GEOLOGY, GEOCHEMISTRY AND STRUCTURAL CONTROLS OF BERYL MINERALIZATION IN THE PRECAMBRIAN PEGMATITES OF PARTS OF IKARA SHEET 103 (NW AND SW), NORTHWESTERN NIGERIA

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DECLARATION

I declare that the work in this dissertation entitled **"Geology, Geochemistry and Structural Controls of Beryl Mineralization in the Precambrian Pegmatites of Parts of Ikara Sheet 103 (NW and SW), Northwestern Nigeria"** has been performed by me in the Department of Geology. The thesis was written and submitted in accordance with the rules and regulations governing the award of Master of Science Degree of the Ahmadu Bello University, Zaria. I further declare that the thesis has neither in part nor in whole been presented as substance for the award of any other degree, either to this or any other university. Where other peoples' work has been drawn upon, acknowledgement has been made.

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Name of Student	Signature	Date

CERTIFICATION

This dissertation entitled "GEOLOGY, GEOCHEMISTRY AND STRUCTURAL CONTROLS OF BERYL MINERALIZATION IN THE PRECAMBRIAN PEGMATITES OF PARTS OF IKARA SHEET 103 (NW AND SW), NORTHWESTERN NIGERIA" by Adamu YUNUSA meets the regulations governing the award of the degree of Master of Science in Geology of the Ahmadu Bello University and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

Dedicated to my father Dr. Yunusa Yahaya Pala who has taught me courage and the true meaning of determination.

ABSTRACT

The geology, geochemistry and structural controls of beryl mineralization in pegmatites of parts of Ikara Sheet 103 was studied to determine their genesis and beryl mineralization. Petrographic studies on the rocks collected from the study area were carriedout using transmitted light microscope. Whole rock geochemical analysis of the rocks and mineral chemistry of beryl were carriedout using XRF and ICP-MS analytical techniques. Study of lineaments and structural attributes were carried out by remote sensing and field measurements using compass clinometer. The area is made up of granites, gneisses, schist and quartzite as major rock types. Structural elements such as foliation, joints, veins and dykes were measured. The major and trace element chemistry of beryl were used to determine the relative fractionation of the pegmatites. Structural imprints of NE-SW trending joints and pegmatite and lineament analysis data defines the structural trends of the area. The rocks originated from metaluminous to peraluminous magma (A/CNK ratio below 1.1) and were probably sourced from an extreme fractionation of syn- to late tectonic granites (Niobium (1.93 to 8.98ppm) and Yitrium (13.67 to 40.36ppm)). The marked negative Eu anomaly and the LILE enrichment (Ba (upto 727ppm), Sr (upto 565ppm) and Rb (upto 310ppm) in the rocks is a typical signature of continental crustal material. Concentrations of Rb (40.7ppm), Cs (1022.5ppm) and Na_2O (0.3wt %) in the beryls analyzed are among the lowest measured in pegmatitic beryl of similar colours worldwide. Beryl from pegmatites of parts of Ikara are compositionally similar to beryl derived from intermediate zones characterized by a low degree of fractionation and formed in a geochemical environment poor in alkaline elements. The discrimination plots of beryl indicate that the formation of the pegmatite was controlled mainly by fractional crystallization. Trace element data shows that the subsequent crystallization of three

intermediate zones reflects changes in melt composition with a general decrease in femic elements and an increase in alkali elements. An evolution was also marked in the beryls REE pattern with an increase in ∑REE from early beryl to late beryl increasing with fractionation.

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CHAPTER ONE

1.0 INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The study area is part of the basement complex of Northwestern Nigeria which lies within the Pan-African mobile belt, underlain by migmatites, gneisses and metasediments of Precambrian age that have been intruded by series of granitic rocks of late Precambrian to Lower Paleozoic age.

The geology of gem deposits focused on understanding the rare and exceptional geologic conditions that give rise to gem quality materials; however, understanding how gem deposits formed is of more than academic interest because it can provide guidelines for exploration (Groat and Laurs, 2009).

Beryls' complex composition, complex pattern of zoning and resistance to alteration makes it an important tracer of changing conditions during its growth (Černý, 2002; Groat *et al.* 2007). An extensive substitution in beryl crystal structure makes it an excellent petrological and geochemical indicator mineral. Geochemical studies of pegmatitic beryl in Nigeria is very limited; this necessitates the need to synthesize the results obtained from this study to that of pegmatitic beryl worldwide. In this work, beryl samples were used to unravel the evolution history of the pegmatites relative to other gem minerals because they resist alteration and can accommodate major and trace elements, making it an excellent monitor

of its local environment of growth. Furthermore, beryl shows color changes with increasing fractionation.

1.2 LOCATION AND ACCESSIBILITY

The study area forms part of the Federal Survey map of Nigeria Ikara Sheet 103 NW and SW, which falls within the Pan-African basement complex. It is bounded by Latitudes 11° 10′ 0.00″ N and 11° 20′ 0.00″N and Longitudes 08° 05′ 0.00″ E and 08° 12′ 0.00″ E covering an area of approximately 240 km^2(Fig.1.1).

The study area is accessible by a network of footpaths, dry river channels and streams, minor roads like that from Unguwan Daura through Hayin Jaji to Gidan Barau and that from Dan Lawal to Kankanki through Unguwan Ciroma and Gidan Medawa. Major roads include that from Saulawa through Niima Mapera, Dan Lawal to Ikara; from Gubuci through Sabon kurmin Kogi to Ikara; from Saulawa through Tsauni Miki to Dorayi; from Saulawa through Kanawa to Pampaida and that from Dan Lawal through Unguwan Galadima to Furana.

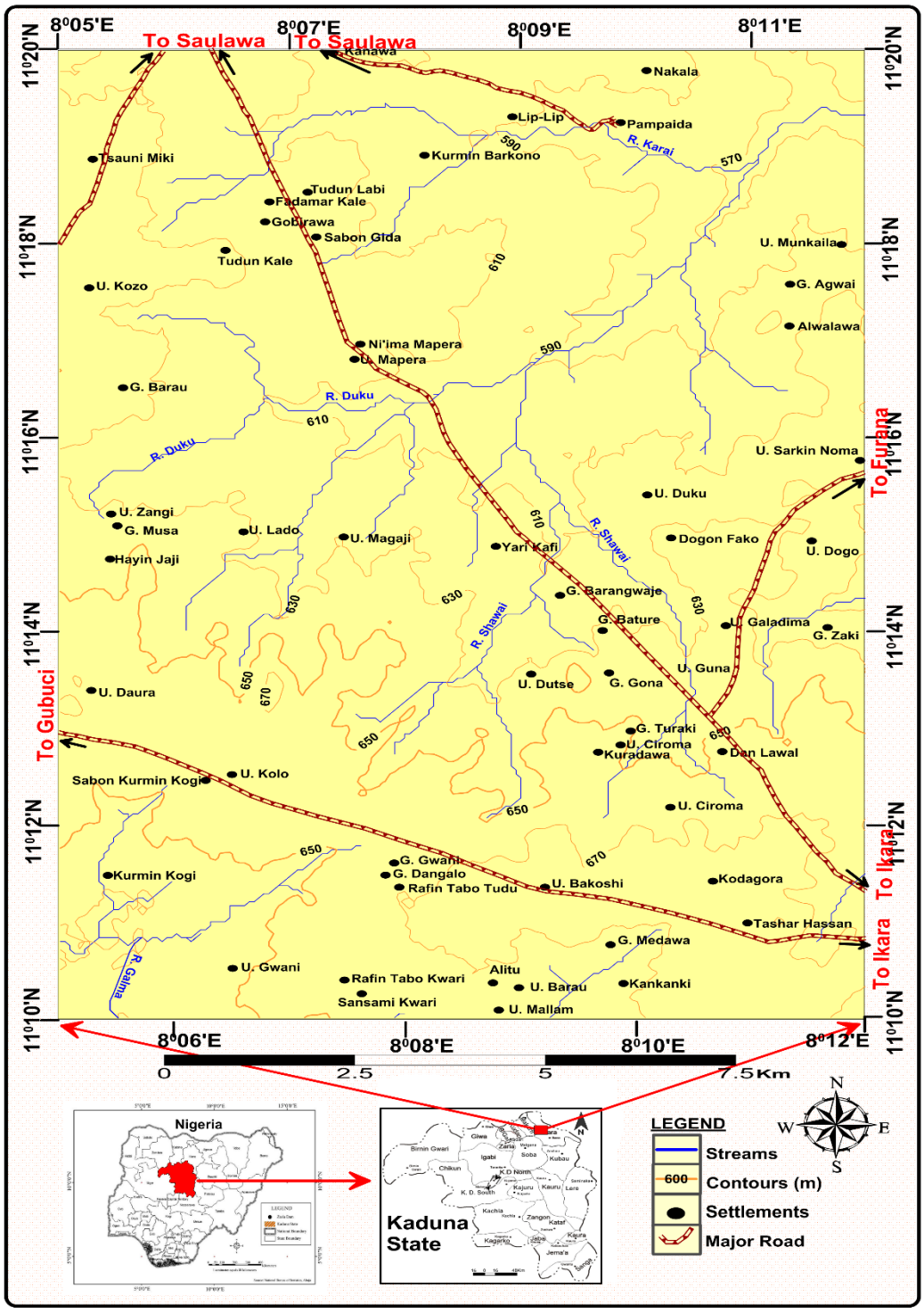


Fig. 1.1: Location map of the study area showing drainage, major roads and settlements.

1.3 RELIEF AND DRAINAGE

Relief in the study area is slightly higher in the southeastern and southwestern part of the study area as compared to the northeastern and northwestern parts. The area is generally undulating with the highest relief of about 2320m above mean sea level at Danlawan Hill and 2200m at Unguwan Kolo ridge.

The area is well drained with rivers and streams taking their sources from the highlands. The rivers are mostly ephemeral, flowing during the rainy season and drying up during the dry season. The major rivers that drain the area are River Galma (Plate 1), River Karai, River Shawai and River Duku (Fig.4.7, page 39). Most of the streams have a dendritic pattern and show radial pattern of flow in some areas. River Duku flows to Tiga dam. However, in some locations along the river channels, surface water occurs as isolated ponds during the dry season. The stream channels are almost parallel to the strike of the basement rocks suggesting that they are structurally controlled.



Plate I: River Galma, near Unguwan Gwani (N11° 10′ 30″ E08° 06′ 29″)

1.4 CLIMATE AND VEGETATION

The study area lies within the Guinea Climatic Zone of Nigeria, characterized by distinct wet and dry seasons with an annual temperature rising to 38˚C between March to May with the lowest temperature values experienced from December to February during Harmattan.

The vegetation is that of the Guinea Savannah of Nigeria which is characterized by open, sub humid broad-leaved savannah woodland vegetation with short to medium grasses. The vegetation of the area is sparse with shrubs and tall trees. The trees grow thick bark that makes it possible for them to withstand the long dry season and bush fires. The dominant trees in the area include Neem tree (*Azadirachta indica*), Baobab (*Adansonia digitata*), Shear butter tree (*Vitellaria Paradoxa*), Locust beans (*Parkia Filicodia*) and Mango (*Mangifera indica*).

1.5 SETTLEMENT AND LANDUSE

The pattern of settlement in the study area is dispersed with houses scattered in the form of farmlands and hamlets, majority of the settlers are indigenous Hausa and Fulani with minor influx of other tribes. Some settlements occur along the roads, streams and river channels.

The land is used intensively for cultivation of food crops such as guinea corn, cassava, potatoes, maize, millet and vegetables like tomatoes, pepper, onions. Rearing of livestock such as cattle, goats, sheep and guinea fowls are common around the settlements which aremostly carried out by the Fulanis. A small portion of the population undertakes occasional artisanal mining of beryl, tourmaline and amethyst during the dry season.

1.6 STATEMENT OF THE RESEARCH PROBLEM AND JUSTIFICATION

Gem mineralization in Nigeria is found in the Pan-African basement rocks, biotite granites of the Younger Granite series and the adjacent volcanic cover (Ike,1988; Abaa, 1991; Fajobi, 1999). The Proterozoic pegmatite host mainly semi precious aquamarine, topaz, gem quality tourmaline and sapphire (Aga, 2004).

Geological evidences indicate that different gemstones occur in Nigeria especially within the pegmatite belt; most of these pegmatites are Neoproterozoic in age (870-550Ma) (Kröner and Stern, 2005).

Gem minerals have been discovered and reported from different parts of Nigeria (Kinnaird *et al.* 1985; Schwarz *et al.* 1996; Vapnik and Moroz, 2000; Aga, 2004; Aga and Ashano, 2008; Aigbe *et al.* 2012; Gbadebo *et al.* 2013; Gezawa, 2013; Akoh, 2014; Solomon, 2014; Olatunji and Jimoh, 2016). Gem minerals are rare because in general, the conditions that promote their formation are unusual and thus worthy of scientific study.

The activities of artisanal miners recently confirm the occurrence of beryl, tourmaline, amethyst and other gem minerals within the pegmatite bodies of the area. This discovery of gems within the pegmatites in the area spurs renewed interest in the economic potentials of these pegmatites and also stimulated the current study. However, the chemistry of beryl from this important pegmatite field has yet to be determined.

1.7 SCOPE OF THE PRESENT WORK

The present work involved geological mapping of the study area on a scale of 1:50,000. Approximately, a month was spent in the field from early March to late March, 2016 during which a data-set was collected. Data collection for this study covered an area of

approximately 240 km^2. Satellite images where used for reconnaissance survey before going to the field for ground truthing. Petrographic studies of the rock samples collected were achieved using petrological microscope. During sampling, care was taken to ensure that weathered samples were avoided and only fresh samples were targeted. Samples were crushed and pulverized in preparation for laboratory analysis. Whole rock analysis of representative rocks and mineral chemistry of beryl samples were undertaken using ICP-MS and XRF. Beryl was characterized geochemically based on major and trace element chemical composition.

1.8 AIM AND OBJECTIVES

The aim of this work is to study the geology, geochemistry and structural controls of beryl mineralization in the pegmatites of parts of Ikara.

The objectives of the study are:

1. Produce a geological map of the study area on a scale of 1:50,000.
2. Determine the petrography and geochemistry of the rocks in the study area.
3. Determine the compositional trends of beryl hosted within the pegmatites of the area.
4. Determine the geochemical evolution of the pegmatite as recorded by beryl.
5. Determine the controls of mineralization in the region.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 INTRODUCTION

Nigeria is underlain by Precambrian basement complex rocks, anorogenic Younge Granites of Jurassic age, Cretaceous to Recent sediments and Tertiary to Recent volcanic rocks. The basement rocks occupy about half of the landmass of the country (Black, 1980). The term 'Older Granite' was introduced by (Falconer, 1911) to distinguish the deep-seated, often concordant or semi-concordant granites of the basement complex from the high-level, highly discordant tin-bearing granites of Northern Nigerian Mesozoic anorogenic ring-complexes known as the Younger Granites.

In order to understand the geology of the study area which is located in the Northwestern Nigeria, the knowledge of the general geology of the basement complex of Nigerias need to be understood.

2.2 THE NIGERIAN BASEMENT COMPLEX

The Nigerian basement complex forms the southern part of the Trans-Saharan mobile belt (Caby, 1987) of Neoproterozoic (750-500Ma) age situated between the Archean to Paleoproterozoic blocks of the West African Craton in the west, the Congo Craton in the southeast and the east Saharan block in the northeast (Fig. 2.1).

The Nigerian basement complex occupies the reactivated region that resulted from plate collision between the passive continental margin of the West African Craton and the active

pharusian continental margins affected by Pan-African Orogeny (Burke and Dewey, 1972; Dada, 2006). The collision at the plate margin is believed to have led to the reactivation of the internal region of the belt. The Nigerian basement complex lies between the West African and Congo Craton and south of the Tuareg shield (Black, 1980). The Nigerian basement complex is part of the Pan-African mobile belt (Kennedy, 1964) as all crystalline shield areas have been reworked (c. 600Ma). Apart from the Jurassic ring complexes and the Burra-Shika Group, most crystalline rocks of the Nigerian basement bear Pan-African tectonics and mineralogical imprints (Dada, 1998). Geochronological evidence indicates that the Nigerian basement complexis polycyclic and includes rocks of Archean (2.0-3.0 Ga) era together with those of Eburnean (2000±200 Ma) and Pan-African (750-450 Ma) event (Ajibade *et al.* 1987; Elueze, 2000; Fitches *et al.* 1985; Turner, 1983).

The basement rocks are believed to be the result of atleast three major orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2700±200 Ma), the Eburnian (2000±200 Ma) and the Pan-African cycles (600±150 Ma). These three cycles were characterized by intense deformation and isoclinal folding accompanied by regional metamorphism and then followed by extensive migmatisation. The Pan-African deformation was accompanied by a regional metamorphism, migmatisation and extensive granitization and gneissification which produced syntectonic granites and homogeneous gneisses (Abaa, 1983). Late tectonic emplacement of granites, granodiorites and associated contact metamorphism accompanied the late stages of this deformation. The end of the orogeny was marked by faulting and fracturing (Gandu *et al.* 1986). (Anifowose, 2004) was of the opinion that the granitic emplacement was probably controlled by fractures within the basement. The Pan-African orogeny (ca. 600Ma) was established as a granite

emplacement period that witnessed the intrusion of Older Granites into the Migmatite-Gneiss-Quartzite complex, Eburnean granitoids and associated schist terrains within the Nigerian basement complex (Woakes *et al.* 1987).

The basement complex rocks have been earlier characterized into different major rock types (Oyawoye, 1964; McCurry, 1976; Rahaman, 1988). However, within the basement complex of Nigeria, four major lithological units are distinguishable (Dada, 2006), namely:

1. The Migmatite-Gneiss-Quartzite Complex
2. The Schist Belt (Metasedimentary and Metavolcanic rocks)
3. The Older Granites and associated granitic rocks
4. Undeformed acid and basic dykes (Volcanics)

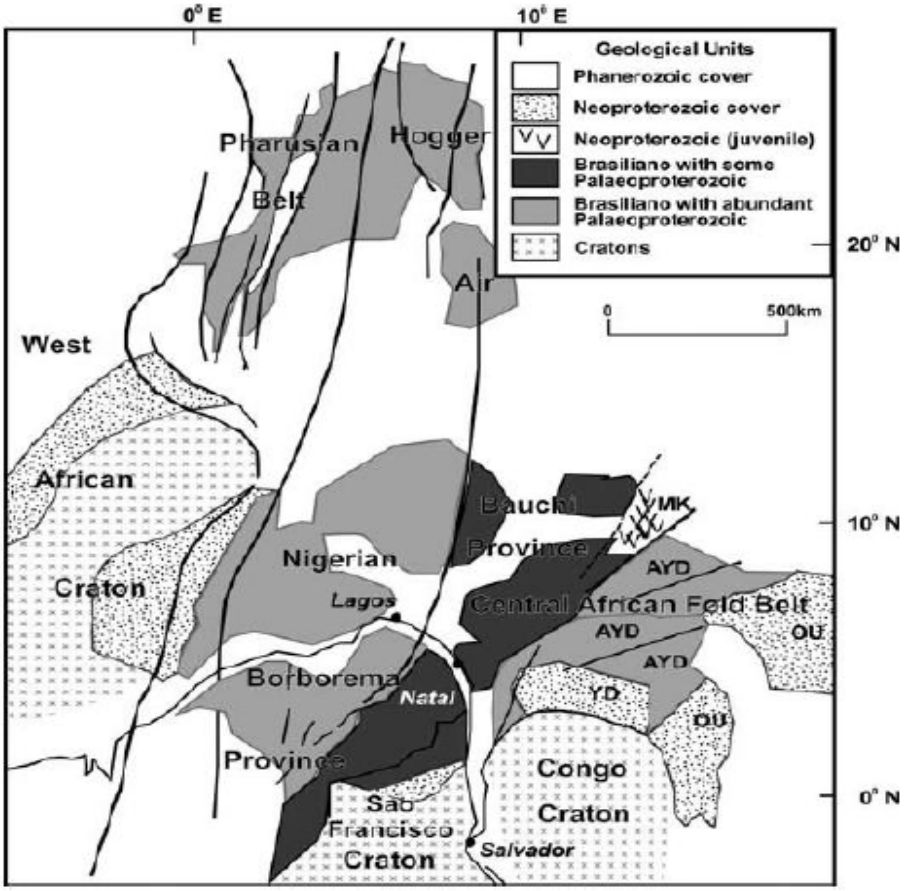


Fig 2.1: Location of the Nigerian basement complex between the West African Craton and Congo Craton in relation to Hoggar and Borborema provinces (adapted from Dada, 2008)

2.2.1 The Migmatite-Gneiss-Quartzite Complex

The migmatite-gneiss-quartzite complex is generally considered as the basement complex "Senso Stricto" (Rahaman, 1988; Dada, 2006). It is a heterogeneous assemblage including migmatized gneisses, banded gneisses and a series of metamorphosed basic and ultrabasic rocks. (Russ, 1957) considered the gneissic complex to represent the oldest member of Precambrian basement in Northwestern Nigeria and that it evolved by successive sedimentation, deformation, metamorphism and igneous intrusion over a vast period of history of the basement. Petrographic evidence indicates that Pan-African reworking led to

recrystallization of many of the constituent minerals of the migmatite-gneiss-quartzite complex during partial melting and most display medium to upper amphibolites facies-metamorphism (Dada, 2008). The gneisses of the migmatite-gneiss-quartzite complex are interwoven with amphibolites that may have been derived from Mg-rich rocks such as continental basalts (Caby *et al.* 1990; Dada, 1999, 2008). (Oyawoye, 1972) noted that the banded gneisses are possibly the oldest rocks in the country, older than granitic 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. It has been difficult to define the protoliths of the banded gneisses (Kröner *et al.* 2001) because of their mixed and complex nature. Some authors suggested that they were metasediments derived from greywacke 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). Gneisses and amphibolites in Nigeria form a bimodal association whose petrological and geochemical characteristics indicate a primary igneous origin (Dada, 1999, 2008). Dada *et al.* (1993) and Bruguier *et al.* (1994) applied modern geochronological methods to unravel the absolute chronology of the migmatite-gneiss-quartzite complex. The migmatite-gneiss-quartzite complex has ages ranging from Pan-African to Eburnean (600-2000 Ma). The migmatite-gneiss-quartzite complex also termed by some workers as – migmatite-

gneiss-granite complex makes up about 60% of the surface area of the Nigerian Basement (Rahaman and Olan, 1978).

The migmatite-gneiss-quartzite complex recorded three (3) major geological events (Rahaman and Lancelot, 1984). The earliest at 200 Ma involved initiation of crust forming processes (for example, the Ibadan grey gneiss of mantle origin) and of crustal growth by sedimentation and orogeny. Next came the Eburnean (2000±200 Ma) marked by the Ibadan type granitic gneisses and was followed by ages ranging from (900 Ma to 450 Ma) represented by the imprint of the Pan-African event which not but only structurally overprinted and reset many geochronological clocks (timing) in the Older rocks, and also gave rise to granitic gneiss, migmatites and other similar lithological units. The paucity of geochronological data is a major problem in understanding the crustal evolution of the migmatite-gneiss-quartzite complex. It is polycyclic but identification of specific events that affected the area has not been possible (Ekwueme, 1990).

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), Eburnian (2000±200 Ma), Kibaran (1100±200 Ma) and Pan-African (600±150 Ma) events (Grant, 1970; Ajibade *et al.* 1987; Dada, 1998). The Liberian and Kibaran events are largely disputed; (Cahen *et al.* 1984) pointed out after assessment of the then available geochronological data (almost exclusively Rb-Sr ages) that the Pan-African Orogeny is an undisputable event that affected the Nigerian Basement. Debate exists whether the Pan-African event was so pervasive that it completely isotopically rehomogenized all older rocks, thereby obliterating all traces of earlier tectono-metamorphic events. (Grant, 1978; Mullan, 1979; Ajibade, 1988; Grant, 1978; Mullan,

1979; Ekwueme, 1987) argued that the Pan-African Orogeny did not overprint all traces of earlier events.

2.2.2 The Schist Belts

The Nigerian Schist Belts forms the supracrustals that comprise of low grade metasediments and metavolcanics-dominated belts trending N-S which are best developed in the western half of Nigeria. The schist belt zone is flanked by migmatite-gneiss-quartzite terrain to the East and West and the same terrain seperates the individual belts within the zone (Turner, 1983; Ajibade *et al.* 1987).

There are thirteen metasedimentary belts in Nigeria, namely: Zungeru-Birnin Gwari, Kushaka, Malumfashi, Kazaure, Wonaka, Maru, Anka, Zuru, Toto, Iseyin-Oyan River, Ife-Ilesha Igara-Kabba-Lokoja belts and Obudu-Oban (Ajibade, 1976; Turner, 1983; Danbatta, 1999, 2008). These schist belts are considered to be Upper Proterozoic supracrustal rocks which have been infolded into the migmatite-gneiss-quartzite complex. The metasediments are poorly represented in the eastern half of the country and this is attributed to the strong migmatization and assimilation effects on the sediments by large volumes of the Pan-African rocks (Ajibade, 1988).

The schist belt occurs predominantly as series of synformal trough and strike ridges intercalated with relic of migmatites and gneisses or intruded granite which separate and/or lie within them. All the schist belts are predominantly composed of metamorphosed pelitic and semi-pelitic rocks, (Ekwueme, 2003); but each belt differs in the amount of such lithologies as conglomerates, greywackes, quartzites, calcareous rocks and volcanic rocks. The lithological variations of the schists include coarse to fine grained clastic, mainly

pelitic to semi pelitic schist, phyllite and Banded Iron Formation (Turner, 1964; Ajibade, 1980). Carbonate rocks (marble/dolomitic marbles) and mafic-metavolcanics (amphibolites) are also prominent members of the schists. (Rahaman, 1976) and (Grant, 1978) suggest that there were several basins of deposition whereas (Oyawoye, 1972) and (McCurry, 1976) considered the schist as relicts of a single supracrustal cover. (Olade and Elueze, 1979) considered the schist to be fault-controlled rift like structures.

There are difficulties in establishing the actual and relative ages of the Nigerian schist belt. They were assigned collectively to the subsurface stage of the Pan-African orogenic cycle by (Wright and McCurry, 1970; Burke and Dewey, 1972; McCurry, 1973, 1976, 1978) among others. More interpretations have pointed to the possibility of more than one generation of schist; (Grant, 1978) used structural and lithological criteria together with isotopic signatures to distinguishing an earlier Kibaran (c. 1100Ma) Kushaka Schist belt from the Pan-African (700-600 Ma) Birnin-Gwari schists to one or other cycle. This hypothesis appears to explain the c.1100Ma isotopic age obtained by (Ogezi, 1977) from phyllites of the Maru belt; (Holt *et al.* 1978) and the Kibaran isotopic over printing of basement gneisses in several regions, (Grant *et al.* 1972).

(Obaje, 2009) and (Ibrahim, 2012) reported that the Maru schist belt is characterized by the dominance of pelitic rocks occurring mainly as phyllites and slates interlaminated with siltstone, banded iron formation containing magnetite, hematite and garnet.

2.2.3 The Older Granites

The Older Granites are believed to be pre-, syn- and post tectonic granitoids which cut both the migmatite-gneiss-quartzite complex and the schist belts. The granitoids include rocks

varying in composition from granite to tonalite and charnockites with smaller bodies of syenite, gabbro and pegmatite (Ajibade *et al.* 1987). The granitoids have yielded radiometric ages in the range of 750-500 Ma which lie within the Pan-African spectrum. They are generally high-level intrusions and anatexis has played an important role (Rahaman, 1988). The Older Granite suite is notable for its general lack of associated mineralization although, the thermal effects may play a role in the mobilization of the mineralizing fluids.

Attempt to classify the Older Granites with respect to timing during an orogenic event are valid over only short distances. Contact features between members of the Older Granite suite suggest the coexistence of several magmas. Granite magmatism is commonly associated with several tectonic settings and various stages during orogenic evolution (Pitcher, 1983; Pearce *et al.* 1984; Chappell *et al.* 1987; Maniar and Piccoli, 1989).

In the Northeastern Nigeria, (Ferré *et al.* 1998) have described hypersthene-bearing monzogranite and quartz-monzogranite rocks of Neoproterozoic age with ferro-potassic transalkaline and metaluminous characteristics which have affinity with within-plate or post collisional stage of the Pan-African orogeny. In Southeastern 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 THE PEGMATITES OF NIGERIA

The term “pegmatite” follows the definition set by (London, 2008)‘an essentially igneous rock commonly of granitic composition that is distinguished from other igneous rocks by its extreme coarse but variable grain size’. Pegmatites represent highly evolved granitic

melts that result from fractional crystallization and are of several interests as they display complex and diverse mineralogy, textures, structures and petrogenetic relationships with evolved geochemical signatures which have challenged petrologists in terms of origin and process of formation. Initially, it was assumed that the coarse textures seen in pegmatites were the result of a relatively stable, extreme long and slow cooling process in the same manner that large crystals typically form in igneous rocks. However, this assumption could not explain all of the textures seen, such as the graphic intergrowth of quartz and feldspar commonly known as graphic granite or the formation of fine grained layers and related dykes called aplites, all of which can be present within the same pegmatite (Fenn, 1986; Rockhold *et al.* 1987; London, 2008); to explain all of these textures, a new explanation was created starting with fractional crystallization and involving rapid crystallization from volatile-enriched magma and strong undercooling (Thomas *et al.* 2012).

Pegmatites originate from residual magmas derived by partial melting of crustal rocks or as products of the final stages of igneous crystallization. Crystallization of such magmas rich in volatiles and rare elements gives rise to the distinctive mineral content and textural features of pegmatites. Gem bearing pegmatites are most likely to be found in geologic environments where the pegmatite magmas crystallized at shallow crustal depths because the less dense aqueous fluid phase required for pocket formation is only able to exsolve from the magma under lower confining pressures. Although Pegmatites are relatively common, only a small percentage contain rare elements and of those even fewer contain the rare elements required for gemstone mineralization because physical and chemical conditions in these instances seem to preclude the formation of gem crystals (Shigley and Kampf, 1984).

Nigeria has a very large pegmatite environment; the pegmatites are widely distributed with a marked concentration of mineralized pegmatite in a broad belt. Thousands of pegmatites occur which have never been mapped or sampled in a systematic and scientific manner (Akintola and Adekeye, 2008). Pegmatites are widespread throughout the basement complex of Nigeria. The study of pegmatite belts has globally increased because of its attractive economic potential; they are known to host economically important mineral deposits such as gemstones and rare metals. By far, the most important zones for mineral production are Mesozoic pegmatites closely associated with Younger Granite magmatism (Abaa, 1991).

In the past, the search for mineralized pegmatites in Nigeria was concentrated within the NE-SW regions (Jacobson and Webb, 1946). However, recent studies of (Küster, 1990), (Okunlola and Ocan, 2002), (Garba, 2002, 2003), (Okunlola and Ogedengbe, 2003), (Okunlola and King, 2003), (Okunlola, 2005), (Okunlola and Jimba, 2006), (Adekeye and Adedoyin, 2007), (Adekeye and Akintola, 2007), (Ero and Ekwueme, 2009), (Adetunji and Ocan, 2010), (Abdullahi, 2013), (Borisade *et al.* 2013), (Omada *et al.* 2015), (Adetunji *et al.* 2016), (Olatunji and Jimoh, 2016), (Abdullahi *et al.* 2017) have contributed to the better understanding of Southwestern and Northern Nigeria pegmatite bodies.

The resurgent interest into the study of Nigerian Pegmatites led to the concentration of its study on discrimination into rare metal mineralized and barren ones in order to elucidate modes and features of mineralization (Matheis, 1981; Matheis *et al.* 1982; Küster, 1990; Garba, 2003). (Okunlola, 2005) classified the metallogeny of the rare metal Ta-Nb pegmatites of Nigeria, outlining seven broad fields namely: Kabba-Isanlu, Ijero-Aramoko, Keffi-Nasarawa, Lema-Ndeji, Oke Ogun, Ibadan-Osogbo and Kushaka- Birnin-Gwari; He

also present geochemical evidence which shows 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) pegmatites of Buck, Oasis, and Noumas pegmatites in U.S.A. The presence of pegmatites in northern part of Mandara Hills, parts of the Oban-Obudu-Mandara-Gwoza complex of eastern part of Nigeria has been reported by (Islam and Baba, 1989) and (Girei, 2015).

(Garba, 2003) mapped mineralized pegmatites enriched in columbite-tantalite minerals from the basement complex of Northern Nigeria. (Olugbenga *et al.* 2010) documented the moderately high Ta, Nb, Sn, Rb, Li and Cs in Precambrian pegmatite in Komu area of Southwestern Nigeria. (Okunlola and Akintola, 2010) investigated the Precambrian pegmatite of Oke-Asa area of Ijero Ekiti and revealed that this pegmatite is variably enriched in rare metals such as tantalum, niobium, lithium, rubidium and strontium. (Akintola *et al.* 2011) revealed Precambrian pegmatites with moderate to high Ta-Nb mineralization in the Awo area of Southwestern Nigeria. (Agunleti *et al.* 2014) worked on the Precambrian pegmatites exposed at Angwan-rimi area of Northcentral Nigeria and concluded that the deposit holds high potential for tantalum mineralization. (Okunlola and Oyedokun, 2009) observed that the pegmatite of the Igbeti area of Southwestern Nigeria display Ta-Nb mineralization potential. (Ero and Ekwueme, 2009) reported mineralization of pegmatite in parts of the Oban Massif area of Southeastern Nigeria.

Most of the world beryl occurs in zoned granitic pegmatites, as homogeneous pegmatites have yielded little beryl (Simmons, 2007). The northeastern portion of the State of Minas Gerais, Brazil, contains the world's greatest concentration of complex granitic pegmatites which are especially noted for the production of gem beryl, chrysoberyl, topaz, tourmaline

and kunzite. Virtually, all varieties of gem beryl are found in Minas Gerais and all except emerald are of pegmatitc origin; most comprehensive overviews of this deposit are found in (Sinkankas, 1981) and (Proctor 1984 and 1988). Investigation into the mineral chemistry of beryl had been conducted on a number of localities worldwide including: Argentina (Sardi and Heimann, 2014), Brazil (Viana *et al.* 2002), Canada (Mihalynuk and Lett, 2003; Adamo *et al.* 2008; Beal and Lentz, 2010; Groat *et al.* 2010, China (Wang *et al.* 2009); Czech Republic (Novák *et al.* 2011; Přikryl *et al.* 2014); Italy (Aurisicchio *et al.* 1988; Bocchio *et al.* 2009); Mozambique (Aurisicchio *et al.* 1988; Neiva and Neiva, 2005); Nigeria (Schwarz *et al.* 1996; Gbadebo *et al.* 2013;); Pakistan (Aurisicchio *et al.* 1988); Slovakia (Uher *et al.* 2010); Vietnam (Huong *et al.* 2011; Fridrichová *et al.* 2015); Zimbabwe (Aurisicchio *et al.* 1988; Černý *et al.* 2003) and Namibia (Boudreaux, 2014; Lum *et al.* 2016).

2.4 TECTONIC AND LITHOLOGICAL CONTROLS OF NIGERIAN PEGMATITE

The end of the Pan-African tectonic event is marked by a conjugate fracture system of the strike-slip fault (Ball, 1980). Fault directions have consistent trends and sense of movement, that is, a NE-SW trending system having a dextral sense of movement and a NW-SE (McCurry, 1971; Wright, 1976; Holt *et al.* 1978; Ball, 1980). Both sets crosscut all the main Pan-African structures including older N-S trending shear zones (mylonites) and late orogenic granites (Ball, 1980; Ajibade and Wright, 1989; Küster, 1990; Garba, 1992).

(Oden, 2012) reported that the strongest pegmatite vein orientation in the granitic pegmatites of Uyanga-Akwa Ibami area of western Oban Massif have strongest orientation in the NNW-SSE, followed by ENE-WSW. Less prominent sets trend in the NNE-SSW and NW-SE directions, these veins preferentially emplaced mainly pre-existing

discontinuities like fractures, joints, faults and foliations. (Okunlola and Ocan, 2009) reported that the rare metal bearing pegmatites around Keffi area, central Nigeria occur in two structural forms: vertically dipping and low-lying pegmatites. (Akintola *et al.* 2012) also reported that the pegmatites of Apomu area, Southwestern Nigeria occur as near vertical dykes and strike mainly in the NNW-SSE direction. (Opara and Emberga, 2015) reported the trend analysis of the lineaments revealed from a structural trend interpretation of the Jos-BukuruYounger Granite ring complex in the NW-SE, NE-SW, N-S and E-W directions with the NW-SE and NE-SW been the dominant trends in the area.

(Küster, 1990) has shown that in Wamba area, Northcentral Nigeria, the emplacement of late Pan-African granites with similar geochemical characteristics with mineralized pegmatite was fracture-controlled and mylonitized along a conjugate set of NE-SW and NW-SE to NNW-SSE striking faults. However, (Akintola and Adekeye, 2008) concluded that the NE-SW and NNE-SSW regional fracture controlling the mineralization of the rare metal pegmatites of Nasarawa area of Central Nigeria are deep seated. (Truswell and Cope, 1963) reported that the rocks in Kushaka schist belt lie in a number of isoclinal fold structures trending NNE which gives rise to a strong foliation parallel to the axial planes of the folds. 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. (Abdulhamid, 2017) reported that mineralized pegmatite in Badafi (extension of the study area) strikes NNW-SSE and NE-SW directions.

(Garba, 2002) and (Okunlola, 2005) noted that rich concentrate of rare-metal bearing 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 have

southern extention up to the Okene-Ogun areas in the southwest. Deformational episodes producing tight to isoclinal folds mainly controlled the mineralized pegmatites in most of the rare-pegmatite fields in Nigeria and these isoclinal folds are linked also to major transcurrent faults (Garba, 2002).

Generally, the fractures in the Nigerian basement complex and associated areas are oriented in four principal directions: E-W, N-S, NE-SW and NW-SE. The N-S fractures are very prominent and are often conformable with other geological trends. The dominant orientation of foliation in the basement rocks is the N-S to NE-SW trends thereby indicating the relevance of the Pan-African orogeny in the evolutionary history of the area. The ancient lineament systems of the Nigerian basement complex are known for controlling the distribution of rare-metal and barren pegmatite with the intersections hosting the richest pegmatites (Okunlola, 2005).

2.5 PREVIOUS WORK OF THE STUDY AREA

The earliest work on the pegmatites in the area was by (Garba, 2002) who reported the occurrence of rare metal pegmatites in Nasarawa and Richifa in central Nigeria and Kushaka, Magami and Maradun in the Northwestern Nigeria; he concluded that the rare metal pegmatites are enriched to varying degrees in the ores of Li, Be, Sn, Nb, Ta, W, B and probably Ce; while some of the rare metal mineralized fields occur in proximity to areas previously known for hydrothermal gold mineralization. Other work conducted in the area was the geological mapping of the basement rocks of the area on a scale of 1:25,000 by some final year undergraduate students of Ahmadu Bello University, Zaria.(Garba, 2003) reported that widespread occurrences of semi precious beryl, aquamarine and tourmaline are known from many areas of the Nigerian Pan-African basement associated

with both rare metal and barren pegmatites. (Abdulhamid, 2017) reported that mineralized pegmatite in Badafi (extension of the study area) are enriched in beryl. A genetic model for the Nigerian gemstones that are associated with Mesozoic alkali granite ring complexes subjected to autometasomatic alteration has been proposed by (Abaa, 1991) and (Schwarz *et al.* 1996). The Nigerian gems are of particular type of pegmatite-related deposits formed by the alkaline alteration of granites (Giuliani *et al.* 1997). Data on fluid inclusions hosted in emeralds of central Nigeria and some conclusions on their trapping conditions were reported (Kinnaird *et al.* 1985; Schwarz *et al.* 1996; Vapnik and Moroz, 2000). To the best knowledge of the writer, the only available geochemical study of pegmatitic beryl from Nigeria is that of (Gbadebo *et al.* 2013), who used both geophysical and geochemical exploration method to determine the compositional trends of specks of beryl hosted within the basement complex rocks of Iwajowa area, Southwestern Nigeria.

The review and description of the basement complex of Nigeria was carried out by several workers including (Jacobson and Webb, 1946; Fargher, 1961; Wright, 1970; McCurry, 1970, 1976; Grant, 1971; Oyawoye, 1972; Rahaman, 1976; Matheis, 1979, 1981; Ajibade, 1982; Matheis and Caen-Vachette, 1983; Kinnaird, 1984; Bowden and Kinnaird, 1984; Küster, 1990; Ekwueme and Matheis, 1995; Garba, 2002, 2003; Okunlola, 2005; Adekeye and Akintola, 2007; Akintola and Adekeye, 2008; Okunlola and Oyedokun, 2009; Ekwueme and Kalsbeek, 2014; Omada *et al.* 2015).

The primary mineralization of tantalum, niobium, tin, beryllium and lithium is hosted in quartz-feldspar-muscovite pegmatites of Nigeria (Kinnaird, 1984).

Alkali elements, Fe-Mg behavior and compositions of certain individual elements as well as the relationships among elements in beryl can be indicators of fractionation and evolution of the pegmatites (Černý, 1975; Černý *et al*. 2003; Neiva and Neiva, 2005; Sardi and Heimann, 2014; Lum *et al.* 2016).

The alkali elements Li, Cs, Na and the ferromagnesian elements Fe and Mg are especially useful indicators of evolution (Černý, 1975, 2002; Aurisicchio *et al.* 1988; Černý *et al.* 2003; Neiva and Neiva, 2005; Sardi and Heimann, 2014; Lum *et al.* 2016). Early studies show that during fractionation, early beryl and the core of individual crystals tend to be enriched in ferromagnesian elements and depleted in alkali elements compared with late beryl and rims of individual crystals (Trueman and Černý, 1982; Černý, 2002; Neiva and Neiva, 2005; Wang *et al.* 2009; Aurisicchio *et al.* 2012; Sardi and Heimann, 2014).

The value of Fe+Mg alone is not the best indicator of relative evolution but combined with Li, Na/Li, Na, Cs and Li+Cs, they show the evolution from least to evolved (Sardi and Heimann, 2014). Processes that can decrease or increase the parameters Fe+Mg and Li+Cs include: melt fractionation, crystallization of other mineral phases that host these elements and reactions with host rocks during evolution (Uher *et al.* 2010; Aurisicchio *et al.* 2012).

The relationship between Rb and Ti has been used in previous studies to understand the relative fractionation of some pegmatite minerals because Ti seems to follow the same order of preference as Rb (Černý *et al.* 1985). For Tanko pegmatite, the concentration of Rb and Ti in beryl increase from early to late beryl and Rb/Ti slightly decreases with increasing Cs content (Černý and Simpson, 1977; Černý *et al.* 1985). Rubidium due to its

hygromagmaphile character can be used to understand the degree of evolution of pegmatite (Raimbault *et al.* 1987).

Some studies have analyzed the Ga content of beryl and found high concentration, for example, the Sebago pegmatite, Maine with upto 79ppm Ga (Wise and Brown, 2010). However, the relationship between Al/Ga and Ga is not a useful indicator of relative evolution of beryl varieties within and among the velasco pegmatites (Sardi and Heimann, 2014).

The chemical behavior of the Rare Earth Elements (REEs) provides a range of geochemical indicators that can be used to constrain the evolution of magmatic and hydrothermal systems (Neiva and Neiva, 2005).

The mineralogical indicators for the degrees of pegmatite evolution have been identified. They are the K/Rb and K/Cs values and the Li, Rb, Cs, F and Ba contents of muscovite (Černý *et al.* 1985; Viana *et al.* 2007; Vieira *et al.* 2011; Neiva, 2013). The K/Rb value and the Rb and Cs contents of K-feldspar (Alfonso *et al.* 2003; Černý, 2005; Oyarzábal *et al.* 2009; Neiva, 2013). The Rb/Ti, Na/Li, Na/Cs, Cs/Naand Mg/Fe ratios of beryl (Černý *et al.* 1985; Černý, 2002; Neiva and Neiva, 2005; Gavrilenko *et al.* 2006; Uher *et al.* 2010; Lum *et al.* 2016) and the Ta/(Nb+Ta) ratio and/versus Mn/Mn+Fe ratio of the columbite-tantalite group (Tindle, 1998; Tindle' and Breaks, 1998, 2000; Neiva, 2013). Moreover, minerals such as mica, K-feldspar, tourmaline, beryl, spodumene, and others have been considered as monitors of the evolutionary history of pegmatites (Henry *et al.*2002; Roda-Robles *et al.* 2007; Muller *et al.* 2012; Yin *et al.* 2013).

Based on a compilation from various studies, (Černý, 2002) determined that pure beryl is colourless, emerald (transparent green beryl) colour is due to the presence of Cr and/or V at the octahedral site, yellow beryl is due to Fe^{2+} in the channels and different proportions of Fe^{2+}/Fe^{3+}corresponds to green, yellow or blue varieties. In our study, we have not measured the relative amounts of Fe^{2+} and Fe^{3+}, we only considered the elements that show significant concentration differences among beryl types.

CHAPTER THREE

3.0 RESEARCH METHODOLOGY

3.1 INTRODUCTION

The method adopted for this research work includes: 1). A desk study, where relevant reports were consulted. 2). Systematic geological mapping of the area using a base map extracted from the topographic map sheet of Ikara NW and SW on a scale of 1:50,000. 3). Landsat (ETM+) of the study area were processed and integrated with detailed geological and structural mapping to delineate lithological boundaries, drainage and structural lineaments. 4). Petrographic analysis of the rocks was also carried out, followed by geochemical analysis of rock and mineral samples and finally, interpretation of the data obtained using computer packages.

3.2 DESK STUDY

Detailed research into previous work done in Northwestern Nigeria and Nigeria as a whole was carried out. In this regard relevant materials like journals, textbooks, published and unpublished works were consulted. This enhanced the understanding of beryl mineralization in the area and in general.

3.3 REMOTE SENSING TECHNIQUE

Remote sensing analysis of the study area was carriedout using Landsat Enhanced Thematic MapperPlus (ETM+). Six bands (1,2,3,4,5 and 7) were downloaded from global land cover facility website of the University of Maryland (http:

//glcfapp.glc.umd.edu/data1). Image processing was carriedout using Envi software. Image processing technique employed includes colour composite, band rationg and lineament analysis. The spectral capabilities of the ETM+ bands were used to determine the best discrimination of the lithologic units. Remote sensing techniques were used basically for lithological mapping and lineament analysis.

3.4 FIELD METHODS

Reconnaissance geological investigation into the area of study was carried out for five days to get insight on the rock types. Detailed geological field mapping was undertaken in order to collect, identify and study the field occurrences cum structural relationship of all the rock types present. The study involved systematic geological mapping initially on a scale of 1:50,000 to establish the lithological relationships of the rock units. Landsat ETM+ covering the investigated area was digitally processed for lithological mapping. Field data measurement involved measuring strike and dip direction with compass clinometer; taking co-ordinates of every sample point and location using Global Positioning System (GPS). Particular attention was paid to the location, mineralogy and physical characteristics of the pegmatite veins and dykes. For each vein and dyke, the structural attitude, length and width, as well as the coordinates were carefully measured. Dimensions of pegmatite veins and dykes were measured with the aid of a measuring tape and traversing. The study of the pegmatite was preceded by a careful study of lineaments. Other structural imprints like joint trends, foliation trends and the trend and dip of rocks were measured. Fractures (joints) were mapped by observing areas in outcrops with no relative movement of the rocks along the fracture plane. Representative rock samples were collected from the rock exposures with the aid of a geological hammer and were assigned numbers; thereafter,

outcrops were observed and described in order to determine their textural and structural characteristics. A careful observation of lithological boundaries was made by observing changes in rock exposures, nature of soil, vegetation and topography. Representative samples of beryl derived from the intermediate zone of the pegmatite were selected from active artisanal mines.

3.5 STRUCTURAL ANALYSIS

Structural studies were carried out to better understand the possible structural controls on formation of the pegmatites and how this links to mineralization. At the initial stage, a careful interpretation of lineaments was conducted and subsequently fracture analysis of the basement rocks as well as the trends of the pegmatites was measured.

3.6 LABORATORY METHODS

3.6.1 Sample Preparation

A total of seventeen samples comprising twelve beryl samples and five rock samples were prepared and sent to the Earth Laboratory, School of Geosciences of the University of Witswatersrand, South Africa.

The samples were prepared in the Earth Laboratory, School of Geosciences of the University of Witswatersrand, South Africa in a clean laboratory which has special HEPA (High Efficiency Particulate Air) filters along with panel and bag filters that remove all airborne contaminants.

3.6.2 Petrographic Analysis

Petrographic preparation of rock slides was carriedout at thin section Laboratory of the Department of Geology, Ahmadu Bello University, Zariawith special emphasis on

identifying the minerals present and micro structural elements that may be present. Four rock samples (Granites and Gneisses) were used for thin section preparation according to the method by (Rowland, 1953). The thin sections were examined using a transmitted light microscope under Plane Polarized Light (PPL) and Cross Polarized Light (XPL) with the aid of a transmitted light microscope. Hence, the study of optical properties of mineral components of the rock was enhanced and photomicrographs of the thin sections produced.

3.6.3 Geochemical Analysis

Twelve samples of beryl and five rock samples were analyzed for major, trace and rare earth elements at Earth Laboratory, School of Geosciences of the University of Witswatersrand, South Africa in which major elements were analyzed with XRF and trace elements with ICP-MS. Major element oxides were done with fused disk method using Li-tetraborate flux while trace elements were done with pressed pellet method for the XRF analysis using the instrument called Axios Max; detailed procedures were described by (Bušatlić *et al.* 2009).

The sample prepared is diluted with an internal standard and introduced into the ICP-MS through a nebulizer where it mixes with argon gas. It then passes through the plasma which is at 75°C. The elements in the sample are ionized by the plasma and become positively charged by losing its loosely bound electrons. These positively charged ions then move into the quadrupole where they are sorted based on their mass to charge ratio. They then move to a detector which receives the ion signal which is proportional to the concentration. The concentration of the sample can be determined through calibration with certified reference material such as single or multi-element reference standards.

3.7 DATA HANDLING AND PRESENTATION OF RESULTS

Data derived from fieldwork and laboratory analysis were subjected to statistical analysis using geo-analytical computer softwares namely: Rose Net, Surfer, Petrograph and Geochemical Data Tool Kit (GCDKit). The results obtained were presented as tables, figures, plates and interpreted based on geological knowledge.

The chemical composition of the rocks were used to determine their geochemical signatures while variation in the concentration of major, minor and rare earth elements in the beryl were used to establish the geochemical evolution and the degree of fractionation of the pegmatite in line with the works of Neiva and Neiva (2005) and Sardi and Heimann (2014).

CHAPTER FOUR

4.0 RESULTS AND INTERPRETATION

4.1 REMOTE SENSING ANALYSIS

Remote sensing technique has proved to be of immense value in mapping and monitoring various earth surface features and resources such as minerals, rocks and water; details of broad spectrum applications for these resources can be found elsewhere (Colwell, 1983). Moreover, remote sensing has been used in geology for lithological discrimination of different rock types and delineation of geological and structural features. This study equally employs these features to characterize the structures in the study area. These structures include fractures (faults and joints) and pegmatite dykes. Measurement of the trend of these parameters were taken from the field and documented.

4.1.1 Lithological and Structural Mapping of the Area

The colour composite images (Figs 4.1 and 4.2) have been constructed by combinations of the ETM+ bands 741 and Bands 754 in red, green and blue respectively; while the ETM+ band ratios (1/3, 5/7, 3/5) and (5/1, 5/7, 4/1) in red, green and blue were also helpful in outlining and discriminating the lithologic units of the investigated area (Figs 4.3 and 4.4).

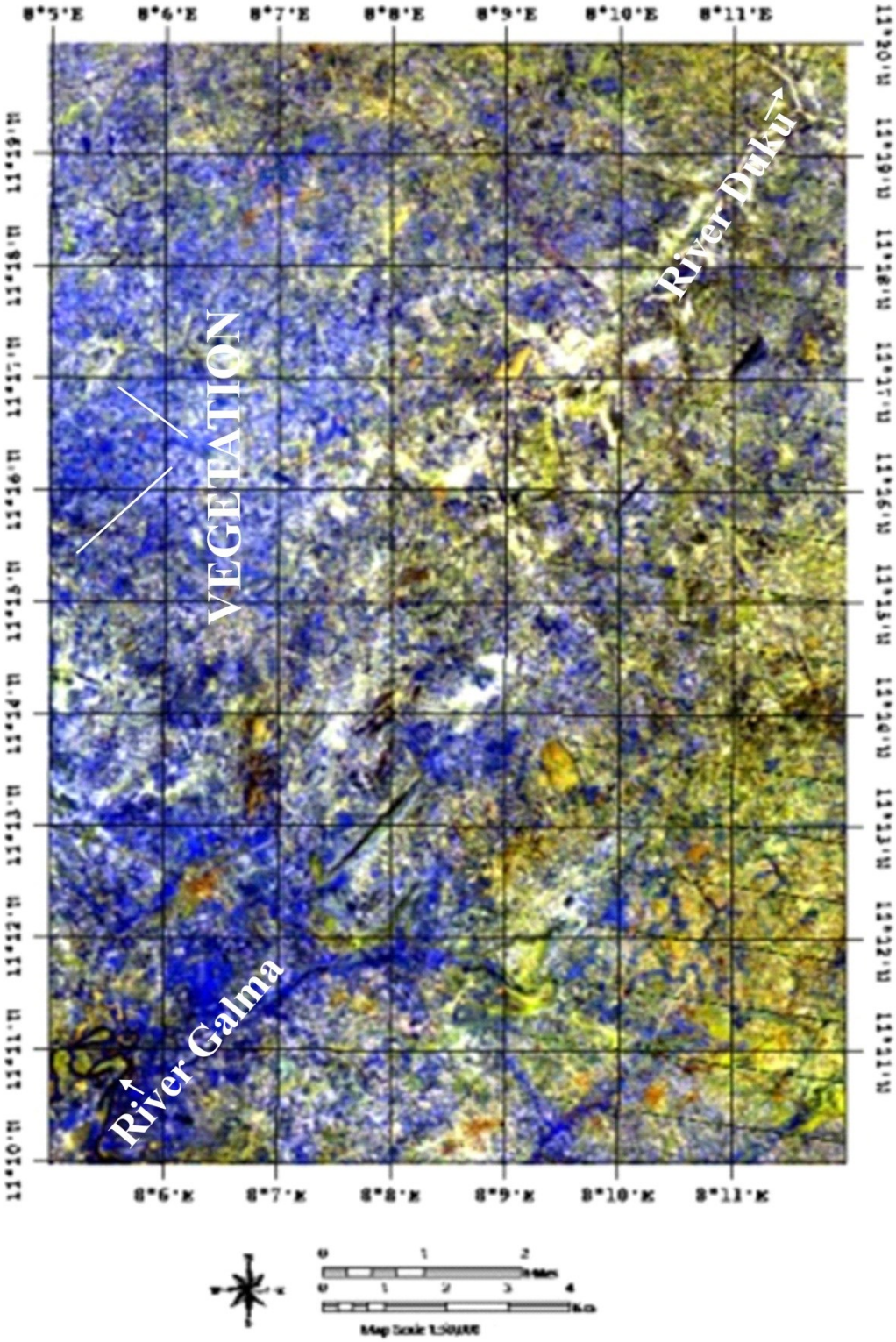


Fig 4.1: ETM+colour composites of the study area Bands 754-RGB showing the geomorphology of the study area.

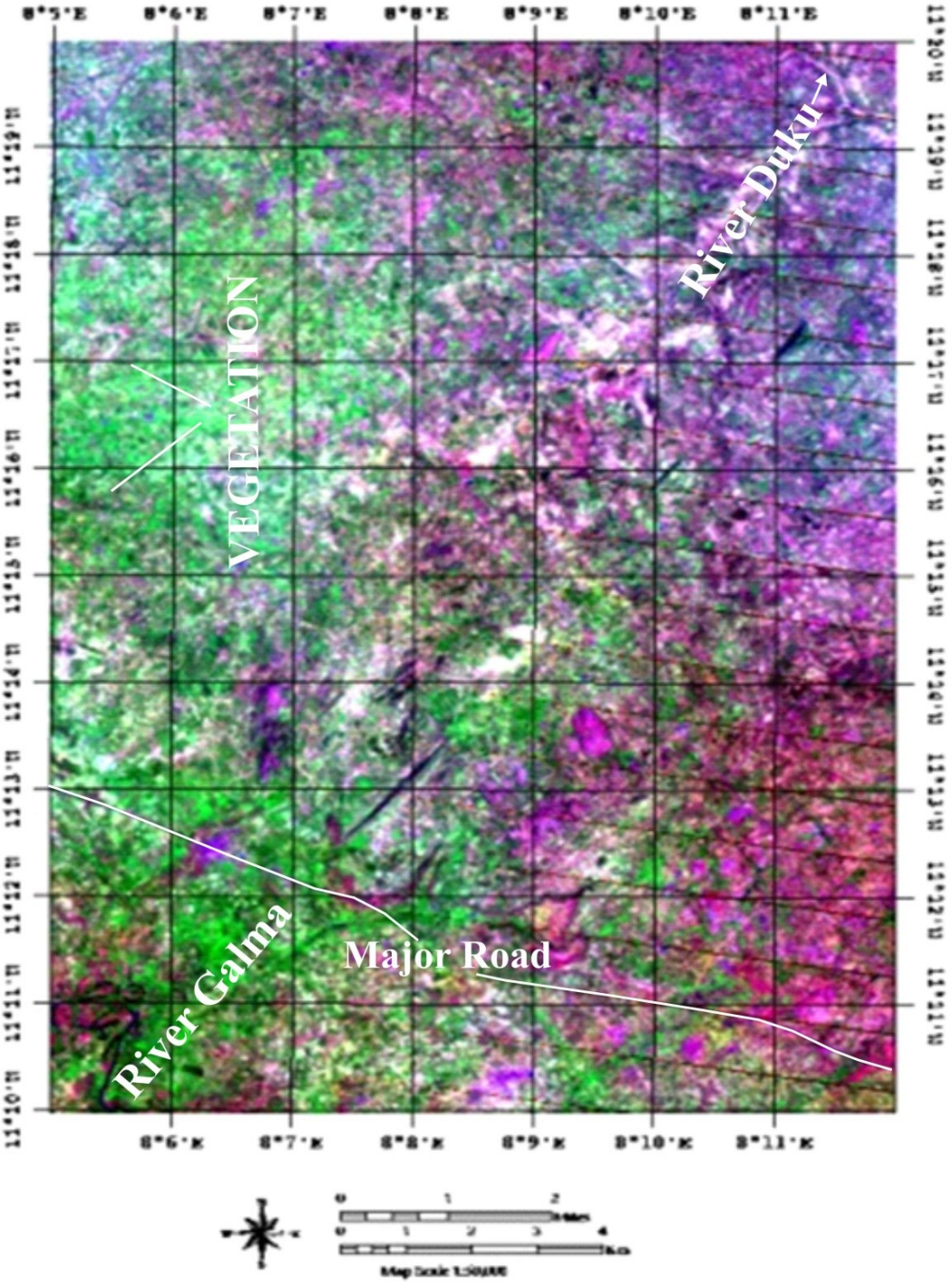


Fig. 4.2: ETM+colour composites of the study area Bands741-RGB showing the geomorphology of the study area (Further identifies drainage patterns and major roads).

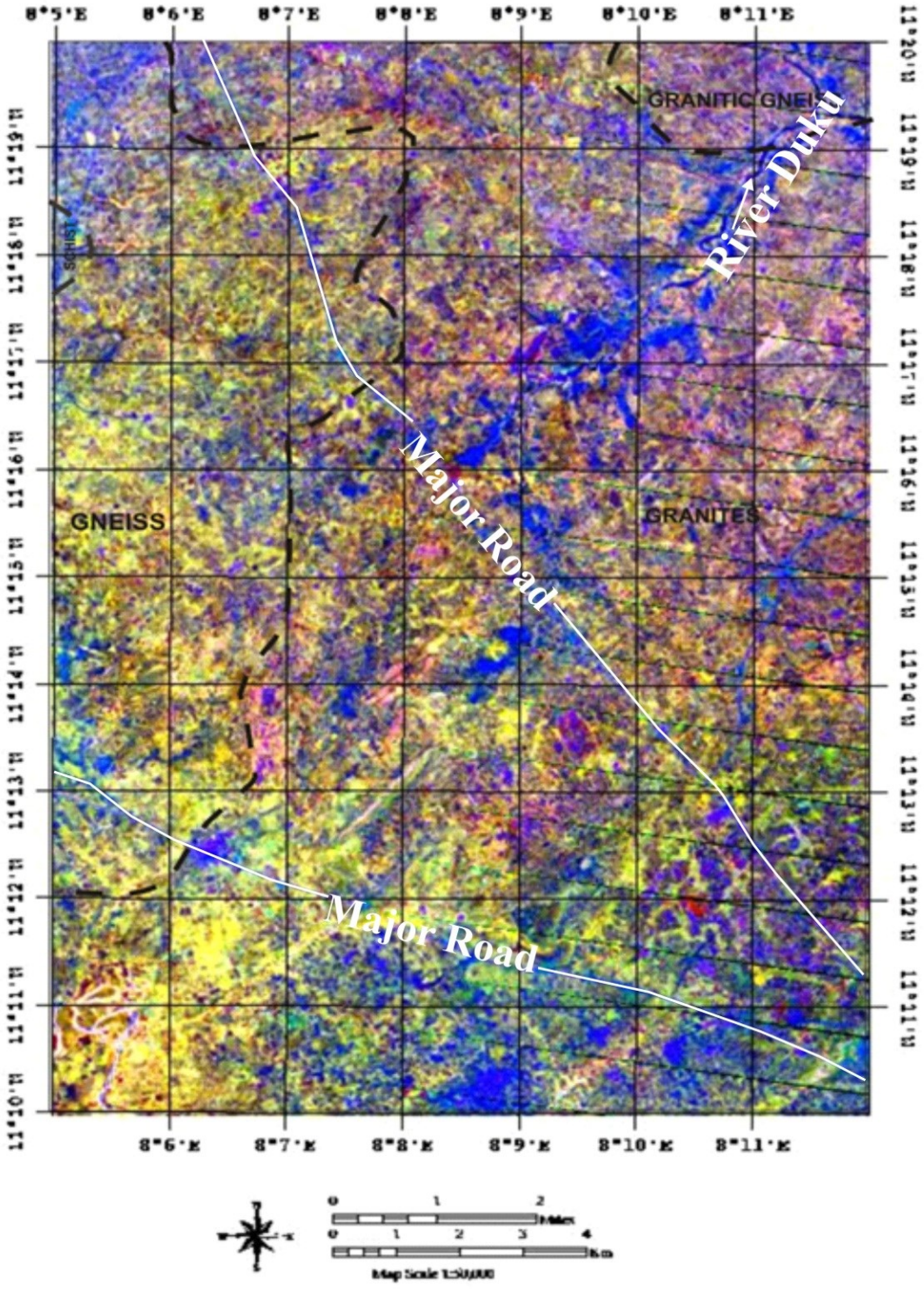


Fig. 4.3: Colour composite ratio image of ETM+ Bands1/3 5/7 3/5-RGB showing lithological discrimination of the study area.

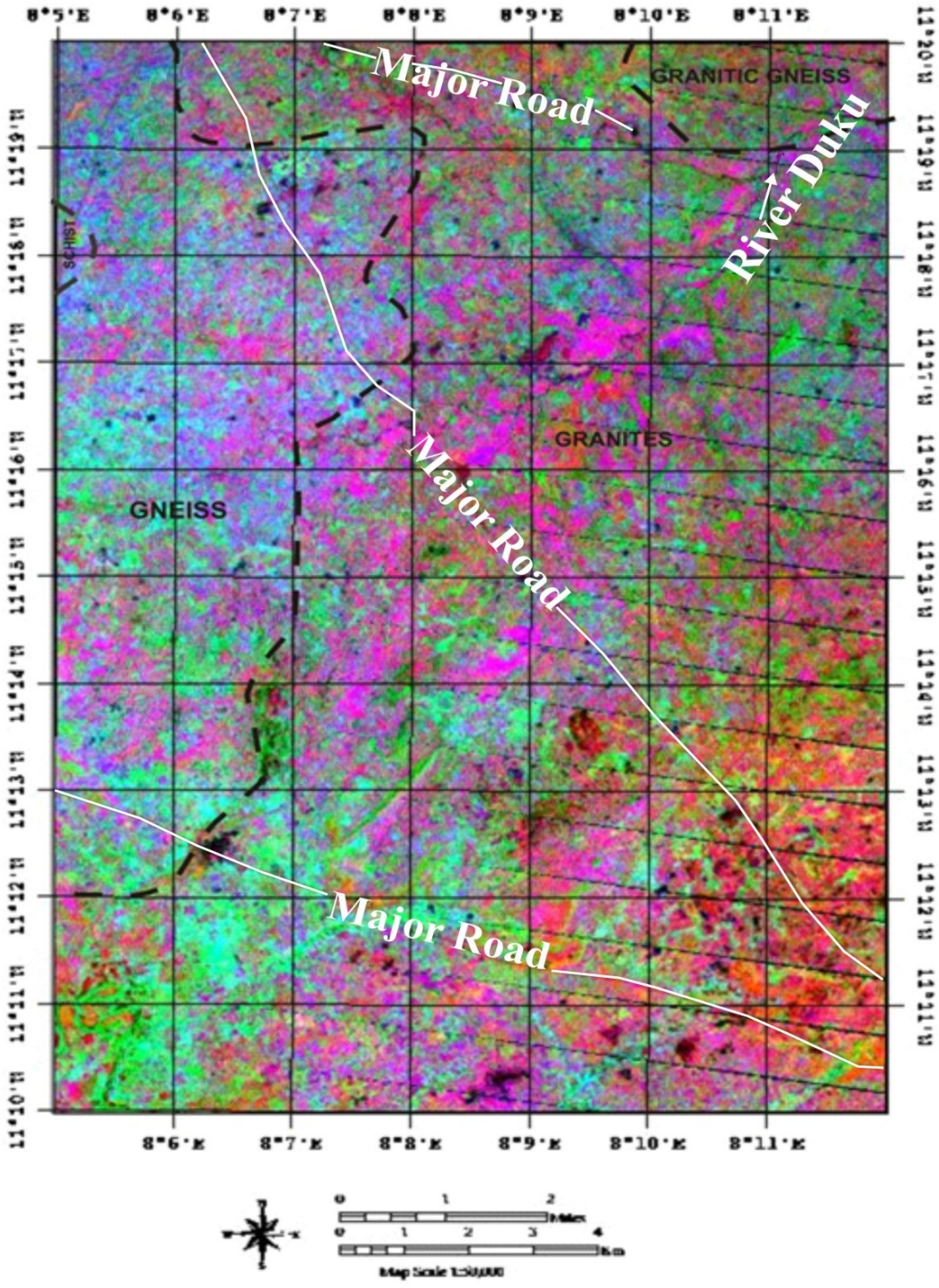


Fig. 4.4: Colour composite ratio image of ETM+ Bands 5/1 5/7 4/1-RGB showing lithological discrimination of the study area.

Lineaments for the study area were extracted using manual digitizing technique from the landsat ETM+ imagery (Fig 4.5) and their dominant direction determined through rose diagram (Fig 4.6).

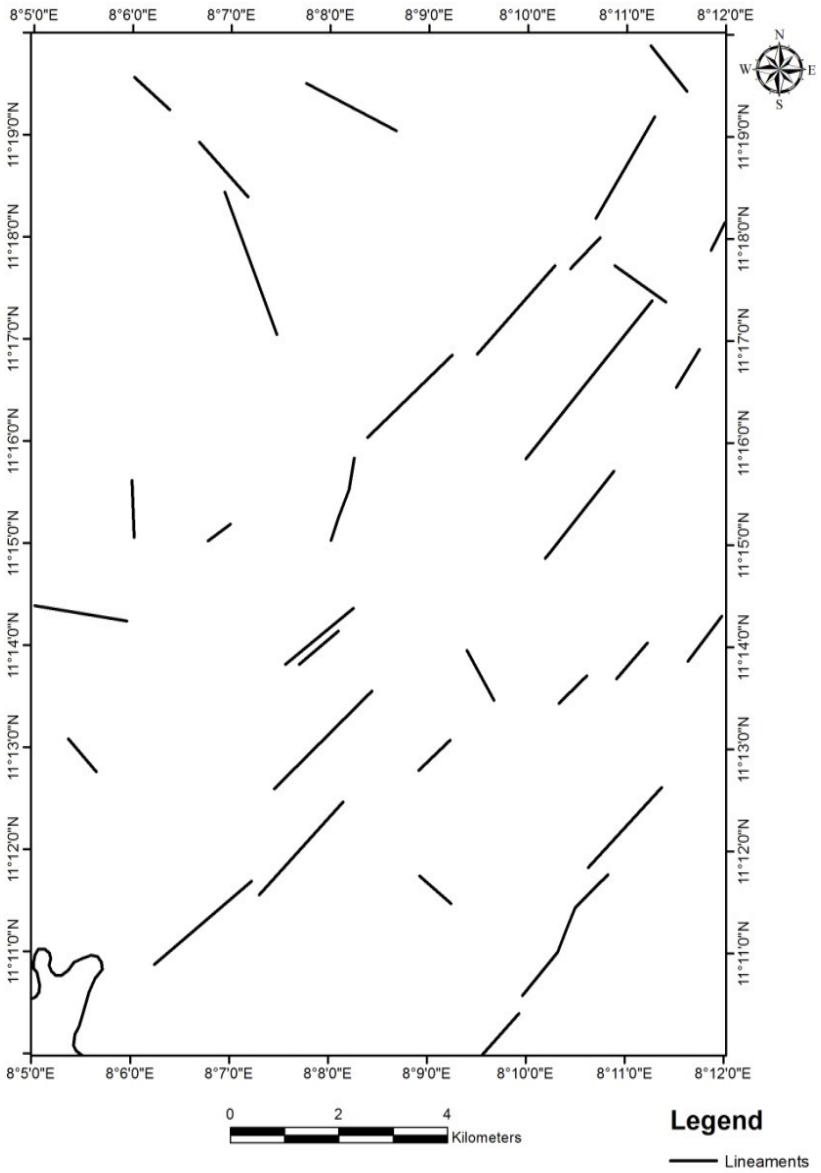


Fig 4.5: Lineament map showing the trends of the lineaments in the study areawith dorminant NE-SW direction.

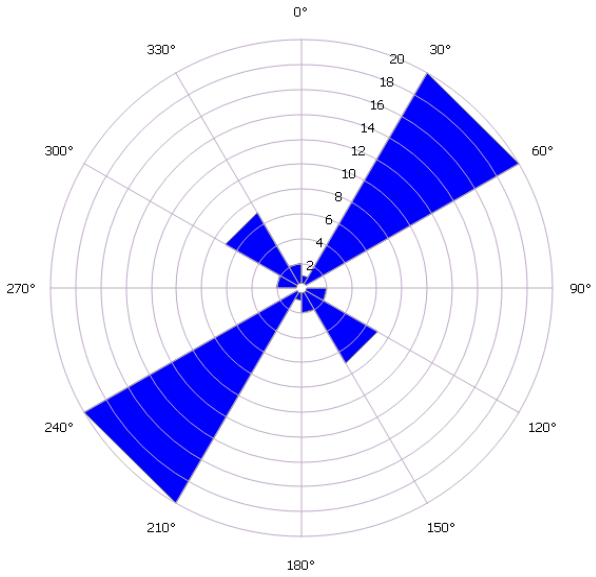


Fig 4.6: Rose plot showing the trends of the lineaments in the study area

These lineaments show a major NE-SW and a minor NW-SE trend with very few of the lineaments intersecting each other. Many of the lineaments mapped on the landsat imagery examined on the ground consisted in part of linear segments of drainage (Fig. 4.7).

The resulting lineament map shows that the strike of economically important structuresis parallel and controlled by NE-SW trending lineaments in the study area. The rose diagram shows the directional frequency of the mapped lineaments over the study area.

Lithological controls for mineralization were also recognized with mineralization common by association with the granites (Fig. 4.8, page 41). The geological map of the study area was produced based on field data and the images produced from the landsat ETM+.

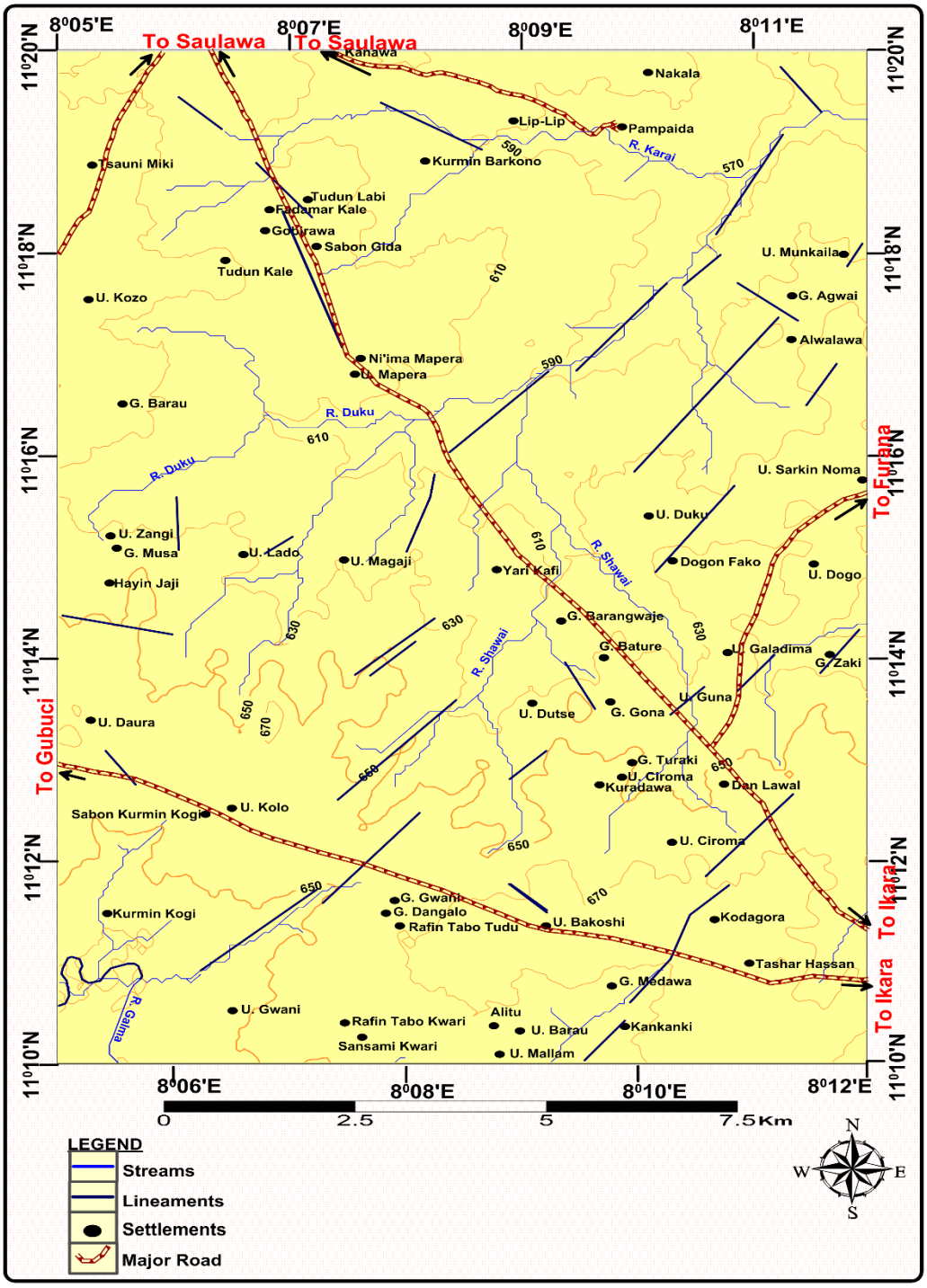


Fig. 4.7: Lineament map superimposed on drainage map of the study area showing the relation of lineaments with drainage pattern.

4.2 FIELD GEOLOGY AND PETROGRAPHY

4.2.1 Introduction

The major rock types in the area are granites, gneisses, quartzites and mica schists (Fig. 4.8). Minor lithologies include: pegmatites, aplites and quartz veins. The southern part of the study area has no visible outcrops except along River Galma channel.

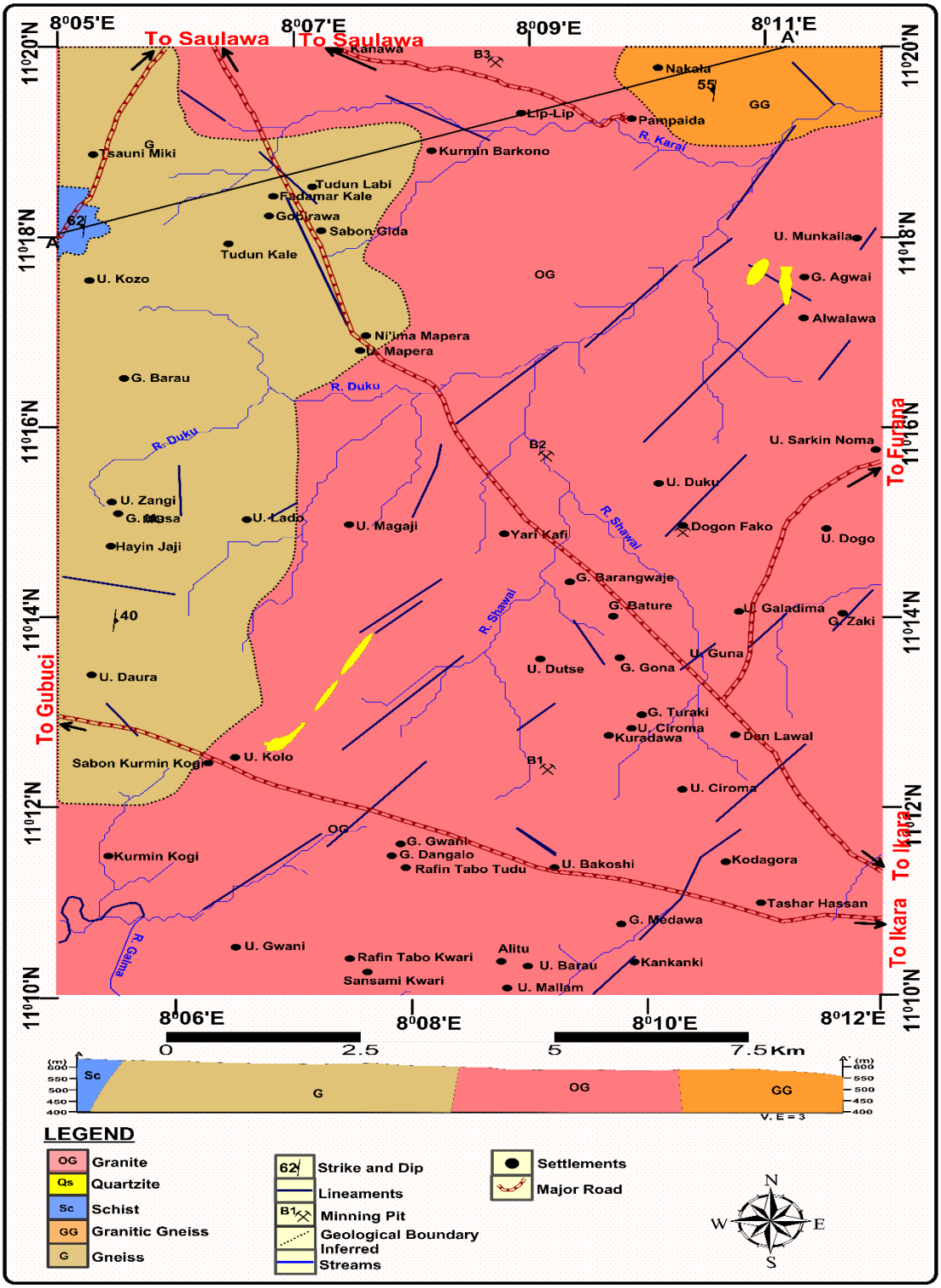


Fig. 4.8: Geological map of parts of Ikara area.

4.2.2 GNEISS

4.2.2.1 Field Relationship

The gneisses occur as lowlying to moderately rising outcrops of N-S trending units and are marked by the development of foliations. The gneisses occupy the western portion of the study area. They are highly foliated with dark bands of hornblende and biotite while the light bands are made up of quartz and feldspar.

Three varieties of gneiss are observed in the study area on the basis of texture, structure and mineralogy; sheared gneiss, banded gneiss and granitic gneiss. The sheared gneiss occurs as low-lying outcrops around Unguwan Lado and most of the outcrops are found along stream and river channels. They mostly trend in the North-South direction. It is recognized by its distinctive foliation (gneissocity).

The banded gneiss is medium-grained, pink to light grey in colour with a well-defined fabric which is defined preferentially by oriented felsic and mafic minerals (Plate II). It occurs precisely around Unguwan Daura and Hayin Jaji. The dark brown to grey band contains the mafic minerals, principally biotite. The flakes of biotite are also aligned with their long dimensions parallel to the mineral banding. The banded gneiss is cut by a series of pegmatite dykes, most of which are oriented parallel to the gneissic fabric. Xenoliths occur as fine-grained mafic inclusions of amphibolites occurring within the gneissic bodies.

The granitic gneiss unit occurs as moderately rising outcrop; it crops out mainly in the northeastern part of the study area around Unguwan Nakala with a general trend of E-W orientation. It is leucocratic with medium to coarse grained texture and possesses moderate foliation.



II

Plate II: Banded gneiss (N11˚ 13′ 51.0″ E08˚ 05′ 22.6″)

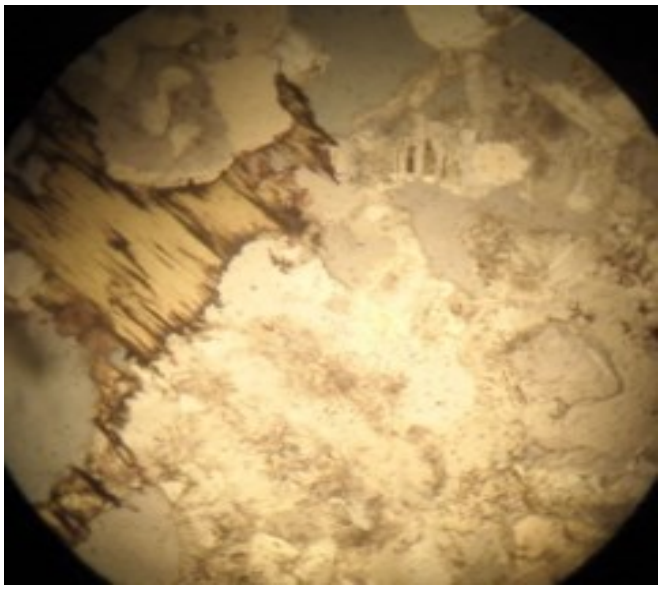
4.2.2.2 Petrography

Banded gneiss

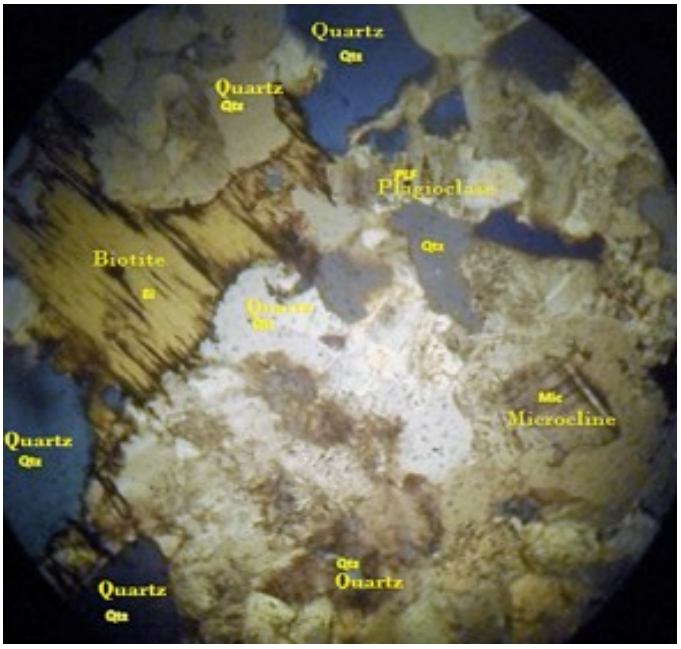
In thin section, the banded gneiss contains quartz, plagioclase feldspar, biotite, microcline, muscovite and orthoclase feldspar. Quartz constitutes about 35%, plagioclase feldspar 25%, biotite 20%, microcline 15%\, muscovite 5% (Plate III). Quartz is partially grey to colourless and has wavy extinction; it displays subhedral to anhedral habit. Plagioclase is partially grey in colour and exhibits albite twinning with an extinction angle of 16˚, the plagioclase crystals are strongly pleochroic from light to dark grey. Microcline is colourless but appears cloudy in PPL. It exhibits cross hatch twinning under cross nicols. Other minerals in the thin section are; biotite which is brown in colour, exhibits pleochroism and occurs as plates and laths which show preferential alignment with the foliation plane. Orthoclase appears altered with low relief.

Biotite gneiss

In thin section, the biotite gneiss contains biotite, plagioclase feldspar, quartz, muscovite, perthite and opaque minerals. Biotite constitutes 35%, plagioclase feldspar 25%, quartz 15%, muscovite 10%, perthite 5% and opaque minerals 5% (Plate IV). In PPL, the leucocratic band is composed of quartz and plagioclase feldspar while the mesocratic band consists predominantly of foliated biotite. In XPL, the microcline displays tartan twinning pattern with mymekitic intergrowth texture. Microcline is altered in places into sericitewhile plagioclase feldspar is also altered to sericite. Biotite is the dorminant mineral in the rock and its content is far more than the content of perthite.

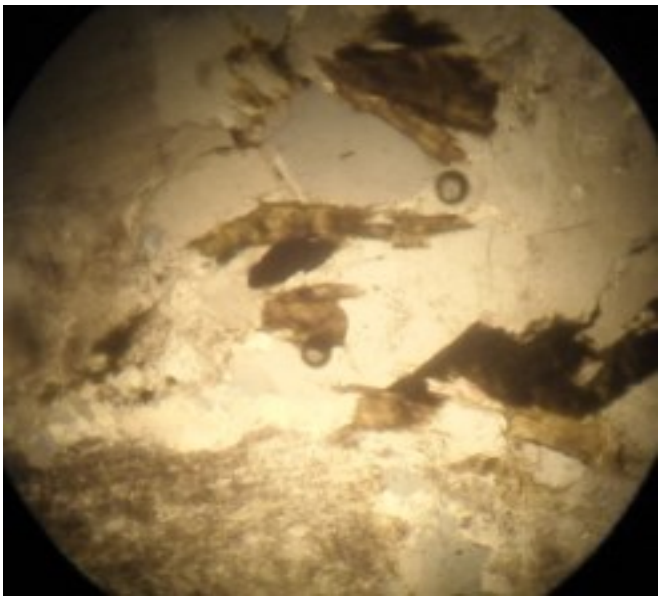


III (PPL)

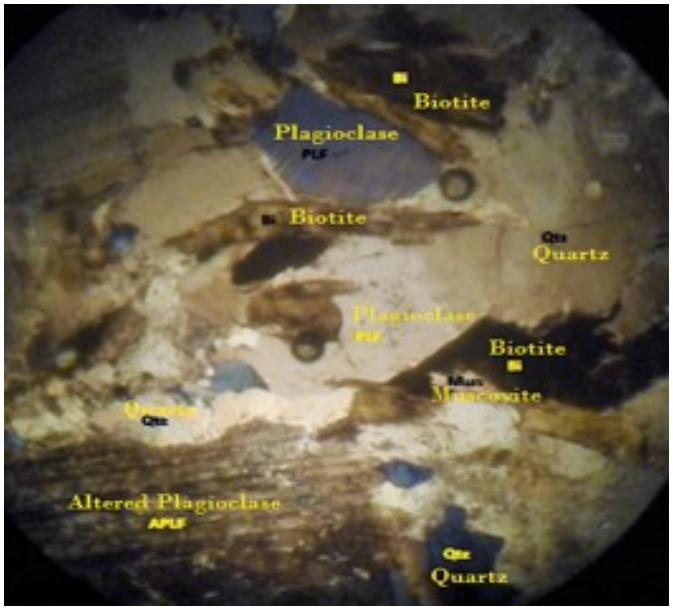


(III) XPL

Plate III: Photomicrograph of banded gneiss showing essential mineral composition (Qtz = Quartz, PLF = Plagioclase feldspar, Bi = Biotite, Mic = Microcline).



IV (PPL)



IV (XPL)

Plate IV: Photomicrograph of biotite gneiss showing essential mineral composition (Qtz = Quartz, PLF = Plagioclase Feldspar, Bi = Biotite, Mus = Muscovite, APLF = Altered Plagioclase feldspar).

4.2.3 SCHIST

4.2.3.1 Field Relationship

The schist occurs as a flat-topped hilly ridge in Dorayi area. The ridge is about 20 meters in height. The schist is highly weathered. The schistose structure present in the schist has been partly or totally obliterated by weathering; the schistocity however is weak and trends N-S to NE-SW. The schist is located in the Northwestern part of the study area and is reddish brown in colour (Plate V). The minerals present in the rock have been weathered, as such only quartz and feldspar could be identified. The schists are also poorly exposed along road excavation and river channels.



Plate V: Schist exposure with flat top (N11° 18′ 10.5″ E08° 05′ 09.0″)

4.2.4 QUARTZITE

The quartzites occur as linear ridges (NE-SW) with an average height of 35 meters above the surrounding. The quartzite has been affected by weathering (Plate VI); this could be responsible for the occurrence of quartzite cobbles on the ridge and quartzite pebbles in the lowland areas surrounding the hill. The fresh sample of the quartzite is light grey in

colourand appears glassy. The ridge is orientated in a northeast-southwest direction. Some quartzite boulders occur at high topography and run hundreds of meters; such as the Jina Hill and that west of Kuradawa. The quartzite west of Kuradawa is a highly weathered and fractured milky quartzite.



Plate VI: Quartzite ridge of Jina hill (N11° 17′ 20″ E08° 11′ 17″)

4.2.5 GRANITES

4.2.5.1 Field Relationship

The granites are exposed as oval shaped bodies. The granites seen vary in composition and texture. Interms of colour and texture, it varies from pink to grey pink, medium to coarse grained and porphyritic. These rocks are characterized by joints and are affected by weathering. Wide and narrow veins are commonly seen on the rock and some of these are deformed to form microfaults. These granitic exposures are characterized by distinguishing structures such as faults, joints, veins and dykes. Generally, the granites are oriented in NNE-SSW direction and occupy about 65% of the study area.

The medium to coarse grained granite forms homogeneous sheet like bodies in places. It occurs in contact with banded gneiss in some places and also occurs as isolated inselberg with whale-back (Plate VII) and some places in boulder form with irregular outline scattered in the field. It consists of high and low-lying hills of myriads of flat boulders.

The porphyritic granite occurs as boulders and as low-lying dome-shaped outcrops. Porphyritic granite exposure in the study area is characterized by joints, quartz veins and aplitedykes as observed ateast of gidan barau. A definite boundary between the coarse-grained granite and banded gneiss was observed at (N11˚ 13′ 02″ and E08˚ 06′ 49″) of the study area.



Plate VII: Domal nature of the granite (N11˚ 11′ 57″ E08˚ 10′ 32″)

4.2.5.2 Petrography

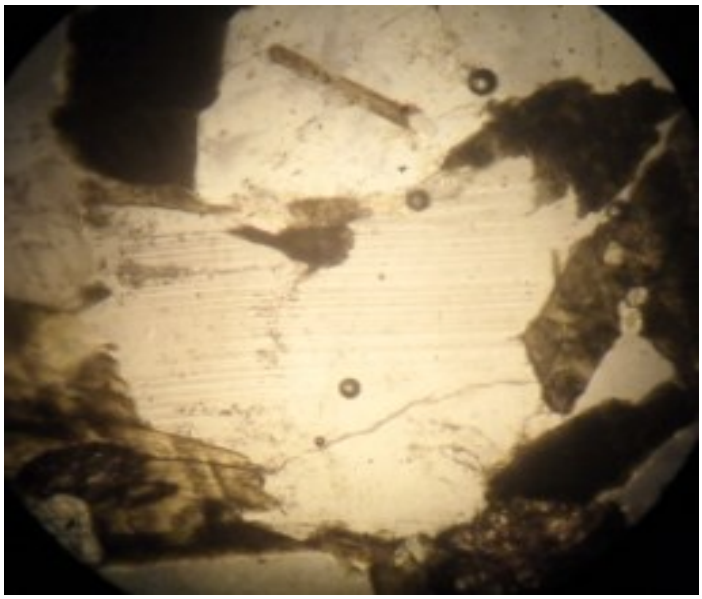
Porphyritic granite

In thin section, the porphyritic granite contains plagioclase feldspar, biotite, quartz, orthoclase feldspar, muscovite, microcline and hornblende. Plagioclase feldspar constitutes

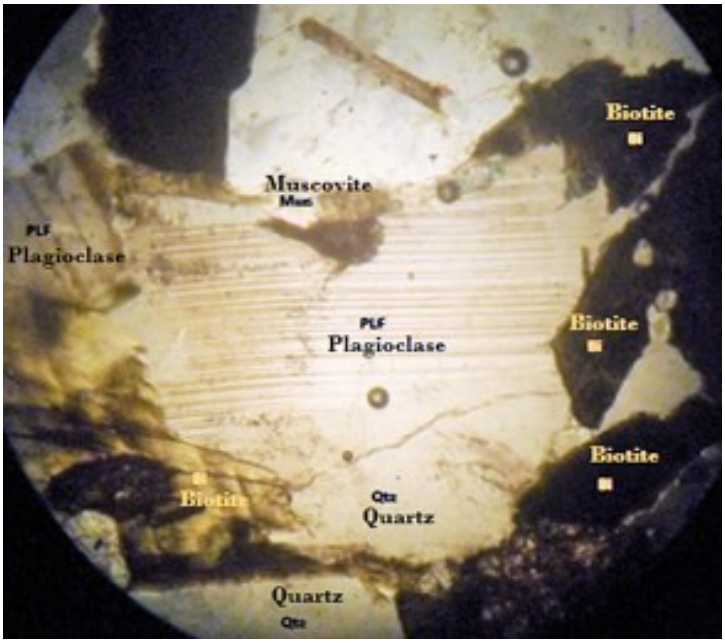
about 25%, biotite 25%, quartz 20%, orthoclase 10%, muscovite 10%, microcline 5%, hornblende 5% (Plate VIII). The thin section shows large subhedral phenocryst of plagioclase set in the medium grained groundmass of quartz, microcline and biotite. Muscovite appears yellow, pleochroic to dark green with moderately high relief and parallel cleavage; birefringence is third order green. Plagioclase seems to be sutured and shows multiple lamellae twinning. Hornblende appears brown in colour and non pleochroic.

Coarse grained granite

The coarse-grained granite contains quartz, biotite, microcline, plagioclase feldspar, perthite, orthoclase feldspar. Quartz constitutes about 30%, biotite 20%, microcline 20%, plagioclase feldspar 15%, perthite 10%, orthoclase feldspar 5% (Plate IX). Quartz is colourless, subhedral with low relief. Biotite is yellowish brown in colour, pleochroic to dark brown with moderate relief; it appears as subhedral to euhedral crystal wth straight cleavage. Microcline is colourless, non pleochroic with low relief and no visible cleavage; it appears as subhedral crystal with first order white to grey birefringence; it also shows cross-hatched twinning. Plagioclase is brown, non pleochroic with low relief. It appears euhedral to subhedral in shape with first order grey to white birefringence; it also shows lamellae twinning. Perthite is colourless, non pleochroic with low relief; it shows subhedral shape with the presence of alteration.

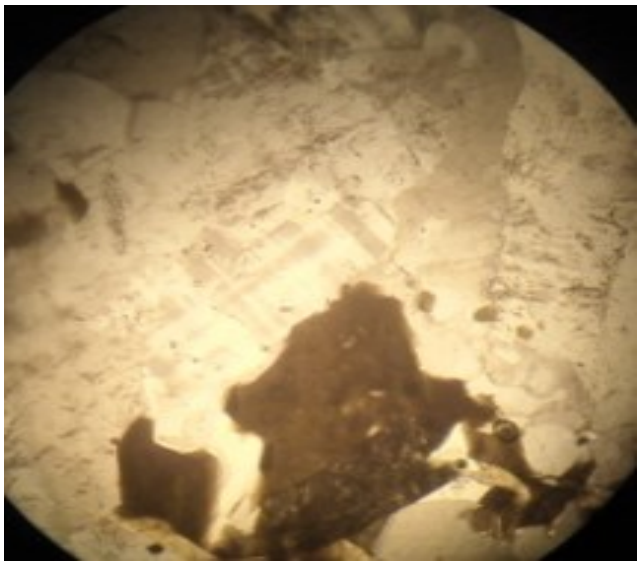


VIII (PPL)

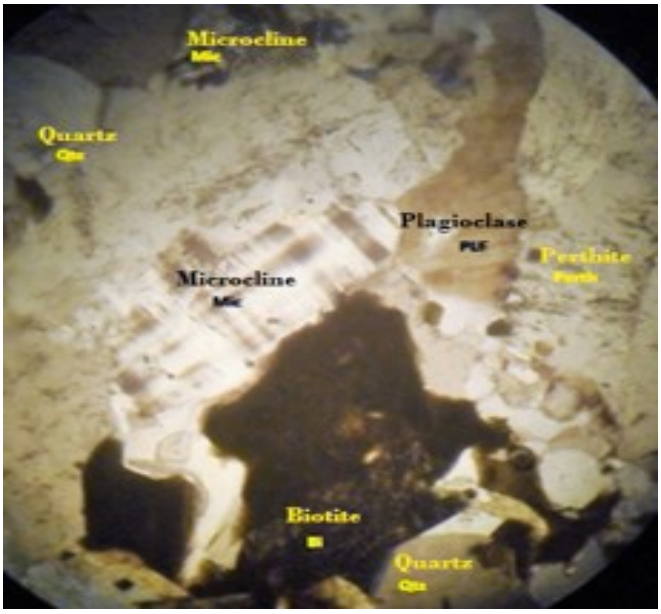


VIII (XPL)

Plate VIII: Photomicrograph of porphyritic granite showing essential mineral composition (Qtz = Quartz, PLF = Plagioclase Feldspar, Bi = Biotite, Mus = Muscovite).



IX (PPL)



IX (XPL)

Plate IX: Photomicrograph of coarse-grained granite showing essential mineral composition (Qtz = Quartz, PLF = Plagioclase Feldspar, Bi = Biotite, Mic = Microcline, Perth = Perthite).

4.3 PEGMATITES OF THE STUDY AREA

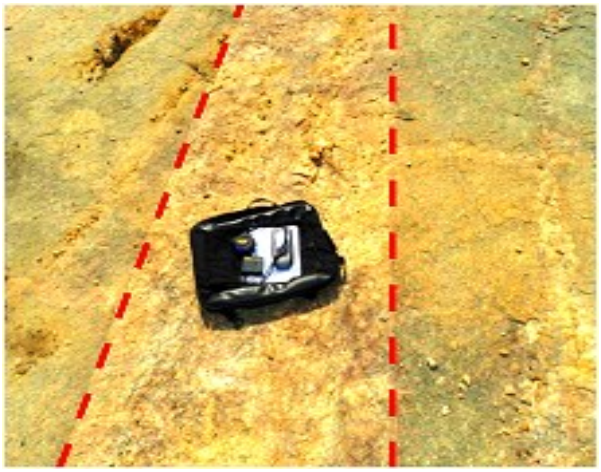
The pegmatites of the study area consist predominantly of small, layered and weakly zoned dyke but include a small number of large, internally zoned pegmatite bodies occurring as a near vertical dyke.

A total of 12 pegmatite samples, 12 host rock samples and 18 beryl samples were collected after which 17 samples of both beryl and host rock were selected for geochemical analysis. Representative samples of beryl were derived from the intermediate zone of the pegmatite. Three varieties of beryl samples were obtained from local miner pits. The host rock for the studied beryl is the coarse-grained granite.

There is no sign of interaction between the pegmatite and the enclosing granites except at contact. The pegmatite consists of discrete dykes that form a NE-SW trending bodies. The pegmatites in the study area are long and narrow bodies with most having width less than two meter wide with a length of atleast ten meters and sometimes more in width from a few meters to hundred meters. The contact between the pegmatite and the host rock range from very sharp to gradational (Plate X). Two classes of pegmatite were encountered in the field, these are: the beryl type pegmatite (Plate X) and the amethyst type pegmatite (PlateXI). The beryl bearing granitic pegmatite occurs mainly southwest of Kuradawa and northwest of Unguwan Duku while aquaberyl bearing pegmatite occur NNW of Lip-Lip (Fig. 4.8, page 41); amethyst bearing pegmatite occurs at Dogon Fako. The beryl pegmatite dyke has an average width 2.0 meters and was traced for approximately 50 meters; it has a strike of approximately 65˚ and dips at 20˚-22˚; the principal minerals for the dyke are quartz+feldspar+biotite. Major accessory phases are beryl, tantalite and tourmaline. The amethyst pegmatite dyke has an average width between 10.0 meters and was traced for

approximately 100 meters; it has a strike of approximately 75° and dips at 22°; the principal minerals for the dyke are quartz and feldspar. Major accessory phases are amethyst, tantalite and tourmaline. Muscovite is the most abundant mica occurring in the pegmatite of the study area while biotite is few. Pegmatite within the vicinity of the mining site has been weathered. The pegmatite also occurs as dyke swarms particularly along the margins of the plutons. The pegmatite bodies dip vertically to subhorizontally and strikes mainly in the NE-SW direction intruding into the granites.

Mining activities in the area until now are artisanal in nature (Plate XII and XIII). The mining site was opened by miners using drills, pickaxes, digger, tunnel and shovel. The technique for finding gemstones in the study area is at artisanal level; miners dig along the strike of the pegmatite to get luck. The technique for finding and recovering gemstones have changed today, the most widely used gemstone exploration techniques are ground penetrating radar and trace element analysis. The trace element analyses involve seeking signature elements as clues to where gems may lie while ground penetrating radar provides subsurface mapping of potential gem bearing pockets or vugs.

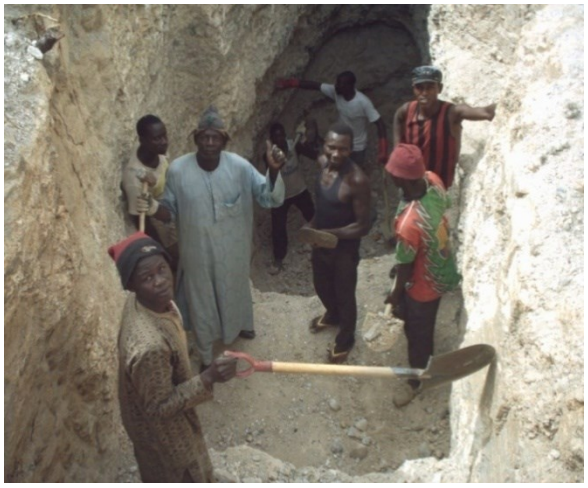




X **XI**

Plate X: Sharp contact between the beryl bearing pegmatite with the host granite (N11° 12′ 44″ E08° 09′ 03″).

Plate XI: Amethyst bearing pegmatite (N11° 14′ 45.6″ E08° 10′ 20.7″).





XII **XIII**

Plate XII: Active artisanal mining pit for beryl, SW of Kuradawa (N11° 12′ 27″ E08° 09′ 11″).

Plate XIII: Active artisanal mining pit for aquaberyl, NW of Lip-Lip (N11° 19′ 48.6″ E08° 08′ 44.5″)

4.3.1 Gemstones within the Pegmatites of the Study Area

Gem minerals in the study area occur in pockets within the pegmatites. Artisanal miners in the area quickly learn that each pegmatite is unique with its own set of pocket indicators. They also learn that despite careful attention to these clues, the location of productive gem pockets is still largely a matter of luck and hard work. Certain mineralogical aspects of the pegmatite serve to indicate the presence of pocket bearing pegmatite; such as the presence of mica within the pegmatite (Plate XIV). The presence of dominant white mica (muscovite) in a pegmatite indicate shallow pocket of gemstones while pinkish mica (muscovite) dominance indicate deep pocket of gemstones. Changes in mineralogy either as distinct mineral species or chemical changes within a specific crystal may indicate a nearby presence of economically important cavity of gemstones.

Mining in the study area is done by pick and shovel from the surface and later followed with explosives into the pegmatite as the pegmatite widens with depth. Beryl samples were collected from three artisanal mining sites in the study area. Representative samples of beryl derived from the intermediate zone of the pegmatite were collected for the study. The beryl is always spatially associated with anhedral quartz, feldspar and masses of biotite and muscovite. Some beryl crystals are irregularly scattered through a matrix of feldspar, quartz, mica and other minerals. The dominant colours of the beryl from the area are pale green, bluish green and pale yellowish green. In pegmatites of parts of Ikara, beryl constitutes the most important economic mineral and it has been mined. The artisanal mining performed in the year 2011 by Rich Quarry Nigeria Limited in Dogon Fako extracted about 25 tonnes of amethyst.



Plate XIV: Muscovite mica

4.4 STRUCTURES

Gneisses have few fractures compared to granites because of its ductile nature. This section of the chapter provides explanation on the importance of structures as controls of the gem mineralization.

4.4.1 Syntectonic Structures

***Foliation*:** The gneiss has been affected by different orogenies which are manifested as foliation and other structural forms. Foliation shows the effect of pressure as a factor of metamorphism assuming importance in the formation of the rock. It is identified by the compositional banding of mafic and felsic minerals on the outcrops (Plate XV). Most foliations on the rocks of the study area have an approximate N-S orientation with different degrees varying from each other.



Plate XV: Foliation on gneiss at east of Hayin Jaji (N11° 14′ 45.1″ E08° 05′ 41″)

***Exfoliation*:** Exfoliation joints are among the youngest fractures in bedrock outcrops and have specific common characteristics such as increasing joint spacing with depth and a lack of hydrothermal mineralization on their surfaces (Everitt, 2009). This structure is observed on coarse-grained granite giving rise to large scale sheeting of the rock (Plate XVI).



Plate XVI: Exfoliation on coarse grained granite (N11° 12′ 07″ E08° 12′ 15″)

***Xenolith*:** The gneisses host a small number xenoliths of dolerite; this xenolith occurs as pods (Plate XVII). The coarse-grained granite also hosts xenoliths of reworked granitic materials in various random orientations.



Plate XVII: Xenolith of fine grained amphibolite in gneiss (N11° 14′ 47″ E08° 07′ 56″)

4.4.2 Post-Tectonic Structures

***Joints*:** The joints observed are tectonic in origin (Plate XVIII), ranging from parallel to orthogonal jointing systems. Joints found in most rock exposures have a dominant NE trend, hence some trends NW. Some of the joints are filled with minerals such as quartz and feldspar in veins and pegmatites. Multiple fracture orientations were measured in outcrops. Structural trend discontinuity orientation was obtained and reported in azimuth.



Plate XVIII: Extensional fracture on coarse-grained granite near Gidan Gona (N11° 13′ 27″ E08° 09′ 37″)

***Veins*:** Veins of different sizes were found in the study area. Both the quartz and pegmatite veins are small in thickness varying from few millimeters to some centimeters. The average thickness of the pegmatite vein is 2.2-centimeter trending in different directions. The quartz veins are abundant throughout the granites and appear to be related to cretaceous deformation of the country rocks. The veins are typically thin, quartz rich and contain no beryl. The quartz veins are irregular cross-cutting each other (Plate XIX).



Plate XIX: Cross-cutting quartz veins in granite (N11° 13′ 35.9″ E08° 09′ 41.9″)

***Dykes*:** Two categories of dykes were observed in the study area on the basis of textural variation. Aplite dykes were seen occurring on granitic bodies formed from the residual melt after most of the crystallization of the granites is completed. The aplites are light grey in colour, very fine-grained and equigranular. The average thickness of the aplite dyke is 1.5 meters, trending in the North-South direction. Pegmatites are spatially related to aplites and thereby display aplitic margins (Plate XX). Pegmatites and aplites have long been recognized as texturally contrasting rocks whose composition and features bespeak close genetic affiliations (Tuttle and Bowen, 1958). The Pegmatite dyke occurs both in the granites and gneisses with varying width and length; the Pegmatite that occurs along the river channel has been affected by chemical weathering (Plate XXI). Aplites have been observed in the field to be associated with the pegmatites in few places.





XX **XXI**

Plate XX: Pegmatite dyke at the margin of an aplite dyke suggesting a much faster cooling, nucleation and crystal growth (N11° 13′ 33.1″ E08° 09′ 37.1″)

Plate XXI: Pegmatite dyke exposed along a river channel (N11° 12′ 32.3″ E08° 09′ 17.3″)

***Faults*:** Fault zones in the mapped area were marked by quartz veins. It is observed that microfaults occur on the granites; these faults commonly displace quartz veins (Plate XXII). The occurrence of faults in the study area was relatively little as compared to other structures.



Plate XXII: Displacement of quartz vein on granite indicating a dextral fault (N11° 13′ 36.0″ E08° 09′ 44″)

4.5 FRACTURE ANALYSIS OF THE BASEMENT ROCKS

Fractures can be defined as a planar or sub planar discontinuity which forms due to an external or internal stress (Fossen, 2010). They are usually found in brittle structures as their rock body accommodates the stress or deformation in showing the marks when they lost cohesion through fracture characteristics (George *et al.* 2012). Tectonic fractures commonly form in rock when the tensile strength of the rock is exceeded; they are therefore, important structures for constraining the deformational history of the rocks.

Multiple fracture orientations were measured on outcrops and reported in azimuth 0˚-180˚ with the aid of a compass clinometer. High fracture density is observed in the granites compared to the gneisses.

All the fracture (joint) values for both granite and gneiss were measured and plotted on a rosette diagram (Fig. 4.10 and 4.11); the trends of the pegmatite were also measured and

plotted on the rosette diagram (Fig. 4.9). Extensional fractures (Joints) characterized in the crystalline basement rocks of the area shows that the orientation of the strike of the fractures are dominantly in the NNE-SSW direction on the granites (Fig. 4.10) while dominant on NW-SE direction on the gneisses (Fig. 4.11). The most prominent strike directions for the pegmatite dyke are: NE-SW, NW-SE and ENE-WSW while minor set occur in the NNE-SSW and WNW-ESE. The trend of the granites generally agrees with the geologic and lithologic relationships of the Pan-African suites and indicates that the Pan-African event played a major role in the structural evolution of the rock. The trends of the gneisses are indicative of pre-Pan-African orogeny. The rosette diagrams for the fractures in the granites were compared with those based on the strike of the pegmatites, it was evident that they almost follow the same trend; hence the emplacement of the pegmatites was largely influenced by these structures probably in the late Pan-African.

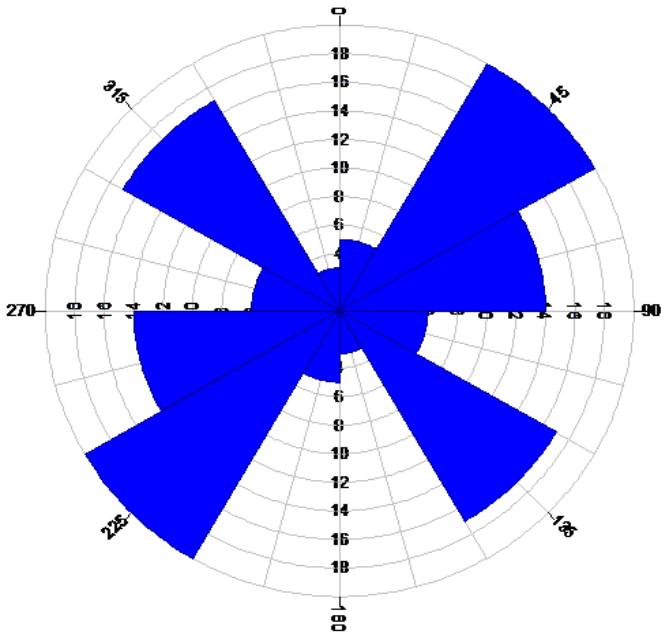


Fig. 4.9: Rose diagram plot of the orientation of pegmatite veins/dyke in the study area.

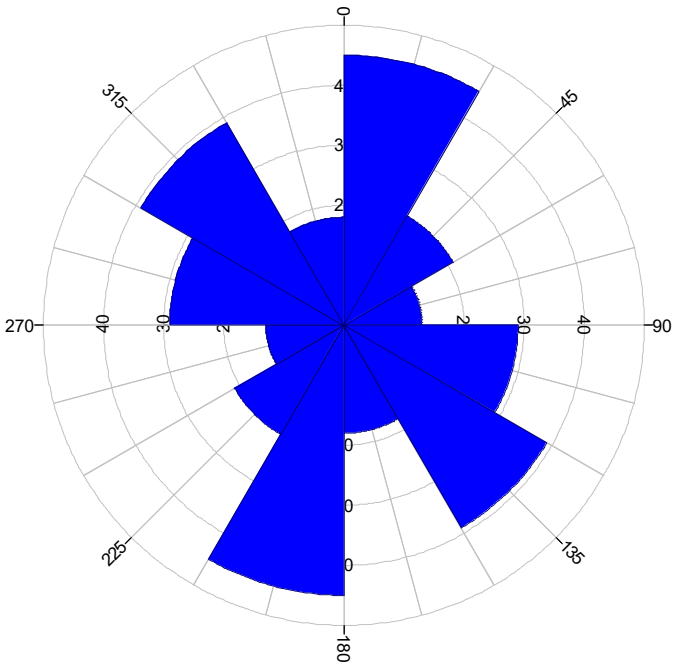


Fig. 4.10: Rose diagram plot of the orientation of joints on granites of the study area.

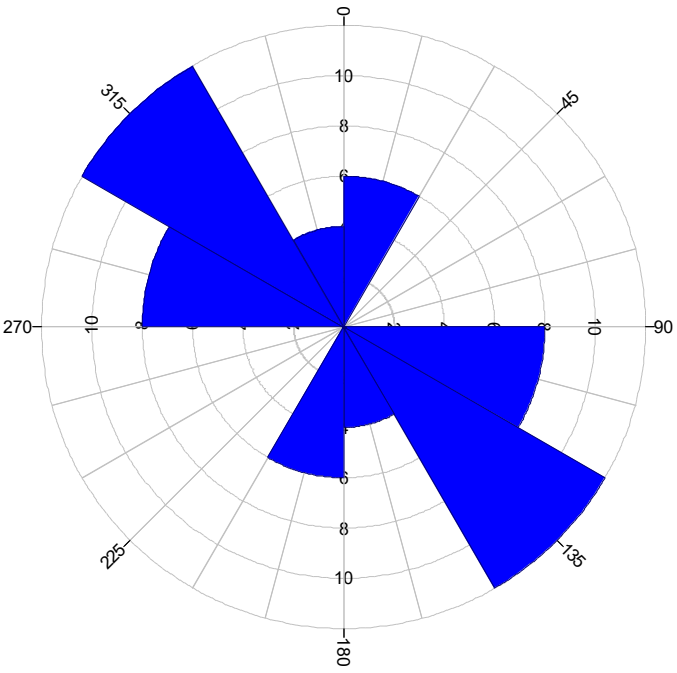


Fig. 4.11: Rose diagram plot of the orientation of joints on gneiss of the study area.

4.6 WHOLE ROCK GEOCHEMISTRY

The geochemical analysis results from rocks in the study area are presented in Tables 4.1, 4.2 and 4.3.

4.6.1 Major Element Geochemistry

Table 4.1: Major element composition of the rocks (values in wt%)

	Granite		Gneiss		
Oxides	ZD	ZE	ZA	ZB	ZC
SiO_2	70.22	71.00	63.96	71.21	73.88
Al_2O_3	14.59	14.31	16.65	14.45	13.62
Fe_2O_3	0.27	0.25	0.51	0.29	0.15
FeO	2.20	1.98	4.11	2.34	1.24
MnO	0.04	0.04	0.07	0.07	0.07
MgO	0.31	0.54	1.87	1.16	0.39
CaO	1.27	1.01	3.79	2.47	1.78
Na_2O	3.27	3.34	4.19	3.95	4.36
K_2O	6.10	6.20	2.91	2.83	2.92
TiO_2	0.31	0.31	0.83	0.40	0.18
P_2O_5	0.17	0.20	0.30	0.19	0.07
Cr_2O_3	0.00	0.00	0.01	0.01	0.00

The major element data (Table 4.1) reveal that the investigated granite and gneiss are characterized by high silica content showing a compositional average (averages 70.61wt%) for granites while (averages 69.68wt%) for gneiss and low contents of MnO (averages 0.04wt%) for granite while 0.07wt% for gneiss, MgO (averages 0.43wt%) for the granite and 1.14wt% for gneiss, TiO_2 (averages 0.31wt%) for the granite and 0.47wt% for gneiss, CaO (averages 1.14wt%) for the granite and 2.68wt% for gneiss, and P_2O_5 (averages 0.185wt%) for the granite and 0.187wt% for gneiss. Total alkali content (Na_2O+K_2O)

averages 9.46wt% for the granite and 7.05wt% for gneiss while Al_2O_3 averages 14.45wt% for the granite and 14.91wt% for the gneiss, K_2O averages 6.15wt% for granites and 2.89wt% for gneiss and is higher than Na_2O which averages 3.31wt% for the granite and is lower than 4.17wt% Na_2O for gneiss. The alumina (Al_2O_3) is greater than the alkali Na_2O+K_2O+CaO in all the rock samples.

4.6.2 Major Element Composition

The results of chemical analysis of the rocks are presented in Table 4.1. The major element composition of the granites was used to evaluate the characteristics and mode of emplacement of the protolith (Figs.4.12, 4.13, 4.14, 4.15 and 4.16).

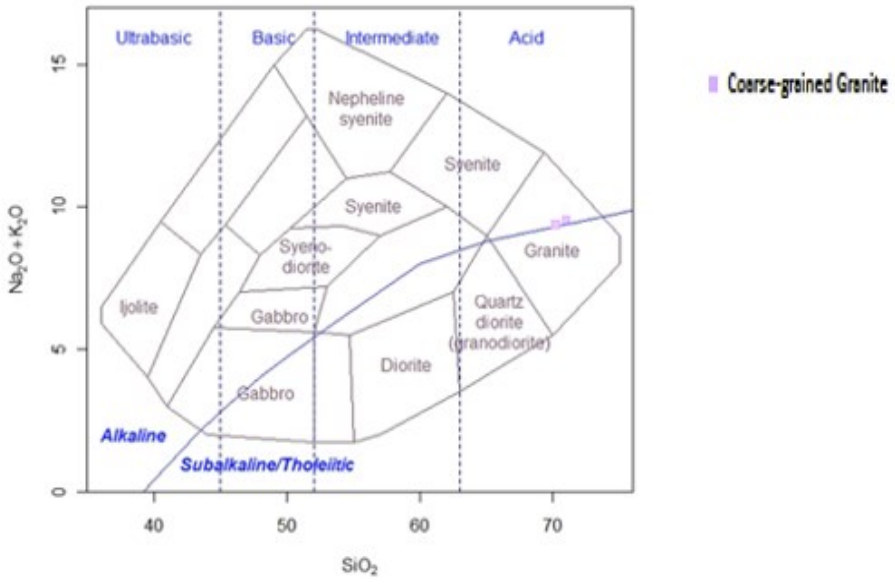


Fig. 4.12: Na_2O+K_2O versus SiO_2 plot (Cox *et al.* 1979) showing the classification of the granitic rocks

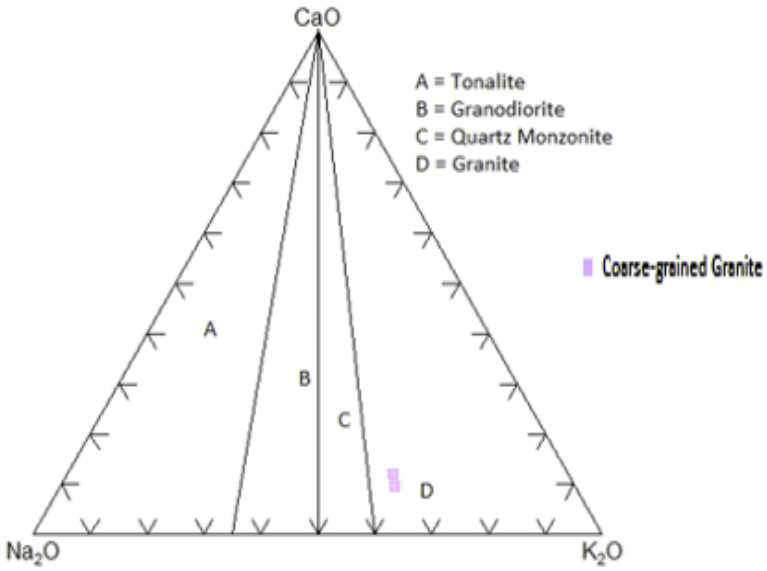


Fig. 4.13: CaO – Na_2O – K_2O Ternary variation plot showing the plots of coarse-grained granite in the study area (Barker and Arth, 1976)

The rocks were classified based on chemical plots of total alkali silica (TAS) diagram of (Cox *et al.* 1979) and triangular plot of (Barker and Arth, 1976). In the total alkali-silica (TAS) diagram (Fig. 4.12), the coarse-grained granite samples plot in the field of "granite". Compositional plots of the rocks in CaO-NaO-K_2O ternary diagram (Fig. 4.13) indicate that the data plots in the field of granite for the coarse-grained granite samples.

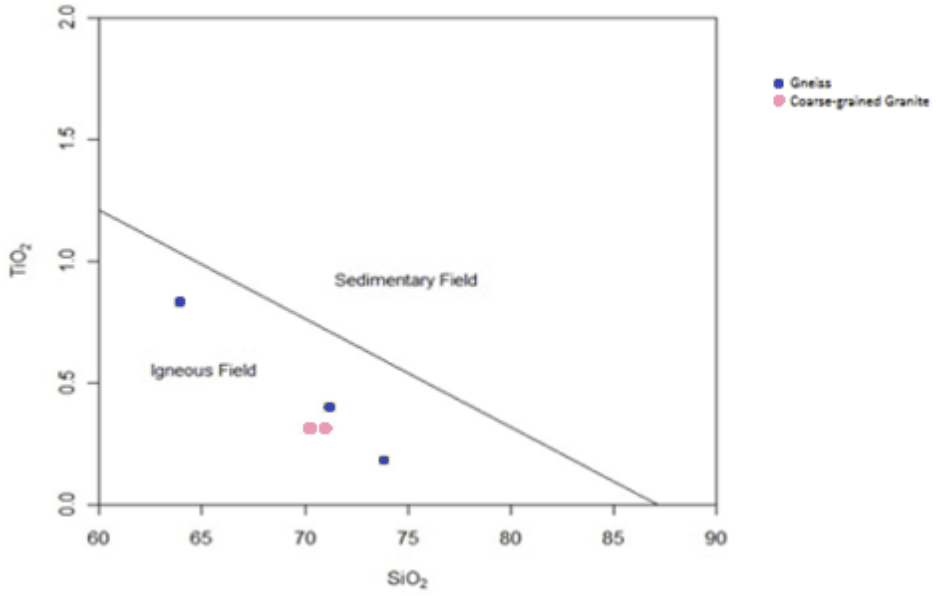


Fig. 4.14: TiO_2 versus SiO_2 discrimination diagram (adapted from Tarney, 1977)

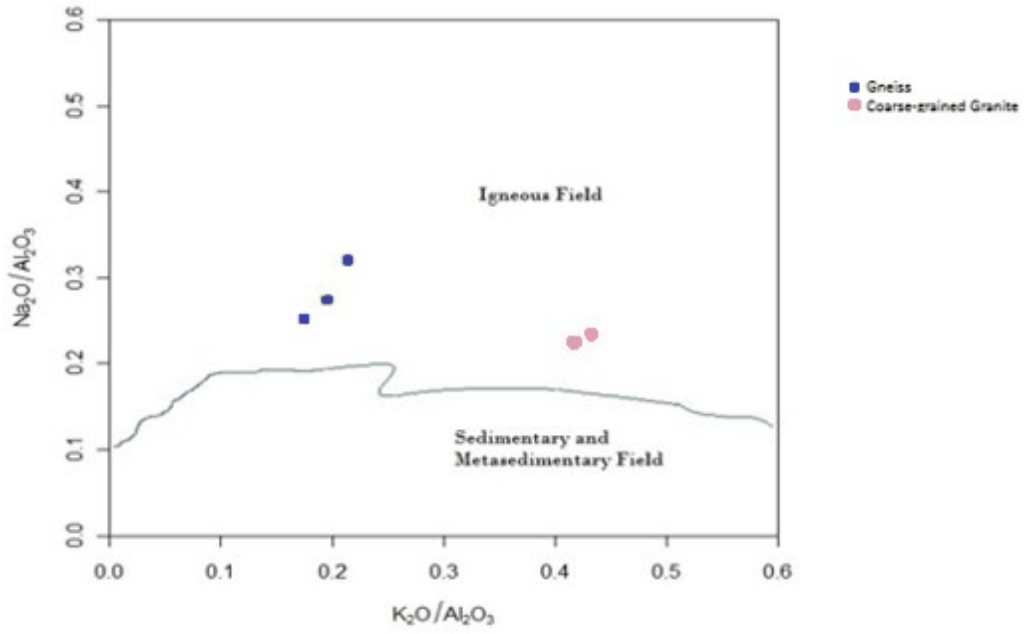


Fig. 4.15:Na_2O/Al_2O_3 versus K_2O/Al_2O_3 (adapted from Garrels and Mackenzie, 1971)

Various models were used to determine the origin of the rocks. TiO_2 versus SiO_2 (Fig. 4.14) was used to discriminate between igneous and sedimentary/metasedimentary rocks.

Furthermore, Na_2O/Al_2O_3 versus K_2O/Al_2O_3 plot (Fig. 4.15) was also used; the plot for the rocks fall within the igneous field which suggest that the protolith of the rocks was derived from partial melting of crustal rocks.

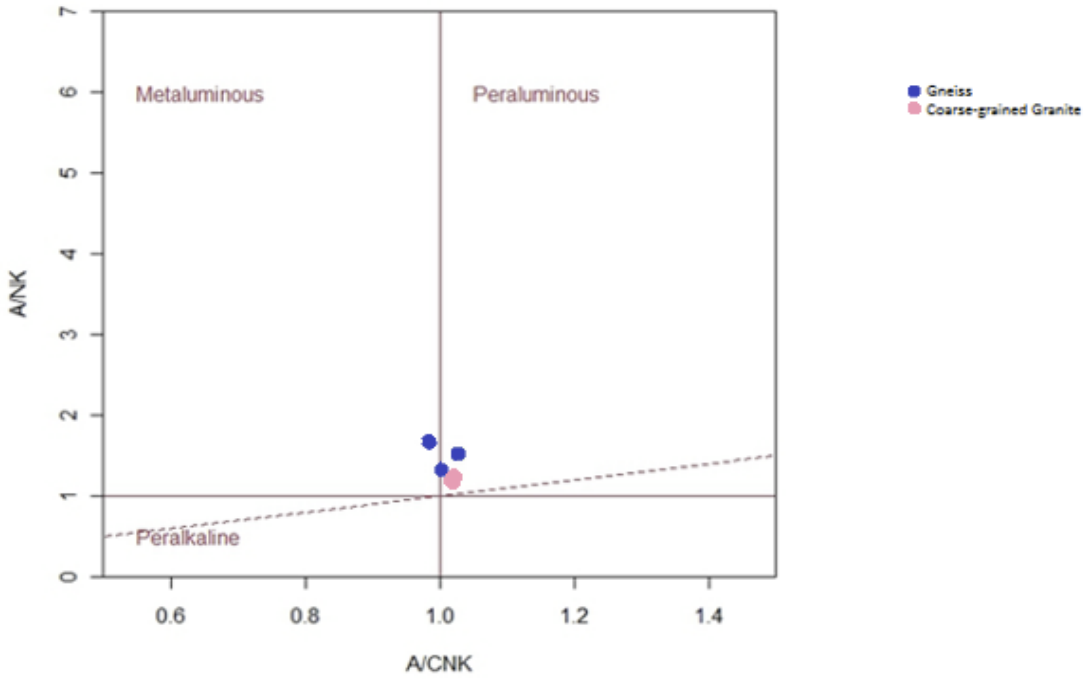


Fig 4.16: A/NK versus A/CNK of the granites and gneisses showing their distribution (adapted from Shand, 1943)

The plot of the rocks on the A/NK versus A/CNK (Fig. 4.16) shows that all the samples with the exception of one sample of coarse-grained granite have A/CNK ratio above unity and accordingly are classified as peraluminuous. Therefore, the investigated rocks have a metaluminous to slightly peraluminuous nature. Furthermore, the most distinctive and simple chemical property that characterize I-type and S-type granitoids is their A/CNK ratio which is below 1.1 for I-type granites and greater than 1.1 for S-type granites (Chappell and White 1974, 1978; White and Chappell, 1977; Hine *et al.* 1983). Fig 4.16

shows that the investigated rocks fall within the I-type field as their A/CNK ratios are less than 1.1.

4.6.3 Trace Element Characterization

The results of trace element analysis of the rocks are presented in Table 4.2 while tectonic setting discrimination diagrams are presented in Figs. 4.17 and 4.18.

Table 4.2: Trace element composition of the rocks (values in ppm)

Elements	Granite		Gneiss		
	ZD	ZE	ZA	ZB	ZC
Sc	2.51	1.59	8.10	9.61	3.65
V	4.15	4.78	82.69	45.45	11.08
Cr	d.l	8.88	28.37	13.78	7.41
Co	4.49	3.02	11.30	7.18	1.89
Ni	1.93	5.52	8.98	6.32	2.64
Cu	6.43	3.61	6.40	5.22	7.17
Zn	46.51	43.90	99.65	45.31	45.81
Ga	23.36	19.20	30.50	18.42	30.06
Rb	310.92	304.02	153.37	162.41	202.09
Sr	135.17	236.72	565.07	343.11	198.05
Y	40.36	33.43	22.84	13.67	20.86
Zr	229.43	214.62	272.38	125.60	102.99
Nb	25.37	17.45	19.18	14.62	30.14
Mo	1.22	0.21	0.45	0.53	d.l
Ba	717.05	585.86	727.05	582.81	157.84
Pb	50.06	49.82	24.71	35.64	58.81
Th	22.56	45.43	21.97	14.11	8.65
U	8.24	7.30	4.40	2.85	2.30
As	0.66	0.90	0.73	0.45	0.40

4.6.4 Tectonic Classification

Tectonic discrimination diagrams based on trace elements have been devised for granitoid rocks (Pearce *et al.* 1984), these plots diagnose the settings in which the protoliths were formed (Arculus, 1987; Twist and Harmer, 1987). On the Nb versus Y diagram after Pearce *et al.* 1984, the granitic rocks plot largely in the field of syncollisional and within plate granite (Fig. 4.17) while on the Rb versus Y+Nb diagram after (Pearce *et al.* 1984), the rocks plot in an overlap between within plate granite and ocean ridge granite (Fig. 4.18).

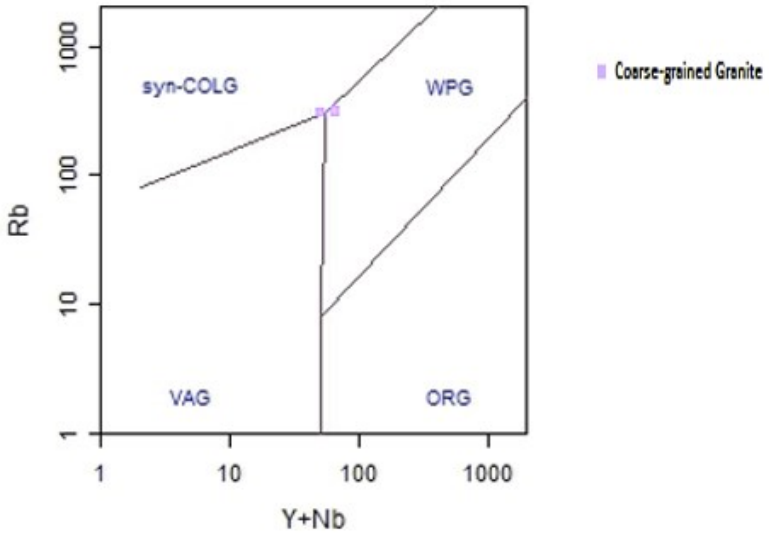


Fig 4.17: Rb versus Y+Nb discrimination diagram (Pearce *et al.* 1984) showing the volcanic arc and within plate tectonic setting of the granitic rocks.

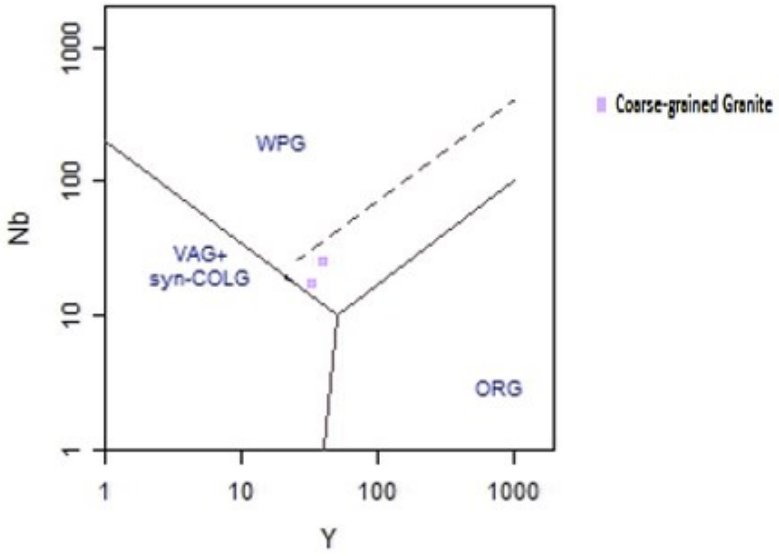


Fig. 4.18: Nb versus Y discrimination diagram (Pearce *et al.* 1984) showing the volcanic arc and within plate tectonic setting of the granitic rocks.

4.6.5 Rare Earth Element Geochemistry

The rare earth elements (REEs) data is presented in Table 4.3 and the REE data spider diagram is also presented in Fig. 4.19.

Table 4.3: Rare earth element composition of the rocks (values in ppm)

Elements	Granite		Gneiss		
	ZD	ZE	ZA	ZB	ZC
La	31.26	56.78	44.35	18.37	7.21
Ce	83.12	127.64	130.3	51.58	21.40
Pr	8.22	14.34	10.75	3.57	1.95
Nd	30.08	50.36	40.56	12.30	7.22
Sm	5.87	10.68	7.11	2.12	1.60
Eu	1.02	0.59	1.46	0.55	0.29
Gd	5.52	9.95	6.33	2.26	1.50
Tb	0.74	1.24	0.70	0.29	0.21
Dy	3.62	4.94	2.96	1.50	1.22

Ho	0.63	0.70	0.50	0.28	0.27
Er	1.78	1.69	1.47	0.83	1.02
Tm	0.23	0.17	0.19	0.10	0.19
Yb	1.44	1.04	1.22	0.64	1.51
Lu	0.21	0.15	0.17	0.09	0.26

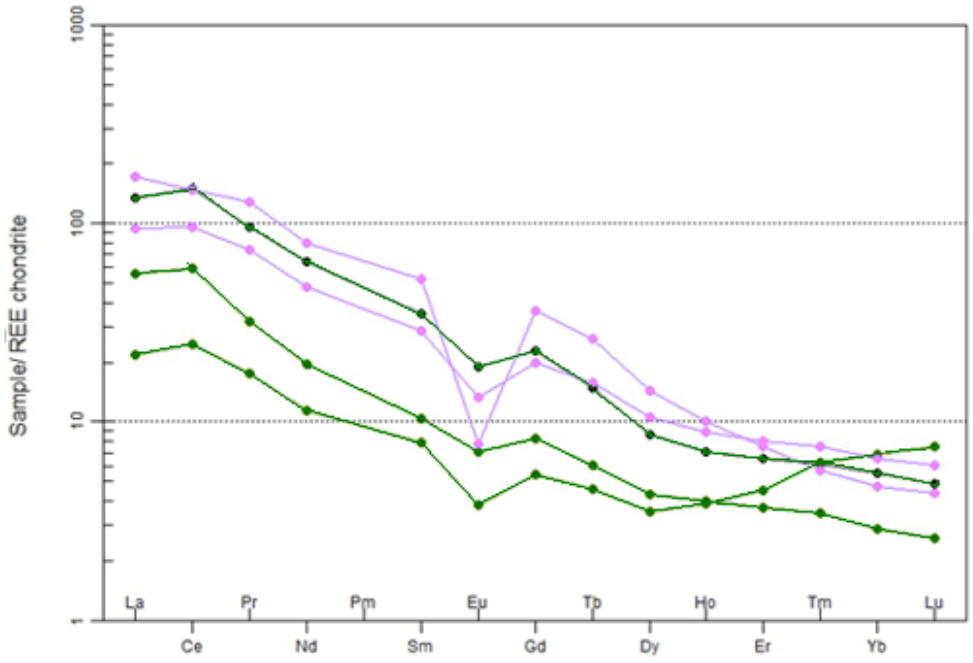


Fig 4.19: REE pattern of whole rock in the study area, normalized to chondrite (Normalization value after McDonough and Sun, 1989).

4.7 MINERAL CHEMISTRY

Major element composition of beryl is presented in Table 4.4. Trace element composition of beryl, Rare Earth Elements (REE) and Alkali/Femic element ratios are presented in Tables 4.5, 4.6 and 4.7. Discrimination plots of beryls were applied in the interpretation of the evolution of the pegmatite (Figs 4.20, 4.21, 4.22, 4.23, 4.24, 4.25 and 4.26).

4.7.1 Major Element Chemical Composition of Beryl

In beryl from Pegmatites of parts of Ikara, Iron contents do not exceed 1.14wt% FeO. Beryl (2) has higher average concentration of Iron compared to other beryls. The average Iron contents (0.12wt%) for Beryl (1) and Beryl (3) are similar. Beryl (1) and Beryl (2) have similar Manganese content. Beryl (1) contains higher average value of Magnesium (0.08 wt% MgO). Alkali element contents are low with Beryl (3) having the highest concentration of sodium (upto 0.30wt% Na_2O) and K_2O (upto 0.22wt%).

Table 4.4: Major element composition of beryl in pegmatites of the study area (values in wt%).

	Beryl 1				Beryl 2				Beryl 3			
Oxides	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
SiO_2	65.79	66.19	65.79	66.04	65.52	69.58	66.56	66.83	64.67	64.65	64.29	64.89
Al_2O_3	18.30	18.37	18.46	18.39	18.17	16.22	17.77	17.63	16.58	15.51	15.58	16.62
Fe_2O_3	0.12	0.12	0.12	0.14	0.13	0.13	0.13	0.12	0.12	0.12	0.12	0.13
FeO	0.99	0.91	0.96	1.14	1.00	1.01	1.05	0.94	0.90	0.97	0.98	1.03
MnO	0.01	0.01	0.01	0.02	0.02	0.01	0.01	0.01	0.03	0.04	0.04	0.03
MgO	0.08	0.09	0.06	0.09	0.06	0.06	0.06	0.06	0.06	0.09	0.08	0.06
CaO	0.02	0.03	0.03	0.04	0.04	0.02	0.03	0.03	0.03	0.04	0.03	0.03
Na_2O	0.19	0.19	0.18	0.19	0.20	0.22	0.26	0.21	0.26	0.30	0.22	0.20
K_2O	0.02	0.03	0.03	0.02	0.05	0.04	0.16	0.05	0.05	0.22	0.11	0.07
TOTAL	85.52	85.94	85.64	86.07	85.19	87.29	86.03	85.88	82.70	81.94	81.67	83.06

4.7.2 Trace Element Composition of Beryl

Trace element contents are presented in Table 4.5 and graphically represented in Figs. 4.20, 4.21, 4.22, 4.23, 4.24 and 4.25. Comparatively, Beryl (2) has greater average content of Ba (1.09ppm) and Sr (0.60ppm). Beryl (3) has greater average contents of Zn (121.17ppm), Ga (37.69ppm), Rb (32.93ppm), Cs (861.45ppm). A relative enrichment in Cr (average 4.67ppm) and Ti (average 123.82ppm) is observed in Beryl (1) compared to other beryl. Overall, tantalum and niobium contents are low with the exception of sample A4 of Beryl (1) which reaches about Ta (12.67ppm) and Nb (27.19).

Table 4.5: Trace element composition of beryl in pegmatites of the study area (values in ppm)

	Beryl 1				Beryl 2				Beryl 3			
Elements	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
P	59.78	2.39	14.43	8.43	5.05	12.70	4.37	4.02	18.97	10.06	4.51	10.42
Ti	435.8	8.23	16.83	34.41	14.42	19.83	10.34	13.26	257.3	51.98	17.93	11.6
V	4.33	3.32	2.35	1.38	1.71	3.89	4.71	5.11	45.57	11.38	25.16	10.03
Cr	6.51	5.70	2.48	3.96	4.65	2.68	3.27	2.70	3.22	4.26	3.51	3.56
Ni	8.05	4.01	4.23	6.04	4.79	4.73	3.71	3.80	4.67	3.11	5.31	4.27
Cu	1.83	1.37	1.24	1.92	1.30	3.28	1.28	1.18	1.92	1.92	1.19	2.57
Zn	81.92	71.19	103.2	106.4	76.83	84.87	64.87	65.15	97.86	150.4	108.8	127.6
Ga	37.22	36.18	36.08	35.66	41.92	30.55	31.66	31.32	36.62	35.50	41.32	37.33
As	1.74	1.67	0.39	0.95	1.20	1.02	1.26	3.44	0.55	1.04	0.56	0.52
Rb	13.82	17.97	12.43	13.63	23.03	13.84	22.91	17.01	29.55	30.90	40.70	30.58
Sr	0.39	0.39	0.38	0.26	0.90	0.22	0.52	0.74	0.25	0.66	0.19	0.18

Zr	0.73	0.40	0.24	5.49	0.58	0.48	0.40	0.49	0.78	6.73	3.98	0.40
Nb	3.34	1.15	0.46	27.19	3.00	0.77	1.01	3.25	2.92	5.42	0.99	0.35
Cs	552.7	574.9	432.3	579.7	687.4	470.9	568	543.3	729.7	731.9	1022.5	961.7
Ba	0.5	0.87	0.82	1.01	1.85	0.37	1.32	0.80	0.41	1.37	0.41	0.22
Hf	0.03	0.04	0.01	0.48	0.04	0.04	0.04	0.04	0.04	1.47	0.83	0.03
Ta	0.21	0.83	0.06	12.67	0.42	0.39	0.83	2.86	0.33	0.81	2.18	0.16
W	0.1	0.60	0.28	9.40	0.48	0.22	0.72	0.69	0.13	12.71	0.06	0.05
U	0.03	0.15	0.10	1.84	0.14	0.15	0.15	0.50	0.06	0.49	0.15	0.07
Th	0.003	0.07	0.003	0.003	0.02	0.007	0.07	0.19	0.008	1.27	0.20	0.004
Sc	2269	992	1198	1019	1199	1816	1226	1511	1.12	1.02	0.99	1.51
Y	3.13	2.19	3.35	4.13	2.64	8.74	2.27	10.38	4.00	4.00	1.00	1.00

Table 4.6: Alkali and Femic element ratios

Element Ratio	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
Rb/Ti	0.032	2.18	0.74	0.40	1.60	0.70	2.22	1.28	0.12	0.59	2.27	2.64
Mg/Fe	0.062	0.076	0.048	0.061	0.046	0.046	0.044	0.049	0.051	0.071	0.063	0.045
Cs/Na	3920	4077	3226	4111	4645	2889	2958	3483	3801	3327	6273	6498
Na/Cs ($*10^{-4}$)	2.55	2.45	3.1	2.43	2.15	3.46	3.38	2.87	2.63	3.01	1.59	1.54

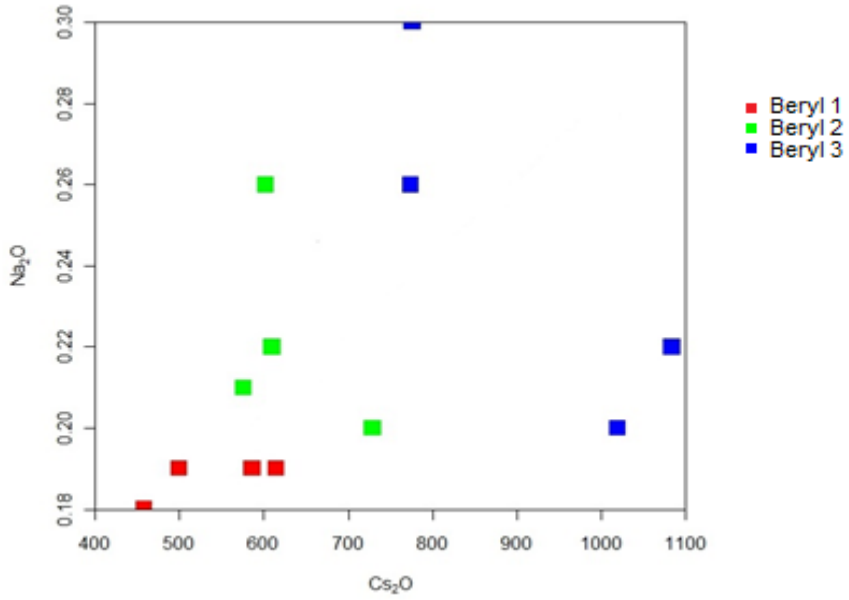


Fig. 4.20: Na_2O versus Cs_2O diagram showing the compositional trend of beryl in the study area

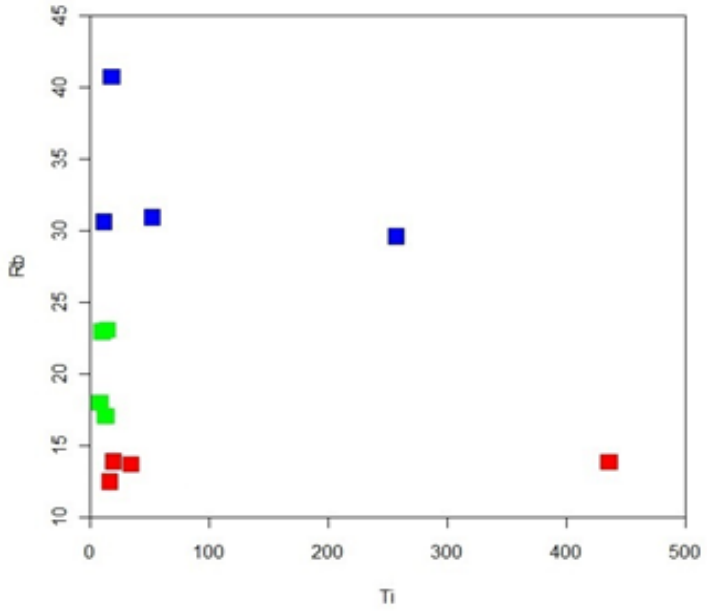


Fig. 4.21: Rb versus Ti diagram showing the compositional trend of beryl in the study area

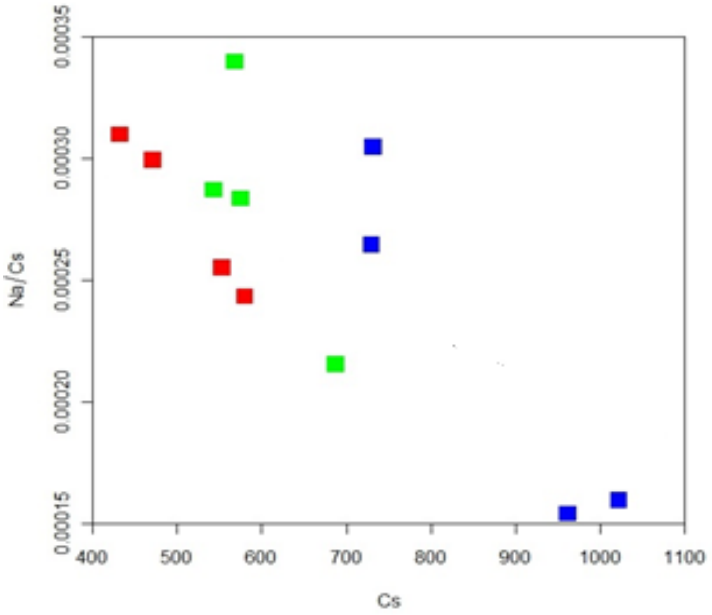


Fig 4.22: Na/Cs versus Cs showing the compositional trend of beryl using element ratios and abundance

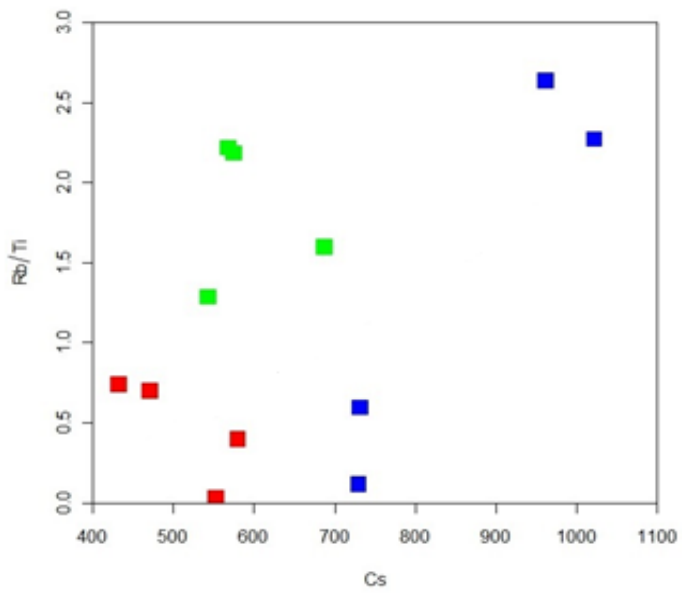


Fig 4.23: Rb/Ti versus Cs showing the compositional trend of beryl using element ratios and abundance

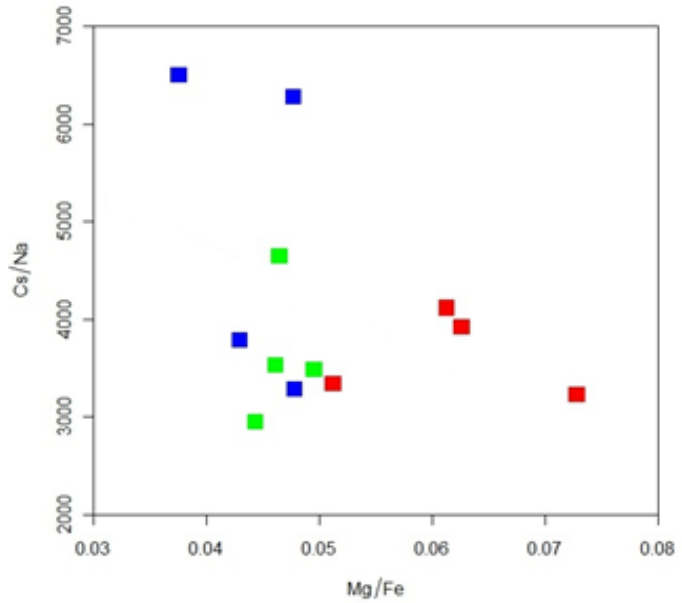
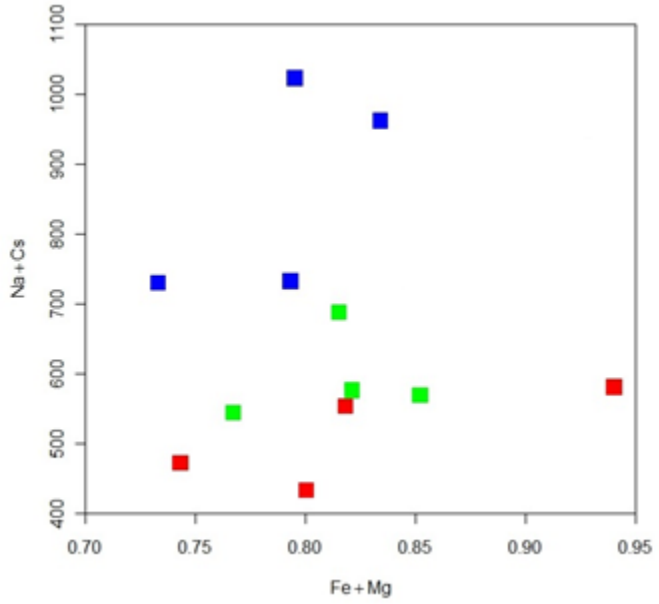


Fig. 4.24: Cs/Na versus Mg/Fe diagram showing the fractionation characteristics of beryl based on alkali and femic elementsratio



b.

Fig. 4.25: Na+Cs versus Fe+Mg diagram showing the fractionation characteristics of beryl based on alkali and femic elements content

4.7.3 Rare Earth Element Composition

The rare earth element content of beryl samples are presented in Table 4.7 and a spider diagram also presented in Fig. 4.26.

Table 4.7: Rare earth element composition of beryl in pegmatites of the study area (values in ppb)

	Beryl 1				Beryl 2				Beryl 3			
Elements	A1	A2	A3	A4	B1	B2	B3	B4	C1	C2	C3	C4
La	95.23	107.8	74.97	68.23	109.1	74.13	92.74	76.67	85.42	58.2	51.18	55.73
Ce	65.67	202.2	118.59	149.47	517	76.95	135	228.9	89.7	184.2	1118.1	57.52
Pr	1.22	1.82	1.39	0.962	1.67	1.84	1.03	3.12	2.61	10.71	111.59	1.57
Nd	3.99	5.67	4.13	4.75	6.45	6.52	4.47	15.5	9.73	4.85	367.6	5.99
Sm	0.75	0.22	0.33	0.20	0.75	0.51	0.68	2.58	0.86	9.18	80.35	0.83

Eu	0.14	0.05	0.12	0.25	0.52	0.34	0.24	0.47	0.20	3.93	1.22	0.11
Gd	1.25	1.78	1.42	1.62	3.74	1.73	1.36	4.15	1.51	10.67	62.1	1.42
Tb	-0.33	-0.3	1.81	-0.28	-0.19	-0.13	-0.35	0.07	-0.27	1.14	2.90	-0.37
Dy	0.22	0.18	0.09	0.15	0.11	1.02	0.30	2.03	0.67	8.22	4.17	0.72
Ho	-0.23	-0.40	-0.26	-0.23	-0.25	-0.13	-0.32	-0.02	-0.16	1.29	-0.02	-0.30
Er	-0.07	-0.09	-0.04	0.04	- 0.01	0.44	-0.21	0.58	0.51	6.08	1.86	-0.18
Tm	0.26	-0.41	-0.39	-0.32	-0.33	-0.25	-0.39	-0.32	1.58	0.64	- 0.24	-0.37
Yb	-0.1	-0.19	-0.03	0.21	0.08	1.14	-0.13	0.65	0.16	9.40	1.37	-0.30
Lu	-0.31	-0.38	-0.34	-0.30	-0.27	-0.1	0.39	-0.25	-0.28	1.11	-0.16	-0.41

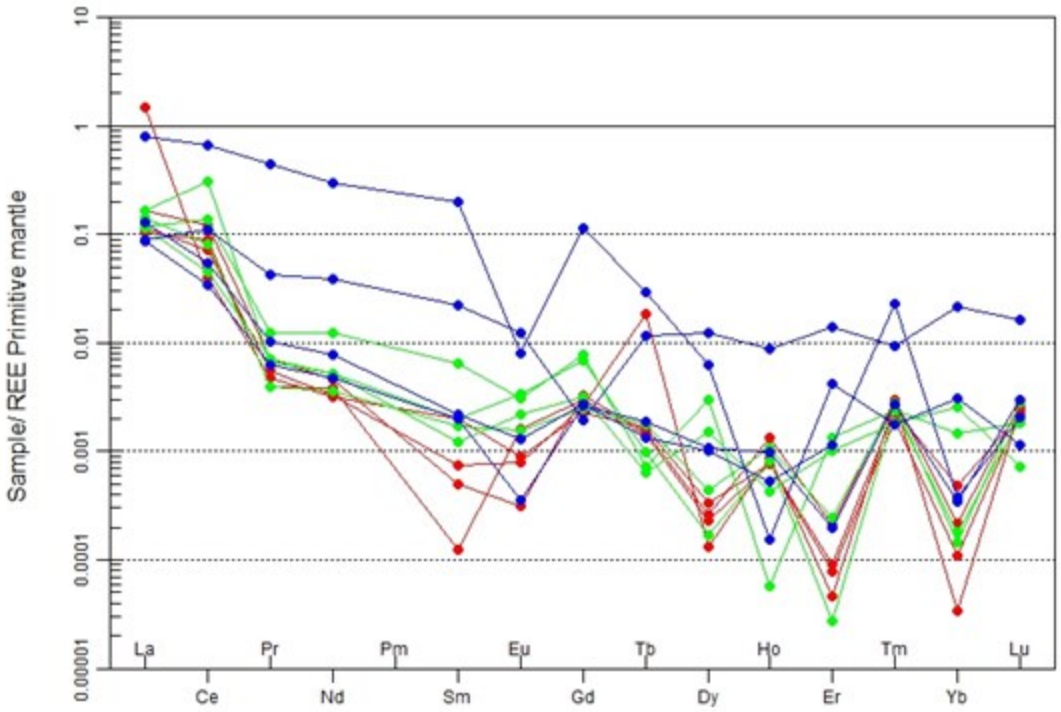


Fig 4.26: Chondrite normalized REE patterns of beryl from pegmatites of parts of Ikara. (Normalization value after McDonough and Sun, 1995).

CHAPTER FIVE

5.0 DISCUSSION, CONCLUSIONS AND RECOMMENDATIONS

5.1 PROTOLITH OF THE GRANITES AND GNEISSES IN THE STUDY AREA

Geochemical composition of the rocks reflects the composition of their source magma and on the basis of distinct geochemical attributes, the granites were classsified as I-type. The differences in chemical composition of the granites and gneisses result from the major input of source materials. Distinct geochemical aspects including high SiO_2 (>70), Na_2O/K_2O, molar A/CNK ratio > 1.1, high Rb (153.37- 310.92) and Sr (135.17-565.07) for the granites and gneisses suggest the derivation of the rocks from crustal materials. Many models for granite petrogenesis assume that only high silica granites (SiO_2>70wt%) are capable of representing pure melts derived from partial melting of crustal rocks (Chappell *et al.* 1987). The result of the trace elements shows that Ba (157.84-727.05) is the most abundant trace element in the rocks; this indicated that the granites and gneisses in the study area harbor some radioactive minerals. The granites and gneisses can be classified according to the presumed origin of the parent magma; as such, the plots of Na_2O/Al_2O_3 against K_2O/Al_2O_3 by (Garrels and Mackenzie, 1971) and that of TiO_2 against SiO_2 by (Tarney, 1977) showed that the samples plotted within the igneous field which indicates that some of the compositional characteristics of sedimentary rocks may be present. However, the origins of I-type magmas are, and always have been in dispute. Most I-type magmas are dominantly crustal in origin as reflected in their oxygen isotope ratios; Thus, the S-I dichotomy in granite typology is unlikely to reflect sedimentary versus igneous sources, but rather the nature of the peritectic minerals entrained by the ascending granitic melts (Clemens *et al.*

2011). The protoliths of the granites and gneisses could have been derived from the partial melting of crustal rocks at low pressure, thus, producing metaluminuous to slightly peraluminuous character. The CaO-NaO-K_2O ternary variation plot shows that the coarse-grained granite samples are the possible sources of the pegmatite fluids through fractionation because they fall on the granite trend based on (Barker and Arth, 1976). Identification of parental fertile granite is an important exploration tool in the search for rare-element pegmatites because their discovery can greatly reduce the search area (Breaks and Tindle, 1996). Fertile granites tend to be silicic (quartz rich) and peraluminuous resulting in the crystallization of Al-rich minerals such as muscovite, garnet and tourmaline (Černý and Meintzer, 1988). More evolved fertile granites contain beryl, ferro-columbite and Li-bearing tourmaline (Breaks and Tindle, 1997). The granitic rocks as shown from this study are metaluminuous to peraluminuous in character. Studies have revealed that many I-type granites have metaluminuous to peraluminuous characteristics (Chappell *et al.* 2012). The metaluminuous nature of the granitic rocks precludes an origin from the melting of a strongly peraluminuous sedimentary protolith; this character requires a metaluminuoous protolith such as the mantle or other igneous sources (Ferré *et al.* 1998).

5.2 RARE EARTH ELEMENTS DISTRIBUTION PATTERN OF THE ROCKS

The REE distribution shows that the rocks are enriched in the LREE and relatively depleted in the HREE and they exhibit negative Eu anomaly indicating that the rocks are fractionated. Magma of such composition is assumed to have evolved extensively. This geochemical character can be attributed to the presence of zircon, apatite as accessory phases in the melt causing depletion in the HREE. The typical profile shown by the granites and gneisses (enrichment in LREE and depletion in HREE) is similar to REE profiles of

other evolved rocks (Solomon, 2014) and (Abdulhamid, 2017). Enrichment of LREE relative to HREE in rock samples is probably caused by the presence of hornblende in felsic melt (Rollinson, 1993) while negative Eu anomaly is due to fractionation of plagioclase in melt (Taylor *et al.* 1986). The REEs pattern of the rocks is typical of the Pan-African granitoids of Nigeria.

5.3 STRUCTURAL CONTROLS ON MINERALIZATION

The significance of structural control on hydrothermal gem formation is determined by the theory that structural processes critically affect and control hydrothermal fluid flow (Hobbs *et al.* 2000; Zhao *et al.* 2009). It is now recognized that the formation of hydrothermal mineral deposit is often the result of interaction between several key processes including structural and geochemical processes (Zhang *et al.* 2008). Studying and understanding key structural factors controlling mineralization in an area could lead to the determination of exploration targets and subsequent discovery of ore bodies (Dugdale, 2004; Liu *et al.* 2010). Rock deformation has been known as a major mechanism responsible for fluid flow in the crust (Sibson, 1994; Cox, 2005). Therefore, the importance of structural control in the exploration for potentially economic viable pegmatites cannot be overemphasized.

The rose diagram plotted from the landsat ETM+imagery (Fig 4.6, page 38) shows orientations that are generally comparable to that of (Ananaba and Ajakaiye, 1989) for the basement rocks of Nigeria. NE-SW is apparent which is consistent with the observations of (Ajakaiye *et al.* 1986; Olasehinde and Annor, 1990; Goki *et al.* 2011) in which they related such trends to deep seated basement lineations.

The rosette diagram plotted shows that the general trend of the pegmatite and joints of the granites are almost in the same direction, this implies that the tectonic forces that led to the fracturing of the outcrop were more pronounced in the NE-SW direction. Therefore, lineaments of NE-SW trends within the granite will help in proceeding further for exploration which is also inline with the works of (Wright, 1976) who suggested that such trends have connections with oceanic fracture zones and may harbor mineralization. The mineralization extends along strike and not along intersection of trends. Though folding and faulting are not prominently displayed on the rocks, the fact that the rocks were fractured (jointing) is an evidence of paleo-tectonic magmatic cycle associated with the Pan-African orogeny (Obaje, 2009). The widespread occurrence of fractures is a characteristic feature of the basement complex tectonics (Oluyide, 1988).

Plots of the granite samples in Rb versus Y+Nb (Pearce *et al.* 1984) occupy the field of Within Plate Granite (WPG) and Syncollisional Granite while that of Nb versus Y occupy an overlap zone between WPG from attenuated continental lithosphere and Ocean Ridge Granite from anomalous ridge segment. This overlap is not of great practical significance since these two granite types have strongly contrasting geological characteristics (Pearce *et al.* 1984). The tectonic setting of the rocks in the WPG and Syncollisional suites indicate probable source from anatexis process of the metasedimentary rocks in the area. This discrimination diagrams are probably a misleading idea to discriminate the tectonic setting for granites in the continental crust (Zhang *et al.* 2007).

5.4 BERYL COMPOSITION AND EVOLUTION OF THE PEGMATITE

The chemical composition of beryl was used to infer the degree of fractionation of the pegmatiites. In beryl from Ikara area, Na dominates (0.18-0.30wt% Na_2O) over K (0.02-

0.22wt% K_2O) and the relationship Na_2O/K_2O always exceed unity which indicates that these are sodic beryl varieties according to the scheme of (Černý, 1975). (Černý, 1975), (Hawthorne and Černý, 1977) assigned this type of beryl to pegmatites with albite-rich assemblages but poor in alkalis.

Beryl (3) has the highest Cs and Rb, lowest Na/Cs ratio and lowest Mg/Fe contents among all the studied sample of beryl, this reflect the highest degree of evolution among the studied pegmatites. Based on the lowest Cs and Rb, highest Na/Cs ratio and highest Mg/Fe contents among all the beryl samples analyzed, the lowest degree of evolution is inferred from Beryl (1). This suggest that Beryl (1) formed in the early stages of crystallization of the various pegmatites and incorporated less Na, Rb and Cs compared with Beryl (2) and Beryl (3) which have the highest Na, Rb and Cs contents and the lowest Na/Cs ratio which is consistent with indicators of evolution obtained in previous studies (Černý, 2002; Černý*et al.* 2003; Sardi and Heimann, 2014). Among the pegmatites with the highest Cs contents in beryl are pegmatites from the Czech Republic (~35000ppm Cs, (Novák and Filip, 2010), the Tanco pegmatite (~22500Cs, (Černý and Simpson, 1977), Pegmatite from Greer lake, Canada (~11000ppmCs, (Černý and Turnock, 1975) and the Salinas and Piauhy pegmatites, Minas Gerais, Brazil (~30500ppm Cs, (Aurisicchio *et al.* 1988; Deer *et al.* 1997).

To understand the relative evolution of the pegmatite as recorded by beryl, the chemical composition of this beryl was compared with beryl of similar colour from pegmatite worldwide. Alkali contents in beryl from pegmatites of parts of Ikara reflect a low degree of melt evolution compared with pegmatitic beryl worldwide. Na, Cs and Rb contents are among the lowest measured in pegmatitic beryl of similar colours worldwide and similar to

those in beryl from pegmatites in the Czech republic (Colombo and Lira, 2006), Italy (Bocchio *et al.* 2009) and Argentina (Sardi and Heimann, 2014). For example, the highest Cs (1022.5ppm) and Na_2O (0.30wt%) content in Beryl (3) from pegmatites of parts of Ikara are in the order of magnitude lower than those measured in the greenish beryl of Tanco pegmatites (< 2.4wt% Cs_2O, 1.8wt% Na_2O, (Černý and Simpson, 1977). Rubidium contents in beryl from pegmatites of parts of Ikara are similar or higher than in some beryl contents of the Bratislava and Bojna pegmatites, Slovakia (Uher *et al.* 2010), Erongo pegmatite, Namibia (Lum *et al.* 2016) and Pampeana pegmatite, Argentina (Sardi and Heimann, 2014) and lower than those in the evolved pegmatites from the Czech Republic (Novák and Filip, 2010) that have the highest Rb content (~1500ppm). Cs/Na ratio along with Rb/Ti and Mg/Fe demonstrates that beryl from Ikara area reflect a lower dergree of evolution compared to the Minas Gerais pegmatite. Mn contents in the beryls attain higher values than those in beryl from other pegmatites except that of Velasco pegmatite (Sardi and Heimann, 2014) which are similar. Beryl from pegmatites of parts of Ikara has much lower Rb (< 31ppm) contents as compared to that in the Tanco and Altai No. 3 pegmatites. Overall, Beryl (1) has lower Rb content and low Rb/Ti values than Beryls (2) and (3). The extremely low Rb contents in beryl from pegmatites of parts of Ikara is consistent with a very low degree of evolution compared to the Tanco pegmatites (Manitoba, Canada) and Altai No. 3 pegmatites (Altai, China).

Compositionally, this beryl is similar to those from a pegmatite in the Punilla district, Argentina and velasco district, Argentina. The evolution trends in the beryls show an increasing Cs and Cs/Na with decreasing Mg and Mg/Fe from less evolved to more fractionated pegmatites. Such variation is in accordance with the general fractionation

behavior of these elements in magmatic systems and is in good agreement with previous studies of beryl in pegmatitic system (Lum *et al.* 2016; Sardi and Heimann, 2014). The trend of alkali variation conforming to the patterns established for beryl from rare-element pegmatites may be atttribited to magma fractionation.

5.5 RARE EARTH ELEMENTS IN BERYL

Rare earth element patterns provide a link between the mineralogy and geochemical indicators of magmatic evolution and may explain processes occurring during late stage magmatic fractionation. Despite the sum of the REE of the Ikara beryl being typically low, the discontinuous pattern of the REE is consistent. The discontinuous LREE-enriched patterns occur with a break in slope at Pr to shallower and positive trends with moderate negative Eu anomaly. Discontinuous REE patterns occur in volatile and flux-rich evolved igneous rocks and accessory minerals (Liu and Zhang, 2005). In contrast, beryl from the Velasco pegmatite has patterns characterized by slightly decreasing LREE contents, strong negative Eu anomaly and slightly increasing HREE while that of the Namivo pegmatite has decreasing HREE with a pronounce negative Eu anomaly. The moderate negative Eu anomalies in beryl from pegmatites of parts of Ikara are likely the result of the incorporation of Eu into plagioclase. The Eu anomaly is consistent with a late stage evolution when all plagioclase in the granitic pegmatite had already fractionated Eu.

(Neiva and Neiva, 2005) showed that the concentration of REE in beryl increases from the external zone to the late core of the pegmatite which suggests that REEs in beryl can provide information about the evolution of the crystallizing melt. Considering the alkali elements as good indicators of relative evolution, the findings that late beryl (Beryl (3)) is rich in REE as compared to early formed beryl (Beryl (1) and Beryl (2)) is consistent with

the study of beryl from Mozambique by (Neiva and Neiva, 2005). This study suggests that fractional crystallization produces an increase in the REE contents of the pegmatite in disagreement with other studies (Morteani *et al.* 1995; Sardi and Heimann, 2014). The general increase of the REE with increasing fractionation (Fig. 4.26, page 82) indicates a slight increase in the residual siliceous or hydrous fluids. However, the fact that an early beryl also shows high REE content indicates that this behavior is not completely systematic.

5.6 CONCLUSIONS

The geologic mapping of the study area reveals that the lithologic units in the area include: granites, gneisses, quartzite and schist. Structural overview of the lithologic units revealed that the study area has witnessed several episodes of deformation leading to re-orientation and obliteration of the pre-existing structural framework.

The rock samples vary in composition from metaluminuous to weakly peraluminous (A/CNK<1.1); therefore, the primary parental magma of these samples were likely metaluminous. Geochemical data interpreted strongly indicated an igneous protolith for the rocks and also identified the granitic nature of the rocks. The geochemical data of the rock samples show that there is no danger in this material with respect to harzadous metals. The arsenic and lead contents are consistently very low. The rocks of the district are of no toxic danger to the environment.

Results of structural analysis indicate definite structural control for the pegmatite emplacement and make it possible to delimit prospective areas. Mineralization in the study area is structurally controlled by the dykes, fractures and veins which provide the structural

framework for epigenetic mineralization in the study area. From the lineament analysis, it is evident that the trends of lineament have significant control on pegmatite emplacement. Lithological controls for mineralization were also recognized with mineralization common by association with the granites

The major and trace element compositions of beryls in the pegmatites of the Ikara area reflect compositional changes in the magmatic melts during crystallization. The relative evolution of beryl among the pegmatites from the Ikara area is well described by the alkali element contents (Rb, Cs, Na) and the Na/Cs ratios. Beryl (3) has the highest Rb and Cs contents, the lowest Na/Cs ratios and among the lowest Fe+Mg contents reflecting the highest degree of fractionation among the pegmatites. Beryl (1) evidences the lowest degree of evolution based on the low Cs and Rb contents and high Na/Cs ratios in beryl. This reflects the crystallization of Beryl (1) during an early stage and Beryl (2) and (3) during the late stage of crystallization of the melt. In general, the degree of pegmatite fractionation increases to the North as indicated by the geochemistry of beryl from pegmatites of parts of Ikara. Therefore, fractionation of the pegmatite field increases from the South to the North; this suggest that the source pluton may be located to the South of the study area at depth.

Late beryl has the highest REE contents of all the beryl analysed from pegmatites of parts of Ikara which suggest that fractional crystallization produced an increase in the REE contents of the pegmatitic melt. The host rocks and the beryl samples have similarities in geochemical signatures, that is, enrichment in LREE and depletion of HREE with negative Eu anomaly indicating that the fluid that lead to beryl mineralization might have originated from the host rocks during the hydrothermal process.

5.7 RECOMMENDATIONS

This dissertation serves as a basis for further studies. For future studies, the following aspect needs to be investigated:

1. Additional studies of the beryl with an electron probe micro-analyser would further the geochemical understanding of the pegmatite, especially the content of light elements.
2. There is a need to carry out a detailed geophysical survey of the area to determine the areal extent and other hidden gem minerals likely to be associated with this pegmatite using ground penetrating radar.
3. Backscattered electron images of beryl crystals should be undertaken to show the lateral chemical variation in the crystals.

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