GEOLOGY, GEOCHEMISTRY AND STRUCTURAL CONTROL OF KERAWA TENTALITE MINERALIZATION, SHEET 123 KADUNA NE, NORTH CENTRAL NIGERIA

BY

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A THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES AHMADU BELLO UNIVERSITY ZARIA IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTER DEGREE IN GEOLOGY

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DECLARATION

I declared that the work in this thesis titled **GEOLOGY, GEOCHEMISTRY AND STRUCTURAL CONTROL OF KERAWA TANTALITE MINERALISATION, SHEET 123 NE KADUNA NW NIGERIA** has been carried out by me and in the Department of Geology, Faculty of Physical Science, Ahmadu Bello University, Zaria. The information derived from the literature has been dully acknowledged in the text and the list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution

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CERTIFICATION

This thesis titled **GEOLOGY, GEOCHEMISTRY AND STRUCTURAL CONTROL OF KERAWA TANTALITE MINERALIZATION; SHEET 123 NE KADUNA NW NIGERIA** by Mohammed Usman meets the regulations governing the award of degree of masters of Science in Geology of Ahmadu Bello University, and is approved for contribution to knowledge and literary presentation.

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DEDICATION

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

ABSTRACT

Geological, structural and geochemical studies of the study area (Kerawa NE Kaduna) were undertaken to determine the tantalite bearing pegmatite. The study area is underlain by migmatite gneiss, schist, granite, granodorite, and pegmatite. Field, petrographic structural and geochemical studies of the muscovite from pegmatite in the study area have been undertaken with a view to characterize them based on their geochemical nature, determine their genesis and their tantalite mineralization potentials. Geological mapping on a scale of 1: 50,000 reveals that these pegmatites intrude the host granodiorite, trending NE-SW. Muscovite from the pegmatites were sampled and analyzed for major, trace and rare earth elements using inductively couple plasma mass spectrometry (IC-PMS) using litho-4 and peroxide fusion techniques. The samples of the host rock and the other lithologic units were analyzed using X-ray fluorescence (XRF) techniques. The result obtained revealed that the pegmatites are peraluminous and belong to the rare element class. The high Li-Cs-Ta values in the muscovite suggest that the pegmatite group belong to the lithium-cesium-tantalum (LCT) family of the rare element class. The plot of K/Rb ratio vs Rb, REE chemistry and the gradual increase of Rb, Cs, K, Nb, Ta, Li, F, P, Ti and U in muscovite of the pegmatites indicate fractional crystallization that lead to late stage concentration of the rare metals. Fractionation trends of muscovite indicate that the pegmatite crystallized from the margins inward, thus mineralization is primarily magmatic: Alteration led to complex internal zonation with muscovite rich replacement zones. These late zones are further enriched in Nb - Ta and Sn indicating that magmatic and metasomatic processes played a role in metal enrichment.

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CHAPTER ONE

INTRODUCTION

1.1 LOCATION AND ACCESSIBILITY OF THE STUDY AREA

The area of study lies in sheet 123, Kaduna NE and is located between longitudes 7°15'E and 7°30'E and attitudes 10°45'N and 11°OO'N. It covers an area of about 750 square kilometer within the Zaria Division of Kaduna State, Kaduna North Western Nigeria (fig. 1.1)

Owing to the rugged nature of the terrain, the area is relatively inaccessible by car. However, network of footpaths made the area accessible

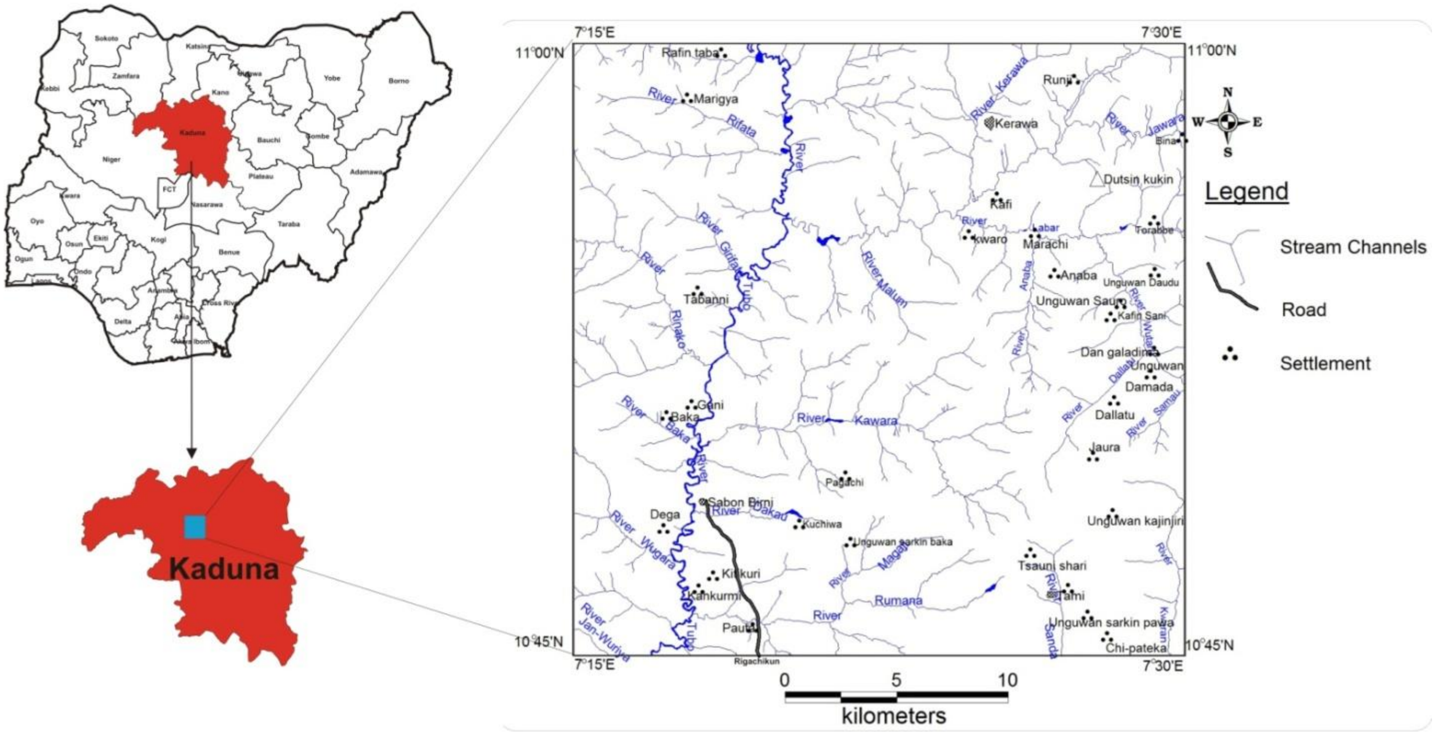


Fig. 1.1 Location and drainage map of the study area

1.2 CLIMATE AND VEGETAION

The area of study lies within the Tropical climate with distinct wet and dry season. The rainfall is concentrated in the short wet season which starts from mid-May to October whilst the dry season begins from November and last around April. An average annual precipitation of about 1,200 mm have been recorded for the area with a generally high day time temperature while during the harmattan the nights are very cold. The primary vegetation is characterised by grasses, shrubs and a few scattered trees, fringing forest with tall trees and well covered undergrowth along stream and river channels. The vegetation has been greatly modified by the agricultural activities of the inhabitants and consequently a mixture of grasses and short tress of the derived Guinea Savannah type now covers the area.

1.3 RELIEF AND DRAINAGE

The area of study is gently undulating except where the pegmatite forms low ridges. The area is made up of peneplain land and occasionally punctuated by hills measuring up to 667m above sea level. All the streams draining the area flow southward and are mainly dendritic in pattern fig. 1.1 conforming to the topography of the area. The streams dry up during the long dry season.

1.4 PREVIOUS WORK

Ike, (1988) worked on the late-stage geological phenomena in the Zaria basement granites and noted that many fracture-controlled phenomena in the Nigerian Basement such as mineralization are northeast-trending. He also worked on the petrogenesis of Older Granite batholiths in Zaria area, he observed that the abundance of pegmatite in the marginal zones of the batholiths as well as its roof zones is a pointer to late stage availability of excess water and volatiles during the formation.

Wright and McCurry (1971) produced a geological map of Zaria sheet 102SW and reported the occurrence of economic minerals such as gold and amethyst. McCurry, (1971) worked on Zaria sheet to determine the nature of Pan-African orogeny in northern Nigeria and the abundance of pegmatites in the marginal zones of the batholith and its roof zones is a pointer to late stage availability of excess water and volatiles.

There is low knowledge of the regional metallogeny of Ta-Nb mineralization within the Nigerian Precambrian pegmatites (Okunlola 2005). Rare-metal pegmatites containing economic concentrations of columbite-tantalite ore minerals are widely spread within (600 ± 500 Ma) Basement Complex of Nigeria. Kinnard (1984) working on contrasting styles of Sn-Nb-Ta-Zn mineralization in Nigeria found that there exist two distinct and economically important types of primary Sn-Nb-Ta-Zn mineralization in Nigeria.

1.5 STATEMENT OF RESEARCH

The world economy at present is growing at a rate comparable to technological development that necessitates an increasing demand for rare metals, with this trend likely to continue into the future. In recent times, there has been renewed interest in the study of pegmatites globally because of its attractive economic potentials. The increase in global demand for these economic minerals has led to keen interest in prospecting for mineral deposits from different areas in Nigeria (Okunlola and Oyedokun, 2009). In recent times there has being resurgence of interest in the study of rare metal pegmatite occurrences in Nigeria because they are known to host a good number of economic minerals which include tantalum, niobium, beryl and tourmaline. In line with efforts to appraise into some details the petrography, geochemical features and economic potentials in relation to rare metal mineralization of the pegmatites of the different fields, studies such as (Garba, 2002, Okunlola, 2005, 2008; Akintola and Adekeye, (2008); Okunlola and

Oyedokun, 2009; Okunlola and Akinlola, (2010); Akintola *et al*, (2012) have been carried out. Most of these workers studied mainly the occurrence and mineralization potentials of the rare metal pegmatites in Southwestern and Northcentral Nigeria. However, not much data exist on the tantalite mineralisation in the study area. The artisanal mining activities are another attractive point to look at. Therefore, it will be worthwhile to study the geology, geochemistry and structural control of the pegmatite in the study area.

1.6 SCOPE OF THE PRESENT WORK

The present work was carried out in two stages; first was reconnaissance survey which was followed by geological mapping and collection of rock samples for petrographic and laboratory studies. The study area was mapped on a scale of 1: 50,000. The techniques employed include transmitted light microscopy for petrography, ICP-MS and XRF for geochemistry, so as to determine the character and the nature of the mineralisation. At each sampling point, the coordinat were recorded as well as the strike and dip direction of the lithologies.

1.7 AIM AND OBJECTIVES:

The aim of this research is to study the tantalite mineralization pattern in the study area through geological, structural and geochemical determinations with a view to determine the genesis and the economic potentials of the deposits. The objectives of the work are to:

i Produce a geological map of the study area on a scale of 1:50,000

ii Define the structural pattern in the study area and their possible control on (tantalite) mineralization.

iii Determine the geochemical characteristics of the mineralization, and

iv Determine the genesis of the mineralization

CHAPTER TWO

REGIONAL GEOLOGY

2.1 INTRODUCTION:

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

This chapter focuses on a review of the regional geology of Nigeria. More emphasis is given to the Basement Complex which consists of the Migmatite Gneisses Complex, the Metasediments and the Older Granite suites.

2.2 THE BASEMENT COMPLEX OF NIGERIAN

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

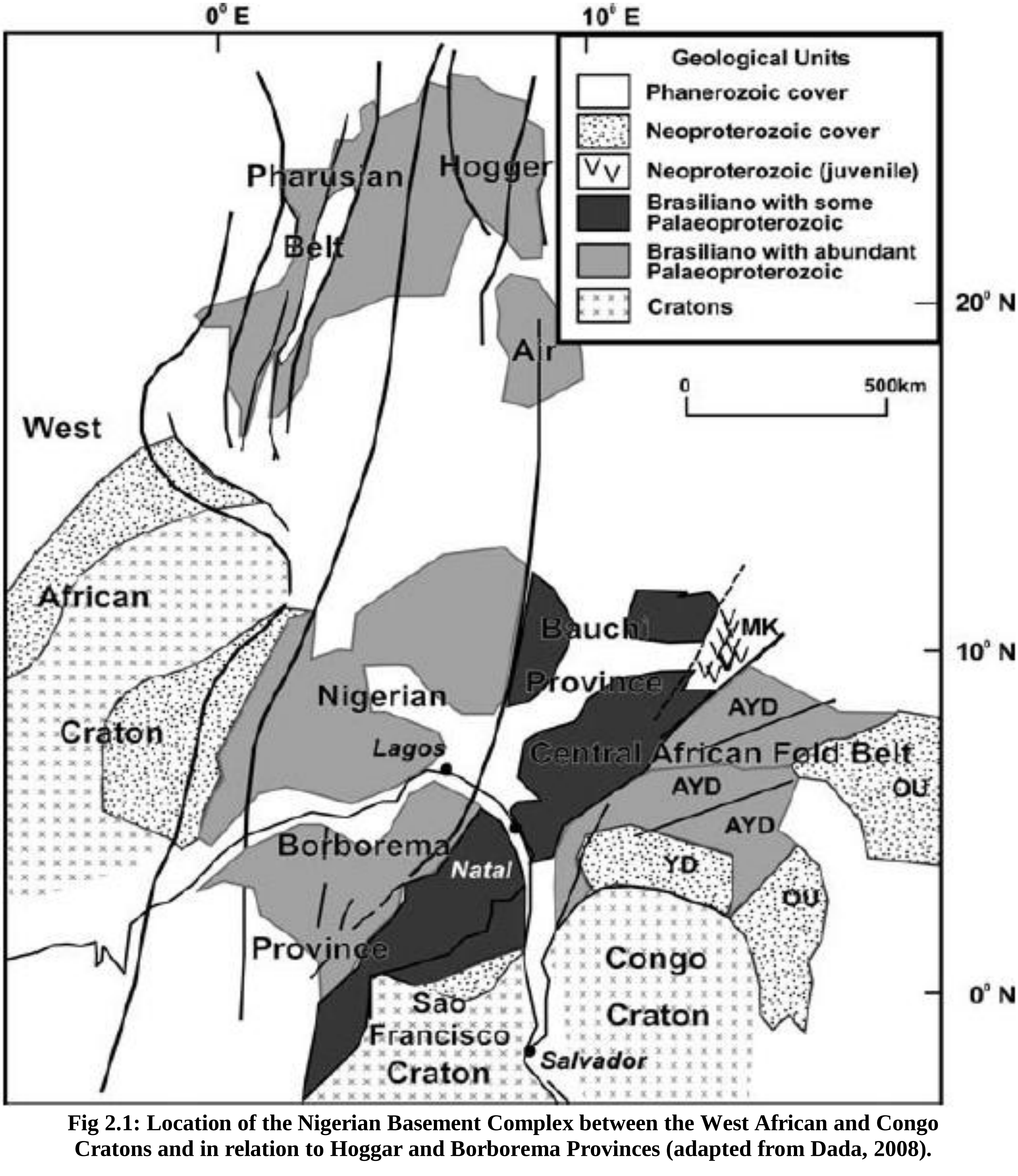


Fig 2.1: Location of the Nigerian Basement Complex between the West African and Congo Cratons and in relation to Hoggar and Borborema Provinces (adapted from Dada, 2008).

2.2.1 Lithologic units

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

i. Polymetamorphic Migmitite-Gneiss Complex.
ii. Metasediments
iii. Older Granite Suites

2.2.1.1 The Migmatite-Gneiss Complex

The Migmatite-Gneiss Complex is generally considered as the basement complex "Senso Stricto" (Rahamam, 1988; Dada, 2006). About half of the Nigerian Basement consists of the Migmatite-Gneiss Complex (Kröner *et al*., 2001). It is a heterogeneous assemblage including migmatized gneisses, banded gneisses and a series of metamorphosed basic and ultrabasic rocks. These rocks strongly resemble the tonali-tetrondhjemite-granodiorite (TTG) suites of Archean and Early Proterozoic terrains elsewhere in the world (Dada *et al*., 1993). Petrographic evidence indicates that Pan-African reworking led to recrystallization of many of the constituent minerals of the migmatite-gneiss complex during partial melting, and most display medium to upper amphibolites facies-metamorphism (Dada, 2008) .The gneisses of the migmatite-gneiss complex are interleaved with amphibolites that may be derived from Mg-rich rocks such as continental basalts (Caby *et al*., 1990; Dada,1999; Dada, 2008). However, there are no conclusive age and isotopic data to elucidate their origin (Dada, 2008). Oyawoye (1972) noted that the banded gneisses are possibly the oldest rocks in the country, older than granite gneiss that yielded a Rb-Sr whole-rock isochron age of 2190±30 Ma. Ajibade (1988) distinguished the ancient migmatites in northern Nigeria from the Pan-African migmatites by their complex polyphase deformation and mylonitization. Possibly because of their mixed and, therefore, complex nature, it has been difficult to define the protoliths of the banded gneisses (Kröner *et al*., 2001). Some authors suggested that they were metasediments derived from graywacke and shale (Freeth, 1971; Burke and Dewey, 1972), whereas others interpreted them as orthogneisses (Onyeagocha 1986; Ekwere and Ekwueme 1991; Kröner *et al.*, 2001). However, most workers agree that migmatization occurred during upper amphibolite-facies regional metamorphism (Oyawoye, 1972; Onyeagocha and Ekwueme, 1990). There is also consensus that metamorphic segregation, partial melting, and injection of leucogranitic material contributed to the formation of the banded gneisses and migmatites (Kröner *et al*., 2001). According to Dada(1999; 2008), gneisses and amphibolites in Nigeria form a bimodal association whose petrological and geochemical characteristics indicate a primary igneous origin. Another study by Elatikpo *et al.*, (2013) revealed that the gneisses within Malumfashi schist belt northwestern Nigeria, have calc-alkaline affinity and igneous origin.

2.2.1.2 The Metasediments

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

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

The “Newer Metasediments” (Oyawoye, (1972) or “Younger Metasediments” (McCurry, 1976) are low-grade sediment dominated schist groups and are composed mainly of pelitic and semipelitic schist, metaconglomerate, quartzite, calc-silicate rock, marble, mafic to ultramafic rocks, acid to intermediate volcanic rocks and rare banded iron formations (Danbatta, 2008). In the western half of the country, they occur as discontinuous north-south trending belts within the basement. There are twelve of such metasedimentary belts namely: Zungeru-Birnin Gwari, Kushaka, Malumfashi, Kazaure, Wonaka, Maru, Anka, Zuru, Toto, Iseyin-Oyan River, Ife-Ilesha and Igara-Kabba-Lokoja belts (Ajibade, 1976; Turner 1983; Danbatta, 1999; 2008).The metasediments are poorly represented in the eastern half of the country and this is attributed by Ajibade (1988) to the strong migmitization and assimilation effects on the sediments by the large volumes of the Pan-African rocks. However, few outcrops of some members of the metasediments particularly quartz schist, biotite schist and calc-silicate rocks occur in Gwoza and Ngoshe area in northeastern Nigeria (Nwabufo and Mbonu, 1988). Furthermore, outcrops of some members of the metaseiments were equally reported in the Oban Massif, Obudu Plateau and the adjoining Cameroon Republic (Ekwueme, 1990; 1991).

In recent years, much attention has been given to the evolution of the metasediments (Annor, 1995; Adekoya, 1996; Olobaniyi, 1997; Annor1998; Danbatta, 1999; 2001; 2003; 2008). The main points of contention that concern the evolution of the metasediments include the timing of formation of the basin of deposition, their age relationship, origin of the mafic and ultramafic rocks associated with some of them, and structural control. All the models proposed over the years for the evolution of the metasediments could be classified under ensialic and ensimatic processes.

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

2.2.1.3 The Older Granite suites

The Older Granite suites comprise the syntectonic to late tectonic granitoids. They intrude both the migmatite-gneiss complex and the metasediments. The granitoids include rocks varying in composition from granite to tonalite and charnockites with smaller bodies of syenite, gabbro and pegmatite (Ajibade *et al.,* 1987). The granitoids have yielded radiometrics ages in the range of 750-500 Ma which lie within the Pan-African spectrum. These Pan-African granitoids are referred to as the Older Granites in Nigeria to distinguish them from the Mesozoic anorogenic granite ring- complexes (the Younger Granites).

Based on orogenic criteria, Truswell and Cope (1963) grouped the Older Granite rocks into synkinematic and late-kinematic types. The synkinematic rocks are usually coarse grained, foliated bodies with gradational contact and contain xenolith of their country rocks, while the late-kinematic types are commonly fine grained, rarely foliated and have sharp contacts with the surrounding country rocks.

Jones and Hockey (1964) have, on the basis of field relationship, mineralogy and texture, rcognised three phases of the Older Granite suite:

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

cases the feldspar megacrysts are commonly aligned along with the biotite which imparts a gneissose appearance to the rock. Rahaman (1976) equated this phase to the synkinematic type of Truswell and Cope (1963). The foliation is usually well developed at the margins of the rock bodies which indicate some degree of movement during emplacement. Rahaman (1988) pointed out that the activity of the fluid phase during the emplacement may also be important in determining the structural feature of the granite mass.

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

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

2.3 Geochronology and Tectonic Evolution of the Nigerian Basement Complex

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

According to Dada *et al.*, (1993) and Dada (1998), U-Pb zircon age of 2.4 to 2.5 Ga on grey gneisses from northern and southwestern Nigeria suggests distinct crustal initiation event with significant crustal growth at the Archean-Proterozoic boundary (Liberian). Ajibade *et al.*, (1987) reviewed the nature of the early Proterozoic Eburnean event in Nigeria, which clearly indicates its importance and involvement in the evolution of the Nigerian Basement Complex. According to these authors, the Eburnean was probably accompanied by sedimentation, deformation, metamorphism and syntetonic igneous activity. The Kibaran is the most controversial event because no granite of that age is found in Nigeria. However, Ogezi (1977) obtained a Rb-Sr isochron age of 1086 Ma on the phyllites from Maru metasediments, northwestern Nigeria. The author interpreted this as the age of metamorphism that affected the sediments. This interpretation implies that there was a major tectonic event in some parts of the Nigerian Basement during the Kibaran. The Pan-African event was related to the collision of Birrimean plate (comprising the present West African Craton) and the Dahomean (comprising the present day Nigeria-Benin Shield) (Burke and Dewey ,1972). The orogeny started with the opening of the Buem Ocean in Neoproterzoic time, its subsequent closure reactivated Dahomean while Birrimean remained stable.Many workers on the Nigerian Basement, (McCurry, 1971; Rahaman ,1976); Cahen *et al.*, 1984) are of the view that the Pan-African orogenic event was the latest, most pervasive and penetrative deformation episode, and that it completely obliterated earlier structures, primary fabrics and metamorphic assemblages of the complex. On the other hand, Grant (1978), Mullan (1979), Ajibade (1988), Fitches *et al*., (1985), and Ekwueme (1987) are of the opinion that although it was pervasive, the Pan-African event did not completely homogenize the rocks of the basement, so that traces of earlier structures still remain within the complex. Many workers considered the Rb-Sr method to be unreliable in dating migmatitic rocks from which most ages older than Pan African were obtained (Kröner *et al*., 2001). Ajibade and Wright (1989) argued that the Nigerian Basement is an aggregation of allochthonous terranes, which explains the relicts of Liberian, Eburnean, and Kibaran orogenic events, as well as the spread of radiometric ages within the Pan-African range (750±450 Ma).

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

2.4 THE NIGERIAN PEGMATITES

Pegmatites occur either as tiny veins (few centimeter in width) or as dykes cross-cutting other rocks. Occasionally they occur as huge bodies of simple or complex mineralogy and structure with rare metal and gemstone mineralizations. The pegmatite belongs to the terminal stage of Pan-African magmatism (Rahaman *et al.*, 1988). The Nigerian pegmatites were formed during the time span of 562–534 Ma, indicating that their emplacement is related to the end of the Pan-African magmatic activity (Jacobson and Webb 1946, Garba 2003). Both barren and mineralized pegmatites occur within the Nigerian Basement Complex (Fig. 2.2).

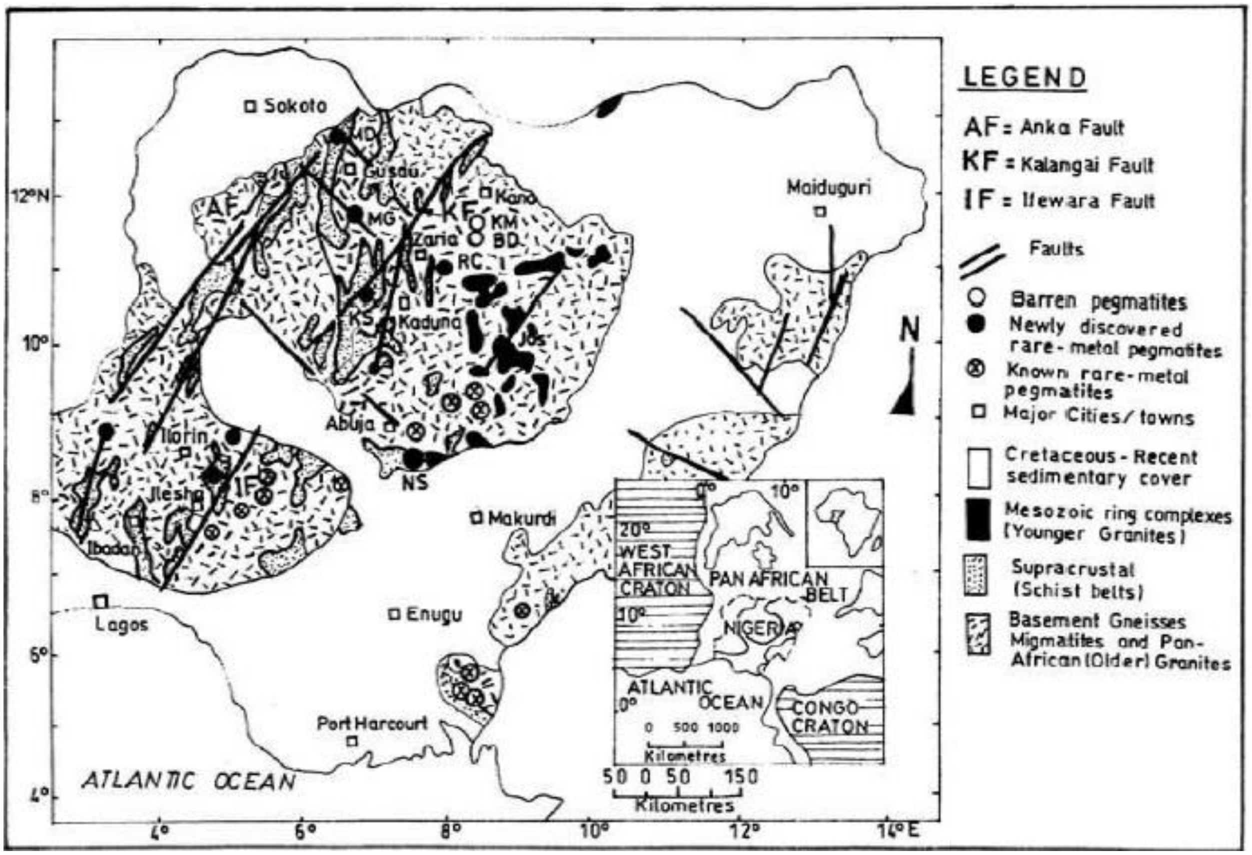


Fig 2.2: Geological map of Nigeria showing the location of barren and rare-metal pegmatites adapted after (Garba, 2003).

2.4.1 Barren Pegmatites

Barren pegmatites bodies are ubiquitous in the Nigerian Pan-African Basement. According to Matheis and Caen-Vachette (1983), the barren pegmatites are about 100 Ma older than the rare-metal pegmatites and are not directly related to any apparent intrusive activity. However, Kinnaird (1984) suggested they are related to calc-alkaline syntectonic granitoid. They are found associated with all the major lithologies of the basement, i.e. gneisess, migmatites, schists and granitoids. The morphology and major mineral composition (quartz–feldspar–mica) are mostly not different from those of the rare-metal types (Garba, 2003).

2.4.2 Rare Metal Pegmatite

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

i. Kabba-Isanlu
ii. Ijero-Aramoko
iii. Keffi-Nasarawa
iv. Lema-Share

v. Oke-Ogun
vi. Ibadan –Osogbo
vii. Kushaka-Birnin Gwarri

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

2.4.3 Petrogenesis of pegmatite

Muscovite is a common rock forming minerals in the terrestrial crust. In granitic pegmatite, it is the fourth major mineral after quartz, k-feldspars and plagioclase with chemical formula as $KAl_2(Si_3Al)\ O_{10}\ (OH)_2$. Due to its crystal structure, muscovite may incorporate several trace elements, many of which are potential indicators of the fractionation degree of an evolving pegmatite melt. The indicator elements reported in literature mainly by Černý (1982) are mobile element such as Na, Ba and Cs which occur preferably in the X-site while others like Ti, V, Cr,Ga, Zn, Y, Nb, Sn, La and Ce are incorporated in the Y-site

The importance of muscovite composition as a clue to internal evolution of pegmatite magma has been discussed by Černý (1982), Černý and Burt (1984), and Joliff *et al*., (1987). The K/Cs and the K/Rb ratios in muscovite are considered as the best indicator of pegmatite evolution (Černý *et al*., 1985; Joliff *et al.*, 1987). These indicators are used in assessment of rare elements in pegmatites. Micas from pegmatites derived from granitic precursor by fractionation normally show a gradual enrichment in Li, Rb, Cs and F with a decrease in Fe, Mg, Ti and K/Cs, K/Rb ratio from internal to external zone.

Pegmatites commonly display extreme fractionation and accumulation of rare lithophile elements beyond the limit observable in the granitic rocks. Sc, Li, B, F, and Rb are incompatible within common silicate so they partitioned into the melt (London., 1999). The enrichment of these elements lead to their precipitation in highly fractionated pegmatite.

Potassium (K) and Rubidium (Rb) have similar ionization potentials and electronegetivities, therefore the geochemical behaviour of Rb is closely similar to K. Potassium (K) is the only major element for which (Sc) can substitute. The electronegetivity and ionization potential of Cs is lower than K with a slightly larger ionic radius (Černý *et al.*,1985). Although Cs and Rb are incompatible in the most important silicate mineral during magma fractionation, Cs is commonly enriched in rare alkalis in fractionated liquid while Rb is highly compatible in mica (Černý, 1985). Cs increases gradually from the outer part rock towards the innermost fractionated zones of the pegmatite. The high Li, Cs, Ta and Rb values of the muscovite and the positive correlation between those elements in the muscovite suggest that the pegmatite belongs to the Lithium-Cesium-Tantalum (LCT) family of rare elements. Continuous increase in Cs occurs only in the most complex bodies of pegmatite on the outskirt of core genetic granitic pegmatite swam, furthest away from their plutonic sources. In order of increasing concentration, the main carriers of Cs are K-feldspar, micas, beryl and pollucite (Černý, 1985).The degree of fractionation is important in determining the potential for mineralisation and the type of mineralisation with which a granite suite is associated. Fractional crystallisation can be measured with the use of compatible/incompatible element ratios and the behaviour of selected trace elements that indicate the incoming or outgoing of crystallising phases.

2.4.4 Structural Control

The ancient lineament system of the Nigeria Basement Complex has been known to control the distribution of rare-metal pegmatite with the intersections hosting the richest pegmatite (Okunlola, 2005). This is especially true in relation to cassiterite (SnO_2) concentration (Ajibade and Wright, 1989; Okunlola, 2005). This may suggest intermittent activeness of these lineaments especially in the late Precambrian times. Garba, (2002) and Okunlola, (2005) noted that rich concentrate of rare metal pegmatites in the late Precambrian terrain of Nigeria are concentrated close to major transcurrent faults, for example, the Kalangai, the Ifewara, and the Anka fault systems which has southern extension up to the Oke Ogun areas in the south west. The trend of the fault and inherent displacement is highly variable according to the type of rock. Mylonitisation, silicification and localized dextral sense of shearing especially of amphibolite and diorite emplacement are some of the surface expressions of the faults and these may represent remnants of obducted ophiolite (Ajibade and Wright, 1989; Garba, 2002; Okunlola, 2005). Deformational episodes producing tight to isoclinal folds mainly controlled the mineralized pegmatites in most of the rare pegmatites fields in Nigeria and these isoclinal folds are linked also to major transcurrent faults (Garba, 2002, Okunlola, 2005). Both the rare metal and gold mineralizations are associated with prominent regional faults in the basement complex of Nigeria (Garba, 2002).

2.4.5 Geochemical Features

The rare-metal pegmatites of Nigeria are generally complex albitised muscovite-quartz-microcline pegmatites with indiscernible to distinct zonations (Okunlola and Jimba, 2006). Extreme fractionation of lithophile elements such as Rb and Cs is a common geochemical feature of the granitic pegmatites, especially the rare-metal bearing types (Černý *et al.*, 1985; Garba

2003, 2005). While enrichment in Rb is an indicator of the degree of fractionation in the granitic pegmatites, enrichment in Cs appears to be the most important discriminator of the rare-metal pegmatites. Okunlola (2005) noted that the rare metal pegmatites of Nigeria are characterized by widespread development of moderate to intense albitization and lepidolite development and with variable internal structure and can be said to be similar to the albite type and the complex lepidolite subtype of Černý, (1986) classification. He also noted that they are similar to the Woringa pegmatites in Australia, Heng Shen pegmatites field in China and Buck pegmatites in Colorado USA. According to Kinnaird and Nex (2013), the Nigerian rare metal pegmatites share similarites with the Damaran pegmatites of Namibia with both having LCT pegmatites and a Sn-W rich pegmatites association.

2.4.6 Mineralization Potential

Mineralization potential of the Nigerian rare-metal pegmatites are highly variable according to the host rock type. Ta-Nb concentrates, which have been won in the Kabba-Isanlu, Ijero-Aramoko, Keffi-Nasarawa, Lema-Share, Oke-Ogun, Ibadan –Osogbo and Kushaka-Birnin Gwarri fields are usually of varying grade in terms of total pentoxide enrichment (Okunlola, 2005). According to Okunlola (2005), the Nigeria pegmatites fields are relatively poorer when compared with the highly mineralized Tanco (Canada), Homestead and Wodinga (Australia) pegmatites but are comparable to low-medium Ta (LCT) pegmatites of Buck, Oasis, and Noumas pegmatites in USA.

2.4.7 Origin

The rare-metal pegmatites have both magmatic and crustal characteristics defined by enrichment of the LREE, marked negative Eu anomaly and relative depletion of the HREE (Garba, 2005). The magmatic origin of the rare-metal pegmatites is not disputable from the REE and lithophile element trends, except that there appears to be evidence of some crustal influence, possibly because of their metasedimentary host rocks (Garba, 2003). According to Garba, (2005) the similarity in their REE distribution pattern in rare metal pegmatites and the Younger Granites cast doubt on their origin from magmas of the main syn-tectonic granitoids (the Older Granites). Garba (2002) suggested that they may have been sourced from peraluminous late-tectonic granites rather than the typically calc-alkaline syn-tectonic granitoids noted by Fitches *et al.*, (1985). The rare metal-enriched pegmatites of southwestern Nigeria are rather products of partial melting and leaching processes of the basement units than the truly pegmatitic phase of proximal Older Granites (Matheis and Caen-Vachette, 1983). Matheis and Emofurieta (1987) also suggest derivation of rare-metal pegmatite mineralization, especially in southwestern Nigeria, from reactivation of deep-seated tectonic lineaments combined with partial melting and external fluid supply. Since the pegmatites appear to be emplaced along major faults lineaments, the albitization and rare-metal mineralization may have been due to late stage fluids available at the close of the Pan-African metamorphic cycle (Ekwueme and Matheis 1995), or due to Na-rich hydrothermal solutions from the mantle along ancient lineaments (Wright, 1970 and Garba, 2002). Kuster (1990) presented evidence to show that the development of rare-metal pegmatites of the Wamba area of central Nigeria is genetically related to the late tectonic granite magmatism which was controlled by the late Pan-African NE-SW and NW-SE shear system. Kuster (1990) also noted that since the degree of mineralization can be correlated with the degree of late Na-metasomatism (albitization), it follows that both granite-related pegmatites emplacement and subsequent mineralization are related to the late-tectonic shear movements. It is probable that the host rocks contributed significantly to the individual characteristic of each pegmatite occurrence, as demonstrated by marked difference between pegmatite in the southwest, southeast and central Nigeria (Matheis and Emofurieta 1987; Ekwueme and Matheis 1995, Garba 2002).

CHAPTER THREE

METHODOLOGY

3.1 INTRODUCTION

The methodology adopted for this research work consists of field study and laboratory analysis. The field study involved geological mapping on a scale of 1:50,000 which was undertaken with topographic map, geologic hammer, compass-clinometers and GPS. The laboratory work involved sample preparation, Petrographic study and geochemical analysis. The petrographic study was undertaken with the aid of transmitted light petrological microscope at the Petrographic Laboratory, Department of Geology, Ahmadu Bello University, Zaria

3.2 FIELD AND PETROGRAPHY

The field exercise was carried out in two (2) stages, first was a reconnaissance visit for five days, followed by the second field visit during which geological field mapping was undertaken on a scale of 1:50,000. Fresh rock and mineral samples were collected for hand specimen examination. Preliminary observation and identification of each constituent mineral were carried out using magnifying lens. Field data such as measurements of strike and dip amount and directions of lineaments with compass-clinometer and recording of the co-ordinates of every sampling point using Global Positioning System (GPS) were also carried out. Other structural elements like trends of fractures, dimension of veins and dykes were also recorded.

For the petrographic studies, rock samples were cut into chips with a cutting machine and subsequently polished using carborundum powder of 0.6, 0.4 and 0.2 mm to obtain slides with required thickness and a perfectly smooth surface. The prepared slides were examined under the transmitted-light petrological microscope to identify minerals and other features that were not hitherto seen with aid of magnifying lens. Modal compositions of the rock types were determined using J-micro vision software, which allowed for both classification and delineation of the various units.

3.3 GEOCHEMICAL ANALYSIS

Geochemical analysis of muscovite samples extracted from the pegmatite were undertaken using Inductively Couple Plasma Mass Spectrometry (ICP-MS) and Whole rock geochemical analyses of representative samples of the rocks were undertaken using X-ray fluorescence (XRF) techniques employed in the determination of major elements at the Multi User Science research laboratory, Ahmadu Bello University, Zaria.

The major elemental composition of the whole rock samples was determined using XRF and results presented as major oxides (K_2O, Na_20, CaO, MgO etc.) while Rare Earth Elements (REE) composition of the muscovite samples from the pegmatite was determined using ICP-MS. This allowed for characterization of the mineralization in the study area as well as determining the origin of the rocks.

CHAPTER FOUR

RESULTS

4.1 INTRODUCTION

Granites are deep-seated igneous rocks composed of quartz, feldspars, mica and other minerals such as amphibole, in grains sufficiently large to be distinguished by the naked eye and possessing a texture produced by the crystals as a whole interfering with one another's free development (Read, 1948).

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

(i) precipitation from an aqueous fluid phase

(ii) crystallization of silicate liquid through an aqueous fluid interface

(iii) crystallization from a hydrous silicate gel

(iv) crystallization from a flux-rich silicate liquid

(v) Crystallization of a granitic melt from margins to center.

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

The compositions of pegmatites reflect an association mostly with two granite types, the S- and the A-types. However, Černý and Ercit (2005) ascribed a small fraction of the Lithium-Cesium-Tantalum (LCT) and Niobium-Yttrium-Fluorine (NYF) pegmatite to I-type (Igneous source|) granite source. Pegmatites of the Lithium-Cesium-Tantalum (LCT) family, especially those enriched in Li, Cs, B, and P, greatly predominate over all others. They indicate that the metamorphosed juvenile sediments from which S-type granites (sedimentary source, mostly postcollisional tectonic environment) arise are particularly prone to yielding pegmatite-forming melts. The abundance of fluxing components in the sources of S-type and A-type (anorogenic) make them distinct from I-type granite. These fluxing components include ligands other than silica and alumina that predominantly influence the properties of pegmatite-forming melts. S-type sources are especially enriched in B, P and F, which is contributed by the eventual melting of amphibole and biotite. The archetypal I-type granites found in subduction zones are notably rich in Cl and are hydrous, but are largely devoid of the fluxing components. They generate enormous volume of quartz veins but lack pegmatite to any significant extent. This distinction points to an essential role for fluxing components like B, P and F, along with H_2O in the formation of pegmatites (Černý *et al*., 2012).

Variation in concentration of major, trace and REE elements in the muscovite is used to determine their geochemical features and petrogenesis.

Important rare- metals (tungsten- rich) pegmatites are known in the Anka (NW) and Kaima (SW) area and bismuth rich types in Zaria area (NW). These new discoveries were made by artisanal miners driven by high prices of columbite and tantalite in last decade. This development has shown that the rare-metal pegmatites in Nigeria are more widely distributed than previously known. Ore grades are very variable between and even within pegmatite bodies, generally ranging from less than 100ppm to greater than 10% (Nb+Ta). In many areas consistent grade of 250-500ppm are noted over large areas. More than 500 tons of Columbite-tantalite concentrates have been produced by artisanal miners from the new pegmatite fields since their discovery. Columbite-tantalite concentrates produced by artisanal miners from some Nigeria rare-metal pegmatite fields show the proportion of Ta_2O_5, Nb_2O_5 and SnO_2 to be 15-43 %, 6-18% and 2-35% respectively.

The field relationship, structures and petrography of the rocks are presented under the sub-heading “geology and petrography”; the geochemistry of the schist, migmatite gneisses, granodiorite, granites and muscovite are presented under the sub-heading whole rock geochemistry.

4.2 GEOLOGY AND PETROGRAPHY

The study area is underlain by Schist, migmatite gneiss, granites, granodiorite, and pegmatites (Fig. 4.1). The migmatitic gneisses constitute about 55% of the area with some pockets of granites at the southern part of the study area which constitute about 5%. Schist and silicified quartz including quartz vein constitute about 5% also, granodiorites are exposed in the eastern part of the area, constitute about 35%.

Of the migmatite gneisses, the banded gneisses constitute the greater proportion, whilst migmatites are found in isolated and irregular patches within the area. Migmatite gneisses are well developed around Marigya, Tabanni, Rafin Taba, Dega, Pauta and other places.

The granites which are found in some places constitute about five percent (5 %) of the total crystalline basement rocks in the area. These rocks are presented in a geological map, Fig. 4.1. Gradational contact relationships between the various rock types were encountered.

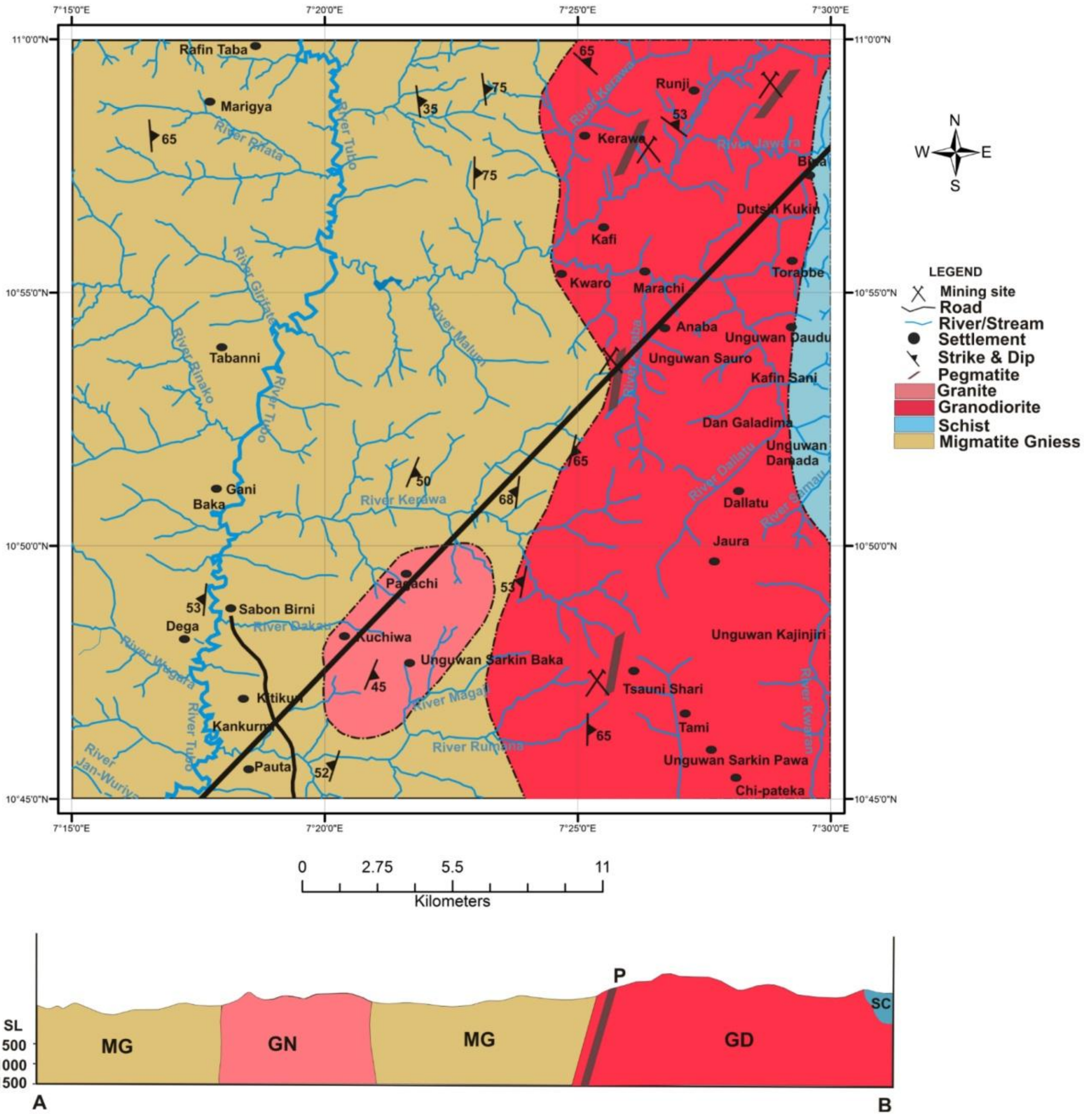


Fig 4.1: Geological Map of the Study Area

4.2.1 Migmatite-Gneiss

The migmatite gneisses are medium grained in texture, they cover about 55% of the study area and found at the western part of the area (Fig. 4.1). The common structures observed in this rock are ptygmatitic folding and compositional banding (Plate I).

Thin section studies revealed that the melanosomes consist of hornblende and biotite while the leucosomes consist of plagioclase and quartz. The hornblende occurs as xenomorphic crystals with moderately high relief (Plate II). Biotite also occurs as xenomorphic crystals with high relief, the crystals are brown in colour. Augite on the other hand, occurs as subhedral crystals which are easily distinguished by their characteristics of two sets of cleavage at angle of about 87˚ and 93˚, while plagioclase occur as colourless subhedral crystals which are easily distinguished by their lamella twining.

Plate I: Photograph of an outcrop of migmatitic gneiss. Location Westhern part of the study area (7˚17′33.21″E, 10˚49′39.35″N)

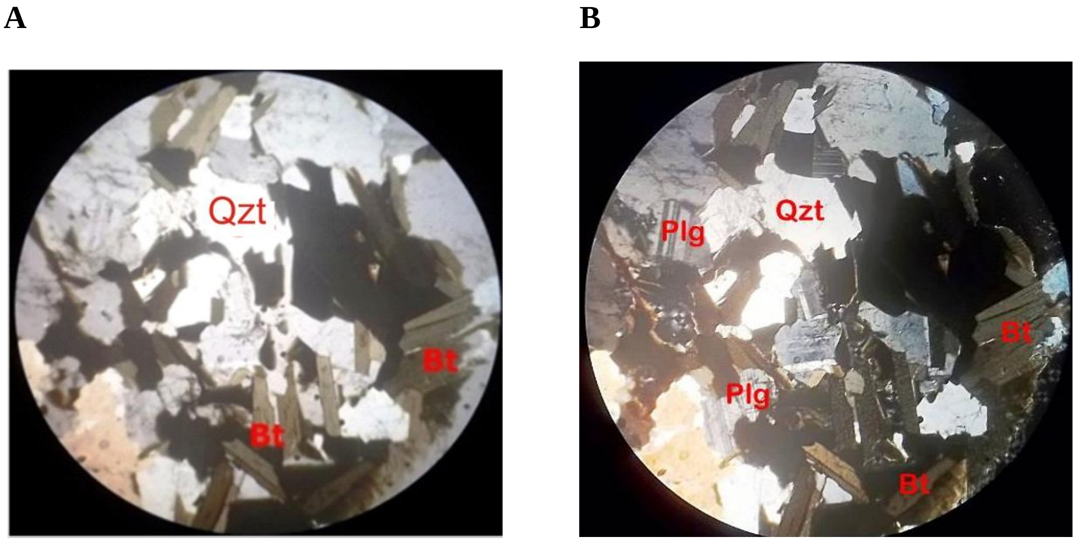


Plate II: A=Photomicrogragh of migmatitic gneiss under PPL; B= photomicrograph of migmatitic gneiss under XPL: Qtz=quartz, Bt=biotite, plg=plagioclase. Location(7˚17′33.21″E, 10˚49′39.35″N). Magnification x40

At the southern part of the area, migmatite gneiss occurs as low-lying massive rock. Texturally, the rock is fine grained but slightly weathered (plate III). The rock shows segregation into light and dark bands with flow banding in places. Both the light and dark bands are aligned in NNE – SSW direction. The rock composed mainly of quartz, microcline, biotite and opaque minerals. The quartz is colourless and anhedral. The microcline is colorless with low relief. In XPL, the microcline depict first 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 is probably magnetite or ilmenite.

Plate III: Photograph of an outcrop of slightly weathered migmatitic gneiss. Location Northwesthern part of the study area (7˚28′28.31E″, 10˚47′43.34″N) aligned in NNE – SSW direction

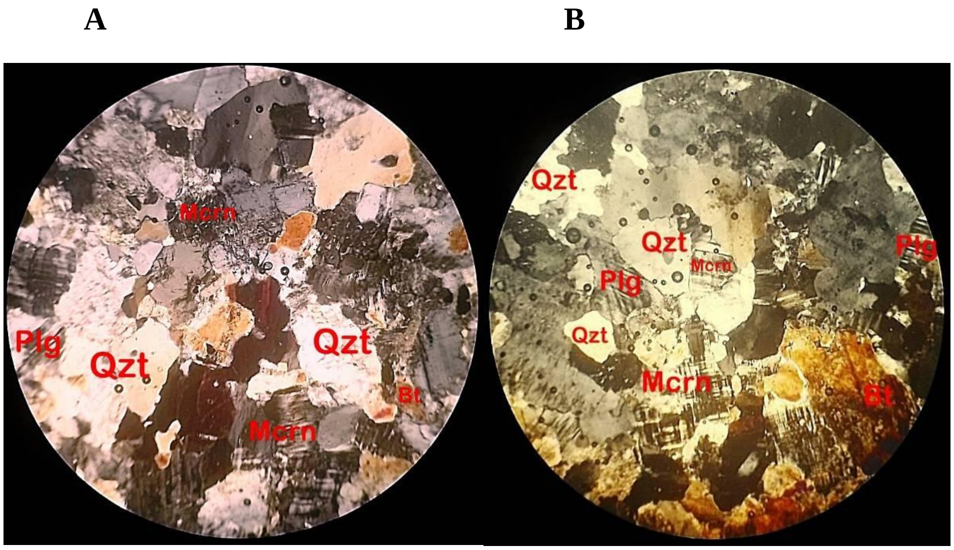


Plate IV: A= Photomicrograph of Migmatitic gneiss under PPL; B. photomicrograph of Migmatitic gneiss under XPL., Qtz=quartz, Bt=biotite, mcrn=microcline, Plg=plagioclase. Magnification x40

4.2.2 Phyllitic Schist

The phyllitic schist has been strongly deformed. In some places, the entire rock section (Plate V) is made up of tiny isotropic debris of unidentifiable minerals with little or no foliation developed. This is said to represent a transitional stage in the development of schist from phyllite by prograde metamorphism.

The schistosity defined by lath-shaped minerals of biotite and hornblende increase in proportion in the area occupied by schist. A highly porphyroblastic facies with rectangular-shaped phenocryst is developed at Runji and north-east of Kerawa.

Plate V: Showing the phyllitic Schist in the Study Area. (7˚29′38.35″E, 10˚58′41.21″N)

4.2.3 Granite

The granite extends from Kuchiwa to Fagachi to north-east of east of Sabon Birni towards Anguwan Sarkin Baka, It forms low narrow ridges that are well-represented topographically, (Plate. VIb). The outcrop is elongated in a north-south direction which is also the trend of the lineation. A small tongue of the granite runs off to the south-west of the Kerawa river valley. This tongue appears to be of a laccolithic nature as at two places the granite was observed to be resting on a floor of banded gneiss (Fig. 4.1). The granite is bounded on two sides by shear fractures, probably faults, which on the eastern side separate it from the granodiorite.

In hand specimen the rock is a light, medium-grained, muscovite -biotite granite. The principal minerals are light - to - dark - brown biotite, muscovite, quartz and feldspar with apatite and apatite as accessories. The texture is xenographic granular grains (Plate. VI).

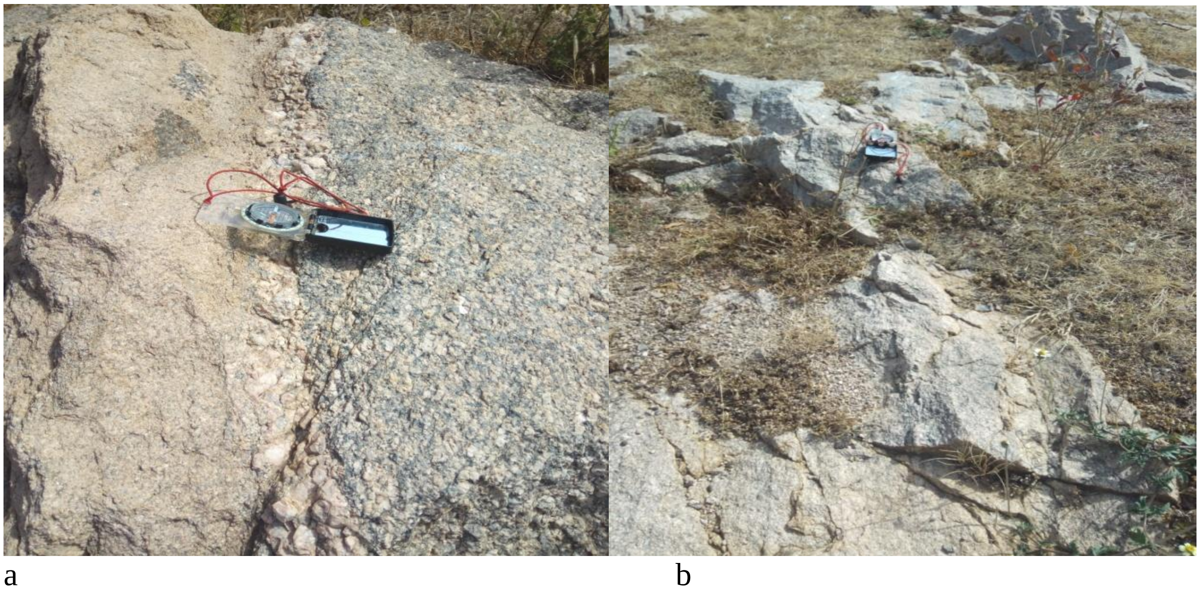
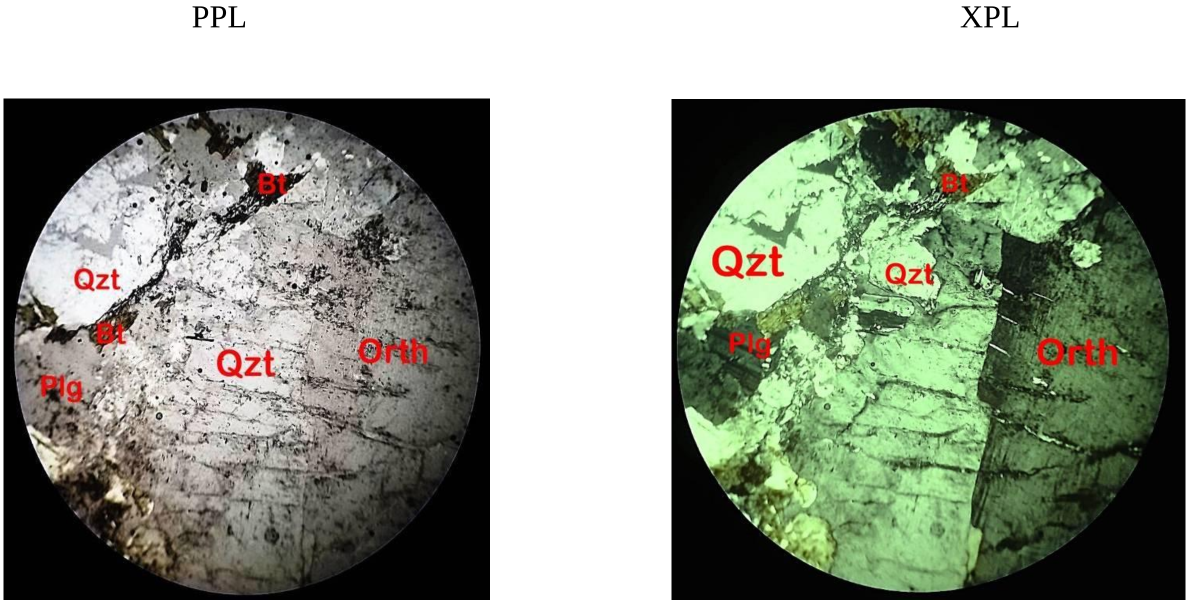


Plate VI: Photograph of an outcrop of Coarse grain Granites in contact with fine grain granite. Location South westhern part of the study area (7˚21′43.03″ E, 10˚47′33.8″N)



PPL

XPL

Plate VII: Photomicrograph of porphyritic granite; Plg. = Plagioclase Quartz, Bt = Biotite, Ort= Orthoclase under PPL and XPL. Magnification x40

4.2.4 Granodiorite

The granodiorite forms fairly high hills between Runji and Kerawa in the north-east. Elsewhere it is low-lying or merges with the gently rolling topography. There is a considerable variation in mineralogy and texture of the rocks. Commonly, it is a medium-grained crystalline rock with traces of white feldspars (plate VIII). Quartz veins and microcline-quartz pegmatites cross-cut the rock at several locatities especially between Runji and Ungwan Damazadu.

In thin section the rock composed mainly of quartz, plagioclase and biotite. The rock differs from granite *sensu stricto* because of its high plagioclase feldspar relative to alkali feldspar. Quartz occurs as discrete crystals characterized by undulatory extinction. Plagioclase is slightly calsic ranging from andesine to labrodorite. The mineral occurs as subhedral crystals characterized by carlsbad twining (plate IX). Biotite occurs as brown crystal with high relief and perfect basal cleavage.

Plate VIII: Photograph of granodiorite, Location: (7°26′4.25″E, 10°58′45.26″)

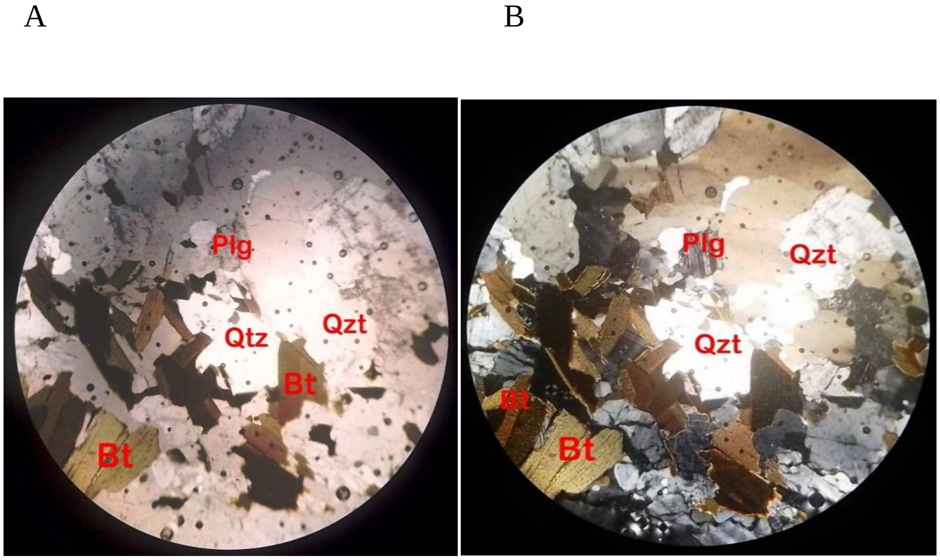


Plate IX: A= Photomicrograph of granodiorite under PPL; B= Photomicrograph of granodiorite under XPL, Qtz=quartz, Bt=biotite. Magnification x40

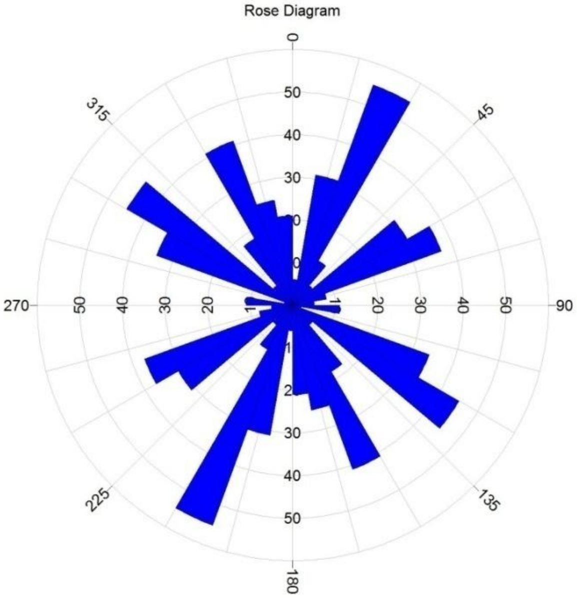
4.3 STRUCTURAL CONTROL

Mapping at scales relevant to a geological problem, with an emphasis on structural geology is very useful in understanding the directional controls on mineralization. There are several methods, one of which is Fry analysis that could be used as a complement to mapping. Using Fry (1979) analysis in mine and prospect scale could help determine the location of successful drilling for mineral potentials. This reduces the spatial bias inherent in the distribution of drilling to determine the direction of the ore-rich zones.

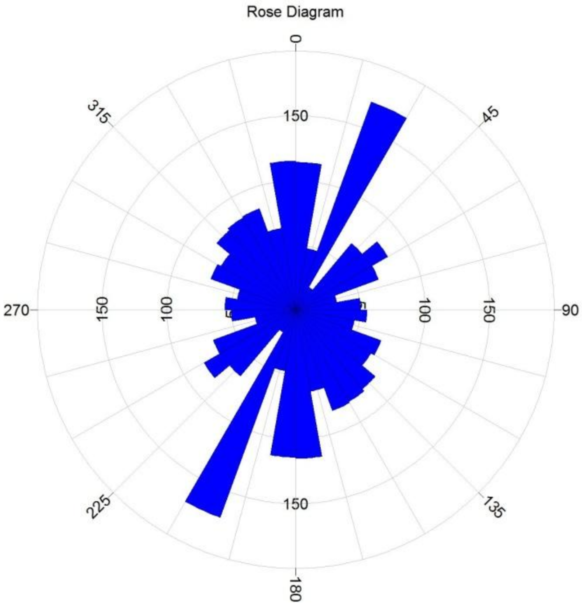
Fry analysis is a geometrical method used in directional studies. It employs spatial autocorrelation of points (fig. 4.3), to assess distribution patterns of mineralization and potential controlling structures at the regional scale (Fry, 1979; Vearncombe and Vearncombe, 1999). Fry analysis for (n) data points, in this case, mining sites will lead to (n (n-1)) translation points. The results of fry analysis (Tab. 4.1) show four prominent trends at a different scale, (Fig.4.2)

Table. 4.1: Summery of the direction of the pegmatite at a different scale

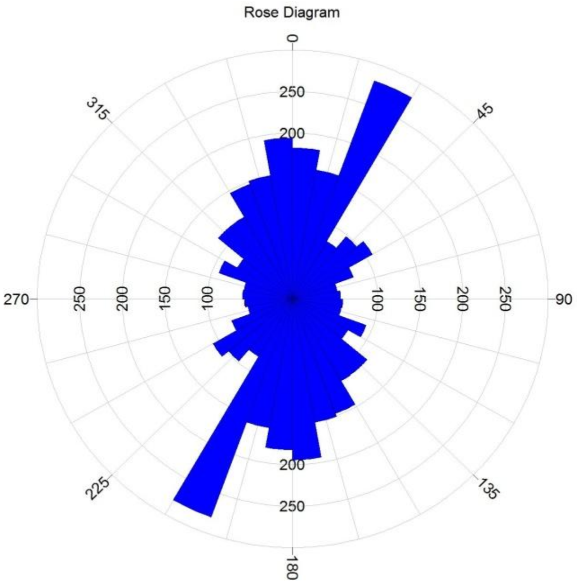
I.D	Class	Main Trends
A	Less than 5km	NE-SW, NW-SE (45°-225°, 315°-135°)
B	Less than 10km	NNE-SSW, N-S (22.5°-202.5°, 0°-180°)
C	Less than 15km	NE-SW (45°-225°)
D	Less than 20km	NNE-SSW, N-S (22.5°-202.5°, 0°-180°)
E	Greater than 20km	NNW-SS (337.5°-157°)
F	Greater than 25km	NN-SS (0°-180°)



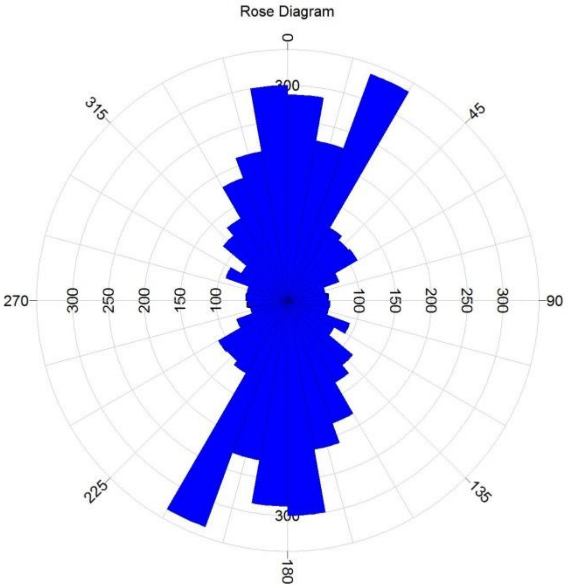
Less than 5km^2



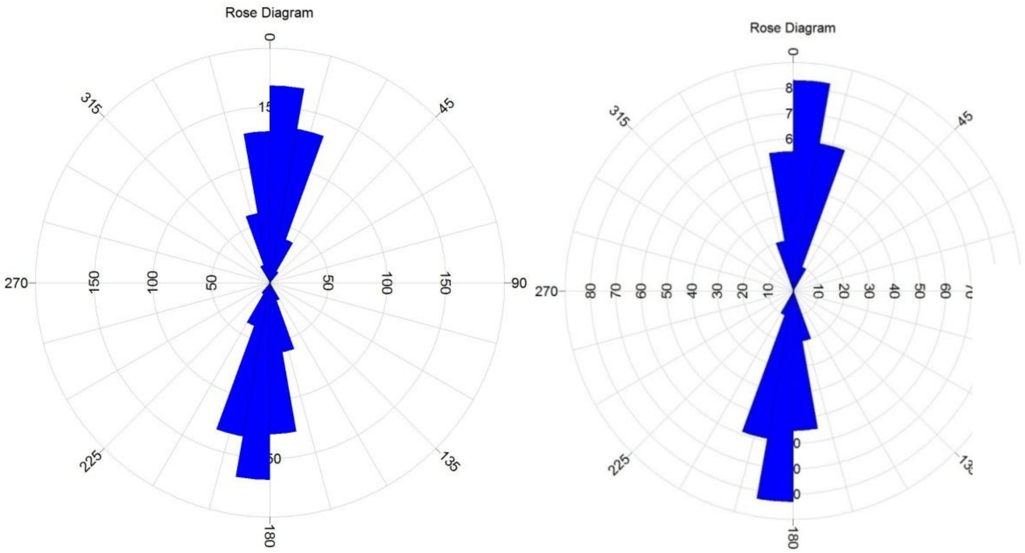
Less than 10 Km^2



Less than 15km^2

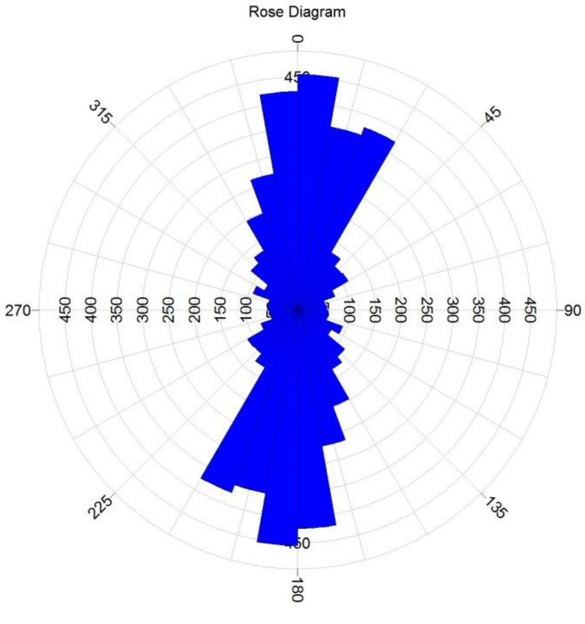


Less than 20 Km^2



Greater than 20km²

Greater than 25 Km²



Total fry points

Fig. 4.2 : **Rose diagrams showing the different directions of the pegmatite from a different distance.**

Fig. 4.2 helped to interpret the spatial patterns of the mineral deposits in the study area. It can be deduced from the rose diagrams that four main trends are perpendicular to each other in pairs which correspond to the results of fry analysis. The aforementioned procedure confirms the structurally controlled mineralization in the study area. Other subsidiary trends are related to the younger fault generations and have no relationship to mineralization. Accordingly, measuring the fractal dimension of faults and occurrence patterns will reveal valuable exploration information.

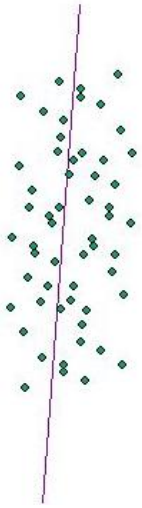


Fig. 4.3: Logarithmic Plot for Number of Cells Showing the Major Trend

4.4 WHOLE ROCK GEOCHEMISTRY

4.4.1 Introduction

Geochemistry is a tool generally used to establish how elements are distributed amongst the components of the earth, why the elements are distributed the way they were and the principles that govern the distribution. Comparative evaluation of the geochemical data of the host granodiorite and the muscovite from different distinct zones of the pegmatite in the study area was carried out. This is to determine the elemental behaviour and use the chemical signature of the granitoids and muscovite to establish tantalite mineralisation potential, the differentiation degree and genesis of the pegmatite.

The analytical data comprising major oxides, trace elements including REE in the muscovite samples and the major oxides from the host rocks are presented in Tables 4.2 - 4.5. The data are also presented on appropriate discrimination plots in order to clearly identify the main geochemical signatures of the rocks and muscovite. The data were then discussed on the bases of rock types and mineral paragenesis for better understanding of the variation in the composition and lithology.

TABLE 4.2: Major elements composition of Granitoids, Migmatite gneiss, Schist and the Muscovite from the pegmatite (all values in weight %)

	Muscovite From Pegmatite (Major Elements)																								
	Wall zone			Intermediate zone			Core zone			Granodiorite					Granite		Migmatite Gneiss					Schist			
SAMPLE ID	S9a	S9b	S9c	S8a	S8b	S8c	S10a	S10b	S10c	S5	S11	S12	S17	S19	S7	S13	S1	S2	S3	S4	S6	S14	S15	S16	S18
SiO_2	55.44	56.5	56.5	47.22	46.2	42.5	44.88	55.88	57.1	67.69	63.2	67.47	68.52	68.12	76.34	76.71	66.22	69.46	67.99	67.16	69.13	68.1	71.52	64.76	67.27
TiO_2	0.07	0.51	0.03	0.077	0.196	0.02	0.08	0.37	0.05	1.42	1.71	0.82	0.78	0.67	0.98	0.38	0.74	0.72	0.84	1.08	1.22	0.61	0.6	0.01	0.3
Al_2O3	26.31	24.8	25.2	34.65	30.78	35.32	35.19	24.81	20.57	14.06	14.51	15.34	14.42	13.72	12.03	12.08	16.77	15.24	15.12	15.96	14.38	17.23	13.31	17.71	15.92
FeO(T)	2.29	4	3.9	2.2	4.1	3.11	1.75	0.76	0.5	4.72	6.7	5.83	4.69	5.08	1.06	1.61	4.68	3.98	6.82	5.28	4.42	2.95	3.1	4.8	7.2
MnO	0.281	0.265	0.22	0.257	0.304	0.31	0.32	0.51	0.08	0.34	0.04	0.42	0.91	0.06	0.02	0.08	0.05	0.05	0.02	0.61	0.97	0.05	0.1	0.2	0.2
MgO	0.1	0.5	0.4	0.2	0.4	0.11	0.05	0.01	0.01	1.97	2.34	1.43	1.29	2.03	0.43	0.93	3.38	1.47	1.42	2.64	2.36	0.66	0.13	0.83	0.91
CaO	0.04	0.01	0.12	0.06	0.1	0.07	0.8	0.2	0.01	3.41	4.51	3.07	3.41	4.37	0.86	0.57	2.67	3.31	3.12	2.05	2.87	3.38	3.62	4.31	3.87
Na_2O	0.41	0.5	0.1	0.1	0.5	0.7	0.67	2.3	0.9	3.77	2.53	1.69	2.33	2.99	3.33	3.32	2.64	2.22	2.25	2.56	1.96	2.76	1.84	2.31	1.83
K_2O	9.08	9.01	8.3	10	11.07	11	11.03	8.22	10.05	1.24	2.21	1.11	1.89	1.9	4.04	3.09	1.06	1.68	1.01	1.26	1.55	2.48	1.59	2.98	1.21
P_2O_2	0.01	0.04	0.1	0.03	0.25	0.01	0.04	0.2	0.01	0.11	0.06	0.07	0.16	0.18	0.02	0.06	0.08	0.06	0.04	0.03	0.09	0.05	0.43	0.43	0.86
LOI	4.2	3.11	3.1	4.61`	4.93	4.91	4.48	4.5	5.24	1.04	0.7	0.8	1.1	0.94	0.4	0.3	0.8	0.1	0.98	1.02	0.56	1.44	1.11	1.2	1.03
Total	98.231	99.245	97.97	99.4	98.24	98.24	99.29	97.027	94.52	99.77	98.51	98.05	99.5	100.06	99.51	99.13	99.09	98.29	99.61	99.65	99.51	99.71	97.35	99.54	100.6

Table 4.3: Trace element composition of muscovite samples from pegmatite
(All values in ppm except where stated otherwise)

	Wall zone			Intermediate zone			Core zone		
Sample I.D	S9a	S9b	S9c	S8a	S8b	S8c	S10a	S10b	S10c
Mo	40	<0.1	<0.1	3	8	5	<0.1	<0.1	<0.1
Cu	21	21	21	21	30	23	5	9	20
Ni	<4	<4	<4	<1	<5	6	<4	<4	<4
Sr	30	70	60	19	14	14	2	3	17
Cr	9	7	5	14	8	9	10	20	19
Ba	<5	20	16	<5	<5	<5	<5	<5	10
Sn	<10	<10	<10	<10	<10	<10	<10	<10	<10
Be	30	60	15	36	14	19	12	32	12
Sc	<10	<10	<10	<10	<10	<10	<10	<10	13
Y	420	310	381	710	360	490	690	467	20
Hf	139	98	76	181	199	209	187	123	32
Li %	6	6	7	10	6	9	29	21	10
Rb	5441	5782	5581	2901	3863	2274	8137	8940	7744
Ta	101	217	298	101	243	233	176	80	190
Nb	432	666	541	409	756	881	432	321	60
Cs	545	387	387	697	201	293	552	326	252
B	<0.1	<1	<1	<0.2	<0.1	<0.1	<0.2	0.3	0.3
F %	38.77	54.2	30.3	50	25.5	47.3	90.4	50.1	254

Table 4.4: Rare earth element (REE) composition of muscovite samples from pegmatite (all values are in ppm)

	Rare earth elements composition of Muscovite from Pegmatite (All Values are in ppm)								
	Wall zone			Intermediate zone				Core zone	
Sample I.D	S9a	S9b	S9c	S8a	S8b	S8c	S10a	S10b	S10c
La	0.3	1.5	0.1	0.3	0.5	0.8	5.9	0.3	3.8
Ce	0.2	2.6	<0.1	0.3	0.3	1.06	5.7	0.2	8.4
Pr	<0.04	0.3	<0.1	<0.04	<0.04	0.3	1.28	<0.05	1.41
Nd	0.1	1.28	1	0.3	0.3	0.5	3.8	<0.1	3.6
Sm	0.1	<0.1	0.2	0.1	<0.1	<0.1	3.8	<0.1	0.8
Eu	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05	0.18	<0.05	0.18
Gd	0.1	0.1	<0.1	0.1	0.1	<0.1	<0.5	0.1	<0.5
Tb	0.1	0.1	<0.1	0.1	0.1	<0.1	<0.1	<0.1	0.1
Dy	<0.1	<0.3	0.4	<0.1	<0.1	0.1	0.3	<0.1	0.3
Ho	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1	<0.1
Er	<0.1	<0.1		<0.1	<0.1	<0.1	<0.1	<0.1	0.2
Tm	<0.03	<0.03	<0.3	<0.03	<0.03	<0.03	<0.03	<0.03	<0.03
Yb	0.1	0.2	0.3	0.1	0.1	0.1	<0.04	<0.04	<0.04
Lu	<0.05	<0.05	<0.5	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05
Y	<3	<3	<3	<3	<3	<3	<3	<3	<3
∑REE	1	6.8	2	1.3	1.4	2.86	20.96	0.6	18.79

Table 4.5: Elemental ratios in muscovite of the pegmatite.

Sample I.D	Wall Zone			Intermediate Zone			Core zone		
K/Rb	0.0255	0.0256	0.1675	0.0244	0.0146	0.0124	0.0210	0.0135	0.0153
K/Cs	0.0199	0.0252	0.0398	0.0143	0.0550	0.0375	0.0166	0.02328	0.0214
Rb/Sr	4068.5	2980	455.529	152.68	276.285	162.428	181.366	82.6	93.016
Rb/Ba	1627.4	1788	774.4	580.2	772.6	454.8	1088.2	289.1	348.812
Nb/Ta	2.4545	4.0125	0.3157	4.0495	3.1111	3.7811	4.2772	3.0691	1.8154
Rb/Cs	14.740	27.4233	30.7301	7.0315	19.218	7.7610	9.9834	14.9405	14.4211
Y/Nb	1.5972	1.4548	0.3333	1.7359	0.4761	0.5561	0.972	0.4654	0.704
Li/Cs	0.0525	0.0644	0.0396	0.0143	0.0298	0.0307	0.0110	0.0155	0.0180
Li/F	0.3207	0.4191	0.0393	0.2	0.2352	0.1902	0.1547	0.1107	0.2310

4.4.3 Granitoids

The granitoids or granitic rocks in the study area are medium to course grained, and mineralogically composed predominantly of feldspars and quartz. On the Middlemost (1985) diagram (Fig. 4.4), the granites are ploted in the granite field and garanodiorites values are ploted at the verge of granite and granodiorite. This means that granodiorite crystallises before the granite. On the O’ Connor (1965) An-Ab-Or normative diagrams (Fig. 4.5), all the granites plot within the granite field, the granodiorite plot within the granodiorite field while the migmatite gneiss straddle the granodiorite field.

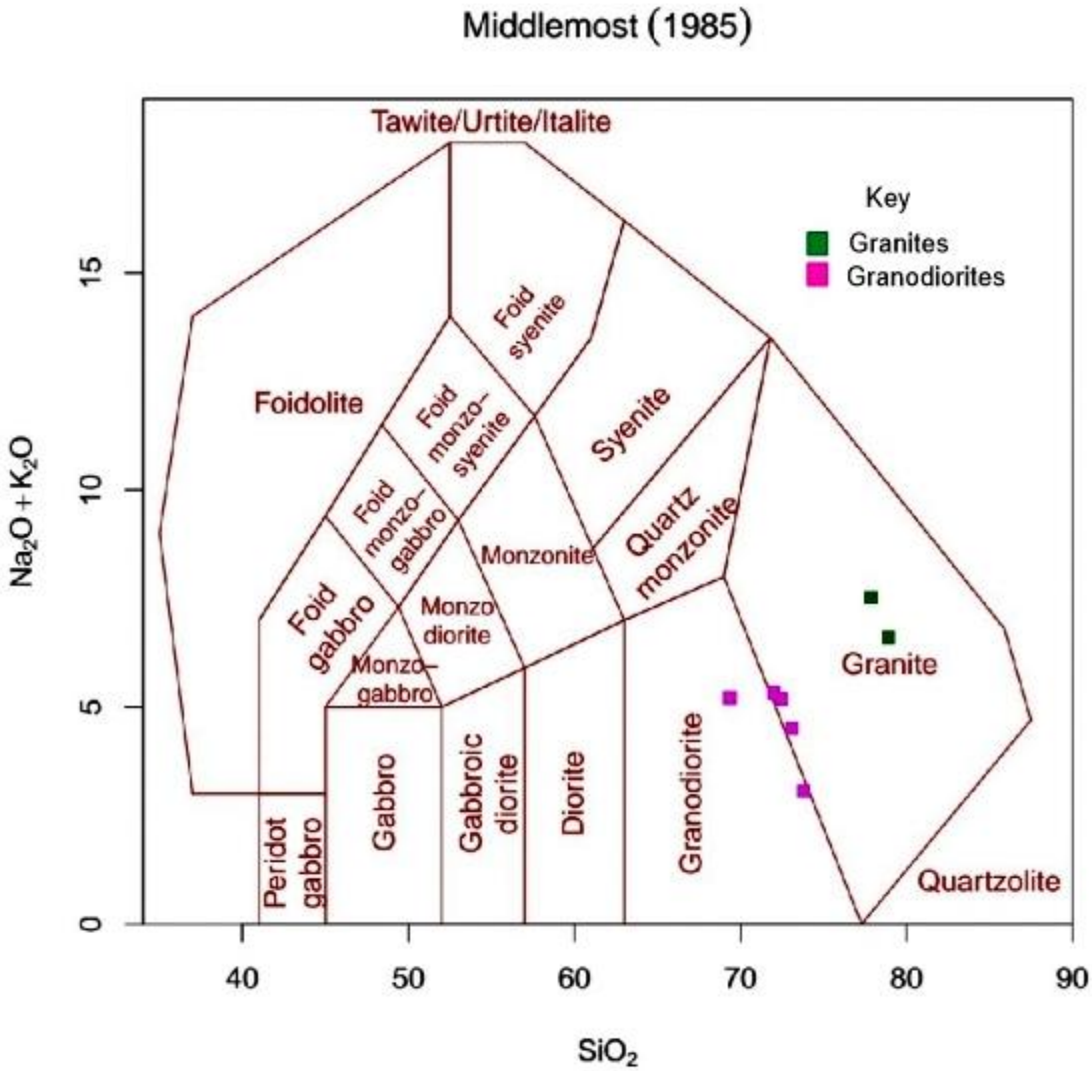


Fig.4.4: Whole rock geochemical data of granitoid plotted on the TAS classification diagram (Na_2O+K_2O versus SIO_2) after Middlemost (1985)

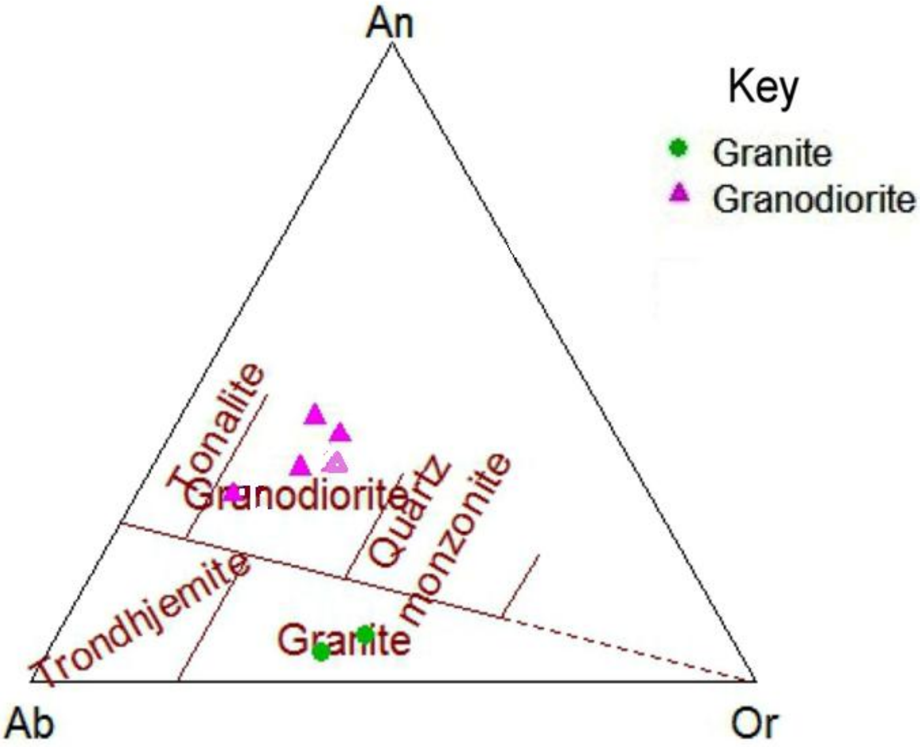


Fig 4.5: Normative An-Ab-Or diagram showing the distribution of the rocks in granitic to granodioritic field (after O'Connor, 1965).

In the discriminant diagram after Batchelor and Bowden (1985) Fig. 4.6, the granodiorite in the study area plots within the mantle fractionates field wheresas the granite straddled on the post orogenic field. This indicates that it is post orogenic.

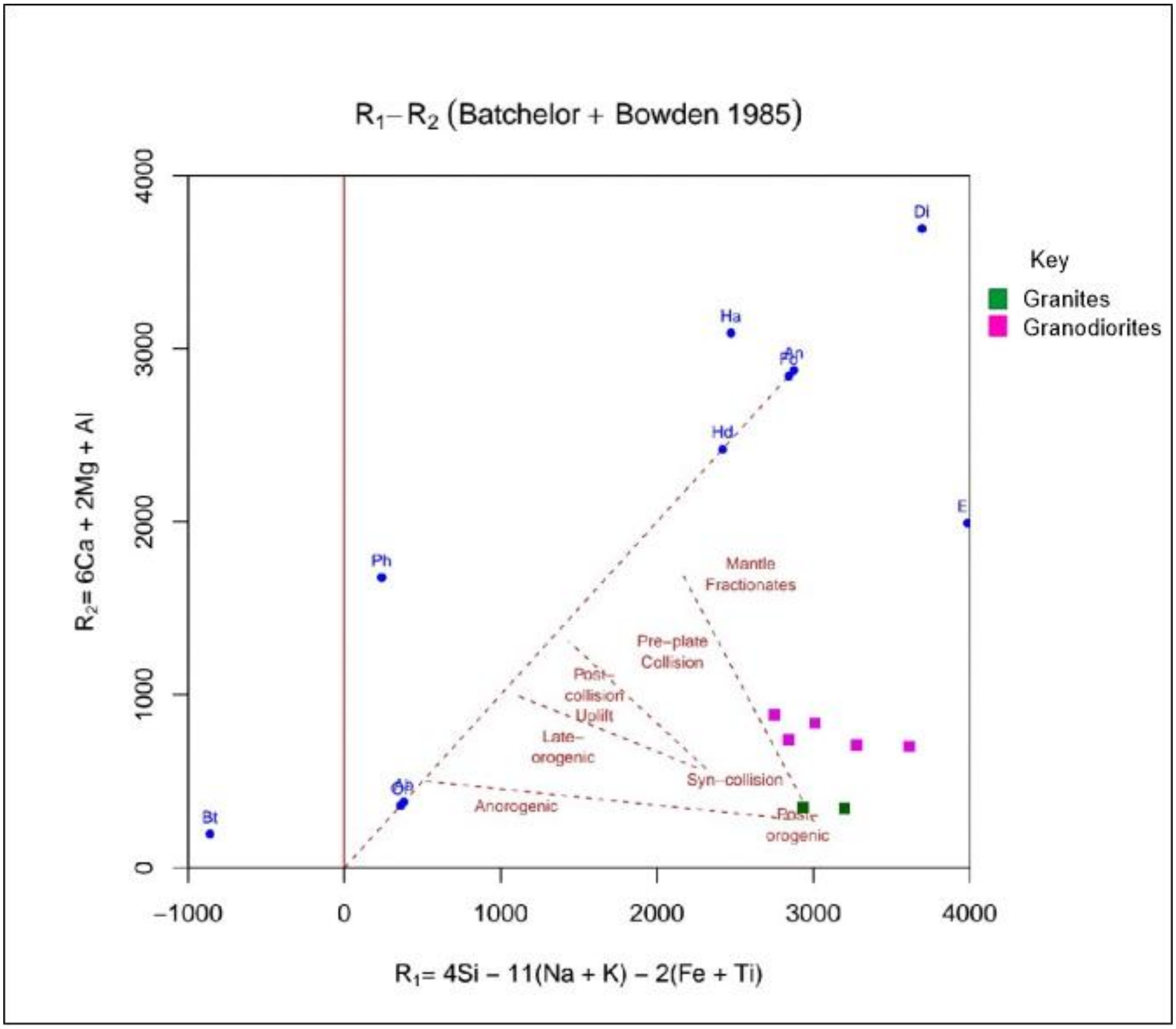


Fig. 4.6: Tectonic discrimination diagram (after Batchelor and Bowden, 1985), showing the tectonic setting of the granite suites within the post-orogenic fields.

The major element composition of the migmatite, granodiorite, granites and the Schist plotted on Harker diagram using SiO_2 as an index of differentiation shows that TiO_2, Al_2O_3, FeOt and MgO, are somewhat scattered in contrast to linear trend for CaO,NaO,P_2O_5 and K_2O (Fig. 4.7).

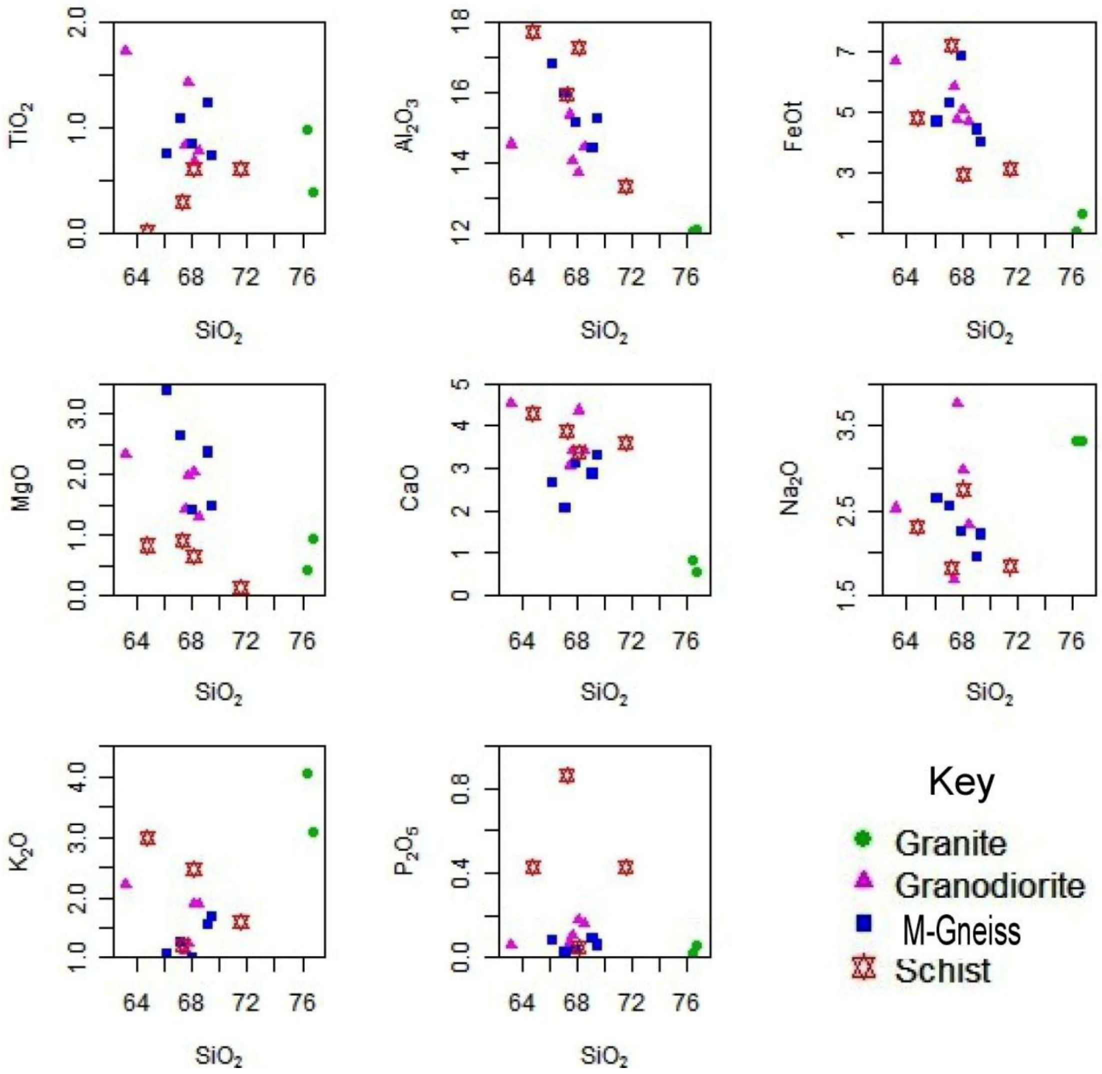


Fig. 4.7: Bivariate plot of major elements of granitoids, schist and migmatite gneiss against SiO_2.

In addition, Al_2O_3 is greater than CaO, Na_2O and K_2O (in molecular proportions). Discrimination based on the molecular ratio alumina to alkalis [$Al_2O_3/(Na_2O+K_2O)$]versus alumina to lime and the alkalis [$Al_2O_3/(CaO+Na_2O+K_2O)$] after Shand (1943), indicates that the granodiorite samples are both peraluminous and metaluminous in the study area (Fig. 4.8).

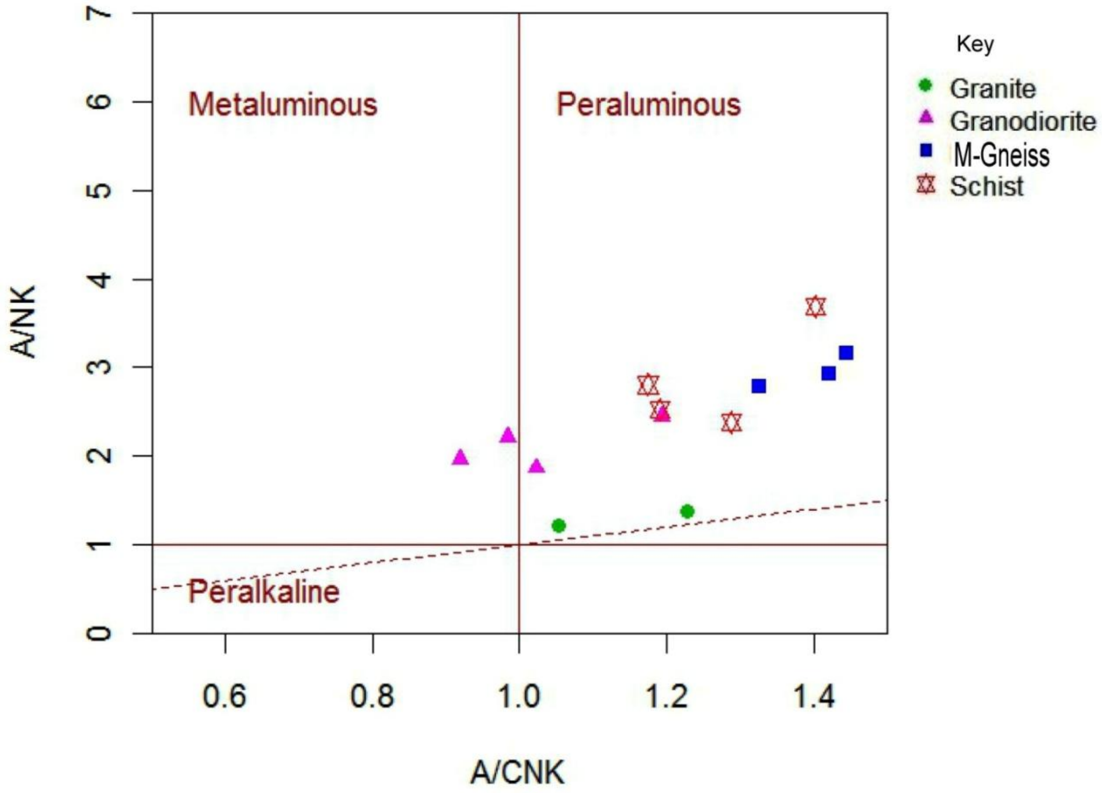


Fig. 4.8: Chemical classification of the granitic rocks using the molecular ratio of alumina to alkalis [Al_2O_3 / (Na_2O+K_2O)] versus alumina to lime and alkalis [Al_2O_3/(CaO+Na_2O+K_2O)] after Shand (1943)

4.5 PETROGENESIS OF PEGMATITE

The K/Rb and K/Cs ratios of the muscovite from the study area (Table 4.5) decrease from the outer zone towards the innermost zone, thus reflecting the increasing differentiation degree as well as mineralization potential of the pegmatite from the outer zone to innermost zone. This is consistent with the observation of Černý, (1985) and London (2008). Plots of K/Rb Vs Rb and K/Cs Vs Cs as shown in Figures 4.9 and 4.10 respectively have been employed in order to provide pictorial view of changes in absolute abundance of those elements within the pegmatite during the process of fractionation.

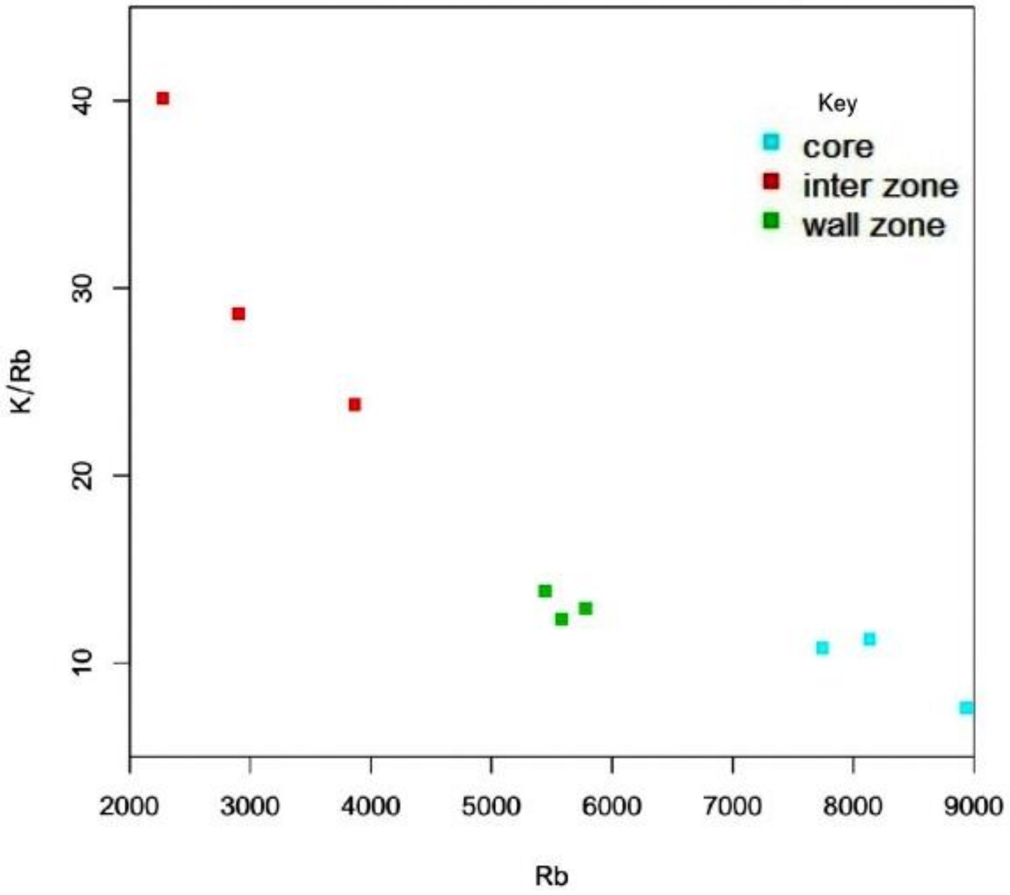


Fig. 4.9: K/Rb versus Rb plot of rocks and mineral making up the pegmatite, in the study area (after Černý *et al.*, 1985).

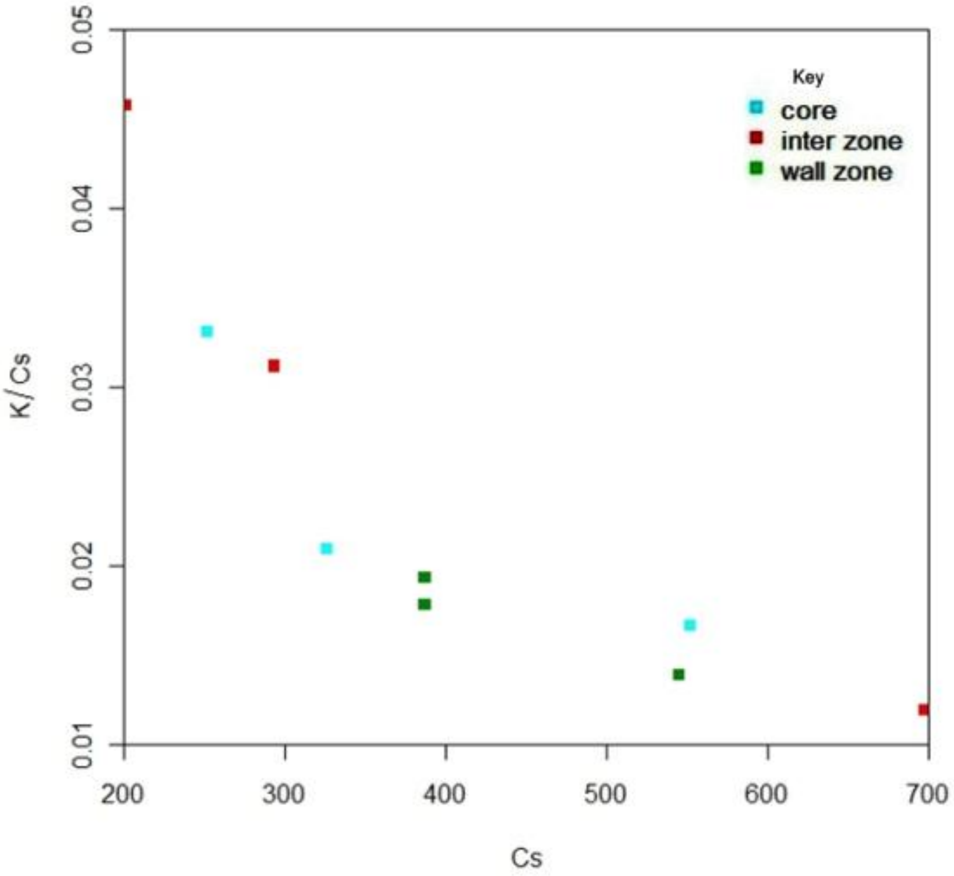


Fig. 4.10: K/Cs versus Cs Variation plot of rocks and mineral making up the pegmatite, in the study area (after Černý *et al.*, 1985).

Rb and Sr are more compatible in plagioclase and alkaline feldspers (London 2005) while Ba is highly compatible in micas and the K-feldspars. This is because mica host most of the Ba in igneous rocks, The Rb/Ba ratio of micas should increase with crystallization of micas. This trend is observed in the samples from the wall zone to intermediate zone and increase in the core zone (Table 4.5). There is an observable increase in the Sr due to the high Rb value with advance crystallization within the pegmatite. Fig. 4.11 and 4.12

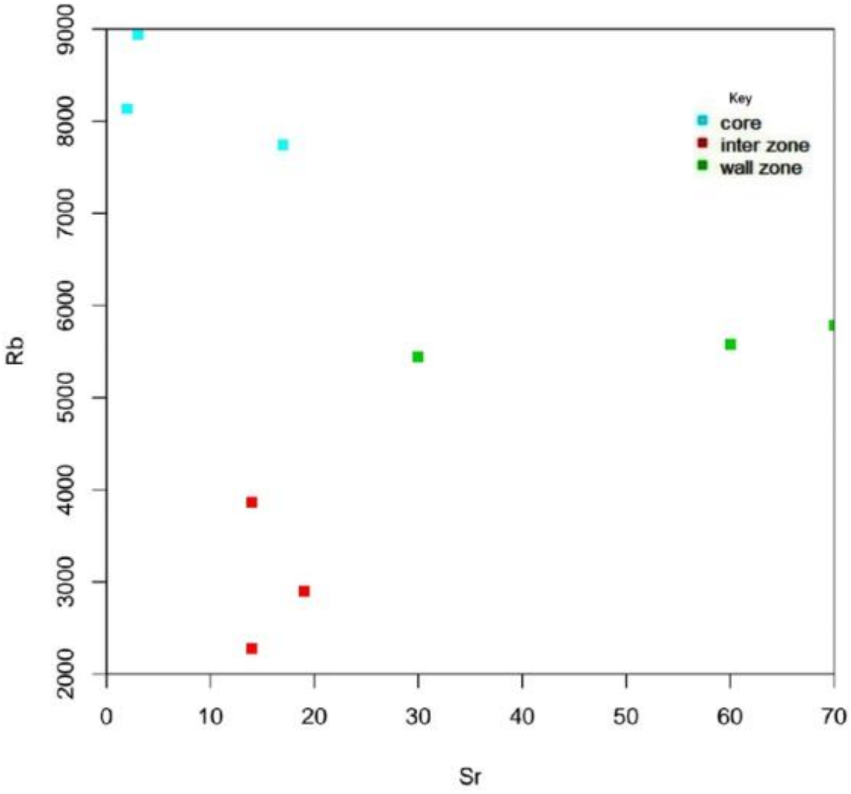


Fig. 4.11: Rb versus Sr plot of the pegmatite, in the study area (after Černý *et al.*, 1985).

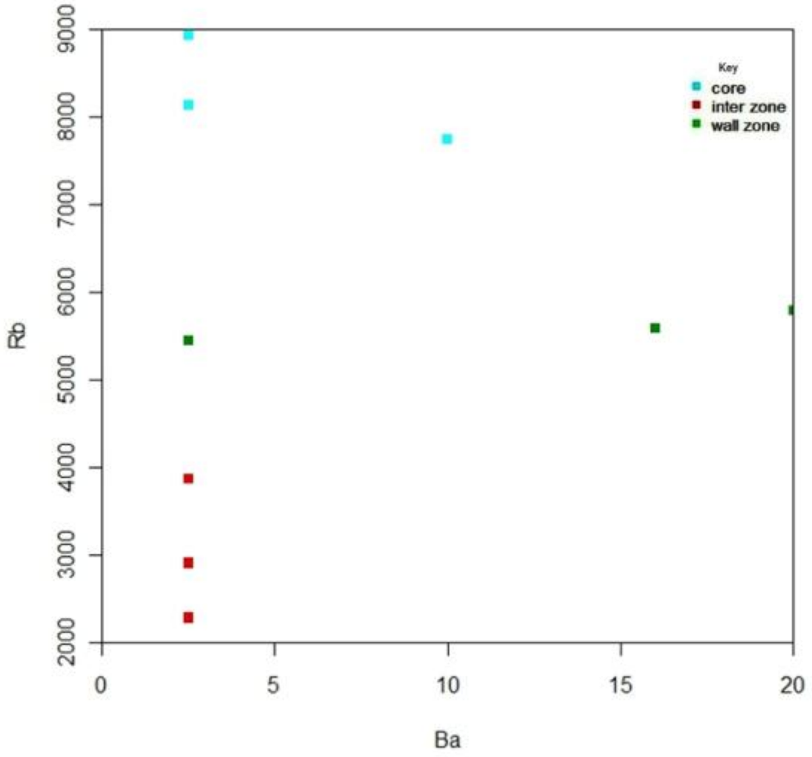


Fig. 4.12: Rb versus Ba plot of the pegmatite, in the study area (after Černý *et al.*, 1985).

4.6 RARE EARTH ELEMENTS (REE)

Knowledge of the behaviour of rare earth elements in aqueous solutions during hydrothermal and metamorphic fluid-rock interaction is critical for the interpretation of REE patterns in hydrothermal mineral. Both REE mobility and immobility have been advocated by many workers (e.g Menzies *et al*.,(1979);Muecke *et al*., (1979) Michard and Albarede, (1986); Brewer and Atkin, 1989;Grauch, 1989; Bau, 1991). The REE distribution pattern in an igneous rocks is controlled by the REE chemistry of its source and crystal-melt equilibria which have taken place during its evolution. The REE pattern has important application in identification of the way in which fractionation of individual minerals occurred during magmatic evolution.

The average sum of rare earth element in Muscovite of the studied pegmatite ranges from 5.37 to 7.21 x condrite in the wall and intermediate while the core zone unit recorded 16.46.The core zone with ∑REE of 16.46 x chondrite recorded the highest value because the REE preferentially partition into magmatic liquid relative to the coexisting crystalline assemblage, and thus crystal fractionation resulted in progressive enrichment of those elements in the remaining melt. The values obtained from the REE were used to plot the chondrite normalised pattern (Fig. 4.13).

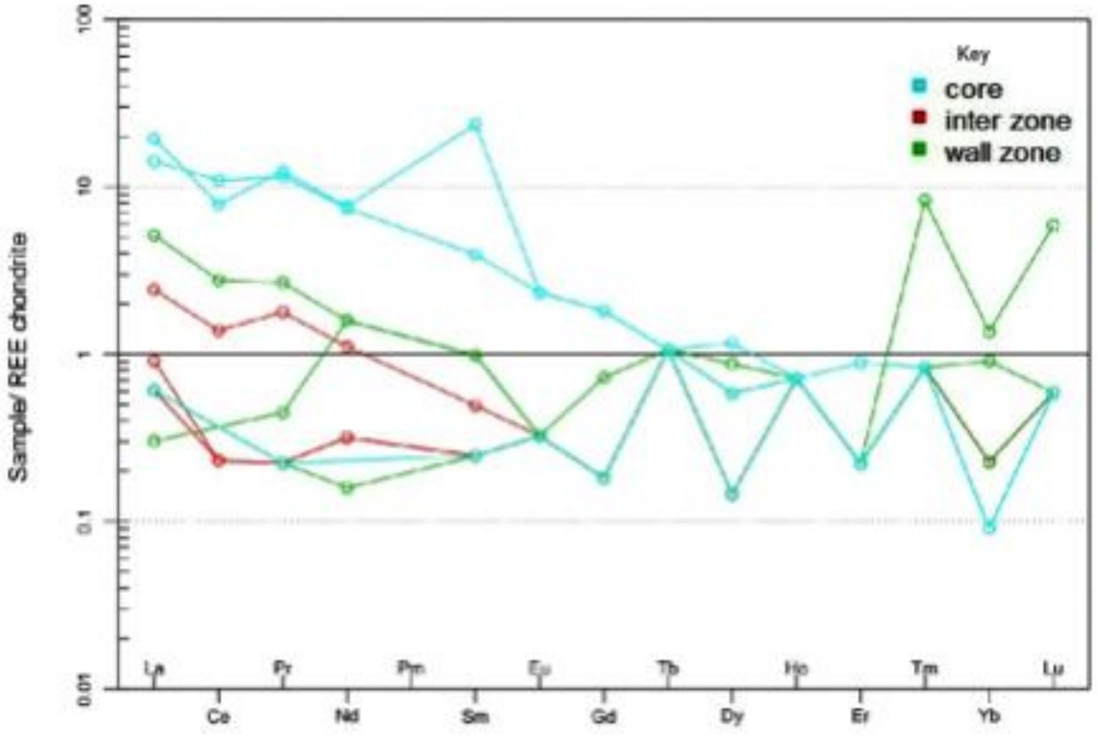


Fig. 4.13: Chondrite (Boynton 1984) normalised REE pattern of the muscovite pegmatite samples from the different zones. (Nakamura 1974)

The REE distribution pattern in muscovite further reflect the interaction between melt and coexisting volatile-rich fluid where in it inherited the REE composition and distribution characteristics of the melt (Bau,1996; Irber 1999). In line with the view of Zhao et al., (2002) fluid-melt interaction during the late stage of crystallisation is the most important factor that controlled the REE fractionation during the evolution of the pegmatite. Trace element data indicate that all of the muscovite from the pegmatite in the study area show a typical enrichment in LREE inherited from the crust compared to fluid derived from a deep seated source that are characterised by a strong enrichment in HREE.

4.7 NIOBIUM-TANTALUM-TIN MINERALISATION

Nb, Ta, W and Sn are (rare metals) elements with high charge to ionic radius ratio, i.e. High Field Strength Element (HFSE) that do not substitute into common rock forming minerals and thus behave incompatibly during crystallization of silicate melt (Linnen and Cuney, 2005). These elements are concentrated mainly by high degree of fractional crystallization of peraluminous granitic melt enriched in fluxing agent like F, B, P, Li and H_2O under an increasing aIkaIinity of the melt, commonly associated with pegmatite of the LCT class (Černý, 1991: London, 2008). The solubility of Nb- and Ta- oxides increases with temperature, increasing alkalinity of the melt and the abundance of fluxing elements in the melt (Linnen, 1998; Linnen and Cuney, 2005). With evolution of a granitic melt, Mn is generally enriched relative to Fe during the fractionation of a pegmatite melt in a closed system (Černý and Ercit, 1985). The enrichment of Mn in the melt is enhanced by the high activity of fluorine (Černý 1985). Fractional crystallization causes the evolution of columbite- tantalite from ferrocolumbite ($FeNb_2O_6$) to manganotantalite [$MnTa_2O_6$]. Therefore, columbite should precipitate from the melt earlier than tantalite

From the muscovite pegmatites in the study area, Fig. 4.9 and 4.10 (K/Rb versus Rb and Cs) show the trend of evolution in the different zones of the pegmatites. As a consequence of fractional crystallization, Ta/(Ta+Nb) will increase in the melt with fractionation from outer zones to more evolved core zone (London 2008).

The composition of the Columbite-tantalite is generally controlled by Fe-Mn substitutions during fractional crystallization, progressing from ferrocolumbite [$FeNb_2O_6$,] to manganotantalite [$MnTa_2O_6$] (Černý l985). The Nb-Ta content of columbite group mineral can be related to that of micas that coexist with them (Van Lichtervelde ***et** al.* 2008). Deduced from the pegmatites in the study area, fractionation probably started from Mn-poor ferrocolumbite towards a slightly Mn- and Nb- enriched manganocolubite and finally to manganotantalite in the more evolved zones. According to (Linnen *et al.,* 2005), the solubility of Fe-rich member of the columbite group mineral in a melt is higher than that of Mn-rich mineral, thus the Fe-rich group will be enriched over Mn-rich group but the enrichment of Fe rich group is controlled by the presence of other iron-bearing minerals such as tourmaline and biotite during evolution (London 2008). According to Černý et *al.*, (1985), Ta-dominant species are restricted to the most highly fractionated complex type of rare-element pegmatite.

Figure 4.14 is a plot of muscovites extracted from the pegmatite. It reveals an important association of Nb-Ta with muscovite- and albite portions of the pegmatite. The lack of correlation of rare-elements with primary K-feldspar suggests that metasomatism may have been the dominant process of Nb and Ta-enrichment (Kontak 2006; Anderson 2013). Both magmatism and metasomatism are therefore, important factors in accumulation of the Nb- and Ta-oxides in the pegmatite.

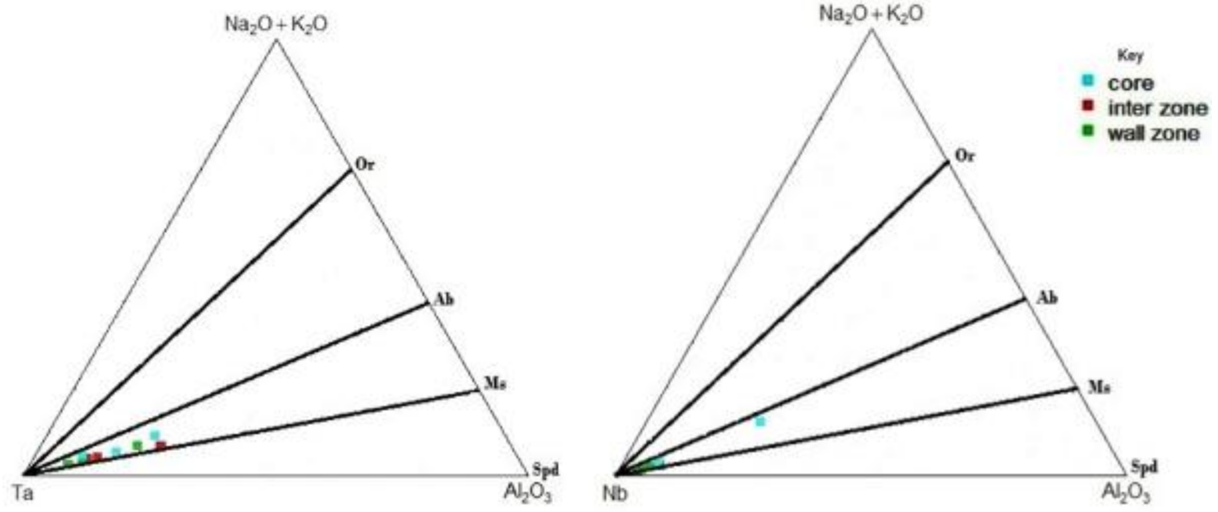


Figure 4.14: Ternary plots to demonstrate the association of Ta and Nb enrichments with the albite and muscovite rich parts of th**e pegmatite (after Kontak, 2006, Anderson.2013). Or= orthoclase, Ab = albite, Ms = muscovite, Kfs = K-feldspar. Spd = spodumene, Ta=tantalum. (Symbols are the same as in Fig. 4.9)**

4.8 Muscovite -Rich Replacement Zones

Albitizaton is a well-known feldspar replacement phenomenon that has been documented in LCT pegmatites from around the world; for example Harding pegmatite, New Mexico. White picacho pegmatite district, Arizona; Moose 11 pegmatite. Canada, Pala district San Diego County, Californja, USA, the Tanco pegmatite Monitoba Canada. To a large extent, sodic-metasomatism (albitization) has affected the pegmatite. This is in accordance with London and Morgan, (2004); London, (2005) metasomatic reaction involves alkali exchange between Na-rich fluids and K-feldspars due to gradients in chemical potentials and temperature, which results in replacement of early K-feldspar with late pink cleavelandite (platy variety of albite), Anderson (2013). This is illustrated in the following equation.

$KAlSi_3O_8 solid + Na+_{aq=} NaAISi_30_{8solid +} K^2_{aq}$
K-feldspar +Sodium— Albite’ + Potassiurn

There is evidence that remobilization of elements during metasomatism (magmatic and/or hydrothermal events) is an important feature of the pegmatite of the study area (Figure 4.14) and hence the implications for the distribution of economically important Nb- Ta oxides. In the muscovite-rich replacement zones, concentrations of 409-756 ppm Nb, 80-298 ppm Ta, 6-29wt % Li. <10 ppm Sn and importantly, 201-697ppm Cs (Table 4.3) were recorded in the three zones of muscovite part of the pegmatite have been documented.

The Nb-Ta- mineralization is concentrated in the Na-rich (albitized) zone thus suggesting that these elements were mobilized hydrothermally along with Na during metasomatism. Experimental work of Tin (2007) shows that the potential mechanism for Sn extraction at the final stages of magma crystallization is through alkalis. The intermediate zone which shows characteristic metasomatic and replacement features with elevated Zn and Sn concentration in the secondary muscovite may also reflect the high solubility of these elements in hydrothermal fluids.

The magnitude and complexity (cross-cutting) of the pegmatite also suggest multiple extensional events possibly with successive pulses of magma injections. Multiple injections of magma adjacent to previously crystallized pegmatite zones could result in metasomatic alteration of orthoclase to muscovite. These magmatic-metasomatic fluids may have added Nb, Ta, Sn and Zn to the system and/or remobilized and redeposited the oxides from early generations of columbite-tantalite.

CHAPTER FIVE

DISCUSSION

5.1 Geology and Petrography

The study area is underlain by migmatite gneiss, schist, granite, granodiorite, and pegmatites. Field observation has revealed that granodiorite is the lithologic unit hosting the pegmatites.

The migmatite gneiss shows segregation into light and dark bands with flow banding in places. Both the light and dark bands are aligned in NNE – SSW direction. The rock composed mainly of quartz, microcline, biotite and opaque minerals. Petrographic studies have shown that the migmatite gneiss is granodioritic in composition and consist mainly of quartz, feldspar, hornblende and biotite cleavage.

The phyllitic schist has been strongly deformed. In some places, the entire rock section is made up of tiny isotropic debris of unidentifiable minerals with little or no foliation developed. This is said to represent a transitional stage in the development of schist from phyllite by prograde metamorphism. The schistosity defined by lath-shaped minerals of biotite and hornblende increase in proportion in the area occupied by schist. A highly porphyroblastic facies with rectangular-shaped phenocryst is developed. It consists of alternation of quartz rich layers and mica rich layers. The quartz rich layers consist of fine to very fine foliated grains that are more or less striated. The thickness of the layers varies across the sample area. The mica rich layers consist of chlorite, and fine biotite.

The granodiorite forms fairly high hills in some places at the north-east. Elsewhere, it is low-lying or merges with the gently rolling topography. There is a considerable variation in mineralogy and texture of the rocks. Commonly, it is a medium-grained crystalline rock with traces of white feldspars. In thin section the rock composed mainly of quartz, plagioclase and biotite. The rock differs from granite *sensu stricto* because of its high plagioclase feldspar relative to alkali feldspar. Quartz occurs as discrete crystals characterized by undulatory extinction. Plagioclase is slightly calsic ranging from andesine to labrodorite. The mineral occurs as subhedral crystals characterized by carlsbad twining. Biotite occurs as brown crystal with high relief and perfect basal.

The granite is elongated in a north-south direction which is also the trend of the lineation. A small tongue of the granite runs off to the south-west in the study area. This tongue appears to be of a laccolithic nature as at two places the granite was observed to be resting on a floor of banded gneiss. The granite is bounded on two sides by shear fractures, probably faults, which on the eastern side separate it from the granodiorite.

5.2 Structural Control

Rose diagrams constructed from the prevailing mining sites revealed that different direction of the pegmatite at different distances were obtained as indicated in Table 4.1. As a whole, the pegmatite is trending NE – SW direction which is in accordance with the Pan-African Orogeny. Other structural features mapped in the study area include asymmetric, isoclinals and some complex folds within the schist and granite gneiss. These fold types are evidently the records of tectonic activities to which the rocks were subjected to, probably during the Pan-African Orogeny.

5.3 Geochemical Analysis

Geochemical study revealed that the granitoids are peraluminous to metaluminous and are mainly S-type granite. This suggests that the granitoids probably formed from the anatexis of schist or aluminouous gneisses of sedimentary origin. The original sedimentary rock probably consists mostly of clay-rich material produced by extensive crystals weathering of continental rocks (Chappell and White, 2011). These sedimentary rocks could therefore be the source of the fertile granitoids from which the rare-metal pegmatite hosting columbite-tantalite mineralization in the study area was derived.

This revealed that the mineralized pegmatites in the study area have high potential for tantalite, since most of the muscovite extracted from the pegmatites plot above the minimum cut-off point for tantalite mineralized pegmatites. Geochemical data obtained from the muscovite is enriched in Ta and REE and that they are the possible sites for these rare elements that are associated with pegmatite.

Considering the internal structure, mineralogical distribution and geochemical data on the granodiorite and muscovite, the proporsal of Roda *et al.*, (2012) "from granite to highly evolved pegmatite" so hereby evoked as the petrogenetic model which best explains the origin of the pegmatite from the study area.

The pegmatite was formed by magmatic fractionation of the residual fluid that formed the Pan-African granite with the possibility of some direct anatetic input. The high Li-Cs-Ta value in the muscovite part of the pegmatite suggest that the pegmatite belong to this lithium-Cesium-Tantalite (LCT) family of the rare earth element class while the content of Li, Rb, Cs, Be, F, Sn, P, B, Ta and Nb in the pegmatite places the group under the albite, spodume, lepidolite to elbaite sub-class as proposed by Černý and Ercite (2005). The pegmatite can be said to be “heterogeneous” because it consist of the different types and sub-types LCT family, Rare Earth class pegmatite.

The intermediate zone and part of the wall zone recorded comparatively higher values of $FeO_{(t)}$ MgO_2, TiO and MnO than the other zones. The relative enrichment of these oxides can be attributed to the enclosing wall-rock. Moreover, the trace element characteristics suggest that the pegmatite forming melt was contaminated by the host rocks through a process of leaching and assimilation while infiltration of fluid from the pegmatite to the host is very minimal and almost negligible.

Based on the major and trace element geochemistry, the trend within the muscovite from the pegmatite (wall intermediate and core zones) is very obvious with the pegmatite being more primitive and less evolved. The element fractionation trend clearly marked by systematic increase in Li, F, Rb, Cs from the wall-rock towards the core coupled with alteration of feldspars to clay minerals suggest that, crystallization, started from outer to inner zones and in a close system. If crystallization did not occur in a closed system, there would have been no progressive concentration of Li and F from the wall rock inward and there would have been no alteration from the late stage residual and this phenomenon correlates with the sequence of zoning established by Černý (1991) for pegmatitic fields and related granodiorite.

CHAPTER SIX

CONCLUSION AND RECOMMENDATION

6.1 CONCLUSION

Based on the petrography, mineralogy and geochemistry, it is most likely that the granodiorite in the study area were produced probably during the Pan-African. The source materials could also be mantle-derived melts during the sub-direction period which formed a hybrid magma that fractionated into S-type. The plot of K/Rb ratio vs Rb, REE chemistry and the gradual increase in Rb, Cs, K, Nb, Ta, Li, F, P, Ti and U from the studied area, indicate fractional crystallization, that lead to late stage concentration of the rare metals.

The systematic increase in elements from the granodiorite to the pegmatite and the similarity in all trends shown in the plots of figures used in the study revealed the importance of chemical fractionation as the main influencing factor on the overall crystallization of the granodiorite and pegmatite from the study area. This is consistent with an internal fractionation model.

Geochemical trends indicate an evolution from a ferrocolumbite to manganotantalite within the different zones of pegmatite. Niobium and Tin are concentrated by extreme fractional crystallization in a flux-rich melt, Fractionation trends of muscovite indicate that the pegmatite crystallized from the margins inward, thus mineralization are primarily magmatic: alteration led to complex internal zonation with muscovite rich replacement zones. These late zones are further enriched in Nb - Ta and Sn indicating that magmatic and metasomatic processes played a role in metal enrichment.

The high Li-Cs-Ta values in the muscovite suggest that the pegmatite group belong to the lithium-cesium-tantalium (LCT) family of the rare element class. The content of Li, Rb, Cs, Be, F, Sn,. P, B, Ta and Nb in the pegmatite place the pegmatite in the albite, spodumene, lepidolite to elbaite sub-class as proposed by Černý and Ercit (2005).

Columbite (Nb_2O_5) and tantalite (Ta_2O_5) are the two main ore minerals from which tantalum (Ta) and niobium (Nb) are extracted respectively. These elements are geochemically associated and are found together in most rocks and minerals in which they occur. This is due to the similarity in ionic radii and valency states of these elements (Ta^{+5}= 0.68A and Nb^{+5}=0.69A), which are fundamental parameters controlling their entry into crystal structures of minerals.

6.1.1 Mineral Potential

The primary mineralization of tantalum, niobium, tin, beryllium and lithium is hosted in quartz-feldspar-muscovite pegmatites (Kinnaird, 1984). This claim reflects here in the study area. Mining of tantalite from both pegmatites and the eluvials started in the area some years ago. The mining continues for the major periods of the year except during the very dry months of February to early April when lack of water makes it difficult to mine and concentrate the minerals. Columbite and cassiterite are recovered as by-products of the tantalite mining, while other pegmatite minerals like quartz, feldspar and mica are being discarded in waste dumps. These new discoveries were made by artisanal miners driven by high prices of tantalite in last decade. This development has shown that the rare-metal pegmatite in the study area hosts a very reasonable amount of the tantalite mineralisation, therefore, Government and private sectors have to step into the mining activities in order to mine at a profitable scale. More than 10 tons of columbite-tantalite concentrates (according to artisanal miners) have been produced from the pegmatite since the discovery. Columbite-tantalite concentrates produced by artisanal miners from some Nigeria rare-metal pegmatite fields show the proportion of Ta_2O_5, Nb_2O_5 and SnO_2 to be 15-43 %, 6-18% and 2-35% respectively.

6.2 RECOMMENDATION

The conclusion drawn from this work regarding the mineralization potential of pegmatites is based on the study of the trace elements compositions of the muscovite 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 out. This will go a long way in confirming some of the observations made in this work.

There should be detailed evaluation of economic potential of the tantalum minerals originating from the pegmatite in the entire study area, where the pegmatite field is situated as more commonly, each mining site carries economic mineral (commodities). It is recommended here that, exploitation of minerals should be based on bulk mining production of all primary minerals without any unnecessary wastage in view of a growing demand for these minerals e.g. feldspars in ceramic and glass industries, mica in the expanding cosmetic industry and rare-metals. Furthermore, this can be used to discourage the selective mining method that leads to unstable walls and pit that are unsafe for working condition.

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