GEOLOGY, GEOCHEMISTRY AND RARE METAL POTENTIAL OF SOME PEGMATITES IN MAKARFI AREA, PART OF ZARIA SHEET 102 NE, NORTH CENTRAL BASEMENT COMPLEX OF NIGERIA

BY

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DECLARATION

I declare that the work in this thesis entitled **"GEOLOGY, GEOCHEMISTRY AND RARE METAL POTENTIAL OF PEGMATITES IN MAKARFI AREA, PART OF ZARIA SHEET 102 NE, NORTH CENTRAL BASEMENT COMPLEX OF NIGERIA"** has been carried out by me in the Department of Geology. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

…… ……

Raliya Aminu Hayatu Date

CERTIFICATION

This thesis entitled **"GEOLOGY, GEOCHEMISTRY AND RARE METAL POTENTIAL OF SOME PEGMATITES IN MAKARFI AREA, PART OF ZARIA SHEET 102 NE, NORTH CENTRAL BASEMENT COMPLEX OF NIGERIA"** by Raliya Aminu Hayatu meets the regulations governing the award of the degree of Masters of Science in Geology (Mineral Exploration) of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

I dedicate this work to my father (Alhaji Aminu Hayatu), my mother (Hajiya Rukayya), my husband (Dr. Aminu Hayatu) and our little son Haneef (Hayat Aminu Hayatu), as well as all my brothers and sisters.

ABSTRACT

Geological mapping of Makarfi area on a scale of 1:50,000, petrographic and geochemical studies of selected rocks and mineral samples were carried out in order to unravel the evolutionary history and rare metal mineralization potential of the pegmatites in the area. The area is underlain by gneisses, granites and pegmatites. The granite suites vary in texture and mineralogy and comprise of; porphyritic hornblende-biotite granite, coarse grained biotite granite, medium grained biotite granite and medium grained muscovite granite. A total of 15 samples comprising seven (7) host rocks and eight (8) minerals were analysed for major, trace and REE using Inductively Coupled Plasma Mass Spectrometry (ICP-MS) using litho-4 and peroxide fusion techniques. The results obtained revealed that the gneisses, which include migmatitic gneiss, biotite gneiss and granitic gneiss are paragneisses, metaluminous with tholeiitic affinity. The granites are peraluminous (A/CNK>1) and calc-alkaline. The granite suites had undergone changes from a more primitive hornblende-biotite I-type variety to a more fractionated muscovite bearing S-type variety. The pegmatites are peraluminous, and the high Li-Cs-Ta contents of its minerals suggests that they belong to the LCT petrogenetic family, rare element class, while the high contents of Li, Rb, Cs, Be, Ga, Sn and Ta places the group under the beryl subtype. A genetic linkage between the granites and pegmatites was confirmed by their K/Rb, K/Ba and Rb/Sr ratios. The pegmatites represent the last stage fraction of liquid remaining after extensive fractional crystallization of granitic magma. Chemical data shows there is enrichment in Li, Rb, Cs, Ta, Sn, Nb and Ga during the differenciation and evolution of the pegmatites. The rare metal mineralization of the pegmatites were evaluated using K/Rb versus Rb, K/Rb versus Cs, Ta versus Cs, Ta versus K/Cs and Ta Versus Ga plots, and they were found to be comparable to other mineralized pegmatites of Nigeria but lower than the highly mineralized Tanco pegmatites. It is hereby proposed that the pegmatites differenciated from the granitic magma through magmatic and post magmatic differenciation processes and were then injected into the weak zones of the gneisses and granites.

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CHAPTER ONE

1.0 GENERAL INTRODUCTION

1.1 INTRODUCTION

Pegmatites are texturally distinct variants of the more common and more voluminous plutonic igneous rock. They occur as segregations within granites and as sharply discordant dikes intruding igneous and metamorphic rocks (London and kontak, 2012). They possess compositions close to the minimum assemblage of granites. Pegmatites have come to occupy a place of increasing significance, since they constitute the source of many important minor and trace elements used by present day technology, e.g. lithium, caesium, beryllium, scandium, yttrium, rare-earths, tin, zirconium, hafnium, niobium, tantalum and uranium. They also provide industrial minerals like ceramic feldspar, mica, and high purity quartz, and a large variety of attractive and highly priced coloured gem minerals and ornamental stones used in jewelries.

Because rare metals are for the most part found only in granitic pegmatites, they would be the focus of this research work. Rare-metal pegmatites are enriched in incompatible elements high-field-strength elements (HFSE) and large-ion lithophile elements (LILE). These elements do not fit into the crystal structure of rock forming minerals. Hence they concentrate in residual melts, such that they increase essentially without moderation until they form their own distinctive minerals, such as tin, columbite, tantalite etc.

1.2 LOCATION AND ACCESSIBILITY OF THE STUDY AREA

The study area lies about 50 kilometers north-east of Zaria in Makarfi Local Government Area (L.G.A) of Kaduna State within Zaria Sheet 102 NE, covering an area of approximately 277 km^2. It is bounded by latitudes 11°21′ 00″ and 11°30′00″ N, and longitudes 7°51′00″ and 8°00′00″E,

(Fig. 1.1). It is bordered by Kano State to the north-west, Ikara L.G.A in the east, Soba L.G.A to south west of Katsina State, and Kudan L.G.A in the west. The area is accessible through the Zaria-Kano major road. Other important roads include; Makarfi-Hunkuyi and Makarfi-Rogo roads in the western part of the study area, a secondary road from Filatan to Ungwan Sagondare Makera, and another one from Makarfi to Yauran, both traverse the area from the south-west to north-east. The area is also accessible through various untarred roads, footpaths and cattle tracks.

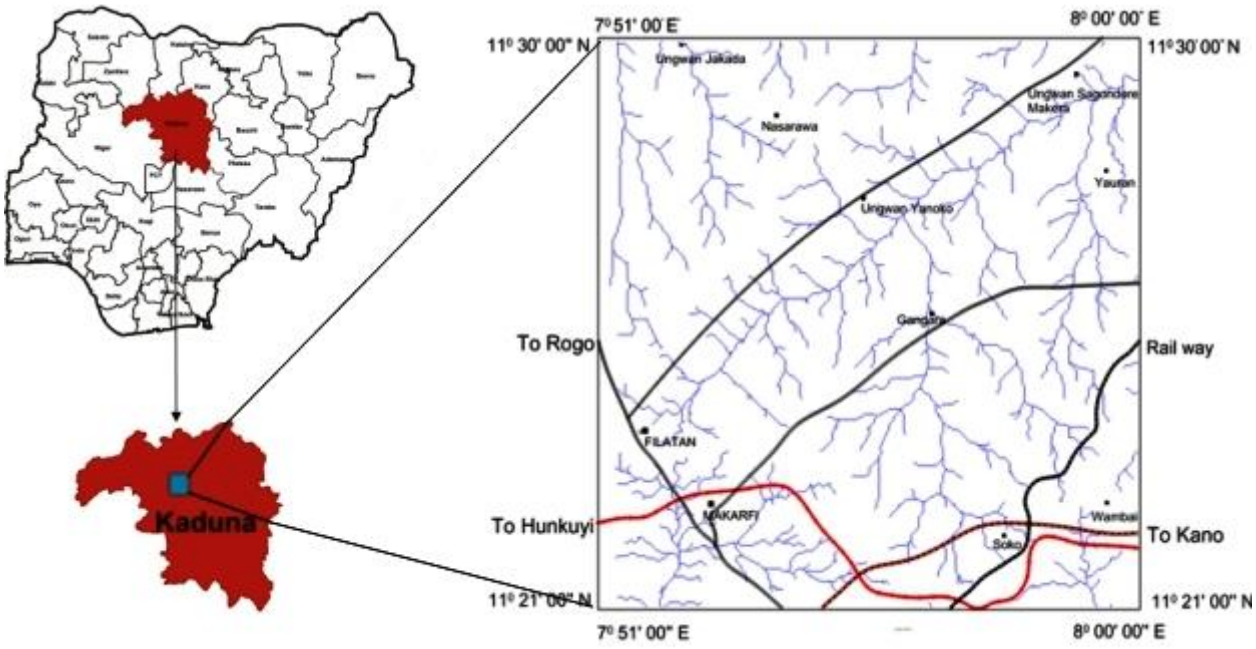


Figure 1.1: Location, drainage and accessibility map of the study area

1.3 CLIMATE AND VEGETATION

The climatic conditions of the study area cannot be separated from that of Zaria, this is because both of them lie on the same latitude, and geographically, all areas on the same latitude are liable to have same climate. Therefore, the area lies within the region which has a Sudan climate with distinct wet season and dry season. The wet season lasts for five months from May to September, while the dry season lasts for about seven months from October-April. During the wet season, the area is completely green, while the vegetation turns dry in the dry season since there is usually no rain, and potential evapo-transpiration rates are very high. The climate of the region is determined by the alternating dominance in the region, by either the day continental air mass (the north-east trade wind) that brings harmattan, or marine air mass from the south (south-west trade wind) that brings wet season. Seasonal variation in rainfall is directly influenced by the interaction of two air masses; the relative warm and moist tropical maritime (mT) air mass which originates from the Atlantic Ocean associated with south-west trade wind in Nigeria; and the relatively cool, dry and stable tropical continental (cT) air mass that originates from the Sahara Desert and is associated with the dry, cool and dusty north-east trades wind known as the Harmattan (Sawa, 2002; Abaje *et al.*, 2012). The dry cT air mass invades the area from November to April, and tends to come along with haze, dust and cold. While the mT invades the area between May to October, and it is usually moist.

According to Hore (1970), the dry season which is winter is also the period of harmattan that is from November to February, the hot season from March to April, May to June is the period of thunderstorm and squalls, while July to October is the wet (rainy) season. The mean annual rainfall ranges between 1000mm to 1750mm (Kareem and Mbason, 2002). Day time

temperatures also vary with a mean minimum of 22^{o}C and a mean maximum of 24^{o}C as the readings are extremely high for most part of the year (ZEMDA, 2015).

In terms of vegetation, the region falls within the Guinea Savannah belt that consist of expansive grassland interspersed with grown trees. The vegetation has been greatly modified by human activities especially farming. The seasonal rainfall in the area adds colours to the vegetation changing them from brown, pale or yellow in the dry season to green in the wet season. During the wet season the vegetation is lush green, but during the dry spell all vegetation except the trees die off. The vegetation are scattered and almost most of the species of plants found in the Savannah are found in the area, notable among them are; locust bean (*parkia filicoidea*), baobab (*adensonia digitat*a), acacia, bombax, shea butter (*vitellaria paradoxa*) Mahogany (*Khaya senegalensis*).

1.4 RELIEF AND DRAINAGE

The area lies on a low lying and gently undulating plain which is part of the central Hausa land plains of Nigeria, which extends almost unbroken from Sokoto to Lake Chad and beyond (Thorp 1970).

The drainage pattern (Fig. 1.1) in the area is dendritic in nature which has always been seasonal with slumping and rain-wash erosion increasing the width of the rivers/streams. The seasonality of the rivers and streams depends on their size, the degree of permeability of regolith, the size of the flood plain, and the gradient of the land surface. The area is well drained by two major rivers; River Kamanda and River Kwakwa and their tributaries such as River Soko and River Kofa. The River Kamanda flows across the eastern side of the area and flows in a NNE-SSW direction, while River Kwakwa flows across the western side of the area and flows in a N-S direction, both are approximately parallel to the regional structural trends. According to Udoh (1970), major

drainages in Nigeria follow these fracture directions. The rivers which drain north-eastwards into Lake Chad, and those which flow north-westwards into River Sokoto.

1.5 SETTLEMENT AND LAND USE

The area is sparsely populated with majority of the people being Hausas and Fulanis. The most prominent settlements in the area are; Makarfi, Filatan, Gazara, Gangara, Wambai, Giwaye Yauran and Nasarawa. The people are actively engaged in agriculture which is their major economic activity. Virtually every piece of land is cultivated. They engage in both crop production and animal husbandry especially cattle rearing. The area is famous for its leading position in sugarcane farming, rice, maize, millet sorghum, perishable goods such as; pepper, onions, vegetables and tomatoes. Other primary production activities in the area include; livestock rearing, carving, black smiting, pottery etc.

1.6 PREVIOUS WORK

The review and description of the Basement Complex of Nigeria was carried out by several workers including Grant (1971), Oyawoye (1972), Rahaman (1976) and McCurry (1970; 1976). The first detailed work in northwestern Nigeria was carried out by Truswell and Cope (1963), who mapped the now classical Kusheriki area and concluded that the gneissic complex, the schist formations and the Older Granites in the area were formed during a single orogenic event, and also that the basement rocks in the area could not be older than Cambrian. McCurry (1970) mapped the quarter degree sheets 101 and 102 in a reconnaissance style based mainly on photogeological interpretation supported by selected field traverses, she distinguished three principal units namely; gneisses, considered to have been metamorphosed more than 2,000 Ma ago; metasediments, mainly schists and quartzites laid down and then metamorphosed during the

Pan-African orogeny, between 750 and 450 Ma; and Older Granites, intruded from 647 to 618 Ma. Wright and McCurry (1970) produced a geological map of Zaria Sheet 102 SW and reported the occurrence of economic minerals such as gold and amethyst. McCurry, (1971) worked on Zaria sheet to determine the nature of Pan-African orogeny in northern Nigeria. Webb (1972), modified the boundaries of the Zaria Granite plutons and proposed the name 'Zaria Batholith' for it, and regarded the plutons as part of a single batholith which extend in a north-south direction for at least 90 km, and up to 22 km wide and can be traced from north of Zaria southward to the vicinity of Kaduna. McCurry (1973) working mainly west of Zaria divided the granites into two main groups according to their field relationships. The first "syntectonic" group comprised elongate batholithic sheets that are partly concordant, and foliated. The second group "late tectonic" are made up of poorly foliated discordant bodies, rich in mafic xenoliths and having a lower proportion of potash feldspar. Ogezi (1977) dated the porphyritic type of the Zaria batholith to have an age of 795±73 Ma and considered them to be Pan-African orogenic granite. Olatunji (1970, 1979) observed more than 100 dykes, 250 pegmatites and 150 quartz veins in at least 21 localities in the Zaria district which on the whole show spatial affinities with the granitic areas. Ike, (1988) worked on the late-stage geological phenomena in the Zaria basement granites and noted that many fracture-controlled phenomena in the Nigerian basement such as mineralization are northeast-trending, and the abundance of pegmatites in the marginal zones of the batholith and its roof zones is a pointer to late stage availability of excess water and volatiles. Garba (2003), studied the pegmatites in the Kinkiba-Richifa area east and northeast of Zaria, and reported the occurrence of gemstones and some rare metals, such as columbite-tantalite, tourmaline, beryl and bismuth. Solomon, (2014), worked on the amethyst mineralization in Dutsen Bakura due east of Kinkiba. Oden *et al.* (2015) conducted a measurement of Pan-African

strain on Zaria batholith and they concluded that the strain markers showed a strong preferred oriented in the N - S direction, a direction which also recorded the highest strain value, and strain analysis of simple shear orientations (NW - SE and NE – SW) showed the NW - SE dominating over the NE - SW direction in terms of strain intensity. A report by final year undergraduate students of Department of Geology, Ahmadu Bello University Zaria that conducted their fieldwork in part of the study area also reported the activities of artisanal miners in the area mining rare metals such as beryl, tantalite, bismuth and tourmaline.

Earlier study of Pegmatites in Nigeria include the work of Jacobson and Webb, (1946) which identified that the pegmatites are of the complex category and also that the rare-metals pegmatites of Nigeria are confined to a 400 km long NE-SW trending belt stretching from Wamba area in central Nigeria to Ibadan area southwest Nigeria. This point of view was refuted by the work of Garba, (2003) and Okunlola, (2005) who showed that rare-metal pegmatites are distributed across and beyond the earlier defined belt of the Nigerian Pan-African basement. Olugbenga and Ofonime (2006) studied the geological setting, petrochemical features and age of rare-metal (Ta-Nb) mineralization of pegmatites of Komu area south-western Nigeria and concluded that the pegmatites are not cogenetic with the surrounding Pan-African granitoids, they are mineralized and compare favourably with other mineralized pegmatites. Akintola and Adekeye (2008) studied the mineralization control and petrogenesis of rare-metal pegmatites of Nasarawa area central Nigeria and proposed that extreme igneous fractionation aided by fluids rich in Boron, Phosphorus and Fluorine led to the concentration of rare metals in the residual melts that formed the pegmatite as it ascends through reactivated ancient fracture. Okunlola and Ocan, (2009) worked on rare-metal (Ta-Sn-Li-Be) distribution in pegmatites of Keffi area central Nigeria and they suggested that the pegmatites are complex with varied mineralogical zonations.

Okunlola and Akinola (2010) studied the petrochemical characteristics of rare-metal pegmatites of Oke-Asa area south-western Nigeria and concluded that the pegmatites are of the rare-element class lepidolite subtype, and are variably enriched in rare-metals. Akintola, *et al.*, (2011), in their work on the Petrographic and Geochemical Evaluations of Rare – Metal (Ta-Nb) Potentials of Precambrian Pegmatites of Awo Area Southwestern Nigeria, noted that the pegmatites are of the LCT petrogenetic family (Rb, Cs, Be, Li, Ga, Sn, Ta < > N (BPF) and of the Beryl sub type with moderate to high Ta-Nb mineralization. Akintola, *et al.*, (2012) worked on the petrochemical evaluation of the pegmatites in Apomu area south-western Nigeria and found that the pegmatites are barren when compared with other rare-metal pegmatites across the world. Similarly, Oden *et al.*, (2013) worked on the geochemical evaluation of pegmatites from parts of Oban massif south-eastern Nigeria and found that they are barren and unmineralized. In their study on the Post-collisional Pan-African granitoids and rare metal pegmatites in western Nigeria, Goodenough *et al.*, (2014), were of the opinion that the pegmatites are of LCT-type enriched in some rare-metals such as tantalum and they post-date the granitoid plutons**.** Akoh and Ogunleye (2014) studied the geochemical evolution of micas and Sn-, Nb-, Ta-mineralization associated with the rare metal pegmatite in Angwan Doka, central Nigeria and found that the pegmatites are magmatic and zonation in the pegmatite bodies resulted from the same petrogenetic process. Jose (2015) worked on the rare-metal (Ta-Nb) mineralization of pegmatites in Egbe area south-western Nigeria and found that the pegmatites are siliceous with a peraluminous composition, genetically linked to the peraluminous S-type granites and are moderately evolved compared with other highly mineralized pegmatites. Girei (2015) studied the pegmatites in northern parts of Mandara hill north-eastern Nigeria and concluded the pegmatites are primitive to moderately fractionate but barren and probably formed from the anatexis of granitic rocks at shallow depth.

1.7 STATEMENT OF RESEARCH PROBLEM

The increasing worldwide demand for rare metals, industrial minerals and other gem minerals has led to renewed interest in the study of pegmatites globally because they are the alternative sources of these minerals. Technological development on the other hand also necessitates an increasing demand for rare metals which are believed to contribute to the growth of the world economy. The increase in global demand for these economic minerals has led to the recent interest in prospecting for mineral deposits in different parts of the world including Nigeria. Pegmatites in Nigeria are known to have generated great interest because they are known to host a good number of economic minerals which include beryl, tantalum, niobium, and tourmaline among others. Several studies such as Garba, (2002), Okunlola, (1998, 2005, 2008), Okunlola and Jimba (2006), Akintola and Adekeye, (2008), Okunlola and Oyedokun, (2009), Okunlola and Akinlola, (2010) and Akintola *et al*, (2012) have been carried out on some pegmatites in Nigeria, in an attempt to appraise into some details the petrography, geochemical features and economic potentials of rare metal mineralization of the pegmatites of the different fields. Most of these studies are restricted mainly on the occurrence and mineralization potentials of the rare metal pegmatites in South western and North central Nigeria. From the review above it is clear that so far there is no detailed study conducted on the rare metal mineralization in Makarfi area. Therefore, there is need for an in-depth study of the pegmatites in the area to assess their rare metal mineralization potential, and to produce a model for their genesis, and compare it to the genesis of other rare metal pegmatites in Nigeria.

1.8 JUSTIFICATION

The work of Garba (2003) has shown that the rare metal pegmatites are not restricted to the NE-SW pegmatite belt as widespread occurrences of rare metal pegmatites are known from many

areas of the Nigerian Pan-African Basement Complex. Although studies such as McCurry (1971 and 1973), Webb (1972), Ogezi (1977), Olatunji (1979) and Ike (1988) have been carried out on the Zaria Sheet, all these studies are restricted mainly to structural and lithological variations within the Zaria Batholiths. As far as can be ascertained, apart from the reported occurrence of the pegmatites and activities of artisanal miners in the study area, no study has been conducted on the rare metal mineralization of the pegmatites. Hence there is need for these pegmatites to be studied and appraised, since they are least studied compared to their south western and north central counterparts which have been extensively studied and found to be enriched in rare metals. A genetic model for their emplacement would be produced to compare the genesis of these pegmatites to their counterparts elsewhere in the world.

1.9 SCOPE OF PRESENT WORK

The present work involves geologic mapping of the study area on a scale of 1:50,000 to study the various lithological units present. Petrographic study of the host rocks was undertaken using transmitted light microscopy. Whole rock geochemical analyses of representative samples of the host rocks and minerals extracted from the pegmatites was undertaken using Inductively Coupled Plasma Mass Spectrophotometry (ICP-MS).

1.10 AIM AND OBJECTIVES

The work is aimed at mapping the geology of the area and studying the geochemical characteristics of the pegmatite bodies with a view to determining their genesis, as well as assessing their rare metal potentials.

The objectives are to:

1. Produce an updated geological map of the study area,

2. Establish the geochemical signatures of the pegmatites and classify them in line with the current classification scheme,
3. Study the trace element (Li, K, Rb, Cs and Ta) distribution in muscovite as a geochemical tool for the assessment of rare metal potential of pegmatites,
4. Determine the origin of the pegmatites using their trace element signatures and
5. Develop a genetic model for the pegmatites.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Nigeria is situated in the West African sub-region (Fig. 2.1) and lies between longitudes 3◦ and 14◦E and latitudes 4◦ and 14◦N. It has a landmass of 923,768 sq. km. It is bordered to the north by the Republics of Niger and Chad and to the west by the Republic of Benin. It shares the eastern borders with the Republic of Cameroon right down to the shores of the Atlantic Ocean forming the southern limits of the Nigerian Territory. Nigeria is underlain by Precambrian basement complex rocks, Younger Granites of Jurassic age and Cretaceous to Recent sediments. The basement complex, which is Precambrian in age, is made up of the Migmatite-Gneiss Complex, the Schist Belts and the Older Granites. The Younger Granites comprise several Jurassic magmatic ring complexes centered around Jos and other parts of north-central Nigeria which are structurally and petrologically distinct from the Older Granites. The Sedimentary Basins, containing sediment fill of Cretaceous to Tertiary ages, comprise the Niger Delta, the Anambra Basin, the Lower, Middle and Upper Benue Trough, the Chad Basin, the Sokoto Basin, the Mid-Niger (Bida-Nupe) Basin and the Dahomey Basins.

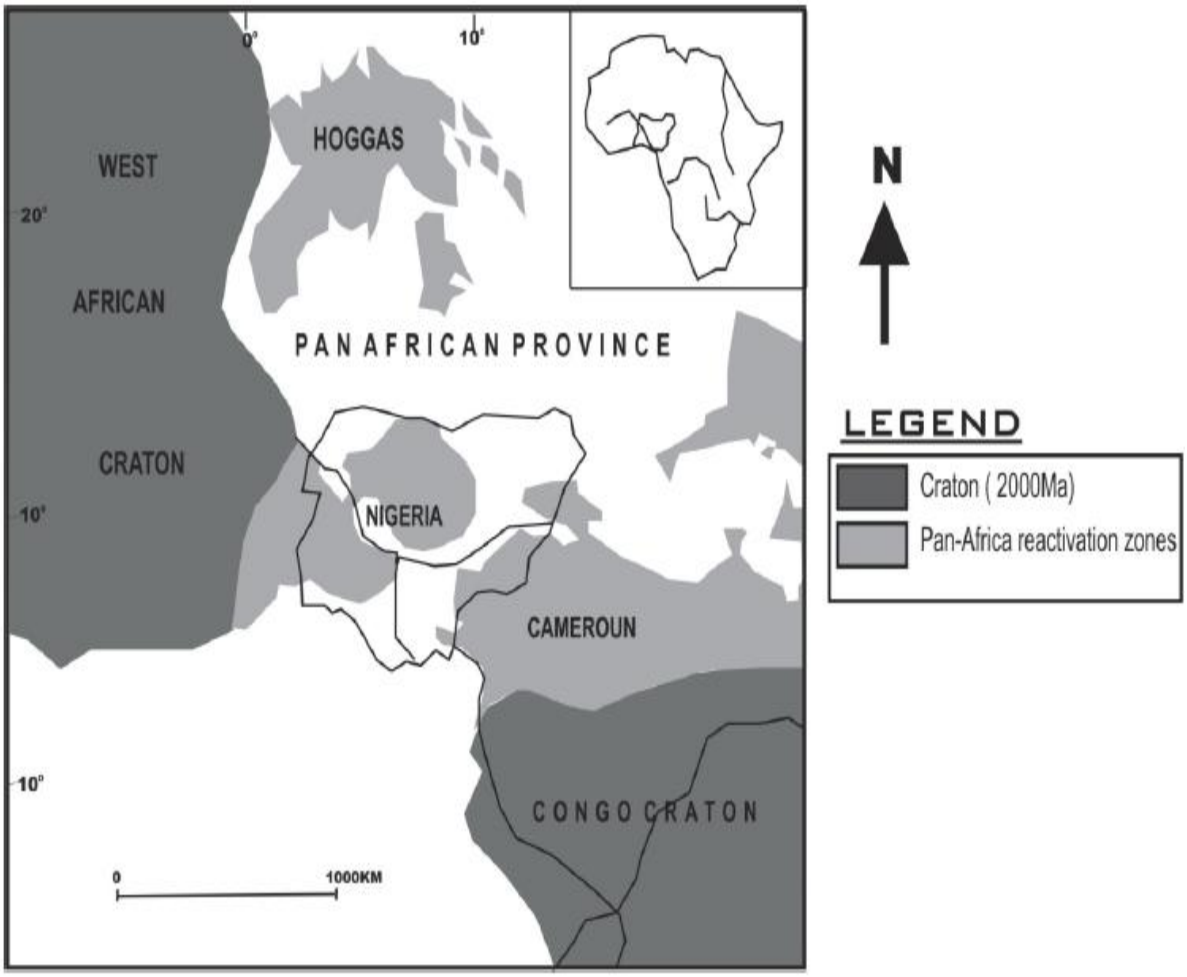


Figure 2.1: Map of parts of African Provinces showing the location of the Nigerian sector of the Pan-African province between the Congo and West African Cratons. (Adapted from Elueze, 1985).

2.2 THE NIGERIAN BASEMENT COMPLEX

The basement complex is one of the three major litho-petrological components that make up the geology of Nigeria (Fig. 2.2) The basement rocks occupy about half of the land mass of the country, and forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons and south of the Tuareg Shield (Black, 1980). The Nigerian Basement Complex occupies the reactivated region which resulted from plate collision between the

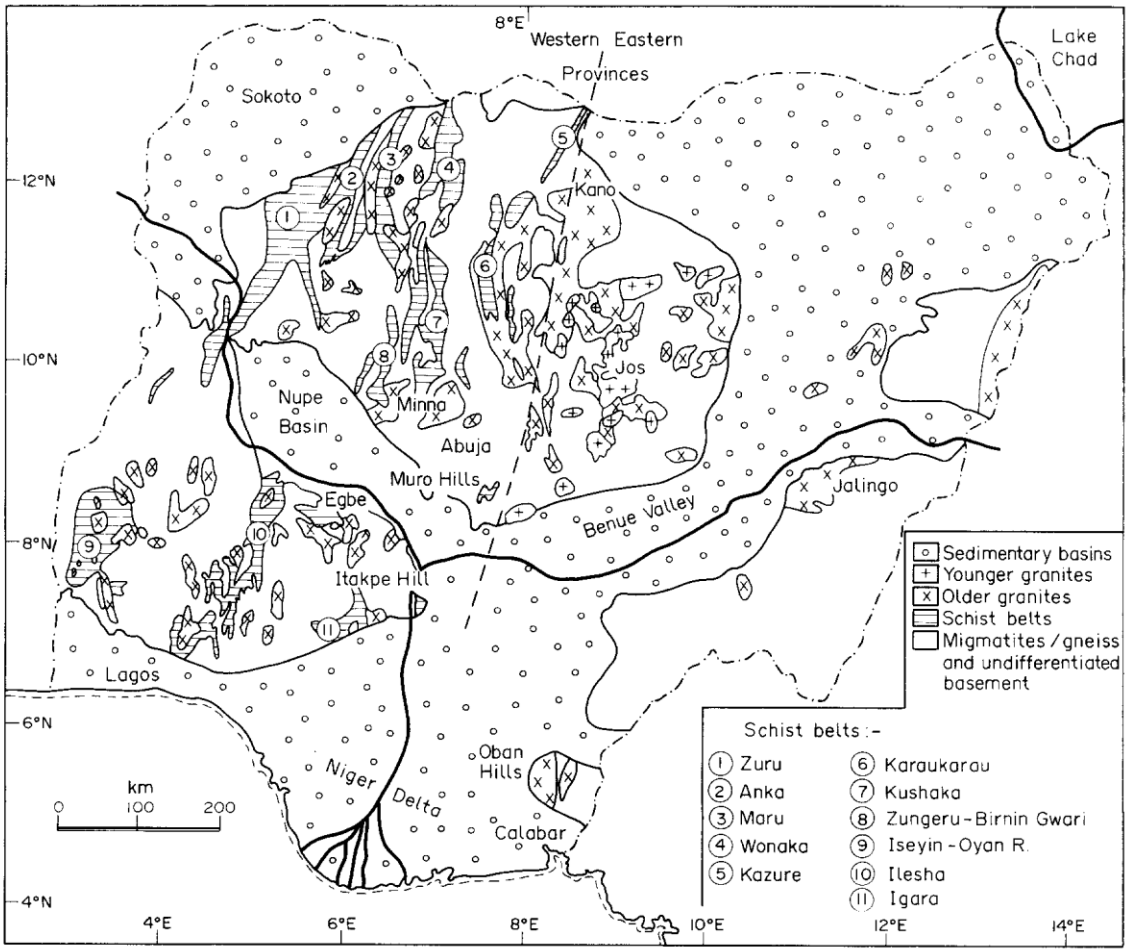


Fig. 2. Outline geological map of Nigeria.

Figure 2.2: Geological map of Nigeria showing the different lithological units (adopted from Ajibade *et al.*, 1989).

passive continental margin of the West African craton and the active continental margin (Pharusian belt) of the Tuareg Shield about 600 Ma ago. (Burke and Dewey, 1972; Black *et al.*, 1979; Caby *et al.*, 1981; Dada, 2006). The basement rocks are believed to be the results of at least four major orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2,700 Ma), the Eburnean (2,000 Ma), the Kibaran (1,100 Ma), and the Pan-African cycles (600 Ma). The first three cycles were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism, which was further

followed by extensive migmatization. The Pan-African deformation was accompanied by a regional metamorphism, migmatization and extensive granitization and gneissification which produced syntectonic granites and homogeneous gneisses (Abaa, 1983).). The later part of the Pan-African Orogeny was characterized by brittle deformation which resulted in a very consistent conjugate strike slip fault system consisting of mainly NE-SW and NW-SE sets of faults (Ball 1980). Late tectonic emplacement of granites and granodiorites and associated contact metamorphism accompanied the end stages of this last deformation. According to (Ajibade *et al.,* 1989), the Nigerian Basement can be divided into two provinces; the Western province approximately west of latitude 8^0N characterized by narrow, sediment-dominated, N-S trending low grade schist belt in a predominantly migmatite gneiss 'older' basement, and the whole is intruded by Pan-African granitic plutons; and the Eastern province comprises mainly a migmatite-gneiss complex intruded by larger volumes of Pan-African granites and the Mesozoic ring complexes of Central Nigeria

The Nigerian Basement Complex is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granites) of the Jos Plateau and is unconformably overlain by Cretaceous and younger sediments. Within the basement complex of Nigeria four major petro-lithological units are distinguishable, namely:

1. The Migmatite – Gneiss Complex (MGC).
2. The Schist Belt (Metasedimentary and Meta-volcanic rocks).
3. The Older Granites (Pan African granitoids).
4. Undeformed Acid and Basic Dykes.

2.2.1 THE MIGMATITE-GNEISS COMPLEX (MGC)

The Migmatite – Gneiss Complex is generally considered as the basement complex *sensu stricto* (Rahaman, 1988; Dada, 2006). The MGC is the oldest, most widespread and abundant rock type in the basement (Ogezi, 1988). It is of Archean-Proterozoic age and a product of long, protracted and possibly polycyclic evolutionary histories. The MGC is varied but consists mainly of gneisses, migmatites, and some older metasediments such as quartzites, carbonates and mica schist (Jones and Hockey, 1964) of different origins as well as meta-igneous rocks of basic and ultra-basic compositions. The gneissic complex has been through at least two tectono-metamorphic cycles, and consequent metamorphism, migmatization and granitization has extensively modified the original rocks so that they generally occur as relict rafts and xenoliths in migmatites and granites (McCurry, 1976). Relict metasedimentary rocks represented by medium-to-high grade calcareous, pelitic and quartzitic rocks occur within the migmatites and gneisses, and they have been described as 'Ancient Metasediments' (Oyawoye, 1972), in order to distinguish them from late Proterozoic supracrustal sediments which are known as 'Younger Metasediments' (McCurry, 1976). These rocks record three major geological events (Rahaman and Lancelot 1984); the earliest, at 2,500 Ma, involved initiation of crust forming processes (e.g. the banded Ibadan grey gneiss of mantle origin) and of crustal growth by sedimentation and orogeny; next came the Eburnean, 2000 ± 200 Ma, marked by Ibadan type granite gneisses; this was followed by ages in the range from 900-450 Ma which represent the imprint of the Pan-African event which not only structurally overprinted and re-set many geochronological clocks in the older rocks, but also gave rise to granite gneisses, migmatites and other similar lithological units. Truswell and Cope, (1963) and Ajibade *et al*., (1979), recognized that the MGC was subjected to considerable cataclastic deformation and this provided the first evidence for a structural break between the gneissic complex and the schist belts. It has ages ranging from Liberian (2800±200

Ma) to Pan-Africa (600±150 Ma). Metamorphism in this group has generally attained the amphibolites facie grade.

The Migmatite-Gneiss Complex makes up about 60% of the surface area of the Nigerian Basement (Rahaman and Ocan, 1978). Obaje (2009) noted that rocks of the Migmatite-Gneiss Complex characterize many areas in northern, eastern and western Nigeria such as: Abuja, Keffi, Akwanga, Bauchi, Kaduna, Kano, Funtua, Okenne, Egbe, Ajaokuta (in northern Nigeria); Obudu and the Oban Massif (in eastern Nigeria) and Ibadan, Ile-Ife, Akure and Ikerre (in western Nigeria).

2.2.2 THE SCHIST BELT

The schist belt are believed to be relicts of a supracrustal cover which was infolded into the Migmatite-Gneiss Complex (Russ, 1957; McCurry, 1973). The Schist belt forms the supracrustals that comprise of low grade, metasediments and metavolcanic-dominated belts trending N–S which are best developed in the western half of Nigeria and are seldom found east of longitude 8º E, though smaller occurrences are found to the east but only sporadically. Ajibade (1988) noted that the metasediments are poorly represented in the eastern half of the country and he attributed it to the strong migmatization and assimilation effects on the sediments by the large volumes of the Pan-African rocks. The Schist belts are best displayed in north-western Nigeria where each formation occupies a discrete belt separated from the others by migmatite–gneiss complex (Ajibade and Fitches, 1981). There are twelve of such metasedimentary belts namely: Zungeru-Birnin Gwari, Kushaka, Malumfashi, Kazaure, Wonaka, Maru, Anka, Zuru, Toto, Iseyin-Oyan River, Ife-Ilesha and Igara-Kabba-Lokoja belts (Ajibade, 1976; Turner 1983; Danbatta, 1999; 2008). The lithological variations of the schist belts have been summarized by Turner (1983) and they include coarse to fine grained clastics, pelitic schists, phyllites, banded

iron formation, carbonate rocks and mafic metavolcanics (now amphibolites), but there remain many unresolved problems. The lithological differences between the belts have been used as evidence to suggest that the schist belts were not deposited in the same basin and further suggesting the presence of two generations of schist belts (Grant, 1978; Turner 1983; Fitches *et al.,* 1985). In recent years, much attention has been given to the evolution of the metasediments (Annor, 1995; Adekoya, 1996; Olobaniyi, 1997; Danbatta, 1999; 2001; 2003; 2008). The main points of contention that concern the evolution of the metasediments include the timing of formation of the basin of deposition, their age relationship, origin of the mafic and ultramafic rocks associated with some of them, and structural control. All the models proposed over the years for the evolution of the metasediments could be classified under ensialic and ensimatic processes. The structural relationships between the Schists and the basement were considered by Truswell and Cope, (1963) to be conformable metamorphic fronts and Ajibade *et al*, (1979) first mapped a structural break. The metasedimentary/volcanic rocks of the schist belts are generally considered to be Proterozoic in age.

2.2.3 THE OLDER GRANITES

The Older Granites are believed to be syn-tectonic to late-tectonic rocks which cut both the Migmatite-Gneiss Complex and the Schist Belts. The granitoids include rocks varying in composition from granite to tonalite and charnockites with smaller bodies of syenite, gabbro, aplite and pegmatite (Ajibade *et al.,* 1989). They are generally deep seated intrusions and anatexis has played an important role (Rahaman 1981). The granitoids have yielded radiometrics ages in the range of 750-500 Ma which lie within the Pan-African spectrum. The term Older Granite was introduced by Falconer, (1911) to distinguish the deep-seated, often concordant or semi-concordant granites of the basement complex from the high-level, highly discordant tin-

bearing granites of Northern Nigeria, the Mesozoic anorogenic granite ring - complexes known as the Younger Granites. Based on orogenic criteria, Truswell and Cope (1963) grouped the Older Granite rocks into synkinematic and late-kinematic types. The synkinematic rocks are usually coarse grained, foliated bodies with gradational contact and contain xenolith of their country rocks, while the late-kinematic types are commonly fine grained, rarely foliated and have sharp contacts with the surrounding country rocks. Jones and Hockey (1964) have on the basis of field relationship, mineralogy and texture, recognized three phases of the Older Granite suite; an early phase comprising of granodiorites and quartz diorites, a main phase comprising coarse porphyritic hornblende granite and syenite and coarse porphyritic biotite granite, and a late phase comprising homogenous granite and dykes and pegmatites and aplites. Early granitoids are foliated calc-alkaline granodioritic intrusions, heterogeneous, fine to medium grained biotite ± muscovite granodiorites with a highly irregular form, whilst later undeformed post tectonic intrusives are monzonitic, sub-alkaline to alkaline in character, homogeneous, porphyritic, medium to coarse grained biotite ± hornblende granites and monzonites with well-defined intrusive form (MacLeod *et al.*1971). Rahaman (1988) discarded the earlier classification of members of the Older Granites suite. In its place he classified them based mainly on the textural characteristics as follows; Migmatitic granites, granitic gneiss, early pegmatite dykes and fine-grained granites, coarse-grained porphyritic granites, slightly deformed pegmatites, aplite dykes and veins, undeformed pegmatites, two - mica granites and quartz veins. McCurry, (1973) divided the granites into two main groups according to their field relationships; Syntectonic group that comprised elongate batholithic sheets that are partly concordant and foliated, and late tectonic group that are made up of poorly foliated discordant bodies, rich in mafic xenoliths and having a lower proportion of potash feldspar.. The Older Granites occur

intricately associated with the Migmatite-Gneiss Complex and the Schist Belts into which they generally intruded. . The Older Granite suite is notable for its general lack of associated mineralization although the thermal effects may play a role in the remobilization of mineralizing fluids. Dada, (2006) suggested that the term Pan-African Granitoids be used for Older Granites not only on the merit of age which was not available at the time they were named Older Granites, but because it covers several important lithologic groups formed at the same time.

2.2.4 THE UNDEFORMED ACID AND BASIC DYKES

The undeformed acid and basic dykes are late to post-tectonic Pan African. They cross-cut the Migmatite-Gneiss Complex, the Schist Belts and the Older Granites. The undeformed acid and basic dykes include:

a. Felsic dykes that are associated with Pan African granitoids on the terrain such as the muscovite, tourmaline and beryl bearing pegmatites, microgranites, aplites and syenite dykes (Dada, 2006)

b. Basic dykes that are generally regarded as the youngest units in the Nigerian basement such as dolerite and the less common basaltic, felsite and lamprophyric dykes.

The age of the felsic dykes has been put at between 580 and 535 Ma from Rb-Sr studies on whole rocks (Matheis and Caen-Vachette, 1983; Dada, 2006), while the basic dykes have a much lower suggested age of ca. 500 Ma (Grant, 1970). Dada (2006) postulated that the structural and geochronological importance of this suite of rocks, which have been put to immense chronological use elsewhere are often overlooked in Nigeria. When they cross-cut basement, they could be used to infer relative age of metamorphic structures and rock suites and could also

suggest the existence of older basement windows in the Nigerian schist belts, apart from the immense guide they provide in sampling for isotope geochemistry, analysis and interpretation.

2.3 PEGMATITES

London (2008) defined pegmatites as: "essentially igneous rock, mostly of granitic composition, that is distinguished from other igneous rocks by its extremely coarse but variable grain-size, or by an abundance of crystals with skeletal, graphic, or other strongly directional growth habits." Most pegmatite bodies are small, with dimensions on the scale of meters rather than kilometers, and display internally complex fabrics. They occur as segregations within granites and as sharply discordant dykes intruding igneous and metamorphic rocks (e.g Jahns and Tuttle 1963; London and kontak, 2012). The vast majority of pegmatites possess compositions close to the minimum or eutectic assemblage of granite (London and kontak, 2012), and hence are called "Granitic Pegmatites".

2.3.1 CLASSIFICATION OF PEGMATITES

Most early schemes were descriptive in nature, and were based on various observable features such as shape or key minerals (see Landes, 1933; Jahns, 1955; Ginsburg *et al*. 1979; Černý, 1982). Most of the current schemes of classifying pegmatites are based on their rare element mineralogy (e.g., Černý and Ercit, 2005). Černý's (1991) revision of that classification scheme is the most widely used classification of pegmatites today. The pegmatite classes are distinguished on the basis of the metamorphic environment of their host rocks (the abyssal class), mineralogy (the muscovite class), elemental composition (the rare-element class), and texture (the miarolitic class). Černý and Ercit (2005) improved this classification by correlating the pegmatite classes with other petrogenetic data, and they expanded the classification to include ten subclasses, four

of which are subdivided into thirteen types, and two types are further broken down into seven subtypes (Table 2.1).

Table 2.1: The pegmatite classification scheme of Černý and Ercit (2005), showing correlation between pegmatite classes. NYF = niobium–yttrium– fluorine family (green); LCT = lithium–cesium–tantalum family (yellow); HREE = heavy rare earth elements; LREE = light rare earth elements (adapted after Černý *et al* 2012).

Class	Subclass	Type	Subtype	Family
Abyssal	HREE			NYF
	LREE			
	U			NYF
	BBe			LCT
Muscovite				
Muscovite–rare element	REE			NYF
	Li			LCT
Rare element	REE	allanite–monazite		NYF
		euxenite		
		gadolinite		
	Li	beryl	beryl–columbite	LCT
			beryl–columbite–phosphate	
		complex	spodumene	
			petalite	
			lepidolite	
			elbaite	
			amblygonite	
		albite–spodumene		
		albite		
Miarolitic	REE	topaz–beryl		NYF
		gadolinite–fergusonite		
	Li	beryl–topaz		LCT
		spodumene		
		petalite		
		lepidolite		

2.3.2 RARE METAL POTENTIAL OF PEGMATITES

Only a small proportion of pegmatites (<1%) possess assemblages that contain uncommon minerals, e.g. those with essential lithium, beryllium, cesium, boron, phosphorus, and tantalum. These exotic rocks are termed rare-element pegmatites (not to be confused with rare earth element pegmatites, which are a subset of rare-element pegmatites) (London and kontak, 2012). The rare metal pegmatites comprise quartz, K-feldspar, plagioclase, muscovite, biotite, and tourmaline with varying amounts of beryl, lepidolite, spodumene, garnet, apatite and accessory minerals including columbite–tantalite, tapiolite, wodginite, microlite, ilmenite and cassiterite (Melcher *et al*., 2013; Wright, 1970). Rare metal pegmatites are enriched in incompatible elements (high-field-strength and large-ion lithophile elements). Granitic pegmatites of the rare-element and, in part, miarolitic classes display extreme fractionation and accumulation of numerous lithophile elements beyond the limits observed in other igneous and postmagmatic assemblages. Quartz and feldspars are the dominant minerals that crystallize from granitic melts, and the rare elements are highly incompatible in these minerals. Thus, extreme fractionation resulting from extended crystallization of quartz and feldspars can generate very high concentrations of rare elements in residual melts (Linnen *et al*., 2012), such that these rare elements increase essentially without moderation until they form their own distinctive minerals, such as, spodumene, columbite, tantalite, tin etc., in the most evolved types of pegmatites (Černý *et al*., 2012).

The rare-element content in a bulk analysis of a fertile granite or pegmatite can be used to determine the degree of fractionation of the sample. The higher the rare-element contents in a bulk analysis, the higher the degree of fractionation and the higher the economic potential of the pegmatite. The following rare-elements are excellent fractionation indicators: Be, Cs, Ga, Li, Nb,

Rb, Sn and Ta. The most highly fractionated samples will have high values of some or all of these elements. Extreme fractionation of lithophile elements such as Rb and Cs is a common geochemical feature of the granitic pegmatites especially the rare-metal bearing types (Černý *et al.,* 1985; Garba 2003, 2005). While enrichment in Rb is an indicator of the degree of fractionation in the granitic pegmatites, enrichment in Cs appears to be the most important discriminator of the rare-metal pegmatites. Elemental ratios can also be used to determine the degree of fractionation and assess the economic potential of bulk samples. The following ratios are excellent fractionation indicators: K/Rb, K/Cs, Nb/Ta and Mg/Li. Low values of K/Ba and K/Cs are believed to be indicative of mineralized pegmatites (Garba, 2003).

2.3.3 DISTRIBUTION OF RARE METAL PEGMATITES

Rare metal pegmatites are examined and exploited around the world in numerous countries and geological ages. Some of the countries include; Canada, Brazil, India and Australia. The pegmatites associated with Archean age granite terrains tend to be the most economic (Galeschuk and Vanstone, 2007).

Mineralized pegmatites are widespread in Africa and occur in the older cratonic areas which have remained stable over the past 1,500 Ma - as well as in the comparatively younger orogens, consisting of mobile zones which have undergone a number of orogenic deformations during the past 1,200 Ma (Clifford and Barton 2012). It is interesting to note that most of the extensively mineralized pegmatite areas so far known are situated south of the equator and are associated with the younger orogens in the Kibaran belt of Uganda, Rwanda, eastern Zaire, and in the Mommbique belt of East Africa, Mozambique, and Madagascar, and in the Damaran of Namibia (Fig. 2.3). One of the largest, continuous regions of mineralized pegmatites in Africa is the Namaqualand-Gordonia-Kenhardt region or the Orange River pegmatite belt which is also of

Kibaran age (Von Knorring and Condlife, 1987). The African continent is richly endowed with rare metal mineralized pegmatites (Landes, 1935; von Knorring, 1970; von Knorring and Condlife, 1987; von Knorring and Fadipe, 1981). Most of Africa's rare metal potentials have been linked to Proterozoic pegmatite fields with the exception of the anorogenic Jurassic tin bearing complexes of Jos plateau in central Nigeria.

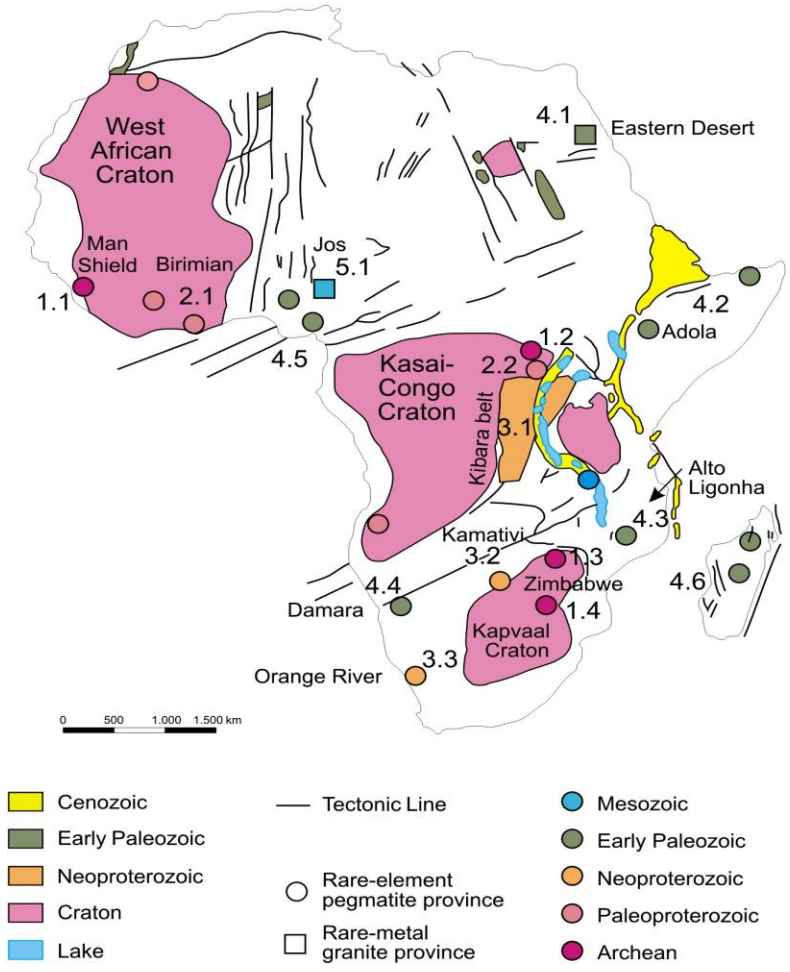


Figure 2.3: Map of African rare-element pegmatite and rare-metal granite provinces (different symbols). Colours indicate age provinces. The numbered provinces are 1.1 Man Shield, 1.2 Congo Craton, 1.3 Zimbabwe Craton, 1.4 Kaapvaal Craton, 2.1 Birimian Province, 2.2 Kibalian in north-eastern DRC, 3.1 Kibara Belt, 3.2 Kamativi Schist Belt, 3.3 Orange River Belt, 4.1 Eastern Desert, 4.2 Adola Belt, 4.3 Alto Ligonha Province, 4.4 Damara Belt, 4.5 Older Granites (Nigeria), 4.6 Madagascar, 5.1 Younger Granites (Nigeria). (Adopted from Melcher, F., *et al* 2013).

2.3.4 NIGERIAN PEGMATITES

Pegmatite bodies in Nigeria intrude generally discordantly, older lithologies of the Schist belt, the Migmatite-Gneiss Complex and the Older Granite suites. Jacobson and Webb (1946), studied the pegmatites of Nigeria and highlighted that it is restricted to a 400 km NE-SW trending belt from the southwestern part to the north central parts of Nigeria. In Nigeria, Pan-African intrusive suites which comprise mainly granites, granodiorites and tonalities are intruded by numerous veins of pegmatites and aplites (Okunlola, 2005). The pegmatites belong to the terminal stage of Pan-African magmatism (Rahaman *et al.*, 1988; Elueze, 1992). Pegmatites occur either as tiny veins (few centimeter in width) or as dykes cross-cutting other rocks. Occasionally they occur as huge bodies of simple or complex mineralogy and structure with rare metal and gemstone mineralizations. The Nigerian pegmatites were formed 562–534 Ma, indicating that their emplacement is related to the end of the Pan-African magmatic activity (Garba 2003). Rare-metal pegmatites which contribute to the mining output are known to occur in two major regions, namely, in southwestern and central Nigeria. The two major regions provide different lithological host rocks to the pegmatites. Rare-metal pegmatites in southwestern Nigeria are exclusively confined to the meta-volcano sedimentary belts while those in central Nigeria are found only in gneissic basement environment (Matheis 1987). Mining is mostly from alluvial placers and/or from deeply weathered primary deposits. The mineralization potential of the Nigerian rare-metal pegmatites are highly variable according to the host rock type. According to Okunlola (2005), the Nigeria pegmatites fields are relatively poorer when compared with the highly mineralized Tanco (Canada), Homestead and Wodinga (Australia) pegmatites but are comparable to low-medium Ta (LCT) pegmatites of Buck, Oasis, and Noumas pegmatites in USA. The Nigerian Older Granite share some geochemical affinities with the LCT family of rare metal pegmatites while the Younger Granites share some geochemical affinities with the NYF

family as recognized by Černý (1991) and Akintola (2008). Both mineralized and barren pegmatites occur within the Nigerian Basement Complex (Fig. 2.4).

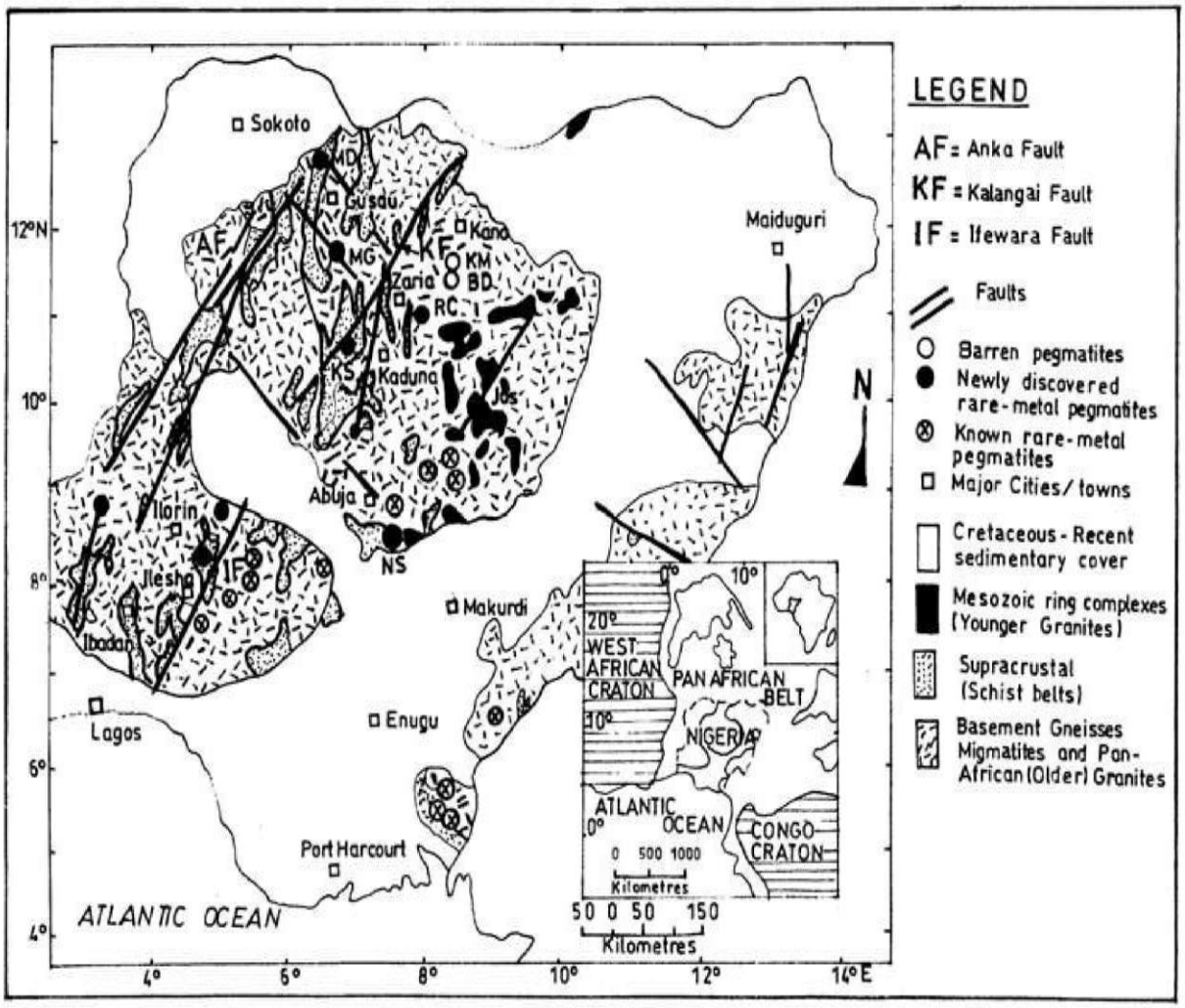


Figure 2.4: Geological map of Nigeria showing the locations of barren and rare-metal pegmatites adopted from Garba (2003).

2.3.4.1 MINERALIZED PEGMATITES

The emplacement of the Nigerian rare-metal bearing pegmatites clearly occurred within the last of three recognizable events of the Pan-African in Nigeria, contemporaneous with the formation of the widespread Older Granite complexes. Rare-metal pegmatites of Nigeria were known to be confined to a 400 km long NE-SW trending belt stretching from Wamba area in central Nigeria to Ibadan area southwest Nigeria. But studies by Ekwueme and Matheis (1995), Garba (2001), Okunlola (2005) show that the Precambrian pegmatites of Nigeria are not restricted to the so called "Tin Province" or "Pegmatite belt of Nigeria", but occur also in the southeastern Nigeria. Occurrences of prominent pegmatites have been reported in the Obudu and Oban massifs in southeastern Nigeria (Ekwueme and Matheis 1995; Okunlola 1998; Kingsley and Ekwueme 2009; Oden et al., 2013). Garba (2003) reported occurrences of newly discovered rare metal pegmatites in Nasarawa and Richifa in central Nigeria and Kushaka, Magami and Maradun in the north-western Nigeria. Okunlola (2005) studied about 200 Precambrian pegmatite bodies from which he recognized and defined 7 broad fields of the Precambrian rare metal pegmatites in Nigeria, namely: Kabba-Isanlu, Ijero-Aramoko, Keffi-Nasarawa, Lema-Share, Oke-Ogun, Ibadan –Oshogbo, and Kushaka-Birnin Gwari. Rare metal pegmatites comprise quartz, K-feldspar, plagioclase, muscovite, biotite, and tourmaline with varying amounts of beryl, lepidolite, spodumene, garnet, apatite and accessory minerals including columbite–tantalite, ilmenite and cassiterite (Melcher *et al.,* 2013; Wright, 1970). Crystals can vary up to 5 cm in size.

2.3.4.2 BARREN PEGMATITES

Barren pegmatite bodies are ubiquitous in the Nigerian Pan-African Basement. According to Matheis and Caen-Vachette (1983), the barren pegmatites are about 100 Ma older than the rare-metal pegmatites and are not directly related to any apparent intrusive activity. However, Kinnaird (1984) suggested they are related to calc-alkaline syntectonic granitoids. They are found associated with all the major lithologies of the basement, i.e. gneisses, migmatites, schists and granitoids. The barren pegmatites comprise quartz, K-feldspar, plagioclase, muscovite and biotite, but lack the accessory minerals that concentrate rare metals. According to Alexander *et al.*, 2012, pegmatites that are most sought for their industrial minerals potential are referred to as "barren," meaning that they lack the gems and rare metals that are the more typical targets for exploitation.

2.3.5 STRUCTURAL CONTROL FOR PEGMATITES EMPLACEMENT

The ancient lineament system of the Nigeria Basement Complex has been known to control the distribution of rare-metal pegmatite with the intersections hosting the richest pegmatite (Okunlola, 2005). Garba, (2002) and Okunlola, (2005) noted that rich concentrate of rare metal pegmatites in the late Precambrian terrain of Nigeria are concentrated close to major transcurrent faults, for example, the Kalangai, the Ifewara, and the Anka fault systems which has southern extension up to the Oke Ogun areas in the south west. The trend of the fault and inherent displacement is highly variable according to the type of rock. Mylonitization, silicification and localized dextral sense of shearing especially of amphibolite and diorite emplacement are some of the surface expressions of the faults and these may represent remnants of obducted ophiolite (Ajibade and Wright, 1989; Garba, 2002; Okunlola, 2005). Deformational episodes producing

tight to isoclinal folds mainly controlled the mineralized pegmatites in most of the rare pegmatites fields in Nigeria and these isoclinal folds are linked also to major transcurrent faults (Garba, 2002, Okunlola, 2005). Late Pan-African granites parental to rare metal pegmatites and gold-bearing veins are closely associated with the fractures in the Pan African mobile belts (Küster, 1990; Ekwueme and Matheis, 1995; Garba, 2002; Okunlola, 2005).

2.3.6 GENESIS OF PEGMATITES

According to London (2005), two competing hypotheses have explained pegmatites either as the direct products of partial melting (anatexis), or as the products of extended fractional crystallization of granitic magmas. Pegmatites of the LCT class (peraluminous, mostly S-type and evolved I-type sources: Černý, 1991a) tend to emanate from the roof zones of their plutons, whereas those of the NYF class (mostly A-types and chemically similar rocks) appear to originate from within the centers of their source plutons (e.g. Simmons *et al*., 2012; Černý, 1991a, b).

The peraluminous pegmatite granites parental to the rare-metal pegmatites were formed by partial melting of mica-rich metasediments along the regional fracture zones as enunciated by Wright (1970), Matheis (1981) and Garba (2002). The rare-metal pegmatites have both magmatic and crustal characteristics defined by enrichment of the LREE, marked negative Eu anomaly and relative depletion of the HREE (Garba, 2005). The magmatic origin of the rare-metal pegmatites is not disputable from the REE and lithophile element trends, except that there appears to be evidence of some crustal influence, possibly because of their metasedimentary host rocks (Garba, 2003). According to Garba, (2005) the similarity in their REE distribution pattern in rare metal pegmatites and the Younger Granites cast doubt on their origin from magmas of the main syn-tectonic granitoids (the Older Granites). Garba (2002) suggested that they may have been sourced from peraluminous

late-tectonic granites rather than the typically calc-alkaline syn-tectonic granitoids noted by Fitches *et al.,* (1985). The rare metal-enriched pegmatites of southwestern Nigeria are rather products of partial melting and leaching processes of the basement units than the truly pegmatitic phase of proximal Older Granites (Matheis and Caen-Vachette, 1983). Matheis and Emofurieta (1987) also suggest derivation of rare-metal pegmatite mineralization, especially in southwestern Nigeria, from reactivation of deep-seated tectonic lineaments combined with partial melting and external fluid supply. Since the pegmatites appear to be emplaced along major faults lineaments, the albitization and rare-metal mineralization may have been due to late stage fluids available at the close of the Pan-African metamorphic cycle (Ekwueme and Matheis 1995), or due to Na-rich hydrothermal solutions from the mantle along ancient lineaments (Wright, 1970 and Garba, 2002). Kuster (1990) presented evidence to show that the development of rare-metal pegmatites of the Wamba area of central Nigeria is genetically related to the late tectonic granite magmatism which was controlled by the late Pan-African NE-SW and NW-SE shear system. Kuster (1990) also noted that since the degree of mineralization can be correlated with the degree of late Na-metasomatism (albitization), it follows that both granite-related pegmatites emplacement and subsequent mineralization are related to the late-tectonic shear movements. It is probable that the host rocks contributed significantly to the individual characteristic of each pegmatite occurrence, as demonstrated by marked difference between pegmatite in the southwest, southeast and central Nigeria (Matheis and Emofurieta 1987; Ekwueme and Matheis 1995, Garba 2002).

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 INTRODUCTION

The methodology for this research work is as follows; literature review of relevant published and unpublished reports, systematic geological field mapping and laboratory work. Rose diagrams were constructed with GeoRose software using the strikes of lineaments obtained during the field mapping in order to determine their dominant direction. Geochemical data interpretation were carried out with geochemical tool kit (GCD kit) through the use of various discrimination diagrams. Results of petrographic studies and whole rock geochemical analysis were used to evaluate chemical characteristics of these rocks and establish the petrogenesis of the rock units and associated rare metal mineralization in the study area.

3.2 FIELD MAPPING

The field investigation involved systematic regional geological mapping on a scale of 1: 50,000. Fresh (un-weathered) representative rock and mineral samples were collected, labelled using a marker and masking tape, packaged in separate sample bags to avoid contamination and transported to be taken to the laboratory for further analysis. Preliminary observation and identification of each constituent rock and mineral were carried out using magnifying lens. Field data, e.g. measurement of strike and dip directions of lineaments with compass-clinometer, and recording of the co-ordinates of every sampling point using Global Positioning System (GPS) were also carried out. Other structural imprints like trends of fractures, dimension of veins and dykes were also recorded. Field pictures were as well taken using a camera.

3.3 LABORATORY WORK

The laboratory work involved sample preparation, petrographic study and geochemical analysis.

3.3.1 PETROGRAHIC STUDIES

For the petrographic studies, nine rock samples were cut into chips with a cutting machine and subsequently polished using carborundum powder of 0.6, 0.4 and 0.2 mm to obtain slides with required thickness and a perfectly smooth surface at University of Jos thin section laboratory. The prepared slides were examined under transmitted light petrological microscope at the Department of Geology, Ahmadu Bello University, Zaria to identify minerals and other features that were not seen with aid of magnifying lens. Modal composition by point counting using JMicroVision (v1.27) software of each of the thin section was carried out in order to estimate the percentage of each mineral constituent present.

3.3.2 GEOCHEMICAL ANALYSIS

Fifteen selected rock and mineral samples comprising seven (7) host rocks, two (2) muscovites, three (3) biotites, one (1) beryl, one (1) unknown mineral (silver or bismuthinite) and one (1) green soil were selected for geochemical analysis. The muscovites, biotites and other mineral samples were extracted from the pegmatites. The host rock samples consist of representative samples of each mappable lithologic unit which include migmatitic gneiss, granitic gneiss, biotite gneiss, mylonite, medium grained granite, coarse grained granite and porphyritic granite. 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 pulverized sample was thoroughly homogenized to obtain a representative portion. The samples were thereafter shipped for major, minor and trace elements (including REE) chemical analysis

at the Activation laboratory Ontario, Canada using a lithium metaborate/tetraborate fusion ICP-MS technique. Rb, Cs and Li were however analysed using sodium peroxide fusion ICPMS. The whole rock analysis was done using standard analytical procedures named “4 Litho” a combination of packages Code 4B (lithium metaborate/tetraborate fusion ICP whole rock) and Code 4B2 (trace element ICP/MS). 4 Litho analyses used $LiBO_2$/Tetraborate fusion ICP for major oxides plus minor elements. Code 4B2 analyses of trace element used ICP-MS. Detection limit is 0.01 wt% for major oxides and 0.01 to 20ppm for trace elements.

CHAPTER FOUR

4.0 RESULTS

4.1 FIELD GEOLOGY, PETROGRAPHY, STRUCTURES AND GEOCHEMISTRY

Geological mapping of the study area reveals that the area is underlain by gneisses, schist and granites as major rocks (Fig. 4.1). Other minor lithologies are pegmatites, mylonite and aplites. The structural features of the study area comprises joints, faults, folds, foliations, dykes and veins. In this section, the field description and thin section interpretation of each rock type would be presented, as well as the structures encountered. Results of geochemistry of the rocks would also be presented.

4.2 GNEISSES

The gneisses occur in the south-western part of the study area. They underlie most of the flat lying, dark brown to grey loamy soils. The gneisses are slightly to moderately foliated, folded, jointed and highly fractured. Despite the fact that the gneisses seldom outcrop, three distinct groups were observed in the field; migmatitic gneiss, granitic gneiss and biotite gneiss.

4.2.1 MIGMATITIC GNEISS

4.2.1.1 FIELD OCCURENCE

The migmatitic gneisses are generally low lying and highly fractured as observed in the field. They are dark grey, massive, fine grained, and show the segregation of melanocratic (dark) and leucocratic (white) bands. It also exhibits characteristic ptygmatitic folding. (Plate I). The migmatitic gneiss encountered at the south-eastern part of the study area around Soko contains

abundant quartzo-feldspathic veins which are folded towards the north. A sharp contact between the gneiss and porphyritic granite was also observed at that same location.

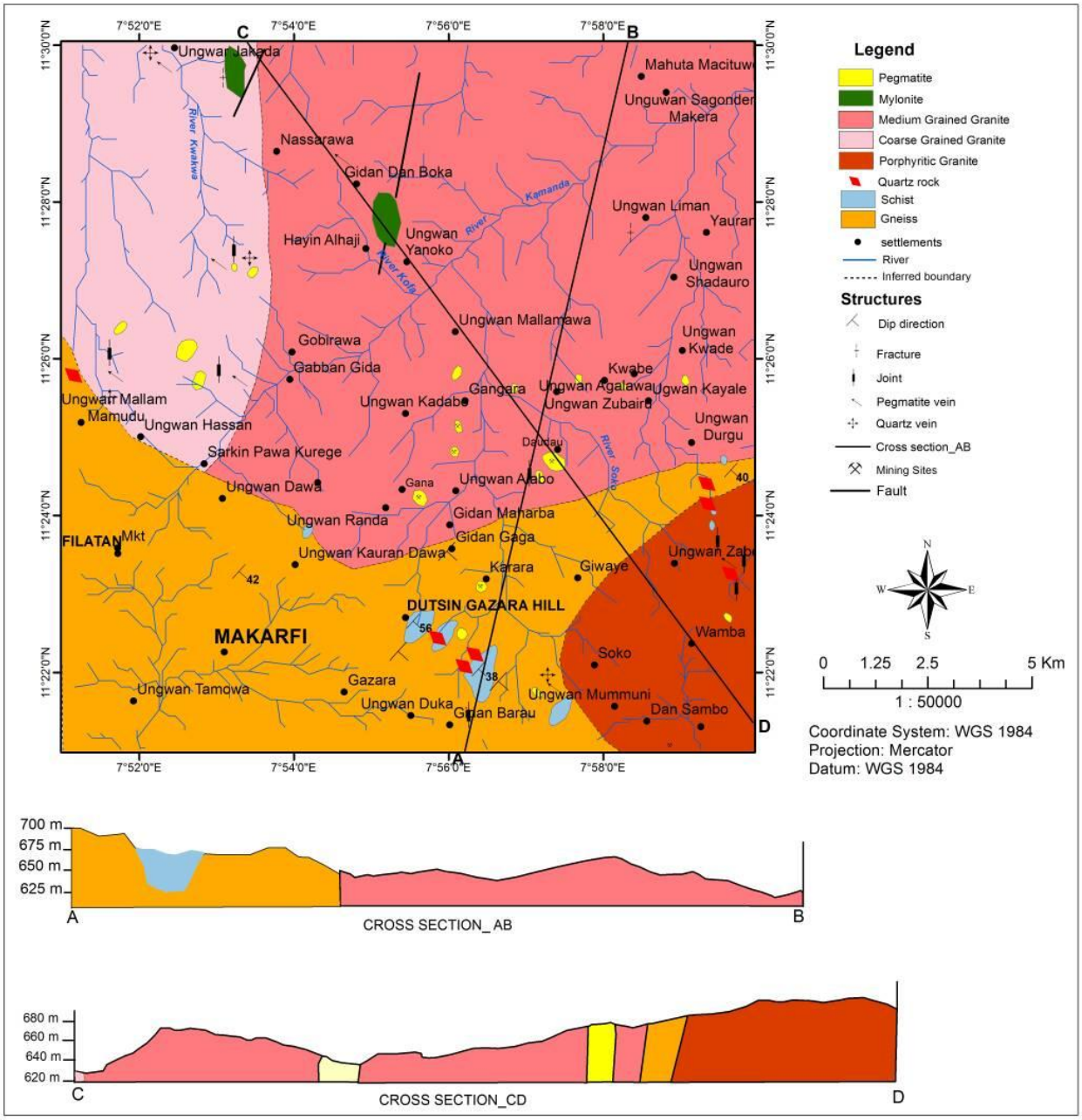


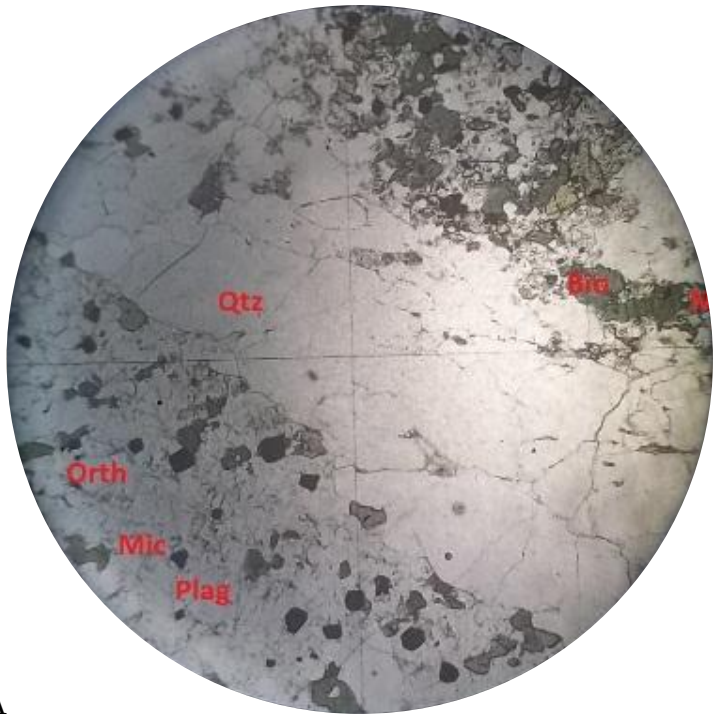
Figure 4.1: Geological map of the study area (Makarfi part of Zaria Sheet 102 NE).



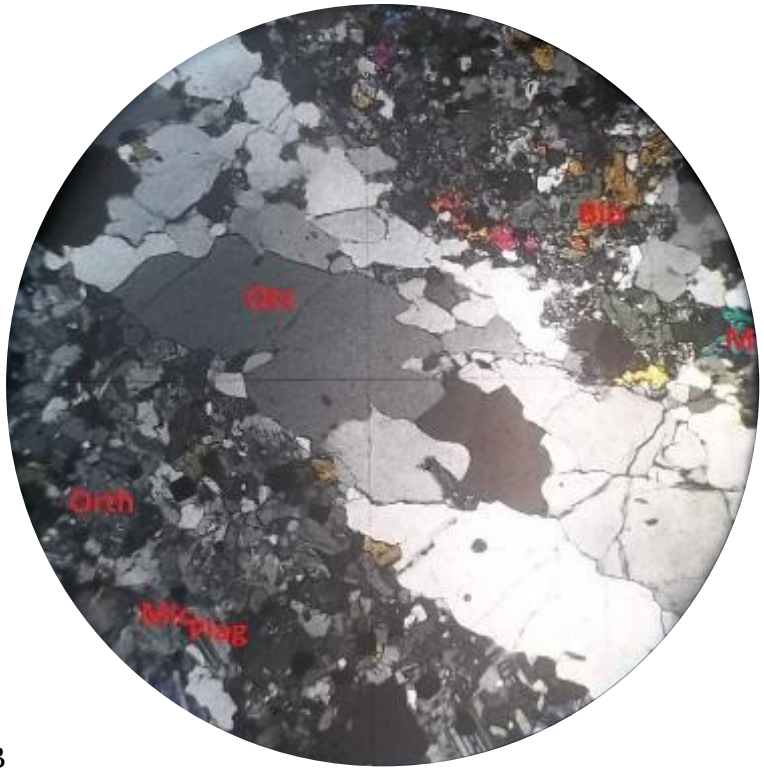
Plate I: Field photograph of migmatitic-gneiss around Jama 'are ($N11^0$ 24′ 15.2″, $E007^0$ 59′ 39.5″).

4.2.1.2 PETROGRAPHY

Petrographic study reveals that the rock (Plate II) is composed of quartz, orthoclase, microcline plagioclase, biotite and muscovite. The quartz which is fractured and exhibits undulose extinction due to probable metamorphic stress constitutes about 40% by volume of the rock. Orthoclase is anhedral, appears cloudy in Plane Polarized Light (PPL) and grey in Crossed Polarized Light (XPL) constitute about 10% of the rock. Anhedral crystal of microcline which is



A



B

Plate II: Photomicrograph of migmatitic gneiss under A) PPL and B) XPL. (Qtz=quartz, Orth=orthoclase, Mic=microcline, Plag=plagioclase, Bio=biotite, M=muscovite). (Magnification X40).

easily distinguished by its characteristic cross-hatched twinning in XPL constitutes about 5% by volume of the rock. Plagioclase constitutes about 20% by volume of the rock. It is anhedral, colourless and exhibits combined albite and Carlsbad twinning in XPL. Biotite is anhedral, brown to pale green in colour with perfect cleavage in one direction constitutes about 20% by volume of the rock. Muscovite is anhedral, colourless with perfect cleavage in one direction constitutes about 5% by volume of the rock.

4.2.2 GRANITIC GNEISS

4.2.2.1 FIELD OCCURRENCE

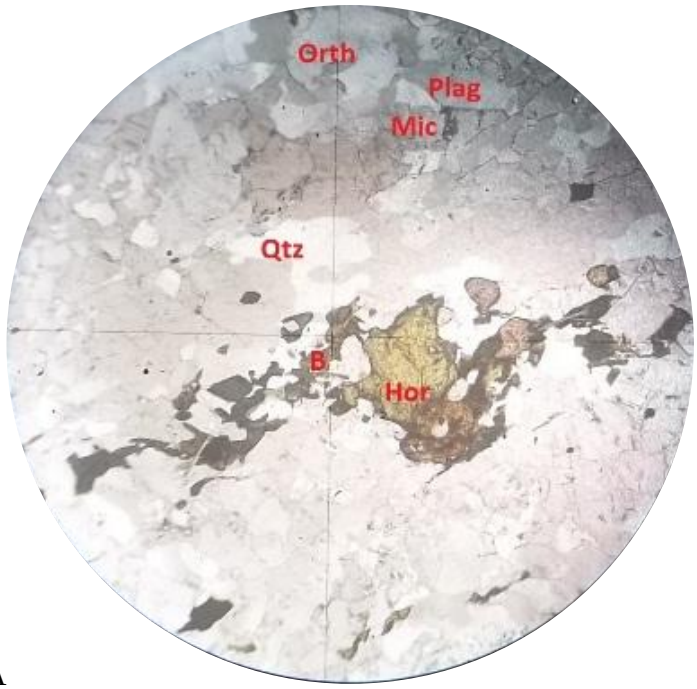
They are the dominant gneisses in the area. The outcrops locally occur as low dome shaped. The gneisses as observed are mostly grey in colour, but a pink variety was encountered at a quarry north-east of Gidan Barau in the south-eastern part of the study area. They are massive, medium to fine grained and slightly to moderately foliated with mafic and felsic lenses defining the foliation (Plate III).



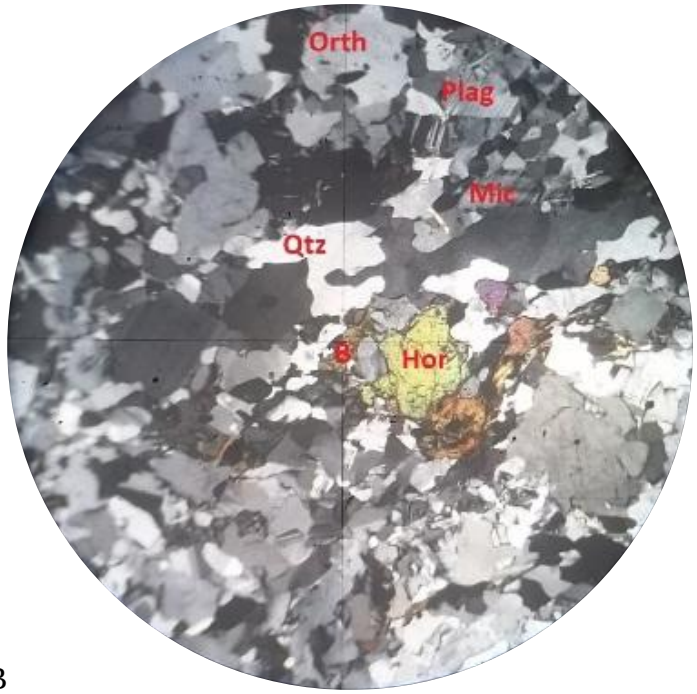
Plate III: Field photograph of granitic-gneiss around Gidan Barau (N11° 21′ 23 3″, E007° 56′ 16.3″).

4.2.2.2 PETROGRAPHY

In thin section (Plate IV), about 30% by volume of the rock is made up of anhedral to subhedral crystals of quartz. The quartz is colourless and non pleochroic. Orthoclase is subhedral, cloudy and constitutes about 15% by volume of the rock. Microcline constitutes about 15% by volume of the rock, it is subhedral and is colourless but cloudy in PPL with low relief, and characteristic cross-hatched twinning in XPL. Plagioclase constitutes about 10% by volume of the rock, it is colourless in PPL and displays polysynthetic twinning in XPL. About 20% of the rock is composed of biotite which occurs as short platy crystals showing weak alignment and alteration to chlorite in some places. Hornblende is light green in XPL and greenish-brown in PPL, has high relief, skeletal and sieve structured with inclined cleavage and constitutes about 10% by volume of the rock.



A



B

Plate IV: Photomicrograph of granitic gneiss under A) PPL and B) XPL. (Qtz=quartz, Orth=orthoclase, Mic=microcline, Plag=plagioclase, B=biotite, Hor=hornblende). (Magnification X40).

4.2.3 BIOTITE GNEISS

4.2.3.1 FIELD OCCURRENCE

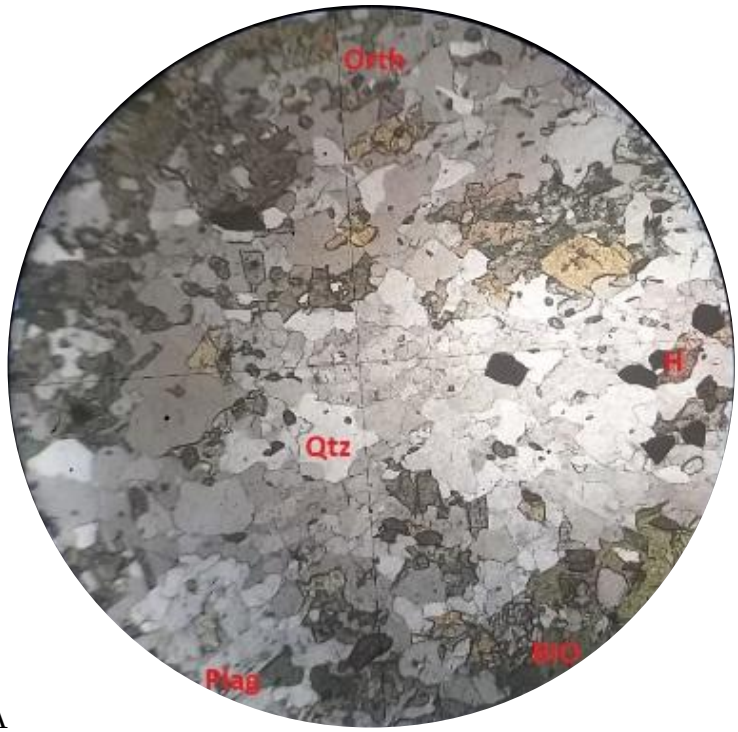
They are dark in colour, massive, fine grained and well foliated with the alignment of more mafic minerals and less felsic minerals (Plate V). They are low lying and found adjacent to the schist into which they grade into with increasing schistocity.



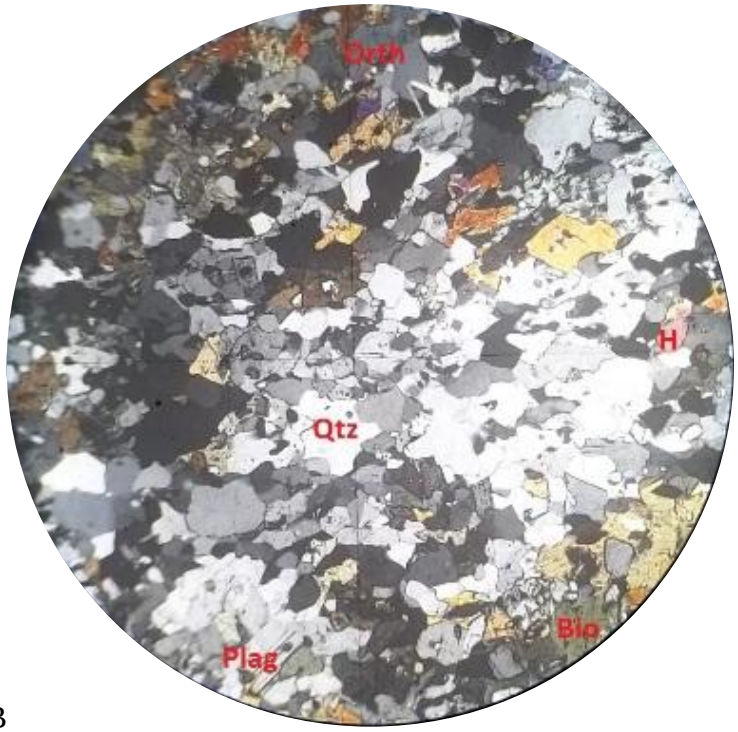
Plate V: Field photograph of biotite-gneiss (N11° 23′ 6.0″, E007° 56′ 15.2″).

4.2.3.2 PETROGRAPHY

Petrographic study (Plate VI) reveals that quartz which appears colourless with wavy extinction constitutes about 25% by volume of the rock. Orthoclase is subhedral, cloudy and constitutes about 10% by volume of the rock. Plagioclase constitutes about 10% of the rock, it is anhedral, cloudy and exhibits polysynthetic twinning in XPL. About 40% by volume of the rock is made up of anhedral crystals of biotite. The biotite is brown in PPL and green in XPL. Muscovite is colourless and constitutes about 7% of the rock. Hornblende constitutes about 5% by volume of the rock, and the remaining 3% is made up of opaque minerals.



A



B

Plate VI: Photomicrograph of biotite gneiss under A) PPL and B) XPL. (Qtz=quartz, Orth=orthoclase, Plag=plagioclase, Bio=biotite, H=hornblende). (Magnification X40).

4.3 SCHIST

They are poorly exposed in the study area, notable exposures were found in SSE part of the map along Zaria-Kano major road. They occur as dome shaped hills and highly weathered into reddish-brown regolith with beds dipping at 38^{o} SE (Plate VII). Due to the high level of weathering, no fresh samples could be obtained.



Plate VII: Field photograph of schist encountered along Zaria-Kano major road (N11° 21′ 54.7″, E007° 56′ 32.5″).

4.3.1 QUARTZ ROCKS

Quartz rocks were also encountered, and for the most part they were observed to be striking N-S. They are mostly found adjacent to the schist, or as intercalations within them, or overlying them. They are characterized by large pebbles of quartz (Plate VIII).



Plate VIII: Field photograph of quartz rock around Jama'are (N11° 24′ 13.9″, E007° 59′ 36.4″).

4.4 GRANITES

The granites cover about two third of the area mapped. They occur as intrusions ranging in size from small low lying outcrops to large whaleback shaped outcrops. They are fractured and well jointed. Aplites, quartz veins, pegmatites dykes and veins were all found to intrude the granites. Based on textural differences, three distinct groups were readily observed in the study area; porphyritic granite, coarse grained granite and medium grained granite.

4.4.1 PORPHYRITIC GRANITE

4.4.1.1 FIELD OCCURRENCE

They outcrop mostly around Soko, Wambai in the south-eastern part of the study area. Two sharp contacts between the gneisses and porphyritic granite were observed (Plate IX). They occur mostly as low lying or whaleback, leucocratic, massive and porphyritic rocks composed of quartz, feldspars and mafic minerals.

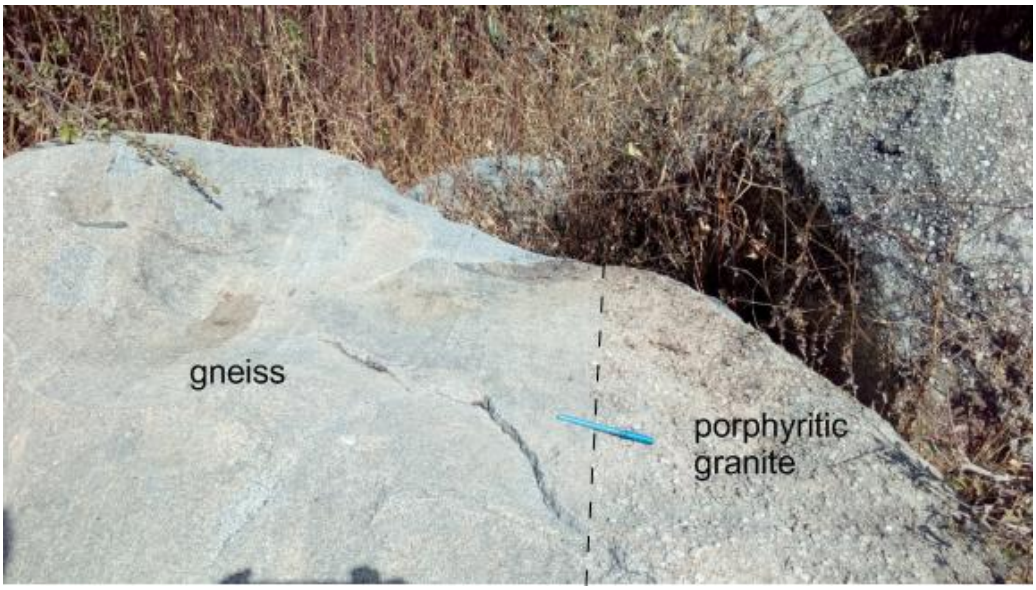
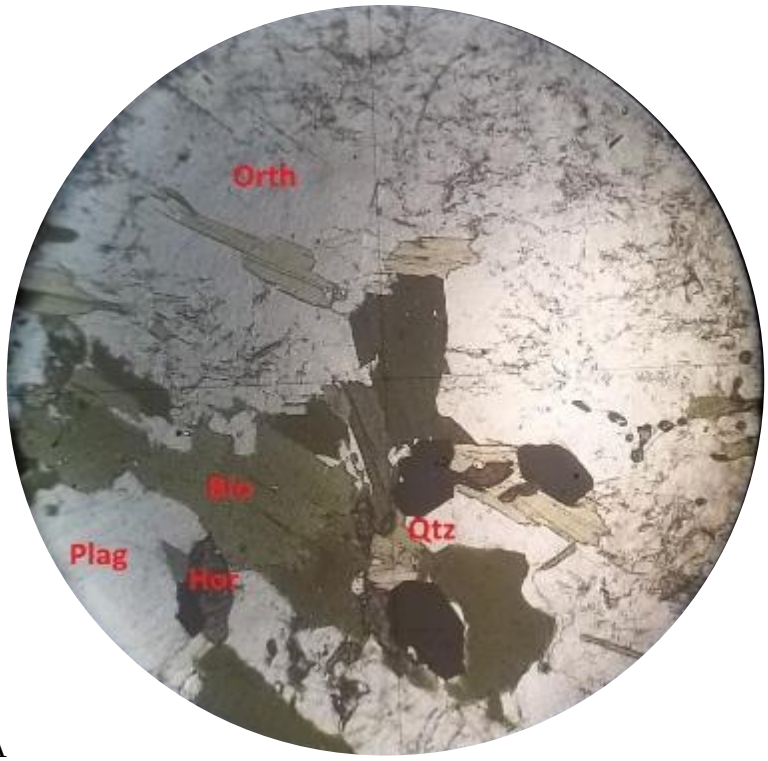


Plate IX: Field photograph of an observed contact between gneiss and porphyritic granite around Soko (N11° 21′ 44.9″, E007° 57′ 34.9″).

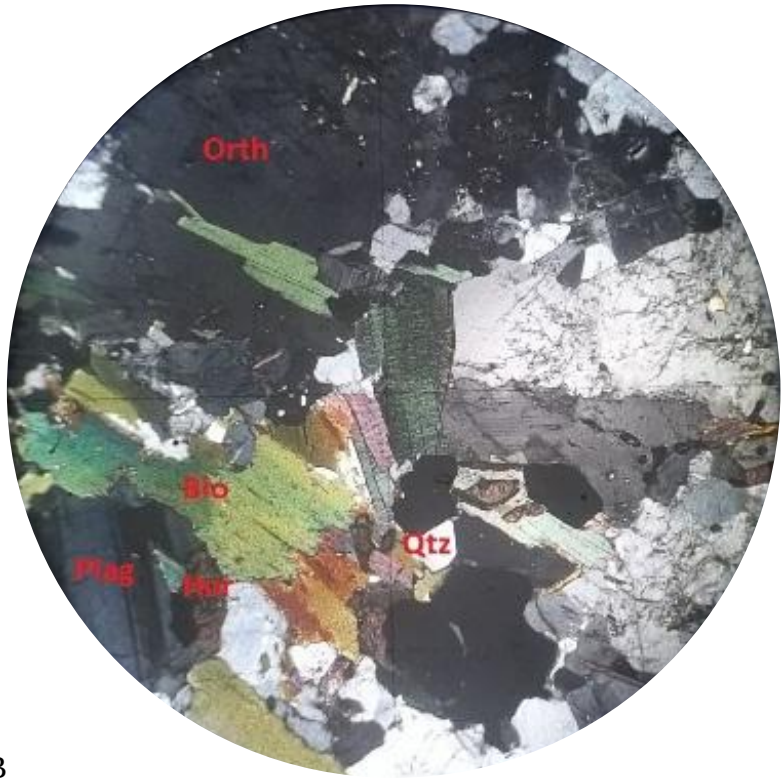
4.4.1.2 PETROGRAPHY

Thin section study (Plate X) reveals that quartz constitutes about 30% by volume of the rock. It is subhedral, colourless and exhibits undulose extinction. Orthoclase constitutes about 25% of the rock. It is subhedral, appears cloudy in PPL and grey in XPL with microperthitic texture and alteration to sericite. Plagioclase, colourless showing combined Carlsbad and albite twinning constitutes about 10% by volume of the rock. Biotite constitutes about 30% by volume of the

rock, it is strongly pleochroic from brownish-green to pale green, platy, subhedral and shows perfect cleavage in one direction. Hornblende with high relief, skeletal and sieve structured with two sets of cleavage inclined constitutes about 5% by volume of the rock. Granophyric texture was also observed. This study reveals that the rock is a porphyritic hornblende-biotite granite.



A



B

Plate X: Photomicrograph of porphyritic hornblende-biotite granite under A) PPL and B) XPL. (Qtz=Quartz, Orth=orthoclase, Plag=plagioclase, Bio=biotite, Hor=hornblende). (Magnification X40).

4.4.2 COARSE GRAINED GRANITE

4.4.2.1 FIELD OCCURRENCE

They cover the north-western part of the study area and found around Ungwan Jakada. They occur mostly as low lying to whale-back leucocratic bodies, massive and composed of coarse to very coarse grained crystals of quartz, feldspars and mafic minerals in hand specimen (Plate XI).



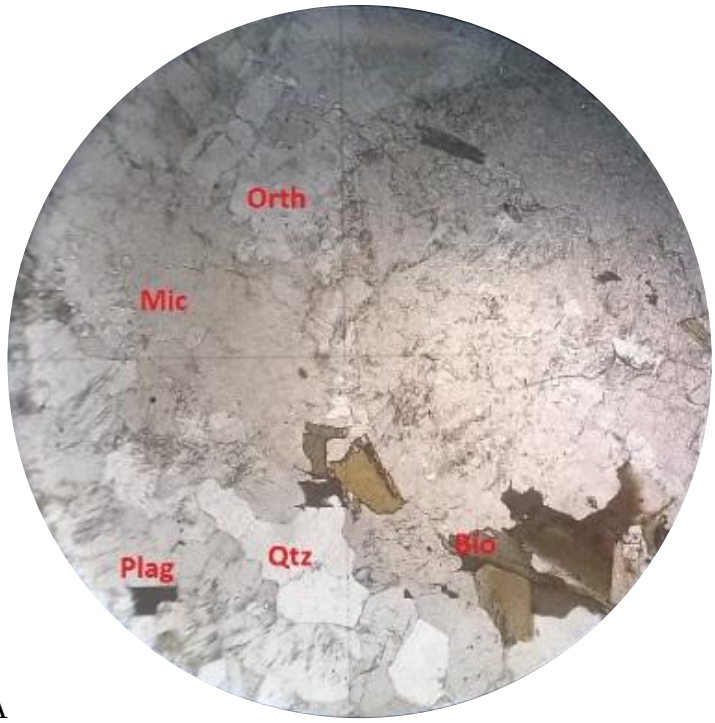
Plate XI: Field photograph of coarse grained granite (N11° 29′ 03.4″, E007° 50′ 32.4″).

4.4.2.2 PETROGRAPHY

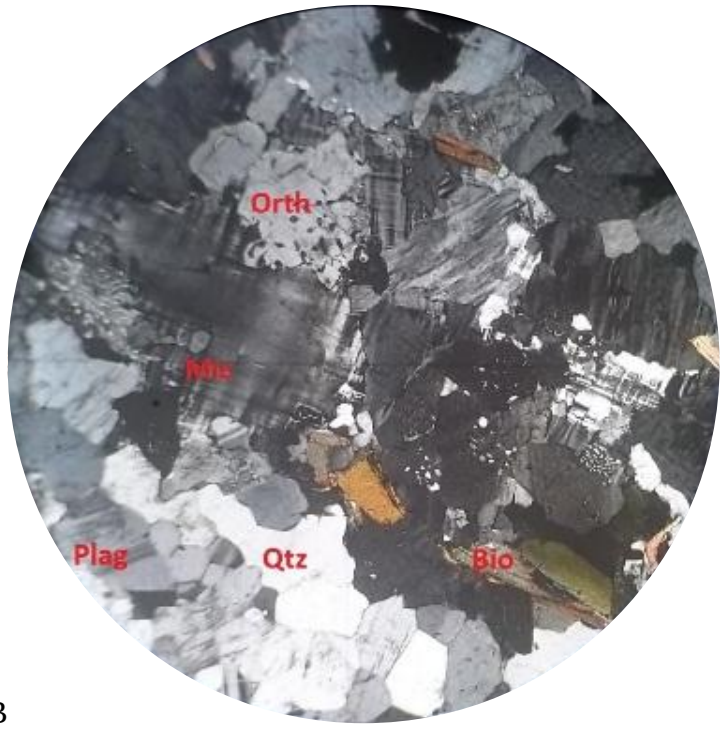
Thin section study (Plate XII) reveals that subhedral crystals of quartz constitutes about 40% by volume of the rock. Orthoclase is subhedral, cloudy and constitutes about 15% by volume of the rock. Microcline constitutes about 20% of the rock. It is subhedral, colourless and shows characteristic cross-hatched twinning in XPL. Plagioclase, colourless, subhedral with combined

Carlsbad and albite twinning in XPL constitutes about 10% by volume of the rock. About 15% by volume of the rock is made up of biotite. The biotite is platy with perfect cleavage in one direction, subhedral, brown in PPL and green in XPL. Myrmekitic and granophyric textures (growth of quartz in orthoclase) were both observed.

]



A



B

Plate XII: Photomicrograph of coarse grained biotite granite under A) PPL and B) XPL. (Qtz=quartz, Orth=orthoclase, Mic=microcline, Plag=plagioclase, Bio=biotite). (Magnification X40).

4.4.3 MEDIUM GRAINED GRANITE

4.4.3.1 FIELD OCCURRENCE

These are the dominant granites in the area. They cover the central and eastern part of the study area, found around areas such asYanoko, Dadin-kowa and Agalawa. They occur mostly as low lying to whaleback hills striking N-S, leucocratic, medium grained, massive and highly fractured (Pate XIII). In hand specimen they are composed of quartz, feldspars and mafic minerals.

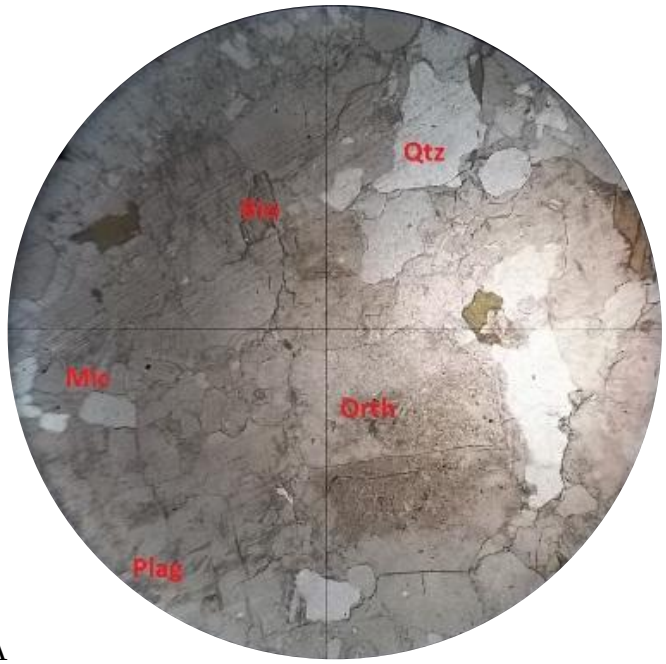


Plate XIII: Field photograph of highly fractured medium grained granite around Agalawa (N11° 25′ 59.7″, E007° 58′ 11.8″).

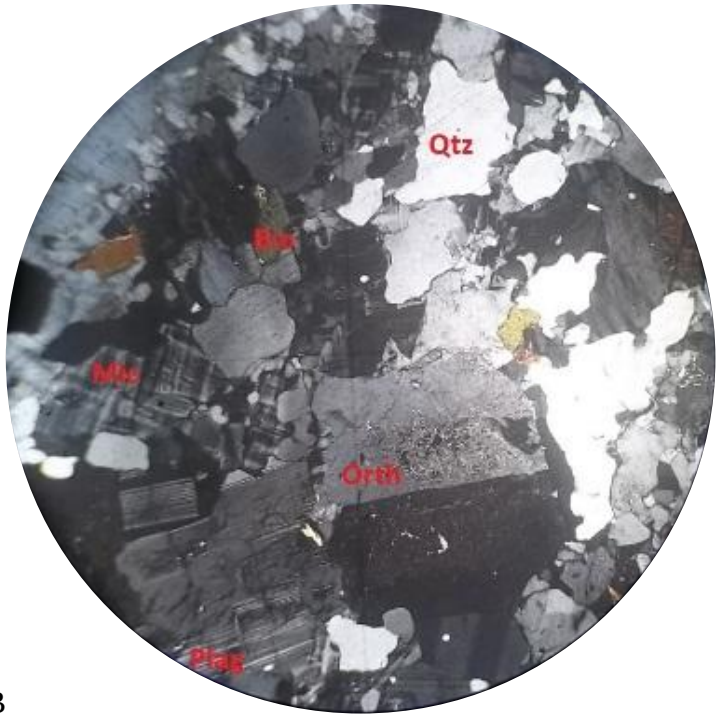
4.4.3.2 PETROGRAPHY

Thin section study reveals that the medium grained granite can be divided into medium grained biotite granite (Plate XIV) and medium grained muscovite granite (Plate XV) based on mineralogical differences.

Thin section study of the medium grained biotite granite (Plate XIV) shows that quartz constitutes about 30% by volume of the rock. It is subhedral and non-pleochroic. Orthoclase constitutes about 20% by volume of the rock. It is subhedral, cloudy and shows Carlsbad twinning in XPL. Microcline constitutes about 20% of the rock. It is subhedral and shows characteristic cross-hatched twinning in XPL. Plagioclase is subhedral, colourless and exhibits polysynthetic twinning in XPL. It accounts for about 15%. About 15% by volume of the rock is made up of biotite flakes. It is anhedral, brown to pale green and occurs mostly at the interstices and over growth within the feldspars. Myrmekitic texture was observed (growth of quartz on plagioclase). While thin section study of the medium grained muscovite granite (Plate XV) reveals that quartz constitutes about 40% by volume of the rock. It is subhedral and exhibits undulose extinction. Orthoclase appears colourless to cloudy with low relief, grey in XPL showing microperthitic texture. It constitutes about 10% of the rock. Microcline, colourless but cloudy in PPL with low relief and exhibits characteristic cross-hatched twinning in XPL constitutes about 20% by volume of the rock. Plagioclase constitutes about 10% of the rock. It is colourless with low relief and displays combined Carlsbad and albite twinning with oblique extinction in XPL. Muscovite is subhedral, shows blue, green and pink interference colours in XPL, shows perfect cleavage in one direction and constitutes about 20% by volume of the rock.

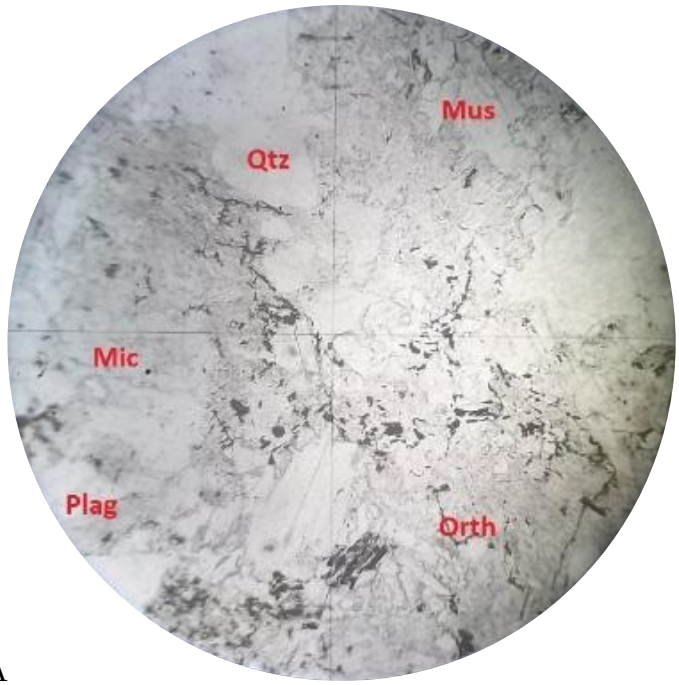


A

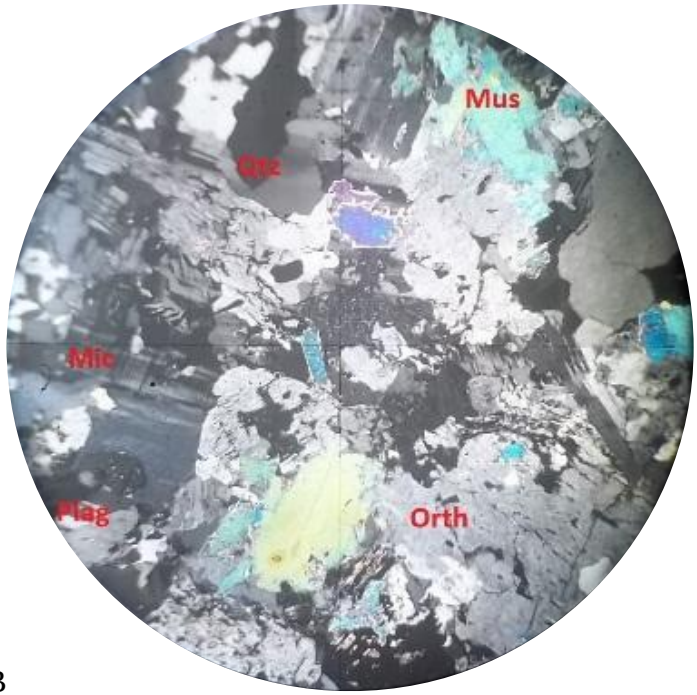


B

Plate XIV: Photomicrograph of medium grained biotite granite under A) PPL and B) XPL. (Qtz=quartz, Orth=orthoclase, Mic=microcline, Plag=plagioclase, Bio=biotite). (Magnification X40).



A



B

Plate XV: Photomicrograph of medium grained muscovite granite under A) PPL and B) XPL. ((Qtz=quartz, Orth=orthoclase, Mic=microcline, Plag=plagioclase, Mus=muscovite). (Magnification X40).

4.5 MYLONITE

4.5.1 FIELD OCCURRENCE

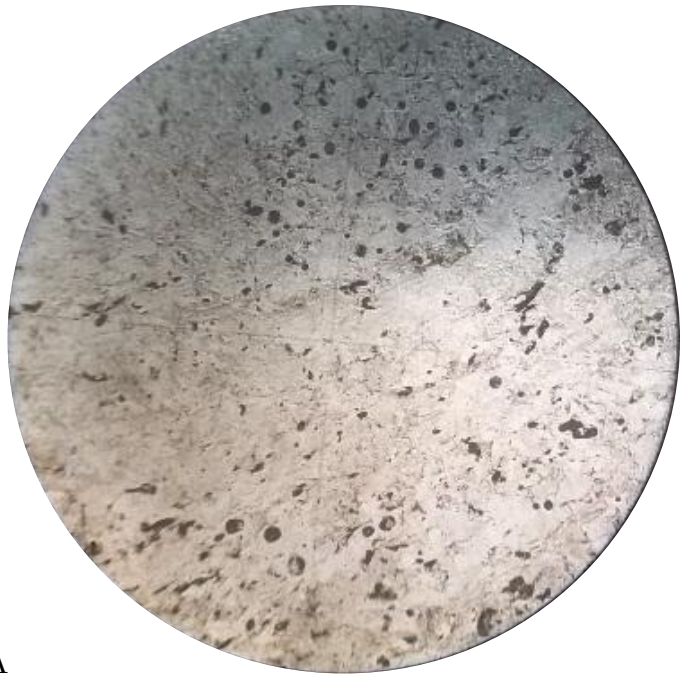
They mostly occur as dome shaped bodies, light pink in colour, fine grained showing lamination of quartz bands with beds dipping at very high angle (Plate XVI). Notable exposures were encountered north of Yanoko and south-east of Unguwan Jakada.



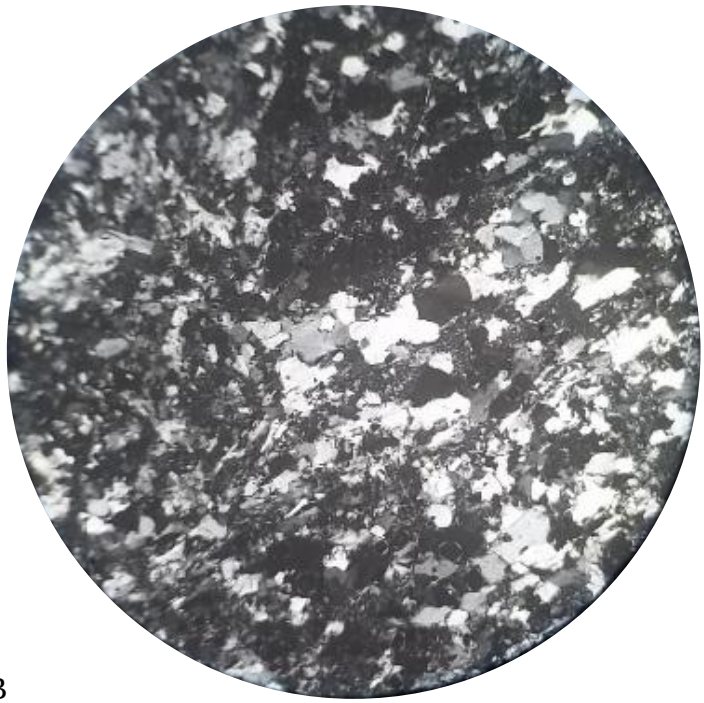
Plate XVI: Field photograph of mylonite exposure encountered north of Yanoko (N11° 27′ 58.2″, E007° 55′ 3.9″).

4.5.2 PETROGRAPHY

Thin section study reveals prismatic minerals of quartz (50%) exhibiting undulose extinction and feldspars (20%) showing weak alignment (Plate XVII), mafic mineral probably biotite (25%), and minor traces of opaque minerals were observed. The mylonite can therefore be qualified as a protomylonite because the minerals are less deformed and it has >50% porphyroroclasts.



A



B

Plate XVII: Photomicrograph of mylonite under A) PPL and B) XPL.

4.6 APLITES

4.6.1 FIELD OCCURRENCE

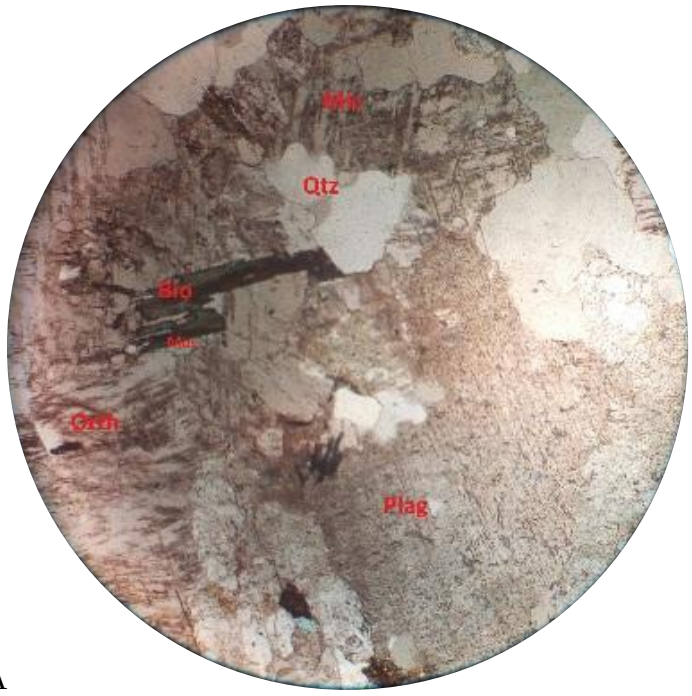
Aplite occurs as small lensoid dyke trending roughly in NNE-SSW as shown in (Fig 4.2) which is consistent with the Pan-African trend. It is a uniformly fine-grained intrusive igneous rock of less than 2 mm and has a characteristic granular texture (Plate XVIII). They are light-coloured, massive and fine grained composed dominantly of quartz, feldspars and mica minerals.



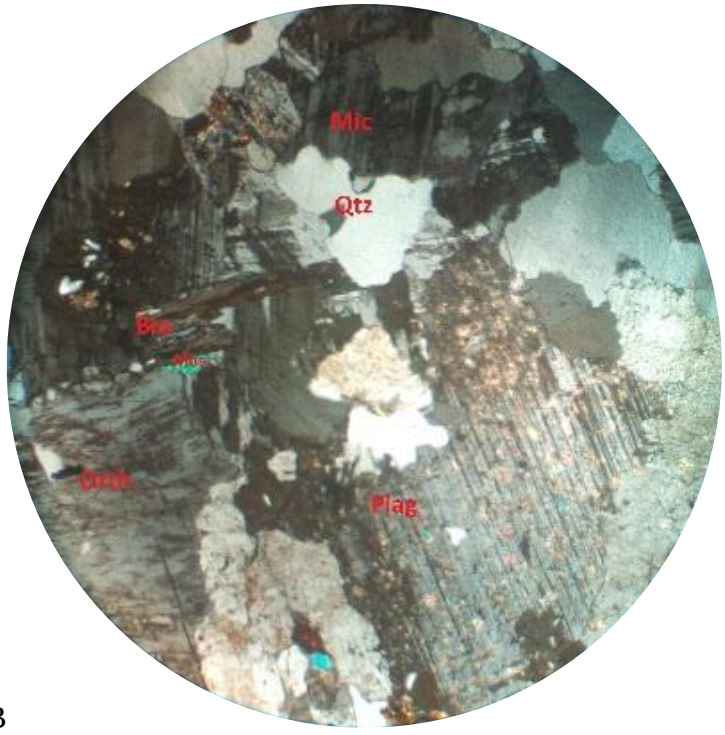
Plate XVIII: Field photograph of an aplite dyke on coarse grained granite (N11° 29′ 02.9″, E007° 51′ 21.6″).

4.6.2 PETROGRAPHY

Thin section study (Plate XIX) reveals that quartz constitutes about 25% by volume of the rock and exhibits undulose extinction. Orthoclase constitutes about 15% by volume of the rock. It appears cloudy in PPL and grey in XPL. Microcline with characteristic cross-hatched twinning in XPL constitutes about 15% by volume of the rock. Plagioclase is cloudy and exhibits polysynthetic twinning in XPL. It constitutes about 20% by volume of the rock. Biotite constitutes about 10% and muscovite constitutes about 5% by volume of the rock. The biotites and muscovites occur within the interstices and as inclusions within the feldspars. They also appear to be growing at the expense of the feldspars in processes called biotization and muscovitization. An opaque mineral probably chromite occurs with characteristic metallic lustre showing brownish colour at the edge occurs as accessory mineral.



A



B

Plate XIX: Photomicrograph of aplite dyke under A) PPL and B) XPL. (Qtz=quartz, Orth=orthoclase, Mic=microcline, Plag=plagioclase, Bio= biotite, Mus=muscovite. (Magnification X40).

4.7 PETROGRAPHIC CLASSIFICATION OF THE GRANITES AND APLITES

The modal compositions based on point counting of the rocks in the study are presented in table 4.1. Considering the modal compositions of the various types of granites identified in the study area, a QAP diagram (Fig. 4.3) was used to establish the petrographic relations of these granites. All the granites plot within the syeno-granite field while the aplite plots within the monzo-granite field.

Table (4.1): Modal composition (based on point counting) of the rocks from the study area. All values are in percentage (%).

Minerals	Migmatitic gneiss	Granitic gneiss	Biotite gneiss	Mylonite	Porphyritic hornblende-biotite granite	Coarse grained biotite granite	Medium grained biotite granite	Medium grained muscovite granite	Aplite
Quartz	40	30	30	50	30	40	30	40	35
Orthoclase	10	15	10	20	25	15	20	10	15
Microcline	5	15				20	20	20	15
Plagioclase	20	10	10		10	10	15	10	20
Biotite	20	20	35	25	30	15	15		10
Muscovite	5		7					20	5
Hornblende		10	5		5				
Opaque mins			3	5					0.5
Total	100	100	100	100	100	100	100	100	100

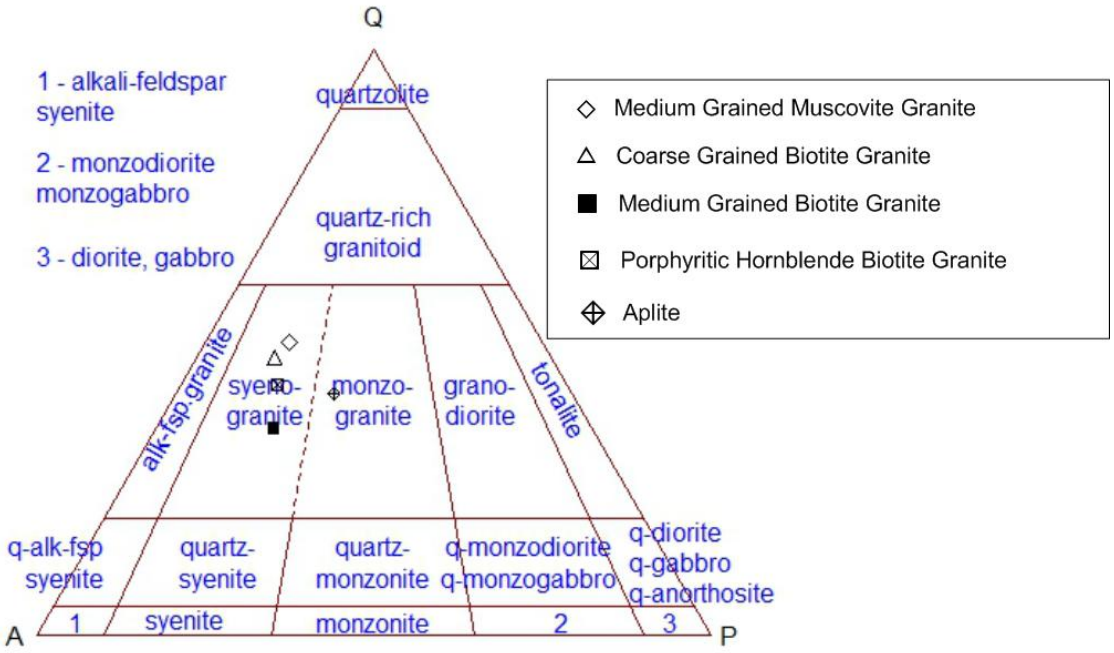


Figure 4.3: Q-A-P ternary plot of the granites and Aplites from the study area (adopted after Streckeisen, 1976).

4.8 PEGMATITES

4.8.1 FIELD OCCURRENCE

Pegmatites are widely distributed within the study area, and they form an interesting part of the geology of the study area. On the basis of field relationship and mode of occurrence, two types of pegmatites have been mapped in the study area.

The first category of pegmatites are high level dykes (Plate XX), they are highly weathered and occur sometimes as dome shaped or whaleback bodies trending dominantly in a NW-SE direction. They occur as vertically dipping dykes and pods in the gneisses, schist and granites. Field observations have shown that they intrude all the older lithologies (gneisses, schist and granites). They are composed of large crystals of quartz, feldspars and micas (over 10cm) (Plate XXI) evidenced by the large boulders of quartz and feldspars, as well as biotite and/or muscovite

sheets (Plate XXII) encountered around them. Due to the high level of weathering of these category of pegmatites, no fresh sample was obtained, but the muscovites and biotites were picked for geochemical analysis. They are the ones associated with rare metal mineralization in the area. Four major concentric zones have been established in this category of pegmatites.

a) The border zone: this zone as observed occurs as the border between the pegmatite and its host rock (Plate XXIII). It was observed to have sharp contact with the host rock. It is fine grained composed of quartz, feldspar and mafic minerals.
b) The wall zone: This zone is thicker (approximately 10m). It is coarse grained and composed of; quartz, feldspar, mica, and tourmaline (Plate XXIVa and b).
c) The intermediate zone: this zone is composed mostly of smokey quartz, feldspar (highly weathered), and mica (mostly muscovite) (Plate XXVa). It is mostly associated with the mineralization (Plate XXVb)
d) The core zone: this zone consists mostly of pure milky quartz (Plate XXVIa and b).



Plate XX: Field photograph of high level pegmatite dyke around Daudau (N11° 24′ 33.5″, E007° 57′ 12.4″).



Plate XXI: Pegmatite showing large crystals of quartz around Daudau (N11° 24′ 34.5″, E007° 57′ 13.4″). (Size of pen is 13.8cm).

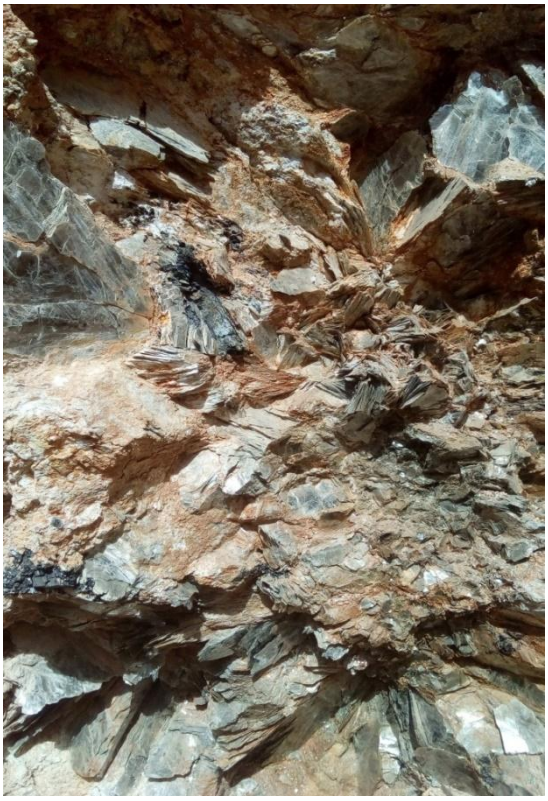


Plate XXII: Field photograph of muscovite sheets at Gana (N11° 24′ 13.0″, E007° 55′ 46.8″).



Plate XXIII: Field photograph of the border zone around Daudau (N11° 24′ 35.5″, E007° 57′ 14.4″).



Plate XXIVa: Field photograph of the wall zone along Gangara road (N11° 24′ 58.4″, E007° 56′ 05.7″).



Plate XXIVb: Field photograph of quartz with tourmaline of the wall zone at Gana (N11° 24′ 13.0″, E007° 55′ 46.8″).



Plate XXVa: Field photograph of the intermediate zone at Gana (N11° 24′ 13.0″, E007° 55′ 46.8″).



Plate XXVb: Field photograph of mineralization (bismuthinite) found within the intermediate zone at Gana (N11° 24′ 13.0″, E007° 55′ 46.8″).

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Plate XXVIa: Field photograph of the core zone at Gana (N11° 24′ 13.0″, E007° 55′ 46.8″).



Plate XXVIb: Field photograph of a vertical section at Gana showing the core and intermediate zone (N11° 24′ 13.0″, E007° 55′ 46.8″).

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The second category of pegmatites occurs mostly as low lying dykes cross-cutting the gneisses and granites (Plate XXVIIa, b and c). They are composed mainly of quartz, feldspars and mafic minerals. They vary in thickness from few centimeters to one meter. They strike mainly in the NE-SW directions concordant with the major structural trend in the area. The general structural trend of the low lying pegmatite dykes is represented in Fig. 4.4.



Plate XXVIIa: Field photograph of a low lying pegmatite dyke within porphyritic granite (N11° 23′ 16.9″, E007° 59′ 47.7″).



Plate XXVIIb: Field photograph of low lying pegmatite dyke within coarse grained granite (N11° 27′ 4.0″, E007° 57′ 20.1″).

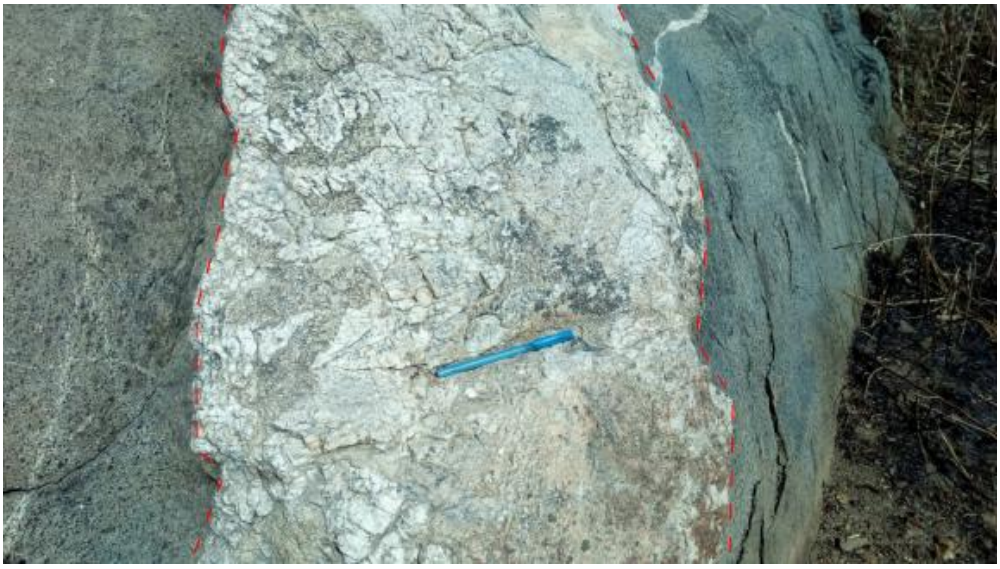


Plate XXVIIc: Field photograph of a low lying pegmatite dyke within gneiss around Soko (N11° 21′ 44.6″, E007° 57′ 33.5″).

4.9 STRUCTURES

Signatures of tectonic activity in the area are seen in the various structural features which are probably due to impacts of metamorphism and deformation on the rocks which may be brittle or ductile. The main structural features in the area comprise dykes, veins, joints, folds, fault, fracture xenoliths and exfoliation.

4.9.1 QUARTZ VEINS

Veins occur as fracture and joint fillings within the gneisses, schist and granites. They are mono-mineralic and appear white in colour containing only quartz (Plate XXVIII). They show a general NW-SE trend as shown in (Fig 4.4, see table AI in appendix) which is also consistent with the Pan-African trend, the vein varies in size from a few centimeters to about 15 cm and often short in strike length hardly exceeding few meters.



Plate XXVIII: Field photograph of quartz vein on coarse grained granite (N11° 25′ 40.0″, E007° 50′ 40.5″).

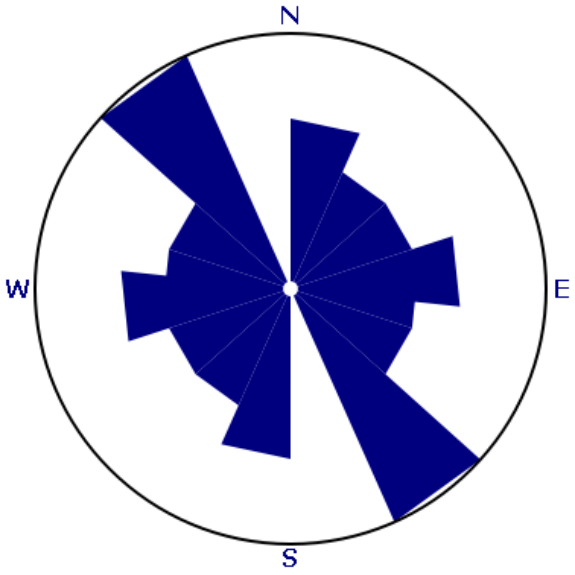


Figure 4.4: Rose diagram showing the dominant trend of quartz veins in the study area.

4.9.2 DYKES

Dykes as observed in the study area occur mostly within the granites. They are mainly of two types; aplite dykes showing a trend of NNE-SSW (Fig 4.2, see table A1 in appendix), and the low lying pegmatite dykes showing of NE-SW trends (Fig 4.5, see table A1in appendix). Both are consistent with the Pan-African trend in the area.

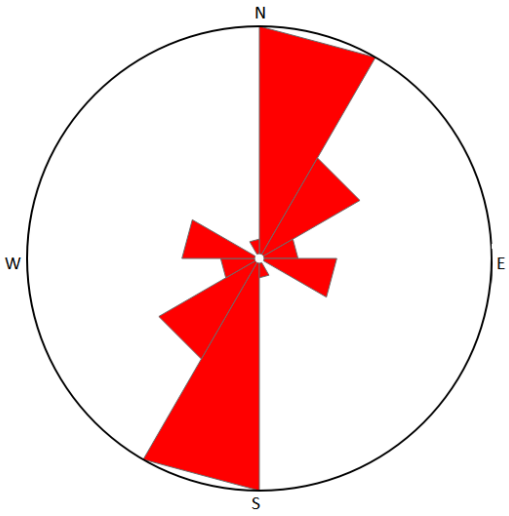


Figure 4.2: Rose diagram showing the dominant trend of aplite dykes in the study area.

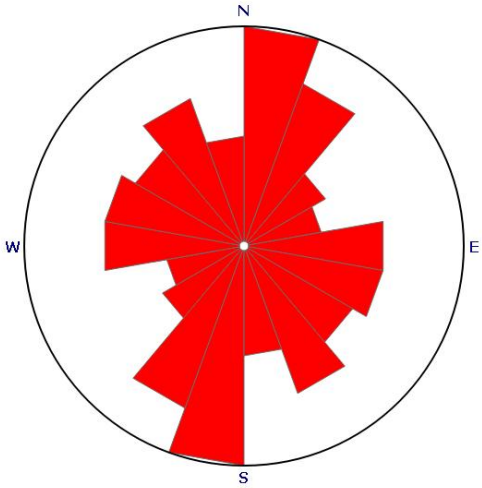


Figure 4.5: Rose diagram showing the dominant trend of low lying pegmatite dykes in the study area.

4.9.3 JOINTS

A joint is a surface fracture without displacement. Joints are the most abundant structural feature observed in the study area. Most of the rocks in the area (especially the granites) have well defined cracks and joints (Plate XXIX). Some of the joints were found to be parallel while some are cross-cutting each other showing that they are formed from different orogenic events or

cooling activities. Strike measurement of the joints and cracks reveal that they have a dominant N-S trend with subordinate NW-SE and NE-SW trends (Fig 4.6, see table A1 in appendix) concordant to the general structural trend in the Nigerian Pan-African basement complex which is known to have undergone both ductile and brittle deformation associated with tectonic activity.



Plate XXIX: Field photograph of parallel joints on granites at location around Daudau (N11° 24′ 35.0″, E007° 57′ 13.5″).

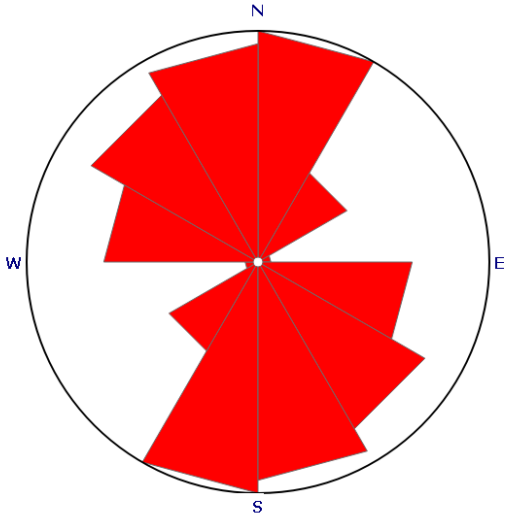


Figure 4.6: Rose diagram showing the dominant trend of joints in the study area.

4.9.4 FOLDS

A fold is a bend in any pre-existing structure in a rock as a result of deformation. Folding is not well developed in the area. It occurs mainly within the gneisses. The types of fold observed in the area of study are; ptygmatitic folding and symmetrical folding of quartzo feldspathic veins on migmatitic-gneiss (Plate XXXa), and symmetrical folding of low lying pegmatite dyke on granitic-gneiss (Plate XXXb).



Plate XXXa: Field photograph of ptygmatic fold on gneiss around Soko (N11° 21′ 44.4″, E007° 57′ 33.3″).



Plate XXXb: Symmetrical folding of low lying pegmatite dyke on granitic-gneiss (N11° 22′ 51.5″, E007° 55′ 45.5″).

4.9.5 FAULTS

A fault is a fracture with relative displacement. Faults in the study area occur mostly within the granites. Both sinistral and dextral faults with few centimeter displacements were observed at different locations. They include sinistral displacement of pegmatite vein by quartz vein (Plate XXXIa), dextral displacement of a quartzofeldspathic vein by a joint (Plate XXXIb), and sinistral fault with evidence of shearing (Plate XXXIc).



Plate XXXIa: Field photograph of sinistral fault trending NW (N11° 24′ 02.4″, E007° 54′ 48.5″).

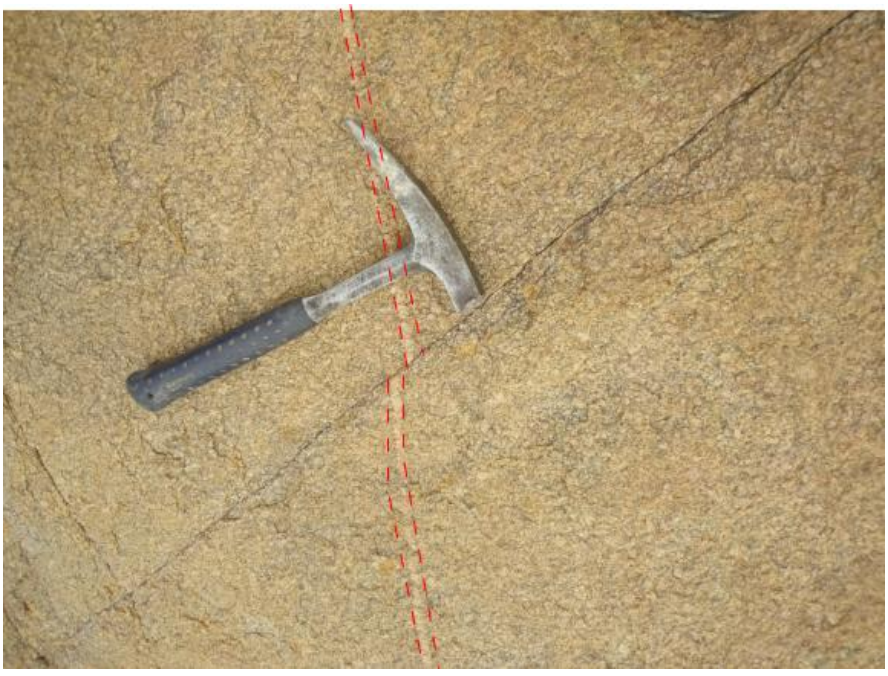


Plate XXXIb: Field photograph of dextral fault trending NE (N11° 24′ 02.6″, E007° 54′ 48.2″).



Plate XXXIc: Field photograph of sinistral fault with evidence of shearing (N11° 24′ 06.6″, E007° 54′ 45.2″).

4.9.6 XENOLITH

A xenolith is an inclusion of the country rock within the host rock. They occur as dark coloured, gneissic in composition, and found within the granitic-gneisses and granites in the study are (Plate XXXII).



Plate XXXII: Field photograph of a Xenolith in porphyritic granite (N11° 23′ 47.7″, E007° 59′ 55.7″).

4.9.7 EXFOLIATION

The separation or peeling of successive thin, onion-like shells from surfaces of rocks (mainly granite) was observed (Plate XXXIII). It is believed to be the result of diurnal temperature variations which is common in regions with moderate rainfall.



Plate XXXIII: Field photograph showing exfoliation on coarse grained granite (N11° 25′ 40.0″, E007° 50′ 40.5″.8).

4.10 GEOCHEMISTRY

Whole rock geochemical analysis provided information on the elemental concentration of the host rocks which provided basis for a comprehensive rock classification, identification of original tectonic setting, determination of the fractionation trends and petrogenesis. Major and minor elements are reported in weight percent (wt %) while trace elements reported in parts per million (ppm). The analytical data obtained are presented in Tables 4.2, 4.4 and 4.5.

4.10.1 MAJOR AND MINOR ELEMENTS GEOCHEMISTRY

Major elements are those elements present in high concentration (>1.0 wt%) while minor elements are those present in concentration between 0.1 wt% to 1.0 wt%, and they typically substitute for a major element in a mineral. Both are expressed as oxides wt%. Major elements chemistry was used in the classification and nomenclature of rocks, in showing the inter relationship between elements in order to infer geochemical processes and to deduce the origin, tectonic settings and evolution of rocks.

The major and minor elements content of the rocks of the study area are variable as shown in table 4.2. The major element composition of the host rocks plotted on Harker diagram using SiO_2 as an index of differentiation (Figs. 4.7a and b) show that TiO_2, Al_2O_3, Fe_2O_3, MgO, CaO and MnO are all negatively correlated with SiO_2, while Na_2O and K_2O are positively correlated. From the geochemical data plotted on the classification diagram total alkali silica versus silica (TAS) of Cox *et al.*, (1979) (Fig. 4.8), all the granites plot within the granite field. Using the feldspar triangle of O'Connor (1965) (Fig. 4.9), the medium grained biotite and medium grained muscovite granites plot within the granite field while the porphyritic hornblende-biotite granite plots within the granodiorite field. On the Debon La Forte B-A (1983) plot, the granites plot in different fields revealing their mineralogical compositions (Fig. 4.10). The medium grained biotite and medium grained muscovite granites plot within the highly fractionated calc-alkaline field while the porphyritic hornblende-biotite granite plots within the calc-alkaline and strongly peraluminous field on the discrimination diagram of Sylvester (1989) (Fig. 4.11). The granites are strongly peraluminous with aluminium saturated index (ASI) ranging from (1.01 to 1.20) and modified alkali-lime index (MALI) ranging from 4.48 to 8.30 (see table B1 in appendix). Similarly all the granites are peraluminous in character as shown on the ANK versus A/CNK

discrimination diagram after Shand (1943) (Fig. 4.12). Plot of the rocks on FeOtot/(FeOtot+MgO) versus SiO_2 and Na_2O+K_2O-CaO versus SiO_2 discrimination diagrams of Frost *et al.*, (2001) (Fig 4.13a and b), reveals that the medium grained biotite and medium grained muscovite granites are alkali-calcic and have higher values of Fe-number hence plot within the ferroans field, while the porphyritic hornblende-biotite granite is calc-alkalic and has low Fe-number hence it plots in the magnesian field.

Table 4.2: Major element composition of rocks in the study area (all values are in wt %)

	Gneisses			Mylonite	Granites		
Oxides	R_2	R_3	R_7	R_1	R_4	R_5	R_6
SiO_2	73.09	50.13	54.9	78.38	73.85	73.33	68.93
Al_2O_3	12.65	14.91	16.77	11.94	14.16	13.85	14.63
$Fe_2O_{3(T)}$	2.81	11.28	9.04	2.04	1.66	1.65	3.02
MnO	0.053	0.235	0.128	0.087	0.024	0.037	0.048
MgO	0.14	4.25	1.98	0.44	0.22	0.11	0.91
CaO	0.76	13.32	12.06	0.01	0.95	0.2	2.68
Na_2O	4.27	0.81	1.9	0.15	4.13	3.61	3.59
K_2O	4.43	0.69	0.32	3.79	4.5	4.89	3.57
TiO_2	0.181	1.851	1.165	0.231	0.113	0.103	0.405
P_2O_5	0.03	0.27	0.13	<0.01	0.09	0.07	0.14
LOI	0.36	0.75	1.43	2.08	0.86	0.97	0.68
Total	98.76	98.51	99.83	99.15	100.6	98.83	98.6
A/CNK	0.96	0.57	0.66	2.73	1.06	1.19	0.99

Legend;

R2= Granitic gneiss.

R3=Biotite gneiss

R7=Migmatitic gneiss

R4=Medium grained biotite granite

R5=Medium grained muscovite granite

R6=Porphyritic hornblende-biotite granite

Molecular A/CNK versus SiO_2 after Chappel and White (1974) was used to classify the rocks into their magmatic origin. On this diagram, the granites occupy both the I-type and S-type granite fields (Fig. 4.14). Furthermore, the mylonite and gneisses have sedimentary progenators except granitic gneiss which plots within the igneous protoliths field as shown on the TiO_2 versus SiO_2 discrimination diagram after Tarney, (1976) (Fig. 4.15).

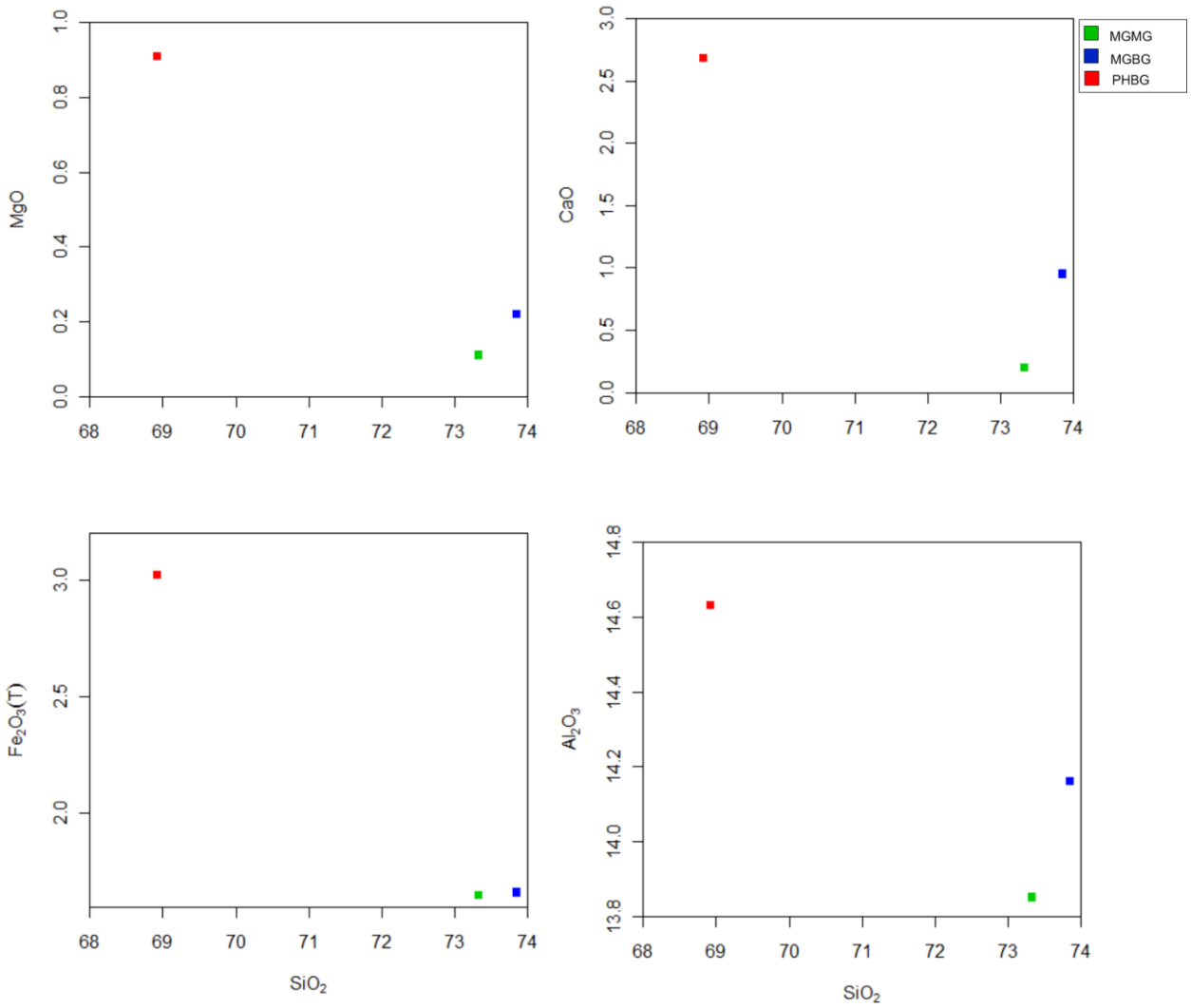


Figure 4.7a: Harker plots of, MgO, CaO, Fe_2O_3t and Al_2O_3 against silica (SiO_2) for the granites in the study area after Harker (1909).

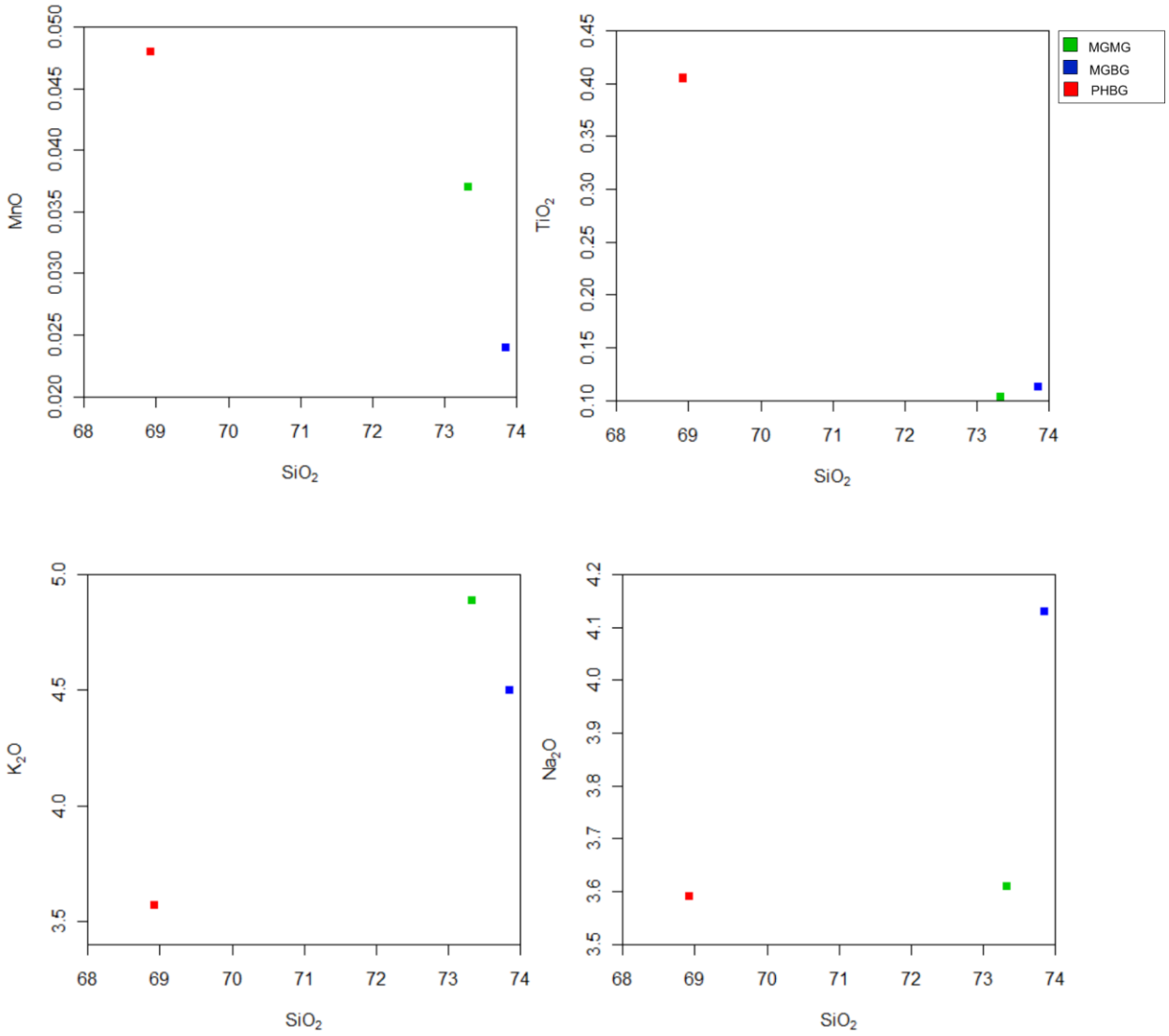


Figure 4.7b: Harker plots of MnO, TiO_2, K_2O and Na_2O against silica (SiO_2) for the granites in the study area after Harker (1909).

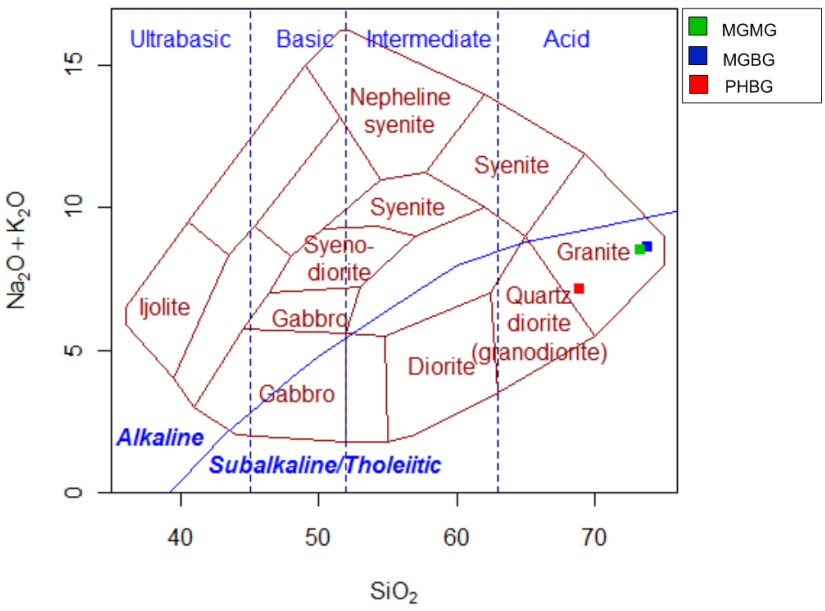


Figure 4.8: Chemical classification of the granites in the study area adapting total alkalis versus silica (TAS) of Cox *et al*., (1979). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

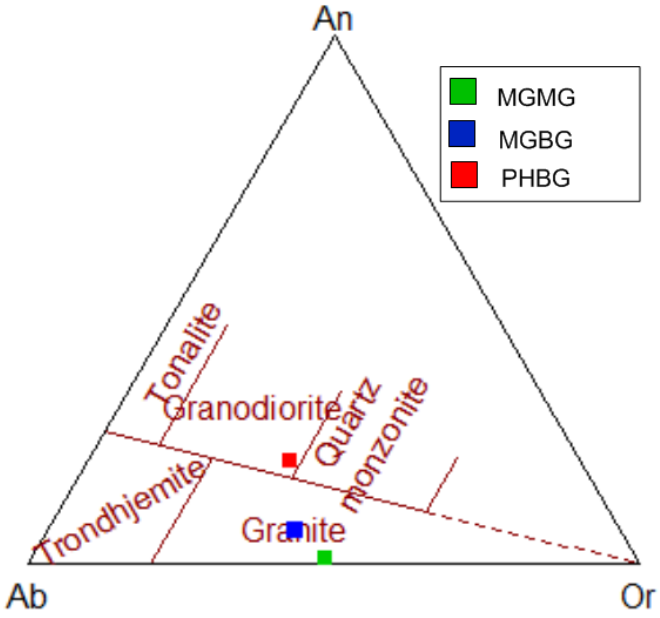


Figure 4.9: Chemical classification of the granites in the study area adopting feldspar triangle of O'Connor (1965). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

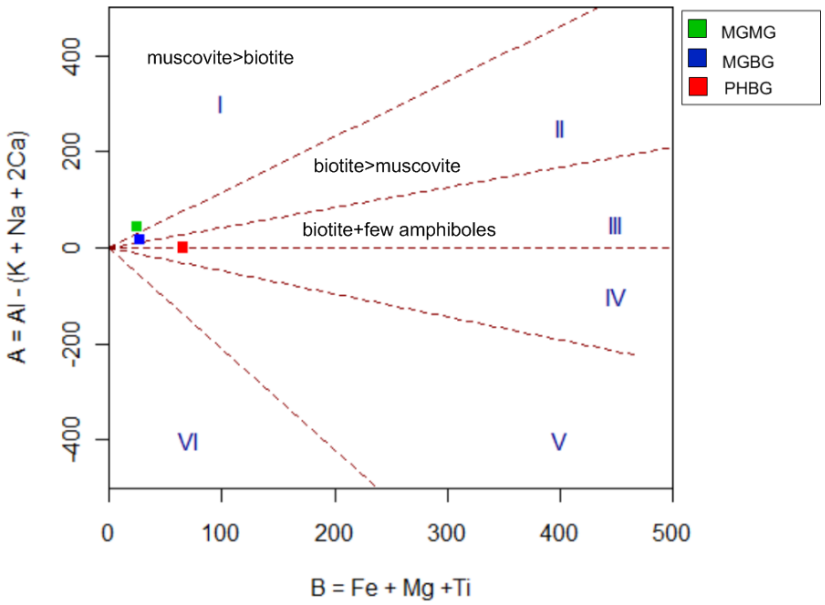


Figure 4.10: Mineralogical classification of the granites adapting A-B diagram of Debon and Le Forte (1983). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

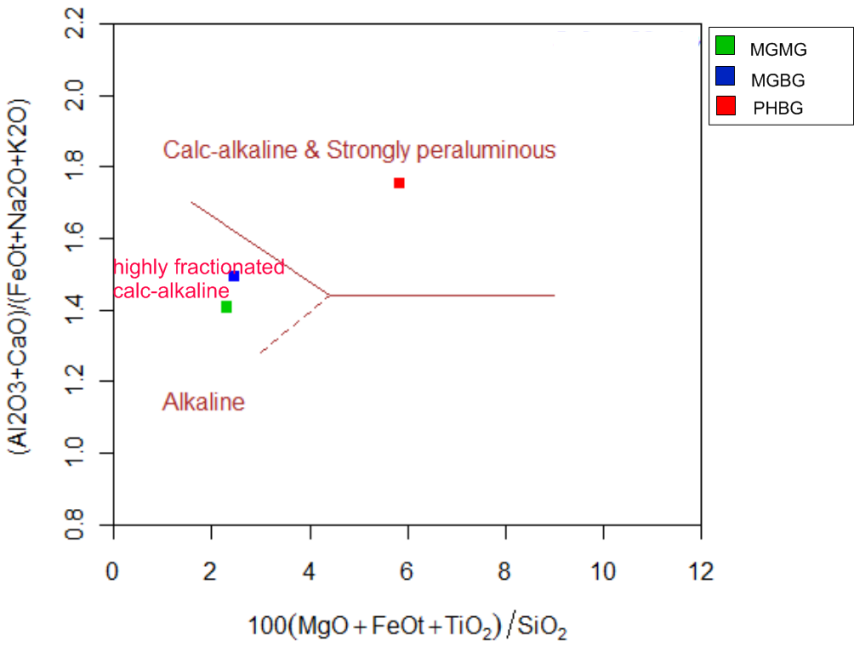


Figure 4.11: Discrimination diagram of the granites after Sylvester (1989). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

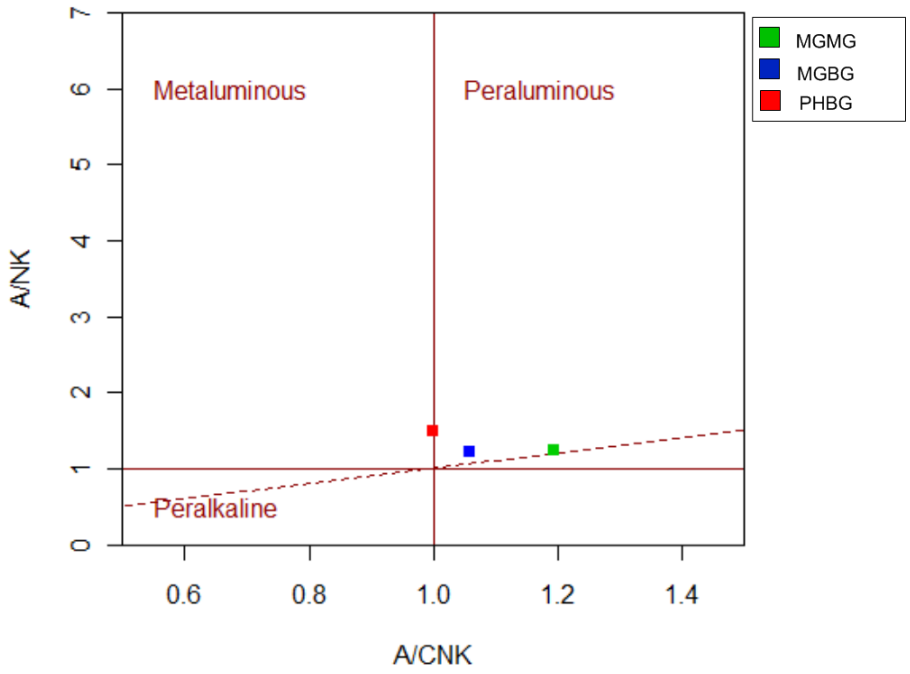


Figure 4.12: A/NK versus A/CNK plots showing the distribution of the granites after Shand, (1943). (A/NK=Al_2O_3/ (Na_2O + K_2O) A/CNK=Al_2O_3/ (CaO + Na_2O + K_2O)). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

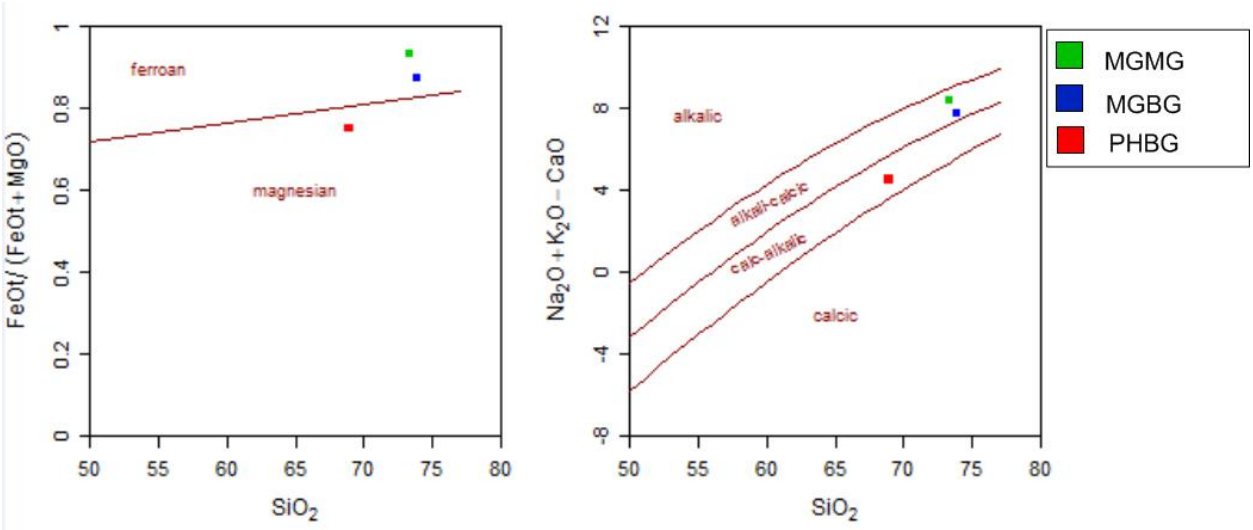


Figure 4.13: a= FeOtot/ (FeOtot+MgO Vs SiO_2 discrimination diagram after Frost *et al*, (2001), b= Na_2O+K_2O-CaO versus SiO_2 discrimination diagram after Frost *et al.*, (2001) for the granites of the study area. (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

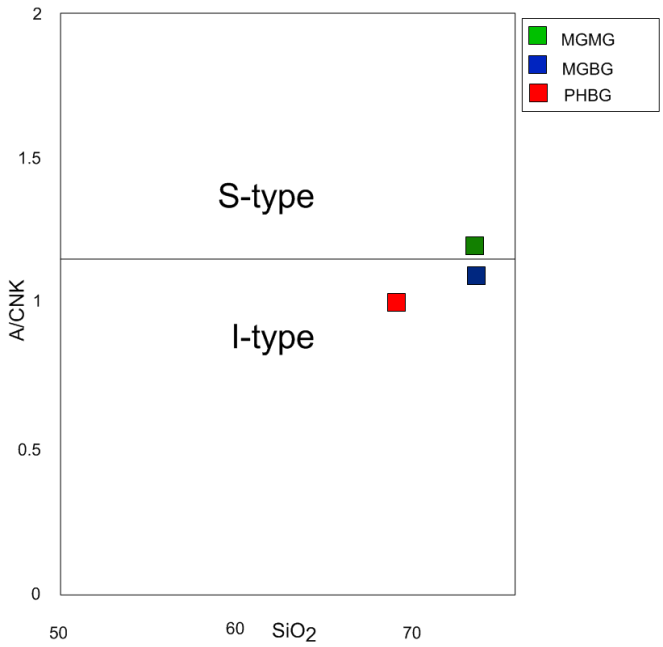


Figure 4.14: Molecular A/CNK ($Al_2O_3/CaO+Na_2O+K_2O$) versus SiO_2 diagram (after Chappel and White, 1974), showing the classification of the granites. (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

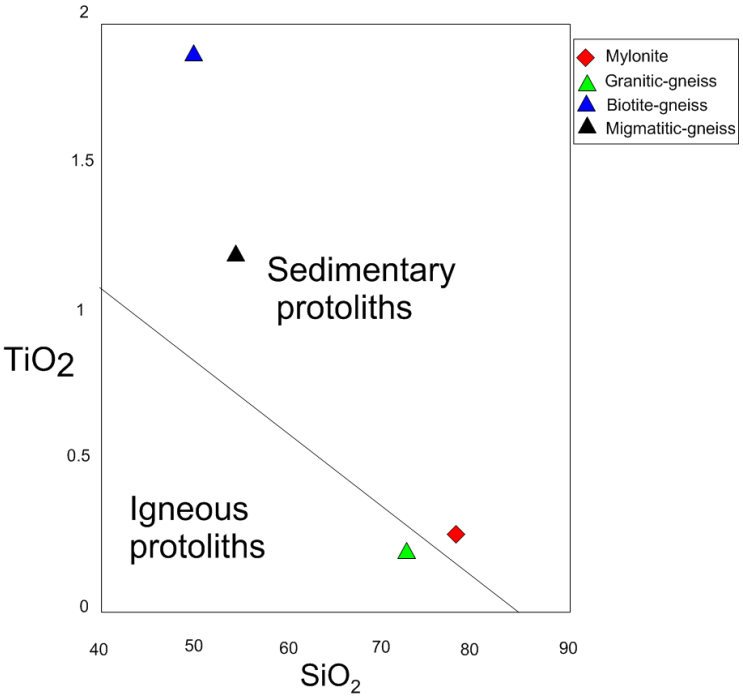


Figure 4.15: TiO_2 versus SiO_2 discrimination diagram after (Tarney, 1976) for the gneisses and mylonite in the study area**.**

4.10.2 TRACE ELEMENTS GEOCHEMISRTY

Trace elements are elements present in concentration <0.1 wt %. They substitute for major or minor elements. Trace elements were used to determine the origin of the rocks and their evolutionary processes in order to constrain magma source and to discriminate between magmatic processes because they are more sensitive to igneous fractionation processes. The trace elements composition and ratios are presented in Table 4.3. A spider diagram for the granites normalized to chondrites values of Thompson (1982) (Fig. 4.16) shows that all the granites have pronounced negative K and Ti with weak Ba, Sr and P negative anomalies. They also have a slight positive Rb, Th, Nb and Ta anomalies. The spider diagram of the gneisses (Figure 4.17) show similar pattern. On the Rb-Ba-Sr ternary diagram (Fig.4.18), the medium grained muscovite granite plots within the strongly differentiated field, medium grained biotite granite plots within the normal granite field while the porphyritic hornblende-biotite granite plots within the anomalous granite field. On the R1-R2 tectonic discrimation diagram of Batchelor and Bowden (1985) (Fig. 4.19), all the granites plot within the syn-collisional field. On the Rb versus Y+Nb plot and the Rb versus Ta+Yb plots of Pearce *et al*., (1984) the medium grained biotite and medium muscovite granites plot within the syn-collisional granite field while the porphyritic hornblende-biotite granite plots within the volcanic-arc granite field (Fig. 4.20). Furthermore on the Hf-Rb/30-Ta*3 ternary plots of Harris *et al*., (1986) (Fig. 4.21), the medium grained biotite and medium grained muscovite granites plot within the syn-collisional granite field, while the porphyritic hornblende-biotite granite plots within the late to post-collisional granite field.

Table 4.3: Trace elements composition of the rocks in the study area (all values except ratios are in ppm).

	Gneisses			Mylonite	Granites		
Elements	R2	R3	R7	R1	R4	R5	R6
Sc	4	33	23	36	3	1	4
Be	5	3	<1	15	7	12	3
V	<5	247	301	9	12	5	42
Ba	362	366	212	42	633	180	915
Sr	59	178	186	3	150	44	598
Y	82	46	16	1	13	26	12
Zr	304	234	88	5	72	77	173
Cr	<20	100	80	<20	<20	<20	20
Co	53	77	68	127	80	66	75
Ni	<20	70	30	<20	<20	<20	<20
Cu	<10	<10	<10	<10	20	20	<10
Zn	50	110	60	50	30	<30	80
Ga	27	21	40	103	23	23	22
Ge	2	2	6	3	1	2	1
As	<5	<5	<5	<5	<5	<5	<5
Rb	132	10	13	994	202	356	131
Nb	25	18	4	115	7	17	10
Mo	<2	<2	<2	<2	<2	<2	<2
Ag	1	0.7	<0.5	<0.5	<0.5	<0.5	0.6
In	<0.2	<0.2	<0.2	0.5	<0.2	<0.2	<0.2
Sn	4	3	<01	306	6	6	2
Sb	<0.5	<0.5	0.6	<0.5	<0.5	<0.5	0.9
Cs	0.8	1.2	3	149	11.5	14.8	10.1
Hf	8.7	5.7	2.2	0.4	2.3	2.5	4.4
Ta	2	1.6	0.7	25.1	1.5	4.8	1.6
W	382	304	336	849	558	479	509
Ti	0.6	<0.1	0.1	2.4	0.9	1.7	0.8
Pb	11	7	7	13	54	41	23
Bi	<0.4	2.7	0.4	41.7	<0.4	<0.4	<0.4
Th	21	4.9	1.6	0.4	7.9	18.3	10.3
U	3.1	0.9	0.6	0.2	32	20.6	2.2
Ratios							

K/Rb	278.59	572.79	204.34	31.65	184.92	114.02	226.23
K/Cs	45968.41	4723.24	885.47	211.15	3248.33	2742.79	2934.22
K/Ba	101.59	15.65	12.53	749.09	59.01	225.52	32.39
Rb/Cs	165	8.33	4.33	6.67	17.56	24.05	12.97
Rb/Sr	2.24	0.06	0.07	331.33	1.35	8.09	0.22
Al/Ga	0.248	0.376	0.222	0.061	0.326	0.319	0.352
Th/U	6.77	5.44	2.67	2.00	0.25	0.89	4.68
Zr/Hf	34.94	41.05	40.00	12.50	31.30	30.80	39.32
Zr/Y	3.70	5.09	5.50	5.00	5.54	2.96	14.42

Legend;

R2= Granitic gneiss.

R3=Biotite gneiss

R7=Migmatitic gneiss

R1= Mylonite

R4=Medium grained biotite granite

R5=Medium grained muscovite granite

R6=Porphyritic hornblende-biotite granite

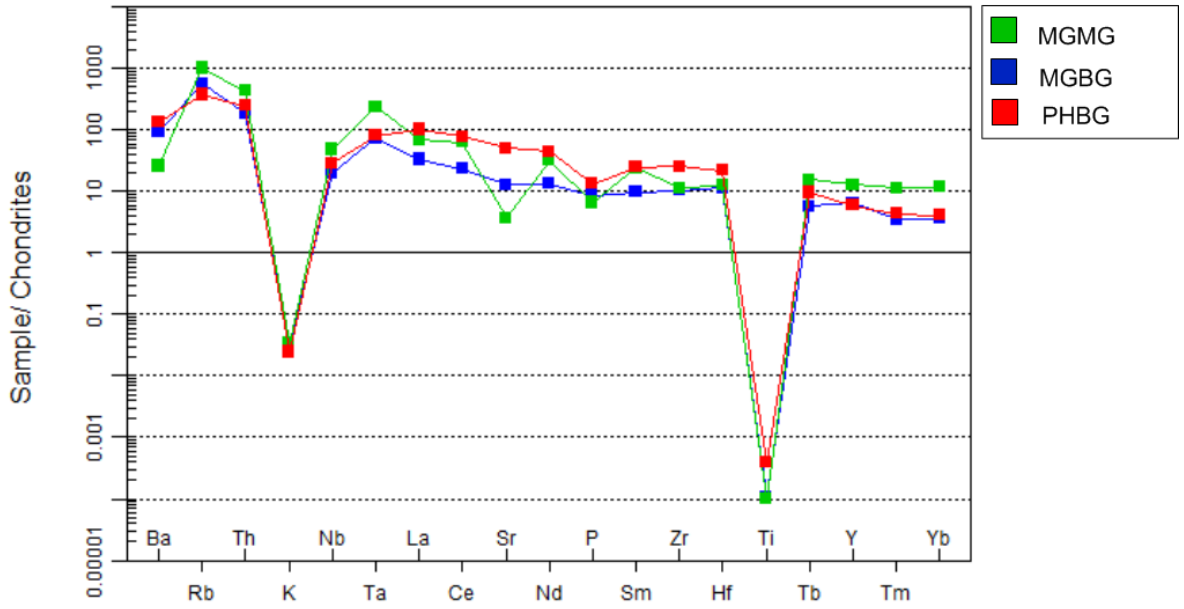


Figure 4.16: Spider plots of trace elements in the granites of the study area. All the plots are normalized to chondrite values after Thompson (1982). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

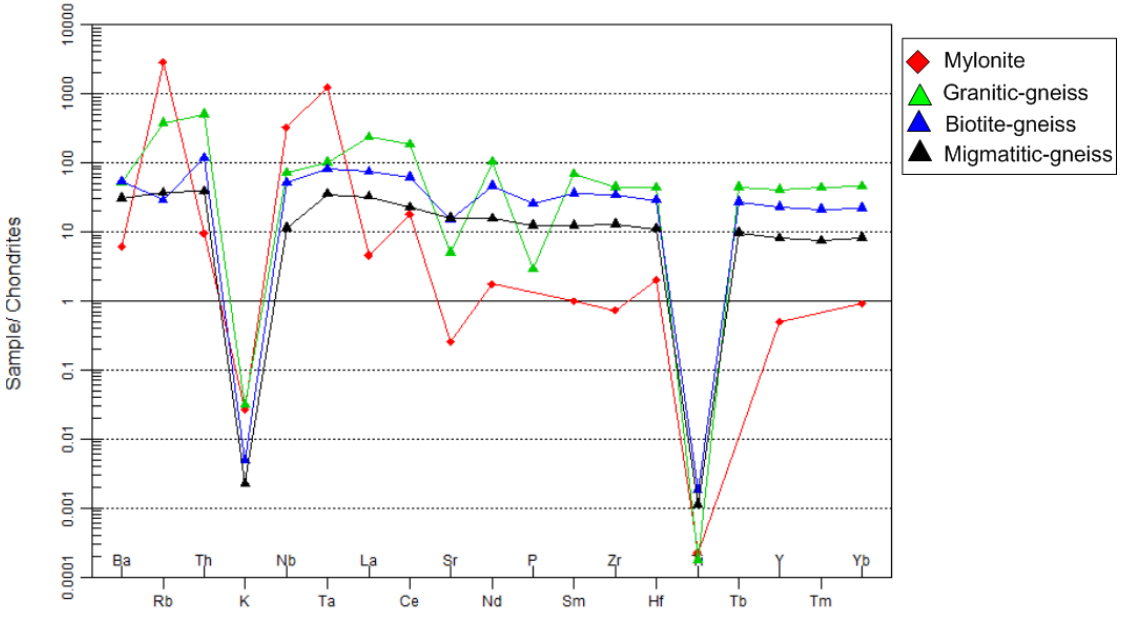


Figure 4.17: Spider plots of trace elements in the gneisses of the study area. All the plots are normalized to chondrite values after Thompson (1982).

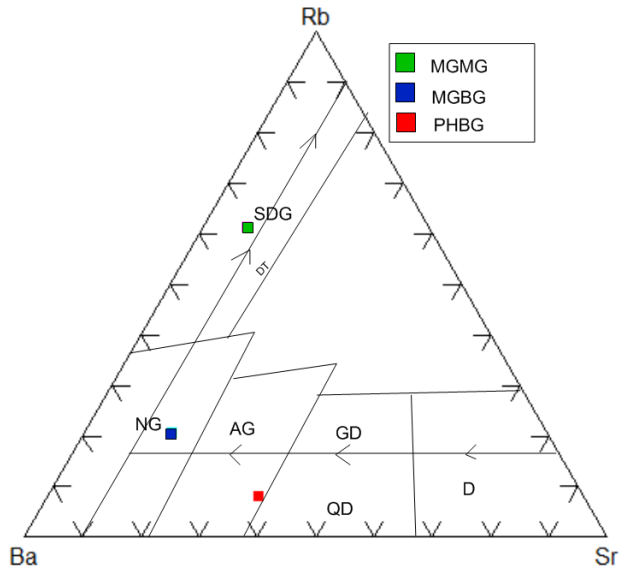


Figure 4.18: Rb-Ba-Sr ternary diagram showing the degree of differentiation of the granites in the study area (after El Bouseily and El Sokkary, 1975) (DT-differentiation trend, SDG-strongly differentiated granite, NG- normal granite, AG-anomalous granite, GD-granodiorite, QD-quartz diorite and D-diorite.). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

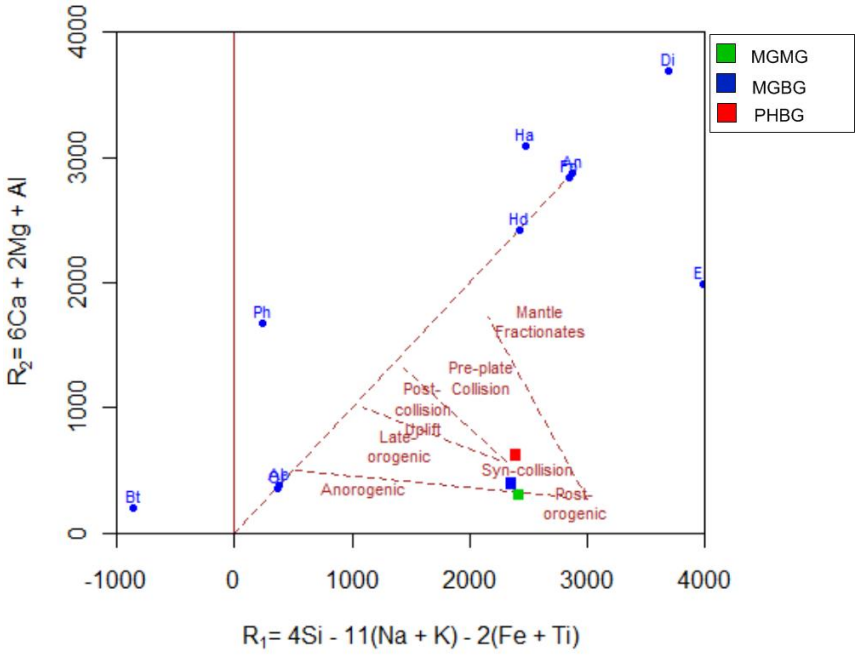


Figure 4.19: R1-R2 tectonic discrimination diagram after Batchelor and Bowden (1985), with plots of (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite) in the study area.

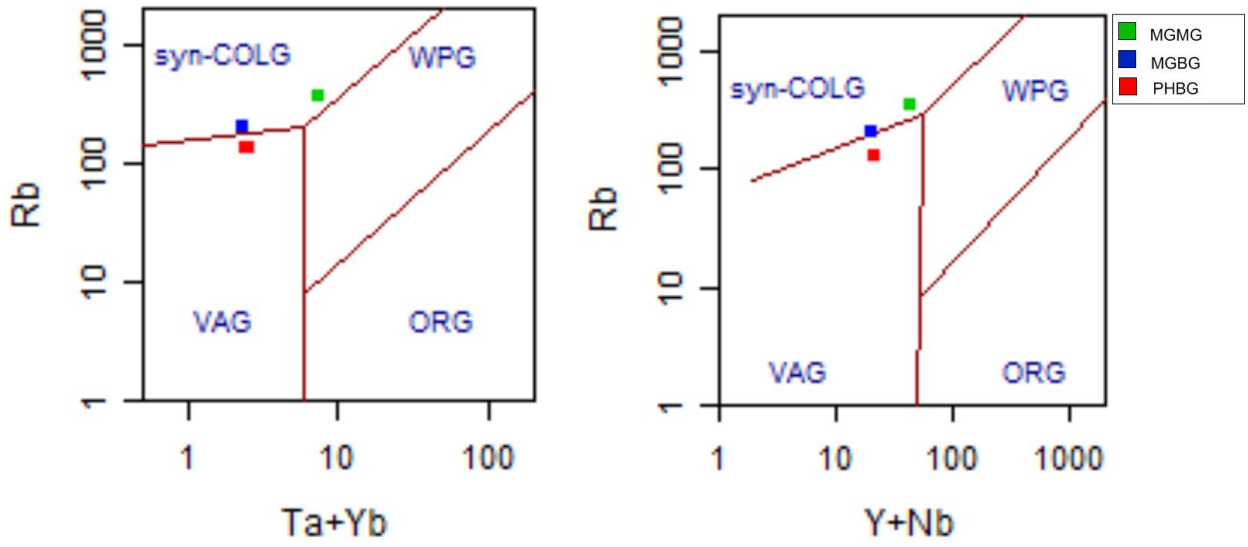


Figure 4.20: Granite tectonic discrimination diagram (aftet Pearce *et al.*, 1984). (syn-COLG=syn-collisional granites, WPG=within-plates granites, VAG=volcanic-arc granites and ORG=ocean-ridge granites), with plots of (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite) in the study area.

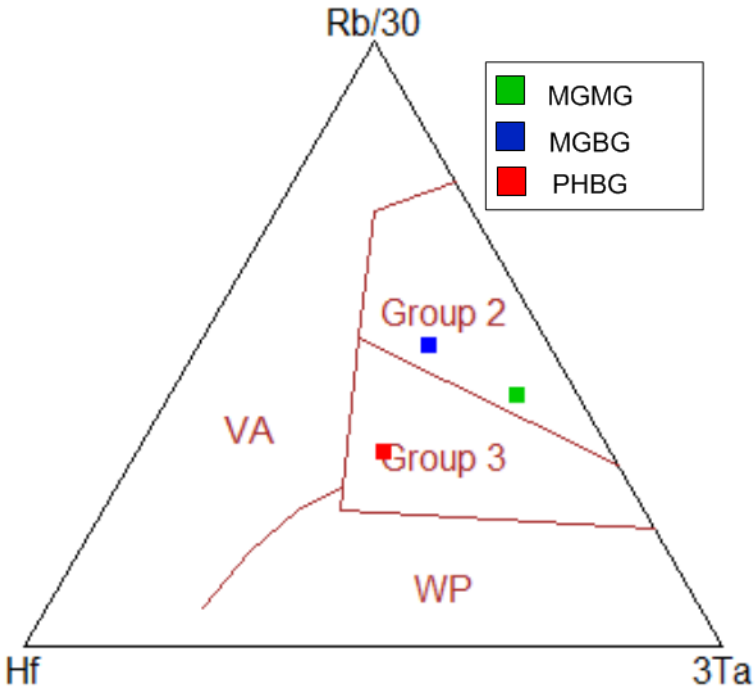


Figure 4.21: Hf-Rb/10-3*Ta discrimination diagram after Harris *et al*., (1986). (VA=volcanic-arc granites, WP=within-plates granites, Group 2=syn-collisional granites and Group 3=late to post-collisional granites), with plots of (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite) in the study area.

4.10.3 RARE EARTH ELEMENTS GEOCHEMISTRY

Rare earth elements are special group of trace elements that have similar physical and chemical properties with atomic number 57 to 71. The rare earth elements data presented in table 4.4 were used in determining the petrogenesis of the rocks through studying the overall shape of the REE patterns and individual element anomalies in order to constrain the source of the melt or the participation of specific minerals in the evolution of the magma. The REE pattern of the granites (Fig. 4.22) display enrichment of the light rare earth elements (LREE) and depletion in the heavy rare earth elements (HREE). The degree of fractionation of the LREE relative to HREE (LaN/YbN) is moderate with values ranging from (5.85 to 24.8). They also display a negative Eu anomally as seen from the REE pattern and Eu/Eu* (<1). The REE pattern of the gneisses (Fig. 4.23) display enrichment in LREE and slight depletion in HREE. The degree of fractionation of the LREE relative to HREE (LaN/YbN) is low with values ranging from (3.42 to 5.13). The gneiss have a negative Eu anomaly except migmatitic gneiss which display a very weak positive Eu anomally and Eu/Eu* of (1.27). Mylonite has a positive Ce anomally with a weak negative Er anomally, and the degree of fractionation of the LREE relative to HREE (LaN/YbN) is equally low.

Table 4.4: Rare earth elements composition of the rocks in the study area (all values except ratios are in ppm).

	Gneisses			Mylonite	Granites		
Elements	R_2	R_3	R_7	R_1	R_4	R_5	R_6
La	77	24.6	10.6	1.5	10.9	22.8	33.5
Ce	160	53.2	19.4	15.5	20.2	54.5	68.1
Pr	17.9	6.93	2.4	0.31	2.32	5.66	7.57
Nd	64.4	29	9.7	1.1	8.4	20.2	27.8
Sm	13.9	7.3	2.5	0.2	2	4.8	5.1
Eu	1.25	2.03	1.11	<0.05	0.45	0.38	1.26
Gd	13.1	8.2	2.9	0.2	2	4.6	3.8
Tb	2.3	1.4	0.5	<0.1	0.3	0.8	0.5
Dy	15.4	8.9	3.2	0.2	1.9	4.9	2.4
Ho	3.2	1.7	0.6	<0.1	0.3	0.9	0.4
Er	9.5	4.9	1.8	0.1	0.9	2.5	1.1
Tm	1.47	0.71	0.25	<0.05	0.12	0.39	0.15
Yb	10	4.8	1.8	0.2	0.8	2.6	0.9
Lu	1.49	0.71	0.28	0.04	0.12	0.4	0.13
Sum	390.91	154.38	57.04	19.35	50.71	125.43	152.71
	Normalized ratios						
Eu/Eu*	0.28	0.81	1.27	NA	0.69	0.25	0.88
LaN/YbN	5.13	3.42	3.93	5.00	9.08	5.85	24.81
LaN/SmN	3.41	2.07	2.61	4.61	3.35	2.92	4.04
EuN/YbN	0.36	1.21	1.76	NA	1.61	0.42	4.00

Legend;

R2= Granitic gneiss.

R3=Biotite gneiss

R7=Migmatitic gneiss

R1= Mylonite

R4=Medium grained biotite granite

R5=Medium grained muscovite granite

R6=Porphyritic hornblende-biotite granite

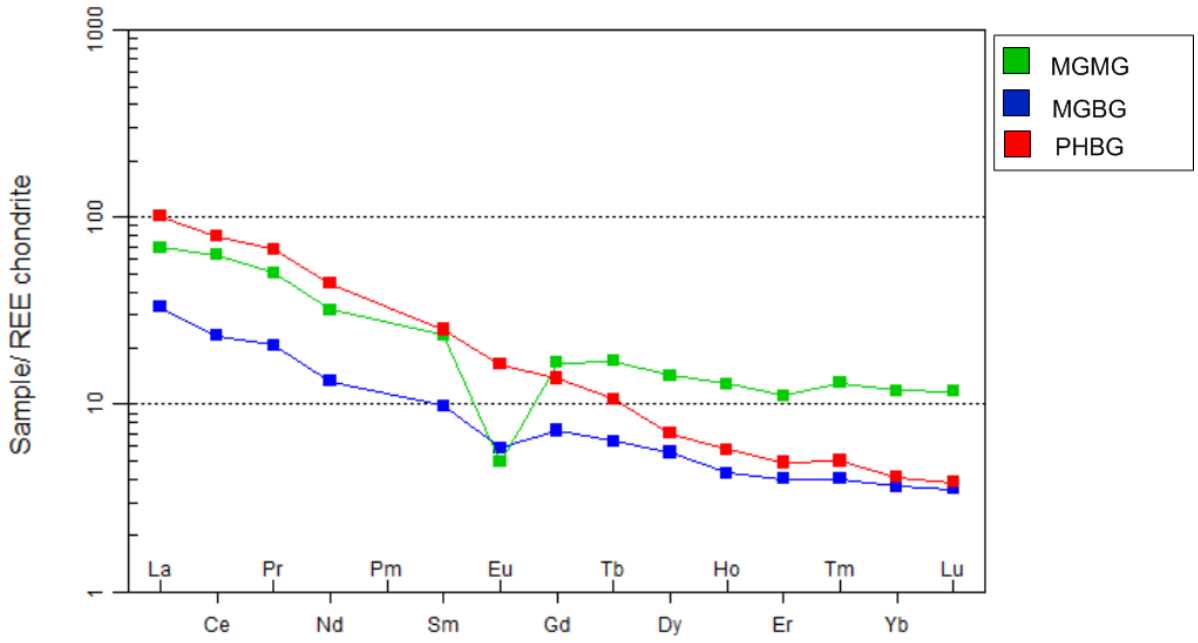


Figure 4.22: Spider plots of REEs in the granites of the study area. All the plots are normalized to chondrite values after Nakamura (1974). (MGMG= medium grained muscovite granite, MGBG=medium grained biotite granite, PHBG=porphyritic hornblende-biotite granite).

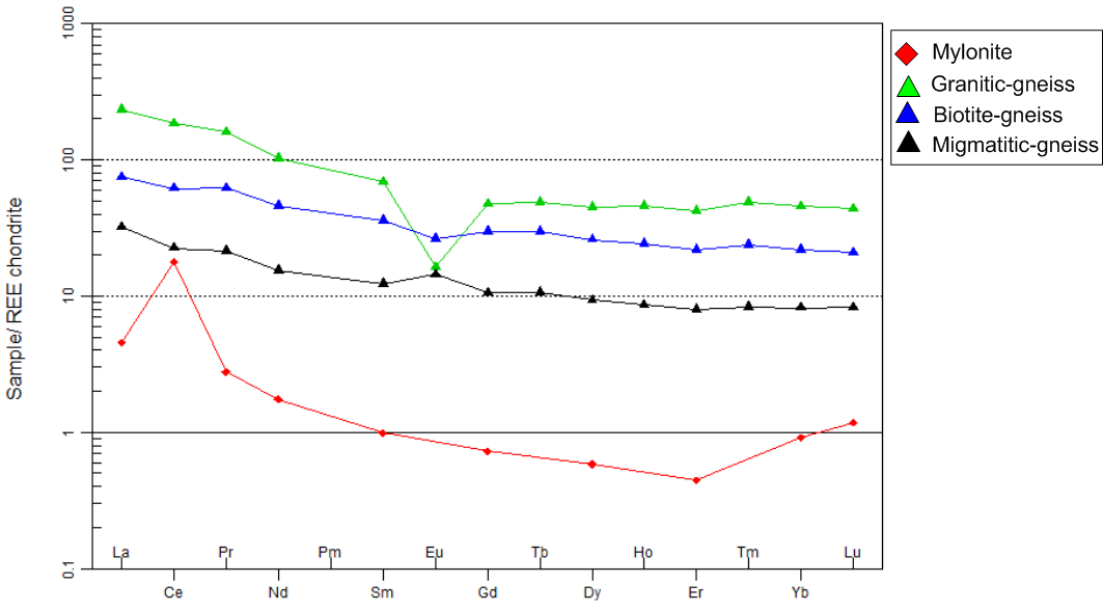


Figure 4.23: Spider plots of REEs in the gneisses of the study area. All the plots are normalized to chondrite values after Nakamura (1974).

4.11. MINERAL CHEMISTRY

Elemental concentration of the minerals obtained from the pegmatites was used to correlate the chemistry of the minerals with associated rare metal mineralization in terms of mineralizing processes, degree of fractionation, classification and petrogenesis of the pegmatites. Major elements are reported in weight percent (wt %) while trace elements reported in parts per million (ppm). The analytical data obtained are presented in Tables 4.5, 4.6 and 4.7 for major and minor elements, trace elements and rare earth elements respectively.

4.11.1 MAJOR AND MINOR ELEMENTS DISTRIBUTION

The major elements composition of the minerals from the pegmatites is presented in Table 4.5. Beryl has the highest SiO_2 content while Bismuthinite has the lowest. Muscovites with an average of 57.02 wt % SiO_2 have higher SiO_2 than the Biotites with an average of 40.47 wt %. Bismuthinite has the lowest contents of all the major element except CaO, which is higher than in muscovites. Soil has the highest CaO and TiO_2 contents while beryl has the highest Na_2O content. Biotites have the highest Fe_2O_3(total), MgO, MnO and K_2O contents while muscovites have the highest Al_2O_3 content.

Table 4.5: Major elements composition of minerals from pegmatites of the study area.

	Muscovites		Biotites			Beryl	Bismuthinite	Soil
Oxide	R_8	R_{11}	R_{10}	R_{12}	R_{14}	R_{13}	R_9	R_{15}
SiO_2	43.28	70.75	42.42	42.54	36.44	66.43	18.21	42.07
Al_2O_3	28.74	17.34	18.47	16.61	16.64	16.81	2.12	15.07
$Fe_2O_{3(T)}$	8.6	1.5	17.03	18.36	22.67	1.21	0.24	17.22
MnO	0.382	0.512	1.022	1.737	1.061	0.038	0.012	0.05
MgO	1.84	0.11	4.86	6.31	5.35	0.18	0.03	0.94
CaO	0.02	0.02	0.26	0.03	0.12	0.01	0.11	1.29
Na_2O	0.41	0.24	0.11	0.13	0.09	0.38	0.06	0.07
K_2O	9.62	5.22	8.49	8.96	8.27	0.11	0.91	0.38
TiO_2	0.971	0.213	2.228	2.1	2.698	0.025	0.045	2.415
P_2O_5	0.01	<0.01	0.17	0.02	0.02	<0.01	0.5	0.06
LOI	4.84	2.9	2.55	1.43	4.44	1.56	7.52	18.97
Total	98.71	98.81	97.61	98.24	97.8	86.76	29.76	98.53
AlCNK	2.58	2.85	1.88	1.67	1.79	22.05	1.65	5.25
Na_2O_3/Al_2O_3	0.0143	0.0138	0.0059	0.0078	0.0054	0.0226	0.0283	0.0046
K_2O/Al_2O	0.3347	0.3010	0.4596	0.5394	0.4969	0.0065	0.4292	0.2521

4.11.2 TRACE ELEMENTS DISTRIBUTION

The study of trace element distribution in feldspars and muscovite is a well-known tool in evaluating the degree of evolution and fractionation of pegmatites (Gordiyenko 1971; Trueman and Černý 1982; Černý *et al.,* 1985 and Gaupp *et al.,* 1984)). This approach has later been broadened to include other minerals (e.g. biotite: Lentz 1992; Hulsbosch *et al.,* 2013). The trace elements distribution in the minerals (table 4.6) was employed in order to classify and discriminate between barren and mineralized pegmatites, evaluate their rare metal potentials, outline the degree of pegmatite evolution as well as in tracing their petrogenesis. The pegmatites are Rare-element class as shown on K/Rb versus Cs plot after Černý and Burt (1984) (Fig. 4.24). The samples also plot within the Beryl subtype field on the Ta/(Ta+Nb) versus Mn/(Mn+Fe) plot (Fig 4.25). Similarly, on the plots of K/Rb versus Cs (Fig. 4.26) and K/Rb versus Rb (Fig. 4.27) all the samples plot within the rare metal bearing fields. On the Ta versus Cs, Ta versus K/Cs and

Ta versus Ga (Figs. 4.28, 4.29 and 4.30) respectively, soil sample plots below the Beus (1966) mineralization boundary. Muscovite from Karara, beryl and bismuthinite mineral samples plot above the Beus (1966) mineralization boundary while all the biotites and muscovite from Gana plot above the Gordiyenko (1971) mineralization boundary. On the Na_2O/Al_2O_3 versus K_2O/Al_2O_3 variation diagram (Fig. 4.31) after Garrells and Mackenzie (1971), all the mineral samples plot within the sedimentary/metamorphic origin field, while on the Zr versus SiO_2 plot (Fig. 4.32) beryl and muscovite from Karara plot within the 'M" (magmatic) field and the rest plot within the 'AM' (after magmatic) field. Spider diagram (Figure 4.33) of the minerals show enrichment in Rb, Nb and Ta with depletion of Ba, K, Sr and Ti.

Table 4.6: Trace elements composition in minerals from pegmatites of the study area.

Elements	Muscovite		Biotites			Beryl	Bismuthinite	Soil
	R8	R11	R10	R12	R14	R13	R9	R_{15}

Sc	21	91	85	103	420	164	3	44
Be	19	22	12	15	485	45180	42	14
V	82	6	220	239	43	30	941	135
Ba	70	33	188	670	268	7	68	483
Sr	7	11	14	17	19	<2	70	245
Y	1	9	27	32	123	11	338	43
Zr	7	9	24	28	5	8	7	161
Cr	50	<20	50	50	<20	<20	90	170
Co	29	115	54	56	12	231	91	20
Ni	40	<20	50	80	<20	<20	<20	50
Cu	<10	<10	<10	10	<10	<10	80	<10
Zn	280	120	550	1050	1450	80	<30	270
Ga	190	200	123	124	171	54	6	25
Ge	5	8	6	7	8	<1	1	<1
As	<5	<5	<5	<5	<5	<5	107	<5
Rb	2280	2390	3680	4260	5050	95	96	34
Nb	383	47	397	131	684	17	57	66
Mo	<2	<2	<2	<2	<2	<2	7	<2
Ag	<0.5	1.5	3	1	0.5	0.8	28.8	1
In	<0.2	1.8	0.7	1.6	3.6	1	0.2	<0.2
Sn	159	298	555	696	1010	6	7	10
Sb	3.2	7	32	7.9	1.4	7.6	3330	1.3
Cs	489	872	3240	2650	1140	3350	35.7	4.1
Hf	0.8	0.5	1.3	1.7	1	0.2	0.6	4.4
Ta	118	41	129	102	153	43.7	53.8	15.8
W	187	871	134	153	61	2040	355	68
Ti	8.6	11.4	21.5	22.4	36	3.3	1.1	3.9
Pb	17	17	22	29	46	25	2320	18
Bi	496	15.4	27.8	20.6	1	512	575000	92.2
Th	1.5	1.3	4.1	7.8	2.1	4.6	443	9.7
U	3.7	0.5	1.2	2.3	5.2	9.2	3000	36.4
Ratios								
K/Rb	35.0257	18.1309	19.1516	17.4600	13.5944	9.6120	78.6894	92.7792
K/Cs	163.31	49.69	21.75	28.07	60.22	0.27	211.60	769.39
Na/K	0.0381	0.0411	0.0116	0.0129	0.0097	3.0876	0.0589	0.1646

K/Ba	1140.84	1313.11	374.88	111.01	256.16	130.45	111.09	6.53
Rb/Sr	325.71	217.27	262.85	250.59	265.79	NA	1.37	0.14
Th/U	0.41	2.60	3.42	3.39	0.40	0.50	0.15	0.27
Ta/Cs	0.241	0.047	0.039	0.038	0.134	0.013	1.507	3.853
Nb/Ta	3.25	1.15	3.08	2.28	4.47	0.39	1.06	4.18
Ta/Nb	0.31	0.87	0.32	0.78	0.22	2.57	0.94	0.21
Mg/Li	0.00036	0.0000663	0.000396	0.000761	0.001344	0.000181	NA	NA
Ta/(Ta+Nb)	0.2355	0.4659	0.2452	0.4378	0.7199	0.7199	0.4856	0.1931
Mn/(Mn+Fe)	0.0469	0.2743	0.0623	0.0948	0.0493	0.0336	0.0525	0.0032

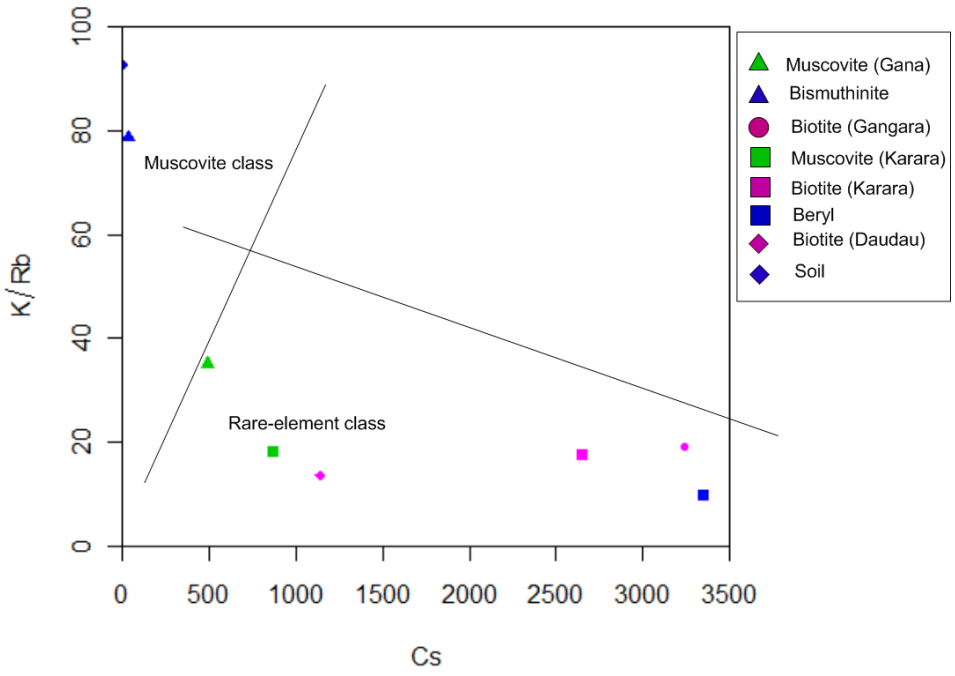


Figure 4.24: K/Rb versus Cs plot after Černý and Burt (1984) of the minerals in the study area showing classification of the pegmatites into muscovite and rare-element class.

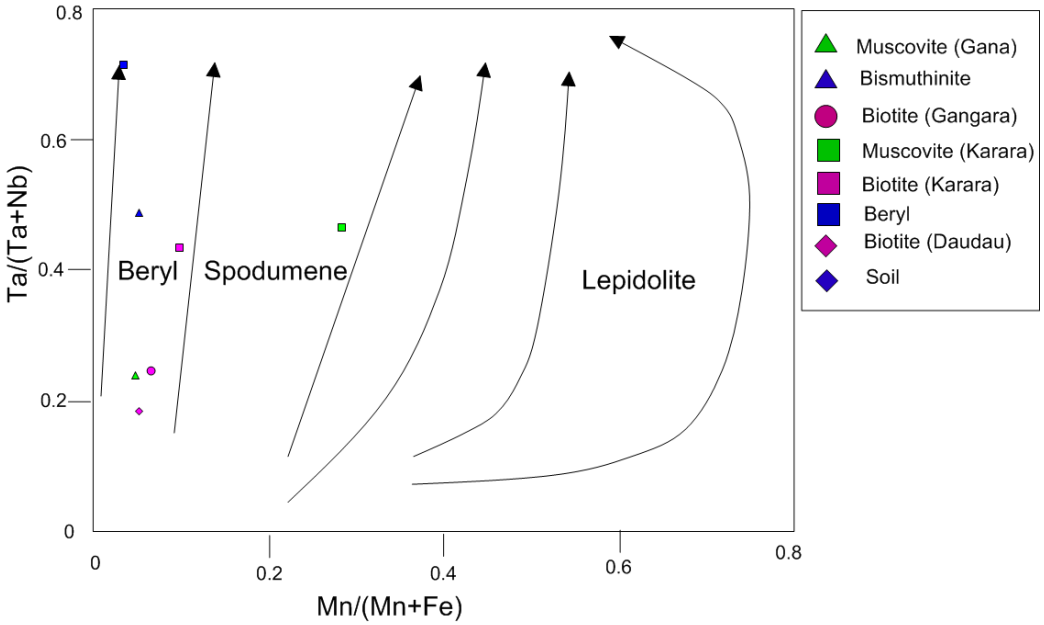


Figure 4.25: Ta/(Ta+Nb) versus Mn/(Mn+Fe) plot of the minerals in the study area showing the classification of the pegmatites into beryl and spodumene sub-types.

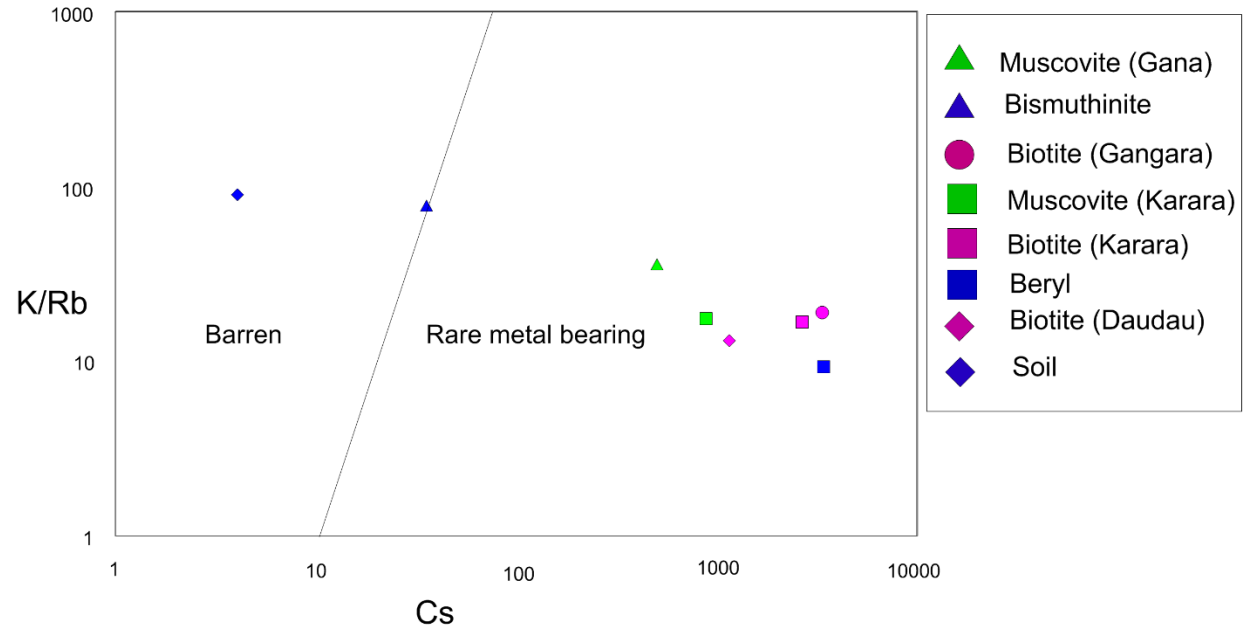


Figure 4.26: K/Rb versus Cs plot after Černý (1982), of the minerals in the study area showing the discrimination of the pegmatites into barren and rare-metal pegmatites).

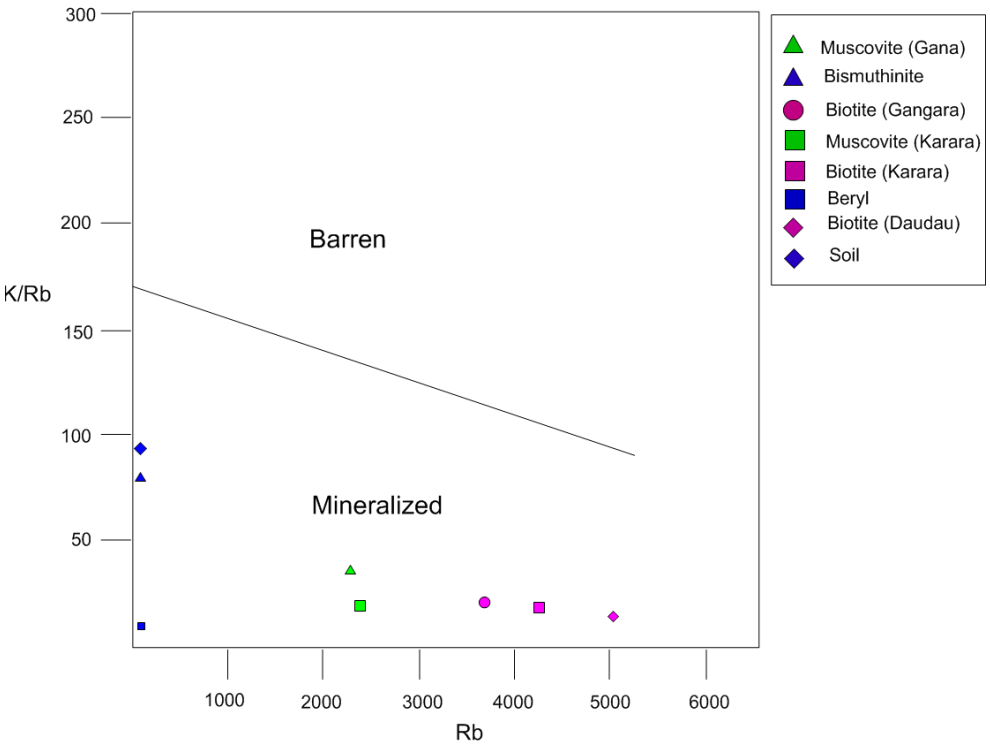


Figure 4.27: K/Rb versus Rb plot after Staurov *et al.,* (1969) of the minerals in the study area showing the degree of fractionation and mineralization of the pegmatites

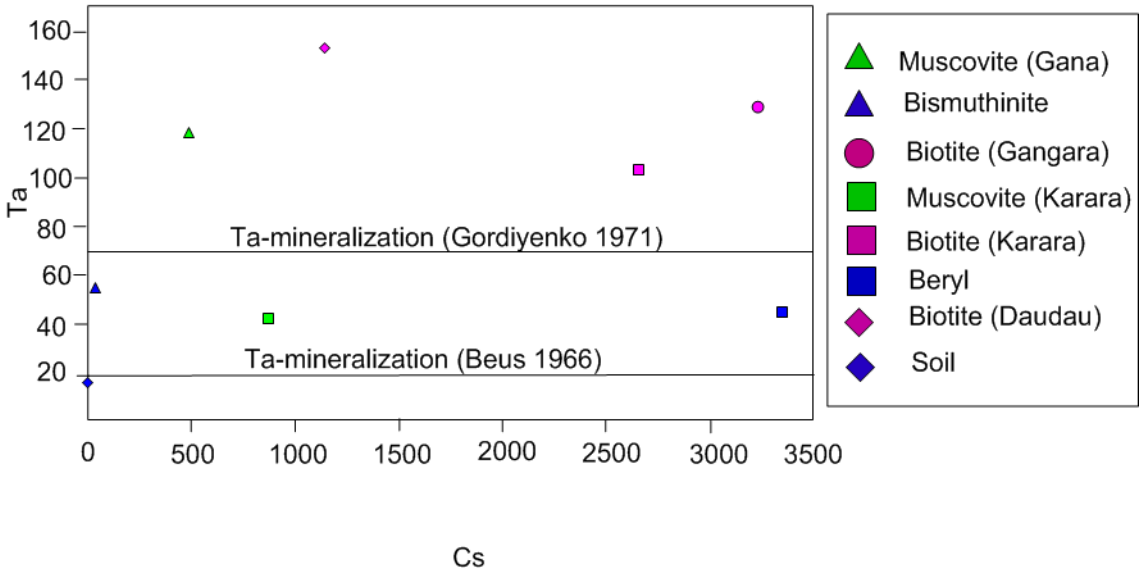


Figure 4.28: Ta versus Cs plot of the minerals within the pegmatites of the study area adopted from Moller and Morteani (1987).

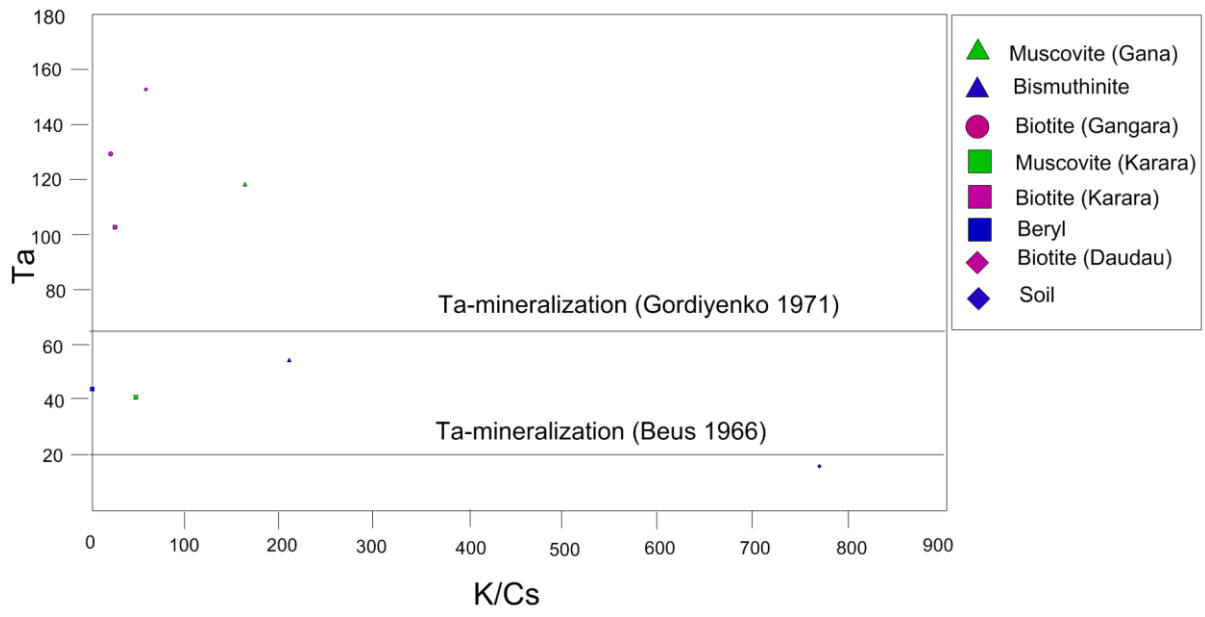


Figure 4.29: Ta versus K/Cs plot after Moller and Morteani (1987) of the minerals from the pegmatites of the study area

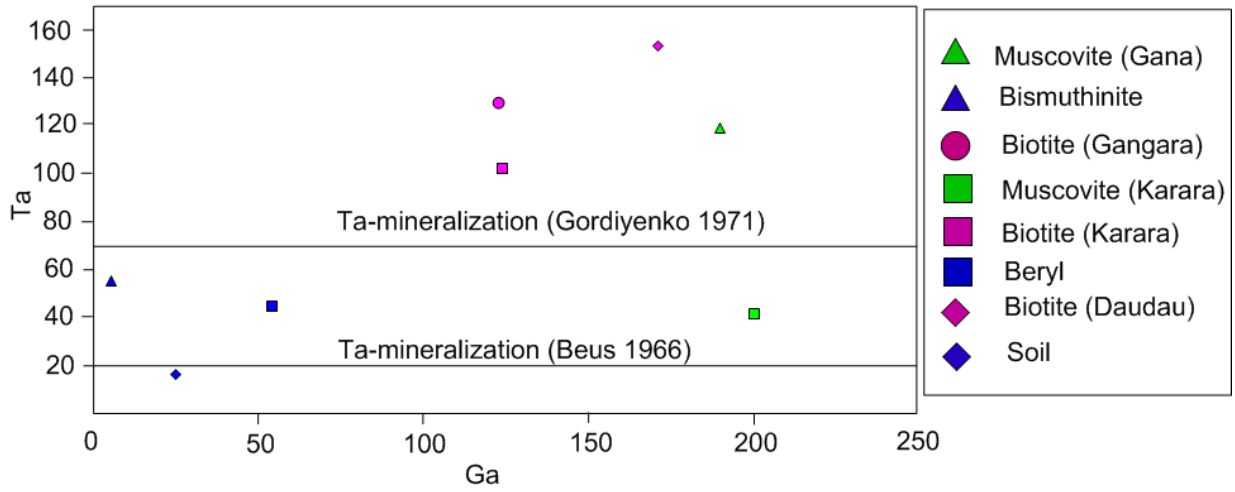


Figure 4.30: Ta versus Ga plot of the minerals from the pegmatites of the study area adopted from Moller and Morteani (1987).

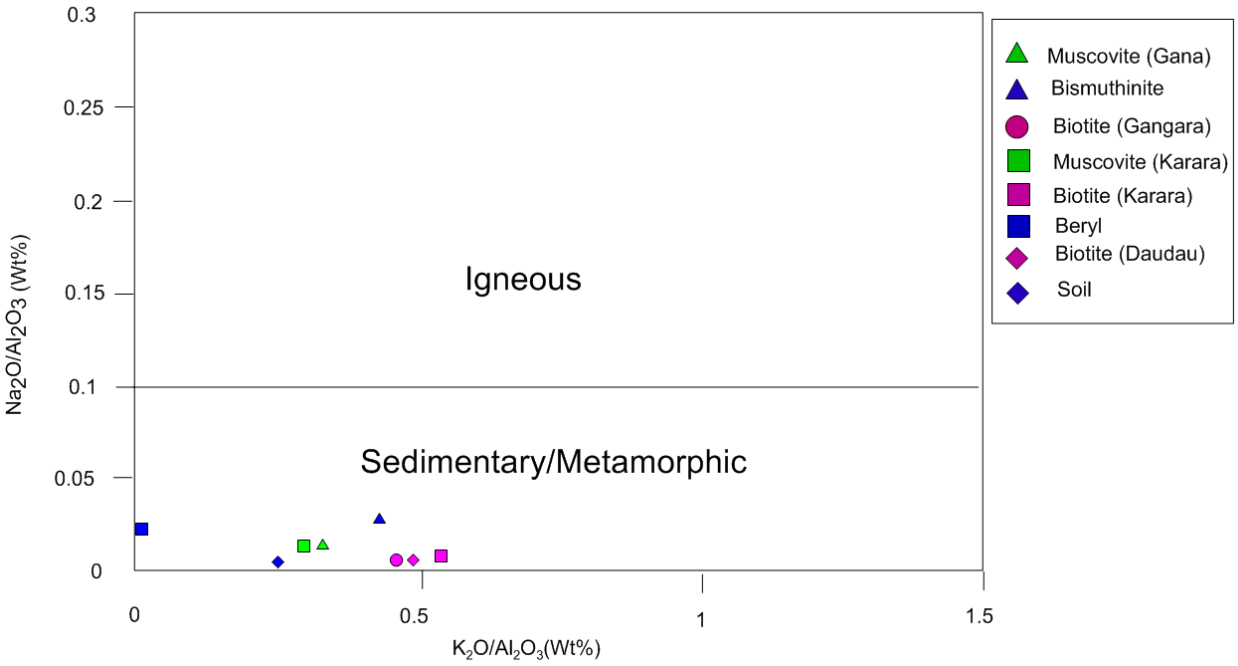


Figure 4.31: Na_2O_3/Al_2O_3 versus K_2O/Al_2O_3 plot after Garrels and Machenzie (1971) showing variation for the field of igneous and metasedimentary rocks of the pegmatites of the study area

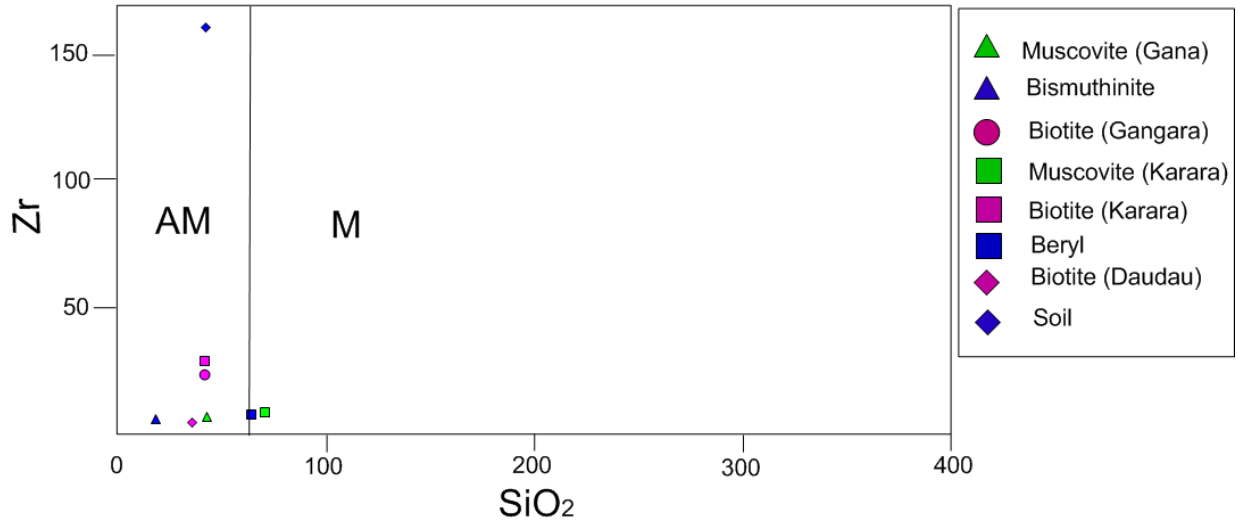


Figure 4.32: Zr versus SiO_2 plot of the minerals showing ancestry of the pegmatites into Magmatic and after magmatic origin.

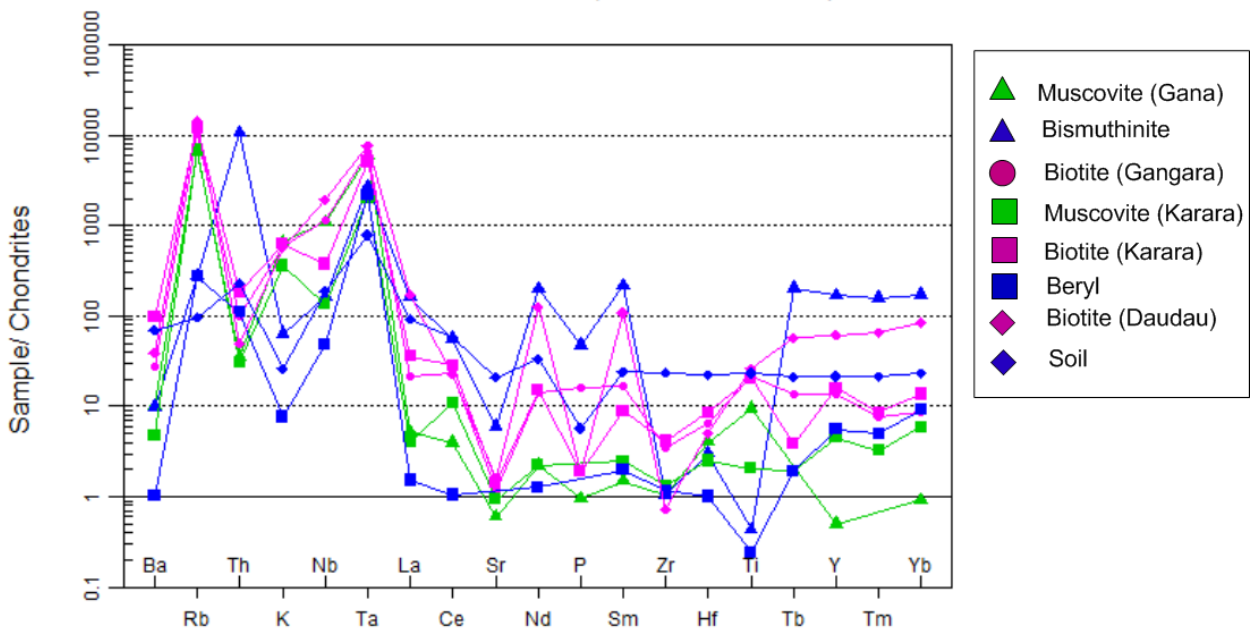


Figure 4.33: Spider plot for trace elements in the minerals from the pegmatites.

4.11.3 RARE EARTH ELEMENTS DISTRIBUTION

The rare earth element composition of the minerals within the pegmatite is presented in Table (4.7) and their normalized REE distribution pattern is shown in (Fig. 4.34). The mineral samples have relatively equal enrichment of LREE and HREE with negative Eu (Eu/Eu*<1) and Ce anomalies. The degree of fractionation of the LREE relative to HREE (LaN/YbN) values are low (0.17 to 5.67).

Table 4.7: Rare earth elements composition of minerals from pegmatites of the study area

	Muscovites		Biotites			Beryl	Bismuthinite	Soil
Elements	R_8	R_{11}	R_{10}	R_{12}	R_{14}	R_{13}	R_9	R_{15}

La	1.7	1.3	7.1	11.8	57	0.5	52.6	30.6
Ce	3.4	9.5	20.6	24.5	19.7	0.9	48.7	49.3
Pr	0.38	0.34	2.22	2.73	18.7	0.16	25.5	5.65
Nd	1.4	1.4	9.1	9.5	79.9	0.8	126	21
Sm	0.3	0.5	3.4	1.8	21.9	0.4	43.6	4.9
Eu	0.06	0.08	0.37	0.13	2.95	0.08	11.8	0.76
Gd	0.3	0.5	3.4	1.2	18.4	0.5	51	5.3
Tb	<0.1	0.1	0.7	0.2	3	0.1	10.5	1.1
Dy	0.3	0.7	3.7	1.5	17.8	1	67.1	7.3
Ho	<0.1	0.1	0.6	0.3	3.5	0.2	12.4	1.5
Er	0.2	0.5	1.7	1.2	11.3	0.7	34.9	4.7
Tm	<0.05	0.11	0.26	0.29	2.22	0.17	5.37	0.72
Yb	0.2	1.3	1.9	3	18.5	2	37.5	5.1
Lu	<0.01	0.25	0.28	0.67	3.39	0.39	5.8	0.83
Sum	8.24	16.68	55.33	58.82	278.26	7.90	532.77	138.76
	Normalized ratios							
Eu/Eu*	0.61	0.49	0.33	0.27	0.45	0.55	0.77	0.46
LaN/YbN	5.67	0.67	2.49	2.62	2.05	0.17	0.94	4.00
LaN/SmN	3.49	1.60	1.28	4.03	1.60	0.77	0.74	3.84
EuN/YbN	0.86	0.18	0.56	0.12	0.46	0.11	0.90	0.43

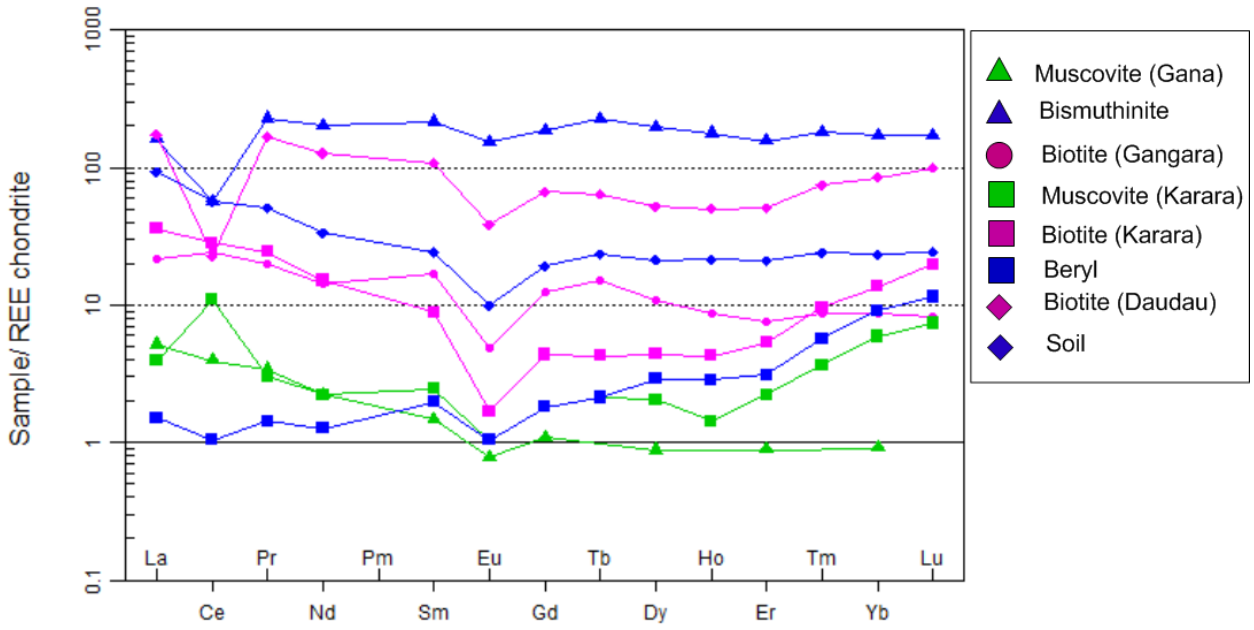


Figure 4.34: Spider plots of REEs of the minerals within the pegmatites of the study area. All the plots are normalize to chondrite values after Nakamura (1974).

CHAPTER FIVE

5.0 DISCUSSION

5.1 INTRODUCTION

The field relations, petrography and geochemical characteristic of the rocks hosting the pegmatites as well as the mineralization potential and petrogenesis of the pegmatites are discussed in this chapter. In addition, a proposed petrogenetic model linking the pegmatites and granites is also presented in this chapter.

5.2 GEOLOGIC EVOLUTION OF THE STUDY AREA

Field observations have shown that the area is underlain by gneisses, schist and granites. Petrographic studies of the gneisses have revealed that the gneisses are composed of quartz, orthoclase, microcline, plagioclase, biotite and hornblende with accessory muscovite. Fracturing and undulose extinction observed in quartz suggest metamorphic stress. Major elements composition revealed that the gneisses are metaluminous (A/CNK<1). TiO_2 versus SiO_2 plot (Fig. 4.15) revealed that migmatitic and biotite gneisses are paragneisses (derived from sedimentary protoliths) while granitic gneiss is ortho-gneiss (derived from igneous protoliths). The REE pattern of the gneisses (Fig. 4.23) is somehow flat and parallel except the granitic gneiss which has a negative Eu anomally and this may be due to crystallization of plagioclase during the crystallization of the source rock since it is derived from granitic protoliths. Petrographic study of mylonite have shown that it is made up of stretched and broken crystals of quartz, feldspar and biotite. This is supported by the major elements data of the rock which reveals that SiO_2, Al_2O_3 and K_2O constitute about 93% of the total elemental contents of

the rock. It is granitic in composition, calc-alkaline, strongly peraluminous (A/CNK>1.2) and sourced from sedimentary protoliths as shown on TiO_2 versus SiO_2 plot (Fig. 4.15). Its REE pattern (Fig. 4.23) shows a positive Ce anomally indicative of reducing condition.

Field observation divided the granites into three major types: medium grained, coarse grained and porphyritic, while petrographic studies further divided the granites into medium grained muscovite granite, medium grained biotite granite, coarse grained biotite granite and porphyritic hornblende-biotite granite. This petrographic classification was supported by B-A plot (Fig. 4.10) which utilizes some of the major elements composition of the granites, and shows the medium grained muscovite granite plots within the muscovite>biotite field, the medium grained biotite granite plots within the biotite>muscovite field and the porphyritic hornblende-biotite granite plots within the biotite+few amphibole field. The medium grained muscovite and medium grained biotite granites are syn-collisional while the porphyritic hornblende-biotite granite plots within the volcanic arc-granite field as shown in (Fig. 4.20). According to Pearce (1996), granite suites that straddle the volcanic-arc and within plate fields are products of post-collision setting. This statement is confirmed by (Fig. 4.21) where the porphyritic hornblende-biotite granite plots within the Group 3 field (Post-collisional setting). Considering the fractionation trend, this may further imply that the porphyritic hornblende-biotite granite is not cogenetic with the medium grained biotite and medium grained muscovite granites. All the granites are calc-alkaline and peraluminous (A/CNK>1). The peraluminosity increases with increasing differenciation (Fig. 4.18) from porphyritic hornblende-biotite granite (1.0) to medium grained muscovite granite (1.19). There is similarly enrichment

in Rb, Cs, Sn and Nb with depletion in Ba and Sr in the course of evolution from porphyritic hornblende-biotite granite to medium grained muscovite granite. The major element composition of the granites plotted on Harker diagram using SiO_2 as an index of differentiation (Fig. 4.7a and b) show that TiO_2, Al_2O_3, Fe_2O_3t, MgO, CaO and MnO are all negatively correlated with SiO_2, forming a well-defined linear trends. Such linear trends might be the result of either hybridization or fractionation (Hassanen *et al.,* 1996) caused by the removal of early formed minerals from the melt. This negative correlation further suggest that the granite suites most likely resulted from fractional crystallization during magmatic evolution. K is strongly depleted in all the granites, while Ba and Sr, which are strongly compatible in granitic systems show slight depletion. Sr decreases readily during the course of fractional crystallization since it replaces Ca in plagioclase while Ba replaces K in K-feldspars as well as in micas, and hence it decreases during the course of fractional crystallization (El Bouseily and El Sokkary 1975). Similarly, according to (Janousek *et al.,* 2002) decrease in Ba with decrease in SiO_2 also indicate an important role of fractionation dominated by biotite, while the depletion of CaO and Sr with increasing SiO_2 content, and negative Eu anomally is consistent with plagioclase fractionation (Eleftheriadis and Koroneos, 2003). Therefore, variation of these lithophile elements in the granites suggests that fractional crystallization was probably responsible for their evolution. Therefore the relatively minor negative Eu anomaly especially in hornblende-biotite granite (Fig. 4. 22) that seems to be inconsistent with plagioclase fractionation is probably due to the hornblende fractionation, which minimizes the Eu anomaly (Henderson 1984; Eleftheriadis and Koroneos, 2003). Furthermore the negative Ti anomaly observed in the trace element spider diagram (Fig. 4.16) suggest the presence

of hornblende or Fe-Ti oxides in the source material (Eleftheriadis and Koroneos, 2003). The granites are depleted in REE (50.71-152.43) compared to the average of 250 ppm (Emmermann *et al.*, 1975). The REE pattern of the granites shows enrichment of LREE and depletion of HREE with a weak negative Eu anomaly thus suggesting the fractional crystallization of plagioclase. The less extreme depletion of the HREE relative to LREE may likely be due to low degree of partial melting and presence of amphibole rather than the presence of garnet (because garnet causes extreme depletion of HREE). Moreover according to (O'Nions and Pankhurst, 1974) enrichment in LREE is the hallmark of crustal and calc-alkaline rocks in general. A/CNK versus SiO_2 plot (Fig. 4.14) reveals that the porphyritic hornblende-biotite granite and medium grained biotite granite are I-type granites (derived from magmas generated by partial melting of mafic and intermediate igneous rocks) while the medium grained muscovite granite is S-type granite (derived from magmas generated by partial melting of sedimentary source rock). This can also be seen from CIPW norm result (see table B2 in appendix) which shows the porphyritic hornblende-biotite granite and the medium grained biotite granite have low average normative corundum (<1%), high Na_2O (>3.2%) and presence of hornblende which according to Chappel and White (1974), these features are hallmark of I-type granites, while the medium grained muscovite granite has average corundum of 2.4 (>1%) which is characteristics of S-type granites. Furthermore, the CIPW norm result has also shown that normative diopside is absent in all the granitites and molecular A/CNK>1 thus suggesting that the granites are S-type. Therefore, from the above characteristics coupled with the result of petrographic studies which reveals the presence of two (2)

feldspars in all the granites, it can be suggested that the granites have a mixed origin and are therefore both I and S-type granites.

5.3 GEOCHEMICAL FEATURES OF THE PEGMATITES

The major element data shows that the pegmatites have low SiO_2, Na_2O and K_2O contents with high Al_2O_3 and Fe_2O_3 contents when compared to values obtained for mineralized pegmatites of Nigeria (Garba 2003, Okunlola 2005, Okunlola and Akintola 2010, Akintola *et al*., 2011 and Oyebamiji 2014). However other major elements such as MnO, Mgo, CaO, TiO_2, P_2O_5 are comparable. The pegmatites are of peraluminous bulk composition (A/CNK>1). Černý (1992) states that the LCT pegmatites has a mildly to strongly peraluminous parent granitic composition. Trace elements data shows that the pegmatites are enriched in rare metals such as Rb, Li, Cs, Be, Nb, Ta, Sn, Zn, W and Ga. With Rb ranging from (34 to 5050ppm), Li (600 to 7400ppm), Cs (4.1 to 3350ppm), Be (12 to 45180ppm), Nb (17 to 684ppm), Ta (15.8 to 153ppm), Sn (6 to 1010ppm), W (61 to 2040ppm) and Ga (6 to 200ppm). These elements are excellent fractionation indicators and the most highly fractionated pegmatites will have high values of these elements. It is believed that the higher their contents, the higher the degree of fractionation and the higher the economic potential of the pegmatites (Breaks *et al*., 2003). The values obtained are higher compared to their average upper continental crust values from Taylor and McLennan (1985) (Be- 3ppm, Cs-3.7ppm, Li-20ppm, Rb-112ppm, Nb-25ppm, Ta-2.2ppm and Sn-5.5ppm) (see table C1 in appendix). These values are however comparable to the values obtained for mineralized pegmatites in Nigeria (Garba 2003, Okunlola 2005, Okunlola and Akintola 2010, Akintola *et al.*, 2011 and Oyebamiji 2014). The pegmatites also have low K/Rb, K/Cs, Nb/ta and Mg/Li ratios, which according to

Kuster (1990) indicates progressive fractionation and possible mineralization. It is also believed that these elemental ratios are excellent fractionation indicators and can be used to assess economic potential of pegmatites (Breaks *et al*., 2003). REE pattern of the pegmatites (Fig. 4.33) show relatively equal enrichment in LREE and HREE with weak Negative Eu and Ce anomally. The negative Eu anomally according to Taylor *et al.*, (1986) suggests fractionation and indicates late metasomatic effect, while the negative Ce anomally according to Garba (2003) is an indication of oxidization condition during rare metal mineralization which possibly involved interaction between magmatic melt fluids and host rocks over great distances. Based on the bulk chemistry and geochemical signatures, the pegmatites are of the LCT petrogenetic family, rare-element class and of beryl sub-type as shown in (Figs. 4.25 and 4.26).

5.4 RARE METAL POTENTIAL OF THE PEGMATITES

The progressive rare alkali fractionation of the pegmatites reveals and confirms they are rare metal pegmatites (Černý 1982; Kuster 1980; Moller and Morteani 1987). According to Garba (2003), while Rb is an indicator of the degree of fractionation of granitic pegmatites, Cs appears to be the most important discriminator of rare metal pegmatites. Using the K/Rb versus Cs (Fig. 4.26) and K/Rb versus Rb (Fig. 4.27) plots, the pegmatites are rare metal bearing. Further mineralization of these pegmatites are evaluated using Ta versus Cs (Fig. 4.28), Ta versus K/Cs (Fig. 4.29) and Ta versus Ga (Fig. 4.30) plots, where the samples falling below the defining lines are considered barren and those above the line are considered mineralized. These plots show the pegmatites plotting above the Beus line of mineralization thus confirming their rare metals mineralization or potential. Ta rich pegmatites are enriched in Ga (Černý 1986),

therefore the high content of Ga is an indication of Ta mineralization. Elemental ratios are also useful in discriminating between barren and mineralized pegmatites. Ta/Nb ratio ranges from 0.21 to 2.57 suggesting preference for possible Ta enrichment. Ta/Cs ratio below 10 grouped the pegmatites in the lack to low mineralized pegmatites in the world (Moller and Morteani 1987, Černý 1992), while low Mg/Li ratio is an indicator of rare metal potential. Low values of Mg/Li, Nb/Ta, K/Rb and K/Cs are believed to be indicative of mineralized pegmatites (Garba 2002). Another important aspect related to mineralization is degree of albitization reflected by low Na/k ratio. In terms of orientation, most of N-S and NW-SE trending pegmatites are mineralized, while none of the NE-SW trending pegmatite is mineralized. The level of mineralization is comparable to other rare metal mineralized pegmatites in Nigeria and from different parts of the world (see table C2 in appendix).

5.5 PETROGENESIS AND PROPOSED MODEL FOR THE PEGMATITES

Calc- alkaline rocks are related to subduction related plate tectonic processes. The similarity in patterns of peaks and troughs in the trace element spider plots of gneisses and granites suggests that they share a common parent (Sedimentary), while that of granites and pegmatites suggests that they share a common process and contaminant. The I-type granites are likely derived from magmas generated by partial melting of mafic and intermediate igneous rocks, while the S-type granites are likely derived by the partial melting of metamorphosed shales that contain aluminous mica and Al_2O_5 polymorphs thus leading to the generation of peraluminous magma. S-type granites contain aluminous rich minerals in addition to biotite, two feldspars and quartz. The most accepted model for the formation of pegmatite is its derivation from granitic magmas, via igneous

differentiation processes. According to Černý *et al.*, (1981) and Černý, (1991), sequential or partly overlapping decrease in K/Rb is a classical indicator of fractionation from granite to pegmatite. In the granites K/Rb ranges from 226.23 in the hornblende-biotite granite to 114.02 in medium grained muscovite granite while in the pegmatites, K/Rb decreases from 92.77 to 9.61. Such sequential decrease in K/Rb from the less fractionated end member of the granite suites to the pegmatite suggest a possible transition from granite to pegmatite via fractional crystallization. Moreover, continuous trends on the K/Rb versus Cs discrimination diagram (Fig. 4.28) is consistent with crystallization from granites to pegmatites thus suggesting a genetic link between them (London 2008). Although the variation plot of Na_2O/Al_2O_3 versus K_2O/Al_2O_3 (Fig. 4.31) reveals sedimentary ancestry of the pegmatites, the Zr versus SiO_2 plot (Fig. 4.32) reveals mixed ancestry (mixed basement plus supracrustal protoliths having homogenous composition) for the pegmatites, thus suggesting the pegmatites to be magmatic with post magmatic metasomatism and post magmatic differenciation processes. Therefore, it seems very likely that the metasomatic replacement and mineralization processes have been generated from both the residual fluids of the pegmatite melt themselves as well as external fluid injections. On the other hand, the high K/Ba and Rb/Sr and low K/Rb ratios show that the pegmatites have granitic origin (Garba 2003). Similarly the associated granites possess the characteristics of fertile granites which are parental to rare metal pegmatites. The model therefore suggests that migmatitic gneiss, biotite gneiss and schist are the country rocks into which the granites and pegmatites intrude. The porphyritic biotite-hornblende granite was earlier emplaced followed by coarse grained biotite granite, medium grained biotite granite, medium grained muscovite granite, aplites and

low lying pegmatite dykes in that order. The high level pegmatite dykes (rare metal pegmatites) on the other hand formed from a residual melt released which is differenciated and contaminated by assimilation of the country rocks and other hydrothermal fluids leading to the concentration of rare metals and alteration of their chemical composition.

CHAPTER SIX

6.0 SUMMARY, CONCLUSION AND RECCOMENDATION

6.1 SUMMARY

The study area is part of the north-western basement complex of Nigeria. The rocks mapped include; migmatitic gneiss, biotite gneiss, granitic gneiss, porphyritic hornblende-biotite granite, coarse grained biotite granite, medium grained biotite granites and medium grained muscovite granites, mylonite as well as pegmatites. Structural features in the area such as joints, veins and dykes show N-S, NE-SW and NW-SW trends all of which are concordant with the general structural trend in the Nigerian Pan-African Basement Complex. Geochemical studies have shown that the gneisses are both ortho-and paragneisses. The granites had undergone changes from a more primitive hornblende-biotite I-type variety to a more fractionated muscovite bearing S-type variety, peraluminous, syn to post tectonic, calc-alkaline and of crustal origin. The pegmatites belong to the LCT family, rare element class, beryl subtype, peraluminous and highly differenciated. The pegmatites are highly fractionated and enriched in rare metals. The rare metal mineralization of the pegmatites are comparable to other mineralized pegmatites in Nigeria and from different parts of the world. Based on the element variation observed from the granites to the pegmatites, it is obvious that magmatic and post magmatic differenciation processes were involved in their formation. Therefore in light of the available geochemical evidence, it appears that fractional crystallization in combination with varying degree of wall rock assimilation is the dominant process involved in the differenciation of the magma. It is therefore proposed that the pegmatites are the products of extended fractional crystallization of granitic magma that was

contaminated by the country rock and other external fluids as it ascends and were then injected into the weak zones of the gneisses and granites.

6.2 CONCLUSION

Based on field relations, mineralogical and geochemical data, the following conclusions can be drawn:

1) The area is a migmatite-gneiss terrain that is intruded by the Pan African (Older Granites) and pegmatites.
2) The geochemical characteristics, mineralogy and petrology of the granites are comparable with typical I-type and S-type granites and were emplaced in a syn to post tectonic collisional setting. Their source is believed to be from the partial melting of mafic/intermediate igneous rocks and partial melting of metamorphosed shale respectively.
3) Based on the values of K/Rb, K/Ba, Rb/Sr, REE distribution pattern and other geochemical indicators, there is a clear relation between the granites and pegmatites.
4) The pegmatites represent late stage residual melts of a less evolved granitic parent (biotite-hornblende granite) which are derived by fractionation accompanied by metasomatic alteration and modification of their chemical compositions.
5) The pegmatites belong to the LCT family, rare element class and beryl subtype, they are highly fractionated and enriched in rare metals particularly Li, Be, Cs, Ga, Rb, Nb, Sn and Ta.

6) Micas (muscovites and biotites) are good geochemical monitors using trace elements (such as Li, Rb, Cs, Ta, Sn, and Ga) and their ratios to evaluate the rare metal mineralization potential of pegmatites.
7) Micas (muscovites and biotites) are good geochemical monitors using trace elements (such as Li, Rb, Sr, K and Ba) and their ratios to understand the petrogenesis of pegmatites.

6.3 RECOMMENDATION

1) Study on the industrial and gem stone potentials of the pegmatites should be carried out.
2) X-ray diffraction (XRD) study should be carried out on the minerals in order to determine the mineral species present.

6.4 CONTRIBUTION TO KNOWLEDGE

1) The geological map of the area has been updated
2) Rare metal mineralization potential of pegmatites in the area has been established.
3) Petrogenesis of the granites and pegmatites have been determined.

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APPENDIX A

Table A1: Quartz Veins, Joints, Low lying Pegmatite dykes and Aplite dykes trend readings.

Quartz veins	Joints	Low lying pegmatite dykes	Aplite dykes
128,354,320,144,152, 170,100,150,50,176, 80,260,50,28,330,84,34 0,320,170,310,200,190, 310,16,24,16, 310,94,100,86,190, 120,360,20,36,202, 210,240.	48,10,0,20,114,160,26 340,98,118,120,98,20,3 2,40,26,6,120,122, 160,122,282,300,18, 20,110,110,110,120, 350,356,330,70,28, 350,90,30,126,140, 168,160,40,310,294, 272,180,330,360,10, 18,350,121,360,50,50,5 0,330,338,58,340, 154,180,134,266,340,13 4,120,122,140,90, 164,134.	226,330,18,32,336,116,50 ,14,40,2,28,280,326,210,6 0,220,0,10,354, 62,16,190,120,316,272,36 0,100,245,278,200, 20,60,86,16,84,360,90,12 0,94,110,92,342,92, 102,16,280,94,208,128, 280,276,324,310,210, 254,354,320,144,152, 170,100,150,50,176,80,26 0,50,28,330,84,340, 320,170,310,200,190, 310,16,24,16,310,94, 100,86,190,120,360,20,36 .	14,80,60,96,22,6,80, 280,194,224,200, 200,210,20,156,220,23 2,184,20,360,36, 40,20,90,110,10,20.

APPENDIX B

Table B1: Calculated values of iron number, modified alkali-lime index and aluminium saturation index for the rocks of the study area.

Sample	Iron number (Fe no)	Modified alkali-lime index (MALI)	Aluminum saturation index (ASI)
R_1	0.81	3.93	2.75
R_2	0.95	7.94	0.96
R_3	0.70	-11.82	0.57
R_4	0.87	7.68	1.07
R_5	0.93	8.30	1.20
R_6	0.75	4.48	1.01
R_7	0.80	-9.84	0.66

Legend;

R2= Granitic gneiss.

R3=Biotite gneiss

R7=Migmatitic gneiss

R1= Mylonite

R4=Medium grained biotite granite

R5=Medium grained muscovite granite

R6=Porphyritic hornblende-biotite granite

Table B2: CIWP Norm for the granites of the study area

	R_4	R_5	R_6
Normative minerals	Medium grained biotite granite	Medium grained muscovite granite	Porphyritic hornblende-biotite granite
Q	30.495	33.222	27.680
C	0.983	2.422	0.322
Or	26.594	28.998	21.098
Ab	34.947	30.547	30.378
An	4.125	0.535	12.381
Di	0	0	0
Wo	0	0	0
Hy	0.548	0.274	2.267
Ti	0.051	0.079	0.103
Tn	0	0	0
Ru	0.086	0.061	0.351
Ap	0.213	0.166	0.332
Sum	98.042	96.204	94.911

APPENDIX C

Table C1: Average abundances and ranges of rare-elements and selected ratios from upper continental crust values from Taylor and McLennan (1985)

	Average upper continental crust (ppm)	Granites		Pegmatites	
		Mean	Range	Mean (ppm)	Range (ppm)
Rb	112	229	131-356	2235.63	34-5050
Li	20	n.d	n.d	17700	600-7400
Cs	3.7	12.1	10.1-14.8	1472.60	4.1-3350
Be	3	7.33	3-12	5723.63	12-45180
Nb	25	11.33	7-17	222.75	17-684
Ta	2.2	2.6	1.5-4.8	82.04	15.8-153
Sn	5.5	4.67	2-6	342.63	6-1010
Ga	17	22.67	22-23	893	6-200
K/Cs	7630	2975.11	2742.79-3248.33	163.04	0.27-769.39
K/Rb	252	175.06	114.02-226.23	35.56	9.61-92.78
Nb/Ta	11.4	4.82	3.54-6.25	2.48	0.39-4.47

Table C2: Average of some trace elements compositions of micas from the study area and some known pegmatites fields in Nigeria and from different parts of the world.

Elements (ppm)	Study area	Kabba-Isanlu	Lema-Share	Kushaka	Magami	Wamba	Harding	Noumas	Tanco
Ta	108.6	207	211	102	63	53	64	74.2	240.9
Cs	1678.2	200	205	174	1000	116	1917	566	2420
Rb	3532	300	152	3410	4000	3150	0.631	0.357	2450
Ga	161.6	35	35	186	117	n.d	123	92	433
W	281.2	48	22	n.d	n.d	n.d	n.d	25.7	21.3
Sn	543.6	28	25	114	234	745	n.d	n.d	n.d
Nb	328	78	65	226	50	238	n.d	n.d	n.d
n	5	28	32	3	3	51	21	29	19

n=number of samples n.d=not determined