GEOLOGY, GEOCHEMISTRY AND STRUCTURAL CONTROLS OF BADAFI PEGMATITE FIELD, PARTS OF KABO SHEET 80 AND IKARA SHEET 103, NW NIGERIA

BY

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DEPARTMENT OF GEOLOGY,
FACULTY OF PHYSICAL SCIENCE,
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DECLARATION

I declare that the work in this thesis titled **"Geology, Geochemistry and Structural Controls of Badafi Pegmatite Field, Parts of Kabo Sheet 80 and Ikara Sheet 103, NW Nigeria,"** has been carried out by me, in the Department of Geology, Faculty of Physical Sciences, Ahmadu Bello University, Zaria. The information derived from the literature have been dully acknowledged in the text and in the list of references provided. No part of this thesis was previously presented for another degree or diploma in this or any other institution.

Abdulhamid Nuhu Tilde

| --- | --- | --- |
| Name of Student | Signature | Date |

CERTIFICATION

The thesis entitled **"Geology, Geochemistry and Structural Controls of the Badafi pegmatite field, Parts of Kabo Sheet 80 and Ikara Sheet 103, Northwestern Nigeria,"** by Abdulhamid Nuhu Tilde, meets the requirements for the award of the degree of Master of Science in Geology of Ahmadu Bello University and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

I dedicate this work to my Late father Abdulhamid Baffa Ibrahim.

ABSTRACT

The geology, geochemistry and structural studies of the granitoids from Badafi area in northwestern Nigeria was carried out. This is aimed at determining the structural setting, petrogenesis and mineralization potential of the rocks in the area. The study area is underlain by migmatite, migmatitic gneiss, granites, aplite and pegmatites. The granitoids vary in texture and composition and comprises of granodiorite, hornblende biotite granite, porphyritic biotite granite, coarse grained biotite granite, medium grained biotite granite and pegmatites. Different generations of pegmatites were mapped in the area and these are divided in to barren with repect to rare metal and mineralized types. The mineralized pegmatites are rich in beryl and they strike in NNW-SSE and NE-SW directions, while the barren pegmatites strike mainly in ENE-WSW direction. Analysis of geochemical data revealed that both migmatite and migmatitic gneiss are peraluminous and have high calc-alkaline affinity. Plots of TiO_2 versus SiO_2 discrimination has shown that they are both orthogneisses (were derived from igneous protolith). On a REE pattern, the migmatite is characterized by slightly fractionated REE with no Eu anomaly but migmatitic gneiss show slight enrichment of LREE and depletion in HREE with weak Eu anomaly. The mineralogical composition of the granitoids such as presence of hornblende and iron-oxide (probably magnenite) couple with the geochemical data such as high Na_2O suggest that the granitoids belong to calc-alkaline, I-type, metaluminous to slightly peraluminous granitoids, derived from partial melting of an igneous protolith. The mineralized pegmatites are characterized by enrichment of some large ion lithophile elements such as Rb and Cs, typically found in fractionated pegmatites. On the K/Rb versus Cs discrimination diagram the pegmatites plot in the field typical of beryl mineralized pegmatites. This is in agreement with the occurrences of beryl mineralization as observed in the pegmatites. The pegmatites also show marked similarity with some beryl mineralized pegmatites in Cross Lake area of central Manitoba. The beryl mineralization in the pegmatites is largely associated with late stage albitization and occurs within vugs (pockets). Evidence from REE pattern suggests that the pegmatites are not co-magmatic with their host post-collision granitoids, but were formed from highly fractionated and fluid-saturated residual melt of aplitic composition.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND

Recent development on activities of artisanal miners has made possible the mapping of newly discovered rare-metal pegmatites especially in north-western Nigeria (Garba, 2003); Nasarawa and Richifa areas in central Nigeria, Badafi, Kushaka, Magami and Maradun in north-west Nigeria, are typical examples. Therefore, it is clear now that rare-metal pegmatites are not restricted to the identified NE-SW belt of Central Nigeria. The Badafi pegmatite field belongs to pegmatites related to late Pan- African tectonic granites occurring in the Pan- African mobile Belt east of the West African Craton.

Pegmatite is a term which signifies the coarsely crystalline veins rich in quartz, feldspar, muscovite and other accessory minerals in varying proportion. Their sizes vary from veinlets of about few millimeters to a few kilometers in length. Generally, pegmatites are very irregular not only interms of distribution, but also in length and composition.

Pegmatites are texturally distinct variants from more common and more voluminious plutonic igneous rocks, such as gabbros, granites, syenites (London and Kontak, 2012). Minerologically we have two types of pegmatites: i) simple; and ii) Complex.

Simple pegmatites have simple mineralogy i.e. they contain only quartz, feldspar and mica and most of them are referred to as “barren”. They do not contain minerals like tourmaline, garnet, beryl, fluorite, lepidolite, spodumene, apatite and topaz, and have no well developed zoning. Complex pegmatites on the other hand, have their minerals arranged in a zonal sequence and many contain assemblages of rare-minerals. Small propotion of complex pegmatites (<1%)

possess assemblages that contain uncommon minerals, for example, those with lithium, beryllium, cesium, boron, phosphorous and tantalum (London and Kontak, 2012).

Two types of Pegmatites can also be distinguished compositionally (Marieke, 2014): i) the Lithium-Cesium-Tantalum-bearing(LCT) pegmatites, which are Peraluminous in composition and are generally emplaced in late to post-orogenic settings; and ii) the Niobium-Yttrium-Fluorine(NYF) Pegmatites, which are peralkaline and generally emplaced in anorogenic settings. For example, in Nigeria in Angwan Doka area North Central the pegmatites are simple and complexly zoned types that are characterized by LCT (Li, Cs, and Ta), and they occur as discordant dykes in the granitic and metasedimentary basement rocks (Akoh and Ogunleye, 2014).

The Nigerian Pegmatites are structurally controlled and according to Okunlola (2005) the ancient lineament systems of the Nigerian Basement Complex have been known to host rare-metal pegmatites with the intersections hosting the richest pegmatites. Garba (2002) and Okunlola, (2005) noted that rich concentrates of rare metal pegmatites in the late Precambrian terrain of Nigeria are concentrated close to major faults of transcurrent for example, the Kalangai fault system, the Ifewara fault system and the Anka fault system, which has southern extension up to the Okeogun areas in southwestern Nigeria. 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).

1.2 LOCATION AND ACCESSIBILITY

The study area is located in the north- western part of Nigeria, and is bounded by latitudes 11^{o} $22^{'}$ and $11^{o}37^{'}$N and longitude $08^{o}8^{'}$ and $08^{o}22^{'}$E, within 1:50,000 topographic sheets; 80 (Kabo SW and SE) and 1:50,000 sheet 103 (Ikara NW and NE) and covers an area of about 770km^2. It falls within Kiru and Bebeji Local Government Areas of Kano state (Fig. 1.1).

There is a network of untarred roads to major tarred roads which make the area highly accessible. The tarred roads include Kano to Kaduna express-way, Kafin-Maiyaki to TudunWada road and Kafin-Maiyaki to Kiru. The numerous footpaths and cattle tracks in the study area have also made it accessible.

1.3 CLIMATE AND VEGETATION

1.3.1 Climate

The climate of the study area falls within the West African savanna zone that is generally characterized by high temperatures throughout the year. In Kano State, there are seasonal temperature changes, indicating a gradual increase from January – April, where maximum values reach as high as 43^{o}C (Olafin, 2008).

Based on the temperature element three main seasons have been recognized: i) Cool and dry season: that lasts from November – Febuary, during which the mean monthly temperature is between 21- 23^{o}C with diurnal range of 12 – 14^{o}C. The Harmattan winds prevail at this period, also this period is characterized by low humidity due to prevalent NE – SW trade wind. The trade winds are laden with appreciable amount of dust particles which frequently obscure sunlight and lead to poor visibility. Also, the dust causes irritation and discomfort.

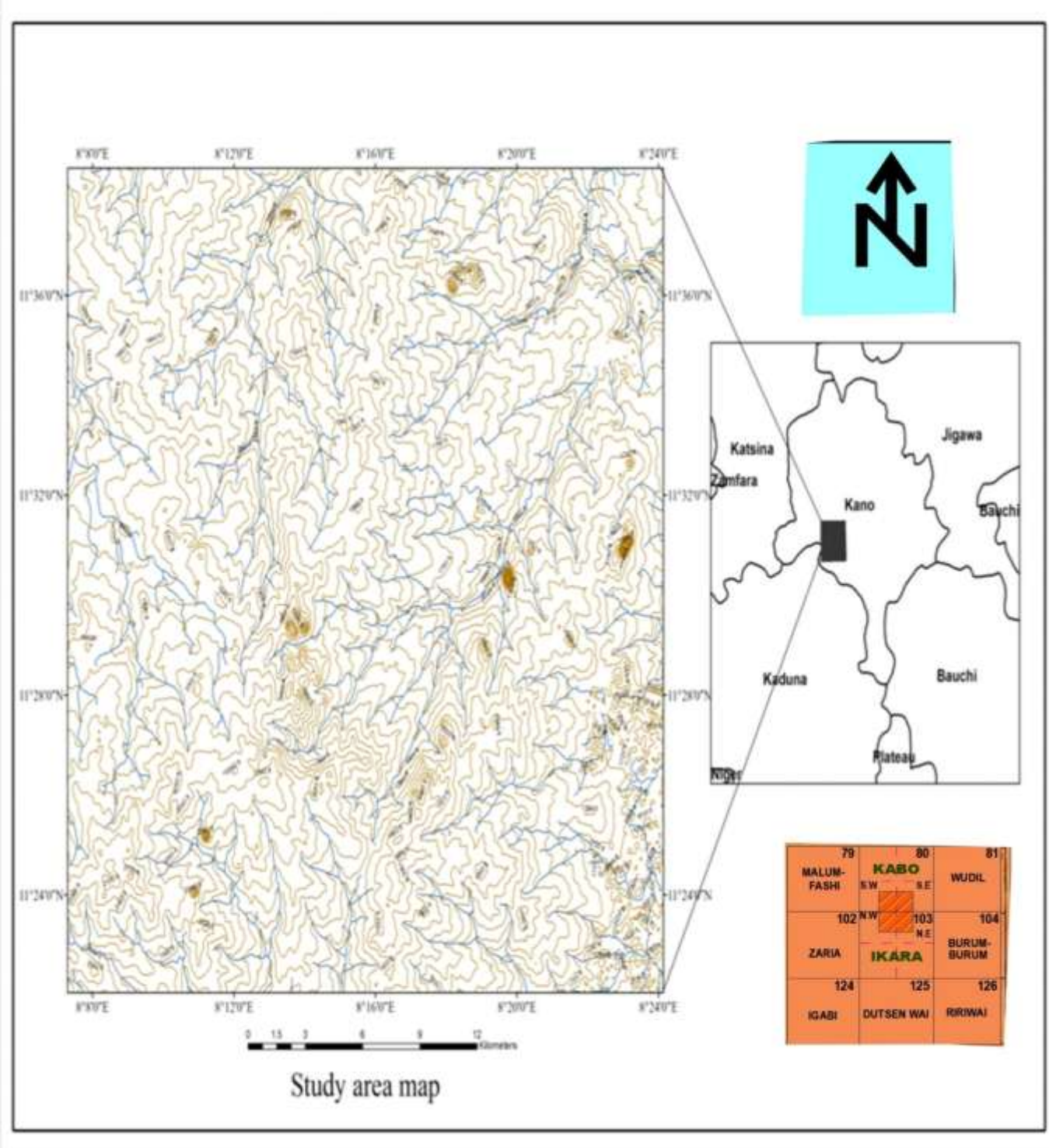


Fig 1.1: Location map of the study area, parts of sheets 80(Kabo SW and SE) and 103(Ikara NW and NE).

ii) Hot and dry season: that lasts from March – May and the mean temperature here is in excess of 35^0c. The hottest days occur between March – April with prolonged dryness and high rate of evapotranspiration, which causes serious shortage of water and also limits the rock – water interaction which results in low chemical weathering of rocks.

iii) Wet season: this is warm with mean monthly temperatures about 26^oC. This is when the amount of rainfall received is larger than the long- term mean. It covers the period from May-October in some part of the state, with a peak in July/August.

The annual amount of precipitation may reach about 1000mm in southern Kano State at Doguwa, Tudun-Wada) while in the Northern extreme, the annual value received is lower than 800mm more especially towards the desert. Although, the annual rainfall values are inconsistent from one year to another, the mean annual amount of precipitation in the study area is about 800mm (Olafin, 2008).

1.3.2 Vegetation

The normal vegetation of the region was originally defined as undisturbed Sudan Savanna and Guinea Savanna (Ibrahim, 2015). It has always been the dry Guinea Savanna in the southern fringe and the Sudan Savanna in the larger part of the region. The normal vegetation has now been subjected to destruction through fuel wood extraction, urban encroachment and population pressure. These leads to the formation of four vegetation zones in the region namely: i) Sudano Sahelian savanna, ii) Sudan Savanna; iii) Guinea Savanna; and iv) protected Guinea Savanna (Ibrahim, 2015).

There are thorny shrubs and small tree species which normally cover the land and abandoned areas of cultivation within the study area. Peculiar among the thorny shrubs are *Isoberhnia,*

Acanthospernum hispidum and *Guiera senegalenisis*. Grasses are the main species of vegetation that dominate both cultivable and uncultivated lands, and these include *Striga gesneriooles, Cyprus rotundus*. The protected Guinea savanna is wood land with grasses, in the class species such as Isoberinia doka and I. tomentosa form the bulk of the scattered woodland. *Parkia filicoidea* (locust) bean tree, shrubs and grasses are abundant; dominant among them are *Piliostigmathornni* (kargo) and *Acacia sieberiana* (Farar kaya).

Agricultural activities are practiced in the study area and the crops produced include; guinea-corn, millet, maize, rice and beans. Vegetables are cultivated as well e.g. onions, carbage, sugar-canes e.t.c. Therefore, the inhabitants of the area are grouped, into two farming communities namely; i) the rainy season farmers; and ii) the dry season farmers. Other factors that affect the vegetation which keep the vegetation low throughout the year are annual bush burning, heavy grazing and cutting down of trees as fuel for cooking.

1.4 RELIEF AND DRAINAGE

The geologic structures of the study area influence the relief as well as the land forms which are relatively flat with some undulations. The high lands occupy more than 50% of the study area and lie on elevation ranging from 450-650m above mean sea level (amsl).The hills may rise higher than 1500m above sea level, and they are commonly seen around Bauda and Gwarmai, and extend up to Tashan Baure in the Northern part of the study area. The other parts are flat-lying with some large igneous intrusions e.g. whalebacks. The lowest elevation is less than 200m and is found at example; Barebari. The drainage in the study area is mostly dendritic parttern in nature, characterized by some seasonal streams.The major rivers and streams in the study area include; Kwanroso, Samu, Garkuwa, Shinkatau, Suya (Fig.1.2).

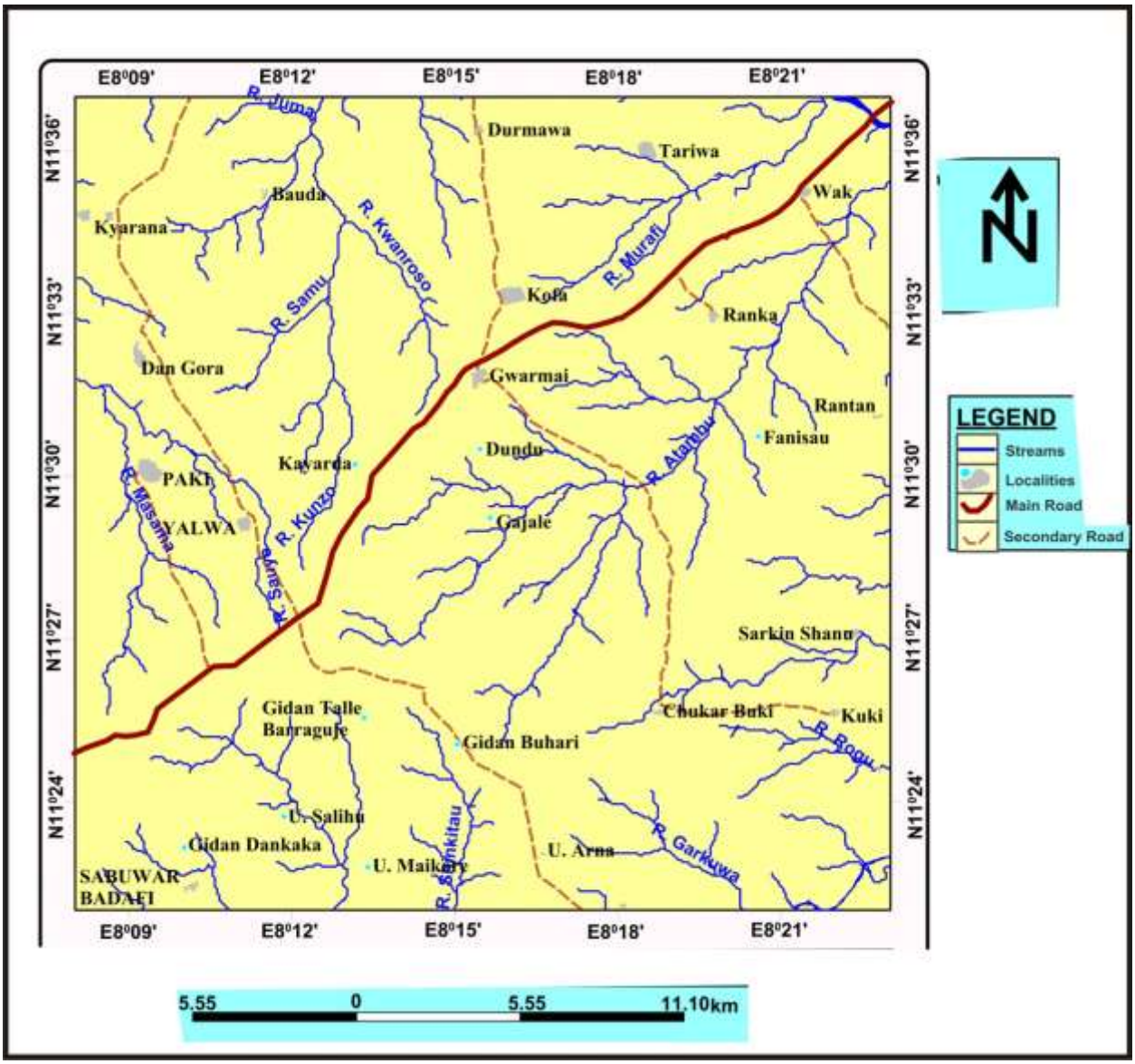


Fig.1.2: Drainage parttern of the study area.

1.5 PREVIOUS WORKS IN THE STUDY AREA

The study area is characterized by the Precambrian rocks of North-western Nigeria which include the migmatized gneissic complex (MGC) of Archean to early Proterozoic age (Grant,

1970, Dada, 1999), N-S trending Schist belts of Upper Proterozoic age (Rahaman, 1988) and Older Granitoid of Pan-African age (Fitches *et al*., 1985). The Basement rocks were affected by four Orogenic episodes, which include the Liberian (2700± 200Ma), Eburnean (2000 ±200Ma), Kibaran (1100 ± 200Ma) and lastly Pan-African Orogenies (600 ± 150Ma), as reported by Oversby (1975), Ogezi (1977), and Fitches *et al*., 1985). The area is well characterized by intrusions of pegmatites and aplite dykes. The pegmatites of the study area have been dated 562-534Ma, Matheis and Caen-Vanchette, (1983) indicating that the pegmatites were emplaced towards the end of the Pan-African magmatic activity.

Garba (2003) carried out a research on geochemical discrimination of newly discovered rare-metal bearing and barren pegmatites in the Pan-African (600± 150Ma) basement of northern Nigeria. He concluded that pegmatite bodies of rare-metal mineralization are found associated with all the major lithologies of the basement (i.e. gneisses, migmatites, schists and granitoids). The morphology and major mineral compositions (quartz-feldspar-mica) of barren pegmatites are mostly not different from those of the rare-metal pegmatite types. He also found out that the pegmatites of Badafi and Kafin- Maiyaki are barren and occur as dykes and lenses in conformity with the regional foliation trend of their host gneisses and migmatites. Occurrences of pegmatites in Angwan Doka area in North Central Nigeria, are genetically related the basement granites formed during the Pan-African orogeny, 550-530Ma.(Akoh *et al.,* 2015).

Okunlola (2005) presented geochemical evidence which showed that the Nigerian pegmatite fields are relatively poorer when compared with highly mineralized Tanco (Canada), Homestead and Wodinga (Australia) pegmatites but they are comparable to low-medium Ta (LCT= Li, Cs, and Ta) pegmatites of Buck, Oasis, and Noumas in U.S.A.

According to Jacobson and Webb (1946) and Garba (2003), the Nigerian Pan-African pegmatites have been the source of Cassiterite and columbite-tantalite production since 1912, especially in Central and Southwestern Nigeria. In Northeastern Nigeria, Islam and Baba (1992) reported the occurrence of pegmatites associated with manganese-bearing ore, large crystals of pure milky quartz and feldspars; and some heavy minerals such as monazite, leucoxene, zircon, cassiterite in stream sediments in Pulka and Ngoshe.

The Pegmatite veins in Oban massif were studied by Oden (2012) and noted that the pegmatites intruded pre-existing discontinuities like joints, faults, fracture lineaments, shear zones and foliations. He also found out that during the growth of the pegmatite vein, elongation per unit width or dilation was greater in granodiorite host rock than in schist. Pegmatite veins that developed in the post-tectonic setting grew freely, both in orientation and dimensions. Simply stated, for tectonic pegmatites, the longer the vein, the wider or thicker it is. The same behavior was notice in the basaltic dykes of eastern Iceland (Oden, 2012). He also noted that most pegmatite widths in Oban massif are between 1.0 – 1.5m. Compared to the pegmatites of Kivu and Manono in eastern D.R.Congo, those of Oban massif could be classified as small size dykes.

1.6 STATEMENT OF RESEARCH PROBLEMS

The presence of pegmatites in the study area was first reported by Garba (2003).The pegmatites that occur in other parts of the country have been studied by many authors e.g. in northeastern Nigeria by Islam and Baba (1992), Girei (2015). In Northwestern to North central Nigeria these pegmatites were studied by Jacobson and Web (1946), Garba (2002; 2003) and Okunlola and Ocan (2009); while in Southwestern Nigeria by Okunlola and Akinola (2010); Akintola et al., 2012.While in the Southeastern Nigeria by Wright (1970); Ekwueme and Matheis (1995). However, not much data exist on the role of existing fractures, joints and lineaments in the

development of pegmatite veins and dykes in the study area. Therefore, it will be a worthwhile research to study the geology, geochemistry and structural relationship of pegmatite dykes in the study area.

1.7 AIM, OBJECTIVES AND SCOPE OF PRESENT WORK

The Work is aimed at studying the geological and structural pattern of the area on a scale of 1:50,000 and thereby determine the role of structural control to the emplacement of pegmatites.

With the following objectives:

i) To produce the geologic map of the study area on a scale of 1:50,000.

ii) To study and map of the pegmatite sub-areas on a scale of 1:10,000.

iii) To determine the petrography and geochemistry of the study area.

iv) To discriminate between rare-metal bearing and barren pegmatites in the study area, base on their trace elements composition.

v) To deduce the structural relationships of the pegmatite dykes in the study area base on field evidences.

The scope of the work includes petrographic study of the rocks samples using petrological microscope, as well as whole rock geochemical analysis of representative rock samples and feldspar samples extracted from pegmatites, using ICP-MS and XRF. The geochemical composition of feldspar will help establish the mode of evolution and mineral potential of the pegmatites in the study area.

1.8 JUSTIFICATION

The Badafi pegmatite field was adjudged to be barren especially with regard to rare metal potential (Garba 2003). However; the pegmatites are currently being exploited for beryl (aquamarine). This situation necessitates a need for further study. This thesis therefore focuses on field, structural and geochemical study of the pegmatites and their associated granitoids in order to determine their petrogenetic evolution and inferred the possible source of the beryl mineralization in pegmatites in the light of new petrological as well as major and trace element data obtained from the rock. It has long been established that detailed petrological and geochemical data of crystalline rock units often yield valuable insight into their petrogenetic history and mineralization potential (e.g Akoh and Ogunleye 2014).

CHAPTER TWO

LITERATURE REVIEW

2.1 PREAMBLE

This chapter is aimed at reviewing previous work done on the regional geology of Nigeria and the geology, characterization and origin of pegmatites of Nigeria. Emphasis is given on the lithologies, structural pattern, and age relationships within the Basement Complex which is part of the study area.

2.2 The Nigerian Basement Complex

The Nigerian Basement Complex is located within the Pan-African mobile belt and lies between the West-African Craton to the west and the Congo Craton to the Southeast (Fig.2.1). It is a continuum between the Hoggar to the north (McCurry, 1976) and the Boborema Province to the south (Caby, 1989; Dada, 2008).The belt was as a result of continental collision (plate tectonics) between two blocks, i.e., the passive continental margin of West African Craton and the active continental margin (Pharusian belt) about 600Ma (Ajibade *et al.*, 1987; Caby *et al.*, 1981; Garba, 2002).

The Nigerian basement comprises of Precambrian basement rocks, anorogenic Younger granites of Jurrasic age.Cretaceous to recent sediments and Tertiary to recent volcanic rocks (Black, 1980) (Fig. 2.2). The basement is divided into two contrasting provinces viz: the Western and the

Eastern Province (Ferre, *et al.,* 1996). The Western Province is characterized by an Archean basement comprising tonalite-tronndhjemite granodiorite (TTG) type Orthogneisses and amphibolites (Rahaman, 1988) which correspond to a gold metallogenic province (Woakes *et al.,*1987) in which amphibolites display greenstone affinities and a cover of synformal schist belts, ranging from greenschist to amphibolites facies.

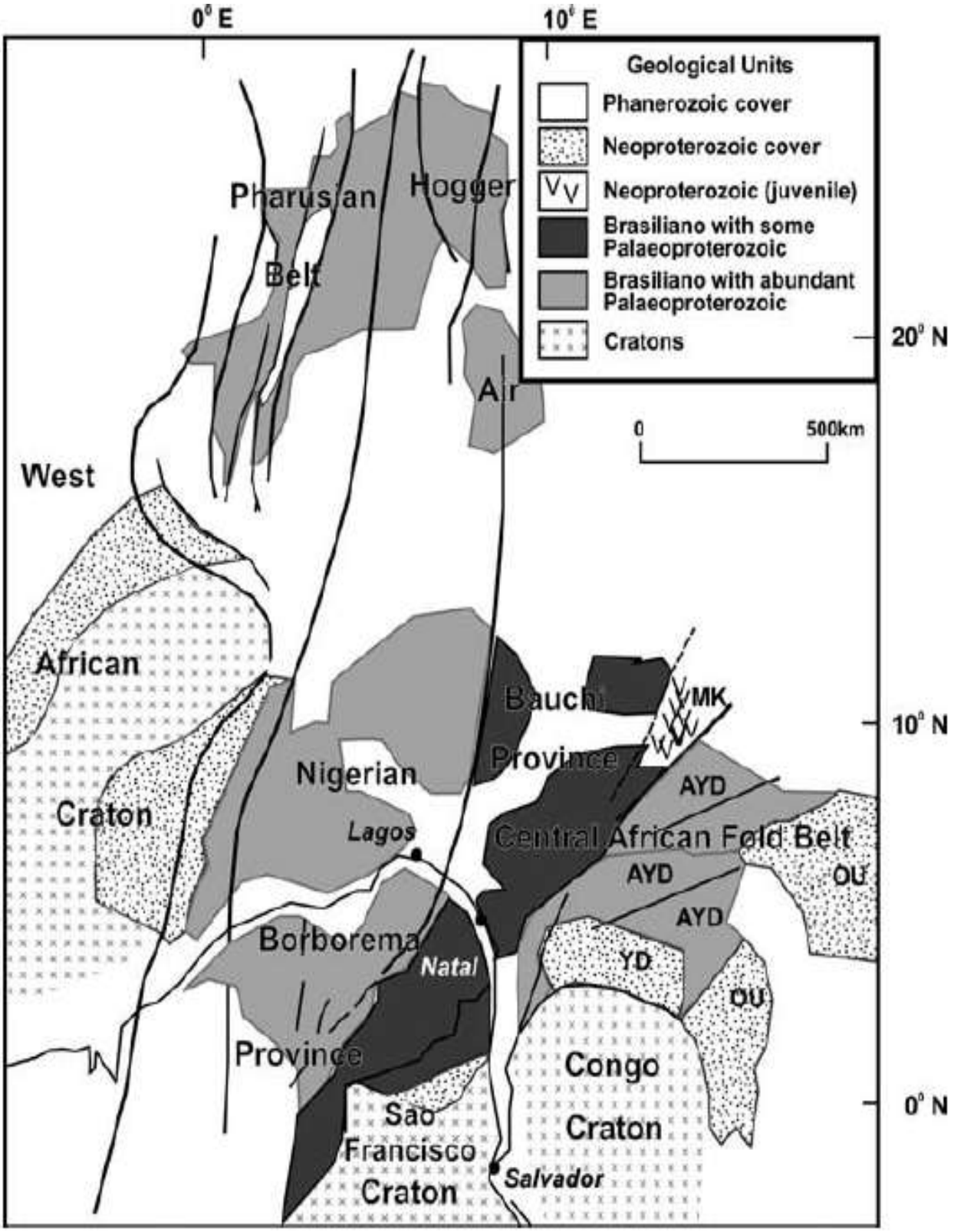


Fig.2.1: Location of the Nigerian Basement Complex between the West African and Congo Cratons, in relation to Hoggar and Borborema Provinces (after, Dada, 2008)

The Eastern Province is characterized by high-grade metamorphic rocks (Onyeagocha and Ekwueme, 1990) pervasive migmatisation and granite plutonism (Ferre *et al.,* 1996) and a tin metallogenic province: the boundary between these two provinces marked by a major lineament on the landsat image (Ananaba and Ajakaye, 1987).

The structural pattern in Nigerian basement is defined by both brittle deformational structures (faults and shear zones) and ductile deformational structures (folds and foliations).It has been reported as comprising NE- SW and N-S lineament superimposed over dominant N-S trends and a NW-SE, NE-SW pair superimposed on a N-S joint set (Annor *et al.,* 1998).

The Nigerian basement consists of five major rock types that include; i). migmatite-gneiss-quartzite complex; ii). Schists belts; iii). Older Granites; iv) metamorphosed to unmetamorphosed calc-alkaline volcanics and hypabyssal rocks; examples tuffs, rhyolites, rhyodacite and v). unmetamorphosed dolerite dykes, basic and syenite dykes.

2.2.1 The Migmatite-Gneiss-Complex (MGC)

The migmatite gneiss is generally considered as the basement complex sensu-strcto (Rahaman, 1988; Dada, 2006) and it is the most wide spread and forms the groundmass in which all other rocks seem to occur. 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, 2008). Oyawoye (1972) recognized the following rock types as part of MGC: banded gneiss; augen gneiss and pegmatites. He also 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± 30Ma.

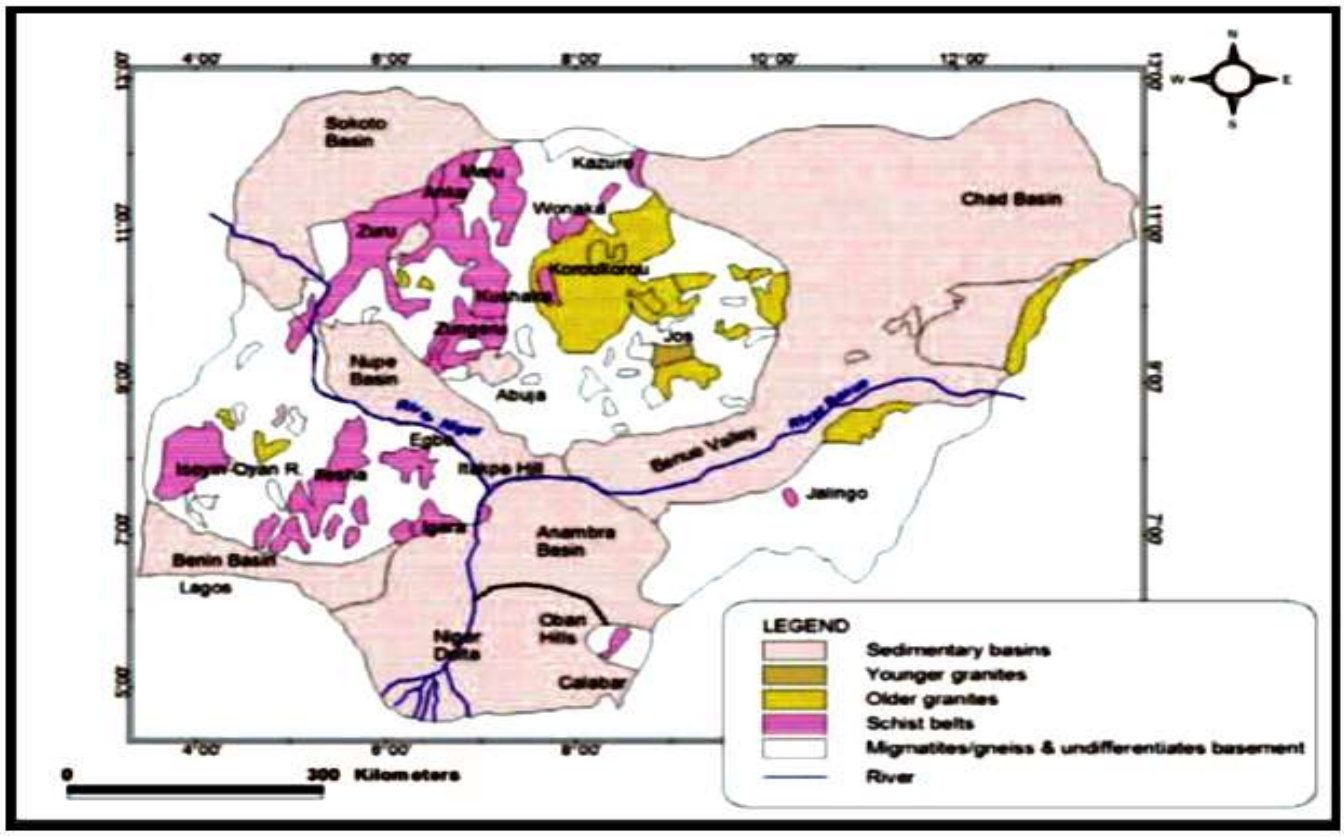


Fig.2.2: Geological Map of Nigeria, showing the distribution of rock types in Nigeria (after Black, 1980).

However, Rahaman (1988) gave a petrologic division of the MGC that includes: (a) grey foliated biotite acid or biotite hornblende quartz feldspathic gneiss of tonalitic to granodioritic composition, which is also known as the "grey gneiss"; (b). mafic and ultramafic components which when present, often outcrop as discontinuous boudinaged lenses or concordant sheets of amphibolites with minor amounts of biotite-rich ultramafic; and (c) Felsic components of a

varied group of rocks consisting essentially of pegmatites, aplite, quartz oligoclase veins and fine-gained granitic gneiss.

These three components may not be present together on a single outcrop. Also, petrographic evidence indicates that the Pan-African reworking led to recrystallization of many of the constituent minerals of the migmatite – gneiss complex by partial melting, with majority of the rock types displaying medium to upper amphibolites facies metamorphism and are Archean in age (Dada *et al*., 1998).

The MGC is heterogeneous assemblage including migmatized gneisses, orthogneisses, para-gneisses and a series of metamorphosed basic and ultrabasic rocks. But Ajibade (1980) distinguished the ancient migmatites in Nigeria from the Pan-African migmatites structurally by their complex polyphase deformation and mylonitization.

2.2.2 Shist Belts

The schist belts are composed of older metasediments and the low-grade younger metasedimentary and metavolcanic rocks that are well developed in the western part of Nigeria (west of longitude 8^{o}E), though smaller occurrence are found in the east. In the South east and Northeastern Nigeria, Rahaman and Ukpong (1981) reported the occurrences of schists in Jalingo and the Oban Hills. There are eight major schist Belts in NW Nigeria, and these include:

i) Anka; ii) Maru; iii) Birnin-Gwari; iv) Wonaka; v) Malumfashi; vi) Kazaure; vii) Zuru and viii) Kushaka (Fig.2.3).

ii) In the south western part of Nigeria there are three of such belts viz:

i) Iseyin-Oyan river belt; ii) Ife-Ilesha belts; and iii) Igarra-Kabba -Lokoja belt.

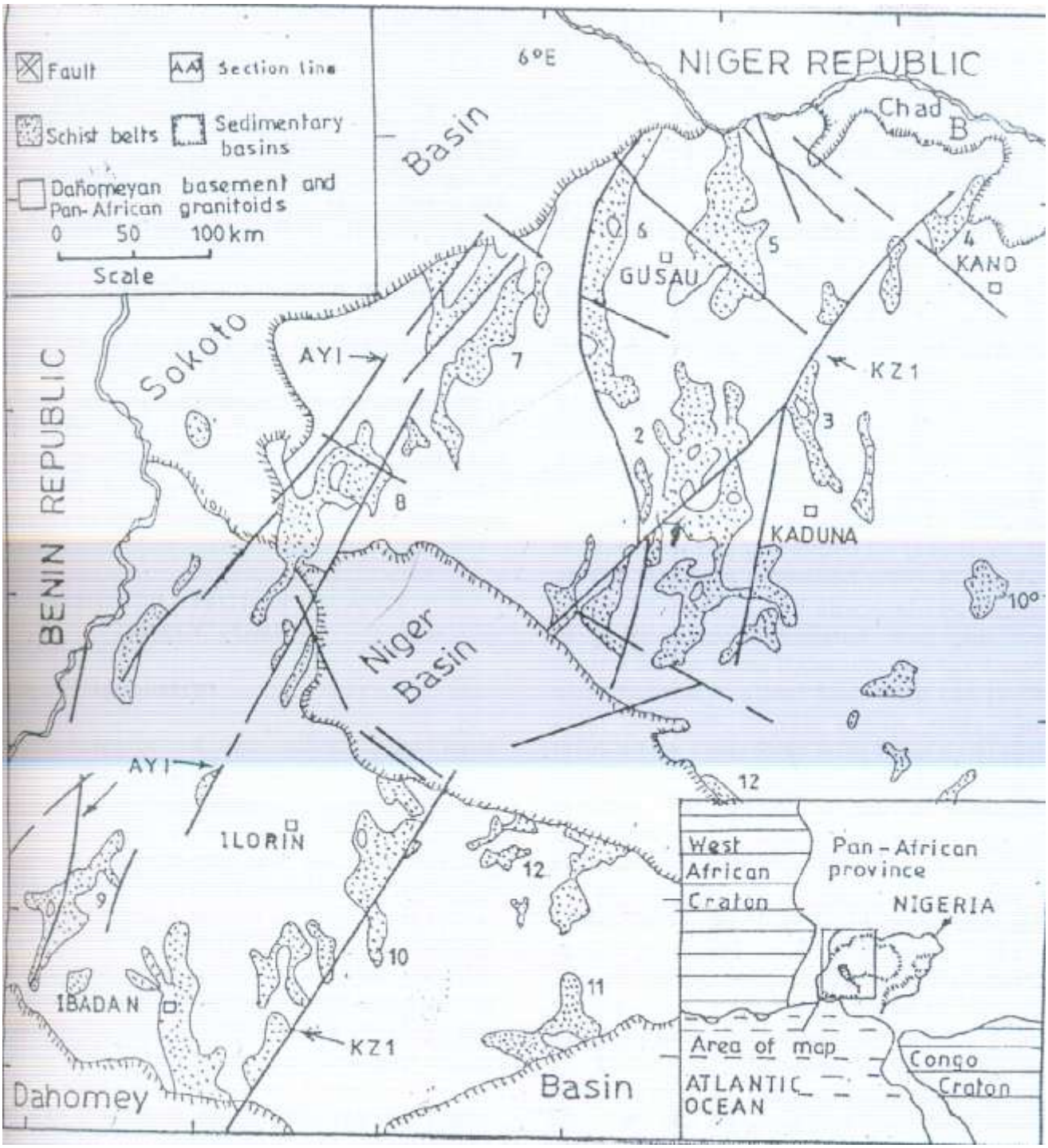


Fig. 2.3: Simplified geological map of the western half of Nigeria, showing the distribution of the schist belts and the locations of major lineaments (after Garba, 2002).

The Iseyin-Oyan river belt appears to form part of the Archean gneiss quartzites schist sequence in the Ibadan area (Burke *et al.,* 1976). The Ife-Ilesha belt consists of two contrasting rock assemblages separated by a NNE trending Ifewara fault (Klemm *et al.,* 1984; Boesse and Ocan, 1988; Elueze, 1988). To the west of this fault are mafic rocks and pelitic schist association, while the eastern part of the fault is made up of quartzites and quartzo- feldspathic gneisses (Effon unit). The Igarra-Kabba-Lokoja belt consist of metapelites with interlayered quartzites and marble (Odeyemi, 1977; Turner, 1983; Annor, 1998).

The lithologies of the schist belts have similarities and generally consist of coarse-fine grained clastics, pelitic schist, phyllites, banded iron formation (BIF), Carbonate rocks (marbles) dolomitic marbles and metavolcanics (amphibolites), example include fragments of ocean floor material from small back-arc basin. Rahaman (1976) and Grant (1978) for example suggest that there were several basins of deposition whereas Oyawoye (1972) and McCurry (1976) considered the schist belts as relicts of a single supracrustal cover. Olade and Elueze (1979) consider the schist belts to be fault-controlled rift-like structures. Based on structural and lithological association Ajibade *et al.* (1979) conclude that the schist belts contained identical deformational histories.

The structural relationship between the schist belts and the basement were considered by Truswell and Cope (1963) to be conformable metamorphic fronts and it was Ajibade *et al.,* (1979) who first mapped a structural break at the Zungeru area (the Zungeru mylonites). The schist belt rocks are generally considered to be Upper Proterozoic in age.

The Nigerian schist belts are assumed to be of two types (Danbatta, 2008); those composed of Older Metasediments (mainly found in SW Nigeria) and the low-grade Younger Metasediments (mainly found in NW Nigeria). The closure of the ocean at the West African cratonic margin led

to the deformation and metamorphism of the sediments and underlying basement during the Pan-African Orogeny (Oyawoye, 1972; McCurry, 1973; Ajibade, 1980; Chukwu-Ike, 1978; Danbatta, 1999). Also Vaniman (1976) considered the existence of a major sedimentary trough to be responsible for the deposition of the Nigerian schist belts.

A similar scenario was postulated by Chukwu-Ike (1978), who argued that the schist belts in NW Nigeria are fault bounded ensialic troughs. Similarly, Turner (1983) considered the Anka belt with Maru, Birnin-Gwari, Wonaka, Malumfashi and Kazaure belts, as originating in one back arc basin. The Zuru and Kushaka belts were also considered to have formed in a seprate basin, with the Zuru quartzites representing basin margin deposits. All the models of evolution of Nigerian schist belts over the years could be classified under ensialic and ensimatic processes, or a combination of the two.

According to those in favour of ensialic evolution processes, crystal thinning in response to initial crustal extension and continental rifting at the cratonic margin some 1000Ma ago, led to deposition of sediments in graben like structures floored by continental crust. The closure of the ocean at the West African cratonic margin led to the deformation and metamorphism of the sediments and underlying basement resulting in the formation of the schist belts and reactivation of older basement during the Pan-African Orogeny (Oyawoye, 1972; McCurry, 1976; 1973; Turner, 1983; Ajibade et al., 1987; Danbatta, 1999). While Vaniman (1976) proposed the existence of a major sedimentary trough to be responsible for the deposition of the Nigerian schist belts, Chukwu- Ike (1978) argued that the schist belts in NW Nigeria are deposited in fault bounded ensialic troughs.

Turner (1983) also considered the Anka belt with the Maru, Birnin Gwari, Wonaka, Malumfashi and Kazaure belts, as originating in one back – arc ensialic basin. The Zuru and Kushaka belts were considered by Turner (1983) to have formed in a separate ensialic basin, with the Zuru quartzite, representing basin margin deposits. Fitches *et al.* (1985) and Udoh (1987) envisaged complex volcano-sedimentary trough deposits, with the formations in the belts being lateral facies equivalents. Corroborating this view, Ajibade, (1976) proposed the formation of back-arc ensialic graben-like structures during Pan-African times to be responsible for the formation of the schist belts. However, recent suggestion by Olabanyi (1997) emphasized the role of Eburnean event in the formation of the Egbe-Isanlu basin due to plume induced continental rift.

Ensimatic models of evolution had also been repeatedly proposed to explain the evolution of some of the scist belts (e.g. Ogezi, 1977; McCurry and Wright, 1977; Holt *et al.*, 1978; Utke, 1987; Danbatta, 1991; Elueze, 1992). For the Anka, Ife – Ilesha and Zuru belts, earlier works suggested that oceanic basins closed to form some of the schist belts, invoking the formation of marginal back-arc basins floored by oceanic materials that accepted sediments. The closure of these ensimatic basins led to the deformation and metamorphism of the sediments and reactivation of Older Metasediments. Holt (1982) observed that the Anka metavolcanics have chemical characteristics of both island arcs and continental environment. He concluded that the schist belts were deposited in a retro-arc ensimatic basin related to the subduction processes along the margin of the West African craton. These schist belts possibly represent additional microcontinents separated from a pre-existing one (Turner, 1983; Utke 1987). The mafic and ultramafic rock units preserved in the Sado fault zone in the Anka belt (Ogezi, 1977; Wright and Ogezi, 1977), the Anka fault system in the Zuru belt and Ifewara fault system have ensimatic

affinities. The Anka and Zuru belts are considered as a pair of belts that evolved through ensimatic processes.

The evolution of the schist belts is also considered in the context of Eburnean deformation, under extensional and compressional regimes (Danbatta, 2008). Schist belts without mafic and ultramafic rocks but with documented presence of Algoma BIFs are considered ensialic and Eburnean in age, while BIFs are absence in those schist belts whose origin is ascribed to ensimatic processes and Pan-African in age (Danbatta, 2008).

The structural control is also important for the evolution of the Schist belts; the huge Anka-Yauri – Iseyin (AYI) and the Kalangai – Zungeru – Ifewara (KZI) lineaments that traverse throughout the area are considered as deep-faults defining tectonic blocks (Danbatta, 2008). Along the AYI fault Zone, Wilson Cycle processes involving the opening and closing of east – west back arc oceans have operated locally. Closure of the basins led to the deformation of the sediments, the reactivation of pre-existing rocks and the formation of the remaining schist belts and syn orogenic plutonism.

2.2.3 **Older Granites**

The term Older Granites or Pan-African granitoids were introduced by Falconer (1911) to distinguish the concordant or semi-concordant granites of the basement complex from the high-level, highly discordant tin-bearing granites of north central Nigeria. They included; the pre, syn and post tectonic granitoids which intruded both the migmatite gneiss-quartzite complex and schist belts. They range widely in age (750 – 450 Ma) and were formed during a magmatic cycle associated with Pan-African orogeny. The rocks range in composition from tonalites and diorites through granodiorites to true granites and syenites. Charnockites also form an important rock group emplaced during this period. They are generally high level intrusions and anatexis has

played an important role during their formation (Rahaman, 1988). The Older Granite suite is notable for its general lack of associated mineralization.

2.2.4 Volcanics and Hypabyssal rocks

Sub-volcanic complexes occur in several places in north-west and north-east Nigeria, (McCurry and Wright, 1977) and are either or partly intrusive into Older Granite bodies. They include: rhyolites, rhyodacites and dacites. Preliminary age determinations in northwestern Nigeria indicate that these rocks were emplaced during epeirogenic uplift and regional cooling towards the close of Pan-African orogeny. This may account for the general absence of chilled contacts and for the high degree of alteration in many of these rocks. Common alterations of minerals are; calcite, epidote and secondary sericite and the original composition is often difficult to determine.

2.2.5 Dolerite Dykes

Dolerite dykes are wide spread in the basement and have been described in association with all the other rock types. They occur as tabular and unmetamorphosed bodies, often with chilled margins. They cut across pre-existing foliation in the host rocks and are regarded by most authors as the young members of the basement complex. They range in size from few millimeters to several metres in thickness. Structurally they mostly tend to follow NE-SW and ENE-WSW directions i.e. they are related to the major fracture directions which have been recognized within the Basement (Rahaman, 1988).

2.3 THE NIGERIAN PEGMATITES

2.3.1 Description

The Pegmatites occur as small veins and dykes cross cutting other rock units. They also occur as huge bodies of simple or complex mineralogy and structure with rare-metal mineralization's. Therefore, the Nigerian Pan-African pegmatites are known to host many metallic and non-metallic minerals that are of economic benefits. The Nigerian pegmatites were formed during the span of 562-534Ma, indicating emplacement related to the end of the Pan-African magmatic activity and have been sources of cassiterite and columbite-tantalite production since 1912,in central and south-west Nigeria (Garba, 2003).

Based on mineralization, the Nigeria pegmatites have been classified into two:- i) barren pegmatites and ii) rare-metal pegmatites (Fig.2.4).

2.3.2 Simple Pegmatites

Barren pegmatites are those bodies, barren of rare-metal mineralization and they are sometimes called simple pegmatites. Matheis and Caen-Vachette (1983) noted that, the simple pegmatites are about 100Ma older than the rare- metal pegmatites and are not directly related to any intrusive activity. 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., gneisses, 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). Also, Barren pegmatites are very important source and are exploited for industrial minerals. For example, in Nigeria, quartz and feldspar constitute the major industrial minerals occurring in the Pan-African pegmatite. Prominent areas where these minerals are exploited include Liga and Lufu hills in northeastern Nigeria, and Ijero area in Southwestern Nigeria (Girei *et al*., 2014).

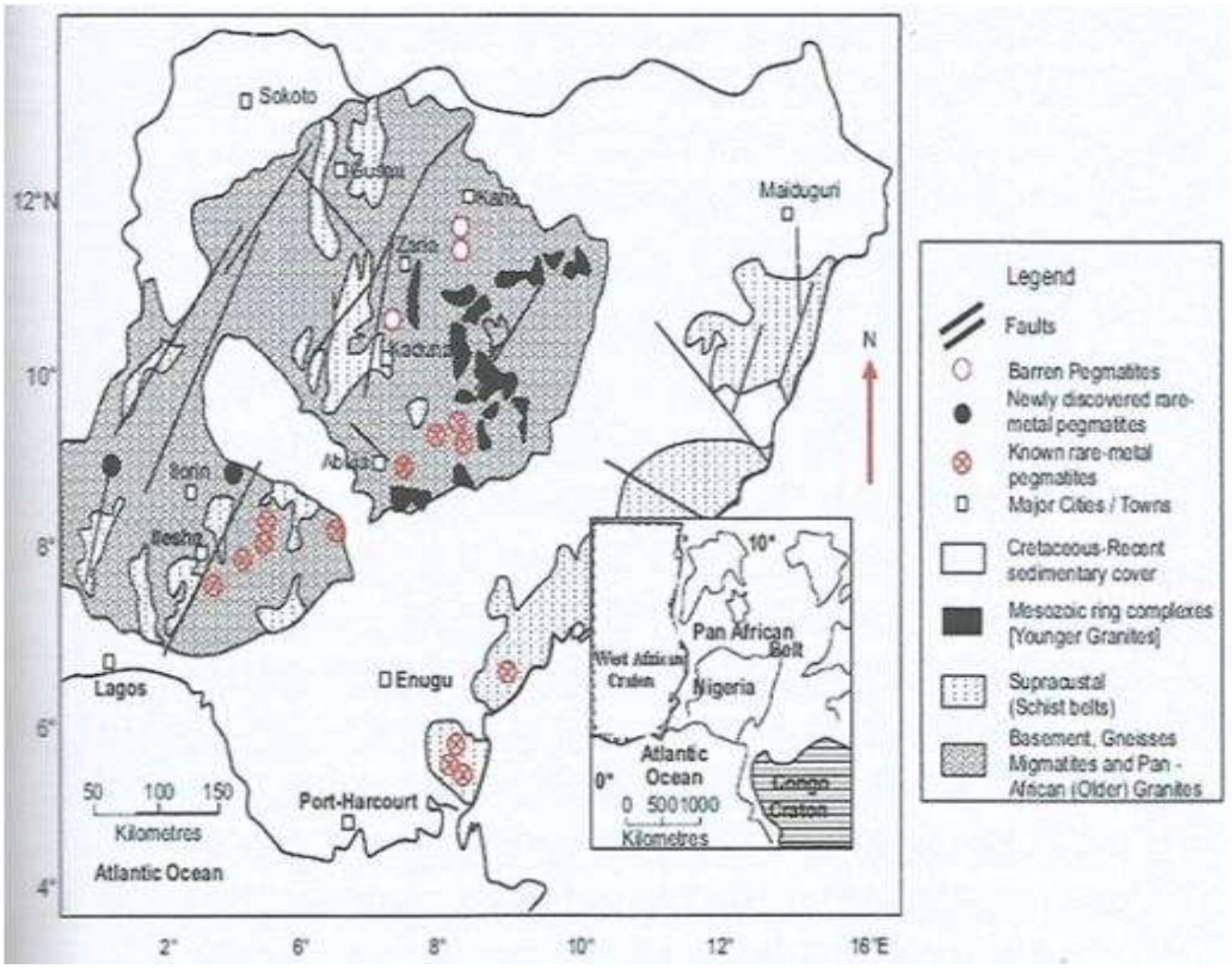


Fig.2.4: Geological map of Nigeria showing the location of barren and rare-metal pegmatites (adapted from Garba, 2003).

2.3.3 Rare-metal Pegmatites

The rare-metal pegmatites of Nigeria are generally complex. They are muscovite-quartz-microcline with indiscernible to distinct zonations (Okunlola and Jimba, 2006). Okunlola (2005) also noted that rare-metal pegmatites of Nigeria are similar to the Woringa pegmatites in Australia. Also, the Nigeria rare-metal pegmatites share similarities with the Damaran pegmatites of Namibia with both having LCT (Li, Cs, and Ta) pegmatites and a Sn-W rich pegmatites association. The occurrence of rare-metal pegmatites have been reported in the Obudu and Oban massifs in southeastern Nigeria (Ekwueme and Matheis 1995; Oden *et al*., 2013). In Northeastern Nigeria similar rare-metal pegmatites were reported by Islam and Baba (1992); and Girei (2015), while, Garba (2003) reported occurrences of rare-metal pegmatites in Nasarawa and Richifa in central Nigeria and in north-western Nigeria in Kushaka, Magami and Maradun. 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 vii) Ibadan- Osogbo viii) Kushaka- BirninGwari.

The Nigerian rare-metal pegmatites have a very common feature of their proximity to major and subsidiary fault structures. They also have sharp contacts with their host rocks, and wall rock alteration (of mostly tourmalinisation) is a common phenomenon (Garba, 2003). The host rocks include migmatite-gneisses, schists and granitoids.

2.3.4 Structural Controls

The ancient lineament systems of the Nigerian Basement Complex are known to control the distribution of rare-metal and barren pegmatite (Okunlola, 2005), Garba (2002) and Okunlola (2005) noted that rich concentrate of rare- metal pegmatites in the late Precambrian terrain of

Nigeria are concentrated close to major transcurrent faults, for example the Kalanngai, the Ifewara and the Anka fault systems which has southern extension up to the Okeogun areas in the southwest.

The trends of the faults and inherent displacement are highly variable according to the type of rock. Mylonitization, silicification and localized dextral sense of shearing especially of amphibolite and diorite emplacement are some of the surface expressions of the faults and these may represent remnants of obducted ophiolite (Ajibade and Wright, 1989; Garba, 2002). Deformational episodes producing tight to isoclinals 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). Therefore, the rare-metal mineralizations are associated with prominent regional faults in the basement complex of Nigeria (Garba, 2002).

2.3.5 ORIGIN OF PEGMATITES

Pegmatites intrusions are common in all phases of the evolution of orogens (Liegoes, 1998). Those that cross-cut the main metamorphic foliation are considered late-post-collitional intrutions, their origin is attributed to a process called orogenic collapse or when the convergence of the plates is at very low rates. The origin of rare-metal bearing pegmatites are also associated with magmatic and crustal influence defined by enrichment of the LREE, and marked negative Eu anomaly and relative depletion of the HREE (Garba, 2005). The magmatic origin is not disputable from the fact that the REE and lithophile element trends, only that there appears to be evidence of some crustal influence, possibly because of their metasedimentary host rock (Garba, 2003).

Garba (2005) noted that the similarity in their REE distribution pattern rare-metal pegmatite and the Younger Granites bring doubt on their origin from magmas of the main syn- tectonic granitoids (the older granites). But Garba (2002) had earlier suggested that they may have been sourced from peraluminous late –tectonic granites rather than the typically calc-alkaline syntectonic granitoids. The rare-metal enriched pegmatites of southwestern Nigeria may be 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). They also suggested derivation of rare-metal pegmatite mineralization, especially in southwestern Nigeria, from reactivation of deep-seated tectonic lineament combined with partial melting and external fluid supply.

The pegmatites are emplaced along major faults, albitization and rare-metal mineralization may have been due to late stage fluids available at the close of the Pan- African metamorphic cycle or due to Na-rich hydrothermal solutions from the mantle along ancient lineaments (Garba, 2002). The development of rare-metal pegmatites of the Wamba area of central Nigeria is genetically related to the late tectonic granite magmatism (Kuster, 1990) which was controlled by late Pan-African NE-SW and NW-SE shear system. He also noted that 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 possible 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).

The aluminosilicate index = AL/alkali ratio (ASI) and the flux content (Li-F-B-P) are therefore important compositional parameters influencing rare-metal enrichment in pegmatitic melts. In

particular, fluxes considerably lower melt viscosity and solidus temperature, allowing pegmatitic melts to travel kilometers away from their source before crystallization starts. Thus, the most fractionated pegmatites are crystallized by large (kilometer scale) dykes, complex internal structures, giant crystal size, and complex mineralogy, textures and assemblages. These characteristics are the result of rapid, disequlibrium crystallization from undercooled, flux-rich melts. Fluxes decrease the nucleation rates by preventing the formation of crystal nuclei, and increase the growing rates by promoting high element diffusivities.

CHAPTER THREE

METHODOLOGY

3.1 PREAMBLE

The methods used for this research work consist of field study and laboratory analyses. The field study exercise involved geological mapping on a scale of 1:50,000 and mapping of the pegmatites and quartz veins on a scale of 1:10,000 which was carried out with topographic map, geologic hammer, compass-clinometer, GPS and measuring tape.

The laboratory analysis involved sample preparation, petrographic study, and geochemical analysis. The petrographic study was undertaken with the aid of petrological microscope at the Department of Geology, Ahmadu Bello University, Zaria. For the geochemical analysis a

combination of ICP-MS and XRF techniques were employed in the determination of major, trace and REE elements which were carried out at the ACME Analytical laboratory, Canada.

3.2 FIELD INVESTIGATIONS

The field exercise was carried out in stages, first was a reconnaissance visit and then followed by the geological field mapping on a scale of 1:50,000. From which fresh rock and mineral samples were collected for hand specimen examination. 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 sample point using Global positioning system (GPS) were also carried out. Field structures of the area were studied, where particular attention was paid to the location, mineralogy and physical characteristics of the pegmatite and quartz veins. Some of the pegmatite dykes were sampled for geochemical analysis. For each pegmatite dyke, its structural attitude, its length and width, as well as the coordinates of its location were carefully measured. Other structures like fractures and joints were also mapped and recorded.

3.3 LABORATORY ANALYSIS

3.3.1 Petrography

Under the petrographic studies, fifteen rock (15) samples were cut in to chips with a cutting machine and followed by polishing using carborundum powder of 0.6, 0.4 and 0.2mm to obtain slides with required thicknesses and a smooth surface. The prepared thin section slides were examined under the petrological microscope to identify minerals and other features that were not identified with the aid of magnifying lens.

3.3.2 Geochemical Techniques

The geochemical analysis consists of a total of twenty samples. Eleven (11) representative whole rock samples; comprising of each mappable lithologic unit which include migmatite, migmatitic gneiss, porphyritic biotite granite, coarse grained biotite granite, medium grained biotite granite, biotite hornblende granite, granodiorite and aplite. In addition, six (6) minerals and three (3) whole rock samples were extracted from the pegmatite dykes and analysed for major and trace elements including rare earth element (REE).

About 1kg of each of the samples was broken in to pieces with a hammer and crushed into smaller pieces with a jaw crusher. The samples were thoroughly homogenized to obtain a representative portion and thereafter pulverized in a disc mill for about two minutes. The pulverized samples were then shipped for major and trace elements analysis at the (ACME analytical laboratory, Vancouver Canada).Using inductively-coupled atomic emission spectro-photometry (ICP-MS) and X-ray florescence (XRF) techniques.

Major elements were analyzed using X-ray fluorescene (XRF). The identification of elements by x-ray methods is possible due to the characteristic radiation emitted from the inner electronic shells of the atoms under certain conditions. The XRF is based on the principle that individual atoms, when exited by an external energy source, emit x-ray photons of a characteristic energy or wavelength. By counting number of photons of each energy emitted from a sample, the element present may be identified and quantitated. Modern XRF instrument are capable of analyzing solid, liquid and thin film samples for major element. The analysis is rapid and usually sample preparation is minimal or not required at all. Therefore, by determining the energy (wavelength) of the x-ray light (photon) emitted by a particular element, it is possible to determine the identity of that element.

The merit of the XRF is that, it is well suited for investigation that involves bulk chemical analyses of major elements. But the demerit is that it cannot distinguish ions of the same element in different valence states, so these analyses of rocks and minerals are done with techniques such as wet chemical analysis or mass spectroscopy.

The trace elements were analyzed by Inductively-coupled Plasma Mass Spectrometry (ICP-MS) from pulps after 0.2g of rock powder was fused with 1.5g $LiBO_2$ and then dissolved in 10ml of trioxonitrate (v) acid (HNO_3). The REE (rare-earth element) contents were determined by ICP-MS from pulps after 0.25g rock powder was dissolved with 5ml of perchloric acid ($HCLO_4$) and trioxonitrate (v) acid (HNO_3) and 15ml of hydrofluoric acid (HF). The analytical precisions vary from 0.1 to 0.5ppm for trace elements and from 0.01 to 0.5ppm for rare earth elements.

CHAPTER FOUR

RESULTS

4.1 GEOLOGY AND PETROGRAPHY OF THE STUDY AREA

4.1.1 Rock types

The study area is composed of low-lying migmatite, migmatitic gneiss, porphyritic biotite granites, coarse grained biotite granite, medium grained biotite granite, hornblende biotie granite,

granodiorite, aplite and pegmatites (Fig.4.1). Contact relationships between the various rock types are commonly gradational although sharp contacts were also encountered.

4.1.2 **Migmatites**

The migmatites occur as low-lying massive rock bodies restricted to the northern and western part of the study area. The rock shows conspicuous segregation into mafic and felsic bands few millimeters to ten centimeter wide. Texturally, it is fine to medium grained (Plate I). In hand lens, light coloured minerals observed are feldspar and quartz which constitute the bulk of the felsic bands, while biotite constitutes the dominant ferromagnesian minerals in the dark bands. In thin section, the rock is composed of quartz, biotite, orthoclase feldspar, microcline, plagioclase feldspar. The quartz is anhedral, colourless with low relief and biotite has moderate relief and shows strong pleochroism from light to dark brown while, plagioclase is commonly sodic albite (An_5-An_{10}) and occur as colourless but cloudy crystals. The orthoclase feldspar displays light grey first order interference colour with albite twinning (Plate IIa and II b).

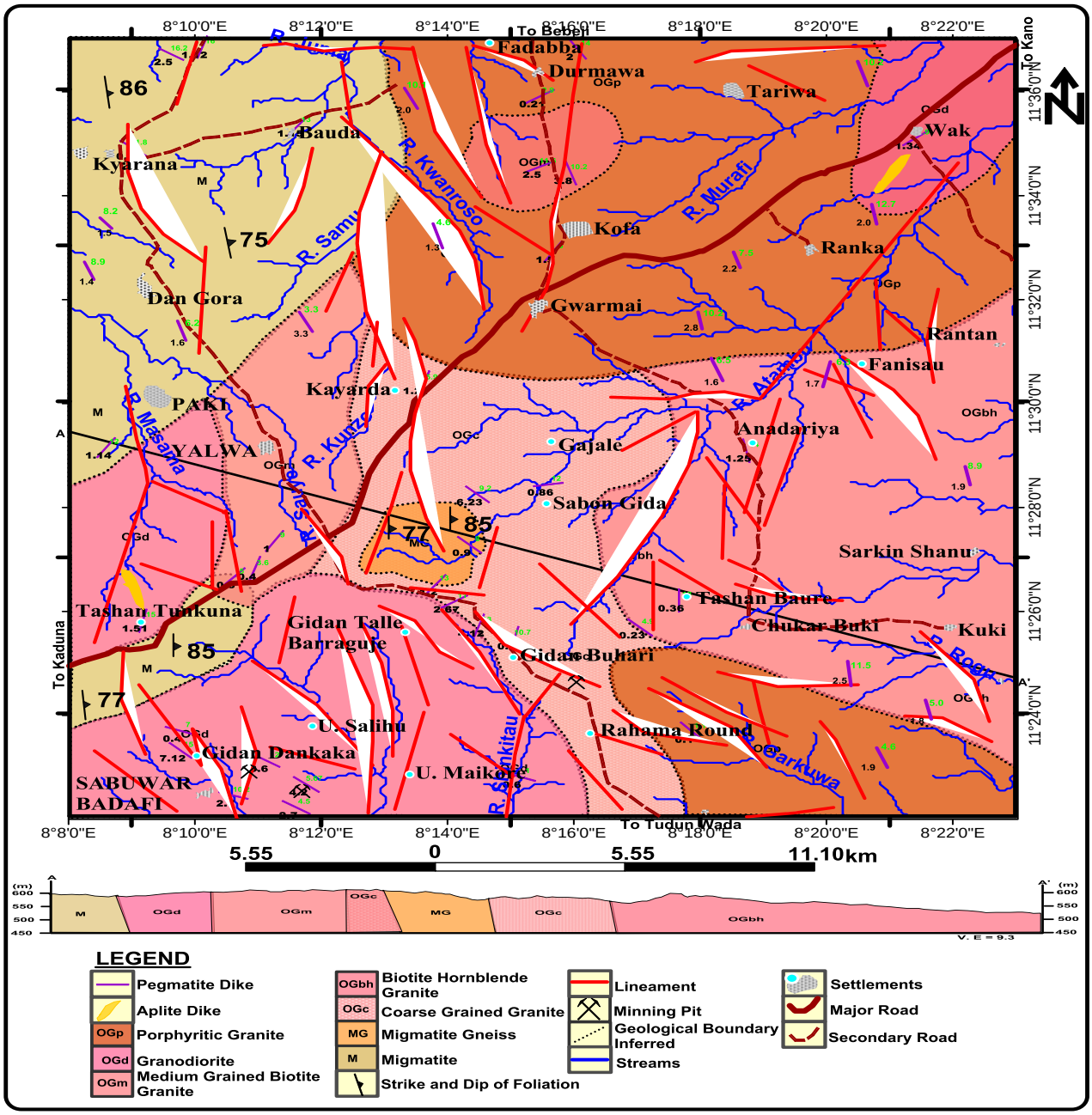


Fig. 4.1: Geological map of the study area.



Plate I: Photograph of an outcrop of migmatite, at Bauda($11^{0}35^{1}13.0^{11}$ N and $008^{0}11^{1}32.7^{11}$E)

PPL XPL

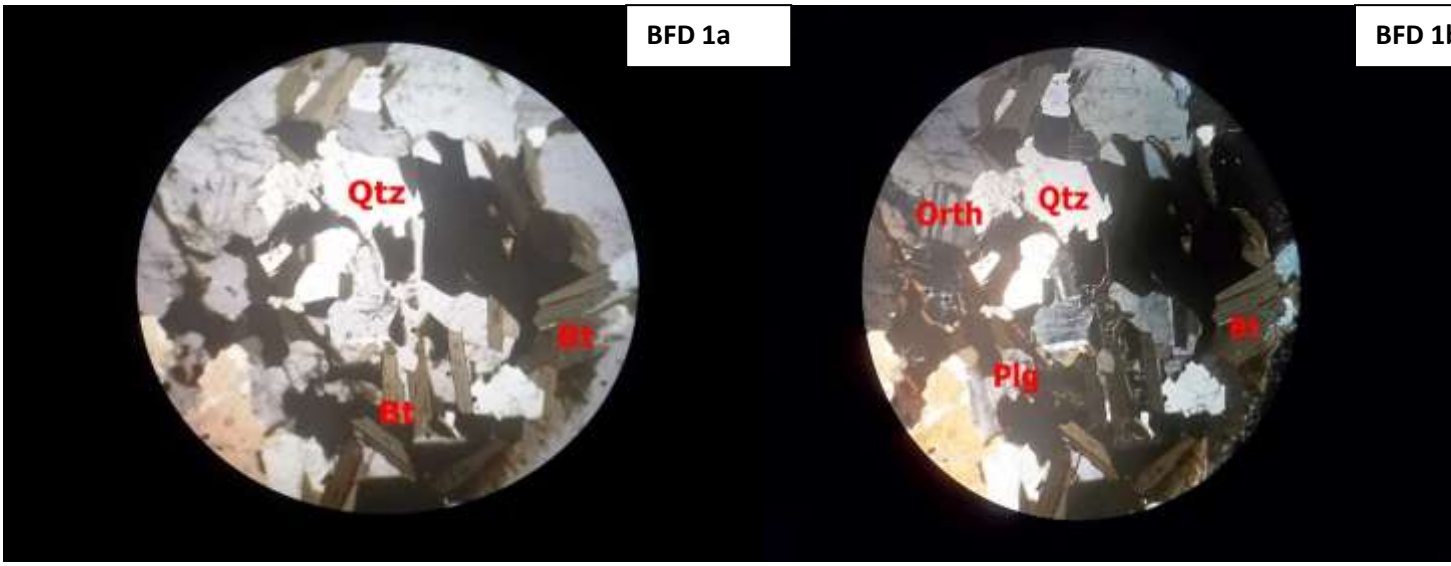


Plate II: a.=Photomicrogragh of migmatite under PPL; b. photomicrograph of migmatite under XPL: Qtz=quartz, Bt=biotite, plg=plagioclase, Orth= orthoclase.(Slide BFD1a & 1b) Location($11^{0}35^{1}13.0^{11}$N and $008^{0}11^{1}32.7^{11}$E). Magnification x40.

4.1.3 Migmatitic Gneiss

The migmatitic gneiss occurs as low-lying massive rock. The rock is poorly exposed and occurs around Gajale area. Texturally, the rock is fine grained but slightly weathered. The rock shows segregation into light and dark bands. Both the light and dark bands are aligned in NNE – SSW direction (Plate III). The rock composed mainly of quartz, K-feldspar, plagioclase, biotite and opaque minerals. The quartz is colourless and anhedral. The microcline is colorless with low relief. In XPL, the microcline depict 1st order grey interference colour and one set of twin lamellae (Plate IV). Biotite also occurs as xenomorphic crystals with high relief, the crystals are brown in colour. The opaque mineral observed in the rocks are probably magnetite or ilmenite.



Plate III: Photograph of migmatitic gneiss, at Kafin-Maiyaki($11^{o}21^{'}35.5^{"}$N and $008^{o}13^{'}43.7^{"}$E).

PPL XPL

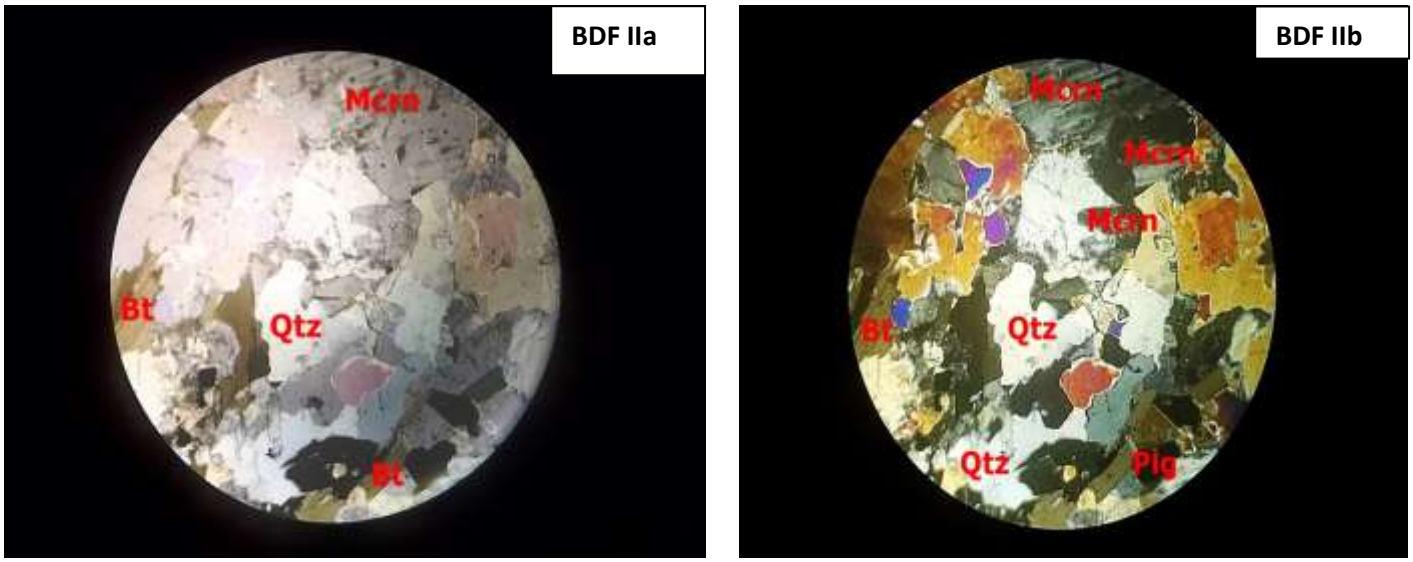


Plate IV: a.= Photomicrograph of migmatitic gneiss under PPL; b. photomicrograph of migmatitic gneiss under XPL., Qtz=quartz, Bt=biotite, mcrn=microcline, Plg=plagioclase. (BDF II a & b) at Kafin-Maiyaki ($11^{o}21^{'}35.5^{''}$N and $008^{o}13^{'}43.7^{''}$E).

4.1.4Granodiorite

The granodiorite occurs largely as inselbergs particularly in the South and Western part of the study area. However, occasionally the rock occurs as large boulders. Texturally the rock is coarse grained and unequigranular (Plate V). In thin section the rock composed mainly of quartz, orthoclase, plagioclase biotite and pyroxene. The rock differs from granite *sensu stricto* because it has high plagioclase feldspar relative to alkali feldspar and the present of pyroxene. Quartz occurs as discrete crystals characterized by undulatory extinction. Plagioclase is calsic ranging from adesine to labrodorite (An_{40} –An_{60}). The mineral occurs as subhedral crystals characterized by carlsbad twining. The orthoclase occurs as colorless but cloudy crystal and is largely altered. Biotite occurs as brown crystal with high relief and perfect basal cleavage. Pyroxene show uneven fracture high relief and green false color (Plate VI a and VIb).



Plate V: Photograph of granodiorite.

PPL XPL

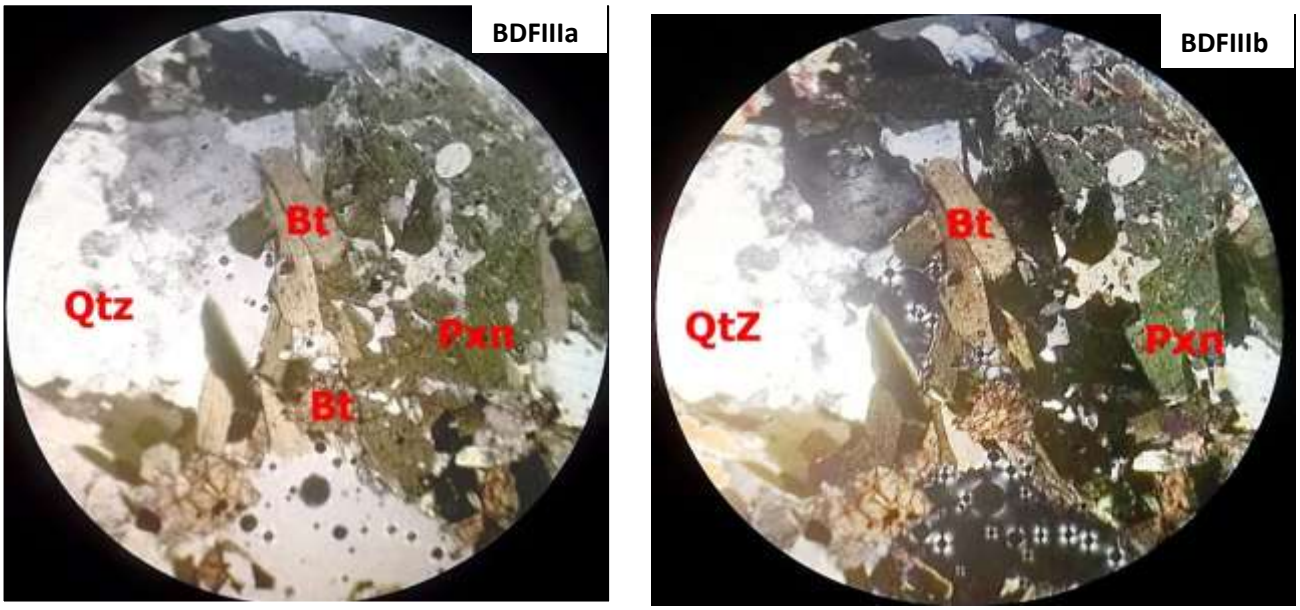


Plate VI:a.= Photomicrograph of granodiorite under PPL; b. Photomicrograph of granodiorite under

XPL, Qtz=quartz, Bt=biotite, pxn=pyroxene (Slide BDF IIIa & b). Location ($11^{o}25^{'}39.6^{''}$N and $008^{o}91^{'}4.5^{''}$E)

4.1.5 Porphyritic Biotite Granite

The porphyritic biotite granite is the most widespread rock type in the study area. The rock is mostly weathered although fresh outcrops were observed. In hand specimen, the phenocrysts are light in colour with the longer axis aligned parallel to the biotite.

Thin section study of the rock sample show that it is made up of large subhedral phenocrysts of orthoclase set in the medium grained groundmass of quartz, plagioclase and biotite. The orthoclase phenocrysts show carlbad twining while plagioclase is compositionally sodic ranging from albite to oligoclase (An_{10}-An_{15}) and generally show polysynthetic twining (Plate VIIa and b). Few quartz phenocrysts were also observed in the rock.

PPL XPL

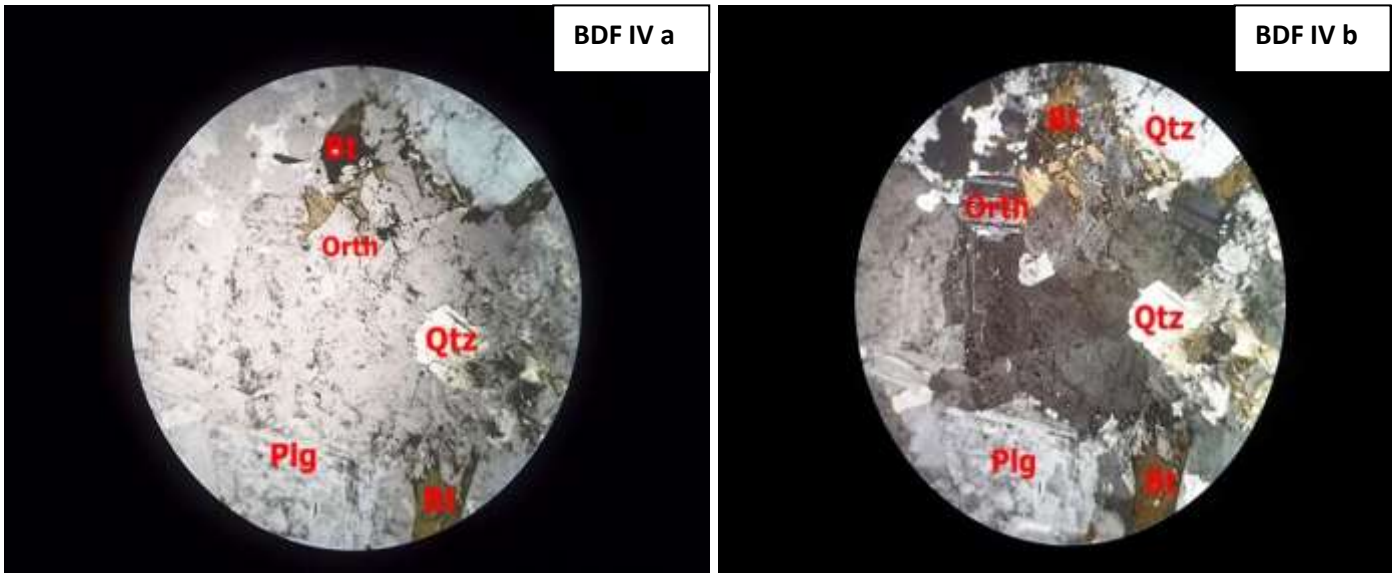


Plate VII photomicrograph of porphyritic granite; a). Plg=plagioclase,Qtz=quartz,Bt=biotite, orth=orthoclase (slide BDF IVa & b) under PPL and b). XPL. Location Durmawa ($11^{o}36^{'}44.2^{"}$N and $008^{o}17^{'}13.7^{"}$E) . Magnification is x40

4.1.6 Coarse Grained Biotite Granite

This rock is highly weathered and poorly exposed (Plate VIII). Texturally, it is coarse grained and ineguigranular. Minerals in thin section are not clear. However, mineral observed with the aid of hand lens include quartz, feldspar and biotite.



Plate VIII: Coarse grained granite at Gajale ($11^{o}25^{'}29.2^{''}$N and $008^{o}15^{'}05.3^{''}$E).

4.1.7 Medium grained Biotite granite

The rock is leucocratic, medium grained inequigranular and massive. Thin section study show that the mineral present in order of abundances in the rock includes quartz, plagioclase, biotite and alkali feldspar. Quartz occurs as polycrystalline crystals with high relief. The mineral is colourless under both plane and crossed polarized light but are easily distinguished from feldspars due to its high relief (Plate IX). Plagioclase is generally sodic ranging from albite to oligoclase (An_9-An_{15}) and occurs as slightly elongated subhedral and colourless crystals with low relief. Under cross polarized light, the mineral show carlsbad twinning. Biotite occurs as subhedral crystals with perfect basal cleavage. The mineral is pleichroic from light to dark brown and has high relief.

PPL XPL

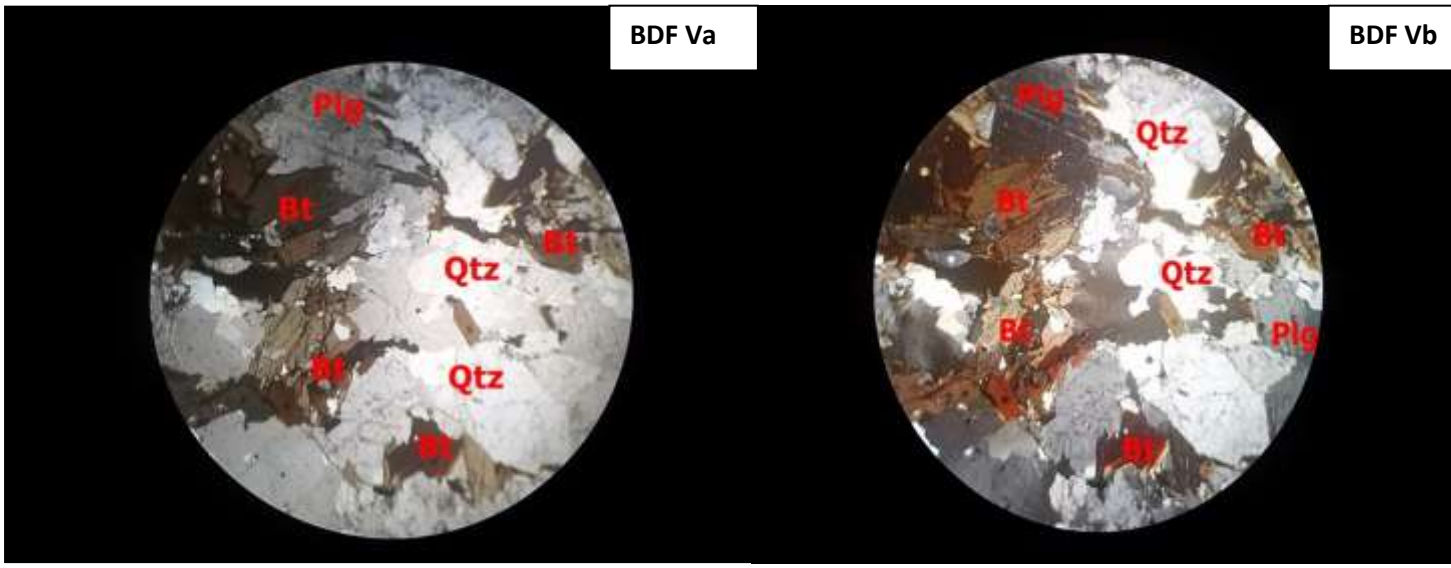


Plate IX: Photomicrograph of medium grained biotite granite; a). under PPL and b). XPL (Slide BDF Va & b) Location at Kofa ($11^{o}35^{'}46.2^{"}$N and $008^{o}15^{'}33.4^{"}$E). Magnification x40

4.1.8 Hornblende Biotite Granite

Hornblende biotite granite occurs as whalebacks, and is texturally a medium grained (plate X). Sharp contact relationships between the hornblende biotite granite and medium grained biotite granite have been mapped in some parts of the study area. In thin section,(slide no. BDF VIa & b) the minerals observed are quartz (35%), biotite (10%), orthoclase (20%), plagioclase (15%), microcline (15%) and hornblende (10%). Orthoclase is the main alkali feldspar observed in the rock however, microcline is also present. Orthoclase has inclusion of quartz in places and plagioclase is commonly oligoclase (An_{12}-An_{16}) and occurs as subhedral crystals that are partially altered in places. Hornblende is characterized by high relief and two set of cleavages that intersect at 60 and 120˚(Plate XI).



Plate X: Photograph of Hornblende biotite granite at Tashan-Baure.

PPL XPL

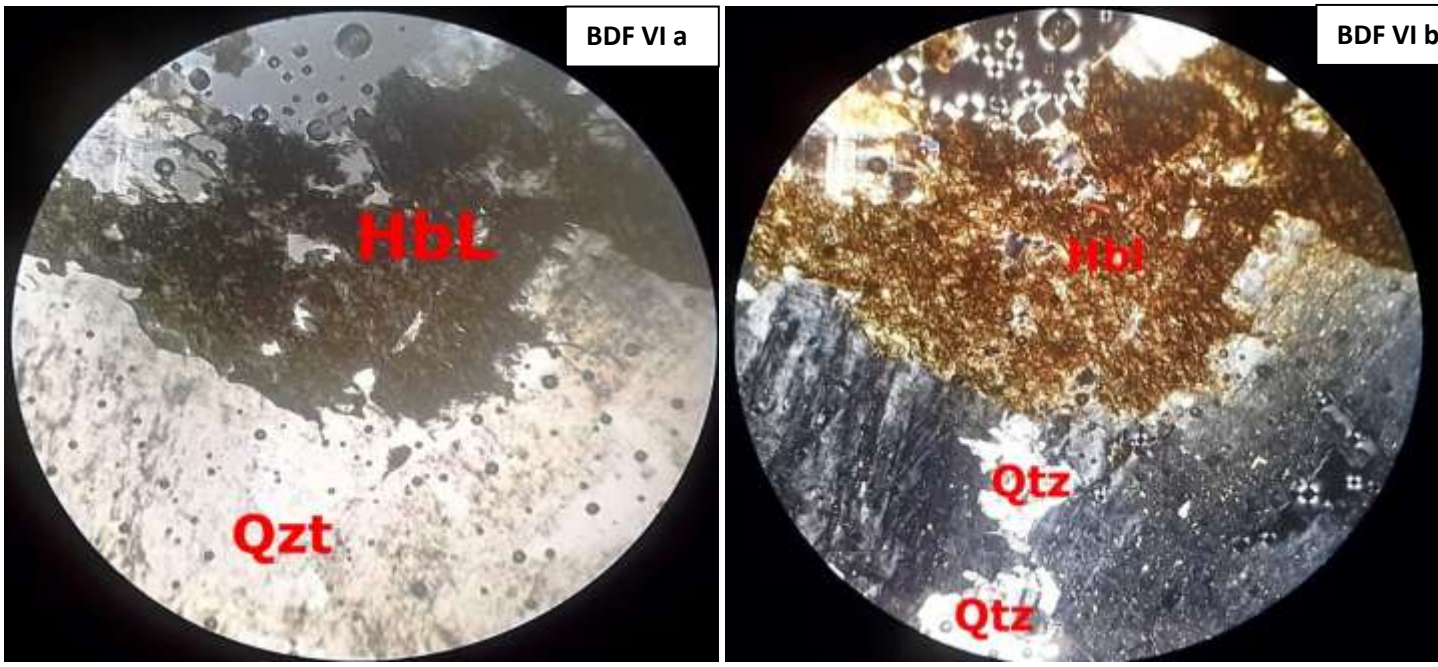


Plate X1: Photomicrograph of hornblende biotite granite under PPL and XPL (Slide BDF VI a & b) at Tashan-Baure ($11^{o}26^{'}10.29^{"}$N and $008^{o}17^{'}29.9^{"}$E). Magnification x40

4.1.9 Aplite

Aplied occurs as lensoid bodies, leucocratic and fine grained in texture. Thin section study show that the mineral present in order of abundance in the rock includes quartz, microcline, orthoclase and biotite. Accessory minerals observed in the rock are tourmaline and few iron and titanium oxide (plate XII). Quartz occurs as large crystals with high relief. Microcline crystals are anhedral with characteristic of cross-hatch twining. However, occassionally, the microcline form granuphyric intergrowth with orthoclase.

PPL XPL

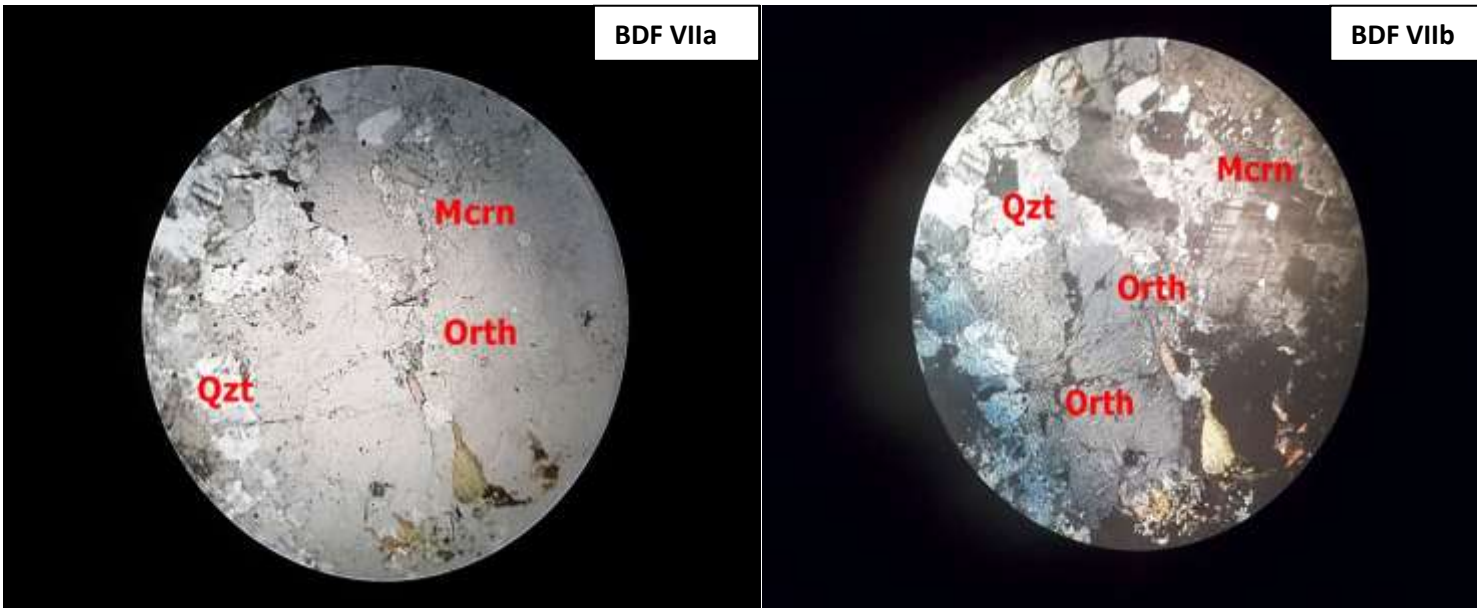


Plate XII: Photomicrograph of an aplite dyke under PPL and XPL (Slide BDF VIIa & b). at Fadabba ($11^{o}25^{'}06.0^{"}$N and $008^{o}8^{'}36.2^{"}$E). Tm = Tourmaline.

4.2 PEGMATITE DYKES

Quartz veins and pegmatites constitute the bulk of minor rocks in the study area. They occur as dykes and irregular bodies. More than 57 pegmatite dykes were studied in the area.

4.2.1 FIELD CHARACTERISTICS OF THE PEGMATITES

Different generations of pegmatites were mapped in the area (Fig. 4.2) and their field relationship i.e. physical properties are presented. It has been noted that some of the pegmatites

are found as sills in the study area especially around Kamfato ($11^{o}36^{'}45^{''}$N, $008^{o}10^{'}21.3^{''}$E) as shown in plate XIII.

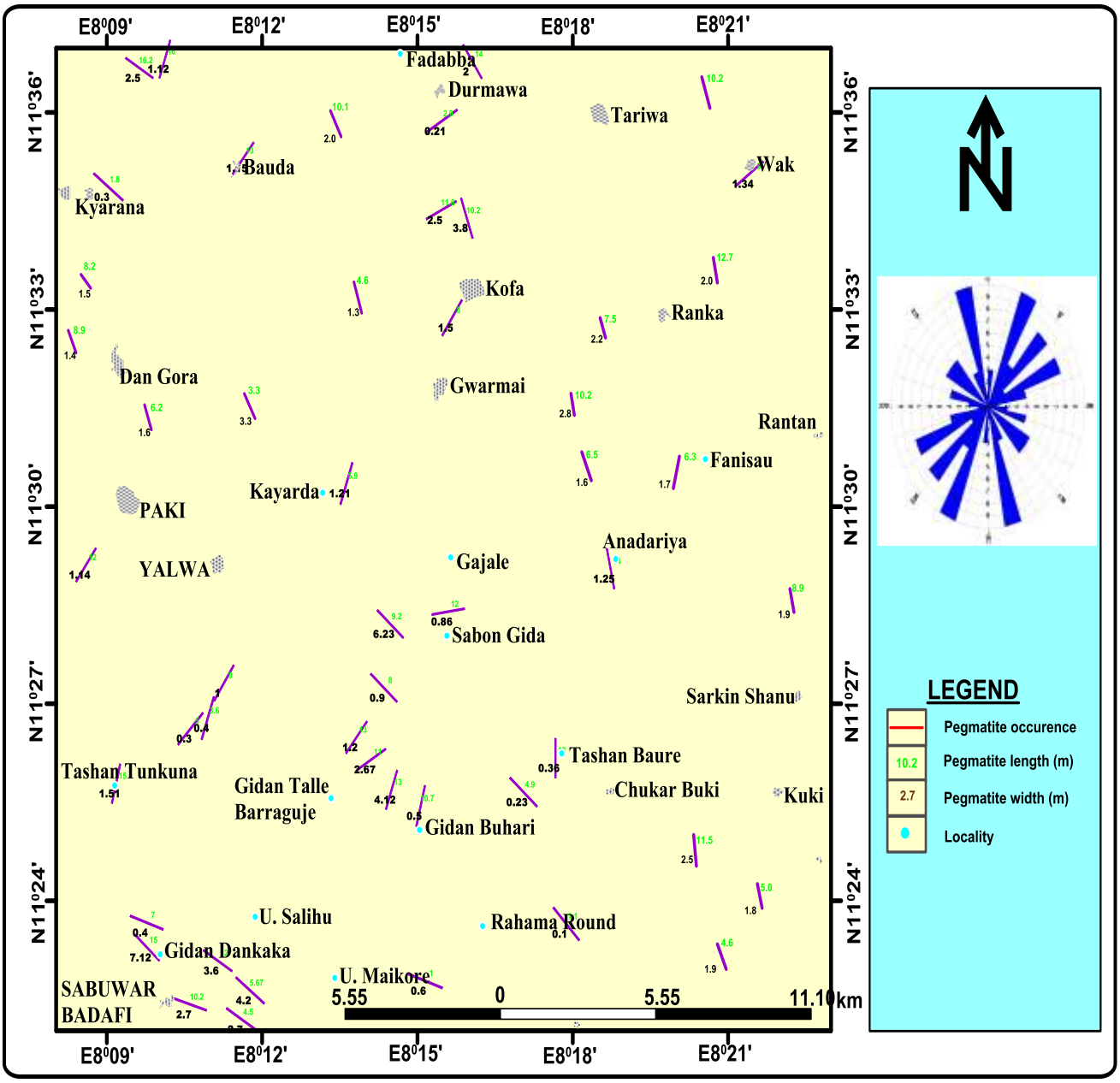


Fig. 4.2: Pegmatite map of the study area.



Plate XIII: A sill of pegmatite at Kamfato ($11^{o}36^{'}45^{''}$N, $008^{o}10^{'}21.3^{''}$E).

By contrast, some pegmatites occur as thin lenses, irregular bodies and some as tabular. Boulders of pegmatites were also observed in some part of the study area especially around Badafi ($11^{o}22^{'}19.8^{''}$N, $008^{o}10^{'}40.2^{''}$E) Plate XIII. Some occur as pods in granites around Kwari ($11^{o}22^{'}29.1^{''}$ and $008^{o}10^{'}36.6^{''}$) Plate XV. Some crystals of black tourmaline and beryl were observed around Atumba, Badafi e.t.c.



Plate XIV: A ridge of pegmatite at Badafi-Sabuwa ($11^{o}22^{'}19.8^{''}$N, $008^{o}10^{'}40.2^{''}$E)



Plate XV: Beryl crystals in one of the pegmatite dyke at Kwari ($11^{o}22^{'}29.1^{''}$N and $08^{o}10^{'}36.6^{''}$E)

Based on the measurement carriedout, the pegmatites are divided into two: finite pegmatites, which are measurable and the infinite pegmatites that is those with unexposed extremities and therefore cannot be measured properly. Also, it has been observed all over the study area that the pegmatites varies in sizes and shapes. They are mostly concentrated in the southern part of the study area, around Badafi-Sabuwa, Rahama, Gajale and Atumba areas. In terms of dimentions, pegmatites of length more than 20m have been recorded around Shinkatau, Gidan-Gwaja, Atumba ($11^{o}27^{'}57.0^{''}$N and $008^{o}13^{'}55.2^{''}$E) but many of the long ones are usually covered at one end or both extremities, but the most frequently occurring lengths are between 10-15m. The pegmatite dykes vary in width, pegmatites with widths above 2.0m have been measured, but the most frequently occurring pegmatite widths are less than 1.0m. They are comparable to the pegmatites of Oban massif in SE Nigeria in that, those of the study area are of similar dimentions and that the pegmatite widths may have been controlled by the host rocks.



Plate XVI: Exposed feldspar and quarzt (inside the pit) at Dankyaure,Badafi.It has($11^{o}23^{'}5.2^{''}$N and $008^{o}11^{'}8.5^{''}$E,)



Plate XVII: Milky quarz and feldspar outside a pegmatite mining pit ($11^{o}23^{'}5.2^{''}$N and $008^{o}11^{'}8.5^{''}$E)



Plate XVIII: Feldspars outside a pegmatite mining pit ($11^{os}23^{'}5.2^{''}$ N and $08^{o}11^{'}8.5^{''}$ E)

Minerallogically, the pegmatites range from simple to complex type. The simple pegmatite composed mainly of quartz, microcline and few traces of muscovite. The microcline in the simple pegmatite is general pink in colour and shows no graphic intergrowth with quartz. By contrast, the complex pegmatites (plates: XVI, XVII and XVIII) composed of quartz, alkali feldspars mainly microline, albite and muscovite. The microline in the complex pegmatite is generally gray in colour. It is very difficult to differentiate the microcline from the albite except in thin section. Occasionally, the microcline forms graphic intergrowth with quartz.

In addition, the complex pegmatites also composed of semi-precious blue crystals of beryl. The beryl crystals appear weathered and generally occur with pockets (vugs) in the complex pegmatite (Plate XV). Host rocks of the pegmatites are gneisses and granites. Sporadic artisanal

mining of alluvial tin was also taking place during the geological mapping of the study area such that the complex pegmatites are also rich in cassiterite.

4.2.2 **ORIENTATION OF PEGMATITES**

The rose diagram is used for the study of the strike or trend direction of the mapped pegmatites. The data collected from the field are organized in to class interval or bin, where each bin represents the number of values or degrees that falls within the specific angular region. A family of concentric circles provides scaled control for the number pegmatites, fractures, joints e.t.c., and orientation values that occupy each bin size.

The rose diagram for the pegmatite dyke shows about four (4) main strike direction, the most prominent of which are NNE-SSW trend, NNW-SSE trend, minor sets occur in the NE-SW trend ENE-WSW (Fig.4.2). The minor sets that occur in NE-SW and ENE-WSW, owes its orientation to the foliation trend in migmatitic gneisses.

The beryl bearing pegmatites are trending mostly in NNE-SSW and NE-SW trend, which correspond with the trend of pegmatites within the Northwestern Basement complex of Nigeria and owes its orientations to preexisting fractures (Garba, 2003). Adekeye and Akintola (2007) reported that in Nasarawa rare-metal pegmatites which are associated with the NE-SW and NNE-SSW regional fault systems and are enriched to varying degrees in ore minerals.

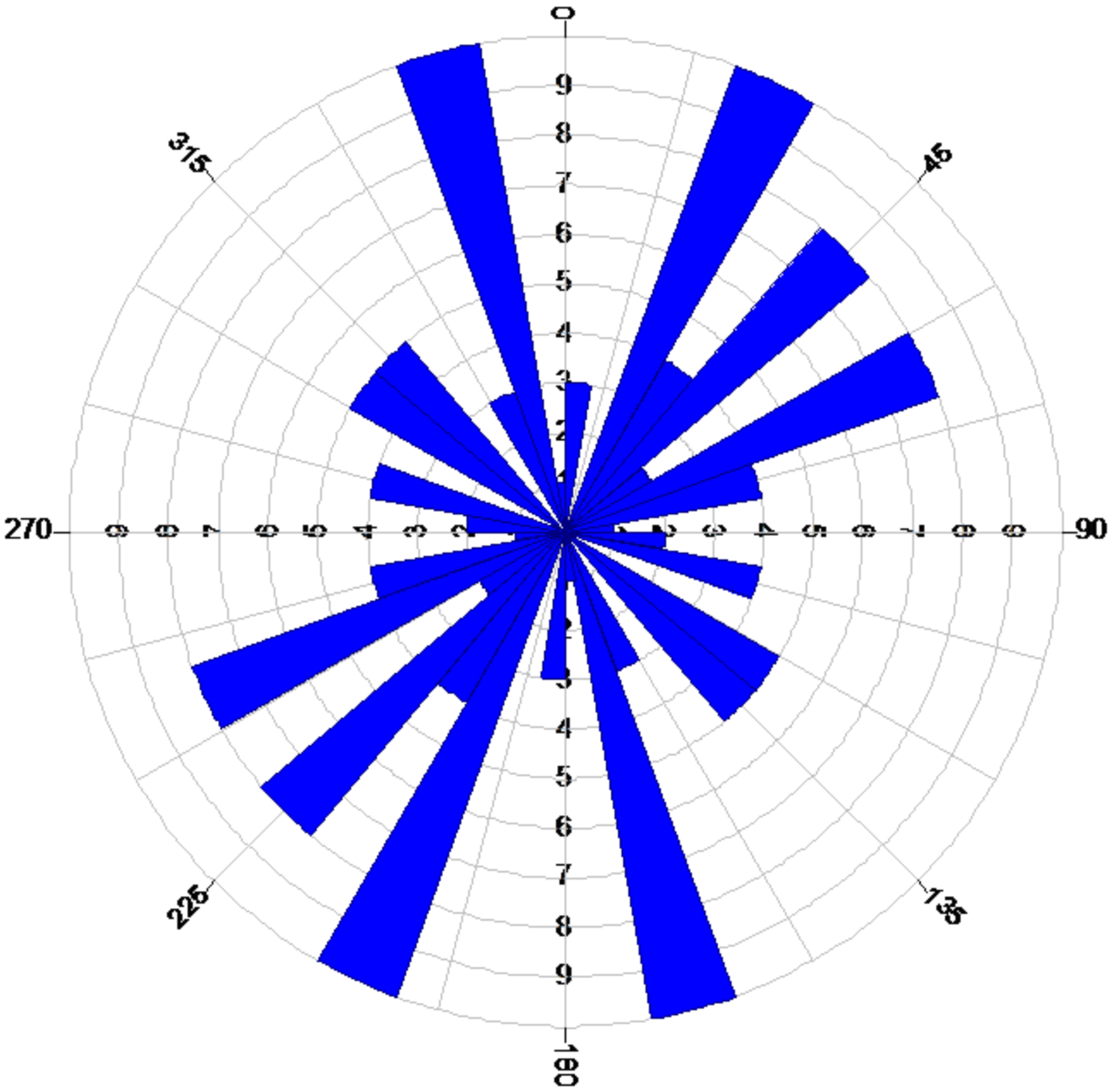


Fig. 4.3: Rose diagram showing the orientation of pegmatites in Badafi Field.

4.3 GEOCHEMISTRY OF ROCKS

The major elements composition of the rocks is reported in Table (4.1). SiO_2 content is 65.22 wt% in the migmatite and 74.46 wt% in the banded gneiss. Compared to the granodiorite which has SiO_2 contents ranging from 63.72 to 71.20 wt%, the granite and the aplite are more SiO_2 enriched. Silica content ranges from 71.35 to 73.37 wt% in the granites and from 74.42 to 74.69 wt% in aplite. Al2O3 content is comparatively higher in the granodiorite (14.51 to 15.34 wt %) than the granites (13.28 to 14.68 wt %) and the aplite (13.99 wt% to 14.30 wt %). However, all the rocks are characterized by low P_2O_5 and TiO_2 contents. P_2O_5 ranges from 0.11 to 0.29 wt% in the granodiorite; from 0.04 to 0.12 wt% in the granites and from 0.01 to 0.03 wt% in aplite while TiO_2 ranges from 0.40 to 0.88 wt% in granodiorite; from 0.20 to 0.36 wt% in the granites and from 0.03 to 0.04 wt % in the aplites.

Table 4.1: Major element composition of the rocks from the study area (Wt %)

Elements	Migmatite	Migmatitic Gneiss	Granodiorite			Granites				Aplites	
Wt%	D13	D6	D1	D11	D8	D4	D9	D3	D5	D10	D12
SiO2	65.22	74.46	63.72	71.20	65.47	71.35	71.70	72.39	73.37	74.69	74.42
Al2O3	16.77	13.24	15.03	14.51	15.34	14.03	14.68	13.28	13.97	13.99	14.30
Fe2O3	4.41	2.78	5.39	2.71	4.29	2.98	2.38	3.32	1.87	0.45	0.66
MgO	1.68	0.36	2.75	0.70	1.83	0.06	0.60	0.29	0.21	0.04	0.06
CaO	3.05	1.41	4.00	2.43	3.42	1.22	1.82	1.20	1.11	0.84	0.78
Na2O	4.38	3.41	3.30	3.49	3.43	3.43	3.33	2.89	3.42	3.37	3.96
K2O	2.67	3.82	3.41	3.51	4.07	5.86	4.50	5.65	5.05	5.94	4.88
TiO2	0.64	0.32	0.88	0.40	0.69	0.30	0.32	0.36	0.20	0.03	0.04
P2O5	0.06	0.06	0.29	0.11	0.22	0.04	0.09	0.12	0.07	0.03	0.01
MnO	0.08	0.06	0.11	0.06	0.07	0.05	0.05	0.04	0.03	0.02	<0.01
LOI	0.8	-0.1	0.7	0.6	0.8	0.4	0.3	0.2	0.5	0.5	0.7
Sum	99.79	99.80	99.63	99.74	99.68	99.72	99.76	99.75	99.83	99.92	99.86

4.3.1 Major Element Characterization

The major element composition of the granodiorite, granites and aplite were plotted on Harker diagram using SiO_2 as an index of differentiation (Figures 4.4a & b) show that TiO_2, Al_2O_3, FeOt, MgO, CaO and P_2O_5 are all negatively correlated with SiO_2, generally forming a well-defined linear trend. Such linear trends might be the result of fractionation (Hassanen *et al.*, 1996).While K_2O and Na_2O show scatter trend.

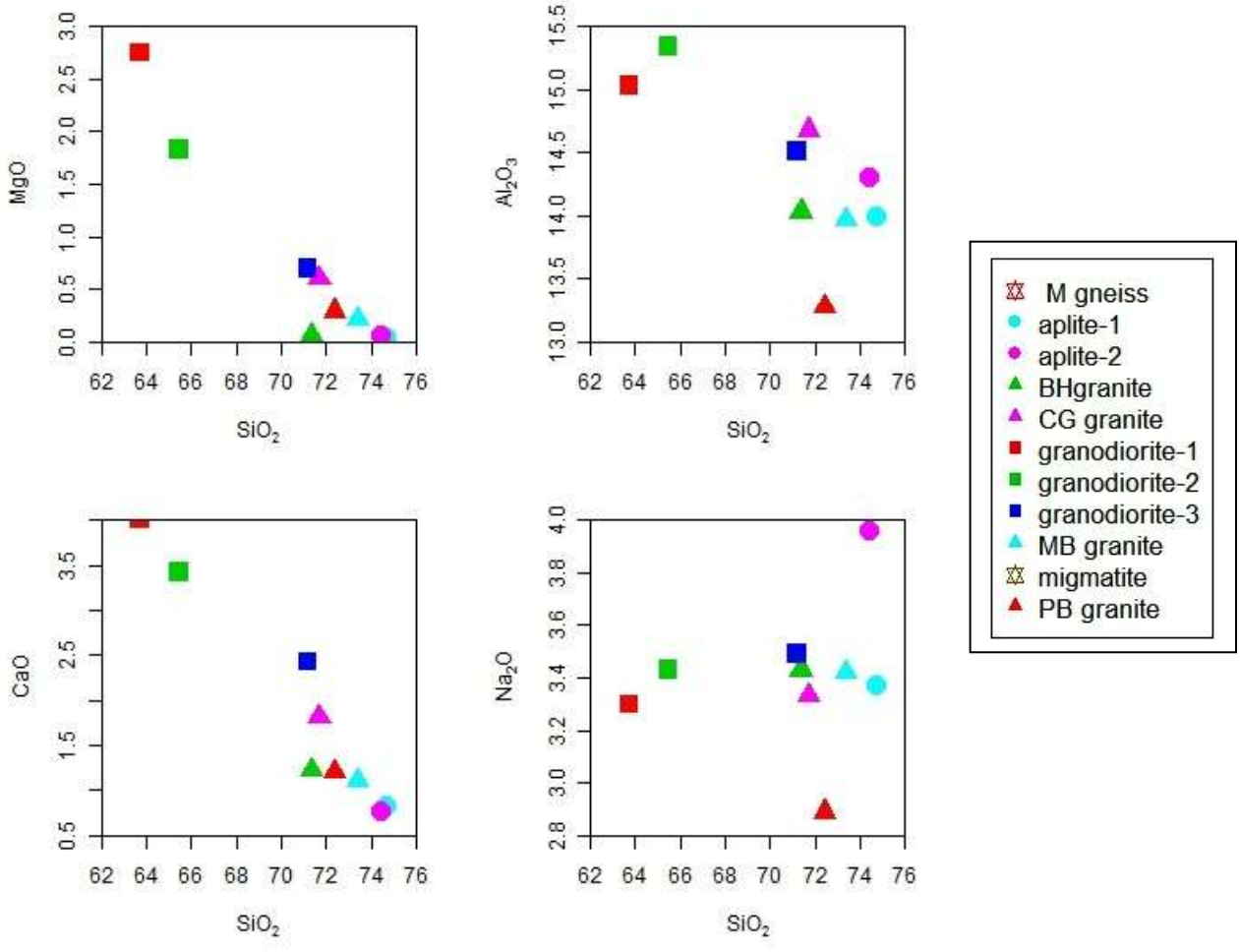


Fig 4.4a: Harker plot of MgO, CaO, Al_2O_3, and Na_2O against SiO_2 for granodiorite, granites and aplite in the study area

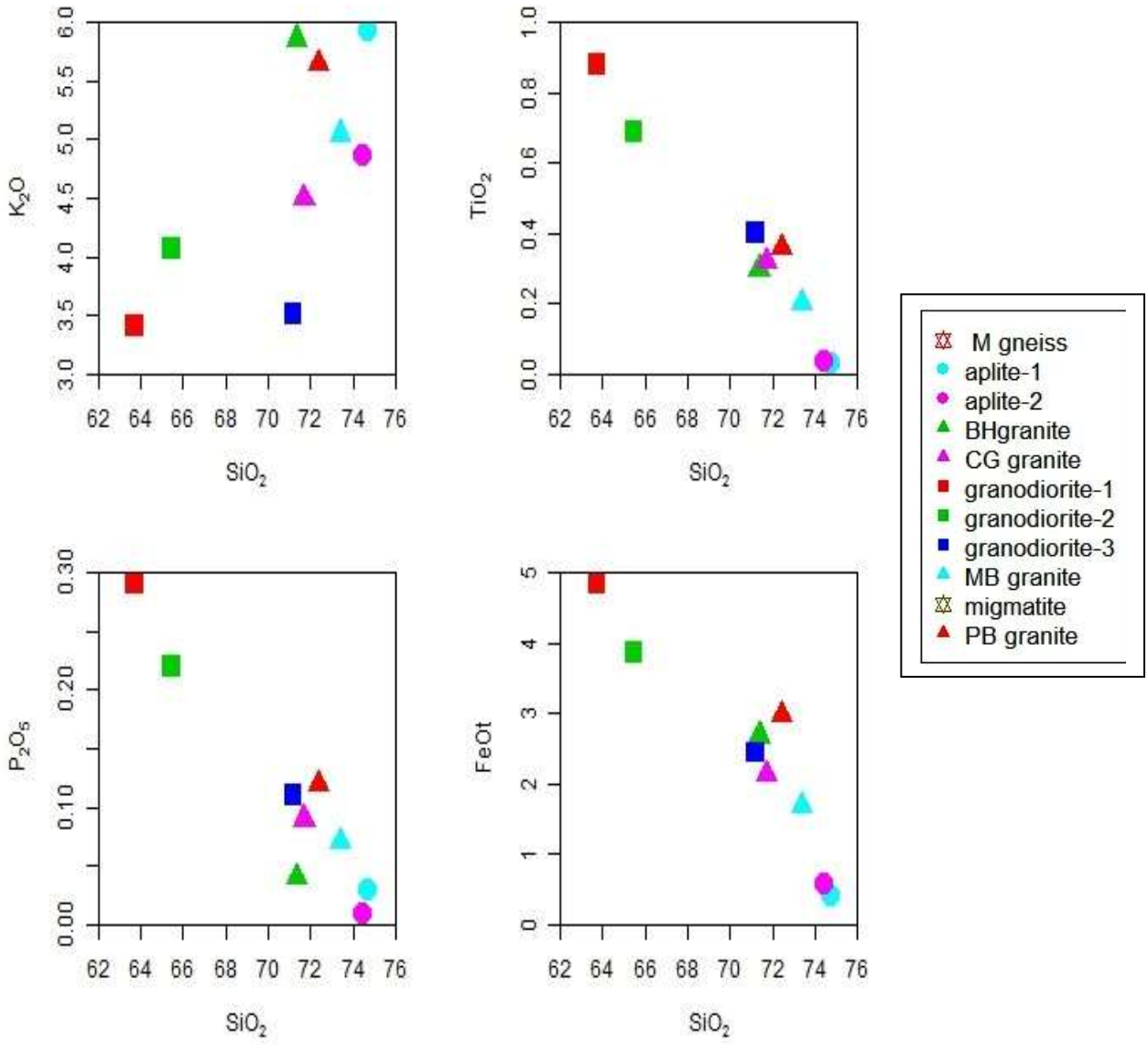


Fig 4.4b: Harker plot of K_2O, TiO_2, P_2O_2 and FeOt against Silica (SiO_2) for granodiorite, granites and aplite in the study area

In the normative An-Ab-Or diagram and alkali vs Silica diagram, the migmatite and the granodiorite plots within the granodiorite field while the migmatitic gneiss, granites and the aplite plot within the granite field (Fig. 4.5).

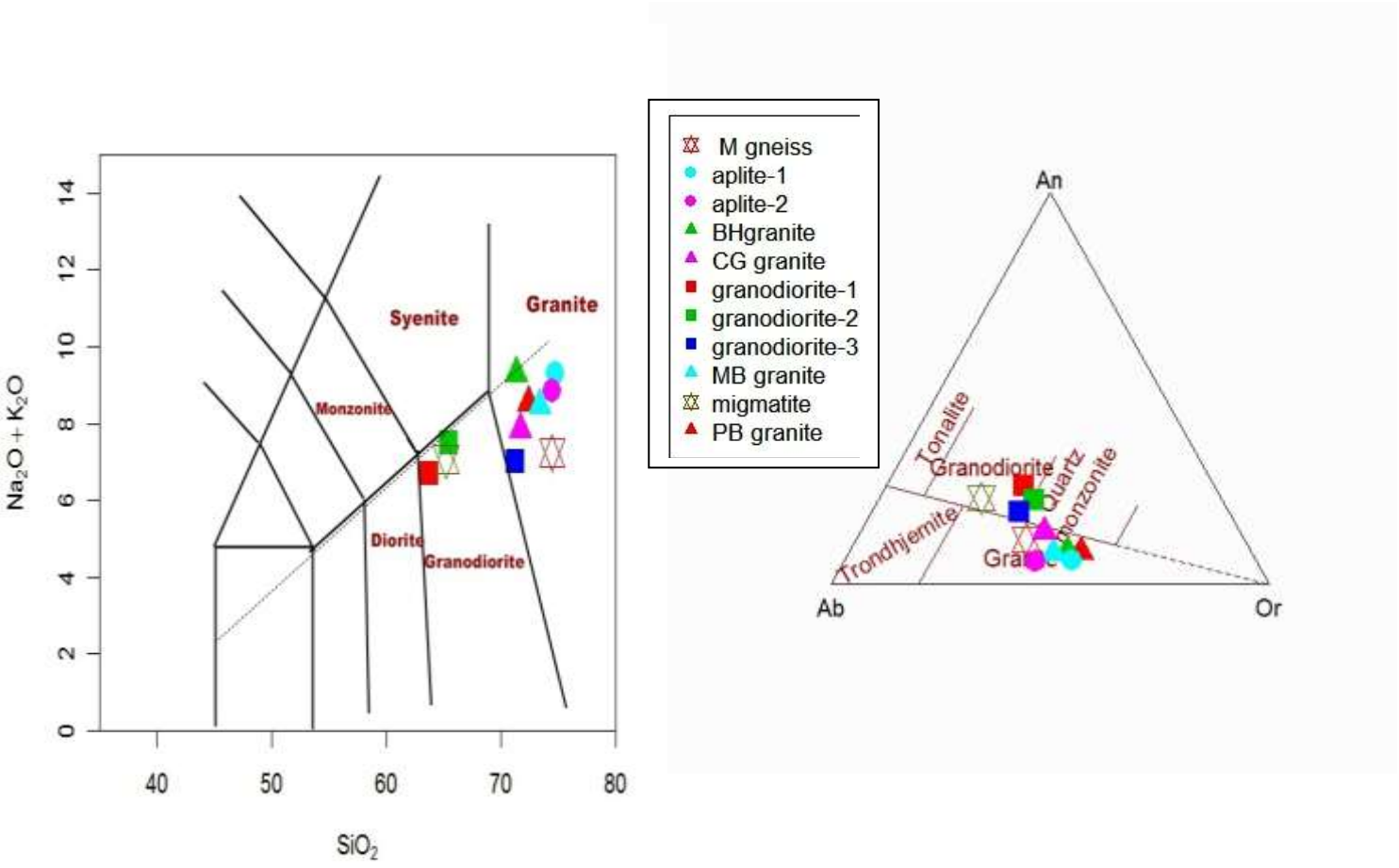


Fig 4.5: a= Normative An-Ab-Or diagram showing the distribution of the rocks in granitic to granodioritic field (after O'Connor, 1965) b: alkali Vs Silica diagram showing the distribution of the rocks in granitic to granodioritic field.

The granodiorite, granites and aplite are metaluminous to weakly peraluminous, while the migmatite and the migmatitic gneiss plot in the peraluminous and metaluminous field respectively (Fig. 4.6).

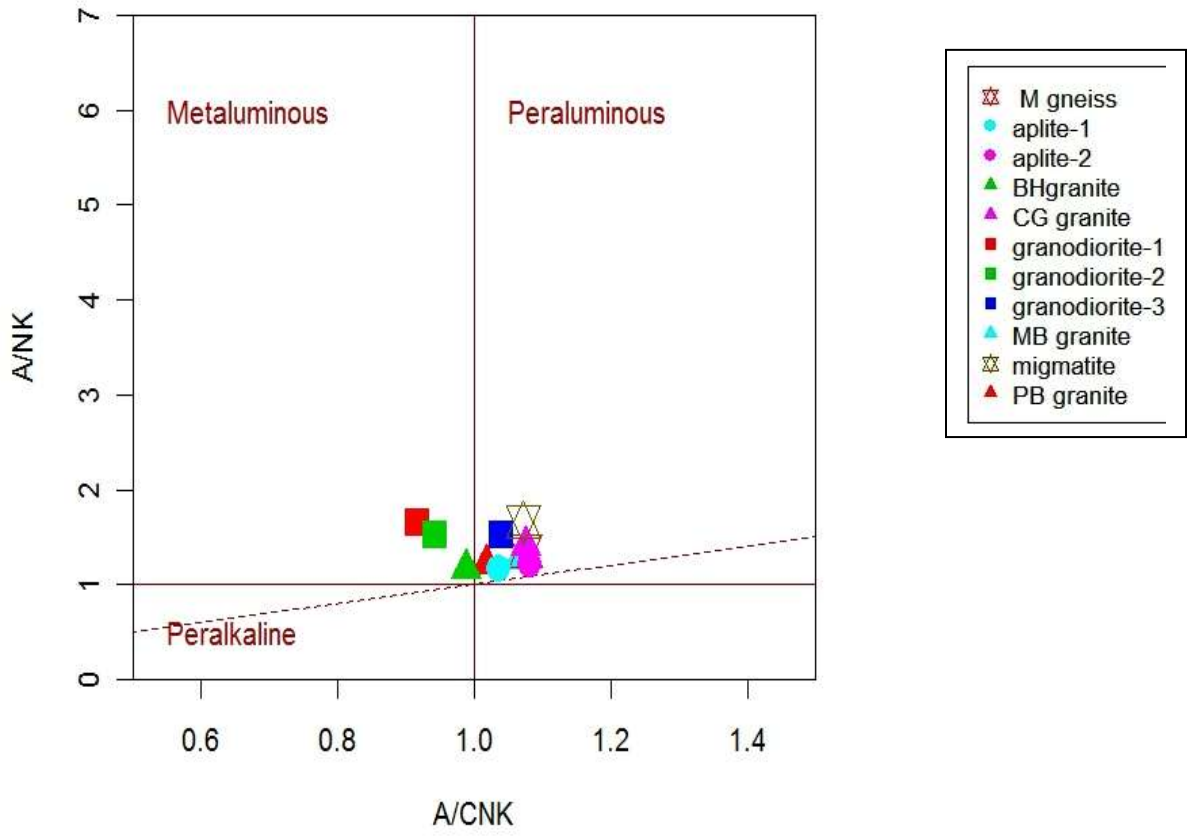


Fig. 4.6: A/NKversus A/CNK plots showing the distribution of the rocks from metaluminous to weakly peraluminous field (after Shand, 1943).

The K_2O contents in the granodiorite, granites and aplite are high and in the diagram of Peccerillor and Taylor (1976) all the rocks plot in the field of high potassium calc-alkaline to shoshonitic series (Fig. 4.7).

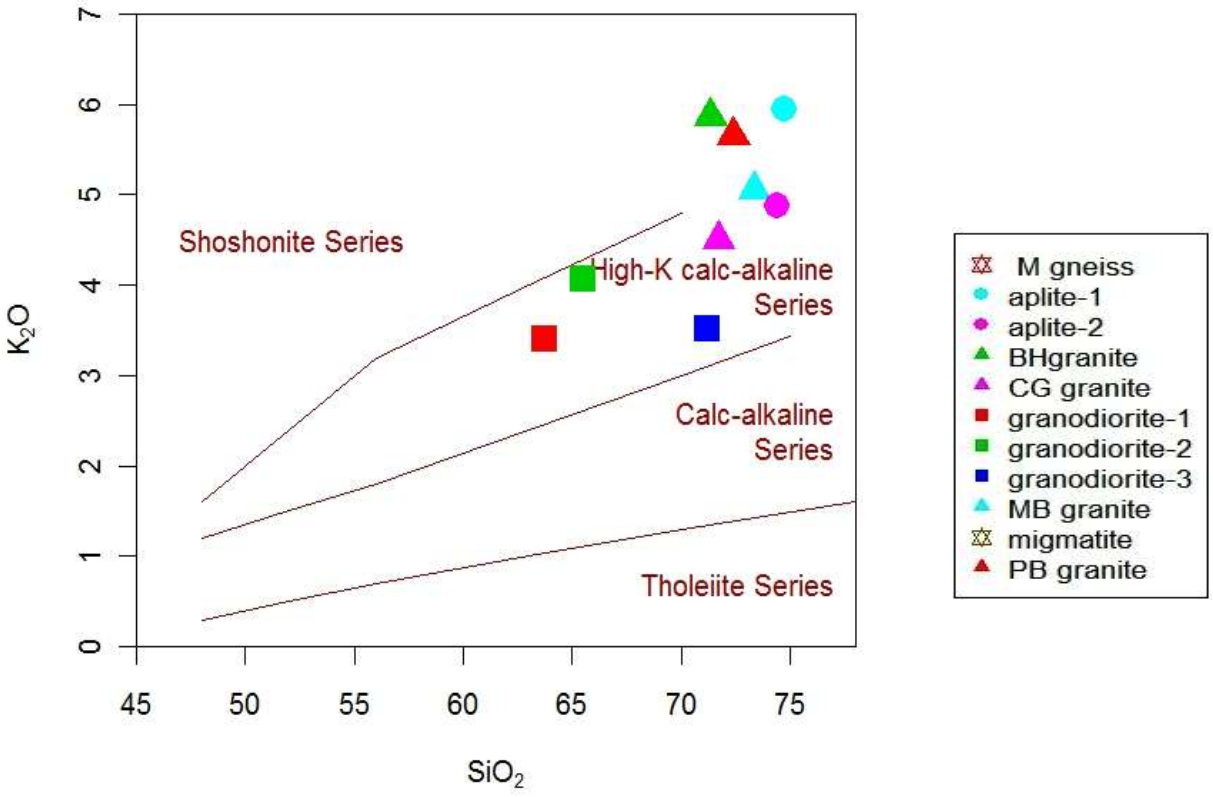


Fig. 4.7: K_2O versus SiO_2 diagram showing the distribution of the rock within the fields of High-K-calc-alkaline and calc-alkaline series after Peccerillo and Taylor (1976).

On the A/CNK versus SiO_2 discrimination diagram (after Chappel and White, 1974; Fig 4.8a), the granodiotite, granite and the aplites all plotted within the field of I-type granites. Moreover, the migmitite and the migmatitic gneiss also have igneous progenators as shown on the TiO_2 versus SiO_2 discrimination diagram (after Tarney, 1976; Fig. 4.8b).

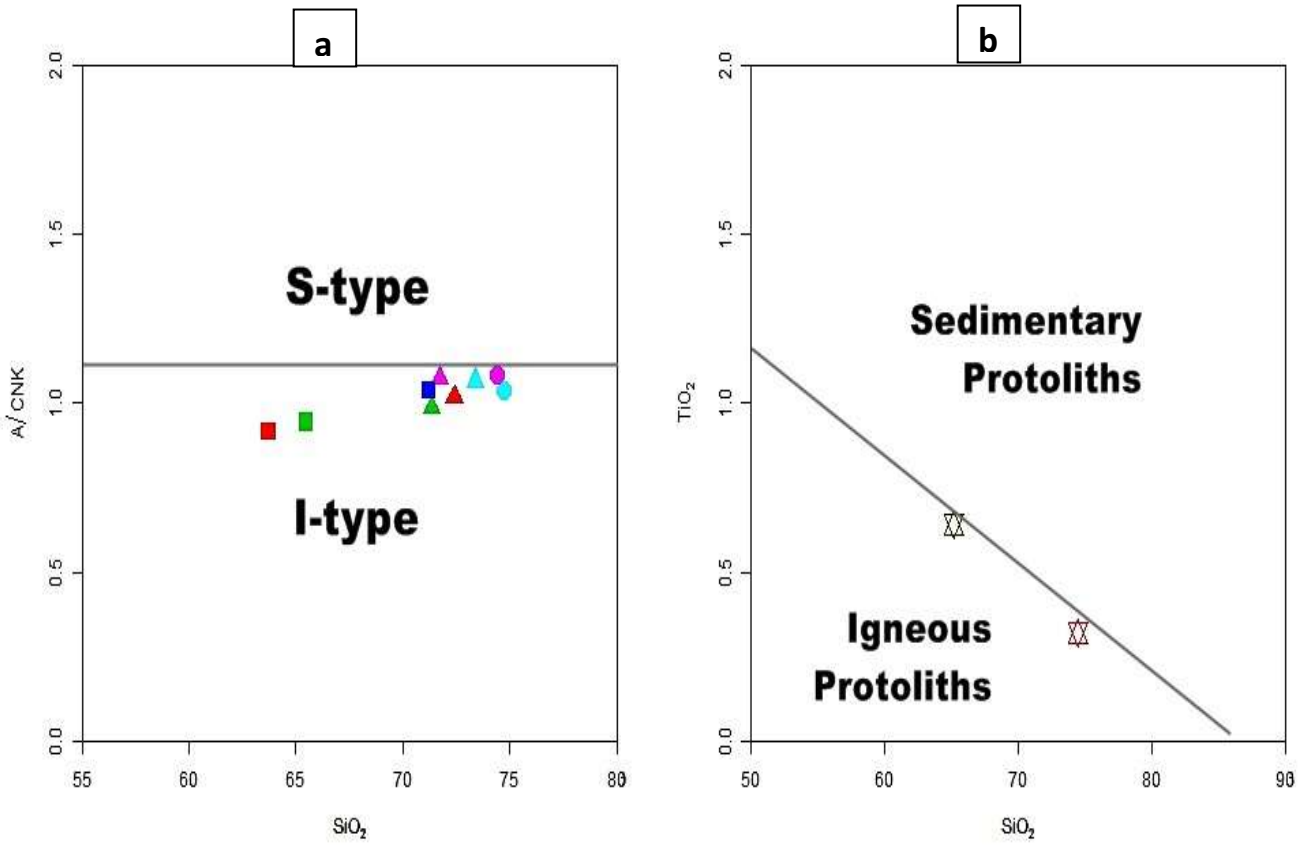


Fig. 4.8 : a= A/CNK versus SiO_2 discrmination diagram (after Chappel and White, 1974), b= TiO_2 versus SiO_2 discrimination diagram after (Tarney, 1976) for the granodiotite, granites and aplite in the study area. Symbols are the same as in Fig. 4.7

4.3.2 Trace Element Characterization

Trace elements are useful fingerprints of the origin of igneous rocks and igneous processes because they exhibit a range in concentration far greater than major elements (Frost and Frost,

2013). 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 petrogenesis (Butler *et al*., 1962, Girei, 2015). The trace element compositions and ratios are presented in (Table 4.2). Multi-element spider diagrams for all the rock samples normalized to primitive mantle are shown in Fig. 4.9. The normalized abundance patterns permit characterization of the rocks. The granodiotite, granites and aplites are depleted in fluid-insoluble elements (e.g Nb, Ta, and Ti) but are enriched in fluid soluble elements (e.g U, K and Pb). These chemical characteristics are refers to as the "arc-like signature" and are typical of crustal rocks (Niu and Ohara, 2009). Similarly, the migmatitic gneiss and the migmatite are also depleted in fluid insoluble elements (e.g Nb, Ta, and Ti) but are enriched in some fluid soluble element (e.g U, and K) but unlike the granites they depict negative Pb anomaly.

Large ion lithophile elements show significant variation in all the rocks. Compared to the crustal average of 90 ppm, Rb is moderately enriched in the granites, granodiorite and aplite. In the granites Rb ranges from 175.90 to 239.80 ppm, from 167.10 to 175.40 ppm in the granodiorite and from 132.40 to 144.80 ppm in aplite. Ba and Sr which are compatible in the granitic system show significant variation in the granodiote (938.00 to 1166.00 ppm), granites (417 to 1272.00 ppm) and aplites (82.00 to 676.00 ppm). Sr decreases readily during the course of fractional crystallization since it replaces Ca in plagioclase as well as K in K-feldspars. Barium (Ba) also replaces K in K-feldpars and hence it decreases during the course of fractional crystallization. Large variation of these lithophile elements in the granites suggests that fractional crystallization was probably responsible for their evolution.

Table4.2: Trace element composition of the rocks from the study area

Elements	Migmatite	Migmatitic Gneiss	Granodiorite			Granites				Aplites	
In PPM	D13	D6	D1	D8	D11	D4	D3	D9	D5	D10	D12
Ba	478.00	578.00	1166.00	1062.00	938.00	1272.00	753.00	825.00	417.00	82.00	676.00
Be	3.00	3.00	3.00	3.00	3.00	3.00	2.00	3.00	6.00	3.00	3.00
Co	52.10	41.50	63.50	45.10	57.80	41.30	56.90	46.90	40.50	57.80	38.10
Cs	9.50	10.10	13.00	11.90	12.20	3.10	4.70	8.40	2.20	2.50	4.10
Ga	20.60	18.00	22.20	21.50	17.90	24.60	22.80	18.50	22.60	21.00	19.10
Hf	6.20	11.10	6.00	5.40	5.30	10.80	7.20	6.40	5.30	2.80	2.10
Nb	13.20	13.20	17.80	16.90	18.30	17.90	20.30	13.20	25.00	9.40	4.80
Rb	162.90	168.60	175.40	168.40	167.10	175.90	202.60	206.00	239.80	144.80	132.40
Sn	2.00	7.00	6.00	5.00	3.00	3.00	2.00	4.00	6.00	<1	<1
Sr	266.60	79.00	539.10	602.00	322.10	143.90	131.20	268.20	92.60	88.10	256.90
Ta	1.40	1.40	1.90	2.00	2.00	1.20	1.40	0.90	1.90	1.50	0.70
Th	11.50	13.30	12.80	13.70	15.50	7.10	18.70	22.60	30.80	5.90	2.40
U	2.30	3.40	3.80	2.60	3.90	1.90	5.60	1.90	4.00	3.50	1.60
V	60.00	<8	101.00	77.00	32.00	<8	9.00	19.00	<8	<8	<8
Zr	220.00	415.80	229.00	197.90	193.30	482.50	270.70	218.70	167.30	51.50	47.80
Y	16.60	56.20	22.50	23.80	21.70	26.60	35.90	19.10	59.30	26.70	15.60
Mo	0.80	0.20	0.20	0.10	0.20	0.30	1.30	0.30	0.20	0.20	0.10
Cu	3.80	0.80	1.00	1.00	0.70	1.80	3.70	1.00	0.50	0.60	0.90
Pb	3.80	3.70	3.40	3.50	3.00	14.90	7.60	8.30	4.50	10.10	6.80
Zn	66.00	49.00	68.00	64.00	51.00	57.00	55.00	55.00	37.00	8.00	7.00
Ni	16.60	0.90	15.60	7.80	2.20	0.20	0.90	1.70	1.40	0.30	0.30
Au	<0.5	<0.5	<0.5	0.70	<0.5	<0.5	0.70	<0.5	<0.5	<0.5	<0.5
Tl	0.80	0.60	0.70	0.60	0.50	0.20	0.50	0.50	0.40	<0.1	<0.1

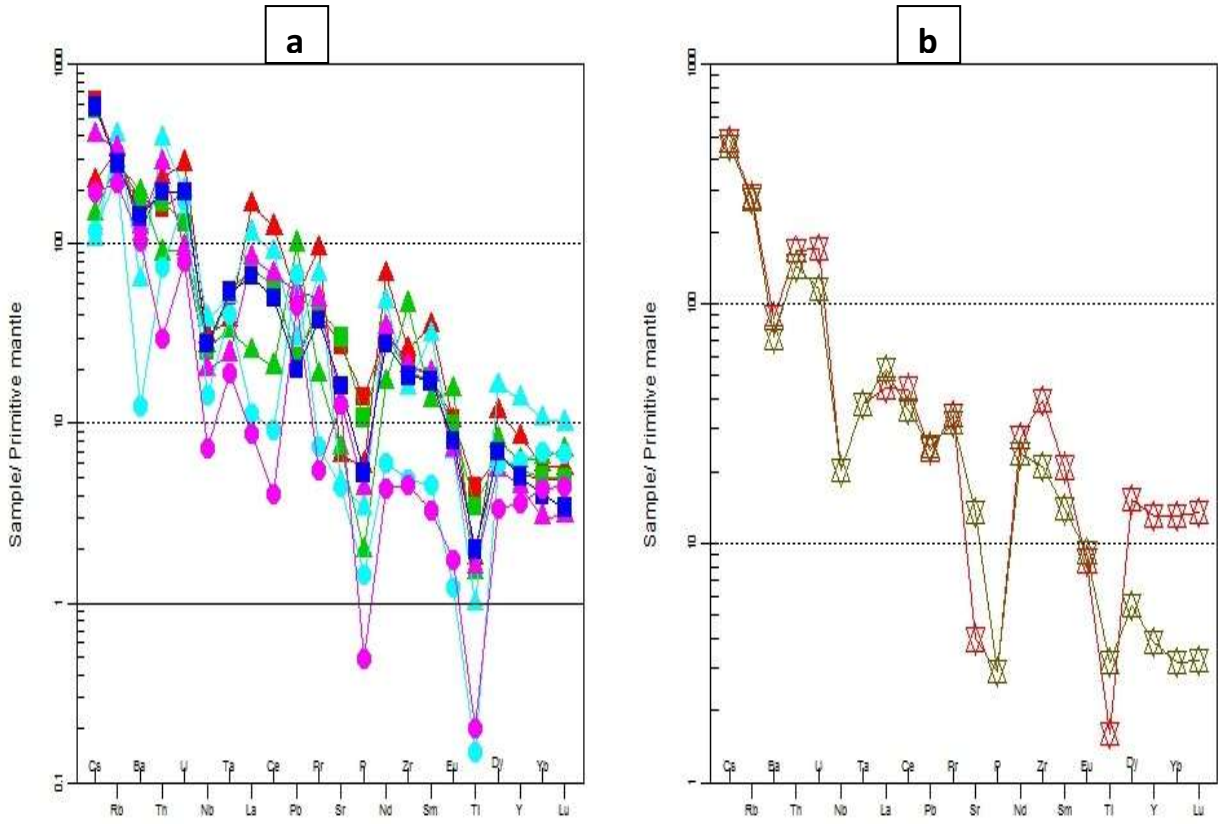


Fig.4.9: Primitive mantle normalized multi-element diagram (after Sun and McDonough, 1989) a=for granites, granodiorite and aplites b=for migmatitic gneiss and migmatites. Symbols are same as in Fig. 4.7

Concentrations of selected trace element plotted on Harker diagram using SiO_2 as an index of differentiation (Figure 4.10a & b), show that Ba, Sr, V, and Zn are all negatively correlated with silica, such elements are said to be compatible.

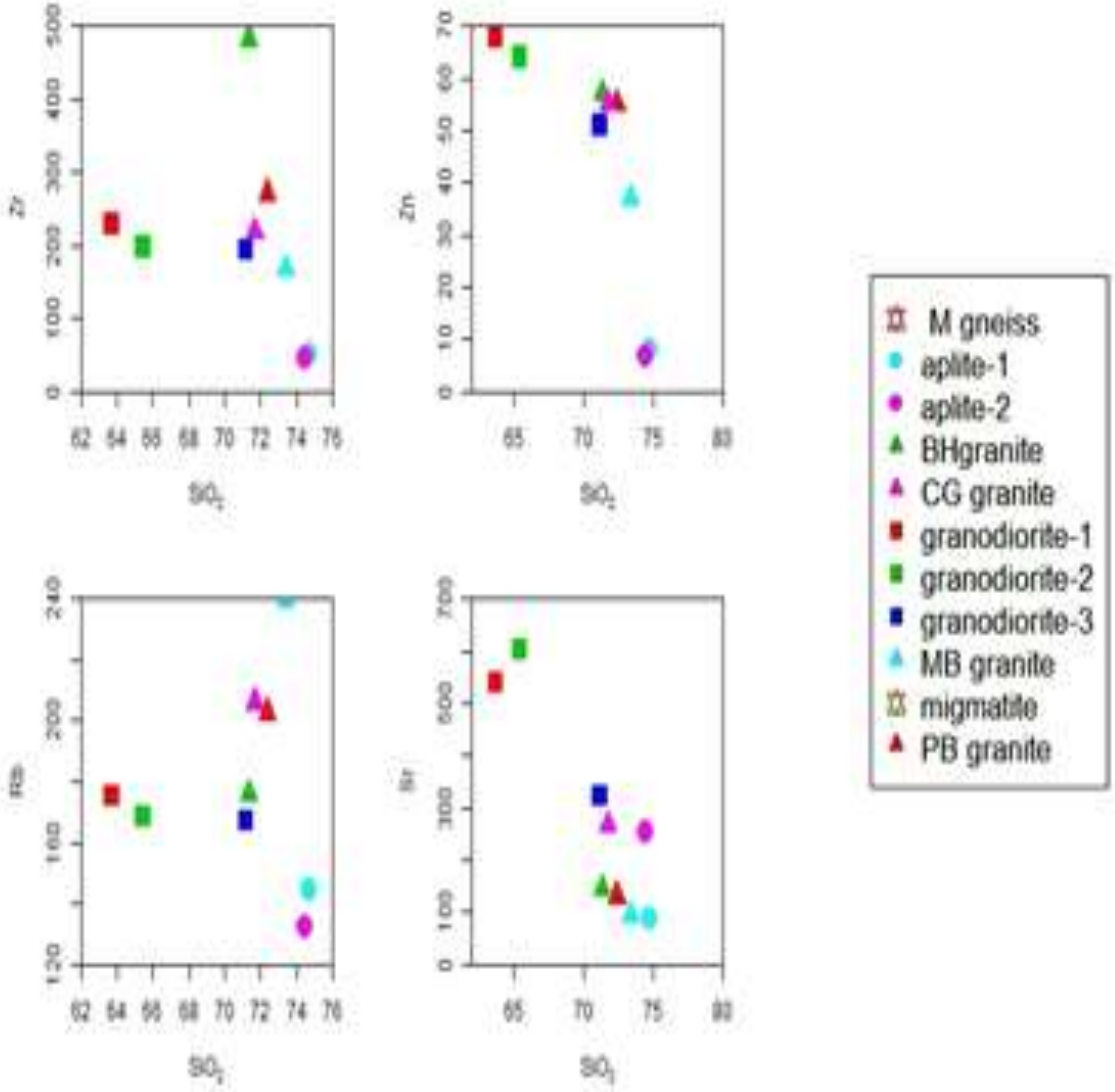


Fig.4.10a: Plot of Zr, Zn, Rb and Sr Vs SiO_2 (Harker, 1909).

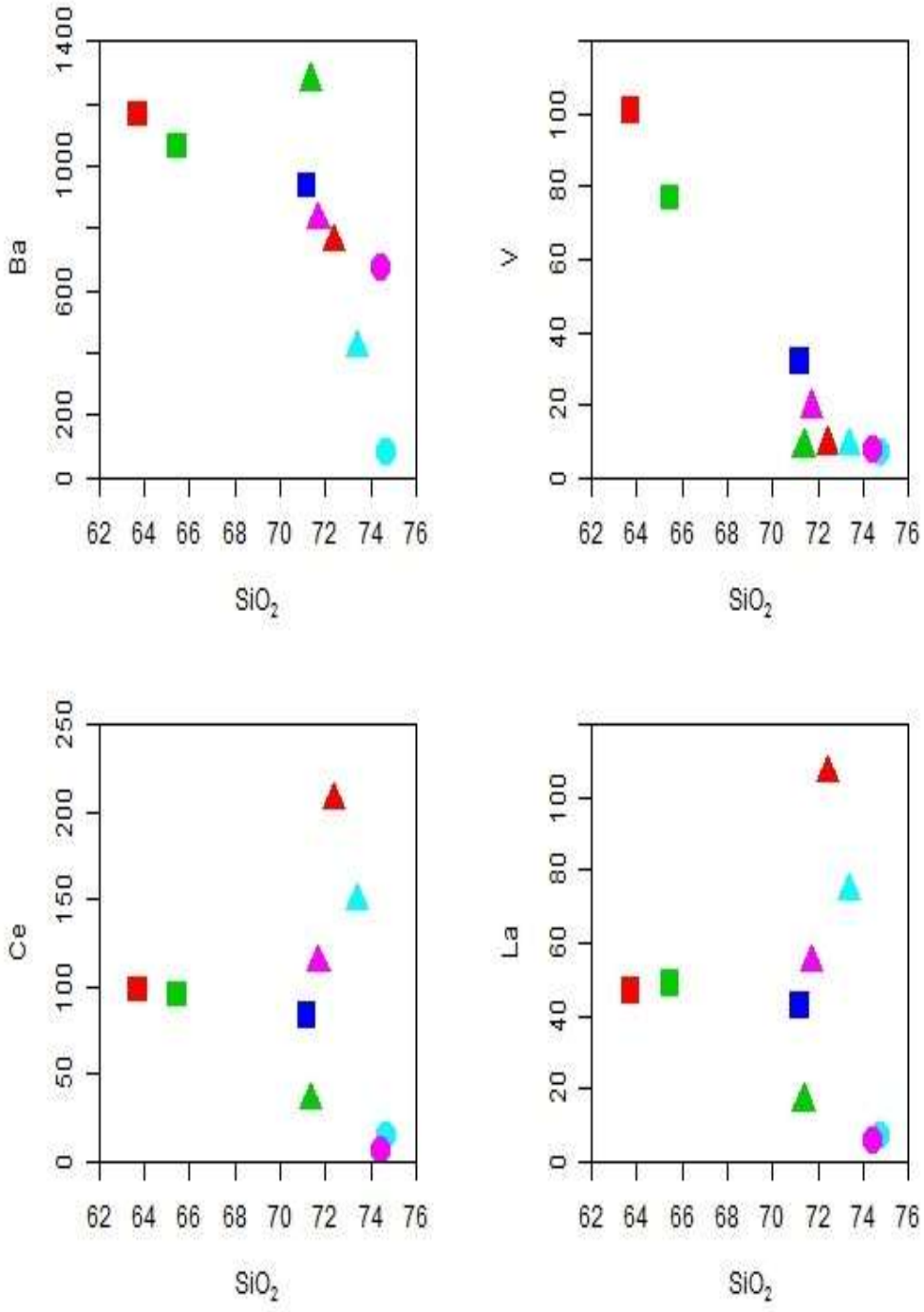


Fig.4.10b: Plot of Ba, V, Ce and La Vs SiO_2 (Harker, 1909)

4.3.3 **Tectonic Setting**

In an Orogenic belt to which Nigeria province belong, due to complexity of the orogenic process, without some key indicators such as timing of subduction of oceanic crust (e.g presence of the youngest arc volcanic rock), timing of the closing stage of oceanic basin (e.g presence of ophiolite) and evidence of high to ultra-high pressure metamorphism related to oceanic and continental subduction, it is fairly difficult to discriminate magmatism in different stages of the orogeny (Song *et al.*, 2015).Plot of Badafi granitoids on the tectonic discrimination diagram of Pearce et al., (1984) Fig. 4.11; shows that the granitoids are distributed within volcanic arc, syn-collisional and within plate granites tectonic setting which is typical of Pan-African post-collisional granites (Pearce 1996; Song *et al.*, 2015). This coulple with high-K calc-alkaline to shoshonitic character of the Badafi granitoids suggest they were formed in post-collisional geotectonic setting.

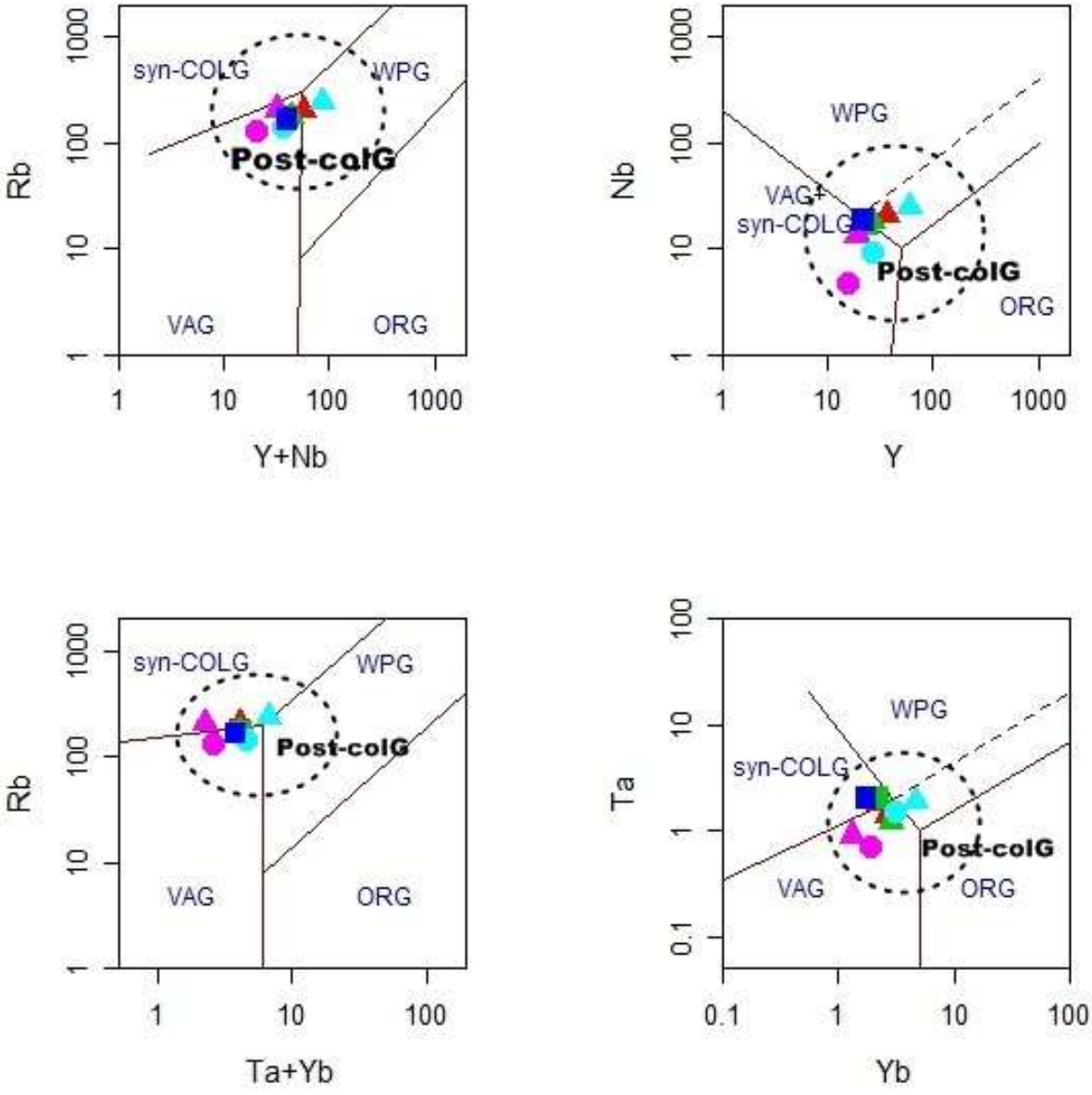


Fig 4.11: Granite tectonic discrimination diagram showing the distribution of the rocks within the field of post-collision granites. (after Pearse *et al.*, 1984). Symbols are same as in Fig. 4.10.

4.3.4 Rare Earth Elements Distribution Pattern

The rare earth elements (REE) data is presented in (Table 4.3) and the REE spider diagram is presented in (Fig. 4.12). The migmatitic gneiss is characterized by slight enrichment in LREE and depletion in HREE with negative Eu anomaly. The migmatite on the other hand is characterized by slightly fractionated REE pattern with small Eu anomaly (Fig 4.12c). With the exception of the biotite hornblende granite and coarse grained granite all the granites are REE enriched (Fig.4.12a); REE abundance range from 352.67 to 466.35 ppm in the granite. However, the granodiorite and aplite are somewhat depleted in REE compared to the average of REE in granite which is 250 ppm as reported by Emmermann *et al.*, (1975). REE abundance ranges from 195.96 to 222.91 ppm in granodiorite and from 29.99 to 49.21 ppm in aplite. Moreover, with the exception of hornblende biotite all the granite and granodiorite show similar REE pattern characterized by enrichment in LREE ([La/Sm]N value ranges from 1.823 to 4.599) and depletion in HREE and slight Eu anomaly (Eu/Eu range from 0.452 to 0.786 (table 4.3). Whereas the hornblende biotite granite is characterized by slight enrichment in LREE and depletion in HREE with slight positive Eu anomaly (Eu/Eu value of 1.289)

Table 4.3: Rare earth element composition of the rocks from the study area

Elements	Migmatites	Migmatitic Gneiss	Granodiorite			Granites				Aplites	
PPM	D13	D6	D1	D8	D11	D4	D3	D9	D5	D10	D12
La	34.6	28.9	46.7	48.7	42.9	16.3	106.6	54.6	74.1	7.4	5.7
Ce	60.2	74.0	98.4	95.2	83.8	34.6	206.4	113.8	148.9	15.4	6.8
Pr	8.11	8.69	10.81	11.20	9.58	4.74	23.70	12.53	17.04	1.90	1.40
Nd	29.4	34.8	40.4	40.3	34.7	21.1	83.9	42.9	59.8	7.5	5.4
Sm	5.63	8.40	7.39	7.26	6.99	5.50	14.26	7.63	12.67	1.86	1.33
Eu	1.40	1.30	1.63	1.50	1.23	2.36	1.58	1.10	1.08	0.19	0.27
Gd	5.33	9.29	6.23	5.86	6.00	5.76	12.15	5.97	12.31	2.64	1.77
Tb	0.73	1.63	0.83	0.85	0.88	0.91	1.56	0.76	1.95	0.54	0.33
Dy	3.71	10.31	4.52	4.50	4.69	5.44	7.84	3.75	10.90	3.99	2.26
Ho	0.60	2.13	0.84	0.83	0.82	1.07	1.36	0.63	2.10	0.93	0.55
Er	1.52	6.35	2.34	2.33	2.09	2.98	3.56	1.70	5.66	2.86	1.70
Tm	0.20	0.93	0.32	0.34	0.28	0.44	0.44	0.21	0.80	0.46	0.27
Yb	1.40	5.71	2.17	2.23	1.77	2.86	2.62	1.33	4.68	3.08	1.91
Lu	0.22	0.92	0.33	0.34	0.23	0.48	0.38	0.21	0.68	0.46	0.30
					Normalised	Ratio					
Eu/Eu	0.786	0.452	0.738	0.707	0.584	1.289	0.369	0.501	0.266	0.264	0.541
(La/Yb)	16.476	3.374	14.347	14.559	16.158	3.8	27.125	27.368	10.556	1.602	1.99
(La/Sm)	3.781	2.116	3.887	4.126	3.775	1.823	4.599	4.402	3.598	2.447	2.636
(Ce/Yb)	10.936	3.296	11.533	10.858	12.041	3.077	20.036	21.762	8.092	1.272	0.905
(Ce/Sm)	2.509	2.067	3.125	3.077	2.813	1.476	3.397	3.5	2.758	1.943	1.2
(Eu/Yb)	2.857	0.65	2.146	1.922	1.985	2.358	1.723	2.363	0.659	0.176	0.404
SumREE	153.05	193.36	222.91	221.44	195.96	104.54	466.35	247.12	352.67	49.21	29.99

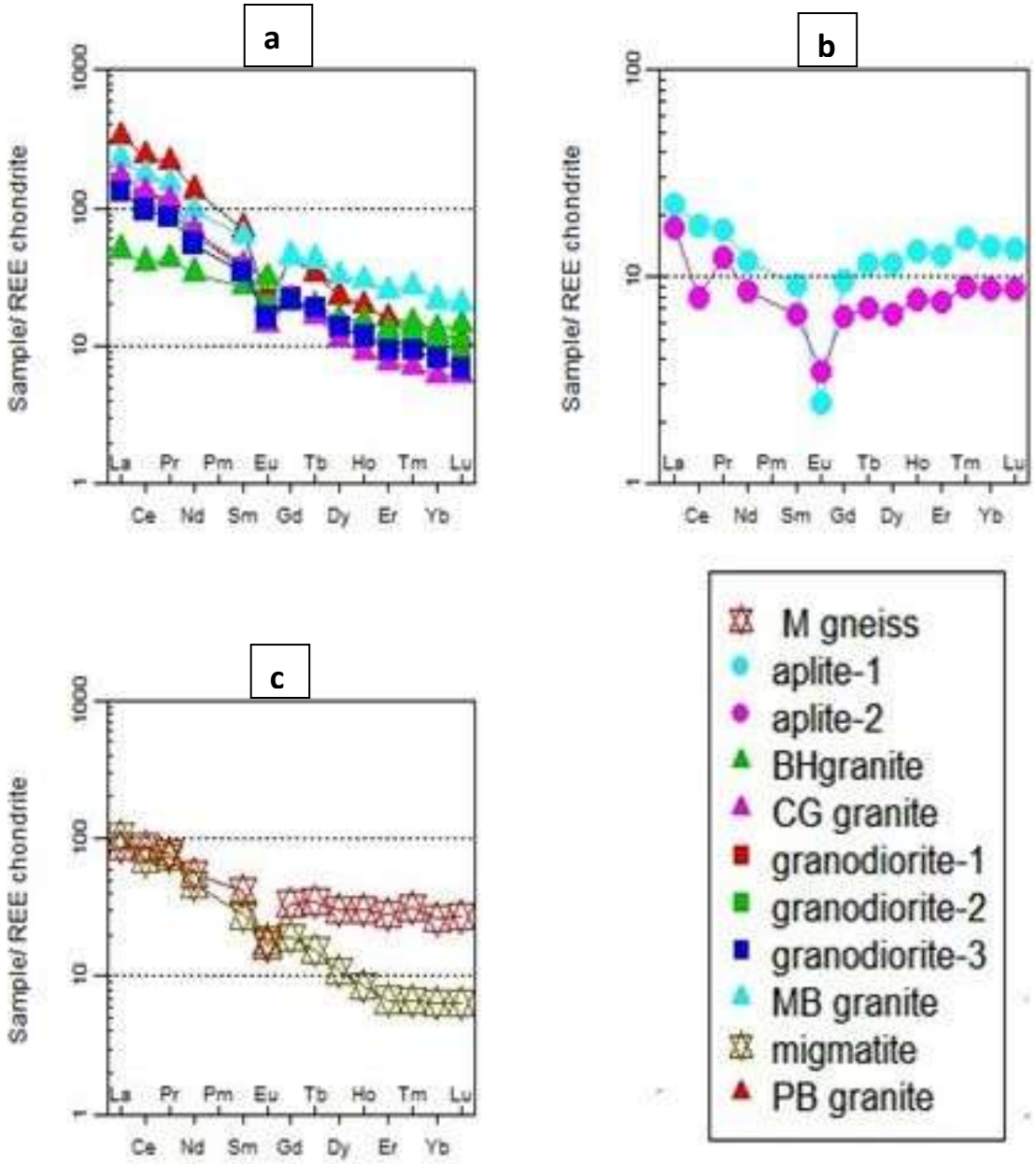


Fig. 4.12: Chondrite normalized REE diagram (after Nakamura, 1974) for (a) granites (b) aplite and (c) Migmatite and migmatitic gneiss.

4.4 GEOCHEMISTRY OF PEGMATITES

4.4.1 Major element distribution in Badafi Pegmatites

The major element composition of Badafi pegmatites is represented in Table (4.4). Silica (SiO_2) is relatively high in the pegmatites. It ranges from 71.73 to 78.78 wt% in whole rock samples of the pegmatites and from 64.84 to 65.22 wt% in K-feldspar samples. The pegmatite has low contents of Fe_2O_3 and P_2O_5. Iron oxide (Fe_2O_3) and phosphorus oxide (P_2O_5) ranges from 0.04 to 0.17wt% and from <0.01 to 0.01 wt %. Ternary plot of K_2O, Na_2O and CaO show that with the exception of one whole rock sample, all the pegmatites are K_2O rich (Fig.4.13).

Table 4.4: Major element composition of Pegmatites and K- feldspar (wt %).

Oxide in wt%	Whole Rock Pegmatite			Minerals K-feldspar					
	D15	D16	D14	L1	L2	L3	L4	L5	L6
SiO_2	71.73	74.96	78.78	65.19	65.28	64.89	65.08	65.22	64.84
Al_2O_3	14.87	13.64	12.73	18.75	19.02	19.08	18.84	18.57	18.95
Fe_2O_3	<0.04	<0.04	0.17	<0.04	<0.04	0.04	0.06	0.06	<0.04
MgO	<0.01	<0.01	0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
CaO	0.07	0.03	0.98	0.05	0.03	0.06	0.07	0.06	0.03
Na_2O	2.34	2.25	5.99	3.04	2.93	3.29	3.28	2.12	2.95
K_2O	9.56	8.69	0.37	12.17	12.41	11.75	11.67	13.10	12.29
TiO_2	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
P_2O_5	<0.01	<0.01	<0.01	<0.01	0.02	<0.01	<0.01	0.02	<0.01
MnO	<0.01	<0.01	0.04	<0.01	<0.01	<0.01	<0.01	<0.01	<0.01
Total	98.65	99.65	99.09	99.28	99.76	99.15	99.04	99.18	99.14

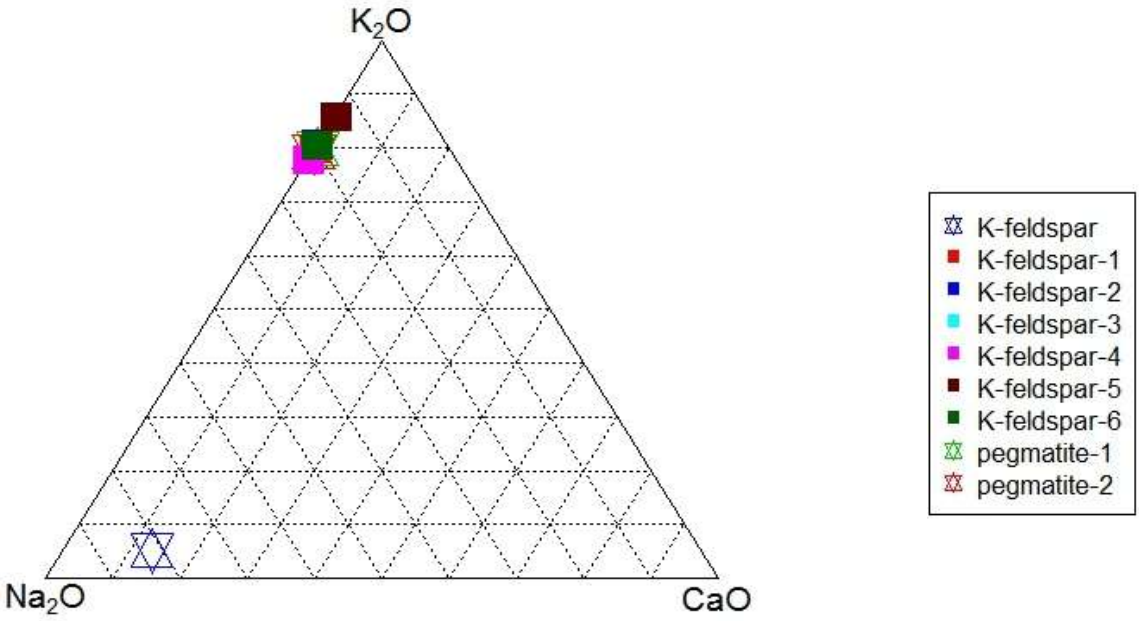


Fig 4.13: Ternary plot showing the distribution of K_2O, Na_2O and CaO in pegmatites (after, Shearer *et al.*, 1985)

4.4.2 Trace and Rare Earth Elements Distribution in Badafi Pegmatites

The trace element composition of the pegmatites is represented in (Table 4.5) and the primitive mantle normalized multi-element diagram is shown in (Fig.4.14). The pegmatites are characterized by negative anomaly of Nb and Ti like the Badafi granitoids but unlike the granitoids, the pegmatites depict positive Ta anomaly and negative Pb anomaly. Rb, Ba and Sr

show significant variation in the pegmatites. Rb ranges from 21.00 to 736.20 ppm in the whole rock and from 839.400 to 1039.200 ppm in K-feldspars from Badafi pegmatites. With the exception of one K-feldspar sample, all the pegmatites and K-feldspar minerals show Ba contents less than 100 ppm typical of fractionated pegmatites (Cerny et al., 1985, table 4.5). Strontium (Sr) content is also very low in the pegmatites. It ranges from 9.40 to 28.20 ppm. The pegmatites are also characterized by low K/Rb ratio (less than 15). Barium Rubidium ratio (Ba/Rb) ranges from 0.022 to 0.133. Low K/Rb and Ba/Rb ratios are also typical of fractionated pegmatites.

Table 4.5: Trace elements composition of Badafi pegmatites (in ppm)

Element In ppm	Whole Rock pegmatite			Minerals K-feldspars					
	D15	D16	D14	L1	L2	L3	L4	L5	L6
Be	16.000	6.000	18.000	5.000	5.000	9.000	8.000	11.000	3.000
Co	35.700	42.400	66.700	17.900	20.500	17.900	22.000	22.200	18.600
Cs	55.800	32.900	3.200	63.100	93.500	60.300	62.400	118.900	92.400
Ga	24.500	17.600	19.600	31.200	48.000	51.700	49.900	30.200	43.900
Hf	0.500	<0.1	0.600	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Nb	18.800	0.100	1.400	1.300	0.300	<0.1	0.200	2.100	0.400
Th	1.000	<0.2	7.700	0.900	<0.2	<0.2	<0.2	<0.2	<0.2
U	2.400	0.200	1.600	0.200	<0.1	0.200	0.300	0.100	<0.1
V	11.000	17.000	<8	12.000	14.000	<8	<8	<8	19.000
Ta	21.300	0.800	1.400	1.200	1.000	0.200	0.200	1.700	1.900
Sn	1372.000	8.000	4.000	11.000	28.000	3.000	3.000	1.000	31.000
Rb	736.200	591.000	21.000	851.700	1105.300	825.900	839.400	899.500	1039.200
Ba	57.000	74.000	2.000	113.000	29.000	21.000	22.000	59.000	23.000
Sr	17.200	18.400	15.700	28.200	9.800	11.400	11.900	20.000	9.400
Ba/Rb	0.077	0.125	0.095	0.133	0.026	0.025	0.026	0.066	0.022
Rb/Sr	42.802	32.120	1.338	30.202	112.786	72.447	70.538	44.975	110.553
K/Rb	10.776	12.202	14.62	11.858	9.318	11.807	11.538	12.086	9.814
Rb/Ba	12.916	7.986	10.500	7.537	38.114	39.329	38.155	15.246	45.183

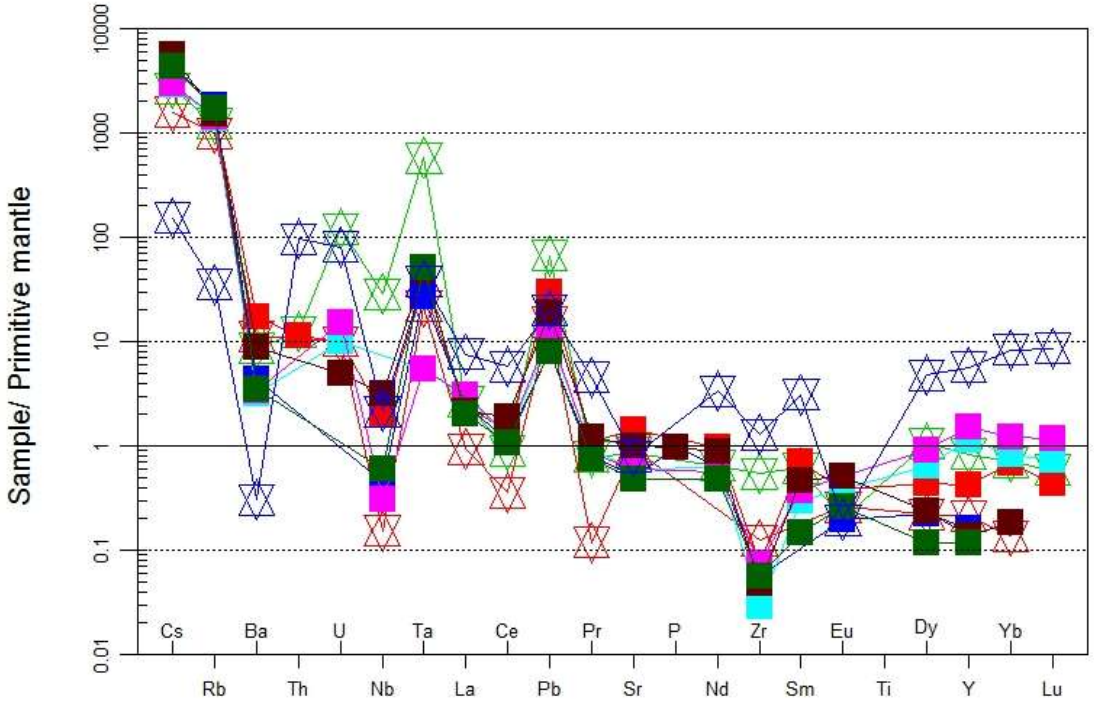


Fig. 4.14: Primitive mantle normalized multi-element diagram for Badafi pegmatites (after, Sun and McDonogh, 1989).Symbols are the same as in Fig. 4.13.

Plot of the pegmatites on K/Rb versus Rb discrimination diagram shows that the pegmatites are moderately fractionated as shown by their high Rb content and low K/Rb ratio. On the K/Rb versus Cs discrimination diagram, the pegmatites plot with the field of rare metal pegmatites (RMP). Similarly using the K/Rb versus Cs discrimination adopted from Morteani *et al.*, 2000), the pegmatites plot within the field of Beryl class of pegmatites (Fig. 4.16b). On Rb versus Ba and Rb versus Sr discrimination plots, the pegmatites plot within the field of beryl and columbite rich pegmatites as defined by Anderson (2013) for Cross Lake pegmatites in central Manitoba.

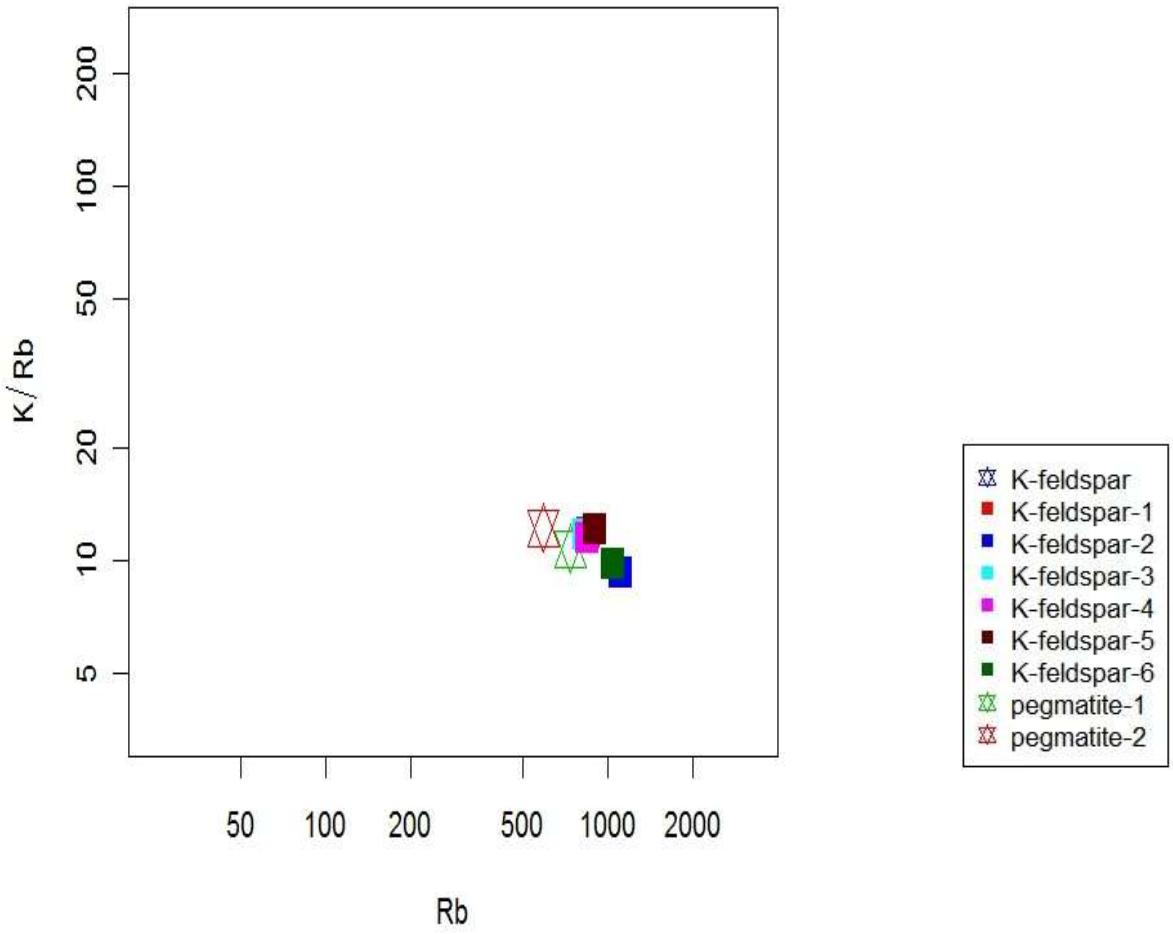


Fig.4.15: K/Rb versus Rb discrimination diagram (after, Cerny et al., 1985).

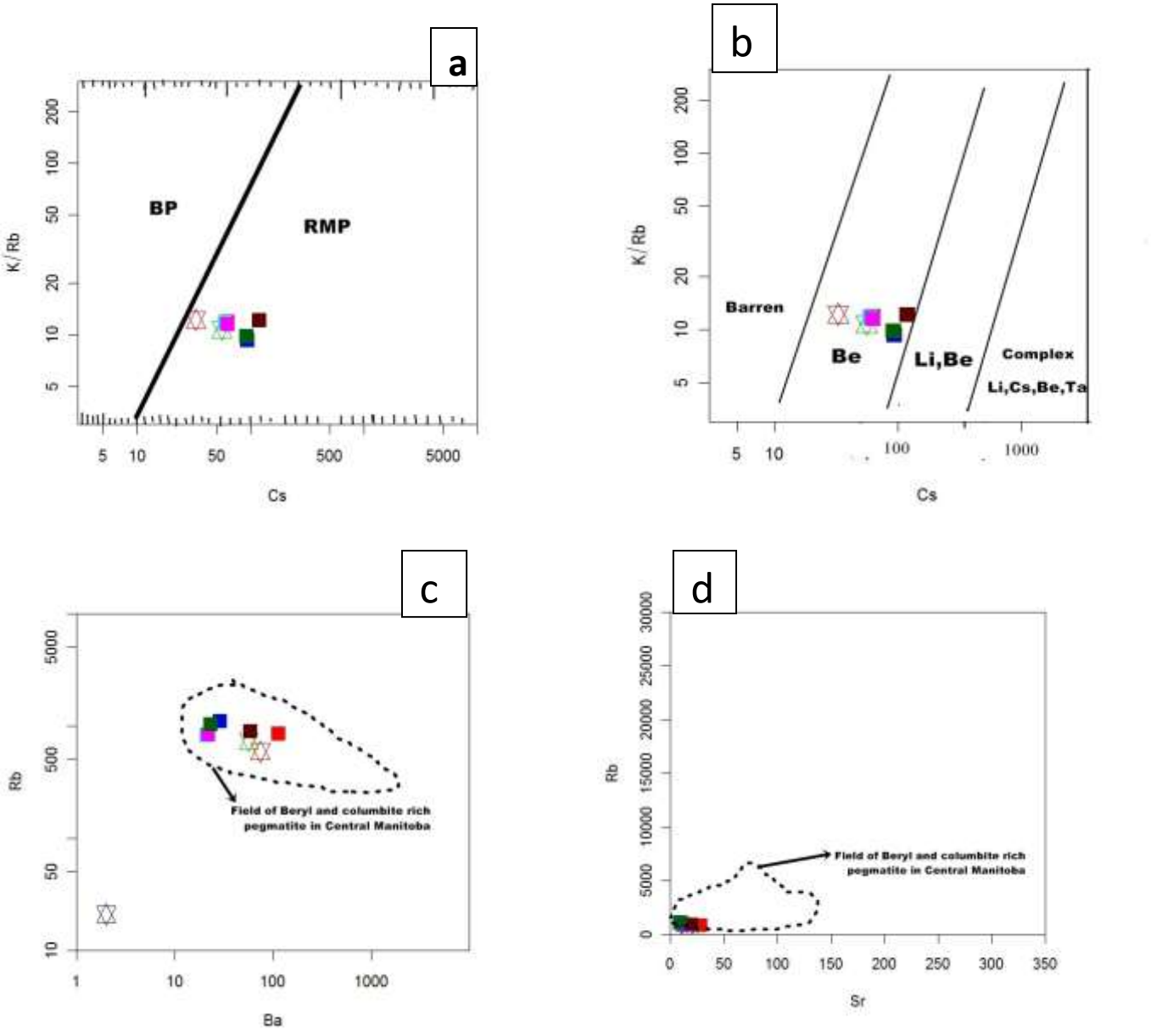


Fig.4.16: a) K/Rb versus Cs discrimination diagram (after Garba, 2003), b) K/Rb versus Cs discrimination diagram (after Morteani et al., 2000), c) Rb versus Ba discrimination diagram (after Cerny et al., 1985), d) Rb versus Sr discrimination diagram (after Cerny et al., 1985). Symbols are as in (Figure 4.15).

On the REE chondrite normalized diagram (Fig.4.17) the pegmatites show co-enrichment of both LREE and HREE with weak Eu anomaly in all the pegmatites except sample D14 which show strong Eu anomaly and has 5.99 wt. % Na_2O content.

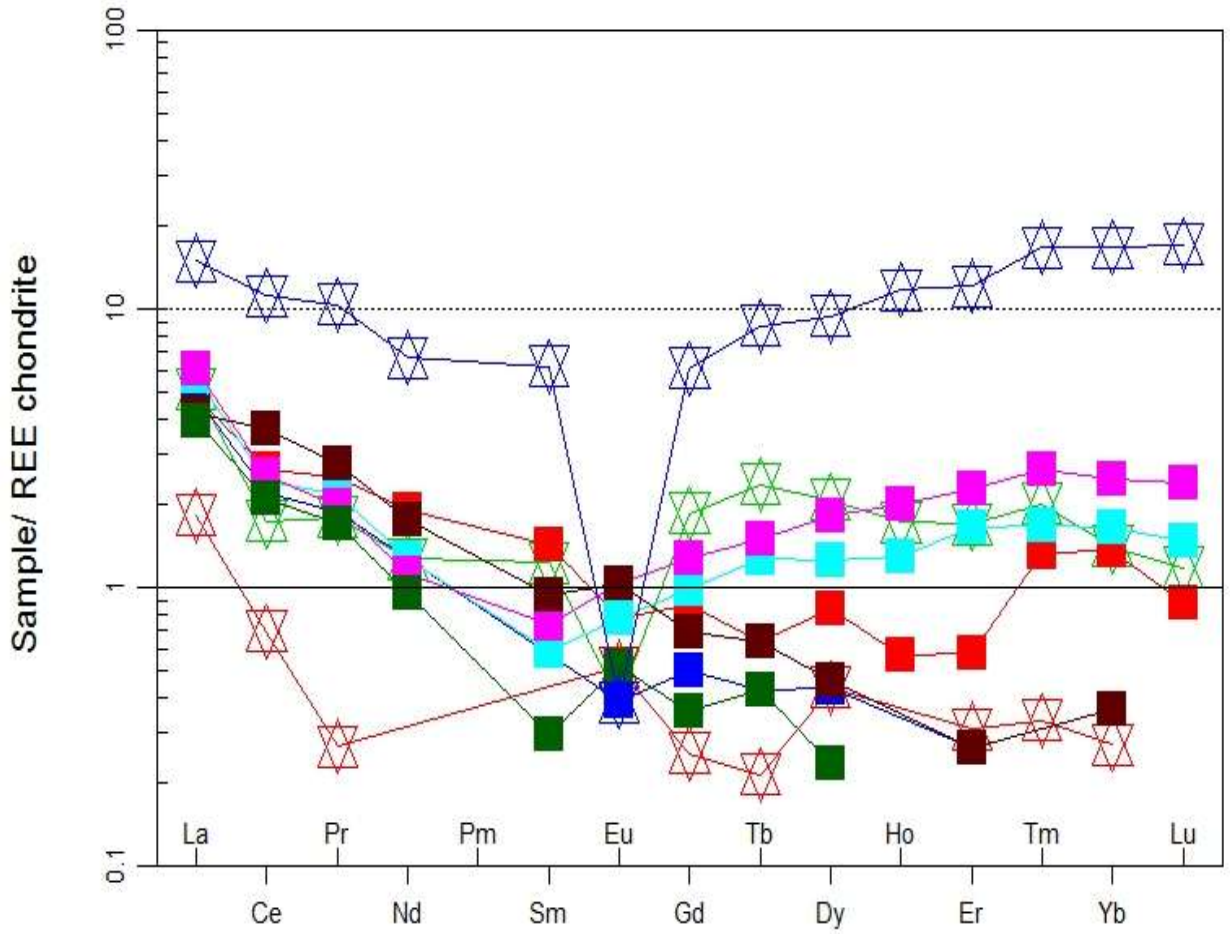


Fig. 4.17: Primitive normalized multi element diagram for Badafi Pegmatites (after, Sun and McDonough, 1989).Symbols are same as in Fig. 4.15.

CHAPTER FIVE

DISCUSSION, CONCLUSION AND RECOMMENDATIONS

5.1 LITHOLOGICAL UNIT AND TECTONIC SETTINGS

Geological mapping of the Badafi pegmatites field has revealed that migmatite, migmatitic gneiss and granites are the major lithologic units hosting the pegmatites. Aplite and pegmatites are the minor rocks mapped in the study area. Petrographic studies have shown that the migmatite consist mainly of quartz, orthoclase feldspar, microcline, plagioclase feldspar and biotite. By contrasts, the migmatitic gneiss consists mainly of quartz, microcline, plagioclase, biotite and opaque minerals. Major elements composition has revealed that the migmatite and the migmatitic gneiss are all peraluminous and have calc-alkaline affinity. TiO_2 versus SiO_2 discrimination (Fig.4.8b) has shown that the two rocks are orthogneiss, i.e. were derived from igneous source. The migmatitic gneiss depicts an REE pattern characterized by slight enrichment of light rare earth elements but depletion in heavy rare earth elements with weak Eu anomaly which probably resulted from intracrustal differentiation in which plagioclase was residual phase.

The migmatite on the other hand is characterized by slightly fractionated REE pattern with no Eu anomaly. Dada *et al*., (1998) reported similar REE pattern in migmatitic orthogneisses in Kabala, northcentral Nigeria. Migmatitic orthogneiss with similar REE pattern was also reported in Mandara Hills northeastern Nigeria by Girei (2015).

The granitoids vary in texture and composition and comprises of granodiorite, hornblende biotite, porphyritic biotite granite, coarse grained biotite granite and medium grained biotite granite. Geochemical and mineralogical data such as the relatively high Na_2O content and the presence of hornblende and iron oxide (probably magnetite) suggest that the granitoids belong to

the calc-alkaline, I-type metaluminous to slightly peraluminous granitoids (Eleftheriadis and Koroneos, 2003) derived from partial melting of igneous protoliths. The K_2O contents in the rocks are high and in the diagram of Peccerillor and Taylor, (1976) Fig. 4.7, all the rocks plot in the field of high potassium calc-alkaline to shoshonitic granites similar to granitoid from eastern Nigeria (Ferre *et al.,* 1998) Bapa-Batie in Cameroon (Chebeu *et al.,* 2011) and Borborema Province in the NE Brazil (Neves and Mariano, 1997).

On the tectonic discrimination diagram(Fig.4.11) after Pearce *et al*., (1984) the Badafi granitoids plot in volcanic arc, syn-collisional and within plate granites tectonic setting which is typical of granitoid that formed at post-collisional stage of an orogeny (Pearce 1996; Song *et al.*, 2015). This, coulpled with high-K calc-alkaline characters of the Badafi granitoids suggest they were formed at the post-collisional stage of the Pan-African orogeny. Liegeois *et al*., (1998) states that post-collisional geodynamic settings are not yet fully integrated in plate tectonics model, which is based on geological processes occurring at plate edges, mid-oceanic ridges, active margins and in intercontinental collisions. Post-collisional settings are often referred to as a relaxation phase following collision. However, this period is also characterised by voluminous magmatism. The collision stage, a period of maximum convergence, is less favourable for ascent of magmas (Bonin, 2004).

5.2 PETROGENESIS OF GRANITOIDS

Field, petrographic and geochemical characteristics are the basic criteria utilized in establishing the petrogenesis of the granitoids and feldspar samples in the study area. Based on field relationship, the granitoids intruded the older basement rocks. The granodiorite and the granites share many mineralogical and geochemical characteristics in common thus suggesting that they can be related by fractional crystallization. For instance, the granodiorite has low content of Sr

and weak Eu anomaly compare to the granites which may suggest the rocks are related via fractionation of plagioclase because plagioclase is the only mineral phase that is known to be able to effectively, simultaneously and consistently fractionate Eu and Sr from other element (Sun et al., 1974, Niu and Ohara, 2009). The granites have higher average Rb/Sr ratios than the granodiorite. The high Rb/Sr ratios in the granites suggest that any fluid present during their formation must have low H_2O content (Haruna et al., 2013). Such Rb/Sr ratios may nevertheless suggests that the granites are residual from the granodiorite after fractionation of hornblende, biotite and minor plagioclase. All these evidences suggest fractional crystallization as the dominant process in the formation of the granitoids.

Enrichment of Ba, and Rb contents in the granitoids precludes its formation by melting of greywackes as melts generated from melting of greywackes are often depleted in these elements (Tindle and Pearce, 1983). Furthermore, melts derived from granulitic residue in the lower continental crust is generally depleted in LILE. Thus, the high content of LILE (e.g Rb, Sr, and Ba) in the investigated granitoids argues against its formation from such melts (Haruna et al., 2013).

In post-collisional settings the formation of high K calc-alkaline to shoshonic I type graninoids is generally attributed to melting of crustal source rocks as a consequence of decompression following crustal thickening (Roberts and Clemens, 1993) or partial melting of a newly form, warm, mafic lower crustal amphibolites as a consequence of under plating by a mafic magma (Neves *et al.*, 2000).

According to Rapp (1997), calc-alkaline I-type granite generally formed through dehydration melting of Archaean tonalites. However, Carstor (2004) revealed that dehydration melting of tonalities would not produced melts with the required calc-alkaline I-type composition. The

Badafi granitoids probably formed through partial melting of tonalitic rocks. Partial melting took place in the presence of water as against the typical dehydration melting proposed by Rapp (1997). Inversion of wet, K rich andesitic magma provided the heat and water for the melting as proposed by Carstor (2004). This model accounts for the high-K to shoshonitic character of the Badafi granitods.

5.3 GEOCHEMICAL FEATURES AND MINERALIZATION POTENTIAL OF BADAFI PEGMATITES

The Badafi pegmatites are generally characterized by enrichment of some large ion lithophile elements such as Rb and Cs typically of fractionated pegmatites (Cerny et al., 1985; Garba, 2003; 2005). The low K/Rb ratio in the pegmatites and K/Rb versus Rb plot (Fig. 4.15) revealed that the pegmatites are moderately fractionated. Furthermore, in the K/Rb versus Cs discrimination diagram (Fig.4.16a), the pegmatites plot within the field of rare metal pegmatites. This clearly revealed that the pegmatites are mineralized with beryl. Using the discrimination plot proposed by Morteani *et al.*, (2000) it has been established that the Badafi pegmatites plot in the field typical of beryl mineralized pegmatites (Fig.4.16b). This is in agreement with the occurrences of beryl mineralization observed in the pegmatite.

The pegmatites also show a mark similarity with some beryl and columbite mineralized pegmatites in Cross Lake pegmatite in central Manitoba (Anderson, 2013). The Be contents recorded in K-feldspars extracted from the pegmatites ranges from (3-16 ppm). However, London (2005) observed that because of its combination of tetrahedral (four-fold) coordination but low valency (2^+), Be should be incompatible in most silicates minerals and in silica rich melt. Such behaviour would lead beryl to precipitate from melt at low concentration of Be (London,

2008). The beryl mineralization in Badafi pegmatites is largely associated with late stage albitization and occur within vugs (pockets) made up of K-feldspars and quartz (Plate XV). Berillium is highly compatible in calcium-bearing plagioclase and muscovite hence the abundance of calcium-bearing plagioclase and muscovite in some granites or granitic pegmatite would preclude beryl saturation (London and Evensen, 2002). The low content of Ca-bearing plagioclase and muscovite in Badafi pegmatites and their conspicuous absence within the pegmatitic vugs favoured the crystallization of beryl (London, 2008).

5.4 PETROGENESIS OF BADAFI PEGMATITES

Modern genetic models for pegmatite crystallization are usually based on the coexistence of highly viscous peraluminous and low-viscosity peralkaline melts, whose hybrid nature is invoked to explain paradoxical features observed within pegmatite bodies (London, 2005, 2008; Thomas et al., 2012; Thomas and Davidson 2012, Beurlen et al., 2011; Bongiolo *et al*., 2015). According to Liégeois *et al*., 1998) pegmatite intrusions are common in all phases of the evolution of orogens. Pegmatites that cross–cut the main metamorphic foliation are considered late– to post–collisional intrusions; their origin is usually attributed to a process called "orogenic collapse", *i.e.*, gravitational failure of the orogenic pile in response to the cessation of horizontal driving forces (*e.g.*, Jademec *et al.*, 2007), or when the convergence of the plates is at very low rates (< 0.5 mm/yr; (Vernant *et al*., 2013).

In Nigeria, rare-metal pegmatites are generally associated with post-collisional granitoids (Garba, 2002; 2003; Okunlola, 2005; Goodenough *et al*., 2014). Garba (2002) linked the genesis of rare-metal pegmatites with the emplacement of post-collisional granitoids and proposed "Orogenic collapse" model for the formation of both rare-metal and gold mineralization in

Nigeria. 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. Evidence from REE geochemistry of Badafi granitoids and pegmatites revealed that the pegmatites are not genetically related to the granitoids. As noted by Garba (2005) the REE pattern of the pegmatites share more similarity with younger granites than the typical pan-African granitoids. It is characterized by co-enrichment of both LREE and HREE with strong Eu anomaly (Garba, 2005) as expressed by one of the whole rock sample. By constrast, the REE pattern of the Badafi granitoids is characterized by an enrichment of LREE and depletion of HREE and moderate Eu anomaly typical of Pan-African granitoids in Nigeria. This suggests that the Badafi pegmatites are not co-magmatic with their host post-collision granitoids.

Nonetheless, London (2008) noted that beryl-bearing pegmatites cannot be derived by direct anatexis of any likely source-material at accepted temperatures of melting rather, the pegmatite can be derived only by protracted and very efficient fractional crystallization of large volume of magma. London and Evensen (2002) utilized a similar model for the accumulation of Be via fractional crystallization. They determined that 95-98% fractional crystallization would be necessary to bring the melt to the threshold of beryl saturation.

The Badafi pegmatites therefore probably formed from highly fractionated and fluid-saturated residual melt with aplitic composition. The melt 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. Therefore, the pegmatites probably originated from the residual magmas that formed at the terminal stage of the Pan-African orogeny (Goodenough *et al*. 2014).

5.5 CONCLUSION

The study area comprises of low lying migmatites, migmatitic gneisses, granitoids, aplite and pegmatites. Petrographic studies have shown that the migmatitic gneiss consists mainly of quartz, microcline, biotite and opaque minerals. By contrasts, the migmatite consist mainly of quartz, orthoclase feldspar, microcline, plagioclase feldspar and biotite. Major elements composition has revealed that the migmatite and the migmatitic gneiss are all peraluminous and have calc-alkaline affinity. TiO_2 versus SiO_2 discrimination has shown that the two rocks are orthogneiss (were derived from igneous source e.g. Dada, 2008). The granitoids vary in texture and composition and comprise of granodiorite, medium grained hornblende biotite, porphyritic biotite granite, coarse grained biotite granite and medium grained biotite granite.

Geochemical and mineralogical data such as the relatively high Na_2O content and the presence of hornblende and iron oxide (probably magnetite) suggest that the granitoids belong to the calc-alkaline, I-type metaluminous to slightly peraluminous granitoids. Major elements composition and a CaO/Na_2O ratio of the granitoids between 0.32 to 1.21 is compatible with the melting of metaigneous protoliths. Geochemical and petrological evidence revealed that the granitoids probably formed through partial melting of tonalitic rocks. Inversion of wet, K rich andesitic magma provided the heat for the melting.

Three different generations of pegmatites were mapped in the study area (Fig. 4.3). They strike mainly in NNE-SSW direction. Field and geochemical evidence has revealed that pegmatites are mineralized. This is in agreement with the occurrences of beryl mineralization observed in the pegmatite. The beryl mineralization in the pegmatites is largely associated with late stage albitization and occur within vugs (pockets) made up of K-feldspars and quartz (Plate XV).

The pegmatites also show a similarity with some beryl and columbite mineralized pegmatites in Cross Lake in central Manitoba. Evidence from REE pattern suggests that the pegmatites are not co-magmatic with their host post-collision granitoids but were formed from highly fractionated and fluid-saturated residual melt with aplitic composition. The melt evolved from granitoid intrusions at a last stage of its evolution.

5.6 RECOMMENDATIONS

The conclusion drawn from this work regarding the petrogenesis and mineralization potential of pegmatites is based on the study of the trace elements compositions of the whole rock and K-feldspars 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.

In addition, it is also recommended that more functional and reliable geochemical laboratories should be established in the country, so as to reduce the cost of analysis and conserve foreign exchange.

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