

GEOLOGY, GEOCHEMISTRY AND PETROGENESIS OF GRANITE SUITES AND
PEGMATITES IN THE NORTHERN PART OF MANDARA HILLS GWOZA SHEET
114, NORTHEASTERN NIGERIA

BY

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AHMADU BELLO UNIVERSITY, ZARIA

FEBRUARY, 2015

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114, NORTHEASTERN NIGERIA

BY

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DEPARTMENT OF GEOLOGY
FACULTY OF SCIENCE
AHMADU BELLO UNIVERSITY, ZARIA
NIGERIA
FEBRUARY, 2015

DECLARATION

I declare that the work in this thesis entitled “**GEOLOGY, GEOCHEMISTRY AND PETROGENESIS OF GRANITE SUITES AND PEGMATITES IN THE NORTHERN PART OF MANDARA HILLS GWOZA SHEET 114, NORTHEASTERN NIGERIA**” has been carried out by me in the Department of Geology, Faculty of Science, Ahmadu Bello University, Zaria. The information derived from the literature has been dully 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.

Bala Musa Girei

Name of Student



Signature

9/03/2015

Date

CERTIFICATION

This thesis entitled **“GEOLOGY, GEOCHEMISTRY AND PETROGENESIS OF GRANITE SUITES AND PEGMATITES IN THE NORTHERN PART OF MANDARA HILLS GWOZA SHEET 114; NORTHEASTERN NIGERIA”** by Bala Musa Girei meets the regulations governing the award of the degree of Master of Science in Geology of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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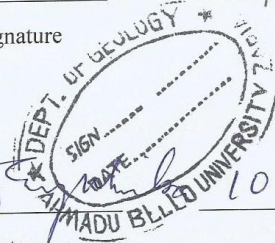
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DEDICATION

I dedicate this work to almighty Allah (SWT), the omnipotent who has given me the will and wisdom to write, the strength to endure and the courage to face all challenges.

ABSTRACT

This research work focused on the petrological and geochemical characteristics of the granites and pegmatites in the northern part of Mandara Hills part of sheet 114 (Gwoza), so as to constrain their evolutionary history and to determine their mineralization potential, based on new sets of petrological and geochemical data. The area is underlain by low-lying migmatite gneiss, amphibolites, granite suites, aplite and pegmatites. The granite suites vary in texture and composition and comprise of diorite, medium grained biotite hornblende granite, porphyritic biotite granite, coarse grained biotite granite, medium grained biotite granite, fine grained biotite granite and tectonised granite (cataclasite). Two types of pegmatites have been mapped in the area. Type-I pegmatite occurs as large oval-shaped bodies trending in E-W directions, and type-II occurs mainly as veins often cross-cutting their host rocks and strike mainly in the NE-SW direction.

The results obtained revealed that the migmatitic gneiss is metaluminous, calc-alkaline and was derived from igneous protoliths. The amphibolite has tholeiitic chemistry and TiO_2 versus SiO_2 discrimination plot shows that it was derived from igneous protoliths. The granite suites on the other hand, are ferroan, calc-alkaline, metaluminous to slightly peraluminous I-type granites. The high Th/U (greater than 2.5), high K and Rb contents, as well as negative distribution trends of Ba, Sr and Nb on trace elements spider diagram suggest crustal source for the granites. The strong negative correlation of most major element with increasing acidity (SiO_2) on the Harker diagram suggest that fraction crystallization has played a significant role in the evolutionary history of the granite suites.

The two types of pegmatites mapped in the study area differ significantly not only in their field occurrences but also in chemistry. The type-I pegmatite shows negative Ce anomaly and has high Rb but low Sr and Ba contents. This pegmatite is also moderately fractionated but barren with respect to rare-metal mineralization. However, the pegmatite hosts “ferroan pyroxmangite” which contains 10.00 wt. % of MnO, 28.33 wt. % Fe_2O_3 and 33.20 wt. % of SiO_2 . The mineral is considered as a potential ore of manganese. This pegmatite probably formed from fractional crystallization of a flux bearing granitic melts and is co-magmatic with the granite suites. The type-II pegmatite, on the other hand is characterized by low Rb but high Ba and Sr contents. This pegmatite is primitive and barren and probably formed from the anatexis of granitic rocks at shallow depth.

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CHAPTER ONE

INTRODUCTION

1.1 GENERAL INTRODUCTION

The study area lies in the northern part of the N-S trending Mandara Hills, northeastern Nigeria. The area is considered as the northern extension of the Obudu-Oban Massifs in the southeastern Nigeria separated only by the Benue Trough (Abaa and Najime, 2006). The area is underlain by migmatitic gneiss, amphibolites, granite suites, aplite and pegmatites. The granites which are in most places intruded by pegmatites constitute about sixty percent (60 %) of the total crystalline basement rocks in the area.

Granites are deep-seated igneous rocks composed of quartz, mica, feldspars and ferro-magnesian mineral such as amphibole or pyroxene, in grains sufficiently large to be distinguished by the naked eye and possessing a texture produced by the crystals as a whole interfering with one another's free development (Read, 1948). Granite *sensu stricto* is rich in potassium feldspar (up to 65% of feldspars) relative to plagioclase, and has a high content of quartz (20-60%). However, with increasing plagioclase / potassium feldspar ratio, and increasing calcium / sodium ratio in plagioclase, granite grades into rocks called granodiorite (plagioclase constituting 65-90% of feldspars) and tonalite (plagioclase constituting 90-100% of feldspars). In addition, with decreasing quartz content (quartz less than 20%), granites grade into (potassium feldspar - rich) syenite or monzonite (Myers, 1997). Granitic bodies carry abundant information regarding their mode of emplacement, sources of melts and the processes of magma evolution occurring at depth (Audrius, 2004). Apart from their compositional features, granitic plutons also contain information on the fields of stress that prevailed during and after their emplacement. Such information is recorded by a range of structural elements varying in scale from millimetres to tens of kilometres. The study of these structural elements also allows conclusions with regard to the geodynamics of crustal plates

during the times when the granitic plutons were emplaced. For all these reasons, the study of granitic intrusions at various scales and regarding various aspects and properties is considered very important to the understanding of the development of continental crust and the related plate-tectonics processes (Audrius 2004).

Many types of granite are associated with pegmatites which may form pods within the granite or coalesce upward and segregate toward the roof of the parent granitic pluton. Pegmatites may also intrude in form of dykes into the surrounding rocks and emanate from the carapace of the pluton, and are in this case defined as epigenetic pegmatites. Pegmatites host an exceptionally diverse range of economic commodities, and academic interest in them stemmed in large measure from the scientific quest to understand ore-forming processes. The origin and internal evolution of pegmatites continue to be debated on some fronts. Different models that have been proposed by the early decades of the 20th century include:

- (i) precipitation from an aqueous fluid phase
- (ii) crystallization of silicate liquid through an aqueous fluid interface
- (iii) crystallization from a hydrous silicate gel
- (iv) crystallization from a flux-rich silicate liquid
- (v) Crystallization of a granitic melt from margins to center.

Each of these models has its advocates today (London, 2011). However, most researchers believe that pegmatites are products of fluid-saturated residual melts with near-haplogranitic compositions. These melts evolved from granitoids intrusions at a last stage and at emplacement depths sufficient to prevent vapour loss typical of volcanic and near-surface magmatic systems (Anderson, 2013).

The compositions of pegmatites reflect an association mostly with two granite types, the S- and the A-types. However, Černý and Erit (2005) now ascribed a small fraction of the LCT and NYF pegmatite to I-type granite source. Pegmatites of the LCT family, especially

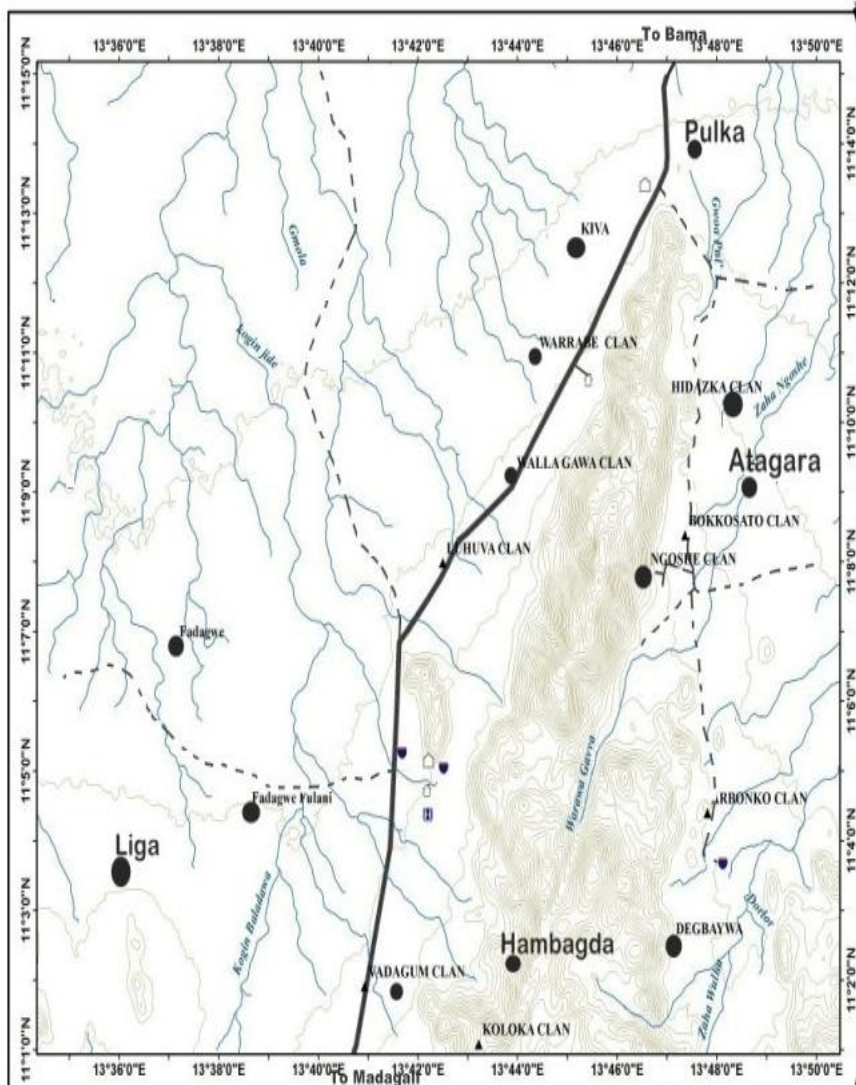
those enriched in Li, Cs, B, and P, greatly predominate over all others. They indicate that the metamorphosed juvenile sediments from which S-type granites arise are particularly prone to yielding pegmatite-forming melts. The abundance of fluxing components in the sources of S-type and A-type make them distinct from I-type granite. These fluxing components include ligands other than silica and alumina that predominantly influence the properties of pegmatite-forming melts. S-type sources are especially enriched in B, P and F, which is contributed by the eventual melting of amphibole and biotite. The archetypal I-type granites found in subduction zones are notably rich in Cl and are hydrous, but are largely devoid of the fluxing components. They generate enormous volume of quartz veins but lack pegmatite to any significant extent. This distinction points to an essential role for fluxing components like B, P and F, along with H₂O in the formation of pegmatites (Černý *et al.*, 2012).

This research work seeks to study the petrological and geochemical characteristics of the granites and pegmatites in the study area so as to constrain their evolutionary history and also determine their mineralization potential, based on new sets of petrological and geochemical data of the rocks. The impetus for this research work is based on the understanding that detailed petrological and geochemical data of crystalline rock units often yield valuable insight into their evolutionary history and mineralization potential.

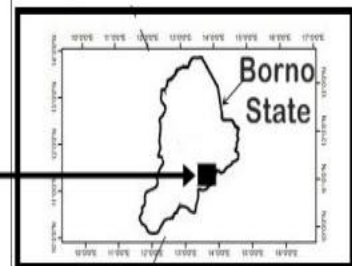
1.2 LOCATION AND ACCESSIBILITY OF THE STUDY AREA

The study area is located in the northeastern part of Nigeria situated within latitude 11°00' and 11°15' N and longitude 13°35' and 13°50'. It lies in the northern part of the N-S trending Mandara Hills (Fig. 1). The Mandara Hills are part of the Oban-Obudu-Mandara-Gwaza Complex which lies in the eastern part of Nigeria (Abaa and Najime, 2006). The hills are separated from the Oban-Obudu Massif by the Benue Rift Trough. To

the north, the hills are bordered by Cretaceous -Pleistocene Chad Basin sediments and to the west by the Tertiary-Quaternary Biu-Basalts. Owing to the rugged nature of the terrain, the area is relatively inaccessible. However, Liga Hill, which is an extension of the main Mandara Hills, is accessible through a motorable road that leads from Gwoza to Damboa. Places such as Atagara, Pulka, Ngoshe and Hambagda are accessible through minor roads and footpaths.



**LOCATION MAP OF GWOZA,
SHEET 114 NE NIGERIA**



LEGEND

- School
- Market
- Police barrack
- Settlement
- Drainage
- Major road
- Minor road

90 Mangure	91 Mari-Sama	90 Galumba
113 Matube	114 Gwoza	115 Yabari
135 Duhu	136 Madagali	

Fig 1.1: Location map of the study area

1.3 CLIMATE

The area lies within the tropical climate zone characterized by two main seasons (wet and dry seasons). The wet season covers the period from May to September with a peak in August. Mean annual precipitation is about 700 mm (Ostaficzuk, 1996). The rains are commonly accompanied by thunderstorms and hardly last for more than three hours at any given time. The effective precipitation is appreciably reduced by high rate of evaporation and evapotranspiration. The dry season is longer, usually lasting seven months (October-April). Temperature variations are extreme (both annual and diurnal). Cold nights are experienced in December and January when temperatures of less than 10°C are recorded but during the day, temperature could rise to over 26°C (Baba 1990). The hamattan period (November-February) is commonly characterized by low humidity due to prevalent NE-SW trade wind. During this period the trade winds are laden with appreciable amount of dust particles which frequently obscure sunlight and lead to poor visibility (Ostaficzuk, 1996). The trade wind and its associated dust commonly cause irritation and discomfort. The hottest days occur between April and June during which time, temperature of over 38°C could be recorded. The prolonged dryness and short rain fall coupled with high rate of evapotranspiration limits the rock-water interaction which results in low chemical weathering of the rocks.

1.4 VEGETATION AND LAND USE

Vegetation is characterized by sparsely distributed short trees and grass cover typical of Sudan Savannah. During the dry season, the grasses dry up and the trees shed their leaves. The common plants include: *Acacia albida*, *Adansonia digitata*, *Melia indica*,

Delomix regia, *Palmae* and *Adenium obtusum* all of which possess the ability of storing water in them against the long dry season (Ostaficzuk, 1996). Soils are poorly developed but commonly sandy with few clay-rich patches. The Northeastern State Survey and Planning Report by Max Loc Group Nigeria (1976) grouped the inhabitants of the area into three farming communities namely:

- (a) The FADAMA (flood plain) community who live and farm on the few flood plains;
- (b) The TABKI (pond) community who settle around the water retaining ponds for the greater part of the year and
- (c) The FIRKI community who live and farm on the clay flat lands.

Crops produced in the area include guinea corn, millet, maize, beans, groundnuts, onion and tomatoes. Hides and skins are however the major agricultural cash product in the area.

In addition to natural climatic factors, annual bush burning and heavy grazing constantly keep the vegetation low throughout the year. Most of the few trees that survive the bush fires are used in towns as fuel for cooking.

1.5 RELIEF

The Liga and the main Mandara Hills form prominent parallel and elongated topographic units in Gwoza area. The hills are about 2000 m above the sea level. The lowest elevation in the area is about 200 m above sea level. The general topography of the area is dominated by the rugged Mandara Hills which extend from Pulka in the north to Hambagda in the south.

1.6 DRAINAGE

Drainage is poorly developed in the area and is characterized by few seasonal streams with trellis to dendritic drainage pattern. The streams rise from near the foot of the hills and flow northwards into the surrounding plain (Fig 1.1).

1.7 PREVIOUS WORK

Falconer (1911) studied the geology of the crystalline basement complex of Nigeria. He introduced the term “Older Granite” to distinguish the orogenic granites of the basement complex which are mainly Pan-African in age from anorogenic granites of northcentral Nigeria which are mostly Mesozoic in age. Okeke (1980) carried out petrological and geochronological studies of some rocks around Liga Hills northeastern Nigeria. He reported that the Liga Hill is composed of granites and pegmatites. The granites are Pan-African in age. Garba (1986) studied some cataclastic rocks in Limankara area, south of Gwoza northeastern Nigeria. According to the author, the cataclastic rocks occur in a 1 km wide N-S trending shear zones, which cut through the pre-existing basement rocks. He noted that the cataclastic rocks developed under fast growing stress during the final stage of the Pan-African Orogeny. Islam and Baba (1989) studied the mineralization potential of the northern part of the Mandara Hills and reported the occurrence of manganese-bearing ore associated with pegmatites, large crystals of pure milky quartz and feldspars, and some heavy minerals such as; monazite, leucoxene, zircon, apatite, magnetite, cassiterite in streams sediments in Pulka and Ngoshe area. A proven reserve of quartz and feldspar at Liga Hills has been put at 1,336,038 and 648,372 metric tons respectively and are currently being mined in the area (Islam and Baba, 1989). Baba (1990) studied Petrography and alkali feldspar geochemistry of rocks in Liga Hills (an extension of the main Mandara Hills). He noted that the rocks are co-genetic and have crystallized from melt of mainly crustal origin.

Okeke (1990) studied the geochemistry of volcanic rocks in Kirawa area northeastern Nigeria. The author noted that the rocks are peralkaline and were derived from the same parental magma. Baba *et al.*, (1996) and Baba (1997) studied the petrology and geochemistry of Liga Hill granitoids and noted that the rocks are co-genetic and have crystallized from melts that are fractionated to different degrees. Abaa and Najime (2006)

noted a good similarity between the Oban-Obudu Massif and Mandara-Gwoza Complex. According to these authors, the two zones are separated by the Benue rift trough. Rock types that are similar in the two zones include gneisses, migmatites, charnockites and series of granites and granodiorite. These authors also considered the whole Oban-Obudu-Mandara-Gwoza Complex as a possible metallogenic province in Nigeria. Baba *et al.*, (2006) studied the petrogenesis of some granite in Pulka area and noted that the granites mainly show I-type characteristic though some traces of S-type features were also observed. The granites were subsequently named “Pulka Granites”. Bassey *et al.*, (2006) carried out a LANSAT study of some part of the northeast basement region and northern Cameroun and identified some NE-SW, N-S, E-W and NW-SE trending structures in Limankara area which extend for over 20 km southward.

1.8 STATEMENT OF THE RESEARCH PROBLEM

The geology of the basement complex of northeastern Nigeria where the study area is situated is the least known in the country. Majority of the work done on the area are essentially preliminary in nature. Although the presence of pegmatites was reported by Islam and Baba (1989) in the northern part of Mandara Hills, northeastern Nigeria, no detail work has been carried out on such pegmatites. By contrast, similar pegmatite which occur in other parts of the country have been studied extensively in the northcentral to northwestern Nigeria by Jacobson and Webb (1946); Kuster (1990); Garba (2002, 2003); Adekeye and Akintola (2007); Akintola and Adekeye (2008); Okunlola and Ocan (2009) and in southwestern Nigeria by Matheis (1987); Okunlola and Oyedokun (2009); Okunlola and Akinola (2010); Akintola *et al.*, (2012)] as well as in the southeastern Nigeria by Schuiling (1967); Wright (1970); Ekwueme and Matheis (1995); Kingsley and Ekwueme (2009); Oden *et al.*, (2013) among others. Abaa and Najime (2006) have proposed that the pegmatites and quartz veins in the basement rocks of the Oban-Obudu-Mandara-Gwoza

Complex should be target for mineral exploration since gem minerals and tin with associated tantalite have been reported in some of the areas. However, no known mineral potential study on the area has been done. It will therefore be a worthwhile research to study the geology, geochemistry and structural settings of such pegmatites as well as the granite suites that are spatially associated with the pegmatites in the area.

1.8 SCOPE OF THE PRESENT WORK

The present work involved geological mapping of the study area on a scale of 1:50,000 followed by petrographic studies of the rock samples collected using petrological microscope. Whole rock geochemical analyses of representative samples of the granite suites and feldspars extracted from the pegmatites was undertaken using ICP-MS and ICP-AES. Mineral identification was carried out using MiniFlex Benchtop X-ray diffraction Instrument. Variation in concentration of major, trace and REE elements in the granite suites was used to determine their geochemical features and petrogenesis. The geochemical composition of feldspars was used to establish the geochemical signatures, mode of evolution, and mineral potential of pegmatites in the study area in line with the work of Gordiyenko, (1971, 1976); Černý *et al.*, (1981) ; Černý (1982); Moller and Morteani (1987); Shearer *et al.*, (1985); Černý and Meintzer (1988); Neiva (1995); Larsen (2002). In addition, an attempt was made to establish the genetic relationship between the pegmatite and the granite suites with which they are spatially associated in the study area.

1.10 OBJECTIVES

The objectives of the research are:

- i. To produce geological map of the study area on a scale of 1:50,000
- ii. To determine the geotectonic setting and petrogenesis of the granite suites and pegmatites
- iii. To evaluate the geochemical signatures of the pegmatites and the surrounding granites.
- iv. To establish and describe the chemical and mineralogical variation in a single pegmatite zones (wall, intermediate and core) and determine the relationship between the zoned and unzone (simple) pegmatites.
- v. To update mineralogical and geochemical data of basement rocks in the study area.

CHAPTER TWO

REGIONAL GEOLOGY

2.1 INTRODUCTION:

This chapter focuses on a review of the regional geology of Nigeria. More emphasis is given to the basement complex which consists of the Migmatite gneisses complex, the metasediments and the Older Granite suites.

Nigeria is underlain by Precambrian basement complex rocks, anorogenic Younger Granites of Jurassic age, Cretaceous to Recent sediments and Tertiary to Recent volcanic rocks. The basement rocks occupy about half of the land mass of the country (Black, 1980).

2.2 The Nigerian Basement Complex

The Nigerian Pan-African Basement is part of an Upper Proterozoic-Lower Phanerozoic mobile belt situated between the West African and Congo Cratons (Fig 2). The belt is interpreted to have evolved by plate tectonic processes which involved continental collision between two blocks, the passive continental margin of the West African Craton and the active continental margin (Pharusian belt) of the Tuareg Shield about 600 Ma (Burke and Dewey, 1972; Leblanc, 1981; Black *et al.*, 1979; Caby *et al.*, 1981; Ajibade *et al.*, 1987; Garba 2002). The Nigerian Basement Complex lies in the reactivated part of the belt (Ajibade *et al.*, 1987).

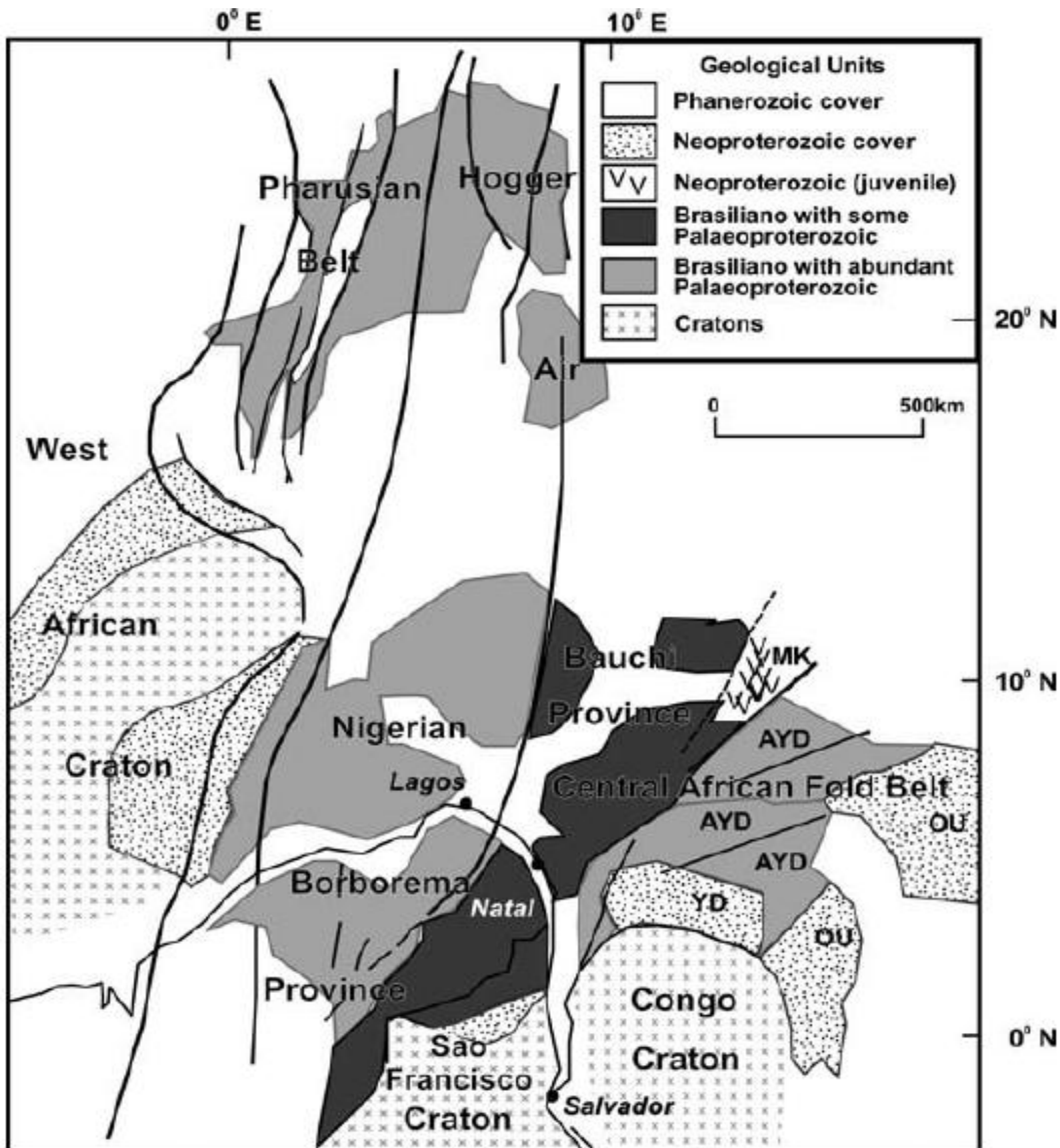


Fig 1.1: Location of the Nigerian Basement Complex between the West African and Congo Cratons and in relation to Hoggar and Borborema Provinces (adapted from Dada, 2008).

2.2.1 Lithologic units

The lithology of the basement complex has been described by many authors namely; Oyawoye (1972); McCurry (1976); Woakes (*et al.*, 1987); Rahaman (1976; 1988); Garba (2003); Dada (2006, 2008); Baba (*et al.*, 2006) among others. The Nigerian Basement Complex is divided into three major lithological units. These include:

- i. Polymetamorphic migmatite-gneiss complex.
- ii. Metasediments
- iii. Older Granite suite

2.2.2 The Migmatite-gneiss Complex

The migmatite-gneiss complex is generally considered as the basement complex “*Sensu Stricto*” (Rahamam, 1988; Dada, 2006). About half of the Nigerian Basement consists of the migmatite-gneiss complex (Kröner *et al.*, 2001). It is a heterogeneous assemblage including migmatized gneisses, banded gneisses and a series of metamorphosed basic and ultrabasic rocks. These rocks strongly resemble the tonali-tetrandhjemite-granodiorite (TTG) suites of Archean and Early Proterozoic terrains elsewhere in the world (Dada *et al.*, 1993). Petrographic evidence indicates that Pan-African reworking led to recrystallization of many of the constituent minerals of the migmatite-gneiss complex during partial melting, and most display medium to upper amphibolites facies-metamorphism (Dada, 2008). The gneisses of the migmatite-gneiss complex are interleaved with amphibolites that may be derived from Mg-rich rocks such as continental basalts (Caby *et al.*, 1990; Dada, 1999; Dada, 2008). However, there are no conclusive age and isotopic data to elucidate their origin (Dada, 2008). Oyawoye (1972) noted that the banded gneisses are possibly the oldest rocks in the country, older than granite gneiss that yielded a Rb-Sr whole-rock isochron age of 2190 ± 30 Ma. Ajibade (1988) distinguished the ancient migmatites in northern Nigeria from the Pan-African migmatites by their complex

polyphase deformation and mylonitization. Possibly because of their mixed and, therefore, complex nature, it has been difficult to define the protoliths of the banded gneisses (Kröner *et al.*, 2001). Some authors suggested that they were metasediments derived from graywacke and shale (Freeth, 1971; Burke and Dewey, 1972), whereas others interpreted them as orthogneisses (Onyeagocha 1986; Ekwere and Ekwueme 1991; Kröner *et al.*, 2001). However, most workers agree that migmatization occurred during upper amphibolite-facies regional metamorphism (Oyawoye, 1972; Onyeagocha and Ekwueme, 1990). There is also consensus that metamorphic segregation, partial melting, and injection of leucogranitic material contributed to the formation of the banded gneisses and migmatites (Kröner *et al.*, 2001). According to (Dada, 1999; 2008), gneisses and amphibolites in Nigeria form a bimodal association whose petrological and geochemical characteristics indicate a primary igneous origin. Another study by Elatikpo *et al.*, (2013) revealed that the gneisses within Malumfashi schist belt northwestern Nigeria, have calc-alkaline affinity and igneous origin.

2.2.3 The metasediments

The metasediments are divided into “Ancient Metasediments” and “Newer Metasediments” (Oyawoye, 1972) or “Older Metasediments” and “Younger Metasediments” (McCurry, 1976).

The “Ancient Metasediments” (Oyawoye, 1972) or Older Metasediments (McCurry, 1976) are high grade metasedimentary remnants in the gneisses and migmatites and are believed to have been formed about 2,500 Ma (McCurry, 1976). They consist of calc-silicate rocks, arkosic quartzite and high grade schist that occur as lensoid relics in the regional gneisses or as paleosomes of migmatites (Danbatta, 2008).

The “Newer Metasediments” (Oyawoye, (1972) or “Younger Metasediments” (McCurry, 1976) are low-grade sediment dominated schist groups and are composed mainly of pelitic and semipelitic schist, metaconglomerate, quartzite, calc-silicate rock, marble, mafic to ultramafic rocks, acid to intermediate volcanic rocks and rare banded iron formations (Danbatta, 2008). In the western half of the country, they occur as discontinuous north-south trending belts within the basement. 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 metasediments are poorly represented in the eastern half of the country and this is attributed by Ajibade (1988) to the strong migmatization and assimilation effects on the sediments by the large volumes of the Pan-African rocks. However, few outcrops of some members of the metasediments particularly quartz schist, biotite schist and calc-silicate rocks occur in Gwoza and Ngoshe area in northeastern Nigeria (Nwabufo and Mbonu, 1988). Furthermore, outcrops of some members of the metasediments were equally reported in the Oban Massif, Obudu Plateau and the adjoining Cameroon Republic (Ekwueme, 1990; 1991).

In recent years, much attention has been given to the evolution of the metasediments (Annor, 1995; Adekoya, 1996; Olobaniyi, 1997; Annor 1998; 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.

According to those in favour of ensialic evolution process, crustal thinning in response to initial crustal extension and continental rifting at the cratonic margin about 1000 Ma ago, led to deposition of sediments in a graben-like structures floored by continental crust. The closure of the ocean at the West African cratonic margin led to deformation and metamorphism of the sediments and underlying basement resulting in the formation of the metasediments and reactivation of older basement during the Pan-African orogeny (Russ 1957; Oyawoye, 1964; 1972; McCurry, 1971; 1976; Vaniman, 1976; Grant, 1978; Chukwu-Ike, 1978; Turner, 1983; Ajibade, 1976; Ajibade *et al.*, 1987., Danbatta, 1999). Ensialic models of evolution had also been proposed to explain the evolution of the metasediments (Ogezi, 1977; McCurry and Wright, 1977; Holt, *et al.*, 1978; Holt, 1982; Utke, 1987; Rahaman *et al.*, 1988; Ajibade and Wright 1989; Danbatta 1991; Elueze 1992). Earlier proponents of this model attributed the formation of some metasediments (eg. Anka, Ife-Ilesha and Zuru metasedimentary belts) to the closure of some oceanic basins. They proposed that some marginal back-arc basin floored by oceanic material were first formed and in which some sediments were subsequently deposited. However, Holt (1982) observed that the Anka metavolcanic rocks have chemical characteristics of both island arcs and continental environments. He concluded that the metasediments were deposited in a retro-arc basin related to subduction processes along the margin of the West African Craton. According to Utke (1987), these metasediments possibly represent additional microcontinents that were separated from pre-existing ones.

2.2.4 The Older Granite suites

The Older Granite suites comprise the syntectonic to late tectonic granitoids. They intrude both the migmatite-gneiss complex and the metasediments. The granitoids include rocks varying in composition from granite to tonalite and charnockites with smaller bodies

of syenite, gabbro and pegmatite (Ajibade *et al.*, 1987). The granitoids have yielded radiometric ages in the range of 750-500 Ma which lie within the Pan-African spectrum. These Pan-African granitoids are referred to as the Older Granites in Nigeria to distinguish them from the Mesozoic anorogenic granite ring- complexes (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, recognised three phases of the Older Granite suite:

1. Early phase which comprises rocks of high colour index and relatively complex mineralogy. The phase comprises of closely intermingled gabbroic, doleritic and granitic rocks usually intruded by acid veins. They are of minor occurrence and do not form distinct topographic features and are usually found as xenoliths within the latter phase. Hockey *et al.*, (1986) have described a number of doleritic xenoliths within coarse porphyritic granite in Lokoja-Auchi area.
2. Main phase includes the most dominant and extensive unit of the Older Granite suites. The rocks, predominantly medium grained biotite-hornblende granite and porphyritic biotite granite, are readily distinguished from others by their characteristic large subhedral pinkish to reddish (occasionally whitish) alkali feldspar set in a medium to fine grained groundmass of quartz, microcline, oligoclase, biotite and hornblende. In many cases the feldspar megacrysts are commonly aligned along with the biotite which imparts a gneissose appearance to

the rock. Rahaman (1976) equated this phase to the synkinematic type of Truswell and Cope (1963). The foliation is usually well developed at the margins of the rock bodies which indicate some degree of movement during emplacement. Rahaman (1988) pointed out that the activity of the fluid phase during the emplacement may also be important in determining the structural feature of the granite mass.

3. Late phase comprises of homogenous granite, as well as pegmatite and aplite dykes. Homogenous granites comprise of fine to medium grained biotite and biotite muscovite granites and granodiorite. Although the homogenous granites are generally equigranular in some varieties the feldspar crystals locally develop to megacrystic size. The homogenous granites are second to the coarse porphyritic granites in abundance and topographic expression. The rocks of this phase generally lack foliation and are evidently intrusive.

In the northeast of Nigeria, Ferre *et al.*, (1998) have described hypersthene-bearing monzogranitic and quartz-monzonitic rocks of Neoproterozoic age with ferro-potassic transalkaline and metaluminous characteristics which have affinity with within-plate or post-collisional granites. They assigned these rocks to the post-collisional stage of the Pan-African orogeny. In southeast Nigeria, Ukwang and Ekwueme (2009) have documented granitic rocks in Obudu Plateau with volcanic arc and syncollisional affinity emplaced with regard to the Pan-African orogeny.

2.2.5 Geochronology and Tectonic Evolution of the Nigerian Basement Complex

The common view, based almost exclusively on Rb-Sr dating, is that the Nigerian Basement evolved during a long and polyphase tectono-metamorphic history, including Liberian (2700±200 Ma), Eburnean (2000±200 Ma), Kibaran (1100±200 Ma), and Pan-African (600±150 Ma) events (Grant, 1970; Ajibade *et al.*, 1987; Dada 1998).

According to Dada *et al.*, (1993) and Dada (1998), U-Pb zircon age of 2.4 to 2.5 Ga on grey gneisses from northern and southwestern Nigeria suggests distinct crustal initiation event with significant crustal growth at the Archean-Proterozoic boundary (Liberian). Ajibade *et al.*, (1987) reviewed the nature of the early Proterozoic Eburnean event in Nigeria, which clearly indicates its importance and involvement in the evolution of the Nigerian Basement Complex. According to these authors, the Eburnean was probably accompanied by sedimentation, deformation, metamorphism and syntectonic igneous activity. The Kibaran is the most controversial event because no granite of that age is found in Nigeria. However, Ogezi (1977) obtained a Rb-Sr isochron age of 1086 Ma on the phyllites from Maru metasediments, northwestern Nigeria. The author interpreted this as the age of metamorphism that affected the sediments. This interpretation implies that there was a major tectonic event in some parts of the Nigerian Basement during the Kibaran. The Pan-African event was related to the collision of Birrimian plate (comprising the present West African Craton) and the Dahomean (comprising the present day Nigeria-Benin Shield) (Burke and Dewey, 1972). The orogeny started with the opening of the Buem Ocean in Neoproterozoic time, its subsequent closure reactivated Dahomean while Birrimian remained stable. Many workers on the Nigerian Basement, (McCurry, 1971; Rahaman, 1976); Cahen *et al.*, 1984) are of the view that the Pan-African orogenic event was the latest, most pervasive and penetrative deformation episode, and that it completely obliterated earlier structures, primary fabrics and metamorphic assemblages of the complex. On the other hand, Grant (1978), Mullan (1979), Ajibade (1988), Fitches *et al.*, (1985), and Ekwueme (1987) are of the opinion that although it was pervasive, the Pan-African event did not completely homogenize the rocks of the basement, so that traces of earlier structures still remain within the complex. Many workers considered the Rb-Sr method to be unreliable in dating migmatitic rocks from which most ages older than Pan African were obtained

(Kröner *et al.*, 2001). Ajibade and Wright (1989) argued that the Nigerian Basement is an aggregation of allochthonous terranes, which explains the relicts of Liberian, Eburnean, and Kibaran orogenic events, as well as the spread of radiometric ages within the Pan-African range (750±450 Ma).

Field evidence has for a very long time (Oyawoye, 1972; McCurry, 1976; Rahaman, 1976; Fitches *et al.*, 1985; Ajibade *et al.*, 1987) recognized the Nigerian Basement as an assemblage of contrasted terranes with a well-developed metasedimentary cover to the west and a largely vestigial crystalline terrain to the east. It is a continuum between the Hoggar to the north (McCurry, 1976) and the Borborema Province to the south (Caby, 1989; Dada, 2008) (Fig1.2). Sutures have been proposed along two transcurrent fault zones, and in particular within the Ife–Ilesha schist belt, which has been interpreted as a back-arc marginal basin (Rahaman *et al.*, 1988), and east-verging nappes (Caby and Boesse 2001; Dada, 2008). Structural studies by Black *et al.*, (1994) and Ferre *et al.*, (1996) have also strengthened the view on the contrasted nature of the Nigerian Basement. The presence of Archean crustal segments in the Nigerian as in Central Hoggar is compatible with an intracratonic setting (Dada 1998). Furthermore, the relict Archean ages strongly support the Continental collision model of Caby *et al.*, (1981) and Caby (1989) that the region and the West African and Sao Luis Cratons must have been part of the same crustal province which was rifted apart, reunited and in part reworked in the Late Proterozoic (Dada *et al.*, 1995, Dada and Rahaman 1995; Dada, 1998).

2.3 THE NIGERIAN PEGMATITES

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 pegmatite belongs to the terminal stage of Pan-African magmatism (Rahaman *et al.*, 1988). The

Nigerian pegmatites were formed during the time span of 562–534 Ma, indicating that their emplacement is related to the end of the Pan-African magmatic activity (Jacobson and Webb 1946, Garba 2003). Both barren and mineralized pegmatites occur within the Nigerian Basement Complex (Fig. 2.2)

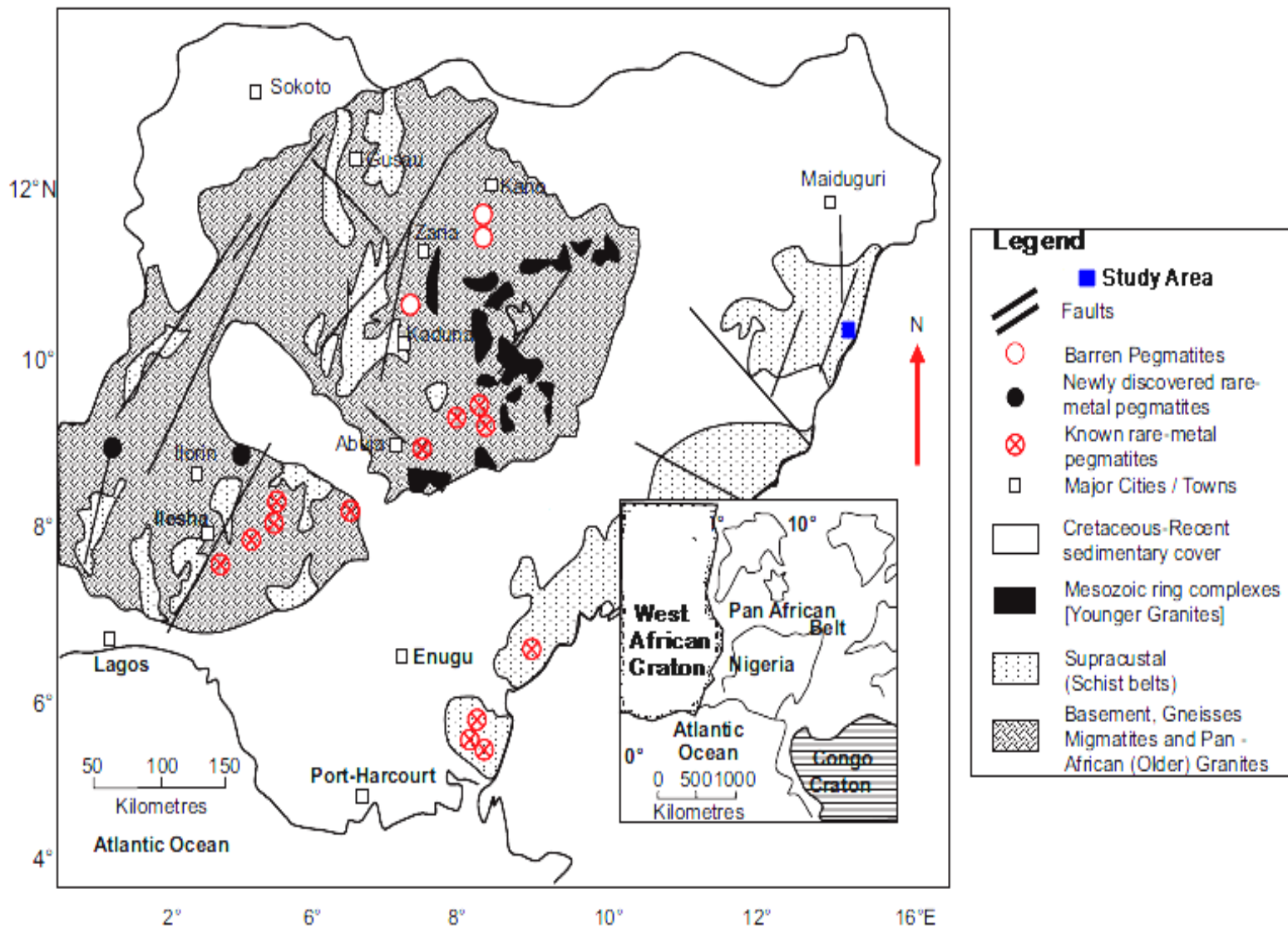


Fig 2.2: Geological map of Nigeria showing the location of barren and rare-metal pegmatites adapted after (Garba, 2003).

2.3.1 Barren Pegmatites

Barren pegmatites 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 granitoid. They are found associated with all the major lithologies of the basement, i.e. gneiss, migmatites, schists and granitoids. The morphology and major mineral composition (quartz–feldspar–mica) are mostly not different from those of the rare-metal types (Garba, 2003).

2.3.2 Rare Metal Pegmatite

Rare metal pegmatite were hitherto thought to be known almost exclusively along the NE- SW striking belt covering about 400 km long stretching from the Wamba area (near the Jos Plateau) in central Nigeria to Ilesha area in southwestern Nigeria (Wright 1970; Kuster 1990). Recently, occurrences of prominent pegmatites have been reported in the Obudu and Oban massifs in southeastern Nigeria (Ekwueme and Matheis 1995; Kingsley and Ekwueme 2009; Oden *et al.*, 2013). Similar rare-metal pegmatites are known to continue into the northeastern Brazil (Holt 1978; Schuiling 1967; Garba 2003). Garba (2003) reported occurrences of rare metal pegmatite in Nasarawa and Richifa in central Nigeria and Kushaka, Magami and Maradun in the north-western Nigeria. Okunlola (2005) defined the metallogeny of the rare metal pegmatites in Nigeria and outlined 7 broad fields, namely:

- i. Kabba-Isanlu
- ii. Ijero-Aramoko
- iii. Keffi-Nasarawa
- iv. Lema-Share
- v. Oke-Ogun
- vi. Ibadan –Osogbo
- vii. Kushaka-Birnin Gwarri

In most of these areas, there are more than a dozen *en echelon* series of dykes, sills and irregular pegmatitic bodies usually forming ridges. Mineralization is in the form of dissemination and discrete concentrations of columbite-tantalite (Garba, 2005).

2.3.4 Structural Control

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). This is especially true in relation to cassiterite (SnO_2) concentration (Ajibade and Wright, 1989; Okunlola, 2005). This may suggest intermittent activeness of these lineaments especially in the late Precambrian times. 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. Mylonitisation, 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). Both the rare metal and gold mineralizations are associated with prominent regional faults in the basement complex of Nigeria (Garba, 2002).

2.3.5 Geochemical Features

The rare-metal pegmatites of Nigeria are generally complex albitised muscovite-quartz-microcline pegmatites with indiscernible to distinct zonations (Okunlola and Jimba,

2006). 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. Okunlola (2005) noted that the rare metal pegmatites of Nigeria are characterized by widespread development of moderate to intense albitization and lepidolite development and with variable internal structure and can be said to be similar to the albite type and the complex lepidolite subtype of Černý, (1986) classification. He also noted that they are similar to the Woringa pegmatites in Australia, Heng Shen pegmatites field in China and Buck pegmatites in Colorado USA. According to Kinnaid and Nex (2013), the Nigerian rare metal pegmatites share similarities with the Damaran pegmatites of Namibia with both having LCT pegmatites and a Sn-W rich pegmatites association.

2.3.6 Mineralization Potential

Mineralization potential of the Nigerian rare-metal pegmatites are highly variable according to the host rock type. Ta-Nb concentrates, which have been won in the Kabba-Isanlu, Ijero-Aramoko, Keffi-Nasarawa, Lema-Share, Oke-Ogun, Ibadan –Osogbo and Kushaka-Birnin Gwarri fields are usually of varying grade in terms of total pentoxide enrichment (Okunlola, 2005). 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.

2.3.7 Origin

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

METHODOLOGY

3.1 INTRODUCTION

The methodology adopted for this research work consists of field study and laboratory analyses. The field study involved geological mapping on a scale of 1:50,000 which was undertaken with topographic map, geologic hammer, compass-clinometers and GPS. The laboratory work involved sample preparation, petrographic study and geochemical analysis. The petrographic study was undertaken with the aid of petrological microscope at the Petrographic Laboratory, Department of Geology, Ahmadu Bello University, Zaria. For the geochemical analysis, a combination of ICP-MS and ICP-AES techniques was employed in the determination of major, trace and REE elements while mineral identification was carried out using x-ray powder diffraction techniques at the ACME analytical laboratory Vancouver, Canada.

3.2 FIELD INVESTIGATION

The field investigation was carried out in two (2) stages, first was a reconnaissance visit for five days, followed by the second field visit during which geological field mapping was undertaken on a scale of 1:50,000. Fresh (un-weathered) rock and mineral samples were collected for hand specimen examination. Preliminary observation and identification of each constituent mineral were carried out using magnifying lens. Field data measurement of strike and dip directions of lineaments with compass-clinometer and recording of the coordinates 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.

3.3. LABORATORY WORK

3.3.1 Petrography

For the petrographic studies, twelve 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. The prepared slides were examined under the petrological microscope to identify minerals and other features that were not hitherto seen with aid of magnifying lens

3.3.2 Analytical Techniques

A total of twenty one (21) samples comprising (Eleven (11) whole-rocks, eight(8) feldspars, one (1) biotite and one (1) unknown mineral were selected for geochemical analysis. The feldspar and biotite samples were extracted from the pegmatites. The whole-rock samples consist of representative samples of each mappable lithologic unit which include migmatitic gneiss, amphibolite, cataclasite, coarse grained biotite granite, medium grained biotite granite, fine grained biotite granite, porphyritic biotite granite, diorite and aplite. About 1 kg of each sample was broken into pieces with a hammer and crushed into smaller pieces with a jaw-crusher. The samples were thereafter pulverized in a disc mill for about two minutes. Each pulverised sample was thoroughly homogenized to obtain a representative portion. The samples were thereafter shipped for major and trace elements analysis at the ACME analytical laboratory Vancouver, Canada using ICP-MS and ICP-AES techniques. In addition, mineral identification was carried out using XRD.

Major elements were analyzed using inductively-coupled plasma atomic emission spectrophotometry (ICP-AES). As a means of dissolving the mineral constituents, the analytical procedure involved addition of 5 ml each of perchloric acid (HClO_4), trioxonitrate (V) HNO_3 and 15 ml Hydrofluoric acid (HF) to 0.5 g of sample. The solution was stirred properly and allowed to evaporate to dryness after it was warmed at a low

temperature for some hours. Four (4) ml of hydrochloric acid (HCl) was then added to the cooled solution and warmed to dissolve the salts. The solution was cooled; and then diluted to 50 ml with distilled water. The solution was then introduced into the ICP torch as aqueous - aerosol. The emitted light by the ions in the ICP was converted to an electrical signal by a photo multiplier in the spectrometer, the intensity of the electrical signal produced by emitted light from the ions were compared to a standard (a previously measured intensity of a known concentration of the elements) and the concentrations were then computed. Analytical precisions vary from 0.1% to 0.04% for major elements.

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

Mineral identification was carried out using MiniFlex Benchtop X-ray diffraction Instrument. The mineral samples were first ground to fine powder about (125 μm). Small powdered samples were then mounted on glass fibers 1 to 1.5 cm in length. The tip of the fiber was then dipped into epoxy and then into the powder. The powdered samples formed spherical shape on the tip of the fiber. The glass fibers were then mounted on a sample holder. Clay materials were used to stabilize the fiber on the holder. A monochromatic x-ray from an x-ray tube was directed toward the powdered sample. Interaction of the incident x-rays with the samples produced a set of diffraction peaks. The diffraction peaks were then converted to a set of d-spacings. The d-spacings from the mineral were then compared with the standard reference patterns.

CHAPTER FOUR

RESULTS

4.1 INTRODUCTION

The results obtained using the methodology discussed in the previous chapter are presented in this chapter. The field relationship, structures and petrography of the rocks are presented under the sub-heading “geology and petrography”; the geochemistry of the migmatitic gneisses, amphibolite, granodiorite, aplite and granites are presented under the sub-heading whole rock geochemistry.

4.2 GEOLOGY AND PETROGRAPHY

The study area composed of low-lying migmatitic gneiss, minor amphibolite, diorite, aplite, granites and pegmatites (Fig. 4.1). Contact relationships between the various rock types are commonly sharp although gradational contacts were also encountered. The results of modal analysis of the rock samples is presented in Table 4.1 while the Q-A-P ternary plot of the rock samples is presented in Figure 4.2

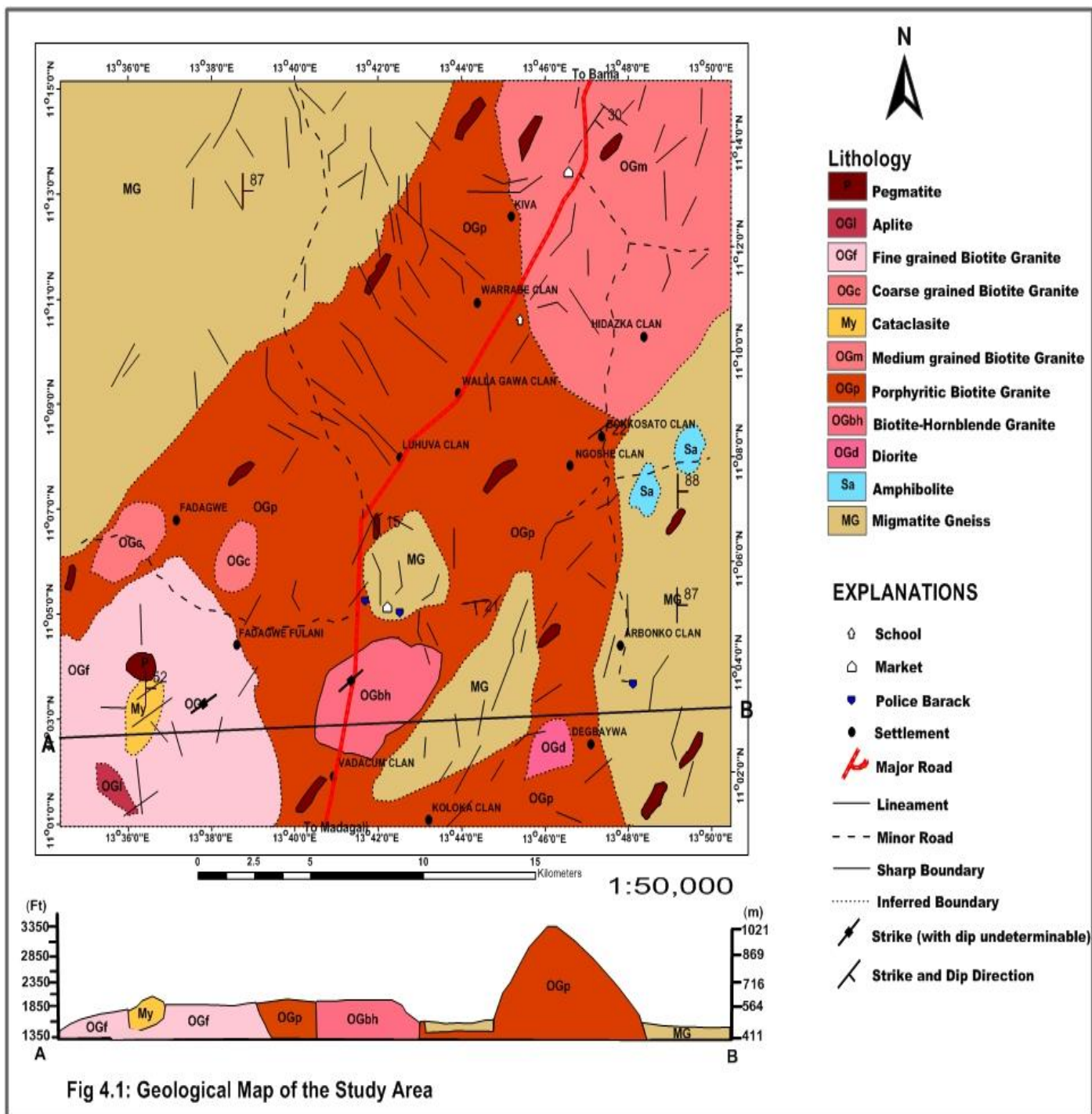


Fig 4.1: Geological map of the study area

4.2.1 Migmatitic-Gneiss

The migmatitic gneisses are medium grained in texture and occur both in the northwestern and southeastern part of the study area. It is believed to have been partially migmatized by the intrusion of acidic magma resulting into distinct felsic and mafic bands of few millimeters to tens of centimeters hence the name migmatitic gneiss. The common structure observed in this rock is ptygmatic folding (Plate I).

Thin section studies revealed that the melanosome (mafic part) consist of hornblende, biotite and pyroxene (augite) while the leucosome (felsic part) consist of plagioclase (andesine-labradorite), quartz and muscovite. The hornblende occurs as xenomorphic crystals with moderately high relief (Plate II and III). Biotite also occurs as xenomorphic crystals with high relief, the crystals are brown in colour. Augite on the other hand, occurs as subhedral crystals which are easily distinguished by their characteristics of double cleavage at angle of about 87° and 93° , while plagioclase occur as colourless subhedral crystals which are easily distinguished by their lamella twining.

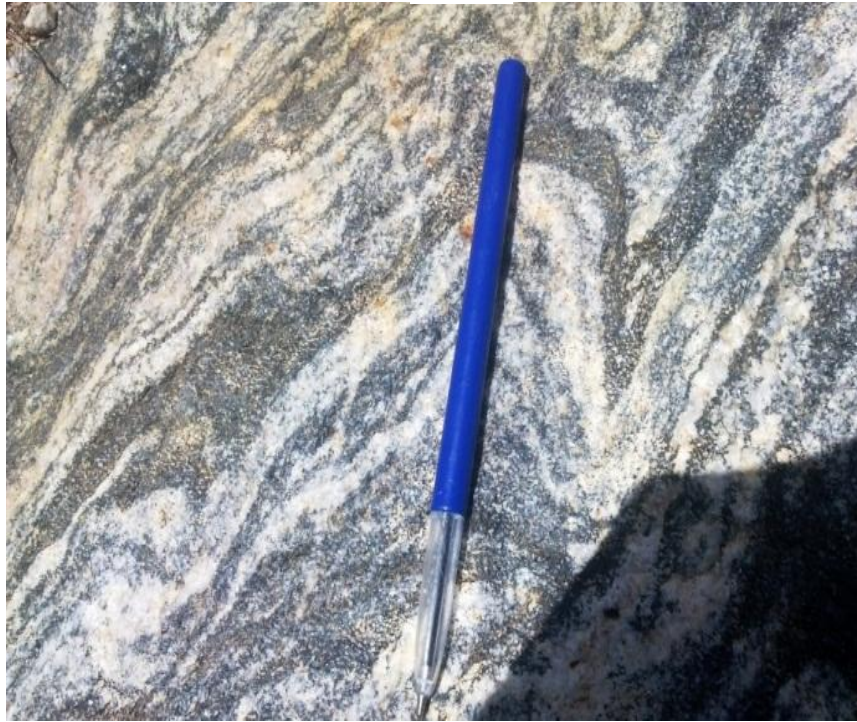


Plate I: Photograph of an outcrop of migmatitic gneiss with ptygmatic folding. Sample location Hambagda Quarry (Latitude $11^{\circ}03'24''$ N and Longitude $13^{\circ}43'22''$ E)

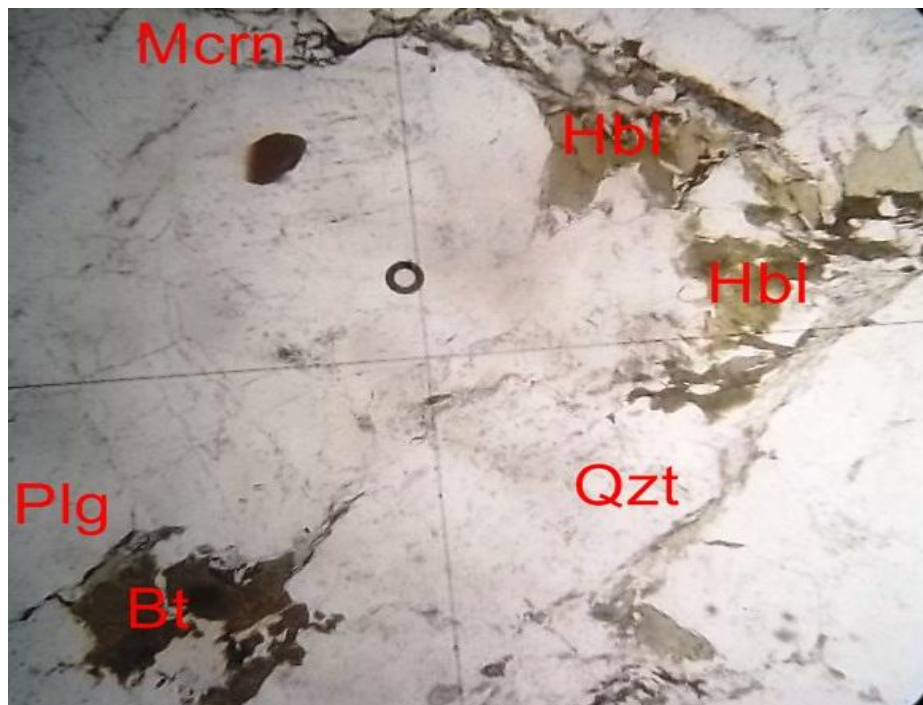


Plate II: Photomicrograph of of migmatitic gneiss under PPL. Qtz= quartz, Mcrn=microcline. Plg=plagioclase, Hbl=hornblende and Bt=biotite. Sample location Hambagda Quarry (Latitude 11°03' 24" 'N and Longitude 13° 43' 22" E)



Plate III: Photomicrograph of migmatitic gneiss under XPL. Qtz= quartz, Mcrn=microcline. Plg=plagioclase, Hbl=hornblende and Bt=biotite. . Sample location Hambagda Quarry (Latitude 11°03' 24" 'N and Longitude 13° 43' 22" E)

4.2.2 Amphibolite

The amphibolites are fine grained in texture (Plate IV) and occur as pockets and lenses interleaved with the migmatitic gneiss in southeastern part of the study area especially within Atagara village. Thin section study of the rock shows that the major minerals in the rock include; hornblende, biotite, plagioclase (labradorite), augite, quartz, iron oxide while accessory mineral includes; apatite and zircon. Quartz cystals occurs

largely as poikiloblastic crystals characterized by inclusion of small grains of hornblende. However, few quartz crystals occur as discrete crystals with no inclusion (Plate V and VI). The crystals are highly fractured as a result of which they show very strong undulatory extinction. Hornblende occurs as subhedral crystal. It has light green to dark green pleochroic colour under PPL and moderate birefringence under XPL. Augite occurs as interstitial mineral between quartz megacryst, the mineral is easily distinguished by its double cleavage characteristic at angle of about 87° and 93° .



Plate IV: Photograph of amphibolite showing minor fold, the location is at Atagara village (Latitude $11^\circ 06' 56''$ and Longitude $13^\circ 49' 25''$ E)

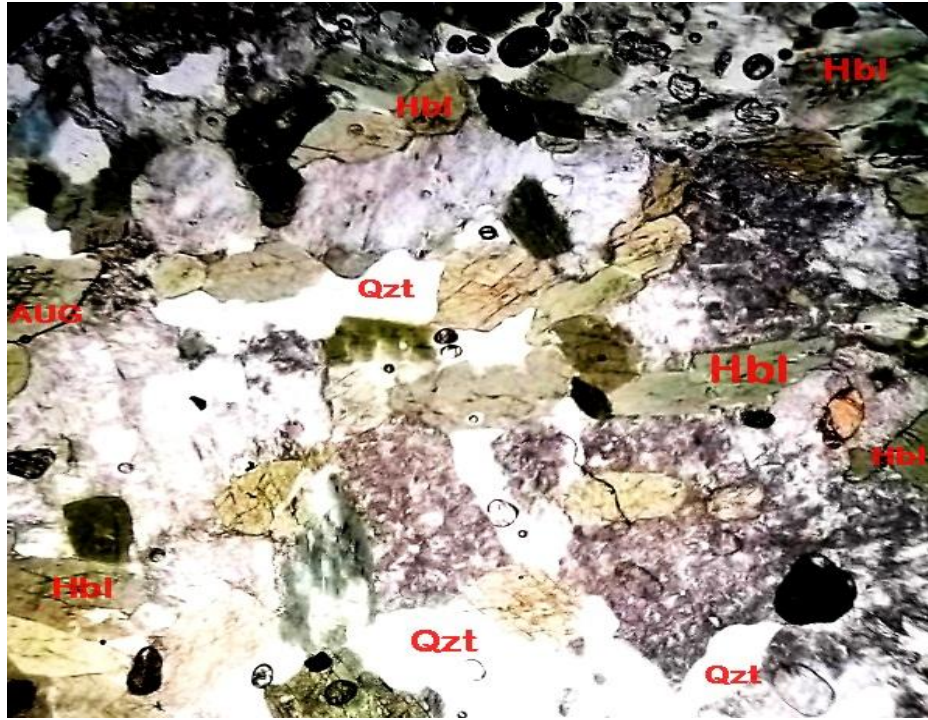


Plate V: Photomicrograph of amphibolite under PPL. Aug=augite; qtz=quartz; Bt=biotite; Hbl=hornblende. Sample location Atagara village (Latitude Latitude 11°06' 56" N and Longitude 13° 49' 25"E)

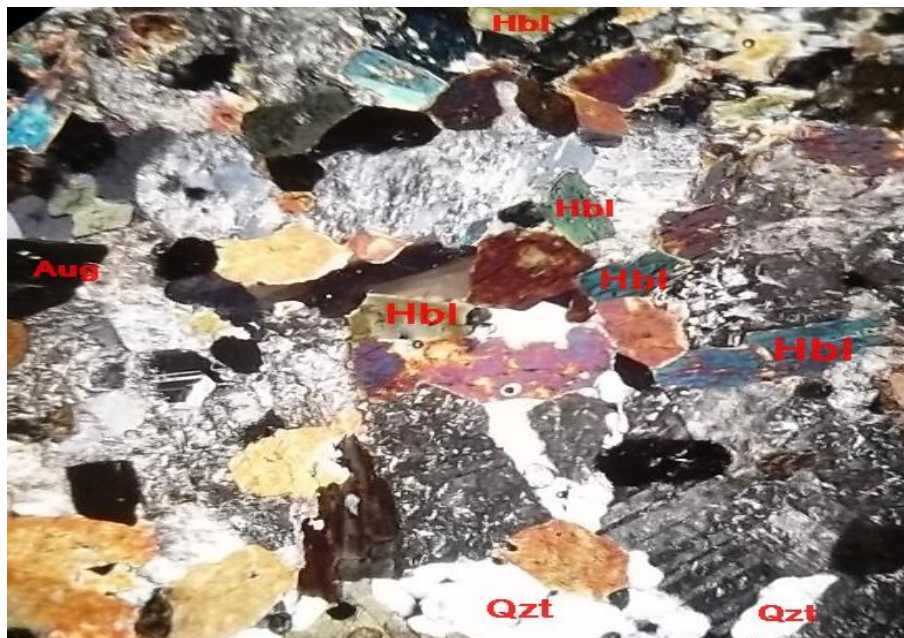


Plate VI: Photomicrograph of amphibolite under XPL. Aug=augite; qtz=quartz; Bt=biotite; Hbl=hornblende. Sample location Atagara village (Latitude Latitude 11°06' 56" N and Longitude 13° 49' 25"E)

4.2.3 Diorite

Diorite occurs as small boulders within the porphyritic biotite granites (Plate VII). It is medium grained in texture. For the most part, the rocks are highly weathered and are poorly exposed. Thin section studies shows that the major minerals present in this rock in order of abundance include; plagioclase, hornblende, quartz, microcline, biotite, augite and garnet (Plate VIII and IX).

Plagioclase occurs as subhedral crystals, which are moderately altered already. The mineral is easily distinguished from microcline by its characteristic of carlsbad twinning while microcline shows cross-hatch twinning. Hornblende occurs as xenomorphic crystals and are easily distinguished from augite owing to the fact that the double cleavages observed in this mineral are parallel to each other while in augite, the double cleavage are at an angle of about 87° and 93° respectively.



Plate VII: Photograph of Diorite outcrop. The location is at Hambagda village (Latitude $11^\circ 02'30''$ N and Longitude $13^\circ 43'23''$ E)

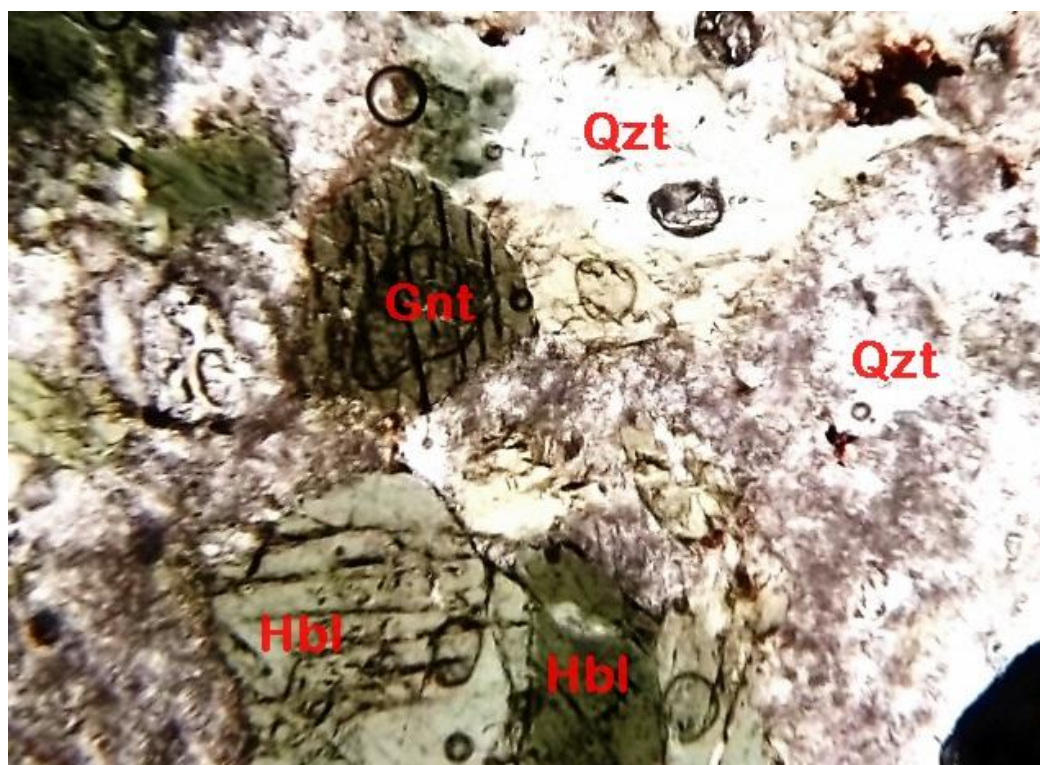


Plate VIII: Photomicrograph of Diorite under PPL. . Qzt=quartz; Gnt=garnet; Bt=biotite. The location is at Hambagda village (Latitude 11° 02'30" ' N and Longitude 13° 43' 23" E)

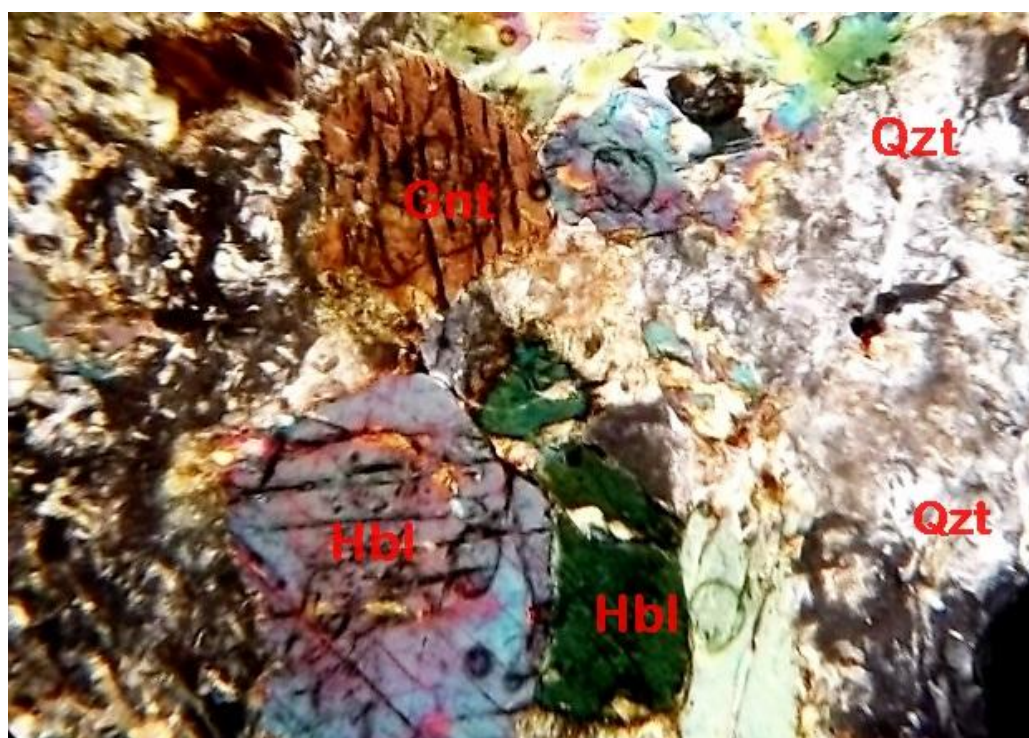


Plate IX: Photomicrograph of Diorite under XPL. Qzt=quartz; Bt=biotite Gnt=garnet. The location is at Hambagda village (Latitude 11° 02'30" ' N and Longitude 13° 43' 23" E)

4.2.4 Medium Grained Biotite Hornblende Granite

This rock occurs together with the porphyritic biotite granite in the south-western part of the study area, especially near Hambagda village where sharp contacts between the two rocks have been observed (Plate X). Thin section study of the rock shows that the major minerals present include quartz, biotite, hornblende, plagioclase and microcline (Plate XI and XII) while accessory minerals present are apatite and opaque mineral.

Biotite occurs largely as poikilitic crystals characterized by inclusion of apatite. However, few biotite crystals occur as interstitial crystals between hornblende crystals with no inclusion. Hornblende occurs as large crystals sandwiched between biotite and quartz. The crystals are xenomorphic and appear green in colour. Plagioclase occurs as colourless subhedral crystals. The mineral is easily distinguished by the characteristic of carlsbad twinning while microcline occurs as subhedral crystals which are easily distinguished by their characteristic of cross-hatch twinning.



Plate X: Photograph of an outcrop in which the sharp contact between the medium grained biotite-hornblende granite and porphyritic biotite granite was observed. Location is at Hambagda village (Latitude 11°02'13" N and Longitude 13°43' 23"E).

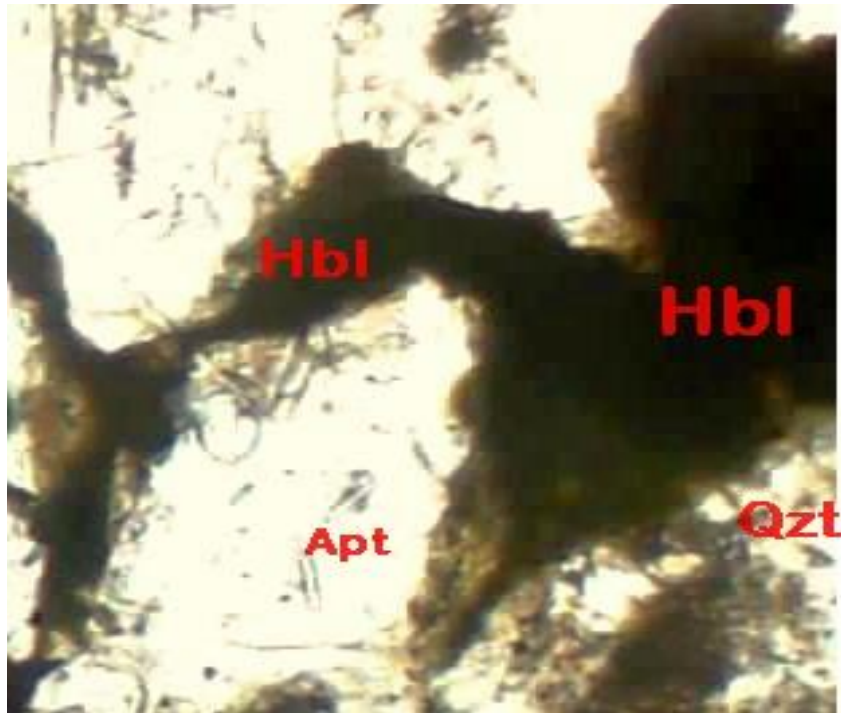


Plate XI=Photomicrograph of biotite-hornblende granite under PPL. Apt=apatite; Hbl=hornblende;. Location is at Hambagda village (Latitude $11^{\circ}02'13''$ N and Longitude $13^{\circ}43'23''$ E).

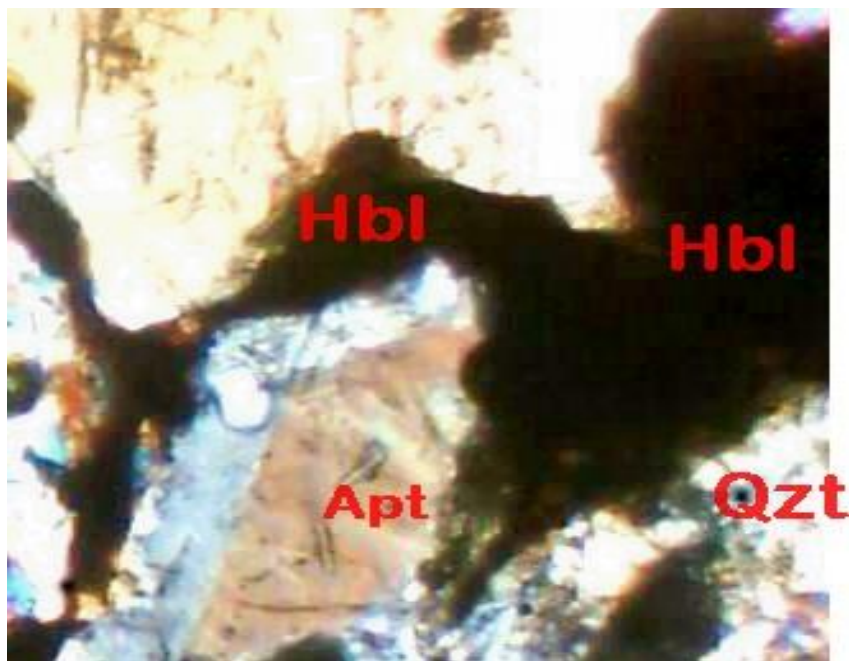


Plate XII: Photomicrograph of biotite-hornblende granite under XPL. Apt=apatite; Hbl=hornblende; Bt=biotite. Location is at Hambagda village (Latitude $11^{\circ}02'13''$ N and Longitude $13^{\circ}43'23''$ E)

4.2.5 Porphyritic Biotite Granite

The porphyritic biotite granite is the most widespread rock type in the study area. Sharp contact of this rock with the medium grained biotite-hornblende granite has been established in the southwestern part of the study area (Plate X). The rock hosts simple pegmatitic veins and is mostly weathered although fresh outcropped were observed in some rock quarries. In hand specimen, the phenocrysts are pink in colour with the longer axis aligned parallel to the biotite flakes thus giving a gneissose appearance to the rock.

Thin section study of the rock sample show that it is made up of large subhedral phenocrysts of microcline set in the medium grained groundmass of quartz, plagioclase, pertite and biotite (Plate XIV and XV). The accesory minerals are iron oxide and zircon.

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Plate XIII: Photograph of porphyritic biotite granite intruded by quartzofeldspathic vein. The location is at Luva quarry (The location is at Luva quarry (Latitude; 11° 06' 49" N and Longitude 13°42' 04" E)



Plate XIV: Photomicrograph of porphyritic biotite granite under PPL. Qzt=quartz; Mcrn=Microcline. The location is at Luva quarry (Latitude; 11° 06' 49" N and Longitude 13°42' 04" E)).



Plate XV: Photomicrograph of porphyritic biotite granite under XPL; Qzt=quartz; Mcrn=microcline. The location is at Luva quarry (Latitude; 11° 06' 49" N and Longitude 13°42' 04" E)

4.2.6 Medium Grained Biotite Granite

Outcrop of this rock was observed within the Pulka quarry in northwestern part of the study area. The outcrop of the granite appears dark due to high content of ferromagnesian minerals like biotite. The rock is generally poorly exposed. It is medium grained in texture. Thin section study shows that the major mineral present include; quartz, microcline, plagioclase (oligoclase) and biotite (Plate XVI and XVII).

Microcline occurs as subhedral crystals which are sandwiched between large crystals of quartz. The mineral appear colourless and it is easily distinguished by their cross-hatched twinning. Plagioclase occurs as colourless subhedral crystals and is easily distinguished by its carlbad twinning. Biotite occurs as elongated discrete crystals which are light brown in colour.

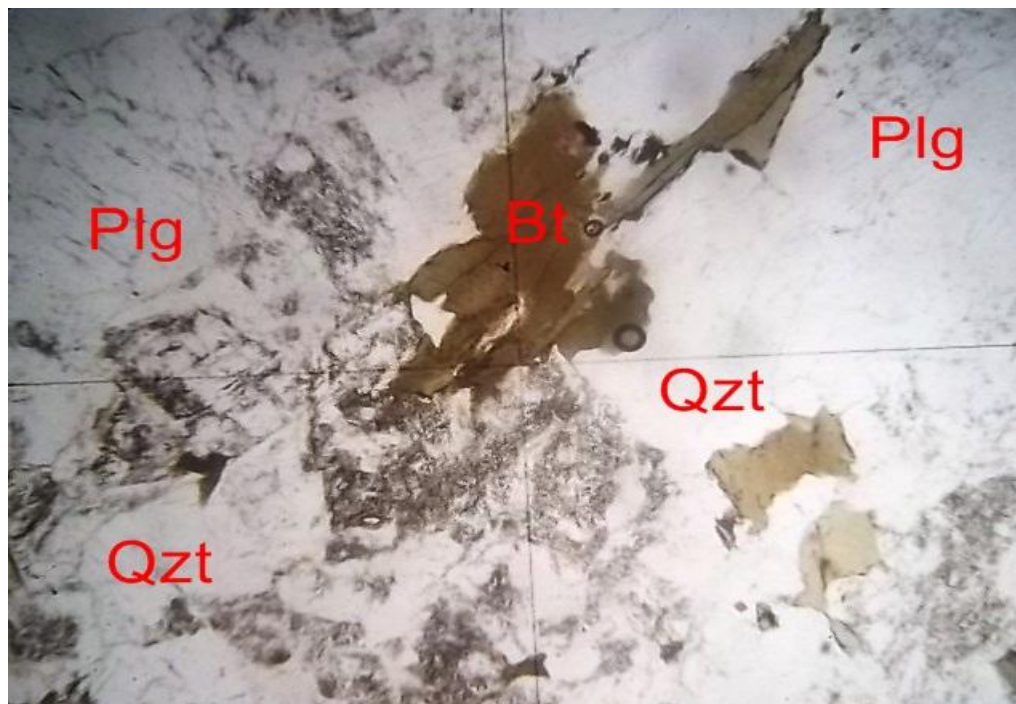


Plate XVI: Photomicrograph of medium grained biotite granite under PPL; Qzt=quartz; Bt=biotite; Mcrn=microcline. The location is at Pulka area (Latitude $11^{\circ}14' 26''$ N and Longitude $13^{\circ}47' 13''$ E).



Plate XVII: Photomicrograph of medium grained biotite granite under XPL; Qzt=quartz; Bt=biotite; Mcrn=microcline. The location is at Pulka area (Latitude $11^{\circ}14' 26''$ N and Longitude $13^{\circ}47' 13''$ E)

4.2.7 Cataclasite

This rock occupies the central portion of Liga Hills. The rock occurs within a fault zone, and field relationship has shown that it is probably derived from the fine grained biotite granite. The rock is dark grey in colour (Plate XVIII) and porphyroblastic and composes of feldspars and quartz. The quartz is blue in colour while feldspars occur as large pink crystals (megacryst). The feldspars and quartz crystals are set in a fine grained groundmass. In thin section, the megacryst are fractured and strained due to the effect of cataclastic processes.

Quartz occurs both as megacryst and in groundmass. The megacrysts are rod-like in shape, highly fractured and show very strong undulatory extinction (Plate XIX and XX). The quartz crystals occurring in groundmass are anhedral and show varying degree of undulatory extinction. Microcline forms the major megacryst in the rock although few crystals of this mineral are also found in the groundmass. The megacryst are subhedral, fractured and strained. Plagioclase (albite) is the most abundant mineral in groundmass and occurs as discrete crystals. The crystals show carlsbad twinning and are easily distinguished from microcline. Biotite crystals occur as tiny flakes. Iron oxide forms a significant proportion of the accessory minerals. It is opaque, subhedral and is usually associated with biotite. Apatite crystals occur as rounded to sub-rounded crystals.



Pte XVIII: Hand specimen of cataclasite. The location is at Liga hills (Latitude $11^{\circ}03'26''$ N and Longitude $13^{\circ}36'33''$)

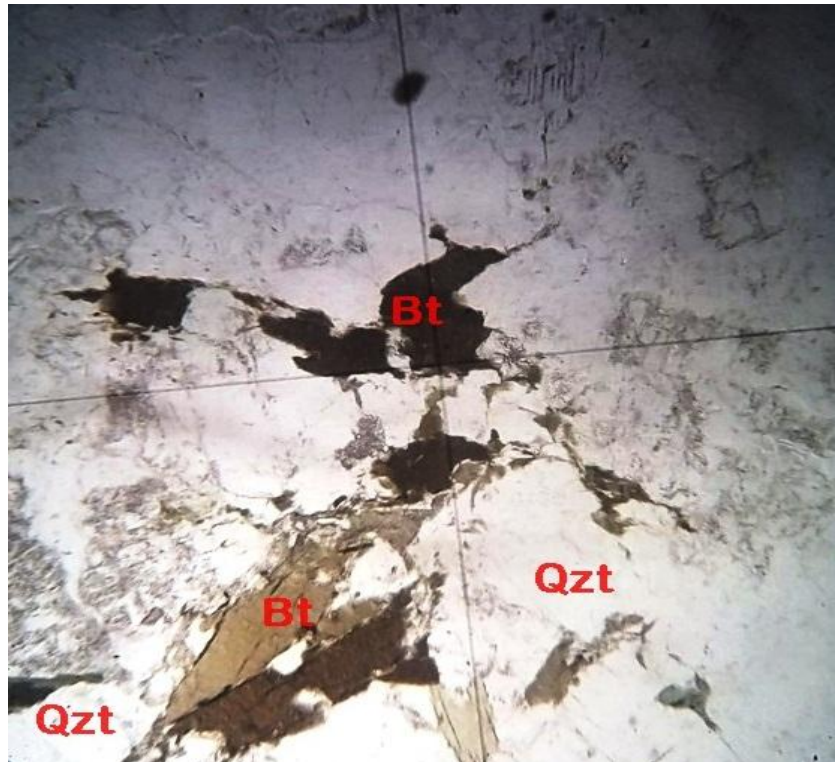


Plate XIX: Photomicrograph of cataclasite under PPL. Qzt=quartz; Bt=biotite;. The location is at Liga hills Latitude $11^{\circ}03'26''$ N and Longitude $13^{\circ}36'33''$)

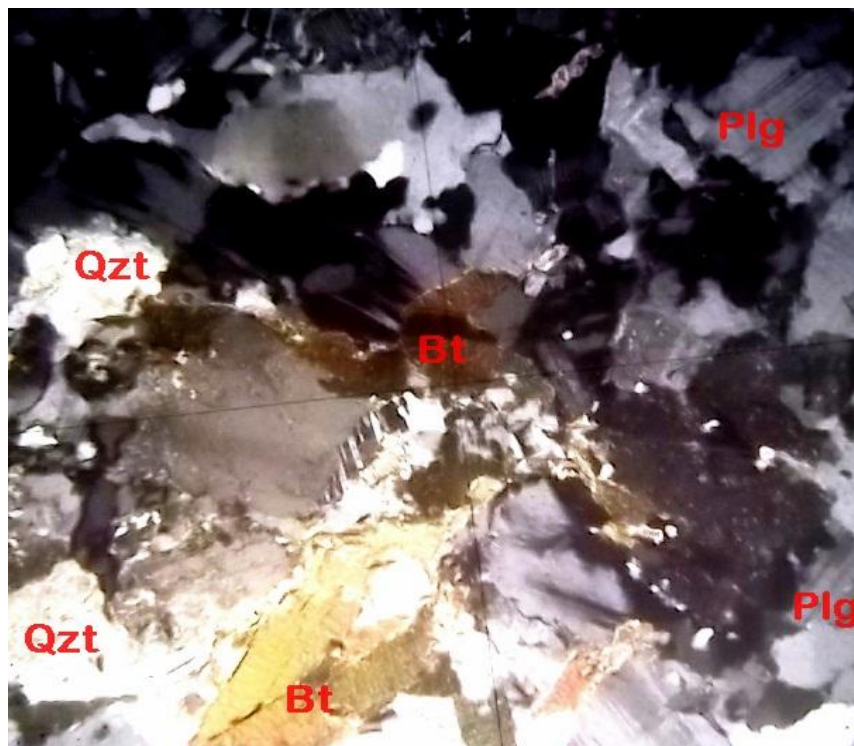


Plate XX: Photomicrograph of cataclasite under XPL. The location is at Liga hills Latitude $11^{\circ}03'26''$ N and Longitude $13^{\circ}36'33''$

4.2.8 Coarse Grained Biotite Granite

This rock occurs within the porphyritic biotite granite. It is coarse grained in texture (Plate XXI). The rock is highly weathered and therefore fresh sample could not be obtained for petrographic study. However, minerals that were identified in hand specimens include feldspar, quartz and biotite.



Plate XXI: Photograph of highly weathered coarse grained biotite granite. It is located north of Liga Hill (Latitude $11^{\circ}03'38''$ N and Longitude $13^{\circ}36'13''$ E).

4.2.9 Fine Grained Biotite granite

This rock occurs in Liga Hills and it is intruded by type-I pegmatites. It is leucocratic (pink) inequigranular in texture and shows evidence of metasomatism (tourmalinization Plate XXIII). Outcrops of the rock are massive and are occasionally jointed (Plate XXII). Petrographic study shows that the major mineral present in the rock include quartz, microcline, Plagioclase and biotite, while zircon, apatite and iron oxide constitute the accessory minerals present in the rock (Plate XXIV and XXV). Quartz occurs as discrete crystals characterized by very faint undulatory extinction, cracks and inclusion of feldspar are common within the larger quartz grains. Microcline is the most dominant mineral and it is characterized by cross-hatch twinning. Plagioclase ranges from albite to sodic oligoclase and occur as discrete crystals with carlsbad twinning characteristic. Biotite constitute a very small proportion of the major mineral, it is light brown in colour and pleochroic from light brown to dark brown under PPL.



Plate XXII: Photograph of fine grained biotite granite. The rock is located at Liga hills (Latitude $11^{\circ}03'27''$ N and Longitude $13^{\circ}36'12''$ E)



Plate XXIII: Photograph of hand specimen of fine grained biotite granite with tormalinization. The rock is located at Liga hills (Latitude $11^{\circ}03'27''$ N and Longitude $13^{\circ}36'12''$ E)

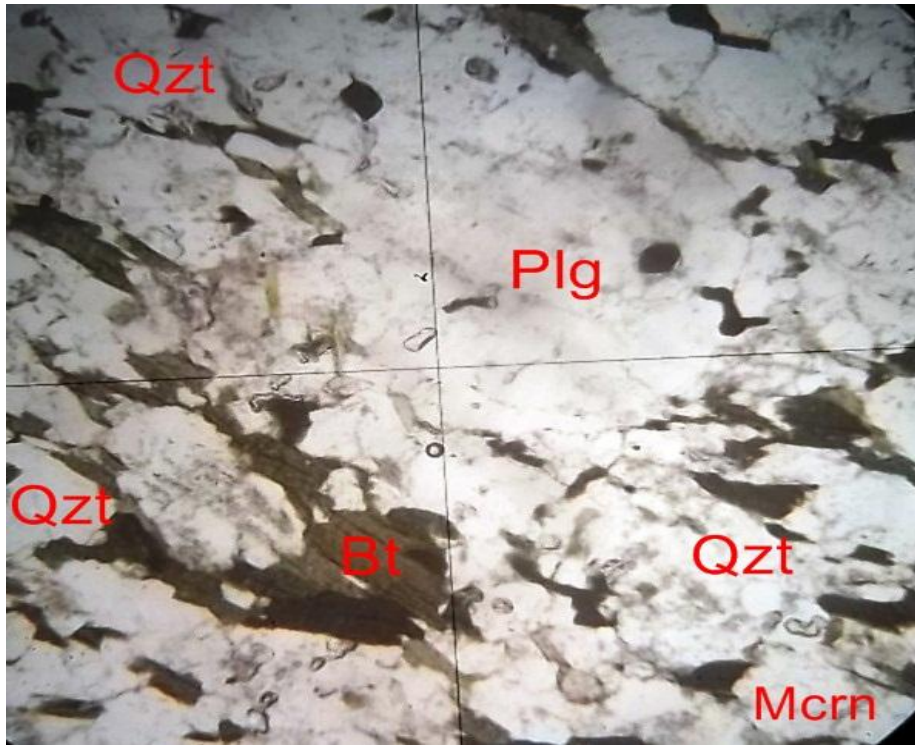


Plate XXIV: Photomicrograph of fine grained biotite granite under PPL. The rock is located at Liga hills (Latitude 11°03' 27" N and Longitude 13° 36' 12" E)

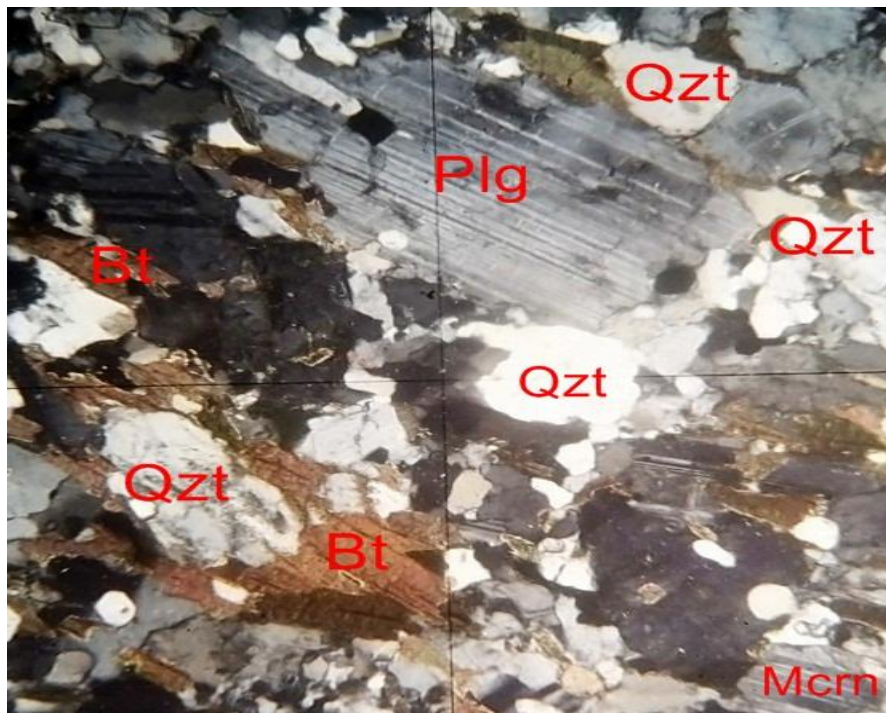


Plate XXV: Photomicrograph of fine grained biotite granite under XPL. The rock is located at Liga hills (Latitude 11°03' 27" N and Longitude 13° 36' 12" E)

4.2.10 Aplite

Aplite occur as small lensoid dyke trending roughly in NNW-SSE. Fresh outcrops are leucocratic (pink), while weathered outcrop appeared reddish brown. Microcline, quartz, and plagioclase form the essential minerals while biotite, apatite and iron oxide are the accessory minerals in the rock (Plate XXVI and XXVII).

Quartz occurs as interstitial crystals between feldspars, and as inclusion in feldspars. Microcline crystals are anhedral with characteristic of cross-hatch twinning. Plagioclase (albite) occurs as subhedral crystals, occasionally, the larger crystals contain quartz inclusions.

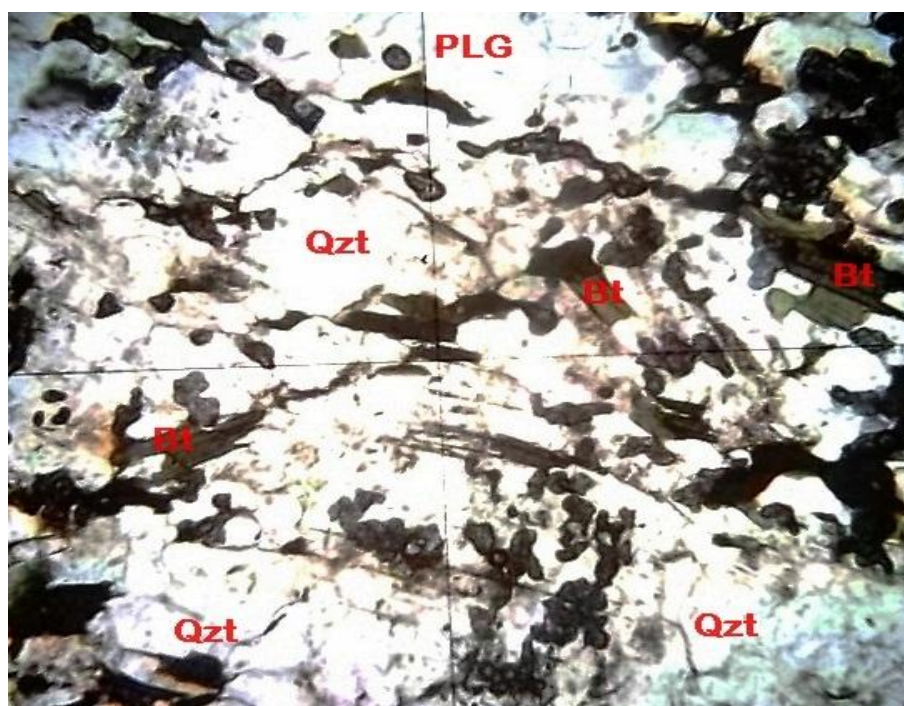


Plate XXVI: Photomicrograph of aplite under plane polarized light. The location is at Liga Hills (Latitude, 11°02' 47" N and Longitude 13°36' 38" E).

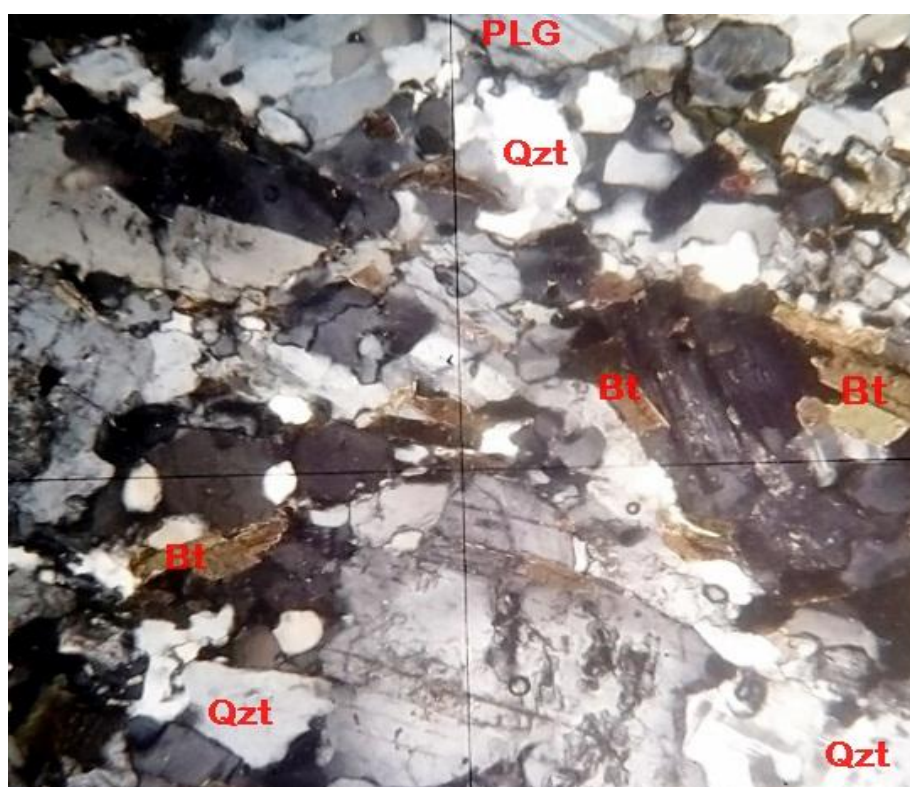


Plate XXVII: Photomicrograph of aplite under cross polarized light. The location is at Liga Hills (Latitude, 11°02' 47" N and Longitude 13°36' 38" E).

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

Minerals	<u>Migmatitic</u> <u>Gneiss</u>	<u>Amphi-</u> <u>bolite</u>	<u>Diorite</u>	<u>Granites</u>						<u>Aplite</u>
	A2	A3	H3	H2	V2	P1	L1	L3	L2	L9
Quartz	35	11	20	25	40	40	41	43	42	41
K-feldspars	10		10	11	26	28	25	34	40	43
Plagioclase	23	20	30	26	24	23	21	12	13	15
Biotite	10	6	10	20	9	9	8	6	4	0.7
Muscovite	5	-	-	-	-	-	0.6	-	-	-
Hornblende	12	52	20	20	-	-	-	-	-	-
Pyroxene	5	10	9	1	-	-	-	-	-	-
Opaque mineral	-	-	-	0.1	0.5	-	2	0.2	0.7	-
Zircon	-	-	-	-	0.5	-	-	0.8	0.2	0.2
Apatite	-	0.8	-	0.9	-	-	0.4	-	0.1	0.1
Tourmaline	-	-	-	-	-	-	-	4	-	-
Epidote	0.2									
Garnet	-	-	1	-	-	-	-	-	-	-
Total	100	100	100	100	100	100	100	100	100	100

Legend

A2=Migmatitic gneiss

P1=Medium grained biotite granite

A3=Amphibolite

L1= Cataclasite

H3= Diorite

L2 and L3= Fine grained biotite granite

H2= Medium grained biotite hornblende granite

L9=Aplite

V2=porphyritic biotite granite

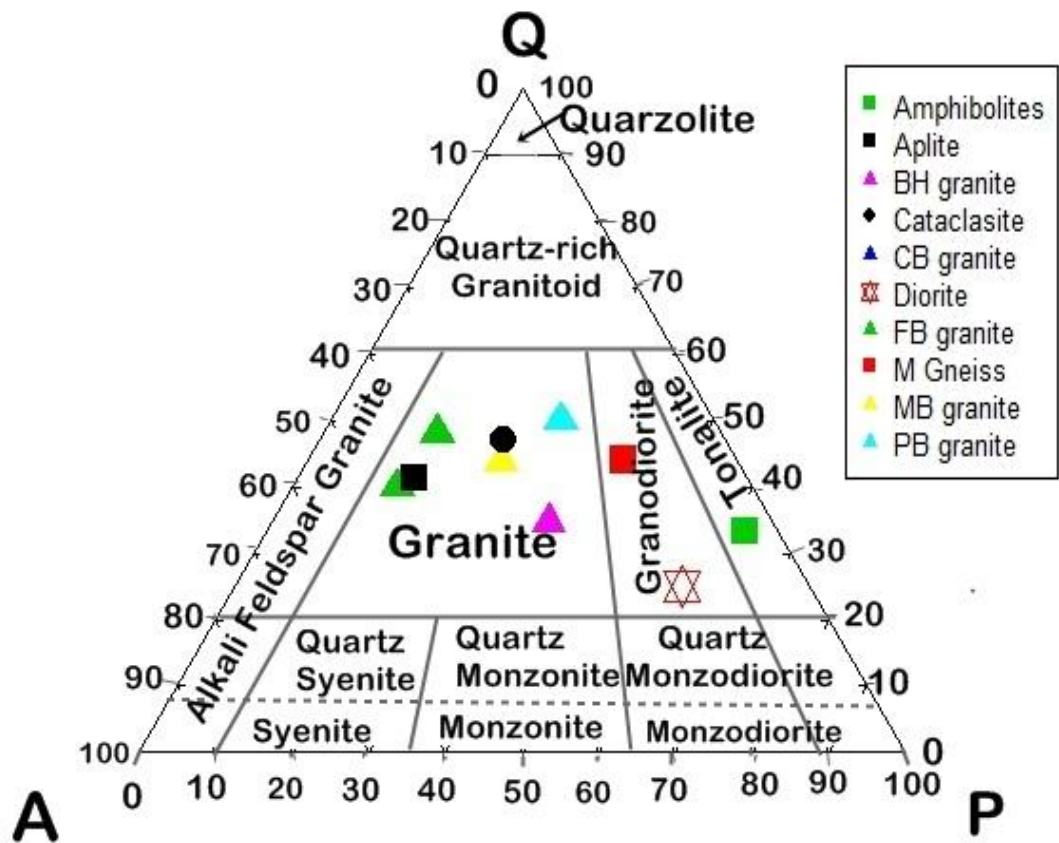


Fig 4.2: Q-A-P ternary plot of the rock samples from the study area (adapted after Streckeisen, 1976).

Legend;

BH granite= medium grained biotite-hornblende granite

FB granite=fine grained biotite granite

M gneiss=migmatitic gneiss

MB granite=medium grained biotite granite

PB granite=Porphyritic biotite granite

4.3 Pegmatites

Pegmatites form an interesting part of the geology of the study area. On the basis of field relation and mode of occurrence, two types of pegmatites have been mapped in the study area. This first category of pegmatite (type-1) occurs as large, zoned, oval-shaped bodies trending in E-W directions. These pegmatites occur in the northern tip of an isolated north-south trending Liga hill which forms part of the main Mandara Hills. The northern and southern parts of Liga Hills is occupied by fine grained biotite granite, while the central portion of the hill is occupied by small bodies of tectonized granite (cataclasite). Apart from the cataclasites, the central portion of the hill is also characterized by the presence of some cobbles of quartzite and mylonized rocks which indicate that the central portion of the hill is cut by a fault zone. The two oval-shaped bodies of pegmatite occur in the northern part of the hill and are hosted by the fine grained biotite granite already described above.

The second category of pegmatite (type-II) occurs as veins. The veins strike mainly in the NE-SW directions concordant with the major structural trend in the area. The general structural trend of the pegmatite is represented in Fig. 4.3

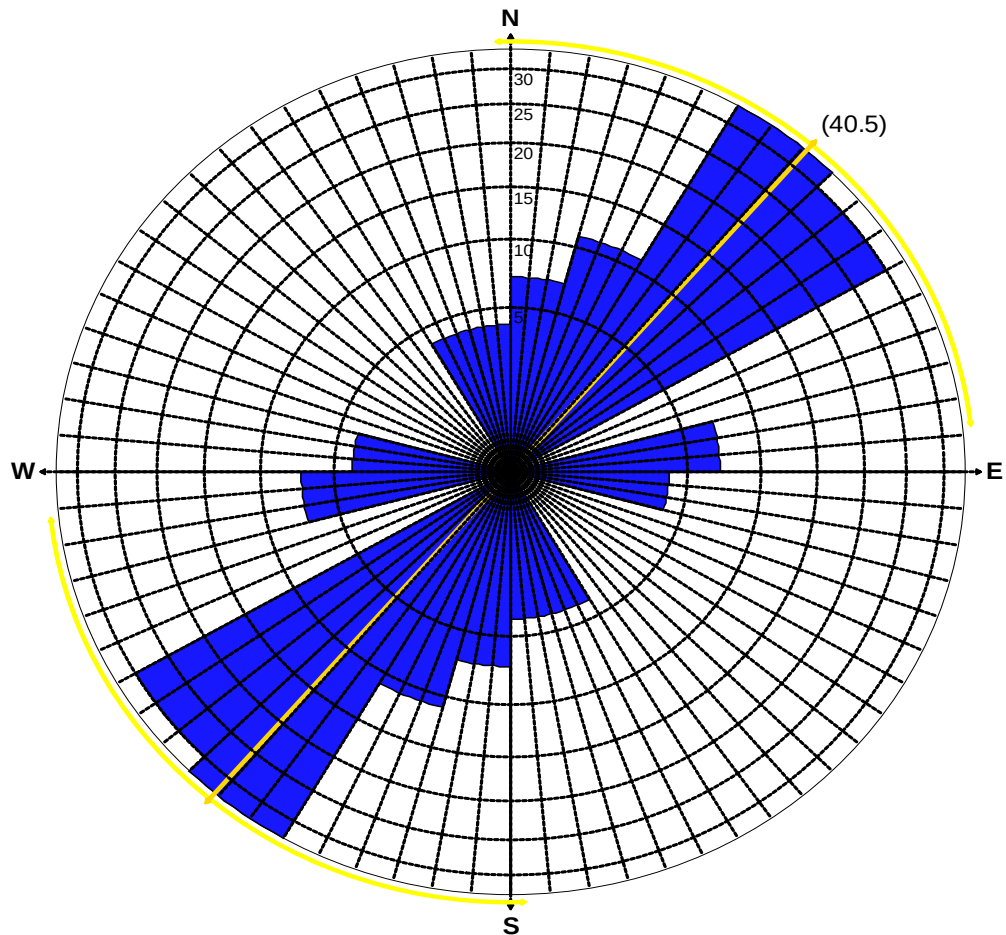


Fig (4.3): Rose diagram showing the general structural trends of the pegmatites.

4.3.1 Type-I Pegmatites

This pegmatite occurs mainly in the northern part of Liga hills forming a morphological unit rising about 50 m above the surrounding plain. A small occurrence of the pegmatite has been recorded in the western part of the hills. Four major concentric zones have been established in type-I pegmatites viz; the wall, intermediate zone-I, intermediate zone-II and the core.

Wall Zone: This zone has sharp contact with the host rock. Because of on-going mining activities in the area, the zone has been disturbed and hence its actual thickness of the zone could not be established during the mapping exercise. Microcline, albite and quartz are the

major mineral constituent, while muscovite occurs in accessory amount (Plate XXVIII and XXIX).

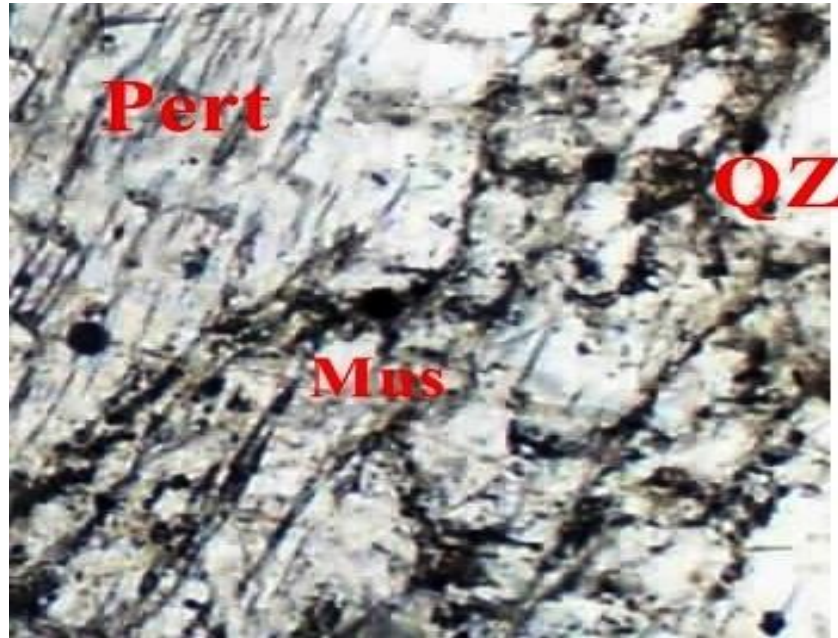


Plate XXVIII: Photomicrograph of the wall zone of type-I pegmatite under PPL; from Liga Hills (Latitude 11°03' 25" N and Longitude 13° 36' 24" E)

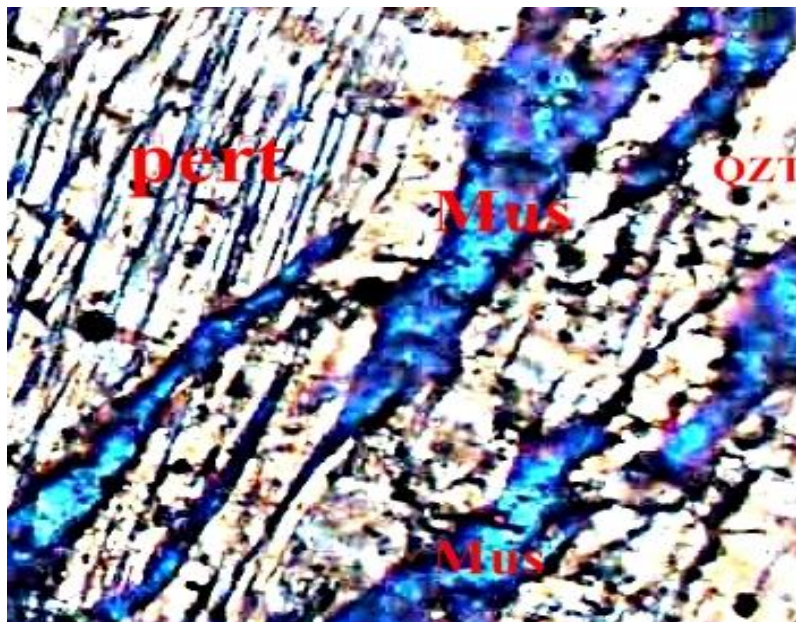


Plate XXIX: Photomicrograph of the wall zone of type-I pegmatite under XPL from Liga Hills (Latitude 11°03' 25" N and Longitude 13° 36' 24" E)

The Intermediate Zone: This zone is divided into two subzones, altogether measuring about 12 m thick. The subzone I (intermediate zone-I) consist of microcline, quartz, plagioclase and minor muscovite (XXX). It is also characterized by the presence of dark brown mineral. The dark brown mineral occurs as discontinuous veins (patches) measuring about 1 m thick (Plate XXXI)

The subzone II (intermediate Zone –II) consists mainly of blocky crystals of microcline. The microcline is pink in colour and constitutes about 90 % of this subzone (Plate XXXII). Quartz, biotite, muscovite, and a dark brown mineral make up the remaining 10 %. The dark brown mineral occurs as small pods within this subzone (Plate XXXIII). Quartz occurs as inclusion within the microcline, while biotite occurs as pockets within the microcline.



Plate XXX: Photograph of a section of the first intermediate zone of type-I pegmatites from Liga Hills (Latitude 11°03' 25" N and Longitude 13° 36' 24" E)



Plate XXXI: Photograph of a section of the second intermediate zone showing sheets of biotite



Plate XXXII: Photograph of a section of the second intermediate zone of type-I pegmatite.



Plate XXXIII: Photograph of a section of the second intermediate zone showing patches of ferroan pyroxmangite.

The Core: the core is about 4 m thick and consists exclusively of milky quartz (Plate XXXIV)



Plate XXXIV: Photograph of the core zone of type-I pegmatites with large crystals of milky quartz.

4.3.2 Type-II Pegmatite

These pegmatites occur as veins cross-cutting their host rocks (Plate XXXV). The veins are about 15 to 25 cm thick and trend mainly in the NE-SW directions concordant to the general structural trend in the area. Quartz and microcline are the major minerals observed in hand specimen, while muscovite occur as accessory mineral.



Plate XXXV: Photograph showing a pegmatites vein within a weathered porphyritic granites at Hambagda village (Latitude 11°02'35" N and Longitude 13° 43' 22" E).

4.4 Structures

Fractures which are products brittle deformation are the most dominant structures mapped in the study area (Plate XXXVI). The fractures strike mainly in the NE-SW directions although few minor fractures trending in the NW-SE and in E-W directions were also observed. The fractures affected all the major lithologic units but are more common in the biotite-hornblende granites. Satellite imagery interpretation carried out by Bassey *et al.*, (2006) indicates NE-SW, N-S, E-W and NW-SE as the major structural trends in Limankara area (south of the study area). Another notable structural feature in the study area is ptygmatic folding, which occurs exclusively in the migmatitic gneisses (Plate I). The lineaments map of the study area is shown in Fig. 4.4 and the rose diagram showing the major structural trends in the study area is shown in Fig. 4.5



Plate XXXVI: Photograph of fracture within biotite-hornblende granite at Hambagda (latitude 11°12' 24" N and longitude 13° 43' 23" E).

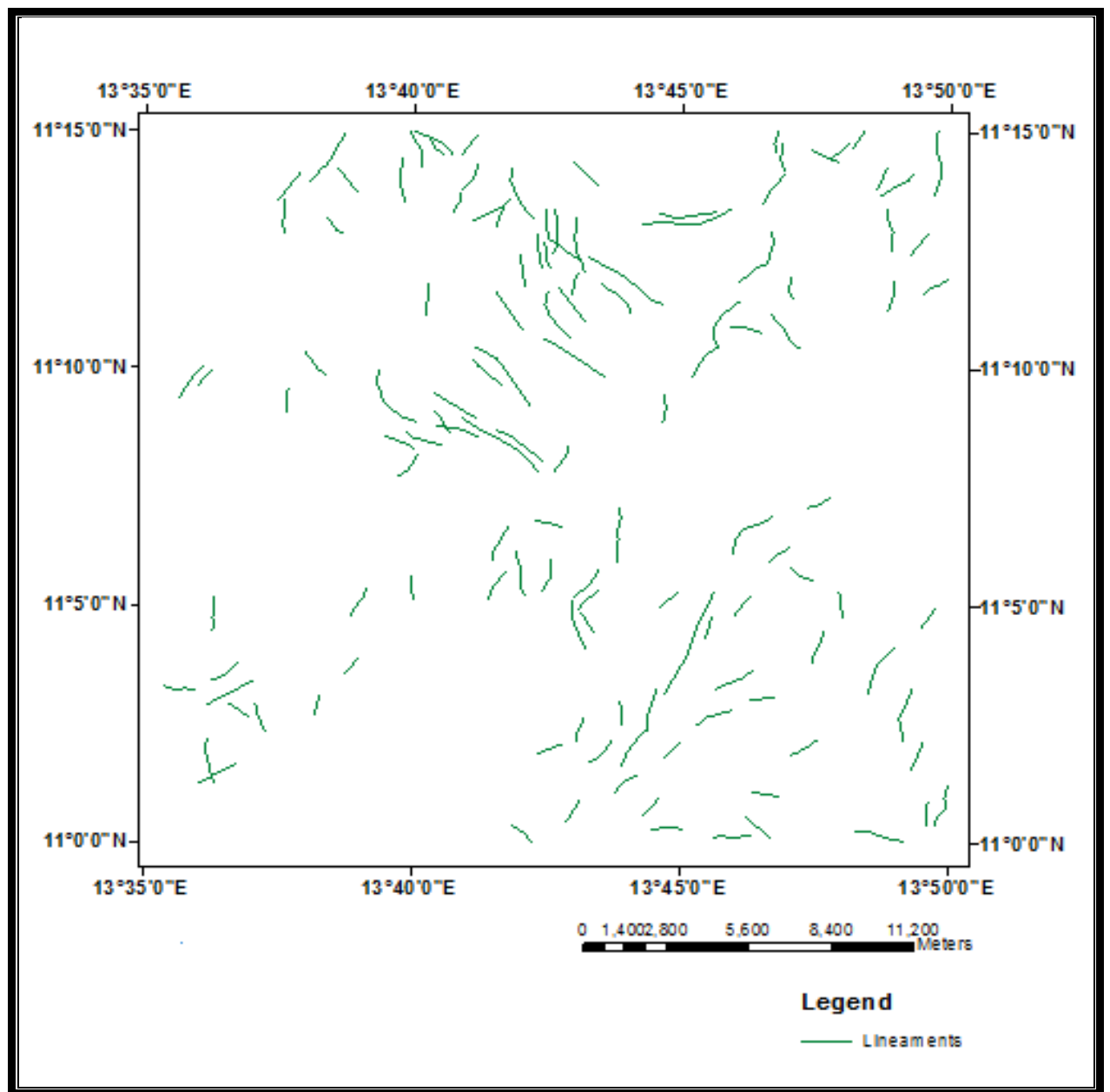


Fig 4.4: Lineaments maps of the study area obtained from satellite images.

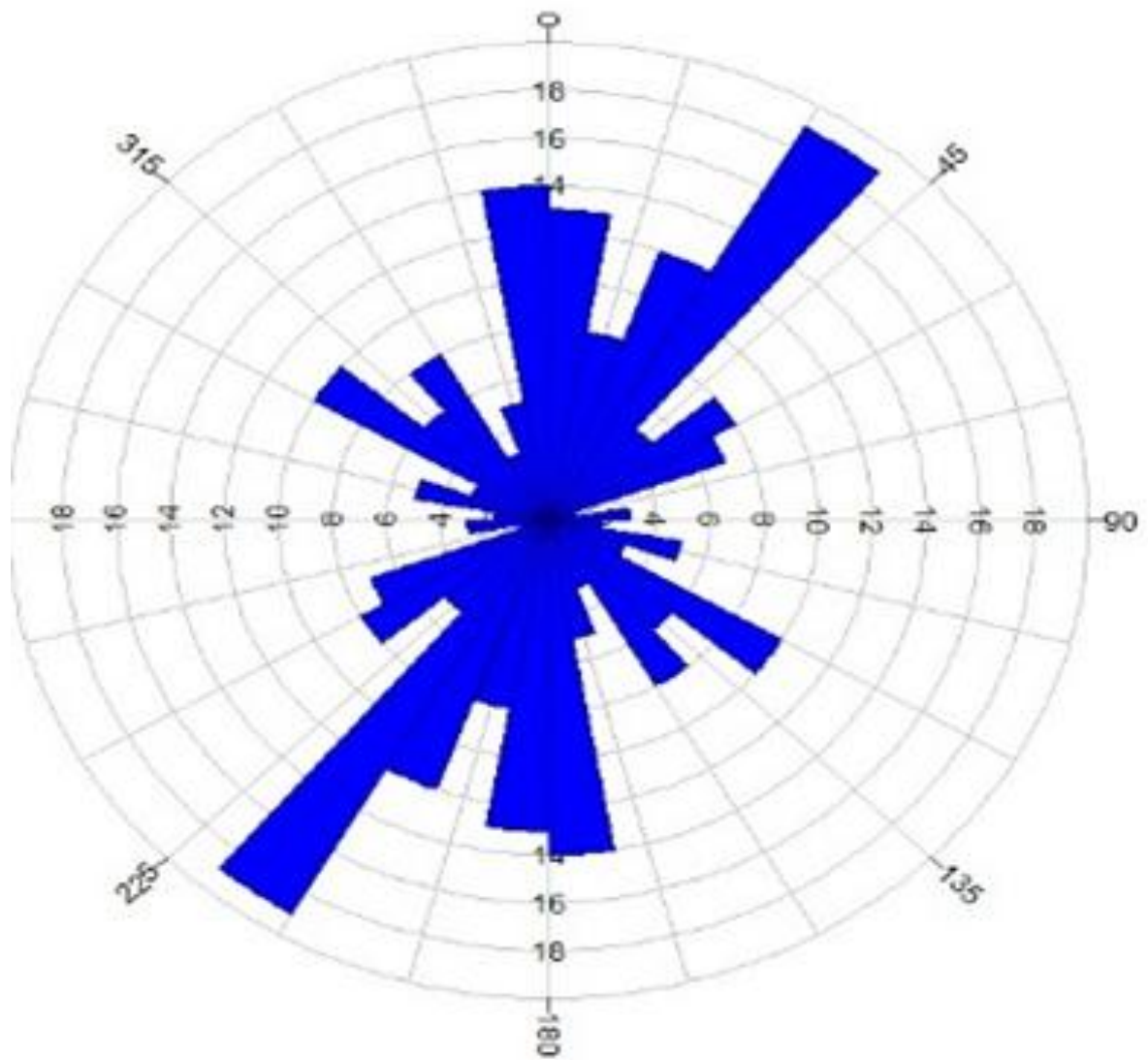


Fig. 4.5: Rose diagram showing the general structural trends of fractures and faults in the study area.

4.5 Whole Rock Geochemistry

A total of eleven whole rock samples were analysed for major and trace elements including rare earth element (REE). These include one representative sample of the migmatitic gneiss, amphibolite, diorite and eight samples of granites. The major elements were analysed by inductively couple plasma atomic emission spectrometry following a lithium borate fusion and dilute acid digestion while trace and REE were analysed by inductively couple plasma mass spectrometry following a multi-acid digestion method. The detail on the analytical procedures adopted has been discussed in the work of Maja *et al.*, (2011).

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

Oxide	<u>Migmatitic</u>	<u>Amphi-</u>	<u>Diorite</u>	<u>Granites</u>							<u>Aplite</u>
	<u>Gneiss</u>	<u>bolite</u>									
	A2	A3	H3	H 2	V2	P1	L1	L4	L3	L2	L9
SiO ₂	71.86	50.14	56.12	68.85	69.88	72.67	75.87	74.13	76.2	77.47	77.57
Al ₂ O ₃	14.93	19.36	14.58	14.23	13.7	12.72	11.02	12.83	11.79	11.05	11.47
Na ₂ O	4.48	2.48	2.82	3.88	3.61	3.55	2.97	3.62	3.49	3.52	3.34
CaO	2.69	2.95	6.62	2.34	2.00	1.07	0.74	1.02	0.73	0.73	0.36
K ₂ O	2.64	2.11	2.25	3.63	3.85	3.93	3.88	4.19	4.02	3.64	3.78
P ₂ O ₅	0.02	0.27	0.31	0.16	0.16	0.07	0.02	0.13	0.01	0.01	0.01
MgO	0.58	5.98	6.82	0.8	0.71	0.36	0.08	0.28	0.05	0.03	0.02
MnO	0.02	0.17	0.12	0.04	0.05	0.03	0.03	0.05	0.01	0.01	0.01
Fe ₂ O ₃	1.52	7.01	7.57	2.77	2.87	1.27	2.34	1.66	0.53	0.4	0.37
FeO	1.36	6.30	6.83	2.50	2.59	1.14	2.11	1.49	0.48	0.36	0.33
TiO ₂	0.25	0.92	1.61	0.43	0.56	0.20	0.25	0.3	0.19	0.03	0.07
Total	100.35	97.69	99.83	99.63	99.98	97.01	99.31	99.7	97.5	97.24	97.33

A2=Migmatitic gneiss

P1=Medium grained biotite granite

A3=Amphibolite

L1= Cataclasite

H3= Granodiorite

L2 and L3= Fine grained biotite granite

H2= Medium grained biotite hornblende granite

L9=Aplite V2=porphyritic biotite granite

4.5.1 Major Element Geochemistry

The major element contents are presented in Table 4.2. Silica (SiO_2) content is 50.14 wt. % in amphibolite and 71.86 wt. % in migmititic gneiss. The K_2O is 2.64 wt. % in migmititic gneiss and 2.11 wt. % in amphibolites. Na_2O is 2.48 wt. % in amphibolite and 4.48 wt. % in migmititic gneiss. The CaO content is 2.69 and 2.95 wt. %, while MgO content is 0.58 and 5.98 wt. % in the migmititic gneiss and amphibolite respectively. Expectedly, the amphibolite has significantly high iron content having FeO and Fe_2O_3 values of 6.30 and 7.01 wt. % respectively while the migmititic gneiss has FeO and Fe_2O_3 values of 1.36 and 1.52 wt. % respectively which are significantly lower than those in amphibolite. However, both rocks are characterized by low content of MnO and P_2O_5 which is 0.02 and 0.02 wt. % in migmatitic gneiss and 0.17 and 0.27 wt. % in amphibolite respectively and high Al_2O_3 content which is 13.36 and 14.93 wt. % in migmititic gneiss and amphibolite respectively.

The granite suites have silica (SiO_2) content ranging from 68.85 wt% in medium grained biotite-hornblende granite to 77.47 wt. % in fine grained biotite granite. MgO content ranges from 0.03 wt. % in fine grained biotite granite to 0.8 wt% in medium grained biotite-hornblende granite. FeO and Fe_2O_3 content range from 0.36 and 0.40 wt. % in fine grained biotite granite to 2.50 and 2.77 wt. % in medium grained biotite-hornblende granite respectively. P_2O_5 content ranges from 0.01 wt.% in in fine grained biotite granite to 0.16 wt. % in in medium grained biotite-hornblende granite while CaO content is 0.73 wt. % in fine grained biotite granite and 2.34 wt. % in medium grained biotite-hornblende granite. TiO_2 content ranges from 0.03 wt. % in fine grained biotite granites to 0.56 wt.% in porphyritic biotite granite. Al_2O_3 content ranges from 11.05 wt. % in fine grained biotite granite to 14.23 wt. % in medium grained biotite-hornblende granite. It can be observed that

SiO₂ and P₂O₅ contents increase from medium grained biotite-hornblende granite to fine-grained biotite granite while FeO, Fe₂O₃, MgO, and CaO decreases from medium grained biotite-hornblende granite to fine grained biotite granite. The cataclasite has lower Al₂O₃ content (11.02 wt. %) relative to other granites. The aplite has higher SiO₂ and Al₂O₃ content (77.57 and 11.47 wt. % respectively) than the granites. The rock also has lower FeO, Fe₂O₃ and MgO (0.33, 0.37, and 0.02 wt. % respectively) than the granites. Expectedly, the major element composition of the diorite is markedly different from those in granites. It has high CaO (6.62 wt. %) and TiO₂ (1.61 wt. %) but low SiO₂ content (56.12 wt. %). The rock has FeO content (6.83 wt. %) and Fe₂O₃ content (7.57wt. %) similar to that of the amphibolite but it has higher MgO content (6.82 wt. %) than the amphibolite.

Normative Compositions

It has been observed that the mineralogy of igneous rock is directly related to the chemical composition. This relationship is called Norm and it is the most popular classification that uses the great majority of the chemical constituents of the rock (Ekwueme, 1993). Accordingly, the commonly used Cross, Iddings, Pirsson and Washington (CIPW) Norm was calculated for the diorite and granite suites samples using geochemical toolkit of Janousek (2006) and the result are presented in (Table 4.3). The result show that normative diopside is completely absent in all the granites. The average normative corundum is less than 1% in all the granites and differentiation index (Di) ranges from 80.16 in the medium grained biotite-hornblende granite to 93.66 in fine grained biotite granite. While the diorite has 8.4% normative diopside and DI value of 44.94 which is significantly lower than that of the granites.

Table 4.3: CIWP Norm for diorite and granites from the northern part of Mandara Hills

Normative Minerals	<u>Diorite</u>	<u>Granites</u>							<u>Aplite</u>
	H3	H 2	V2	P1	L1	L4	L2	L3	L9
Q	7.76	25.88	28.54	34.14	41.37	34.35	41.33	40.37	42.77
C	0.00	0.048	0.33	0.97	0.63	0.78	0.02	1.61	1.23
Or	13.32	21.45	22.75	23.23	22.93	24.76	21.51	23.76	22.34
Ab	23.86	32.83	30.55	30.04	25.13	30.63	29.79	29.53	28.26
An	20.48	10.56	8.91	4.52	3.56	4.24	3.59	0.00	1.77
Di	8.24	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Hy	17.65	3.65	3.32	1.66	1.79	1.66	0.38	0.28	0.28
Mt	10.97	4.02	4.16	1.84	3.39	2.41	0.58	0.77	0.54
Il	2.21	0.82	1.07	0.38	0.47	0.57	0.05	0.36	0.13
Ap	0.73	0.37	0.37	0.17	0.04	0.21	0.01	0.03	0.01
Fr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.99	0.00
Pr	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Sum	105.21	99.64	99.99	96.96	99.31	99.71	97.24	97.78	97.34
DI	44.94	80.16	81.84	87.41	89.43	89.74	92.62	93.66	93.37

The major element composition of the diorite, aplite and the granites plotted on Harker diagram using SiO₂ as an index of differentiation (Figures 4.6 and 4.7) show that TiO₂, Al₂O₃, FeOt, MgO, CaO and P₂O₅ are all negatively correlated with SiO₂, generally forming a well-defined linear trends. Such linear trends might be the result of either hybridization or fractionation (Hassanen *et al.*, 1996). Potassium (K₂O) show somewhat opposite behavior, it increases with increase in SiO₂ but at SiO₂ value of about 75wt% it begins to decrease while Na₂O shows scatter trend.

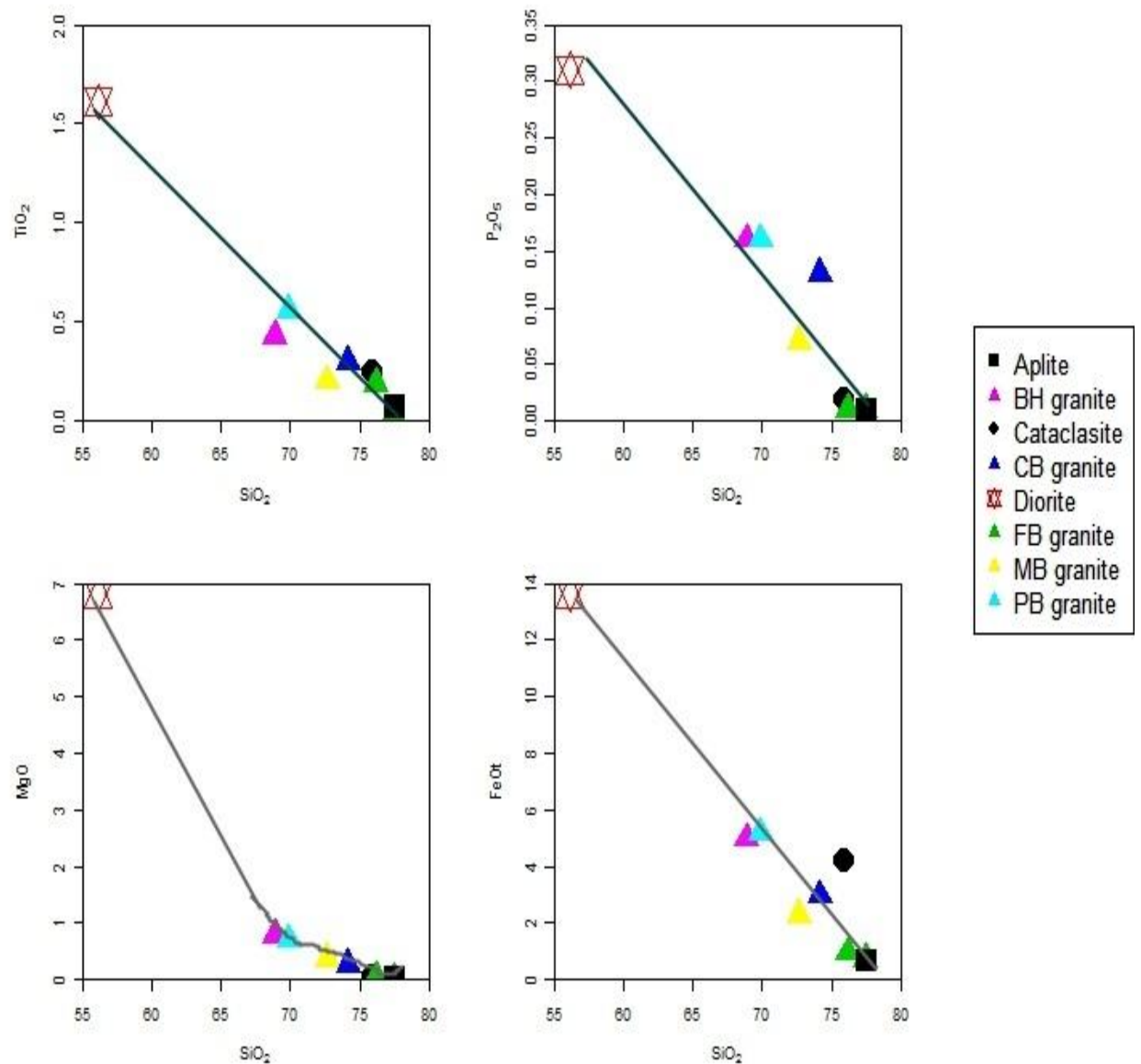


Fig 4.6: Harker plot of TiO_2 , P_2O_5 , MgO and FeOt against Silica (SiO_2) for granites suites and aplite in the study area.

Legend:

BH granite= Medium grained biotite hornblende granite

CB granite=Coarse grained biotite granite

FB granite=Fine grained biotite granite

MB granite=Medium grained biotite granite

PB granite=porphyritic biotite granite

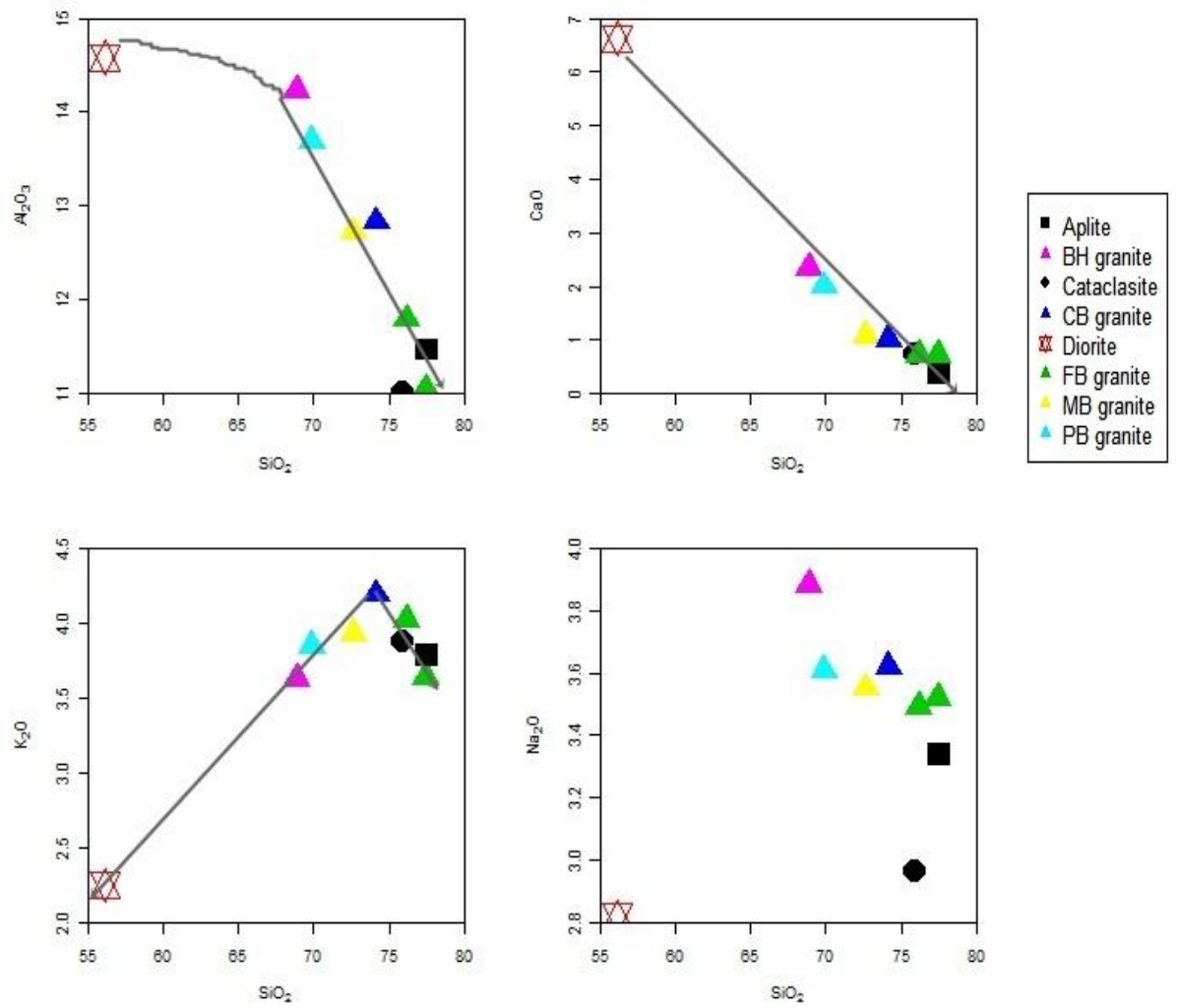


Fig 4.7: Harker plot of Al_2O_3 , CaO , K_2O and Na_2O against silica (SiO_2) for the granite suites and aplite in the study area.

In the normative An-Ab-Or diagram (Fig 4.8) all the granites and the aplite plot within the granite field, the amphibolite and the diorite plot within the granodiorite field while the migmitic gneiss straddle the granodiorite and granite field.

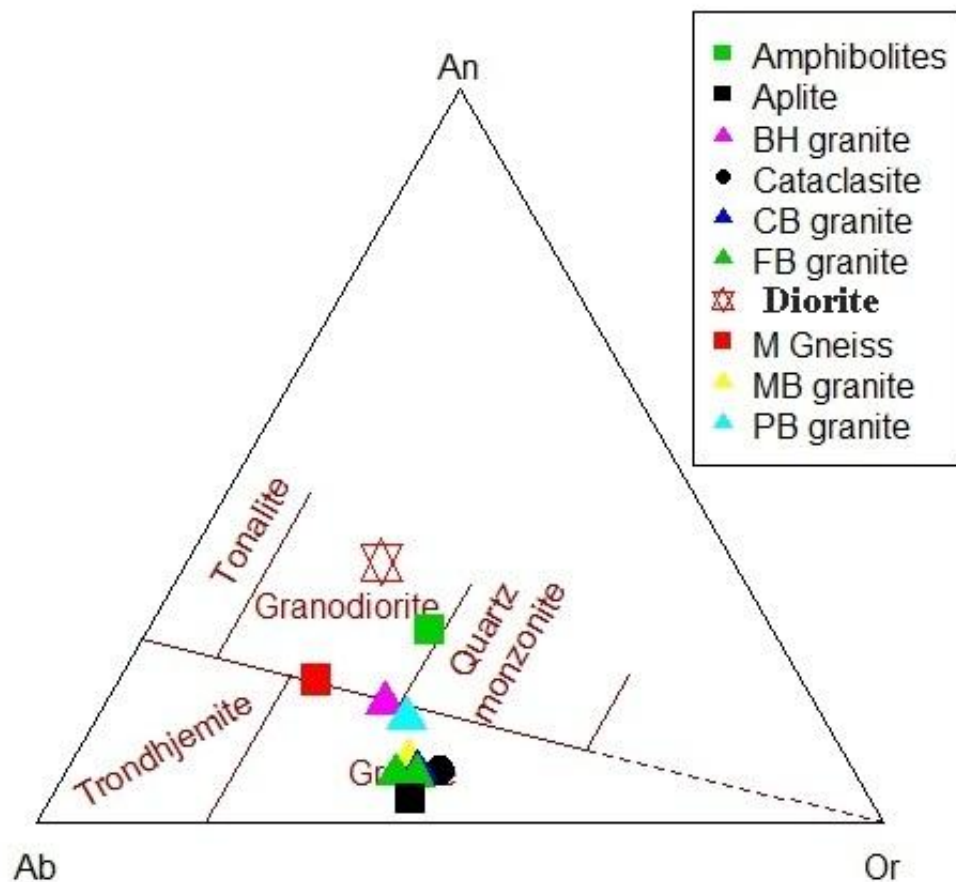


Fig 4.8: Normative An-Ab-Or diagram showing the distribution of the rocks in granitic to granodioritic field (after O'Connor, 1965).

The granites and aplite are metaluminous to weakly peraluminous with aluminium saturated index (ASI) ranging from 0.99 to 1.12 and modified alkali-lime index ranging from 5.17 to 6.79 (Fig 4.9, Table 4.4). The diorite has ASI value of 0.77, MALI value of -1.54 and plot in a metaluminous field, while the amphibolite and the migmatitic gneiss plot in the peraluminous and metaluminous field respectively.

Table 4.4: Calculated values of iron number, modified alkali-lime index and aluminium saturation index of rocks from the northern part of Mandara Hills, northeastern Nigeria

Samples	Iron number (Fe#)	Modified alkali-lime index	Aluminium saturation index
		(MALI)	(ASI)
L1	0.98	6.11	1.06
L2	0.96	6.43	0.99
L3	0.95	6.78	1.03
L4	0.91	6.79	1.05
V2	0.87	5.45	1.01
H 2	0.86	5.17	0.99
H3	0.67	-1.54	0.77
P1	0.86	6.47	1.07
A2	0.82	4.43	0.99
A3	0.81	2.32	1.06
L9	0.97	6.76	1.12

Legend

A2=Migmatitic gneiss

P1=Medium grained biotite granite

A3=Amphibolite

L1= Cataclasite

H3= Diorite

L2 and L3= Fine grained biotite granite

H2= Medium grained biotite hornblende granite

L9=Aplite

V2=porphyritic biotite granite

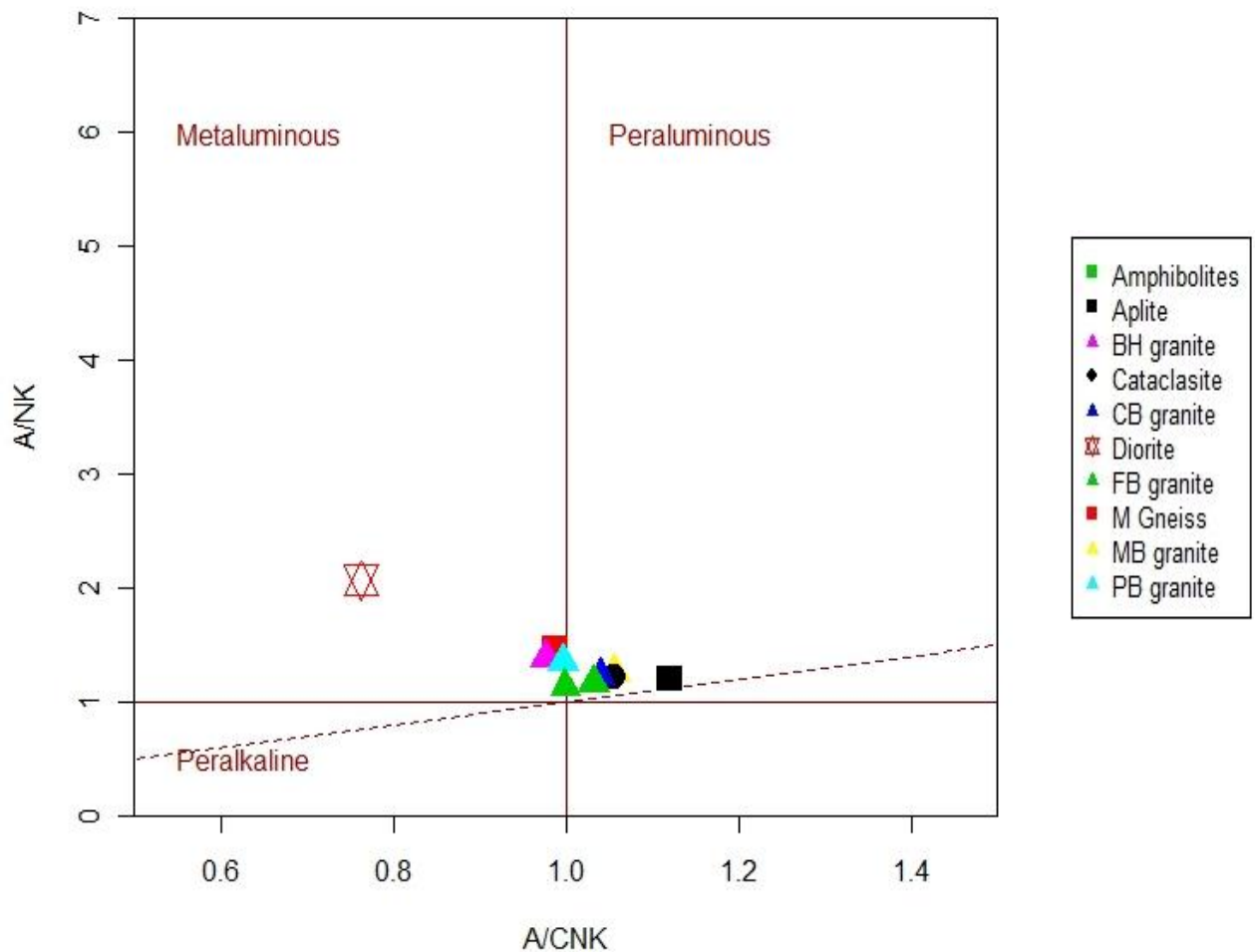


Fig.4.9: A/NK versus A/CNK plots showing the distribution of the rocks from metaluminous to weakly peraluminous field (after Shand, 1943).

AFM plots of the all the rocks (Fig. 4.10) enable classification of the rocks into calc-alkaline and tholeiite series based on the proportion of their CaO, K₂O, FeO*, and MgO content. The migmititic gneiss, the aplite, and all the granites plot in the field of calc-alkaline series owing to the fact that these rocks have high percentage of CaO and K₂O relative to FeO*, and MgO. The amphibolite and the diorite on the other hand, plot within

the field of tholeiite series because these rocks have high percentage of FeO^* , and MgO relative to CaO and K_2O .

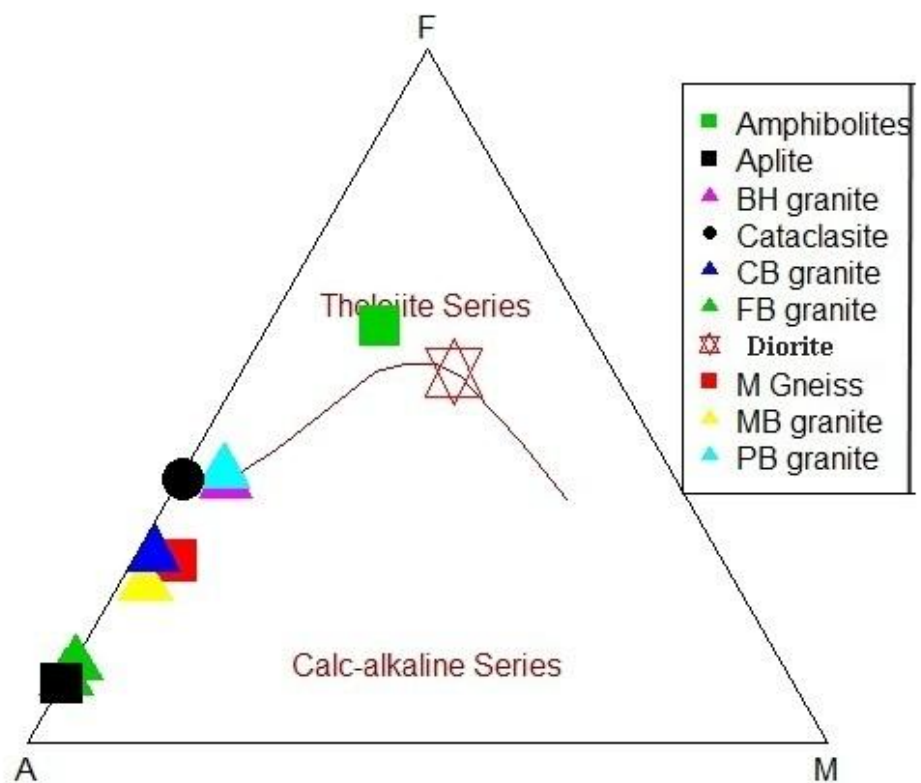


Fig 4.10: AFM plots showing the distribution of the rocks within the fields of tholeiite and calc-alkaline series after Irvine and Baragar (1971),

On the (K_2O versus SiO_2) diagram, only migmatitic gneiss plot within the field of calc-alkaline series. The amphibolite, diorite, aplite, and all the granites on the other hand, plot within the field of high-K-calc-alkaline series (Fig: 4.11).

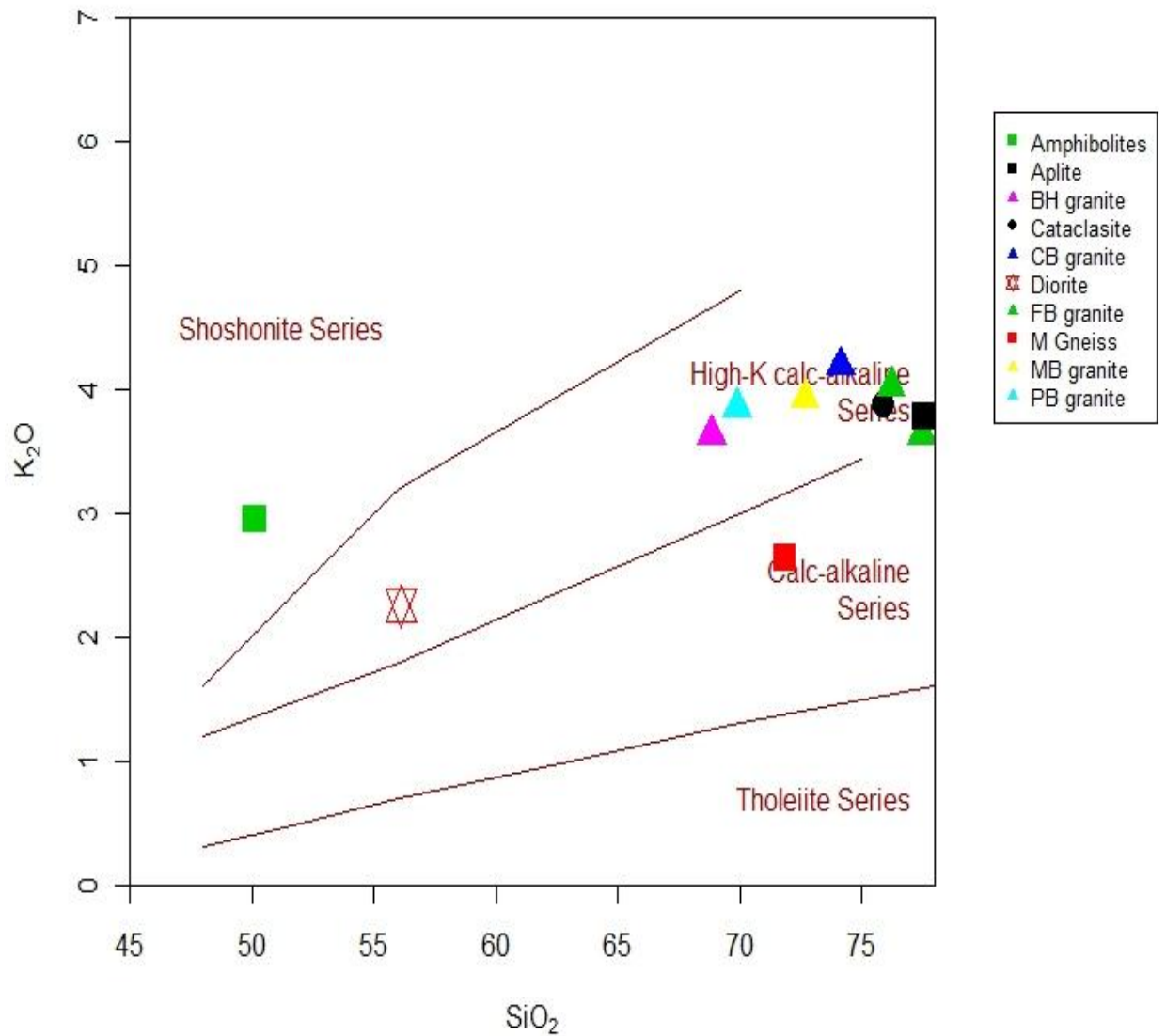


Fig 4.11: k_2O versus SiO_2 diagram showing the distribution of the rock within the fields of High-K-calc-alkaline and calc-alkaline series after Peccerillo and Taylor (1976).

There have been some controversies as to whether the granites in the study area belong to S-type or I-type granite (Islam and Baba 1992; Baba *et al*, 2006). The reason for these controversies is not far-fetched as the CIWP norm result (Table 4.3) has shown that normative diopside is absent in all the granitites thus suggesting that the granites are S-type

(they form from sedimentary progenitors). However, the average normative corundum is less than 1%. According to Chappel and White (1974, this feature is a hallmark of I-type (igneous progenitor) granites. Furthermore, when the granites were plotted on the A/CNK versus SiO₂ discrimination diagram after (after Chappel and White, 1974), Fig 4.12a), all the rocks plotted within the field of I-type granites. Moreover, the migmititic gneiss and the amphibolite also have igneous progenitors as shown on the TiO₂ versus SiO₂ discrimination diagram (after Tarney, (1976) (Fig 4.12b).

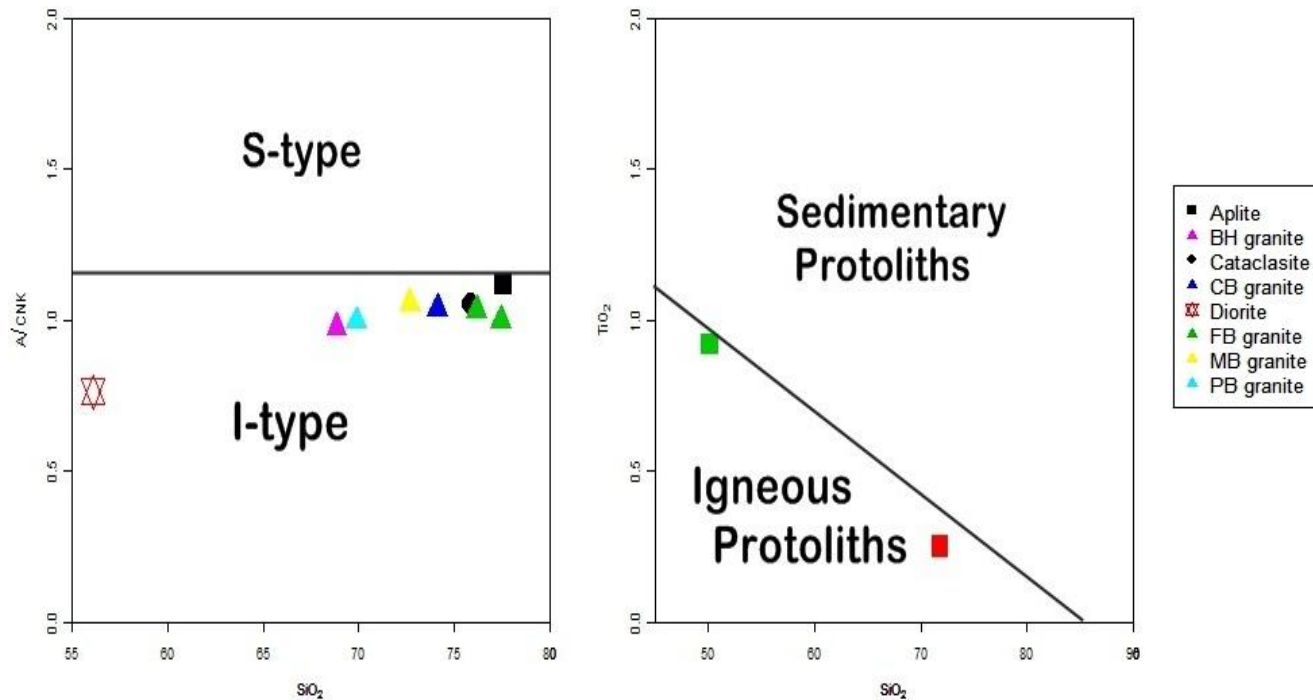


Fig 4.12: a= A/CNK versus SiO₂ discrimination diagram (after Chappel and White, 1974), b= T TiO₂ versus SiO₂ discrimination diagram after (Tarney, 1976) for the granite suites and aplite in the study area.

Fe-number ($\text{FeO}_{\text{tot}} / (\text{FeO}_{\text{tot}} + \text{MgO} = \text{Fe}^*)$) distinguishes ferroan granites, which manifest strong iron enrichment, from magnesian granites which do not (Frost *et al.*, 2001).

Plot of the granites and granodiorite on $\text{FeO}_{\text{tot}}/(\text{FeO}_{\text{tot}}+\text{MgO})$ versus SiO_2 discrimination diagram after Frost *et al.*, (2001) Fig 4.13 a, shows that the granites which have higher values of Fe-number (0.86-0.980, Table 4.4) plot within the ferroans field. The diorite on the other hand has low Fe-number (0.67) hence it plots in magnesian field. The diorite and granites can further be classified into alkali, alkali-calcic, calc-alkalic and calcic on the basis of their modified alkali-lime index (MALI) content (Frost *et al.*, 2001). Plot of the granites and diorite on $\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO}$ versus SiO_2 discrimination diagram reveals that both rocks are calc-alkalic to calcic (Fig 4.13b).

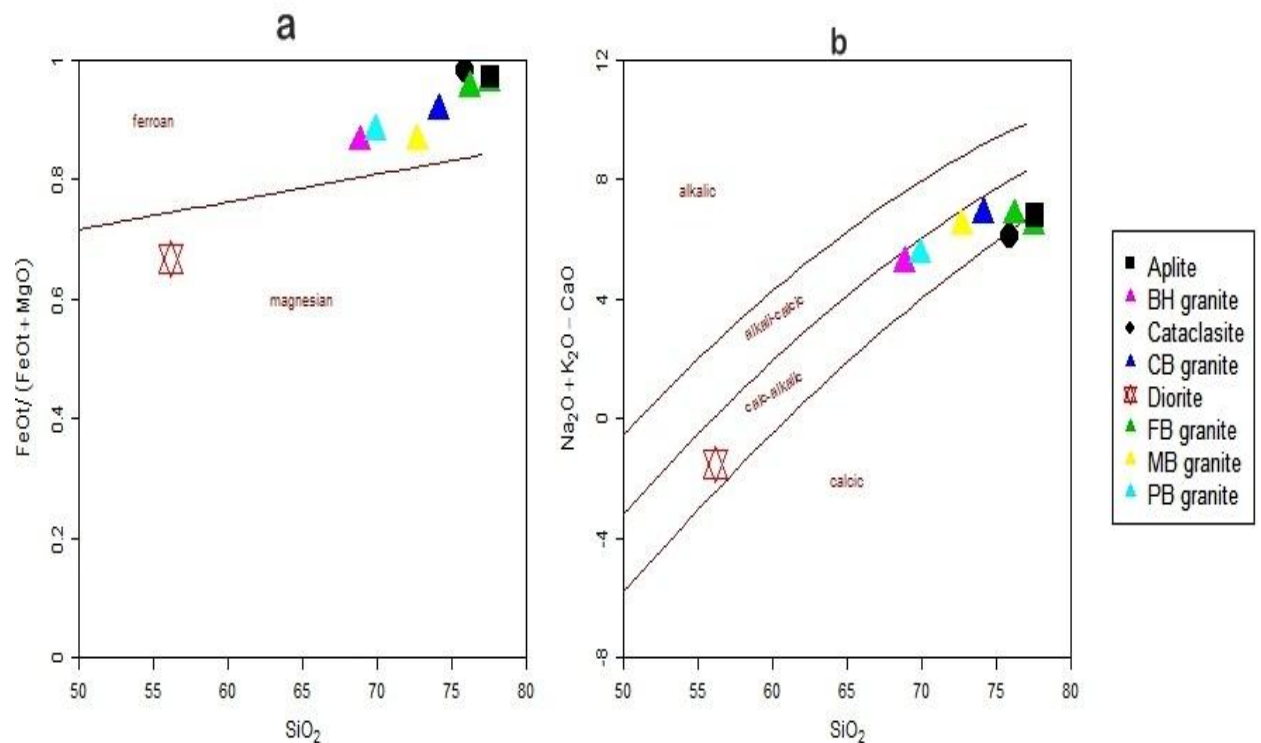


Fig 4.13: a= $\text{FeO}_{\text{tot}}/(\text{FeO}_{\text{tot}}+\text{MgO})$ Vs SiO_2 discrimination diagram after Frost *et al.*,(2001), b= $\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO}$ versus SiO_2 discrimination diagram after Frost *et al.*,(2001) for the granite suites and aplite in the study area. Symbols same as in Figure 4.11

4.5.2 Trace Element Geochemistry

Trace elements play significant roles in revealing the petrogenetic and evolutionary history of rocks. It has been observed that major element composition in rocks tend towards uniformity and it is only their trace element compositions and ratios that provide clues to their unique differences and petrogenesis (Butler *et al.*, 1962, Baba 1990). The trace elements composition and ratios are presented in Table 4.5. Spider diagrams for all the rocks samples normalized to average crust after Weaver and Tarney, (1984) are shown in Fig. 4.14. The normalized abundance patterns permit characterization of the rocks. The migmatitic gneiss, amphibolite and the diorite show similar pattern, they are all characterized by negative anomalies of some high field strength elements (HFSE), namely; Nb, Th, Hf, Zr; and positive anomalies of some heavy rare earth elements (HREE) namely; Tb, Yb, and Y. The diorite is characterized by negative anomaly of some large ion lithophile elements (LILE) namely Sr and Ba, while the migmatitic gneiss show positive anomaly of Ba and negative anomaly of Sr, the granites and aplite on the other hand are characterized by negative anomaly of some LILE (Ba and Sr) and some HFSE (Zr and Nb). Unlike the amphibolite and diorite, these rocks show positive Hf anomaly. The negative Nb anomaly reinforces the calc-alkaline character suggested by the major element data. Furthermore, the granites and aplite show positive anomaly of U and La. The positive U anomaly is more pronounced in the fine grained biotite granite owing to its high uranium content. The ratio Th/U is 5.12 in fine grained biotite granite and 9.56 in porphyritic biotite granite. The migmatitic gneiss has comparatively higher Th/U value (33.00), while the diorite, amphibolite and the aplite have Th/U values of 7.30, 9.71 and 11.14 respectively.

Table 4.5 : Trace elements composition of the rocks in the study area (all values except ratios are in ppm)

Elements	Migmatitic Gneiss	Amphibolite	Diorite	Granites							Aplite
PPM	A2	A3	H3	H2	V2	P1	L1	L4	L3	L2	L9
Rb	52.40	93.40	79.70	126.70	144.10	145.00	174.00	186.10	308.20	261.10	163.10
Sr	836.00	284.00	65.00	364.00	334.00	224.00	76.00	212.00	65.00	57.00	14.00
Ba	1820.00	763.00	618.00	1464.00	1001.00	668.00	525.00	439.00	50.00	32.00	21.00
U	0.40	0.70	1.00	2.80	2.50	1.70	4.20	4.40	54.60	6.00	2.80
Th	13.20	6.80	7.30	19.00	23.90	15.00	30.10	35.10	342.60	30.70	31.20
Ta	0.60	1.10	0.80	1.00	2.50	0.60	3.50	1.80	3.20	0.70	0.50
Nb	2.94	12.72	0.63	8.81	21.56	5.73	45.29	16.27	33.65	2.41	3.21
Cs	1.40	1.40	2.10	2.60	2.63	2.40	3.90	4.10	4.40	4.13	5.10
Ga	17.15	18.24	18.38	21.09	23.61	21.39	21.96	19.09	19.25	17.46	19.88
Hf	0.10	0.80	1.04	5.54	2.51	2.54	7.33	2.47	17.45	0.82	1.56
Zr	4.40	26.50	31.20	195.70	81.20	81.00	220.70	62.50	592.3	25.10	41.70
Sn	0.90	2.50	2.00	1.60	3.30	0.60	6.30	2.60	1.30	0.30	0.50
Be	2.00	2.00	2.00	1.00	2.00	5.00	3.00	4.00	7.00	6.00	2.00
Ni	3.50	76.60	153.80	0.90	3.20	1.00	0.40	0.50	0.10	0.10	0.40
Cr	5.00	95.00	442.00	11.00	9.00	3.00	3.00	6.00	3.00	1.00	3.00
Pb	23.79	8.36	8.04	20.31	25.18	25.87	37.21	27.06	41.05	26.84	25.74
Zn	25.30	99.20	75.80	60.50	67.90	38.60	73.50	35.10	8.60	7.60	12.30
Co	57.10	71.00	59.90	66.00	59.70	58.20	73.90	56.40	47.20	64.10	60.70
V	17.00	26.00	173.00	38.00	39.00	15.00	1.00	17.00	7.00	7.00	1.00
				Ratios							
K/Rb	417.94	262.31	234.63	237.57	222.07	224.83	185.06	186.91	108.37	115.66	192.52
K/Ba	31.97	31.97	31.97	31.97	31.97	48.80	61.33	79.27	668.00	943.75	1495.24
Rb/Sr	0.06	0.33	0.17	0.35	0.43	0.65	2.29	0.88	4.74	4.58	11.65
Rb/Ba	0.03	0.12	0.13	0.09	0.14	0.22	0.33	0.42	6.16	8.16	7.77
Ba/Rb	34.73	8.17	7.75	11.55	6.95	4.61	3.02	2.36	0.16	0.12	0.13
Th/U	33.00	9.71	7.30	6.79	9.56	8.82	7.17	7.98	6.27	5.12	11.14

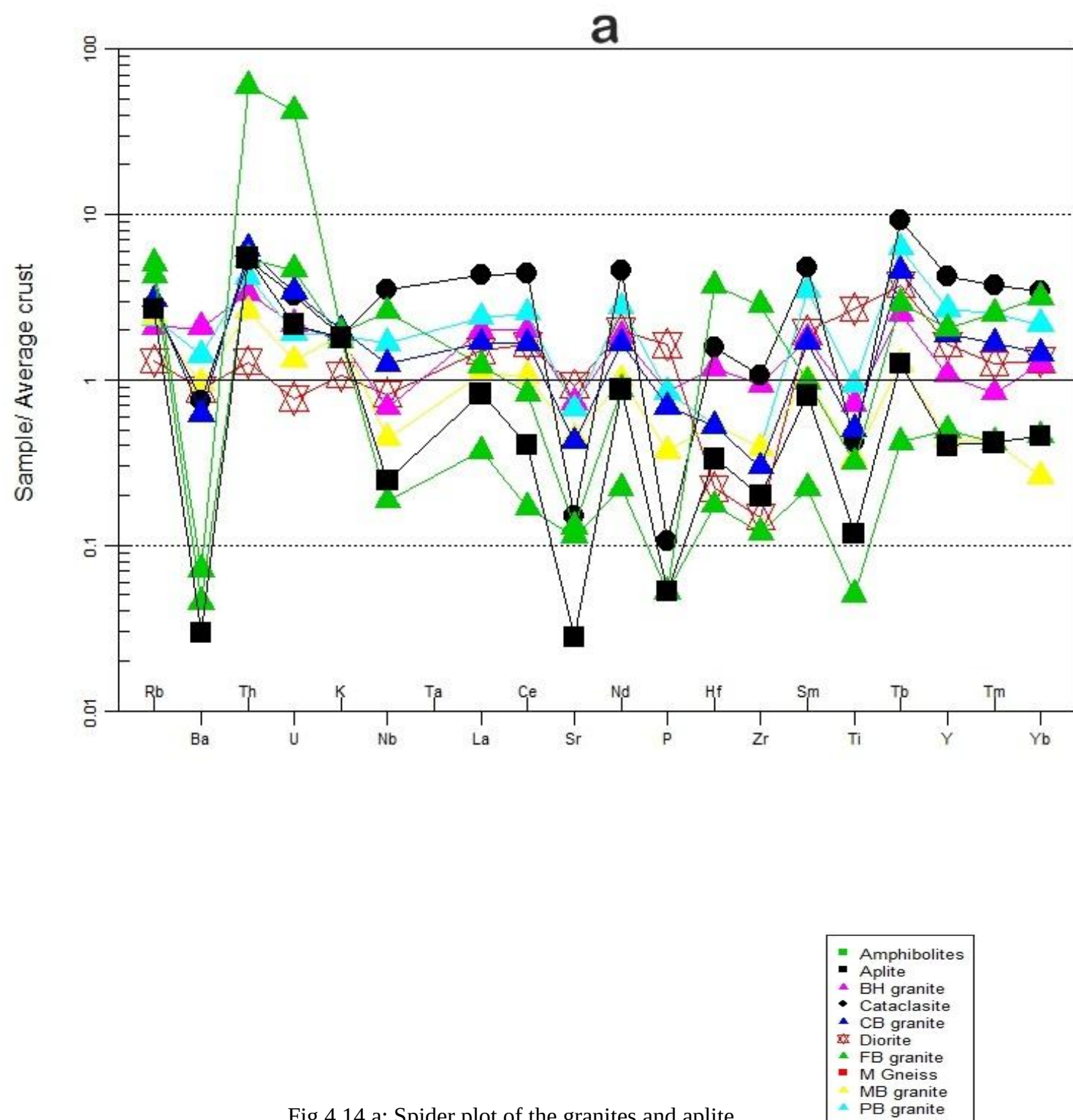


Fig 4.14 a: Spider plot of the granites and aplite

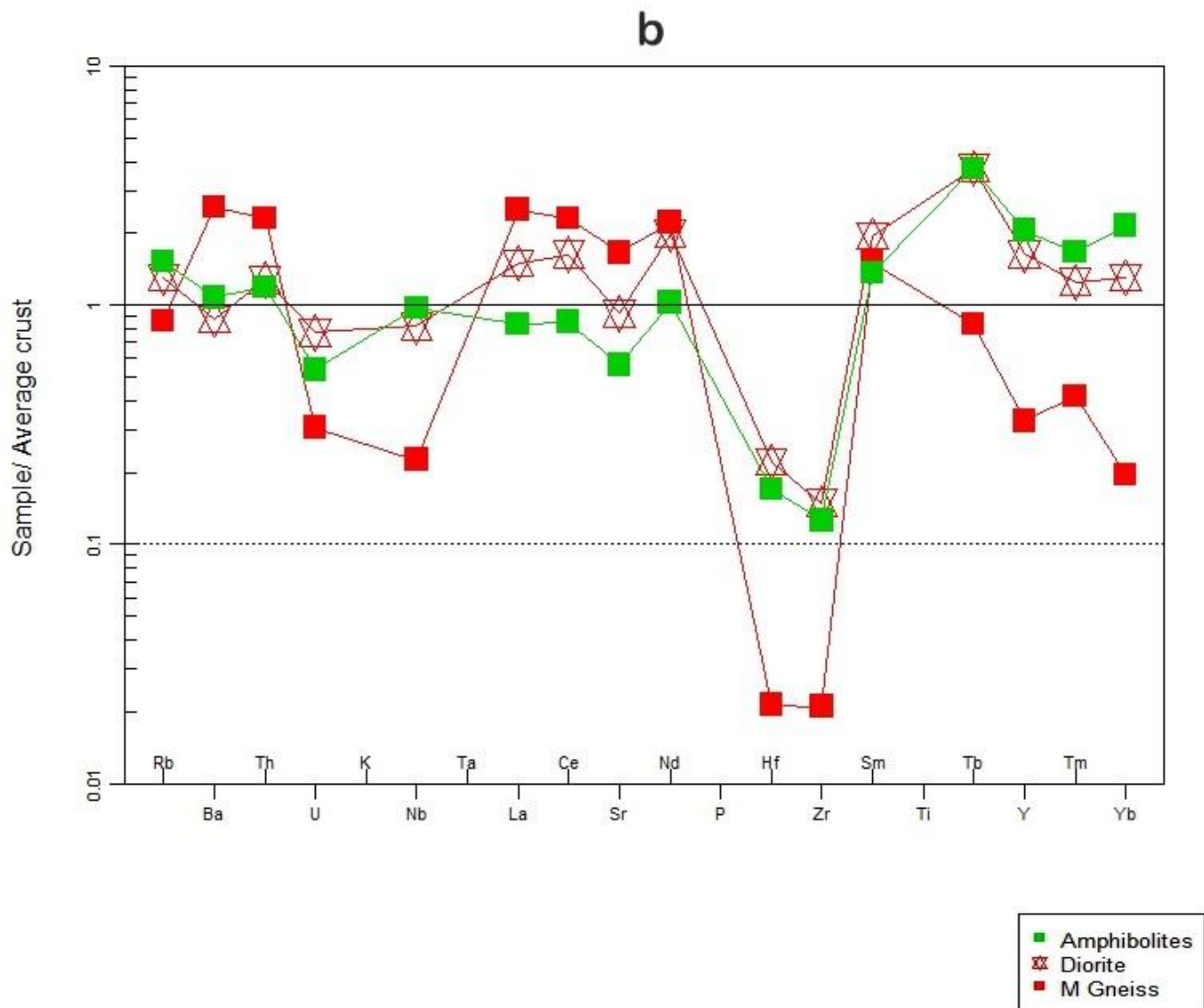


Fig 4.14b: Spider plot of migmatitic gneiss, amphibolite and diorite all normalized to average crust after (Weaver and Tarney 1984).

Concentrations of selected trace element plotted on Harker diagram using SiO_2 as an index of differentiation (Figures 4.15 and 4.16) reveal that Sr, Ba, V, Zn and Co decrease with increase in SiO_2 just like TiO_2 , Al_2O_3 , FeO , MgO , CaO and P_2O_5 . Such trace element are said to be compatible (Zorano *et al.*, 2007). Rb on the other hand shows converse behavior (it correlates positively with SiO_2) and therefore incompatible. Cr and Ni show well-defined linear trend with increase in SiO_2 except for the fact that the diorite has anomalous concentrations of such trace element and plots at the top left hand side of the diagrams.

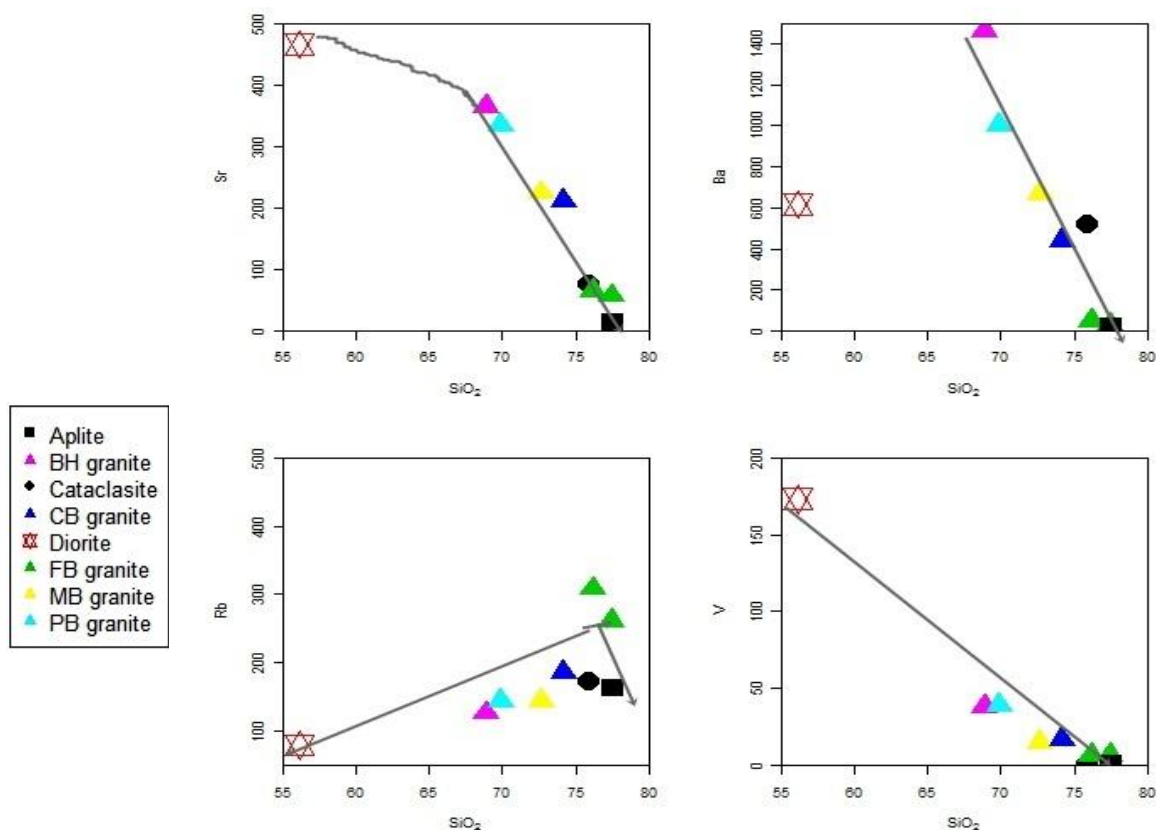


Fig 4.15: Harker plot Sr, Ba, Rb and V against silica (SiO_2) for the granite suites and aplite in the study area.

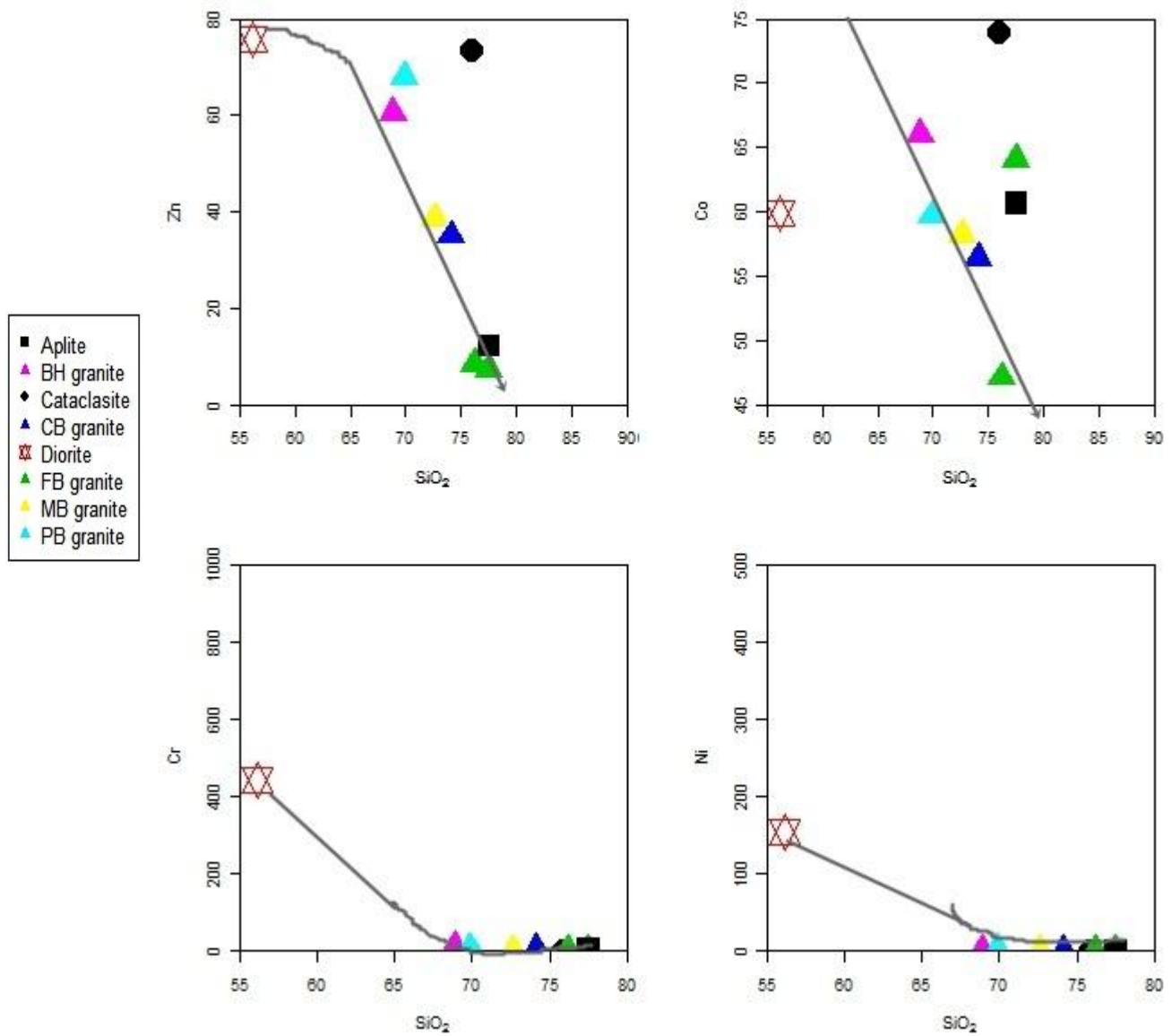


Fig. 4.16: Harker plot of Zn, Co, Cr and Ni against SiO_2 for the granite suites and aplite in the study area. Symbol same as in Figure 4.15

Lithophile Elements Behaviours (Ba, Sr and Rb)

The variation in Ba, Sr and Rb content is very useful in determining whether magmatic evolution was controlled dominantly by fractional crystallization, partial melting or more complex processes (Dall Agnol *et al* 1999). Rb is fairly enriched in all the granites (126.2-308.2 ppm) and slightly depleted in diorite (79.70 ppm) and migmatitic gneiss (52.40 ppm) compared to the mean crustal average of 90 ppm. Ba and Sr, which are strongly compatible in granitic systems, show large variation (32.00 to 1464 ppm and 65 to 364 ppm, respectively), in the granites. Sr decreases readily during the course of fractional crystallization since it replaces Ca in plagioclase as well as K in K-feldspars. Ba also replaces K in k-feldspars and hence it decreases during the course of fractional crystallization (El Bouseily and El Sokkary 1975). Large variation of these lithophile elements in the granites suggests that fractional crystallization was probably responsible for their evolution.

On Rb-Ba-Sr ternary diagram (Fig.4.17), the diorite plots in quartz diorite field; the porphyritic granite, medium grained biotite granite and coarse grained biotite granite plot in anomalous granite field; the medium grained biotite-hornblende granite and the cataclasite plot in normal granite field while fine grained biotite granite as well as the aplite plot in strongly differentiated granites field. Strongly differentiated granites are those that are distinctly impoverished in Ba but enriched in Rb. They represent a very late stage of differentiation. “Anomalous granites” are those that have undergone chemical changes (e.g metasomatism) or were not formed by simple mechanism, while “normal granites” are those that are characterize by “normal” distribution of the three index lithophile elements (El Bouseily and El Sokkary 1975).

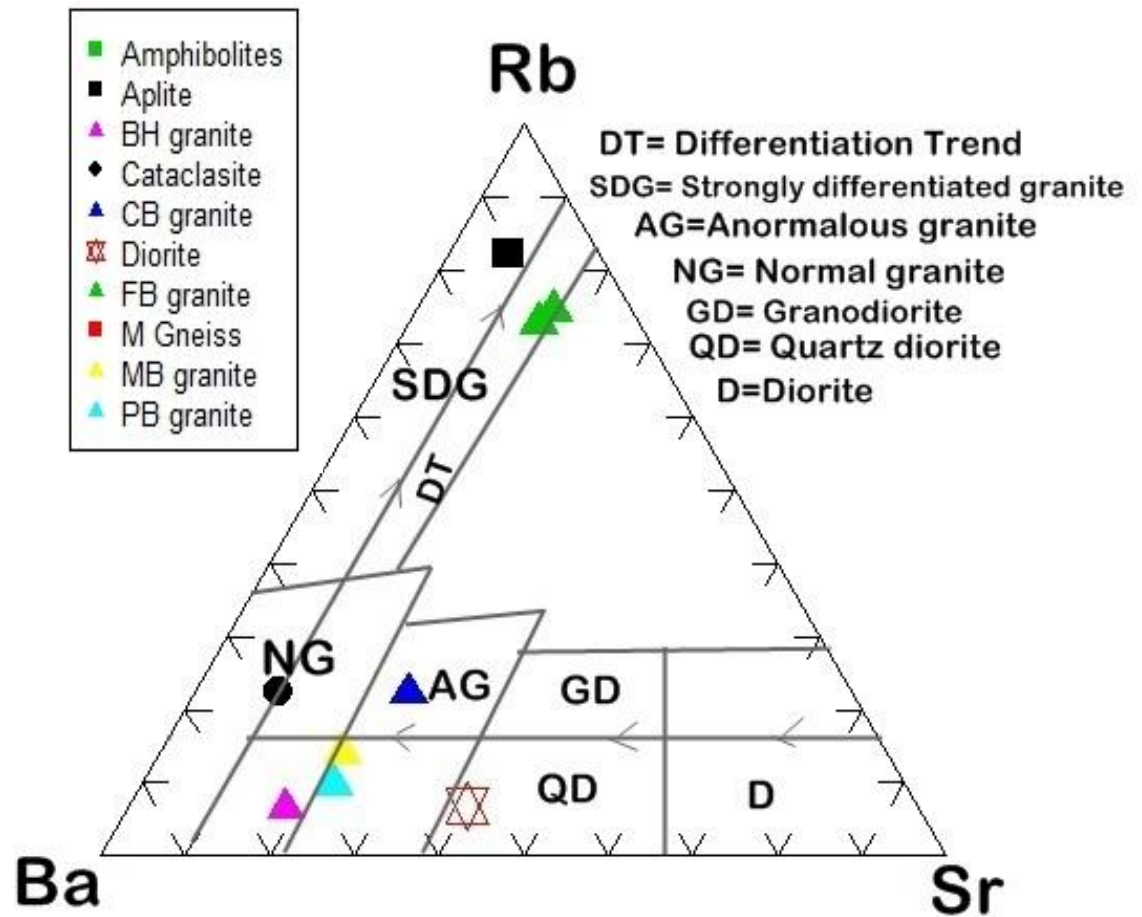


Fig 4.17: Rb-Ba-Sr ternary diagram showing the distribution of the granites and the granodiorite in the study area (after El Bouseily and El Sokkary, 1975).

Tectonic Discrimination

On tectonic discrimination diagram (after Batchelor and Bowden 1985), Fig 4.18), the diorite plot within pre-plate collision field. The granites on the other hand plot within both syn-collision and post-orogenic fields. The less fractionated granites plot within syn-collision and the highly fractionated granitoid plot within the post-orogenic field.

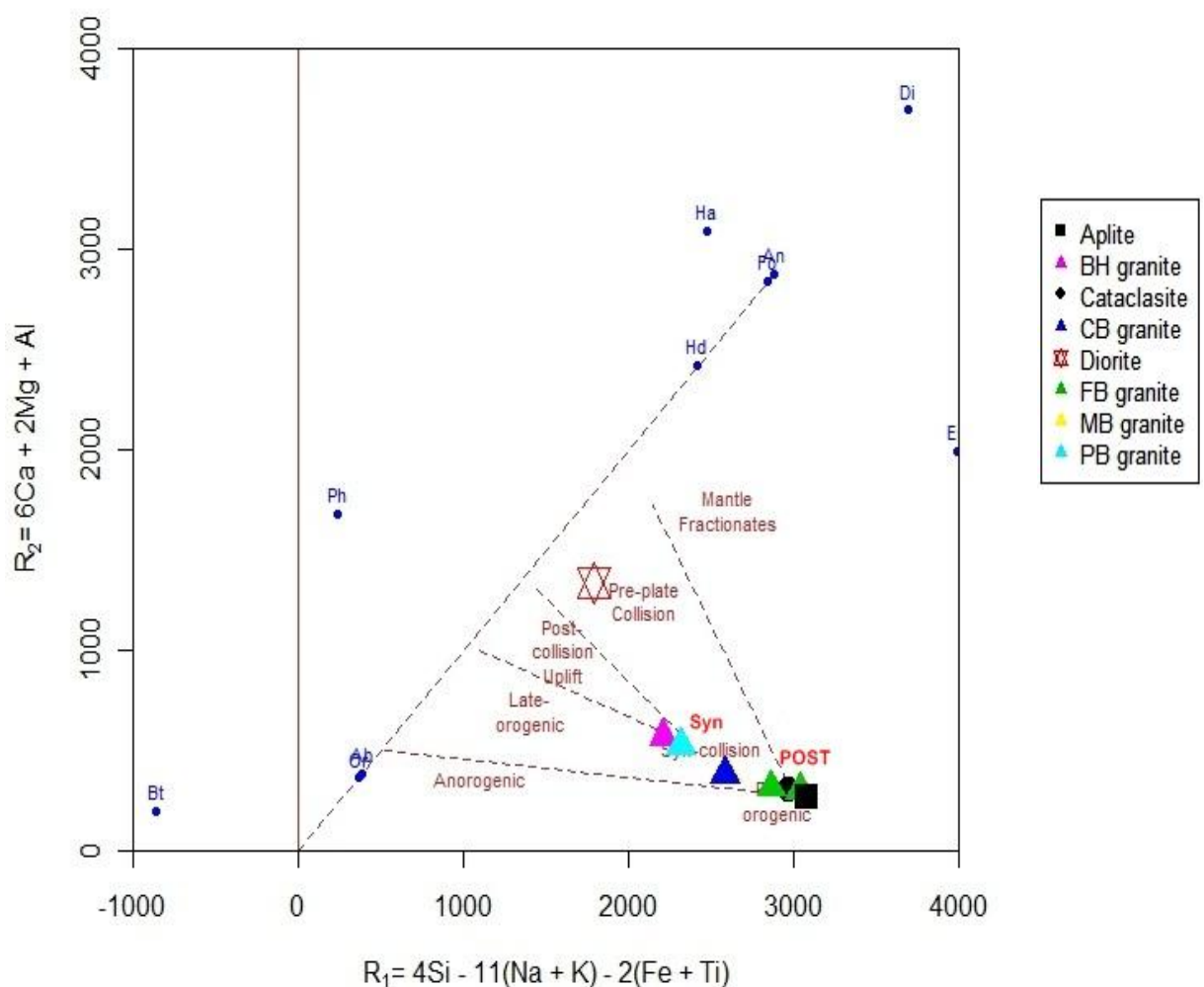


Fig 4.18: Tectonic discrimination diagram (after Batchelor and Bowden, 1985), showing the distribution of the granite suites and aplite within pre-plate collision, syn-collision and post-orogenic fields.

Trace elements can also indicate tectonic affinities of granitic rocks. On the granites discrimination diagram after Pearce *et al.*, (1984), the granites, diorite and aplite all plotted within post-collision granites field (Fig 4.19).

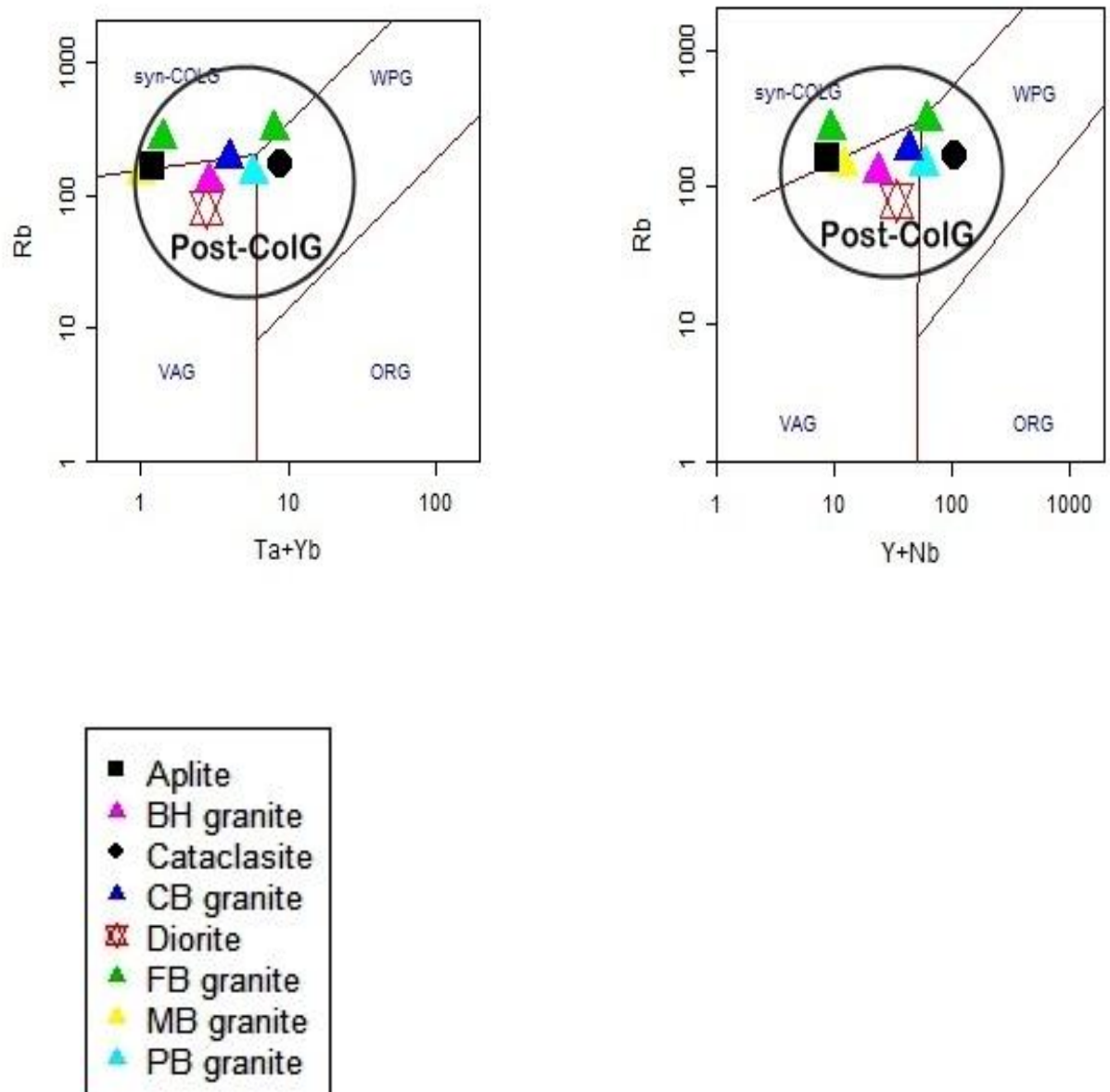


Fig (4.19): Granite tectonic discrimination diagram (after Pearce *et al.*, 1984) showing the distribution of the granites within the field of post-collision granites.

Geochemical Trend

Figures (4.7) and (4.15), show that K_2O and Rb show changes of distribution trends on K_2O versus SiO_2 and Rb versus SiO_2 plots respectively, where positive correlation for $SiO_2 < \sim 75\%$ turns into negative correlation for $SiO_2 > \sim 75\%$. Such changes of distribution trends are not consistent with mixing processes (Zorano *et al.*, 2007); hence the distribution trends as revealed in the Harker diagrams cannot result from mixing between two magmas or from assimilation of older rocks by the magma, but are produced by magmatic differentiation that is partial melting or fractional crystallization; (Wilson, 1989; Zorano *et al.*, 2007). On the other hand, sharp decrease in Sr and Ba with decrease in SiO_2 (Fig 4.14) indicate an important role of fractionation dominated by biotite and feldspars (Janousek *et al.*, 2002). According to Zorano *et al.*, (2007), fractional crystallization, in contrast to partial melting, is a very powerful process to impoverish magmatic liquid in compatible elements; the discrimination between the two mechanisms will be based on the behaviour of these elements. Indeed, in a log of compatible element (Sr, Ba, Zn and V) versus log of incompatible element (Rb) plot, differentiated liquids produced by partial melting will show a sub- horizontal trend whereas fractional crystallization will give rise to a sub-vertical trend (Cocherie, 1986; Martin, 1987, 1994; Zorano *et al.*, 2007). It can be observed from the log of compatible element (Sr, V, Ba and Zn) versus log of incompatible element (Rb) (Fig.4.19) that the elements distribution trends of diorite and granites are vertical without any affinity to the sub-horizontal trend of partial melting. Consequently, it can be proposed that the main mechanism of differentiation is fractional crystallization (Zorano *et al.*, 2007).

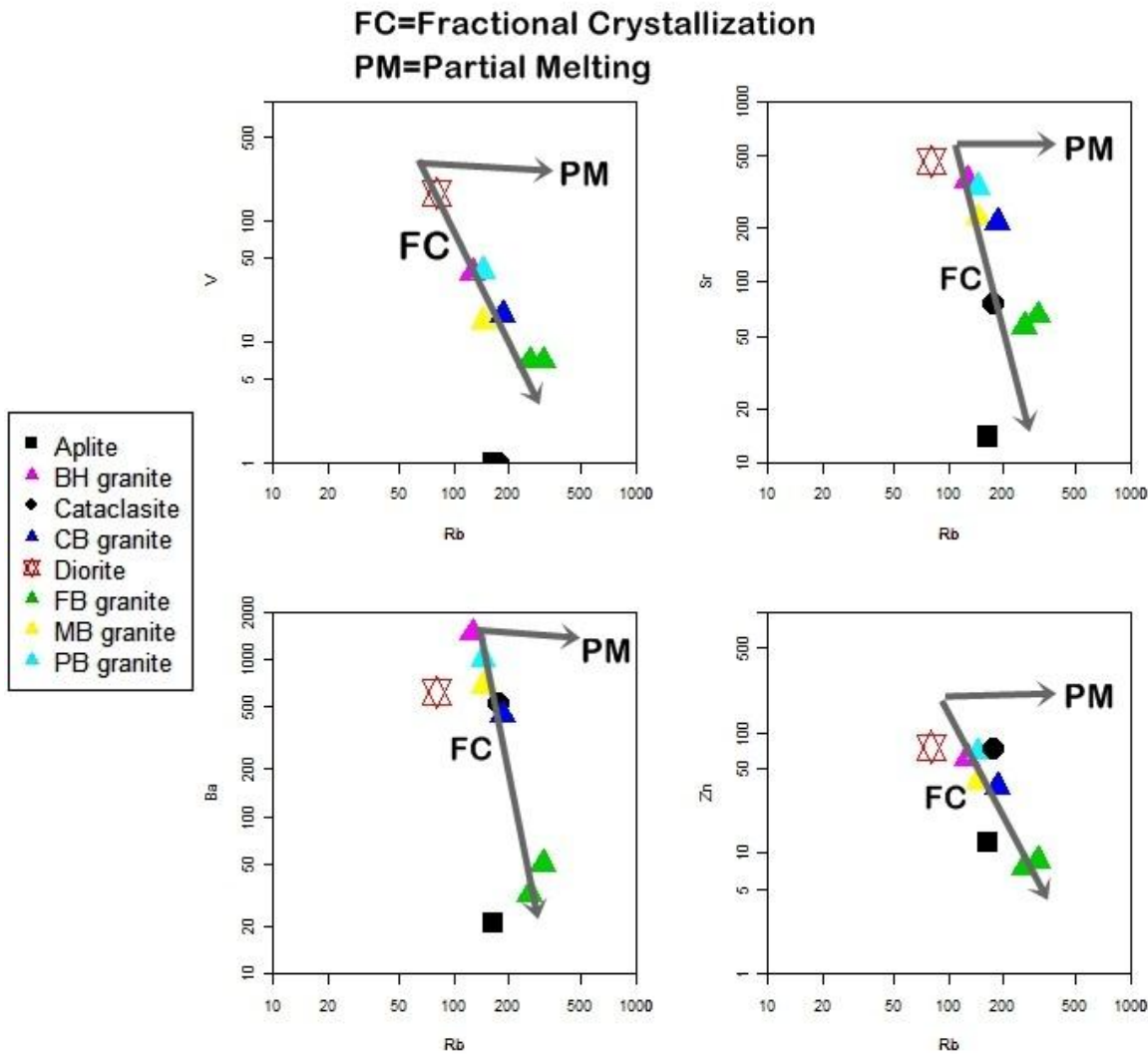


Fig. (4.20): Plot of compatible element (Sr, V, Ba and Zn) Vs incompatible element (Rb) adapted after Zorano et al., (2007) for the granites suites and aplites in the study area.

4.5.3 Rare Earth Elements Distribution Pattern

The rare earth elements (REE) data is presented in Table 4.6, and the REE spider diagram is presented in Fig 4.21 and 4.22. The migmatitic gneiss has sum of REE (Σ REE) values of 280.48 and has distribution pattern similar to that of the migmatised banded gneisses in Kabala, northcentral Nigeria (Dada, 1999 Fig 4.22 b). The granites have similar distribution patterns. The porphyric granite and cataclasite are enriched in REE with sum of REE (Σ REE) values of 336.90 and 569.36 ppm respectively. However, the other granites

are somewhat depleted in REE compared to the average of REE in granite which is 250 ppm as reported by Emmermann *et al.*, (1975). The sum of REE (Σ REE) values range from 30.92 ppm in fine grained biotite granites to 245.55 ppm in medium grained biotite-hornblende granite. The principal carriers of REEs in most granite are the accessory minerals such as monazite, zircon, apatite, xenotime and titanite (Gromet and Silver, 1983; Saleh *et al.*, 2002; Moghazi *et al.*, 2004). Therefore, fractionation of such accessory minerals would result in a lowering of REEs content in the granites (Saleh and El-Nisr, 2013). Furthermore, with the exception of the fine grained biotite granite which show weak fraction of LREE relative to HREE (LaN/YbN value of 4.72), all the granites show high degree of fractionation of the LREE relative to HREE (LaN/YbN values ranging from 9.81 in fine grained biotite granite to 51.00 in cataclasite). The granites also exhibit prominent negative Eu anomalies with Eu/ Eu* value of 0.21 in cataclasite and 1.38 in the fine grained biotite granite. The catclasite has lowest Eu/ Eu* value as a result of its higher absolute REE concentrations (REE=569.36) while the fine grained biotite granite has the highest Eu/ Eu* value as a result of its lower absolute concentration of REE (REE=30.92). Both diorite and amphibolite show similar REE distribution pattern to that of the granites. The Eu/ Eu* values in these rocks are 0.71 and 0.77 respectively. Negative Ce-anomaly which is expressed as $Ce_N/Ce^*_N = (Ce_N/[La_N * Pr_N]^{0.5})$; is more prominent in aplite and fine grained biotite granite (Fig 4.21, Table 4.6). The fine grained biotite granite which host the type-1 pegmatite has average Ce_N/Ce^*_N values of 0.63 while the aplite has Ce_N/Ce^*_N value of 0.43.

Table 4.6: Rare earth elements composition of the rocks in the study area (all values except ratios are in ppm).

Elements	Migmatitic Gneiss	Amphibolite	Diorite	Granites							Aplite
	A2	A3	H3	H2	V2	P1	L1	L4	L3	L2	L9
La	70.40	23.30	42.00	56.30	66.50	30.60	120.20	47.00	34.00	10.30	23.00
Ce	132.38	48.69	93.19	113.45	144.50	60.52	250.06	94.53	47.07	9.62	22.92
Pr	14.30	6.70	11.30	12.40	18.10	6.80	29.10	10.70	5.90	1.70	6.30
Nd	51.20	23.60	45.70	42.20	63.30	23.00	104.40	38.20	20.20	5.10	20.10
Sm	6.20	5.60	8.00	7.30	14.20	4.10	19.40	6.90	4.00	0.90	3.30
Eu	1.40	1.30	1.50	1.10	1.50	0.80	1.20	0.80	0.30	0.30	0.40
Gd	2.70	4.80	5.30	4.60	10.20	1.90	15.50	4.50	3.40	0.50	2.50
Tb	0.20	0.90	0.90	0.60	1.50	0.30	2.20	1.10	0.70	0.10	0.30
Dy	0.70	5.10	4.80	3.30	8.00	1.20	12.70	5.10	4.90	0.80	1.40
Ho	0.10	1.10	0.90	0.60	1.30	0.20	2.20	1.00	1.10	0.20	0.20
Er	0.40	3.40	2.30	1.40	3.50	0.50	5.40	2.30	3.20	0.50	0.50
Tm	0.10	0.40	0.30	0.20	0.60	0.10	0.90	0.40	0.60	0.10	0.10
Yb	0.30	3.30	2.00	1.90	3.30	0.40	5.30	2.20	4.80	0.70	0.70
Lu	0.10	0.50	0.20	0.20	0.40	0.10	0.80	0.30	1.00	0.10	0.10
Sum.	280.48	128.69	218.39	245.55	336.90	130.52	569.36	215.03	131.17	30.92	81.82
Normalised Ratios											
Eu/Eu*	1.05	0.77	0.71	0.58	0.38	0.88	0.21	0.44	0.25	1.38	0.43
CeN/CeN*	0.93	0.87	0.95	0.95	0.93	0.93	0.94	0.94	0.74	0.51	0.42
LaN/YbN	156.44	4.71	14.00	19.75	13.43	51.00	15.12	14.24	4.72	9.81	21.91
LaN/SmN	6.99	2.56	3.23	4.74	2.88	4.59	3.81	4.19	5.23	7.04	4.29
CeN/YbN	112.23	3.75	11.85	15.19	11.14	38.48	12.00	10.93	2.49	3.41	8.33
CeN/SmN	5.01	2.04	2.73	3.65	2.39	3.46	3.03	3.22	2.76	2.51	1.63
EuN/YbN	13.33	1.13	2.14	1.65	1.21	5.71	0.65	1.04	0.18	1.22	1.63

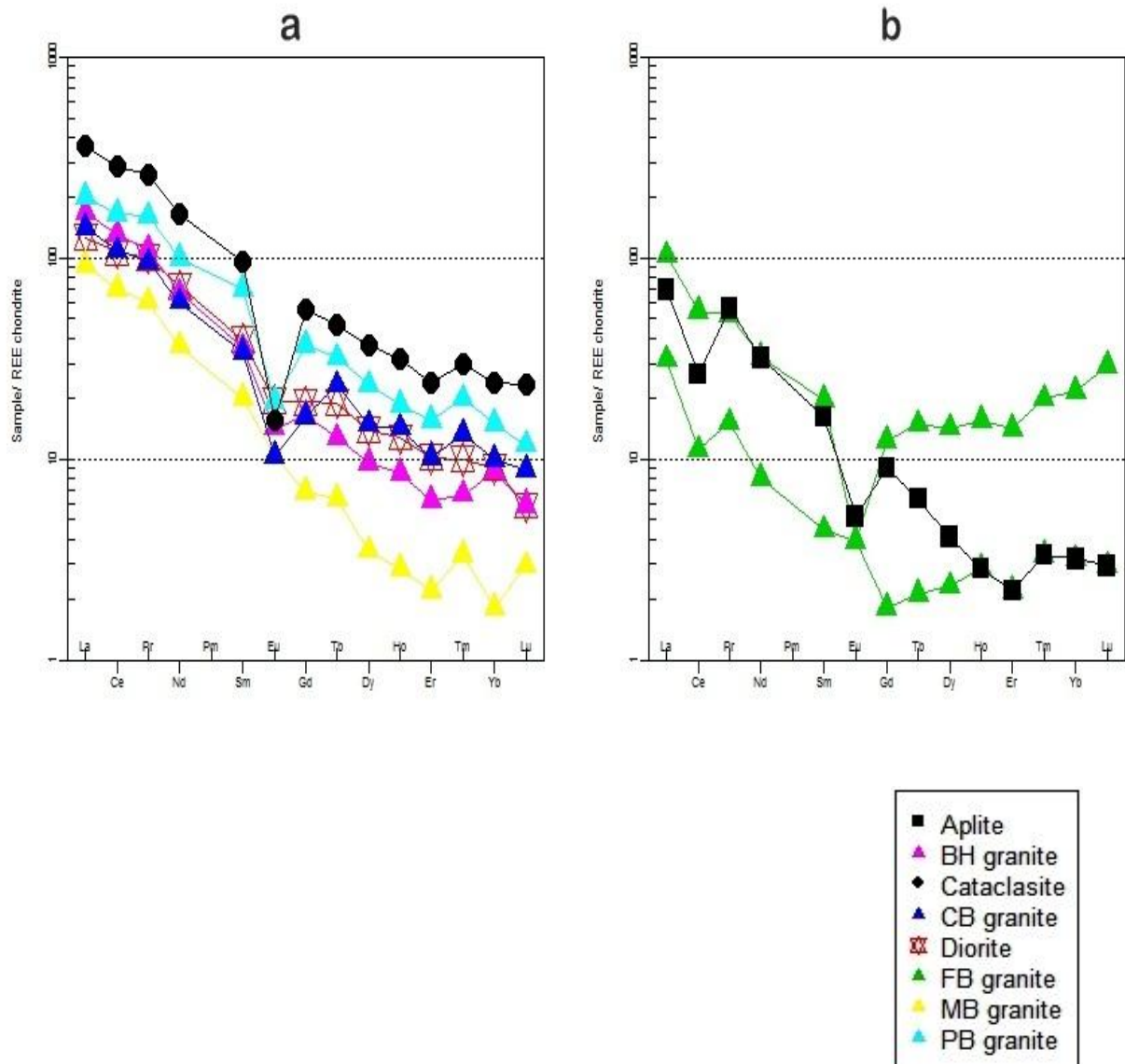


Fig.4. 21: A=Spider plots of granodiorite and some granites which show negative Eu anomaly only, b=spider plot of aplite and fine grained biotite granite showing negative Eu and Ce-anomalies, All the plots are normalize to chondrite values after (Nakamura, 1974).

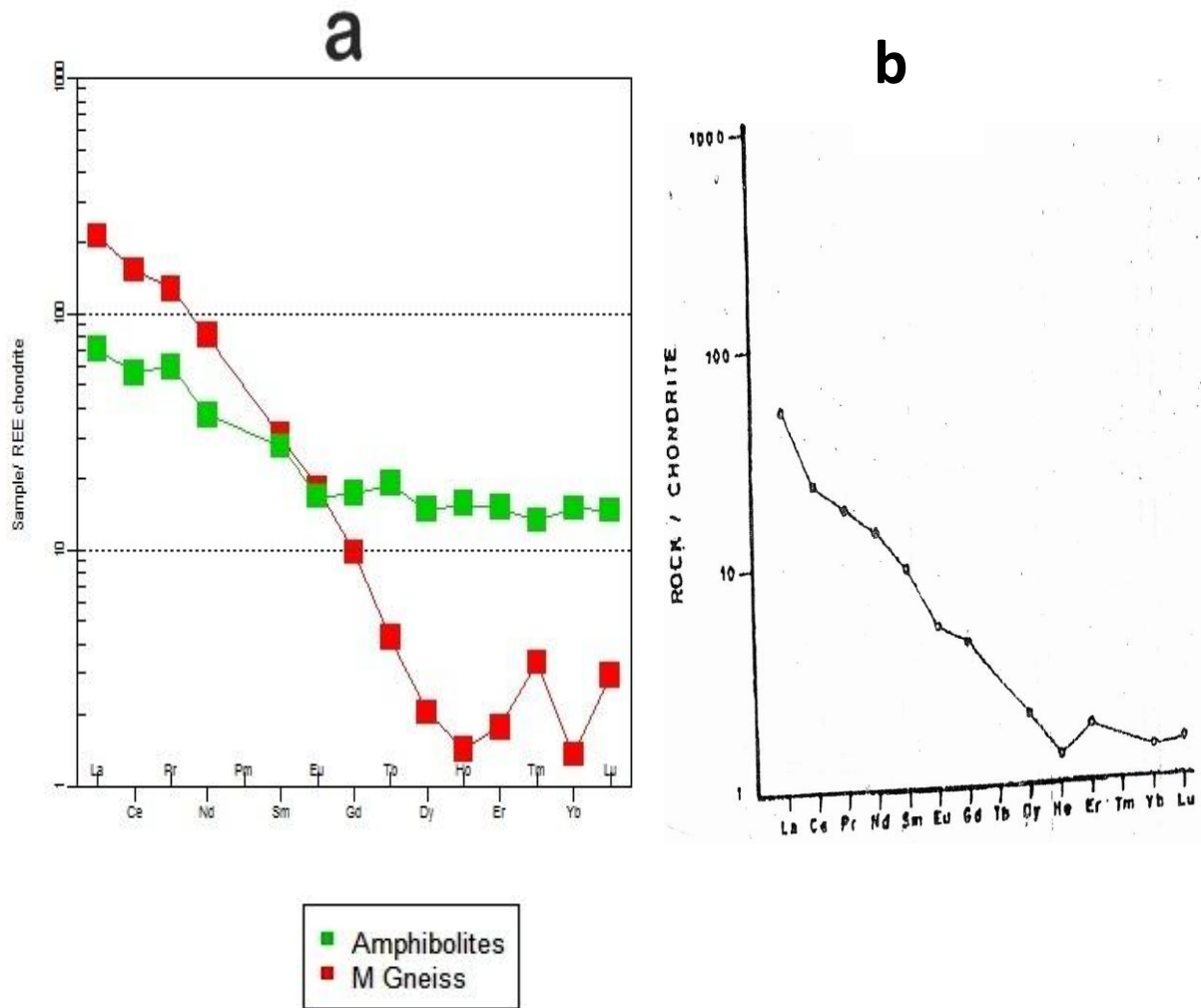


Fig. 4.22: A= spider plot of amphibolite and migmatitic gneiss, b=spider plot of migmatized Kabala-type banded gneiss adapted after (Dada, 1999). All the plots are normalized to chondrite values after (Nakamura, 1974).

4.6 MINERAL CHEMISTRY

The compositional attributes of feldspars can help to determine the degree of fractionation of the magma and the relationships among different pegmatites within a pegmatite field (Shearer *et al.* 1985). Furthermore, the trace-element contents of feldspars and micas indicate economic potential of pegmatites (Trumbull 1995). In this regard, a total of nine mineral samples were analysed for major and trace elements including rare earth element (REE). These comprise of six K-feldspar (three each from type-I and type-II pegmatite), two albite and one biotite samples from type-I pegmatites.

4.6.1 Major Element Distribution in K-Feldspars

The major element composition of K-feldspar from the pegmatites is presented in Table 4.7. Essentially, the major element composition of the type-I and type-II pegmatites are not markedly different from each other. However, some slight differences are noteworthy. SiO_2 ranges from 65.25 to 75.86 wt. % in type-I pegmatites and from 67.29 to 74.10 wt. % in type-II pegmatites. Type-I pegmatites have relatively higher Al_2O_3 and K_2O content with Al_2O_3 and K_2O ranging from 12.39 to 17.21 wt. % and 6.12 to 6.30 wt. % respectively, while Al_2O_3 and K_2O content range from 12.69 to 15.85 wt. % and 4.64 to 5.17 wt. % respectively in type-II pegmatites. Na_2O content ranges from 1.68 to 3.32 wt. % and 1.99 to 2.50 wt. % in type-I and type-II pegmatites respectively. It is noted that K_2O increases from 6.12 to 6.30 wt. % while Na_2O decreases from 3.32 wt. % to 1.68 wt. % from the wall zone to intermediate zone-11 of the pegmatites. This is in consistent with the simple law of evolution by fractional crystallization. Both type-I and Type-II pegmatites have low content of P_2O_5 and TiO_2 . The P_2O_5 and TiO_2 contents range from 0.007 to 0.011 wt. % and 0.002 to 0.003 wt. % respectively in type-I

pegmatites and from 0.005 to 0.014 wt. % and 0.012 to 0.065 wt. % respectively in type-II pegmatites. MgO and Fe₂O₃ contents range from 0.03 to 0.08 wt. % and from 0.09 to 1.29 wt. % respectively in type-I pegmatites and from 0.05 to 0.10 wt. % and from 0.09 to 0.33 wt. % respectively in type-II pegmatite.

Table (4.7): Major elements composition of K-feldspars in pegmatites from the study area

OXIDE	<u>Type-I Pegmatites</u>			<u>Type-II Pegmatites</u>		
	L7A	L7B	L7C	V 1	A 1	H 1
SiO ₂	75.86	65.25	72.86	74.1	70.42	67.29
K ₂ O	6.12	6.24	6.30	4.64	4.43	5.17
Na ₂ O	3.32	1.85	1.68	2.5	1.99	2.33
CaO	0.08	0.15	0.14	0.36	0.24	0.17
Al ₂ O ₃	12.39	17.11	17.21	12.69	14.13	15.85
P ₂ O ₅	0.009	0.007	0.011	0.005	0.014	0.009
TiO ₂	0.003	0.002	0.003	0.065	0.012	0.015
MgO	0.03	0.05	0.08	0.07	0.05	0.10
MnO	0.049	0.062	0.014	0.012	0.011	0.008
Fe ₂ O ₃	0.10	1.29	0.09	0.33	0.10	0.09
FeO	0.09	1.16	0.08	0.3	0.09	0.08

L7A=K-feldspar from the wall zone

L7B= K-feldspar from the intermediate zone-I

L7C= K-feldspar from the intermediate zone-II

V1= K-feldspar from Luva Quarry

A1= K-feldspar from Atagara Village

H1= K-feldspar from Hambagda Village

All the oxide are in weight percent (wt. %).

4.6.2 Trace Element Distribution in K-Feldspars

The trace element composition of K-feldspars from the two pegmatites types is presented in Table 4.8 while the trace element normalized to average crust is plotted in Fig. 4.23. Type-I

pegmatites has somewhat similar REE distribution pattern to that of the granites and aplite. The type-I pegmatite is characterized by negative anomalies of some large ion lithophile elements (Sr, Br) just like the granites and aplite, but unlike these rocks, the type-I pegmatite show positive anomalies of most of the high field strength elements (Zr, Hf, Nb, Ta, U and Th) and some heavy rare earth elements (Tm and Yb). This pegmatite also shows negative anomalies of (P, Tl and Y). The type-II pegmatite on the other hand, shows positive anomalies of some LILE (Sr and Rb) and negative K, Nb and Th anomalies. This pegmatite also shows positive anomalies of some heavy rare earth elements (Tm and Yb) and some HFSE (U and Zr) and negative anomalies of P, Tl and Y.

Table (4.8): Trace elements distribution extracted from feldspars in type-I and type-II pegmaties in the study area. (All values are in ppm). Tungsten carbide pulveriser was used in the pulverization of the samples hence the values of W given here may not reflect the actual values .

ELEMENT	<u>Type-I pegmatites</u>					<u>Type-II Pegmatites</u>		
		<u>K-feldspar</u>		<u>Albite</u>			<u>K -feldspar</u>	-
	L7A	L 7B	L7C	L 5	L 6	V 1	A1	H1
Rb	439.20	724.00	1090	18.9	34.80	171.00	77.10	171.10
Ba	16.00	4.00	2.00	33.00	5.00	94.00	9707.00	1191.0
Sr	9.00	3.00	2.50	24.00	8.00	60.00	845.00	259.00
Li	1.40	5.50	8.3.00	1.5	5.5	3.30	0.80	0.50
Cs	7.90	8.40	9.10	0.30	0.40	4.60	3.00	4.80
Ga	16.71	30.88	42	34.19	38.05	19.41	11.3	19.57
Ta	0.70	10.30	13.00	0.30	0.30	5.90	4.40	3.30
Nb	33.00	44.00	52.00	0.07	0.14	6.48	0.28	0.50
U	1.50	4.20	6.30	0.50	0.10	1.20	0.10	0.10
Th	2.70	3.40	4.30	1.50	0.10	2.50	0.50	0.40
Mo	0.10	0.1	0.14	0.09	0.05	0.99	0.25	<0.05
Cu	0.28	0.33	0.49	0.98	1.02	0.63	1.02	5.57
Pb	24.00	71.45	76.21	29.3	29.38	30.44	57.11	74.33
Zn	2.00	0.80	0.70	10.20	5.90	11.70	2.40	0.70
W	>200.00	>200.00	>200.00	>200.00	176.2	>200.00	>200.00	141.9
Zr	4.90	7.30	10.20	0.30	0.30	7.10	1.00	2.20
Hf	0.23	<0.02	0.24	0.02	0.02	0.55	<0.02	0.09
Sn	0.20	7.80	6.90	0.10	0.10	0.50	<0.10	<0.10
Be	<1.00	2.00	6.00	8.00	13.00	2.00	<1.00	<1.00
Cr	2.00	3.00	4.00	3.00	3.00	3.00	4.00	3.00
Co	51.11	32.50	34.20	28.50	34.60	46.60	47.90	21.80
Tl	2.51	4.87	6.73	0.09	0.20	1.07	0.57	1.3
B	18.00	25.00	23.00	6.00	7.00	N.A.	N.A.	N.A.
F	59.00	71.00	78.00	44.00	49.00	N.A.	N.A.	N.A.
Ratios								
K/Rb	115.66	71.54	47.98	21.26	18	225.14	477.3	250.73
K/Ba	3175.00	12950.00	26150.00	10.30	148.00	409.57	3.79	36.02
K/Cs	1544.07	902.43	661.27	1133.33	1850	8369.56	12266.70	8937.5
Rb/Sr	48.80	241.33	726.66	0.79	4.38	2.85	0.09	0.66
Rb/Ba	27.50	181.00	545.00	0.57	6.96	1.80	0.01	0.10
Th/U	1.80	0.81	0.68	3.00	1.00	2.08	5.00	4.00

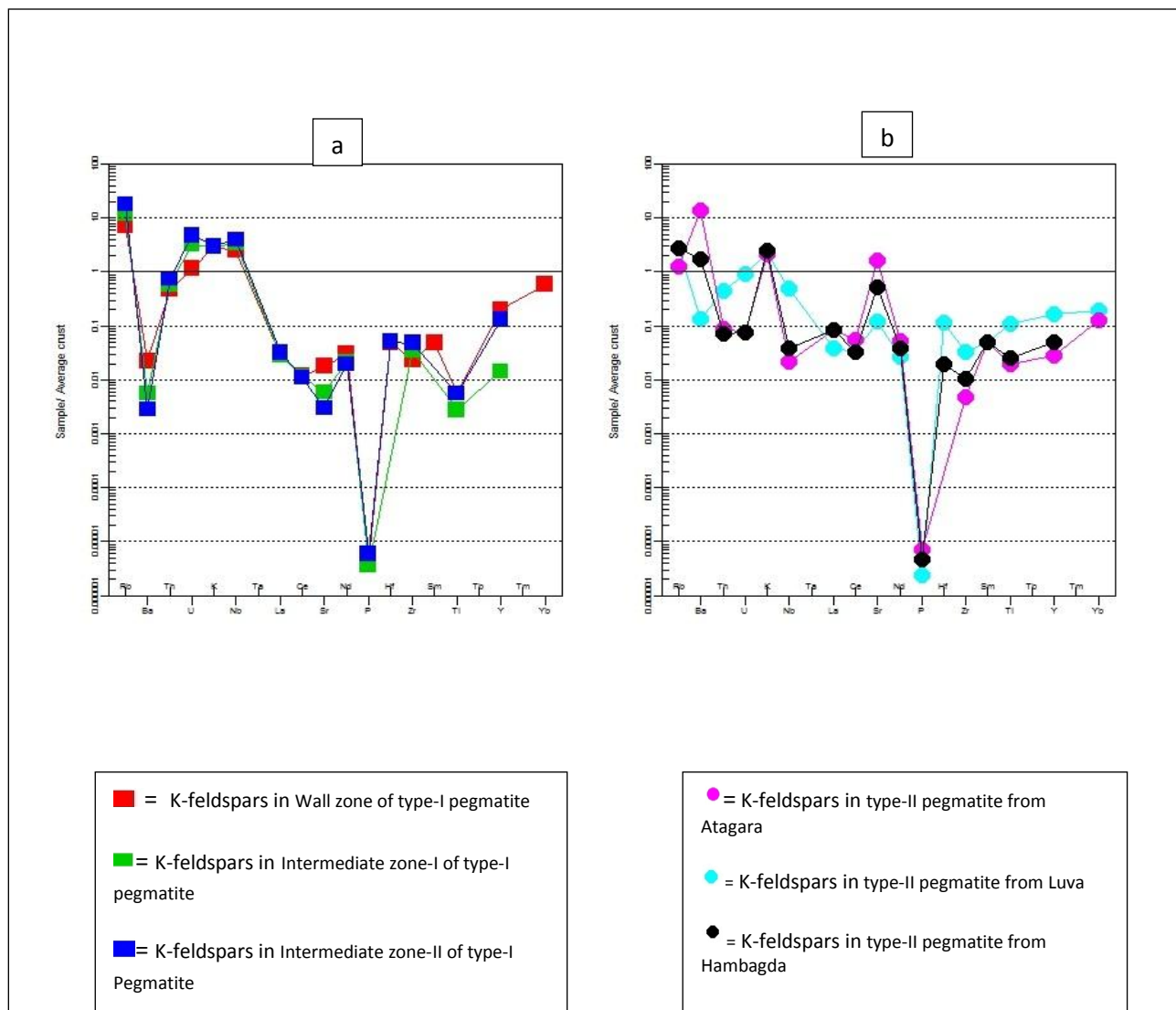


Fig (4.23): Trace element spider diagram normalized to average crust after (Weaver and Tarney, 1984) a=type-I pegmatite; b=type-II pegmatite.

4.6. 3 Lithophile Elements Systematics

Lithophile elements (K, Rb, Ba, Sr and Li) in K-feldspars have been used as indicator of degree of fractionation in pegmatites (Černý 1982; Černý *et al.*, 1985; Shearer *et al.*, 1985;

Larsen, 2002). In type-I pegmatites, Rb increases from 439.20 to 1090 ppm, Li increases from 1.40 to 8.30 ppm and Cs increases from 32.90 to 79.10 ppm, from the wall zone to intermediate zone-II of the pegmatites. By contrast, Ba and Sr decreases from 16.00 to 2.00 ppm and from 9.00 to 2.00 ppm from the wall zone to intermediate zone-II. Rb/Sr and Rb/Ba increase from 48.80 to 726.66 and from 27.50 to 545.00 respectively while K/Ba increases from 3175 to 26150 from the wall zone to intermediate zone-II. K/Rb and K/Cs on the other hand, decrease from 115.66 to 47.98 and from 1544.77 to 661.27 respectively from the wall zone to intermediate zone-II.

Type-II pegmatites on the other hand, is characterized by lower content of Rb, Li and Cs but higher content of Ba and Sr relative to type-I pegmatites. Its Rb content ranges from 77.10 to 171.10 ppm, Li ranges from 0.50 to 3.30 ppm and Cs ranges from 3.00 to 4.80 ppm. Ba and Sr contents range from 94.00 to 1191.20 ppm and from 60.00 to 845 ppm respectively in type-II pegmatite. Type-II pegmatite has higher K/Rb and K/Cs and lower K/Ba, Rb/Sr and Rb/Ba than type-I pegmatites. The K/Rb and K/Cs range from 225.14 to 280.75 and from 8369.56 to 12266.66 respectively in type-II pegmatite. Rb/Sr and Rb/Ba range from 0.091 to 2.55 and from 0.01 to 1.80 respectively while K/Ba ratio ranges 3.79 to 409.57 in type-II pegmatite.

On Rb Vs Sr and Rb Vs Ba bivariate plots, type-I pegmatite which has higher Rb/Sr and Rb/Ba plot at the top-left side of the diagrams while type-II pegmatite which has lower Rb/Sr and Rb/Ba plot at the bottom-right side of the diagrams (Fig 4.24, a and b). K/Rb Vs Rb/Sr and K/Rb /Rb bivariate plots (Fig. 4.24, c and d) enable the discrimination of pegmatites into highly fractionated (evolved) and less fractionated (primitive) pegmatites (Černý 1985; Larsen 2002). As would be observed in Fig. 4.24, type-I pegmatite plot at the bottom-right side

of the diagrams hence are more evolved than the type-II pegmatite which plot at the top-left side of the diagrams (Larsen, 2002).

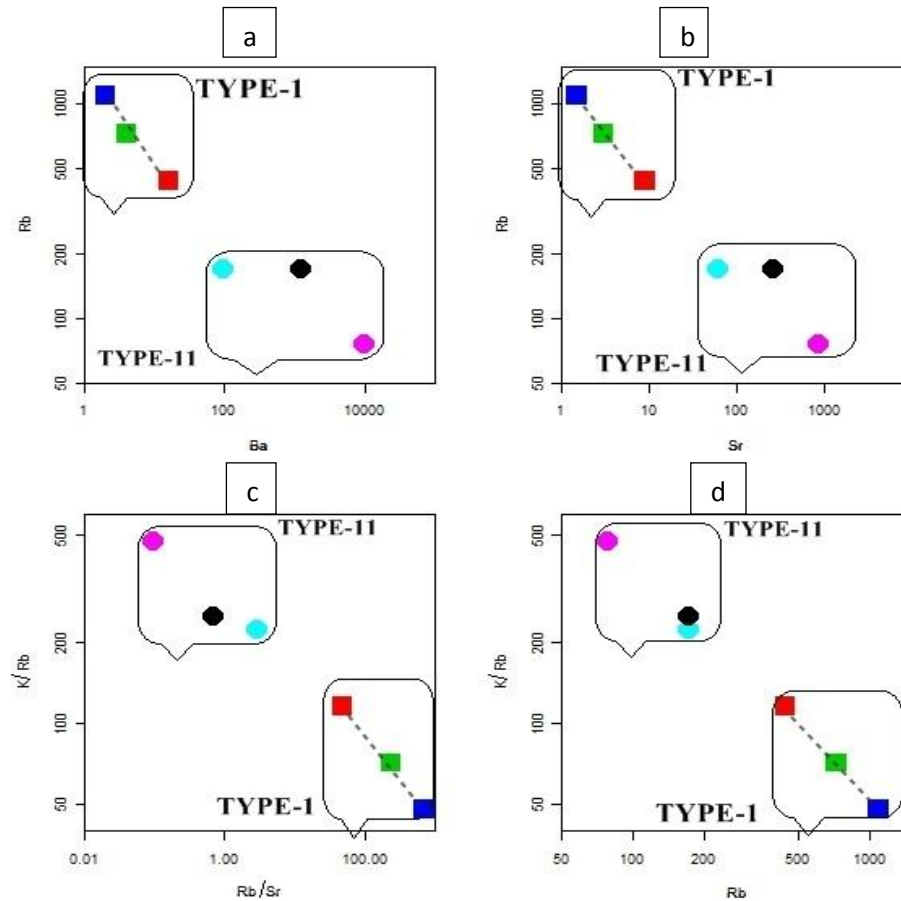


Fig (4.24): Bivariate plots; a= Rb versus Sr, b= Rb versus Ba, c= K/Rb versus Rb/Sr, c= K/Rb /Rb for type-I and type-II pegmatites (after; Černý *et al.*, 1985). Symbol same as in Fig. 4.21

4.6.4 Rare Earth Elements Distribution Pattern in K-Feldspars

The rare earth element composition of the two types of pegmatite is presented in Table (4.9) and their normalized REE distribution pattern is shown in Figure (4.25). Both type-I and type-II pegmatites have low REE concentration with the sum of REE ($\sum$ REE) ranging from 2.13 to 4.67 ppm in type-I pegmatites and from 5.85 to 6.61 ppm in type-II pegmatites. However, the

two pegmatites types exhibit different REE distribution pattern. Type-1 pegmatite is characterized by negative Ce- anomalies and lack well-defined Eu anomaly. Type-II pegmatite on the other hand, is characterized by strong positive Eu anomaly except the pegmatite from Atagara area in which the value of Eu anomaly is similar to that of type-I. Furthermore, Ce-anomaly is absent in type-II pegmatite except the pegmatite from Hambagda which shows slight negative Ce-anomaly. Negative Ce-anomaly is common in the Nigerian rare-metal pegmatites and it suggests an oxidizing condition during the formation of rare metal mineralization (Garba, 2003).

Table (4.9): Rare earth element composition of K-feldspars in ppm from the two types-I and type-II pegmatites in the study area

Elements	Type-I Pegmatites			Type-II Pegmatites		
	L 7A	L7B	L7C	V1	A 1	H 1
La	0.80	0.80	0.90	1.10	2.3	2.3
Ce	0.67	0.65	0.63	1.85	3.15	1.91
Pr	0.20	0.10	0.20	0.20	0.2	0.3
Nd	0.70	0.50	0.50	0.60	1.2	0.9
Sm	0.20	<0.10	<0.10	0.20	0.20	0.20
Eu	<0.10	<0.10	<0.10	0.50	<0.10	0.7
Gd	0.20	0.10	0.20	0.30	0.20	0.3
Tb	<0.10	<0.10	<0.10	<0.10	<0.10	<0.1
Dy	0.50	<0.10	<0.10	0.50	<0.10	<0.1
Ho	<0.10	<0.10	<0.10	0.10	<0.10	<0.1
Er	0.40	<0.10	<0.10	0.20	<0.10	<0.1
Tm	<0.10	<0.10	<0.10	<0.10	<0.10	<0.1
Yb	0.90	<0.10	<0.10	0.30	0.20	<0.1
Lu	0.10	<0.10	<0.10	<0.10	<0.10	<0.1
Sum	4.67	2.15	2.13	5.85	7.45	6.61

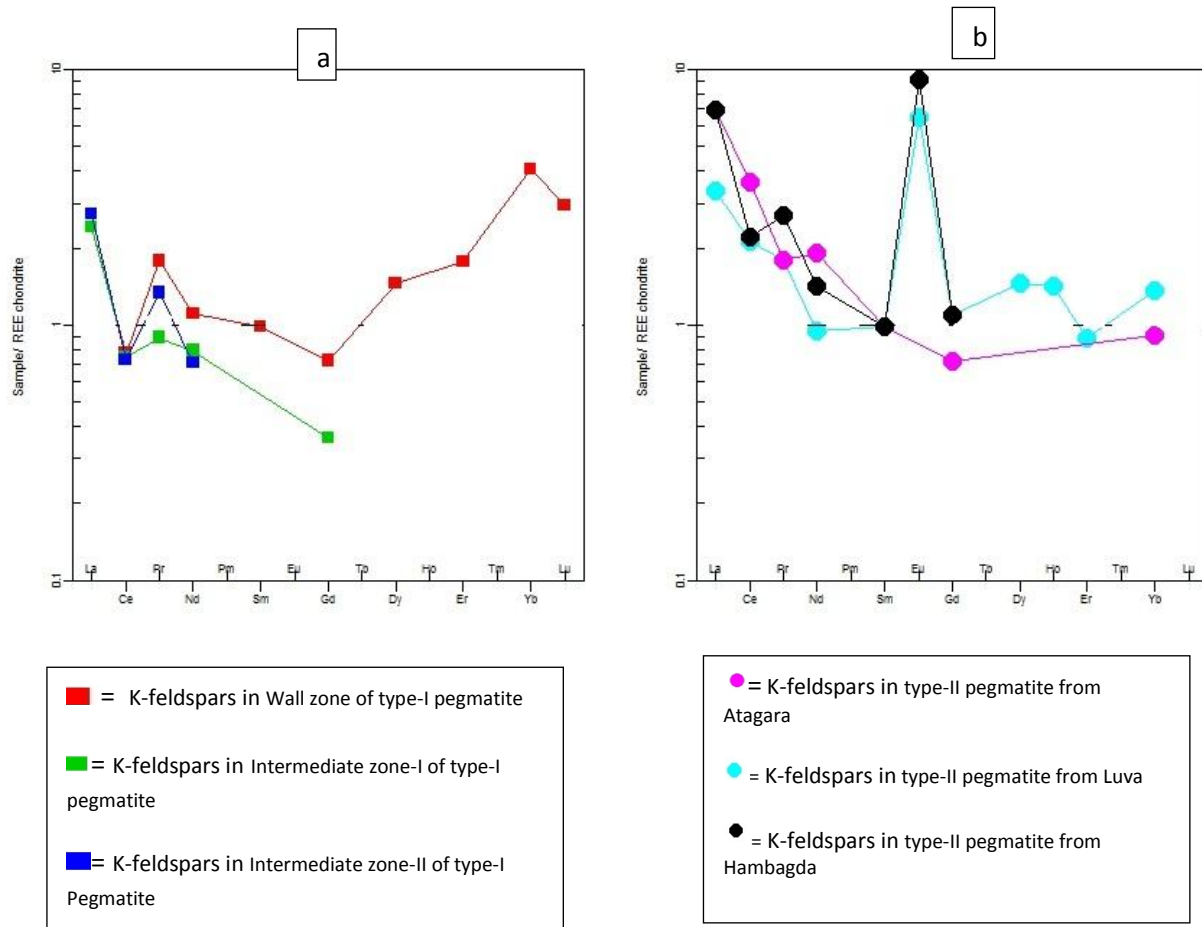


Fig (4.25): Chondrite normalized rare earth element spider diagram after (Nakamura, 1974). A=type-I pegmatites, b=type-II pegmatites.

4.6.5 Albite

The chemical composition of the two albite samples from Type-I pegmatites was also analysed and the average composition of some trace elements (Rb, Cs, Sc and Ta) computed and compared with that of the known pegmatites fields in different parts of the world namely, Hagendorf (Germany), Buck Claim (Canada), Tanco (Canada) and Noumas (South Africa) (Table 4. 10). It can be observed that the albite from the study area have lower Rb, Cs and Ta

relative to all the aforementioned pegmatites fields. However, Sc contents in the pegmatites are higher than those of Buck Claim and Noumas pegmatite fields but lower than those of the Hagendorf and Tanco pegmatite fields.

Table (4.10): Average of some trace elements compositions of albite from type-I pegmatite and some known pegmatites fields in different parts of the world.

Element (ppm)	Study area (very low Ta)	Buck Claim (very low Ta)	Deposit Noumas (low Ta)	Tanco (very high Ta)	Hagendorf (very low Ta)
Rb	31.30	51.00	49.0	679.00	62.00
Cs	0.80	24.00	6.40	2.30	2.30
Sc	0.50	0.008	0.02	2.30	2.10
Ta	0.90	5.60	1.30	14.30	2.10
n	2	1	25	26	1

n=number of samples

4.6.6 Mineral Potential of Type-I and Type-II Pegmatites

K/Rb versus Cs plot enables the discrimination of pegmatite into rare metal and barren pegmatites (Černý, 1982). Figure 4.26 shows that both type-I and Type-II pegmatites in the study area plot within the barren pegmatites field.

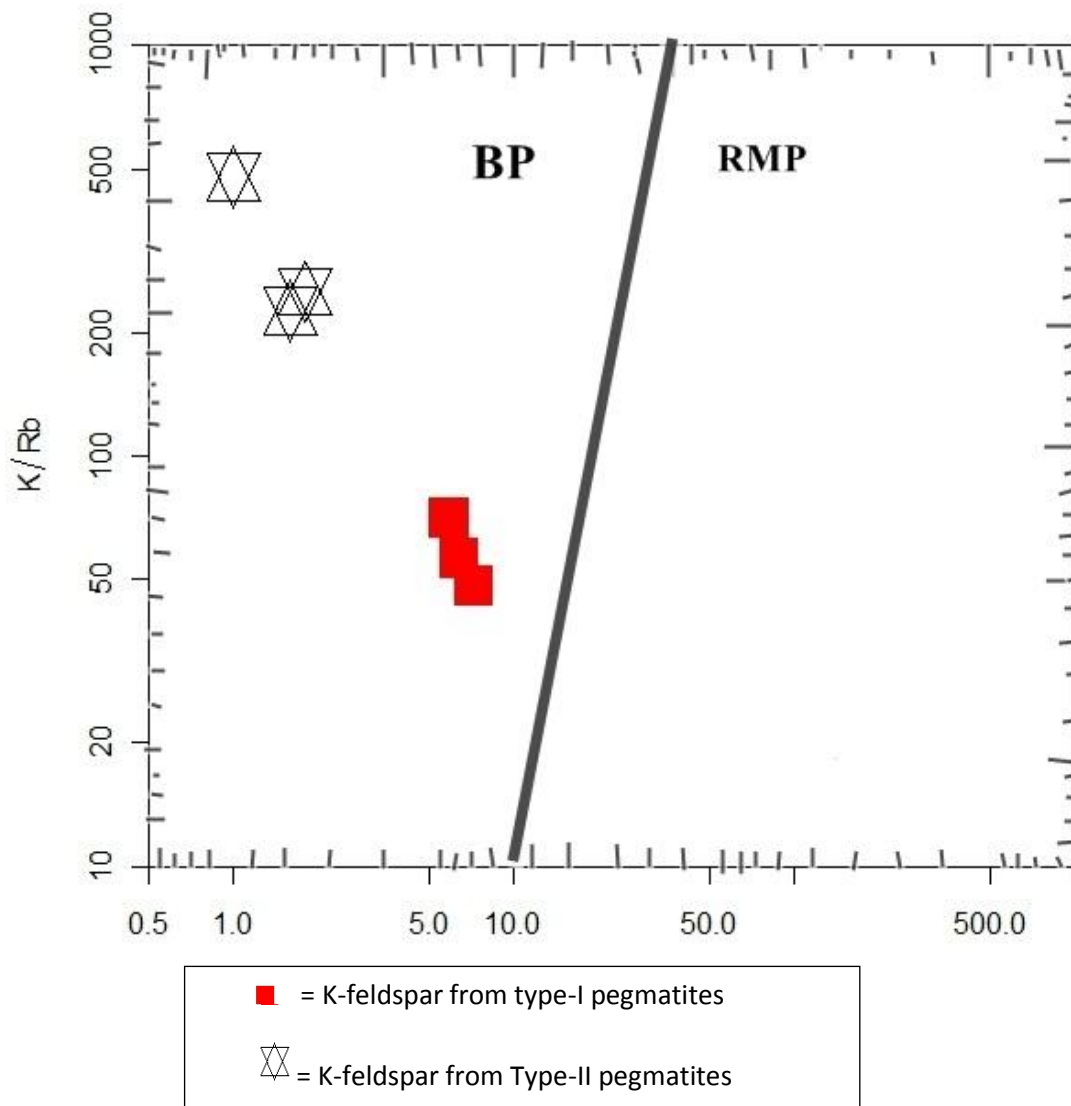


Figure (4.26): K/Rb V Cs discrimination diagram for type-I and type-II pegmatites

4.6.7 “Ferroan Pyroxmangite” and Biotite

“Ferroan Pyroxmangite” is a dark brown heavy mineral found in type-I pegmatite. The mineral occurs as small pods associated with biotite in the second intermediate zone of the

pegmatite (Plate X11 d). The mineral was first named othericssonite ($\text{Mn}_2\text{FeBa}(\text{Si}_2\text{O}_7)$) by Islam and Baba (1990). The name “Ferroan Pyroxmangite” was suggested by Ostaficzuk (1996). Geochemical analysis of the mineral (Table 4.11) reveals that it contains high MnO, Fe_2O_3 and SiO_2 . The mineral is a potential ore of manganese. However, probably due to its high silica content, X-ray diffraction analysis of the mineral has shown that it has low intensity (about 250 counts Fig. 4.27) which is interpreted as background.

Table (4.11): Major element composition in biotite and “ferroan pyroxmangite” in weight percent

	Biotite	“Ferroan	Pyroxmangite”	
Oxide	A	B	C	D
SiO_2	30.20	33.20	35.19	36.60
Al_2O_3	5.04	0.08	0.43	n.d
Fe_2O_3	30.16	28.33	32.92	31.40
FeO	28.32	26.68	n.d	n.d
TiO_2	1.02	0.01	n.d	n.d
CaO	0.11	1.62	5.75	2.50
MgO	0.40	0.13	0.60	n.d
MnO	1.00	10.00	9.92	n.d
Na_2O	0.80	0.01	0.11	n.d
K_2O	2.88	0.02	0.06	n.d
P_2O_5	0.016	0.02	0.02	n.d
sum	99.95	100.1	85.00	70.50

A=Biotite from Liga Hill (present work)

B= “Ferroan Pyroxmangite” from Liga Hill (present work)

C= “Ferroan Pyroxmangite” from Liga Hill (Islam and Baba (1990)

D= “Ferroan Pyroxmangite” from Liga Hill (Ostaficzuk (1996))

Table (4.12): Trace element composition of biotite and “ferroan pyroxmangite” values are in ppm

Elements	A	B
Pb	35.53	1.36
Zn	2504.30	2220.80
Sn	60.90	0.40
Ta	27.70	0.30
Nb	614.58	0.612
U	260.10	4.40
Th	140.50	1.60
Rb	2000.00	0.10
Ba	41.00	5.00
Sr	9.00	1.00
Li	735.30	3.1
Cs	162.30	0.5

A=Biotite from Liga Hill

B= “Ferroan Pyroxmangite” from Liga Hill

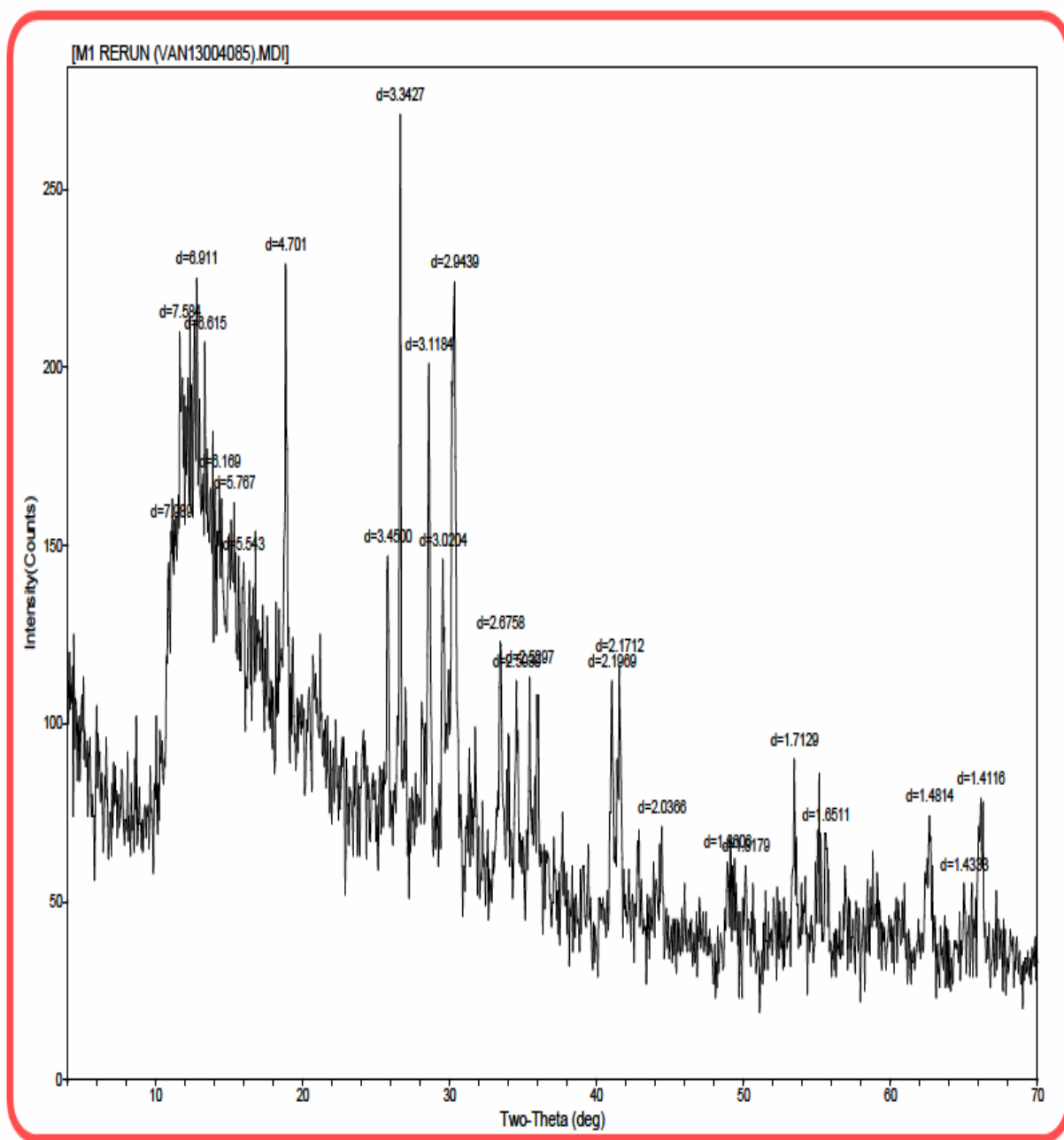


Fig. (4.27): X-ray diffractogram of manganese bearing pyroxenoid.

4.6.8 Relationship between the Granites and the Pegmatites

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 granite suites K/Rb ranges from 237.57 in the biotite hornblende granite to 108.37 in fine grained biotite granite while in type-I pegmatites, K/Rb decreases from 115.66 in the wall zone to 47.98 in the second intermediate zone. Such sequential decrease in K/Rb from the less fractionated end member of the granite suites (biotite-hornblende granites to the second intermediate zone of 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) attest to continuity from granites to pegmatites thus suggesting a genetic link among them (London 2008). By contrast, the type-II pegmatite has K/Rb ranging from 225.14 to 477.30 which are generally higher than those recorded in most of the granites. This suggests that the type-II pegmatite is probably not genetically linked to the granite suites via fractional crystallization.

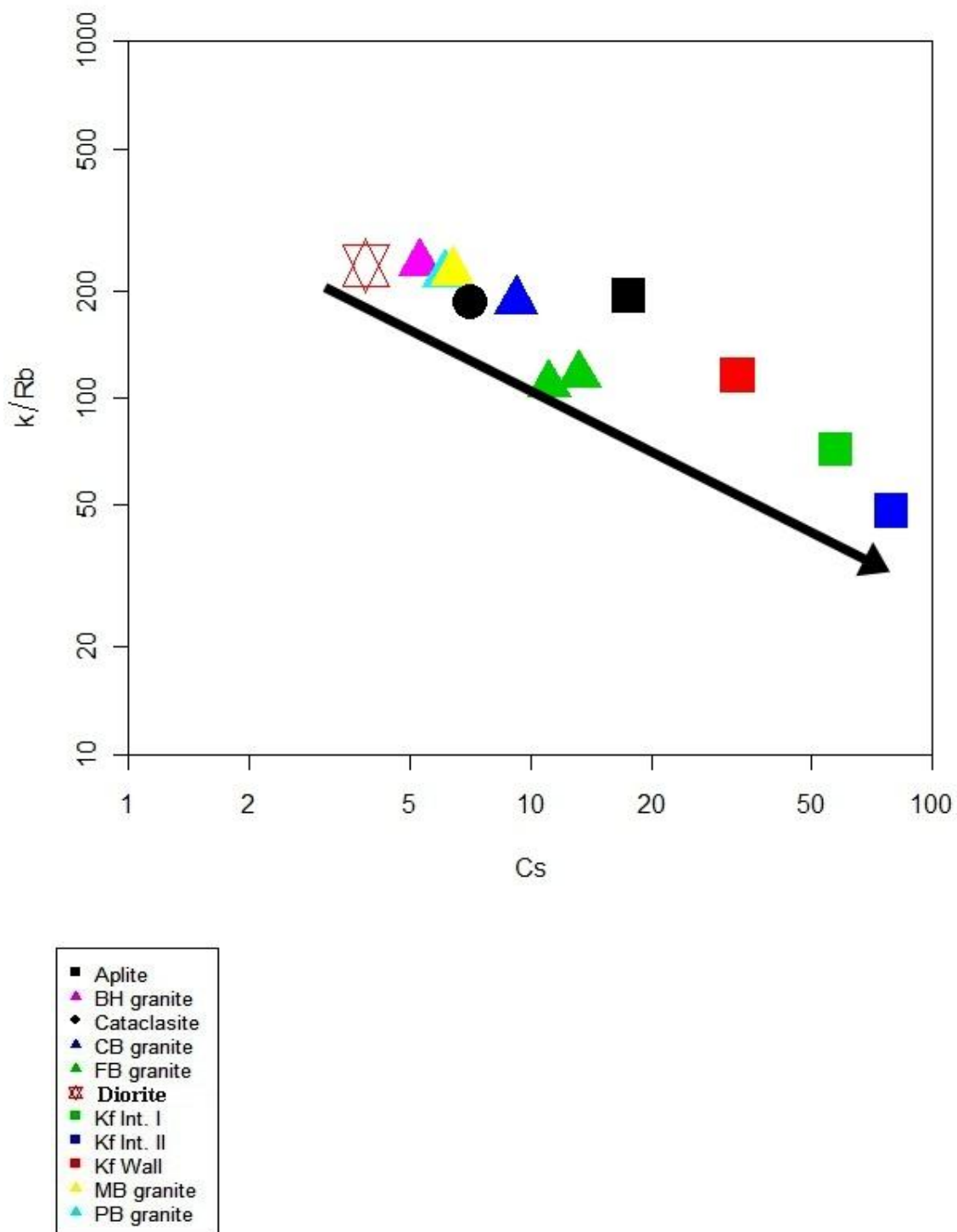


Fig. (4.28): Discrimination plot of K/Rb versus Cs (adapted from Černý *et al.*, 1985)

CHAPTER FIVE

DISCUSSION

5.1 INTRODUCTION

The geochemical characteristic and petrogenesis of the rocks hosting the pegmatites as well as the field relations, mineralization potential and internal evolution 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 FIELD, PETROGRAPHICAL AND GEOCHEMICAL ATTRIBUTES OF MIGMATITIC GNEISS, AMPHIBOLITE AND THE GRANITE SUITES

Field observation has revealed that migmatitic gneiss, amphibolite and granites are the major lithologic units hosting the pegmatites. Other minor rocks mapped in the study area include diorite and aplite. Petrographic studies have shown that the migmatitic gneiss is granodioritic in composition and consist mainly of quartz, feldspar, hornblende and biotite. Major elements composition has revealed that the rock is metaluminous and has calc-alkaline affinity. TiO_2 versus SiO_2 discrimination (Fig. 4.12 b) has shown that the rock is an orthogneiss (was derived from igneous source). In addition, the rock also has a distinctive REE pattern characterised by a slight negative Ho anomaly and slight positive Er anomaly. Dada (1999) has reported some migmatitic banded orthogneisses with similar REE pattern in Kabala, northcentral Nigeria. The amphibolite has tholeiitic chemistry. TiO_2 versus SiO_2 discrimination plot shows that this rock is an ortho-amphibolite (derived from igneous protolith). The rock has REE pattern

characterized by a slight negative Eu anomaly ($\text{Eu}/\text{Eu}^* = 0.77$) which is quite unlike the pattern observed in the migmatitic gneiss mentioned above. However, despite their geochemical dissimilarity, the amphibolite is found interleaved within the migmatitic gneiss in the study area.

The granite suites varies in texture and composition and comprise; medium grained biotite-hornblende granite, porphyritic biotite granite, coarse grained biotite granite, medium grained biotite granite, fine grained biotite granite and tectonised granite (cataclasite). Major element composition has shown that the granites are ferroans, (have Iron number ($\text{Fe}^\#$) ranging from 0.86 to 0.98), mainly calc-alkalic (as shown on the $\text{Na}_2\text{O}+\text{K}_2\text{O}-\text{CaO}$ Vs SiO_2 discrimination diagram (Fig.4.13 b). Ferroan magmatism is a characteristic feature of the Proterozoic eon. The end products of this magmatism are feldspathic rocks that are extremely enriched in FeO relative to MgO ($\text{FeO}/(\text{FeO} + \text{MgO}) > 0.8$) (Frost and Frost, 2013). However, as with granitoids from the southwestern United State of America that contains considerable crustal components, some granite from the study area do not plot in the within-plate granite field or the “A-type” granite fields in (Fig. 4.19), but extend into the volcanic-arc granite fields. According to Pearce (1996), granite suites that straddle the volcanic-arc and within plate fields are products of post-collision setting (Fig. 4.19). Furthermore, geochemical and mineralogical data such as the relatively high Na_2O content, the low CIPW normative corundum (in most cases less than 1%), and the presence of hornblende and iron oxide (probably magnetite) suggest that the granite suites belong to the calc-alkaline, I-type metaluminous to slightly peraluminous granites (Eleftheriadis and Koroneos, 2003). On the contrary, owing to the fact the granite suites as shown from this study are metaluminous to peraluminous in character, Baba *et al.*, (2006) concluded that the granite suites in area have transitional I-type and S-type characteristics. These authors have apparently drawn this conclusion based on the work of Chappell and White (1974), who suggested that all I-

type granites are exclusively metaluminous whereas S-type granites are exclusively peraluminous. However, recent study has revealed that many I-type granites have metaluminous to weakly peraluminous characteristic (Chappell *et al.*, 2012). The diorite is diopside normative hence it is evidently metaluminous (Chappell and White, 1974). Unlike the granites, the diorite is magnesian ($Fe\#=0.67$).

The granites also show negative Nb anomaly which further reinforces the calc-alkaline character suggested by the major elements data. Also worthy of note is the depletion in REE in the granite suites. The sum of REE (ΣREE) in most of the granites is quite low when compared to average REE content of 250 ppm in granite as reported by (Emmermann *et al.*, 1975). This low REE content is probably due to the fractionation of some accessory minerals such as zircon and apatite which are the principal reservoirs of REE in granites (Saleh and El-Nisr, 2013). Enrichment in LREE and depletion in HREE is the general characteristic of all the rocks in the study area. This suggests that the melts from which these rocks were formed equilibrated with residual garnet which is the principal reservoir of HREE, and may also contain high concentration of zircon which is also responsible for HREE retention (Compton, 1978). Moreover enrichment in LREE is the hallmark of crustal and calc-alkaline rocks in general (O'Nions and Pankhurst, 1974) and the depletion in HREE in most of the rocks is due to their concentration in garnet.

5.3 PETROGENESIS

Field, petrographic and geochemical studies are the basic criteria for elucidating the petrogenesis of rocks. Based on field relationship, the rocks in the study area with the exception

of the migmatitic gneisses and amphibolite are found to be intrusive. The sharp contact relationships between the various rocks suggest each lithologic unit had been emplaced and solidified before the emplacement of the subsequent one. Petrographic study reveals that the modal composition of ferromagnesian mineral (biotite) and plagioclase decreases from the less felsic to more felsic end of the spectrum in the granite suites. This suggests that fractional crystallization dominated by fractionation of plagioclase and biotite has played a significant role in the evolution of the granites. The decrease in the concentration of FeOt, MgO, Al_2O_3 and CaO with increasing acidity (SiO_2) supports the earlier observation. The granite suites and the aplite are metaluminous to weakly peraluminous with aluminium saturated index (ASI) ranging from 0.99 to 1.12 and modified alkali-lime index ranging from 5.17 to 6.79 (Fig 4.9, Table 4.4). The diorite has ASI value of 0.77, MALI value of -1.54 and plot in a metaluminous field. The variation trends of most of the major and trace elements in the granite suites can be ascribed to a variety of differentiation processes such as magma mixing, restite unmixing or fractional crystallization (Eleftheriadis and Koroneos, 2003). The absence of mafic enclaves rules out an evolution of the granite suits through magma mixing process (Hassanen *et al.*, 1996). Furthermore, the sub-vertical distribution trend observed in the plot of log of compatible element (Sr, Ba, Zn and V) versus log of incompatible element (Rb) (Fig. 4.20) suggests that the main mechanism of differentiation is fractional crystallization (Zorano *et al.*, 2007). The negative correlations between CaO, P_2O_5 , MgO, FeOt, MnO, TiO_2 and SiO_2 further suggest that the granite suites most likely resulted from fractional crystallization during magmatic evolution. This view is supported by the depletion in Sr and negative Eu anomaly (Maulana *et al.*, 2012). The depletion of CaO and Sr with increasing SiO_2 content is consistent with plagioclase fractionation (Eleftheriadis and Koroneos, 2003). The relatively small negative Eu anomaly especially in

medium grained biotite granite (Fig.4. 21) that seems to contradict plagioclase fractionation is probably due to the hornblende fractionation, which minimize the Eu anomaly (Henderson 1984; Eleftheriadis and Koroneos, 2003) or due to apatite fractionation (Hassanen *et al.*, 1995). The decrease in P_2O_5 , MgO and FeO during magmatic evolution indicates separation of apatite and mafic mineral (such as biotite) during crystallization (Maulana *et al.*, 2012). Early fractionation of apatite and ilmenite was supported by the systematic decreasing trend of P_2O_5 and TiO_2 along with FeO with increasing SiO_2 , respectively (Fig. 4.6). Sharp decrease in Ba with decrease in SiO_2 (Fig.4.15) also indicate an important role of fractionation dominated by biotite (Janousek *et al.*, 2002).

5.4 POSSIBLE SOURCE ROCK (PROTOLITHS)

Possible source rocks (protoliths) of igneous rocks can be interpreted using trace and rare earth elements patterns in conjunction with some major elements discriminations (Maulana *et al.*, 2012). The high-K, calc-alkaline affinity, and negative distribution trend of Nb Ba, and Sr (Fig. 4.13) as well as the enrichment of Rb and K, in the granite suites suggest crustal source (Chappell and White, 1992). In addition, high Th/U (greater than 2.5) in the granite suites suggests continental crust affinity as proposed by (Taylor and McLennan, 1985). However, the metaluminous nature of the granite suites, particularly the less evolved members precludes an origin from the melting of a strongly peraluminous sedimentary protolith. This character requires a metaluminous protolith such as the mantle or other igneous sources (Ferre, *et al.*, 1998). Nonetheless, the slightly peraluminous nature of the granite suites particularly the more fractionated members cannot be explained by an evolution via fractional crystallization dominated by fractionation of plagioclase. This is because fractionation of plagioclase is

expected to decrease the concentration of Al_2O_3 in the melt which will in turn decrease the aluminum saturation index. According to Chappell and White (2012), the peraluminous chemistry of I-type granite can either suggest fractionation of hornblende, or that the source material for the granite is probably slightly peraluminous. The negative Nb and Ti anomaly observed in the trace element spider diagram (Fig. 4.14) suggest the presence of hornblende in the source material (Eleftheriadis and Koroneos, 2003). In their experimental studies Frost and Frost, (2011; 2013) acknowledged that partial melting of tonalitic to granodioritic crustal rocks at low pressure can produce metaluminous to slightly peraluminous high-silica, ferroan, calc-alkalic melts. Therefore, the augite crystals observed in biotite-hornblende granite are probably “peritectic” in origin while the hornblende crystals observed in the two rocks are probably “restitic” in origin (Clemen *et al.*, 2011; Clemen and Stevens, 2012). The xenomorphic (anhedral) nature of these minerals especially the hornblende is not consistent with magmatically precipitated phases. Rather, the augite probably formed as a result of chemical reaction that accompanied the partial melting of biotite and hornblende rich source material and are therefore peritectic; while the hornblende are restite, that is, unmelted mineral that remain after partial melting (Clemen *et al.*, 2011; Clemen and Stevens, 2012).. Therefore, the hornblende-bearing migmatitic gneiss (sample A2) characterized by high Sr contents and slightly positive Eu anomaly ($\text{Eu}/\text{Eu}^*=1.05$) as well as the tonalitic amphibolite (Sample A3) probably form part of the protoliths of the granite suites. Melting of such rocks results in moderate to high K_2O content in the melts and an entrainable peritectic assemblage dominated by clinopyroxene (Clemens and Stevens 2012).

The protoliths of these two meta-igneous rocks however are probably andesitic lavas and pyroclastic rocks which commonly accumulated in back-arc basins associated with destructive

continental margin (Clemen and Stevens, 2012). According to Ajibade and Wright, (1989) and Danbatta, (1991; 2008) similar setting exist in Nigeria. Since melting of the mantle wedge produces the source rocks for these two meta-igneous rock (Clemen and Stevens 2012); this probably accounts for the high concentrations of Cr (442.0 ppm), Ni (153.80 ppm) and MgO (6 wt. %) in the diorite, which according to Dada *et al.*, 1995 are characteristic of rocks that were derived from mantle wedge. Furthermore, it has been established that the meta-igneous rocks that usually formed I-type granites originate from melting of the mantle wedge (Clemens and Stevens, 2012). The I-type granitic magmas will inherit stable and radiogenic isotope signatures that could be misinterpreted to reflect mixing with mantle-derived magmas, especially if the evidence based on isotope compositions were considered in isolation. Isotopic studies carried out on most Nigerian Older Granites suggest mixing of mantle and crustal component in their magmatic source (Dada, 1998). However, unless further work proves otherwise, anatexis (melting) of crustal rocks (with significant contribution from the migmatitic orthogneiss and amphibolite) is hereby proposed for the origin of the granite suites in the study area. Such melting is envisaged to have taken place after the metamorphic episode associated with orogenic activity which is linked to closure of the West African sea located within an ancient convergent plate boundary (Ukaegbu and Ekwueme, 2006).

5.5 GEOCHEMICAL FEATURES AND MINERALIZATION POTENTIAL OF THE PEGMATITES

The type-I pegmatites is moderately fractionated as indicated by their high Rb values (439.20-1090.00 ppm) and low K/Rb (115.56-47.98). However, despite the moderate degree of fractionation, this pegmatite is not mineralized as shown by the K/Rb against Cs discrimination

diagram. Furthermore, the pegmatite also shows distinct negative Ce anomaly (Fig. 4.25) which is the common features of the Nigerian rare-metal pegmatites. According to Garba (2003), the negative Ce anomaly exhibited by this rock suggests oxidizing conditions during rare-metal mineralization. Matheis (1987) 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; or from Na-rich hydrothermal solutions from the mantle along ancient lineaments (Wright 1970, Garba, 2002). Kuster (1990) noted a good correlation between the degree of Na-metasomatism (albitization) and rare-metal mineralization in some rare-metal pegmatites of the Wamba area of central Nigeria and concluded that both granite-related pegmatites emplacement and subsequent mineralization are related to the late Pan-African NE-SW and NW-SE shear movements. Although the geology of Liga Hill where type-I pegmatites are restricted suggest the presence of a fault zone as indicated by the presence of cataclasite and cobbles of quartzite, no evidence of albitization were recorded in these pegmatite. Wallrock alteration in this pegmatite is limited to slight tourmalinization observed in their host granites (Plate XXIII). The tourmalinization probably resulted from fluid-wall rock interaction during the pegmatites emplacement. Hence the lack of any evidence of Na-metasomatism in these pegmatites account for their barren nature with respect to rare-metal mineralization. It is worthy of note however, that the type-I pegmatite although barren with respect to rare-metal mineralization, serve as a host to ferroan pyroxmangite found associated with biotite in the second intermediate zone of the pegmatites. This mineral appears to have crystallized from fluid that accompanied the pegmatite emplacement and is a potential ore of manganese. In addition, the large deposits of pure perthitic microcline feldspars and quartz

which are currently being mined from the pegmatites when properly exploited can serve as a good source of revenue for the country (Girei *et al.*, 2014).

The type-II pegmatite on the other hand is poorly fractionated (primitive) as indicated by their low Rb content (77.10-171 ppm) and high K/Rb content (225.14-477.30). This pegmatite is also barren as shown by the plot of K/Rb against Cs (Fig. 4.24).

5.6 INTERNAL EVOLUTION OF THE PEGMATITES

One of the most conspicuous and enigmatic features of some pegmatites is their sharply bounded internal zonation. The zonation is both mineralogical and textural (London 2014). Study of the mineral zonation in type-I pegmatites has revealed that K-feldspar increases from the wall to second intermediate zone while albite decreases from the wall zone to first intermediate zone and it is completely absent in the second intermediate zone. This finding is consistent with the view of Jahns and Burnham (1969) who attributed mineral zonation in pegmatites largely to the separation of relatively denser silicate melt from the less dense H₂O fluid phase, and the attendant segregation of alkalis such that Na remained in the silicate melt and K partitioned in the aqueous phase (Jahn and Burnham 1969). In line with this model, crystallization of Na-rich phase (albite) from the melt fraction occurred more rapidly and probably led to concentration of the albite rich phase in the outer zone of pegmatite while the crystallization of the K-rich phase (K-feldspar) from aqueous phase occurred slowly in the crystallization history leading to the concentration of more of the K-rich phase in the inner zones of pegmatite. This accounts for the absence of albite in the second intermediate zone and the increase in the proportion of K-feldspars from the first intermediate zone to the second intermediate zone. However, experimental evidence by (Burnham and Nekvasil, 1986; Anovitz and Blencoe, 1999; Schafer *et*

al., 1999; Student and Bodnar, 1999) has condemned the underlying precept of this model. For instance, the “fractional distillation” of K from Na that was the central precept of this model has been shown, through multiple methods, to be incorrect (Burnham and Nekvasil, 1986; Anovitz and Blencoe, 1999; London 1992, 1996). Rather than an enrichment of K over Na in aqueous fluid, as postulated by Jahns and Burnham (1969), the K* value (molar K / [K + Na]) of aqueous fluid in equilibrium with granitic melt is essentially the same as that of the coexisting granitic liquid (Burnham and Nekvasil, 1986), or slightly less than that of the melt (Anovitz and Blencoe, 1999; Schafer *et al.*, 1999; Student and Bodnar, 1999, London 2014). Furthermore, Jahns and Burnham (1969) speculated that thermal gradients were the ultimate cause of mass transport and separation of K and Na; however, the likely thermal gradients in pegmatites, which cool from the outside inward, would have enriched the outer zones of the pegmatite in K-feldspar and sodic plagioclase, and the hotter, inner zones in more calcic plagioclase (London, 2014). This is not consistent with the feldspar distributions seen in type-I pegmatite in the study area.

Inter-lithophile elements ratios have shown however, that fractional crystallization is the most plausible model that explains the evolution of zoning in type-I pegmatites. For instance, the decrease in K/Rb and increase in Rb/Ba and Rb/Sr from wall to the second intermediate zone is consistent with fractional crystallization. According to Shearer *et al.*, (1985), potassium feldspar (the most dominant minerals in the studied pegmatites) most probably crystallized from a minimum melt (Albite-K-feldspar- Quartz) from the wall zone to the core of the pegmatite. This is further supported by the decrease in Ba and Sr and the increase in Cs and Li from the wall zone to the second intermediate zone. Likewise in albite, Ba and Sr decrease while Cs and Li increase from the wall zone to intermediate zone. This also suggests that the albite crystallized from wall zone to intermediate zone and it further suggest that fractional crystallization played

an important role in the evolution of the pegmatite. However, fractional crystallization cannot provide any good explanation for the large crystals of feldspars (e.g. the blocky crystals of microcline) that were recorded in the intermediate zones of the pegmatites (Plate XXII). According to London (2008), P, F and B (fluxes) among other functions play a vital role in suppressing successful nucleation of some crystals (minerals). Inhibited nucleation of crystals reduces the number of competing crystals, which makes the development of relatively few but gigantic crystals that comprise most pegmatites possible. Although the proportion of fluxes in the pegmatites (F ranges from 59-78 ppm, B ranges from 18-25 ppm while P ranges from 3-5 ppm) is rather small to warrant any significant role in suppressing crystal nucleation which lead to the developments of the gigantic crystals, London (1999, 2005, 2008) is of the opinion that accumulation of such fluxing components in a boundary layer of liquid along crystal growth front can provide a means of reconciling the low concentrations of fluxing components in pegmatites with their important role in promoting the growth of giant crystals. Hence fractional crystallization of a flux-bearing rather than flux-rich granitic melt is the most “preferred” model for evolution of type-I pegmatites since this accounts for both the mineral zonation and the occurrence of some gigantic crystals observed in the pegmatites. Ferroan pyroxmangite which is found associated with biotite in the intermediate zone of the pegmatite probably crystallized from Mn, Fe and Zn rich residual fluids.

The type-II pegmatite on the other hand, shows no textural or mineralogical zonation. Rather, the distribution of grain size (texture) and mineralogy in the pegmatite is somewhat homogeneous.

5.7 FROM GRANITES TO PEGMATITES: A PROPOSED PETROGENETIC MODEL

This model is adopted and modified after Shearer and Papike, (1992). It seeks to explain the origin and genetic relationship between pegmatites and granite suites in the light of the available field and geochemical evidence. The comparatively low SiO_2 , Rb, and Pb; and high Sr and Ba medium grained biotite-hornblende granite all make it a good candidate whose composition approaches that of a parent rock. Inter-element correlation always starts from this rock (Figures 4.15 and 4.16). The model therefore suggests that the biotite-hornblende granites was earlier emplaced followed by porphyritic biotite granite, medium grained biotite granite, coarse grained biotite granite and fine grained biotite granite in that order. The cataclasite is probably part of the fine grained biotite granite which was affected by cataclastic processes. The aplite and type-I pegmatites on the other hand formed from a residual melt released after the emplacement of the fine grained biotite granite. The model is supported by field relationship such as the sharp contact between the rock units as observed in some places and the well-defined linear trend on the K/Rb against Cs discrimination diagram (Fig. 4.28).

The type-II pegmatite shows enrichment of Ba relative to Rb on the trace element spider diagram (Fig.4.18). According to Tang and Liu (2002), enrichment of Ba relative to Rb on trace element spider diagram suggests partial melting. This pegmatite therefore probably formed from partial melting of the surrounding granites at shallow depth.

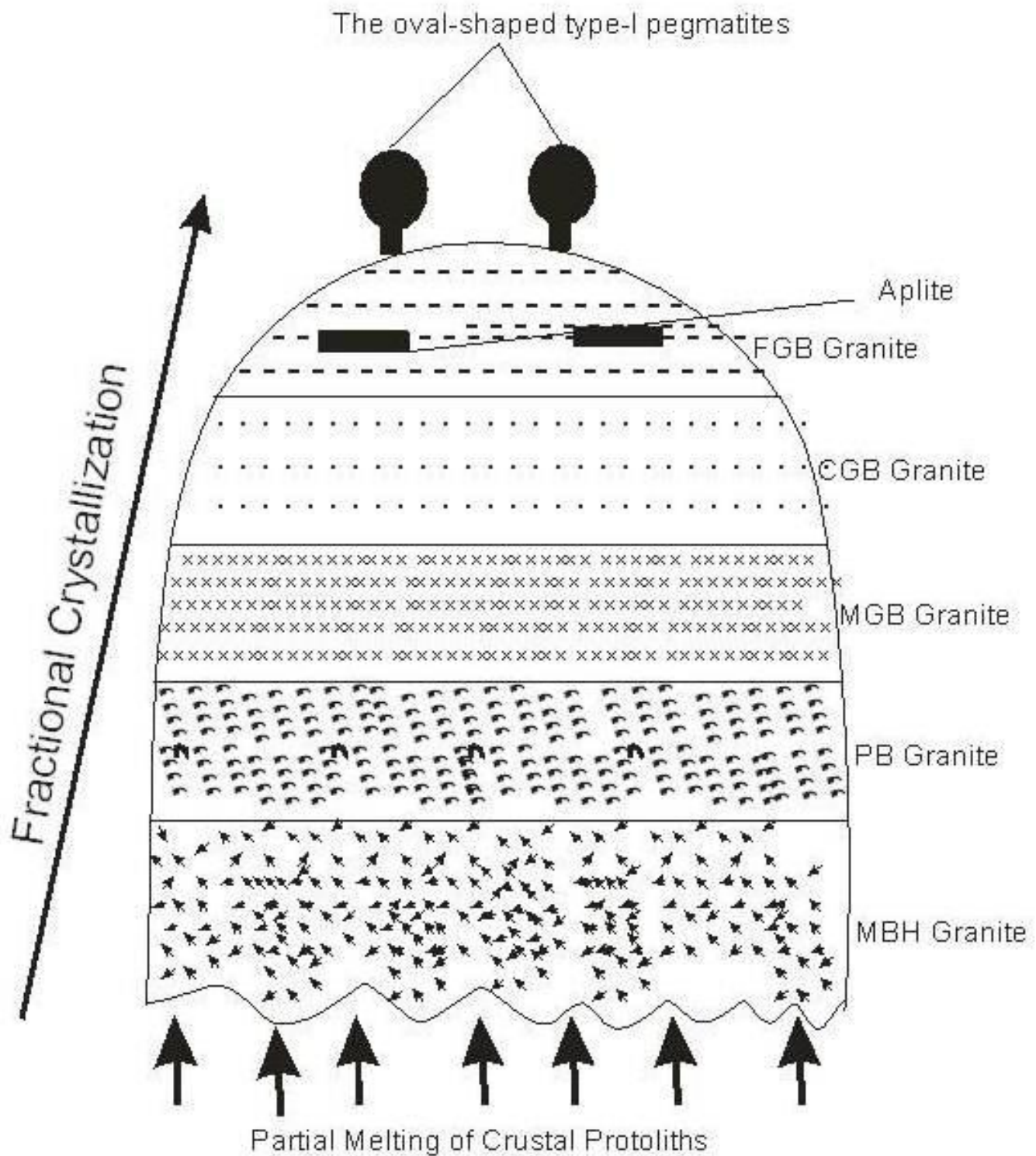


Fig 5.1: Models suggested for the generation of type-I pegmatite modified from Shearer and Papike, (1992)

CHAPTER SIX

CONCLUSION AND RECOMMENDATIONS

6.1 CONCLUSION

The study area comprises of low-lying migmatitic gneiss, minor amphibolite, aplite, granite suites and pegmatites. The granite suites vary in texture and composition and comprise of diorite, biotite hornblende granite, porphyritic biotite granite, coarse grained biotite granite, medium grained biotite granite, fine grained biotite granite and tectonised granite (cataclasite). Two types of pegmatites have been mapped in the study area. This first category of pegmatite (type-1) occurs as large, zoned, oval-shaped bodies trending in E-W directions. The second category of pegmatite (type-II) occur as veins which often cross-cut their host rocks and strike mainly in the NE-SW direction, concordant with the major structural trend in the Nigerian Basement Complex. Contact relationship between the various rock types are commonly sharp although gradational contacts were also encountered in some places. Petrographic studies revealed that quartz; microcline, plagioclase and biotite constitute the major minerals present in the rocks, while apatite and zircon are the most dominant accessory minerals present in the rocks. Geochemical studies have shown that the migmatitic gneiss is metaluminous and has calc-alkaline affinity. TiO_2 versus SiO_2 discrimination plot (Fig 4.12b) reveals that the rock is an orthogneiss (derived from igneous source). The migmatitic gneiss shows REE pattern similar to some migmatitic banded orthogneisses in Kabala, northcentral Nigeria. The amphibolite has

tholeiitic chemistry and TiO_2 against SiO_2 discrimination plot shows that it has igneous protoliths. The granite suites are ferroan, calc-alkaline, metaluminous to slightly peraluminous, post-collision I-type granites and were derived through partial melting of crustal rocks.

The type-I pegmatite is composed of quartz, microcline, plagioclase and biotite. This pegmatite is genetically linked to the granite suites. This pegmatite is also moderately fractionated and barren of rare-metals. However, the pegmatite hosts “ferroan pyroxmangite” which is a potential ore of manganese. In addition, the large crystals of pure quartz and feldspar in type-I pegmatite which are currently being mined in the study area, if properly exploited can serve as a source of revenue for the country. The type-II pegmatite on the other hand, is a primitive and barren pegmatite which was probably derived via partial melting of the surrounding granites at shallow depth.

6.2 RECOMMENDATIONS

The conclusion drawn from this work regarding the internal evolution and Mineralization potential of pegmatites is based on the study of the trace elements compositions of feldspars (K-feldspars and albite) extracted from the pegmatites. It is therefore recommended that more detailed studies of the trace elements composition of muscovite in the pegmatites should be carried. This will go a long way in confirming some of the observations made in this work. Isotopic studies should also be carried out in order to confirm the petrogenetic model proposed in this work.

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