). Concentration of Sn is low in the Alkali granites and the other rock units of the Birnin Kudu Complex, compared to those of Banke and Ririwai Complexes. This suggests that Sn does not form an independent mineral phase in an alkaline environment but substitute mainly in the common rock-forming minerals and in certain cases in pyrochlore and other Nb-rich accessory minerals during sodic metasomatism (Ogunleye*et al.,* 2006).

6.3 ECONOMIC GEOLOGY

For thousands of years man has relied on the structural reliability of stone to take on the world’s greatest architectural feats. From Egypt’s timeless pyramids, to Michelangelo’s David, great men have always looked to nature for the most durable and pure building materials. The same is true today, stone continues to be the most durable, beautiful, and low maintenance material to work with. When you install stone into your kitchen or bathroom, you capture thousands of years of the world’s hard work in your home.

In Africa, most of the commercial granites come South Africa (73%) and Zimbabwe (22%). The remaining 5% comes from Angola, Zambia, Egypt, Namibia and Nigeria (Pivko, 2004).

The dimension stone industry in Nigeria is still in its infancy and therefore the need to key into this lucrative business, looking at the federal government’s interest in diversifying the economy through the improvement of the solid mineral industry. The study area is endowed with hard massive granites exhibiting typical features of granites used as dimension stones including beautiful colours (pinkish, whitish and dark colours), lack of pronounced cracks (typical of anorogenic granites) and durability.

6.4 CONTRIBUTION TO KNOWLEDGE

This research project is the first geological study carried out on the Birnin Kudu Complex at the scale of 1: 25,000.Therefore, the major contribution of the work to knowledge are

(1) Production of a geological map of the Complex on a scale of 1: 25,000.

(2) Petrological characterisation of the Complex and delineation of the various lithologies in the Complex.

(3) Petrographic description and mineralogical characterisation ofconstituent rocks of the Birnin Kudu Complex.

(4) Geochemical data on the constituent rock units of the Birnin Kudu Complex have been assembled.

(5) The Complex was clearly delineated and classified as belonging to the Younger Granites Province of Nigeria.

(6) Petrogenetic description of the Complex was attempted.

6.5 RECOMMENDATIONS

. Oxygen isotope analysis in quartz should be employed in order to determine the age of the Complex and produce a suitable petrogenetic model for the Complex.

Suitable geophysical survey for deep seated investigation should be carried out like those of Ajakaiye*et al*., (1986) with a view to investigate and identify the magma chamber.

Distinct source of A-type granite should be identified by obtaining sufficient geochronological data, as done by (Anderson *et al*., 2009).

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