GEOLOGY, GEOCHEMISTRY AND GENESIS OFAMETHYST MINERALIZATION AND ASSOCIATED ROCKS IN DUTSEN BAKURA HILL, NORTHCENTRAL NIGERIA

By

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M.Sc/Sci/03276/2009-2010

THESIS SUBMITTED TO THE SCHOOL OF POSTGRADUATE STUDIES AHMADU BELLO UNIVERSITY, ZARIA; IN PARTIAL FULFILLMENT OF THE REQUIREMENTS FOR THE AWARD OF MASTERS OF SCIENCE DEGREE IN GEOLOGY

DEPARTMENT OF GEOLOGY
FACULTY OF SCIENCE
AHMADU BELLO UNIVERSITY,
ZARIA

MAY, 2014

DECLARATION

I declare that the work in this thesis entitled "Geology, Geochemistry and Genesis of Amethyst Mineralization and Associated Rocks in Dutsen Bakura Hill, NorthCentral Nigeria" has been carried out by me in the Department of Geology. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any other institution.

…… ……

Solomon, Anche Rose Date

CERTIFICATION

This thesis entitled "Geology, Geochemistry and Genesis of Amethyst Mineralization and Associated Rocks in Dutsen Bakura Hill, NorthCentral Nigeria" by Rose Anche Solomon meets the regulations governing the award of the degree of Masters of Science [Geology (Mineral Exploration)] of the Ahmadu Bello University, and is approved for its contribution to knowledge and literary presentation.

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DEDICATION

This project work is dedicated to the Most High God, the all knowing God for His protection, guidance and inspiration.

My parents Mr. and Mrs. Solomon Anche, this journey has indeed been a long one, you made me see reasons why I should not give up my dreams and aspirations. I love you so much. And my three brothers, John Anche Solomon, Gideon Idzi Solomon and Paul Aku Solomon they are indeed rare gems in my life.

ACKNOWLEDGEMENT

I wish to acknowledge with profound gratitude the tireless and endless contribution of my major supervisor Dr. A. A. Ibrahim for his invaluable assistance, support and guidance in the course of the work. Also, I appreciate my second supervisor, Dr. P. O. Ogunleye who assisted immensely, always at hand to attend to pressing academic questions and for reading the work.

Let me acknowledge the moral support of the current Head of Department, Dr H. Hamza and the former Prof. U. A. Danbatta. Prof. I. Garba, Dr A. E. Ikpokonte, Dr. E.A. Bala, Dr. S.A. Alagbe, Dr. V.E. Obiosio, Dr. T. Najime, Dr. J. Ayok, Dr. I. Yusuf, Dr. M. L. Garba and the P.G coordinator Dr. I. Hamidu.

I want to appreciate Mr. Shehu S. Magaji who is a friend that sticks closer than a brother, your sacrifices are immeasurable. To my colleagues and friends: Bala Musa Girei, Rakiya Bello-Bayero, Usman Abubakar, Abubakar Tahir, K'tso Nghargbu, Helen Onaji, Juliet Akoh, Mahmud Muhammad Abdul, Aminu Kakangi, Hidayat Umar and a host of others too numerous to mention, I owe a big salute.

Let me appreciate in a special way my family Elder and Mrs. Solomon Anche, for making me believe in myself and their endless financial contribution to this course, my beloved brothers John Anche Solomon, Gideon Idzi Solomon and Paul Aku Solomon; you guys are wonderful.

I must not forget the academic staff and non-academic staff of Nuhu Bamalli Polytechnic, Zaria, most of who are my friends, I appreciate you all. To Mr. Godwin Amedu who despite tight work schedules, made out time to ensure that I got my work on time on every occasion, I say a big thank you. To those who by commission or omission I could not mention their names who have contributed through prayers I say may God reward you.

ABSTRACT

Dutsen Bakura Hill is located within the North-Central part of the Nigeria Pan-African Orogenic belt. The Dutsen Bakura Hill is an example of an amethyst bearing vein mineralization in an uplifted faulted metamorphic terrain. The host rock is sheared gneiss that has been affected by Pan African tectonism. These tectonic events resulted into fracturing, faulting, folding and metamorphism of the rocks in the area. The host rocks of the amethyst veins are marked by considerable shearing and breciation attributed to brittle deformation.The vein is a late stage epithermal deposits with a NE-SW trend consistent with the Pan-African structural trend. Mineralization in the vein consists of bands of milky quartz and amethyst formed in a two stage sequence considered as a gneissic makeover of quartz. Major element distribution indicates an increase in SiO_2 content from the granite gneiss host to the core of the vein. Incompatible trace and lithophile elements ratio Ba/Nb, Nb/Ta, Zr/Hf and Pb/Nd values in granite gneiss and sheared gneiss are similar but differ from that of milky quartz and amethyst. There is a decrease in concentration of some trace elements such as the lanthanides from the gneissic host to the core of the vein as the SiO_2 content increases. The REE distribution pattern in the hostrock is marked by enrichments of LREE, depletion of HREE and marked Eu anomaly with slight positive Ce anomalies. On the other hand, the mineralized vein shows no pronounced negative Eu anomaly and it REE pattern is irregular, with the characteristic REE tetrad effect. The oxygen isotope data of the quartz extracted from the granite gneiss and that of the milky quartz and amethyst is 7.1‰, 12.1‰, 17.1‰ respectively. There is a trend from low to high oxygen isotope values from the granite gneiss to the milky quartz and amethyst within a single filling phase. The oxygen isotope signature constrained the source of the vein material to greywackes and siliciclastics rocks. Furthermore, the oxygen isotope results constrained the mineralizing fluid within the range of metamorphic fluids with possible involvement of meteoric fluid. The amethyst mineralization in Dutsen Bakura is thus considered as precipitated from silica-rich fluids produced by deformation during cataclastic metamorphism.

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CHAPTER ONE

INTRODUCTION

1.1 BACKGROUND OF THE STUDY

The geology of gem deposits is focused on understanding the rare and exceptional geologic conditions that give rise to gem-quality materials. These conditions may include the availability of occasionally uncommon major constituents, the presence of adequate chromophores, limited concentrations of undesirable elements, open space, an environment conducive to forming crystals of sufficient size and transparency, and a favourable environment for mining.

Amethyst is the violet variety of α-quartz. The name is from the Greek word a-methy-stos meaning one who does not get drunk, due to its alleged ability to protect its owner from the negative effect of alcohol consumption.

The role of trace amounts of iron and radiation in the formation of amethyst colour has been broadly established, although details about the responsible colour centres are still unknown (Rossman, 1994). However, the origin of the colour has been attributed to a number of different factors; for example Cohen (1989) has provided evidence of the nature of the colour centre in quartz and its relationship to the structure of the mineral.

Amethyst is found in a variety of geological environments such as alpine clefts, epithermal veins, miaroles in granitic rocks, or geodes in basaltic lavas. There are miscellaneous occurrences in calcareous rocks, sandstone and quartzite in which there is no genetic connection with igneous rock. Occurrence of amethyst has been reported also in an agatized tree of Yellowstone Park and Arizona (Gilg *et al*., 2002).

Brazil and Uruguay are the world leaders in the production of gem quality

amethyst from geodes in basaltic rocks of the Parana´ Continental Flood Basalt Province. In Brazil, the deposits of economic interest are found in the Ametista do Sul region, south of Iraı' and in the northern tip of the State of Rio Grande do Sul. Amethyst deposits are located at Artigas in the north-western part of Uruguay near its border with Brazil.

Gemstones including amethyst occur in the Nigerian Basement Complex. The gemstones are associated with pegmatite dykes, veins, and alluvium (Ike, 1988; Danbatta, 1991; Fajobi, 1999).

Moreover, it is highly unlikely that the amethyst mineralization would be the same everywhere; different localities can produce a unique amethyst to that particular region or even to that particular vein. This fact necessitates a closer look at the amethyst mineralization in the study area with a view to establishing its nature, extent, genesis and economic potential. The knowledge of the geology and geochemistry of the study area is necessary for the development of a proper strategy for the exploration and exploitation of this deposit. However, understanding how gem deposits form can provide guidelines for exploration.

1.1.1 Chemistry of amethyst

The violet colour of amethyst has been attributed to the presence of trace elements as inclusions in the quartz matrix, or as substitutes for silicon, or in interstitial positions in the quartz crystal lattice, and to the exposure of quartz to natural ionizing irradiation (Lehmann and Moore, 1966, Lehmann, 1971, Cohen and Makar, 1982, and Partlow and Cohen, 1986). Aluminum and iron are the trace elements usually assigned as substitutes for silicon in the quartz lattice. If Al^{3+} or Fe^{3+} replace Si^{4+} in the centre of a SiO_4 tetrahedron (designated as Al_{Si}^{3+} or Fe_{Si}^{3+}), the charge deficiency requires an interstitial positive monovalent ion in the vicinity to neutralize the electric charge. H^+, Li^+, and Na^+ are usually considered as charge compensators

(Bahadur, 1993, 1994 1995, 2003 and 2006, Guzzo *et al.*, 1997, Bachheimer, 1998). Interstitial Fe^{4+} was also proposed as charge compensator for Fe_{Si}^{3+} (Lehmann, 1971). The formation of Fe_2O_3 micro-inclusions and the presence of oxygen vacancies were also used to explain the formation of yellow colour of some amethysts after heating to form citrine (Dotto and Osotani, 1991). The colour in amethyst is specifically attributed to the Fe^{4+} ion in an interstitial site, with absorption bands at 3.54, 2.28, and 1.30 eV (Hassan and Cohen, 1974). However, formation of amethyst requires both the presence of substitutional $A1^{3+}$ and suppression of the A_l, A_2, and A_3 colour bands, which it creates (Partlow and Cohen, 1986). Cohen, (1985) proposed that amethyst formed in the following manner accounts for the above stated properties: $A1 - O^- \rightarrow A1 - O^o + e^-$ (formation of trapped holes centre A_l, A_2, and A_3 by ionizing radiation). $Na^+ + e^- \rightarrow Na^o$ (interstitial alkali ion traps electron centre). $Fe_i^{3+} \rightarrow Fe_i^{4+} + e^-$ (quenching of trapped hole on aluminium by electron furnished by $A1 - O^o + e^- \rightarrow A1 - O^-$ radiation induced oxidation of interstitial ferric iron).

Lattice distortion may also contribute for the formation of colour in amethyst. This is expected if an iron atom replaces a silicon atom. The ionic radius of the iron is large enough to cause distortions in the tetrahedral configuration of the quartz lattice. The iron also has an electronic configuration very different from the one of silicon. Its outer electrons are 3d64s2, whereas the aluminum outer electrons are 3s22p1, like the silicon radius, 3s22p2. This difference causes additional distortions in the lattice in the vicinity of an iron atom because the tetrahedral configuration causes crystal field splitting of the 3d-orbitals of iron into two groups, with a lower energy splitting difference. Adekeye and Cohen, (1986) demonstrated that the interstitial ferric ion is located in specific channels in the α-quartz structure, particularly within the $(10\bar{1}1)$ rhombohedral plane.

Amethyst is very commonly polysynthetically twinned according to the Brazil law (twin plane $\{11\bar{2}0\}$; composition plane $\{l0\bar{1}l\}$) only, whereas other varieties of α-quartz commonly contain Dauphine′ twins or combined Dauphine□-Brazil laws (Frondel, 1962). The positive rhombohedral (r) faces of the Brazil twinned crystal have been observed to contain higher ion concentrations than other zones of the same crystal (Schlossin and Lang, 1965). It has long been noted by Frondel (1962) that amethyst coloration is more intense in r faces of polysynthetically twinned crystals, correlating with the preferential concentration of iron in this zone (Fig.1, 2). Adekeye and Cohen, (1986) proposed that Brazil law twinning in amethyst forms in response to stress on the α-quartz structure caused by incorporation of ferric iron. Therefore, the colour, iron content, and twinning in amethyst are interrelated. Heating studies by (Cohen and Hassan, 1974) demonstrated that loss of colour in amethyst occurs rapidly at 380°C. As the colour was restored by irradiation, this transition is apparently electronic. Heating to 400-450°C or above produced irreversible loss of amethyst colouration, suggesting thermally driven diffusion of iron from the interstitial sites **(**McArthur *et al.*, 1993).

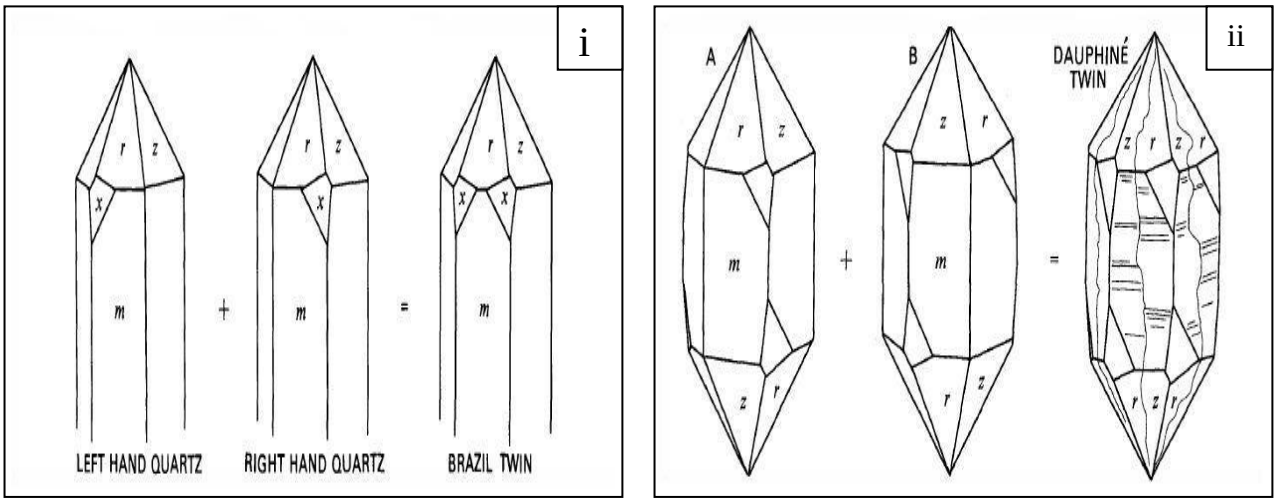


Figure 1: Brazil (i) and Dauphine (ii) twinning inquartz structure (Vos, 1976).

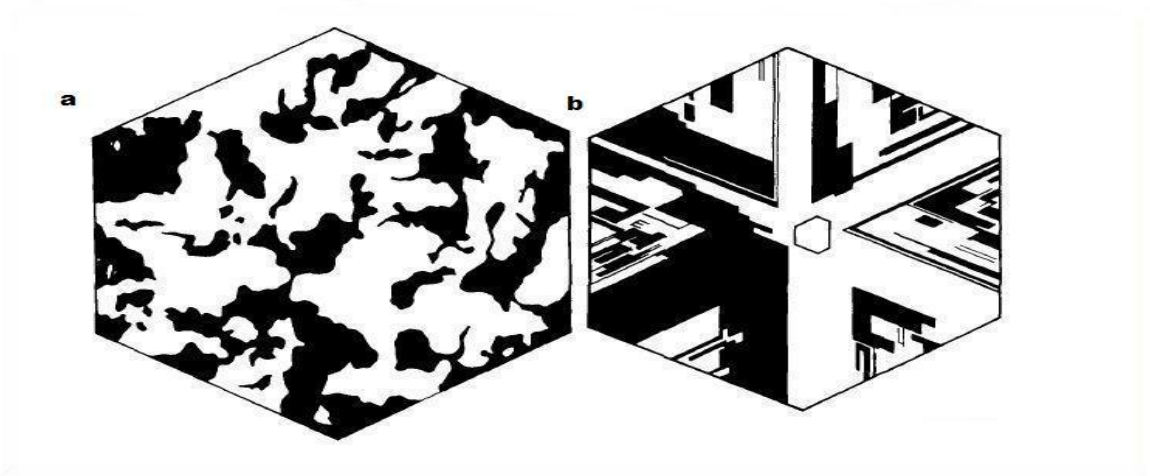


Figure 2: The contrasting character of (a) Dauphine twinning and (b) Brazil twinning (After Leydolt, 1855). (a) and (b) above represents the cross-sectional views.

1.2 LOCATION AND ACCESSIBILITY

The study area lies about 30 kilometres southwest of Zaria in Igabi Local Government Area of Kaduna State and lies within Sheets 124 (Igabi NE), approximately covering an area of 115.57 km^2. It is bounded by Latitude 10°55□00□ and 11°00□00□N and Longitude 7°55□00□ and 8°00□00□E.

The area is accessible through motorable feeder road which extend from Maigana to Ungwan Rimi on the Zaria-Jos road. Access to the Dutsen Bakura Hillamethyst mineralized vein and most part of the area is by numerous foot paths and cattle tracts (Fig. 3).

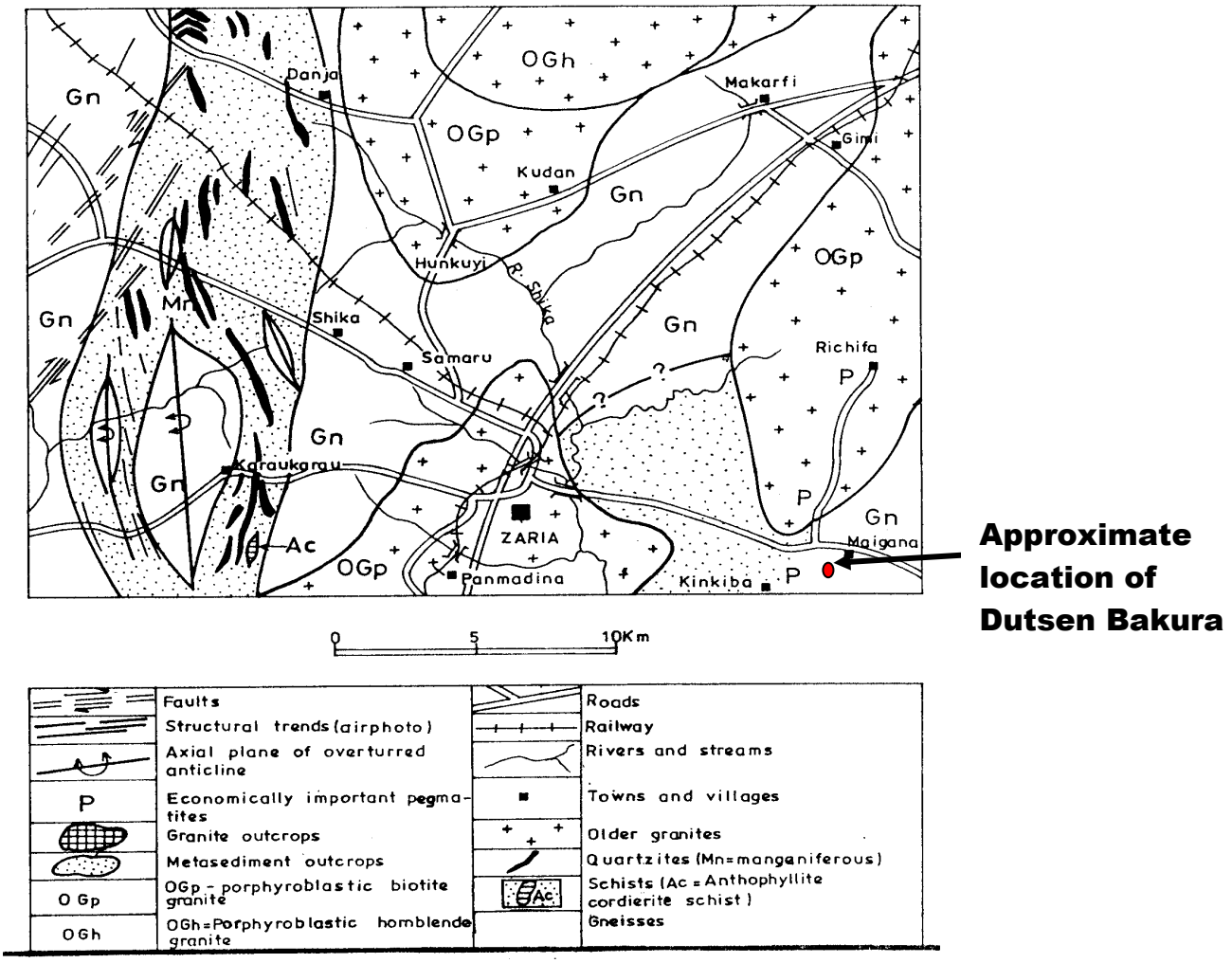


Figure 3: Approximate location of the study area in Geologic map of Sheet 102 (Zaria) (after Webb 1972)

1.3 RELIEF AND DRAINAGE

The study area is part of the vast, dissected plain of northern Nigeria. The relief of the area is generally flat to gently undulating punctuated by isolated hills like the Dutsen Bakura HillHill with an altitude of 734 m then flat lying outcrops like the Ungwan Rimi hill and the Dutsen Gidan Rano. Outcrops in the area are poorly exposed and are mostly weathered. The altitude of the study area ranges from 600 to 740 m above sea level. Rivers in the study area, like river Rafin Gadan Maigana and Rafin Gadan Tofa are tributaries to Kubani River which is located outside the study area. The rivers in the Dutsen Bakura HillHill area are ephemeral during the period of field work; these river channels were dry in the dry season. The rivers generally flow in all direction from Dutsen Bakura HillHill hence exhibiting a radially, dendritic drainage pattern (Fig. 4).

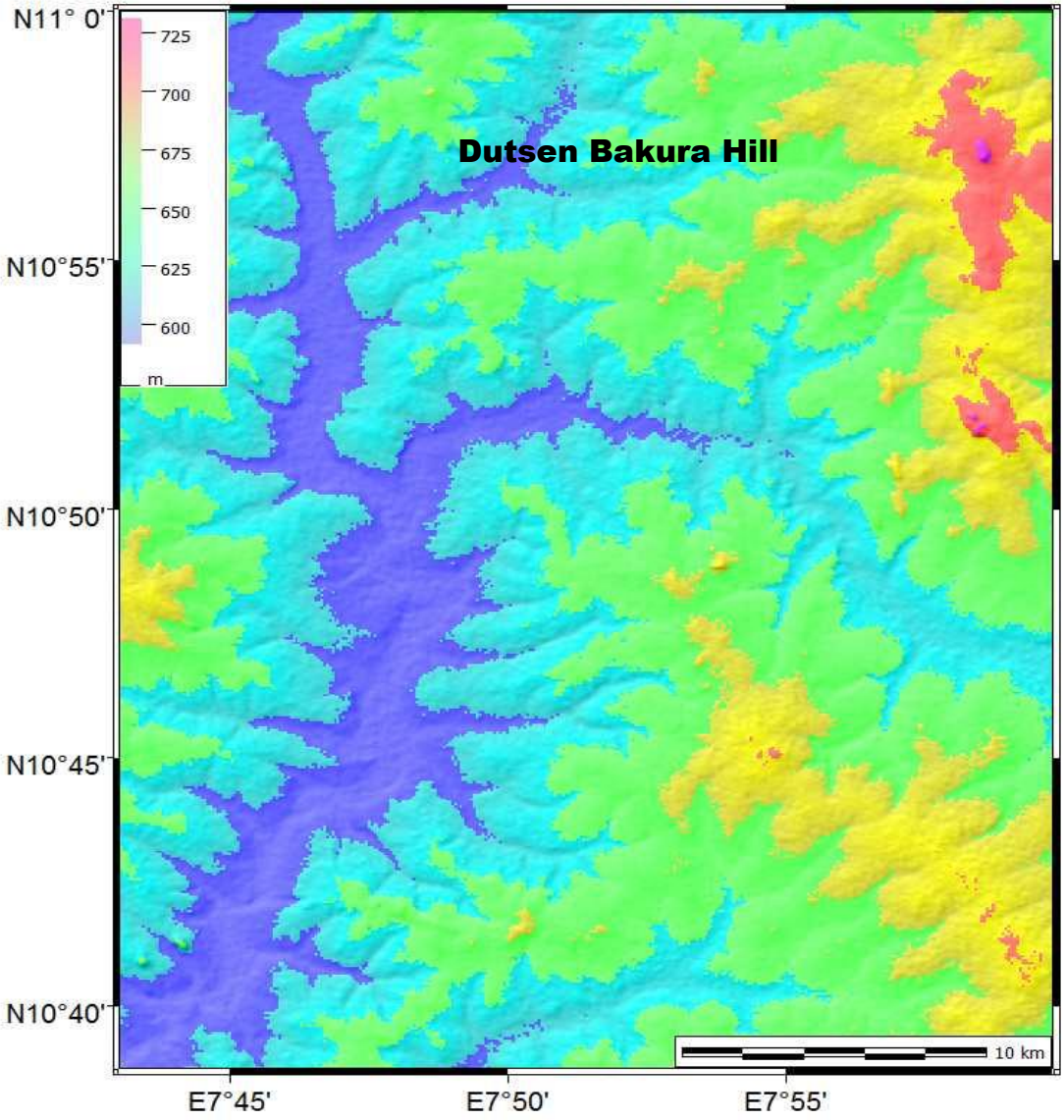


Figure 4: Relief and drainage pattern 3D satellite image of Dutsen Bakura Hill

1.4 CLIMATE AND VEGETATION

The study area lies within the Guinea climatic belt of Nigeria characterized by distinct wet and dry seasons (Boubour *et al.*, 1984).The wet season begins in late April and ends in September when it becomes mostly hot. The dry season during which there is no rainfall occurs from October to March. Day time temperatures range from 12 to 44ºC (IAR Metrological Unit, 2011) but during the Hamattan (December-January), it can be relatively cold, windy and dusty. The area has an average annual precipitation of 1107.2 mm (IAR Metrological Unit, 2011).

The area lies within the Northern Guinea Savannah belt of Nigeria and it is characterized by open, sub-humid broad - leaved Savannah woodland vegetation with short to medium grasses. The vegetation on the whole has been greatly altered by poor land-use practices which includes over grazing, bush burning, falling of trees for firewood and clearing of bushes for cultivation. Some common trees species in the areas include locust bean (*Parkia biglobosa*), baobab (*Adansonia digitata)* and Shea butter tree (*Butyrospermum parkii* or *Vitallaria paradoxin*).

1.5 SETTLEMENT AND LAND USE

The most prominent settlements in the area are Maigana, Soba, Katuka and Ungwan Rimi. The resident of these settlements comprise the Hausas and the Fulanis. Farming which is normally practice during the wet season is their major occupation. In addition, dry season farming is practiced mostly in the wetland (Fadama) that fringes river channels. The other settlements in the area are Sabon Kaura, Gidan Rano and Sabon Bakura. The land is cultivated for maize, sorghum, millet, sugarcane and rice. The Fulanis however commonly practice animal husbandry. The flood plains and local swamps are used for irrigation during the dry season mostly for cultivation of tomatoes, pepper and vegetables. A small proportion of the population

undertakes occasional artisanal mining of the amethyst during the dry season for income to sustain their families.

1.6 PREVIOUS WORK

There appears to be no previous geological work on the occurrence of amethyst in the study area. However, Olatunji (1968) reported the occurrence of amethyst in south-western Zaria where amethyst occurs as veins in Dala, Panmadina, Hange Hill and Zaria aerodrome. He described them as near surface vein filling mineralizations which were formed by crystallization of residual solution in fissures and cavities of the granite gneiss resulting from regional igneous activities.

The review and description of the Basement Complex of Nigeria was also done by several workers including Grant (1971), Oyawoye (1972), Rahaman (1976) and McCurry (1970; 1976). McCurry and Wright, (1971) divided the granitic bodies on Sheet 21 on a scale of 1:100,000 into syntectonics and late tectonic granites on the basis of field observations. McCurry, (1971) worked on Zaria Sheet 21 to determine the nature of the Pan-African orogeny in northern Nigeria. She suggested that the whole area was affected by two successive phases of intense deformation which resulted in tight isoclinal folding trending in (i) East-Northeast-west-southwest and (ii) North-South axes. She further observed that the crystalline basement was reactivated and the supracrustal cover regionally metamorphosed. Two phases of progressive metamorphism accompanied the deformation, which were separated and followed by static metamorphic phases. She concluded from the structural and metamorphic evidence that the Pan-African event reached the status of an orogeny in North-Western Nigeria.

Ike, (1988) worked on the petrogenesis of Older Granite Batholith in Zaria area. He observed that the abundance of pegmatite in the marginal zones of the batholith as well as its

roof zones is a pointer to late stage availability of excess water and volatiles during the formation of that rock.

Garba, (2002) studied the geochemical characteristic of gold mineralization near Tsohon Birnin Gwari in northwestern Nigeria. Based on REE pattern, he proposed that the fluids are of crustal origin which were forced along the Kalangai transcurrent fault and subsequently channeled to depositional site via subsidiary shear zones during the late Pan-African (600±150 Ma) thermo-tectonic event. He noted that the geological setting and geochemical character of the mineralization are similar to what have been reported from Bin Yauri area of northwestern Nigeria and many area of Archean and younger mesothermal gold mineralization in the world.

McArthur *et al.,* (1993) studied the Thunder Bay Amethyst Mine which exploits a vein system in which the main zoned sequence consists of chalcedony, colourless quartz and three to four stages of amethyst. The main sequence surrounds fragments of a brecciated earlier sequence containing chalcedony, colourless quartz, and prasiolite, which appears to be a thermally bleached amethyst. These authors reported that the vein system occupies a fault in Archean granodiorite and is associated with a narrow zone of chloritic and hematite alteration overprinted by weak argillic alteration. They are of the opinion that the amethyst deposits were formed from basinal brines expelled from Sibley Group sediments. The brines dissolved silica by alteration processes accompanying their passage through granitic basement rocks in basin marginal faults. Amethyst was deposited on mixing with meteoric water. At the Thunder Bay Amethyst Mine, this limit is no higher than approximately 115° C and may be as low as approximately 90° C.

Gilg e*t al.,* (2002) worked in the Ametista do Sul area, Rio Grande do Sul, Brazil, amethyst-bearing geodes which are hosted by an approximately 40 to 50 m thick subhorizontal high-Ti basaltic lava flow of the Lower Cretaceous Parana□ Continental Flood Basalt Province.

They discovered that the typically spherical cap-shaped, sometimes vertically elongated geodes display an outer rim of celadonite followed inwards by agate and colourless and finally amethystine quartz. Calcite formed throughout the whole crystallization sequence, but most commonly as very late euhedral crystals, sometimes with gypsum, in the central cavity. Their studies showed that fluid inclusions in colourless quartz and amethyst are predominantly monophase and contain an aqueous liquid. Two-phase liquid–vapour inclusions are rare. And they concluded that the most likely source of silica, calcium, carbon, and minor elements in the infill of the geodes are the highly reactive interstitial glass of the host basalts leached by gas-poor aqueous solutions of meteoric origin which ascended from the locally artesian Botucatu aquifer system in the footwall of the volcanic sequence. The genesis of amethyst geodes in basalts at Ametista do Sul, Brazil, is thus considered as a two-stage process with an early magmatic protogeode formation and a late, low temperature infill of the cavity.

Pati e*t al.*, (2007) studied the Giant quartz veins occurring in the Archean Bundelkhand Craton (29, 000 km^2) which represent a gigantic Precambrian (approx 2.15 Ga) silica-rich fluid activity in the central Indian shield. They observed that the veins show imprints of strong brittle to ductile–brittle deformation, and in places are associated with base metal, gold incidences and pyrophyllite-diaspore mineralization. Base on the geological and geochemical data, these authors proposed that the giant quartz veins were emplaced as a result of some tectonically controlled polyphase hydrothermal fluid activities.

Lauren *et al.*, (2010) studied the stable isotopes (C, O, S) and mineralogy of the world-class amethyst-geode deposits of the Los Catalanes gemological district, Uruguay. These authors attempted to establish the nature of the processes operative during mineral deposition. Based on the variations in the $\delta^{18}O$ values of silica minerals in geodes (chalcedony, quartz and amethyst),

which are much larger (21.2–31.5‰) than that of the Ametista do Sul area of southern Brazil, they attributed the mineralizing processes to a post-eruption environment characterized by low temperature and strong interaction of the lava flows with meteoric water.

1.7 AIM, OBJECTIVES AND SCOPE OF PRESENT WORK

The present study focuses on the geology, the geochemistry and oxygen isotope characteristic of the amethyst mineralization of the study area with a view to formulating a model for its origin and to determine the geological controls of the mineralization.

The work involves the study of the field distribution of the various lithologic units and their petrography. Geochemical analysis of the rock and mineral samples for major and trace elements were carried out together with oxygen ($\delta^{18}O$) isotope analysis. The objectives of the research therefore are:

i) to establish the general geological setting of the amethyst mineralization

ii) to produce a detailed geological map of the area on a scale of 1:10,000.

iii) to determine the protolith of the source of the rock hosting the amethyst mineralized vein.

iv) To constrain processes operative during the formation of the amethyst mineralization.

This will involve:

a) Satellite images study of the area

b) Geological mapping and systematic collection of representative rock samples.

c) Petrographic, (thin section and hand specimen) studies of the lithologic units.

d) Geochemical analysis using XRF, and ICP-Mass spectroscopy techniques to generate major, trace and rare earth element data.

e) Oxygen isotope analysis of the host rock, milky quartz and amethyst samples.

CHAPTER TWO

LITERATURE REVIEW

2.1 INTRODUCTION

Nigeria lies in the extensive region east of the West African Craton and northwest of the Congo Craton which was affected by the Pan-African orogeny about 600±150 Ma. The Nigerian Basement Complex lies to the south of the Tuareg shield. Evidence from the eastern and northern margins of the West African Craton indicates that the Pan-African belt evolved by plate tectonics processes which involved the collision between the passive continental margin of the west African craton and the active continental margin (Pharusian belt) of the Tuareg Shield about 600 Ma ago (Burke and Dewey, 1972; Leblanc, 1976; 1981; Black *et al*., 1979; Caby *et al.*, 1981). 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 in the reactivated part of the belt.

The basement complex of Nigeria comprises of three (3) broad lithological groups: The Precambrian Basement Complex composed mainly of migmatite gneiss, Older Granites and metasediments (schist belt); the Triassic-Jurassic anorogenic Younger Granite province of north-central Nigeria (Figure 5). Other rocks comprising the geology of Nigeria are the sedimentary basins of Nigeria: these are Chad basin of the northeast, Sokoto basin of the northwest, the Niger-delta in the south, the Benue trough linking the Chad basin to the Niger-Delta and the Niger (Nupe) basin forming an aborted link from the Sokoto basin to the Niger-Delta (Rahaman, 1989).

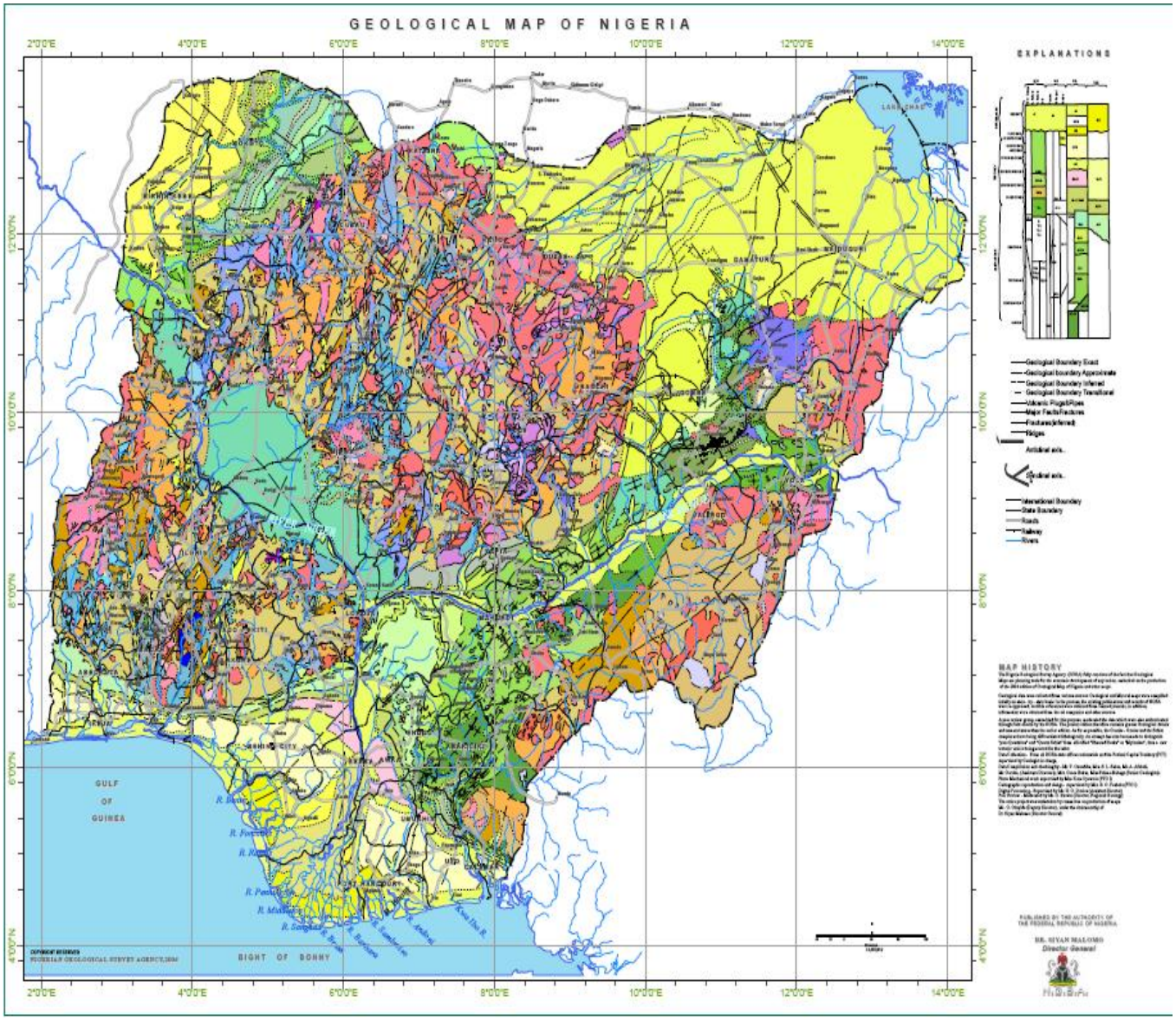


Figure 5: Generalized geological map of Nigeria showing the different geological units (after Nigeria Geological Survey Agency, 2004)

The Nigerian Basement Complex forms the southern part of the Trans-Saharan mobile belt (Caby, 1987) of Neoproterozoic (750-500 Ma) age situated between the Archean-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. 6). The basement complex is one of the three major lithological components that make up the geology of Nigeria (Fig. 4).The Nigerian Basement Complex forms a part of the Pan-African mobile belt and lies between the West African and Congo Cratons and south of the Tuereg shield (Black, 1980). The Nigerian Basement Complex was affected by the Pan-African orogeny (600±150 Ma) and it occupies the reactivated region which resulted from plate collision between the passive continental margin of the West African Craton and the active Pharusian Continental margin (Burke and Dewey, 1972; Dada, 2006). The basement rocks are believed to be the results of at least three major orogenic cycles of deformation, metamorphism and remobilization corresponding to the Liberian (2,700±200 Ma), the Eburnean (2000±200 Ma) and the Pan-African cycles (600±150 Ma). These three cycles were characterized by intense deformation and isoclinals folding accompanied by regional metamorphism, and then followed by extensive migmatisation. The Pan-African deformation was accompanied by a regional metamorphism, migmatisation and extensive granitisation and gniessification which produced syntectonic granites and homogeneous gneisses (Abaa, 1983). Late tectonic emplacement of granites and granodiorites and associated contact metamorphism accompanied the late stages of this last deformation. The end of the orogeny was marked by faulting and fracturing (Gandu *et al.*, 1986, Olayinka, 1992). The Nigerian Basement Complex is intruded by the Mesozoic calc-alkaline ring complexes (Younger Granite) of the Jos Plateau and is conformably overlain by Cretaceous and Younger sediments.

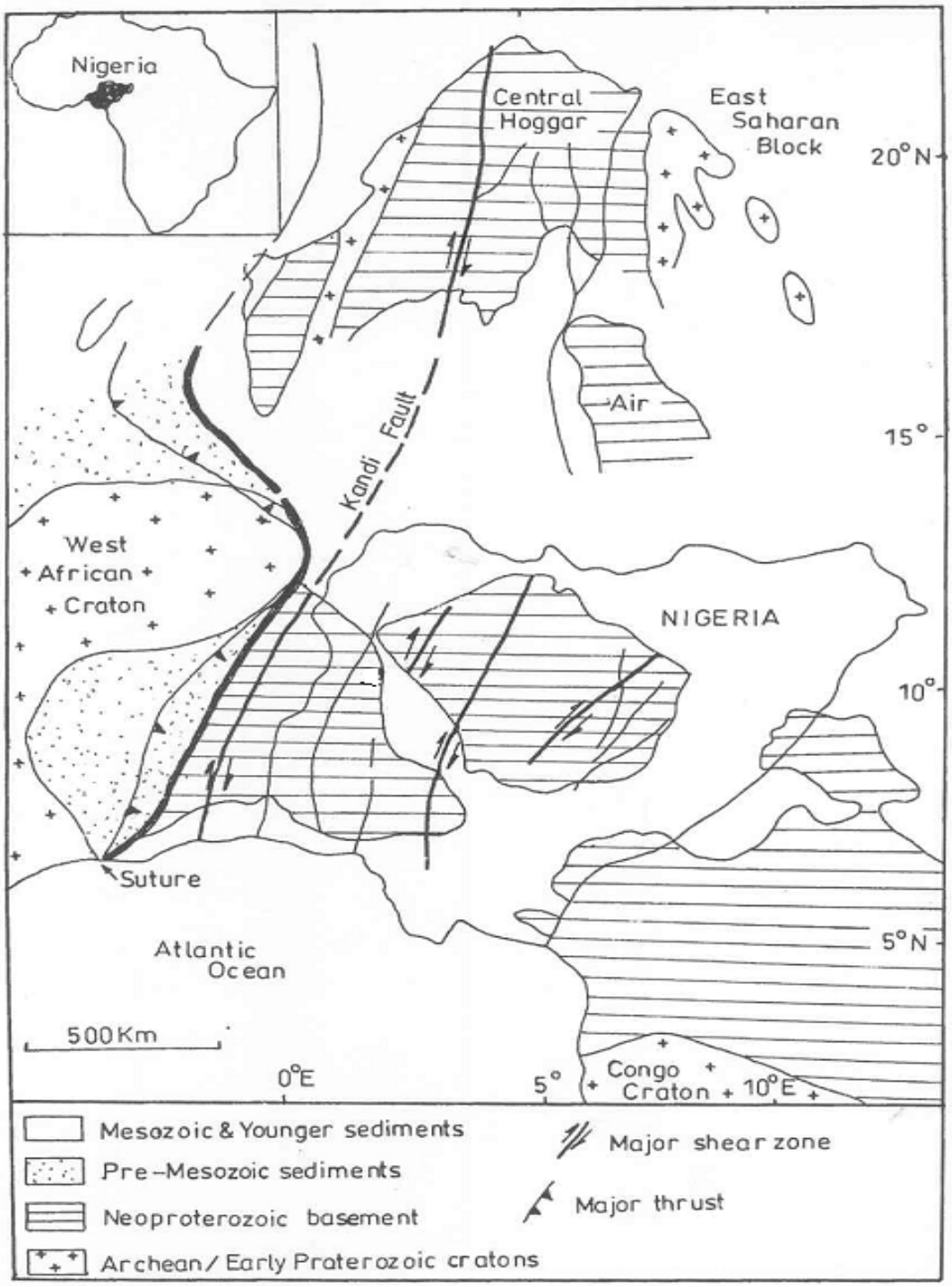


Figure 6: Map of the location of Nigeria between the West African Craton and the Congo Craton (after Wright, 1985).

2.2 THE NIGERIAN BASEMENT COMPLEX

The Nigerian Basement Complex is part of the Benin-Nigeria shield, situated within a Pan-African mobile zone extending between the West African Craton in the west and the Gabon-Congo Craton in the southeast. The Nigerian basement complex comprises gneisses, migmatites and supracrustal sequences which have yielded relict of Archean, Paleoproterozoic, as well as Neoproterozoic ages (Oversby, 1975; Rahaman *et al.*, 1983; Annor, 1995; Dada, 1998; Dada *et al.*, 1998; Ekwueme and Kroner, 1993; Ferre *et al.*, 1998). The Neoproterozoic (Pan-African) orogenic imprints in the Nigerian Basement Complex were characterized by high grade metamorphism, folding, faulting and widespread granite plutonism.

Within the basement complex of Nigeria four major lithological units are distinguishable, namely;

i. The Migmatite-Gneiss Complex (MGC), a heterogeneous assemblage of predominantly amphibolite-facies migmatites, orthogneisses, paragneisses, and minor-basic to ultrabasic rocks (Rahaman, 1988);
ii. The Schist Belts, believed to overlie the MGC and consisting mainly of psammitic to pelitic metasedimentary rocks with interlayered granitoid gneisses and rare amphibolites, interpreted as metavolcanic rocks (Turner, 1983);
iii. The Older Granites, (Pan-African granitiods) intruding both the migmatite-gneiss complex and the schist belts and composed of tonalitic to granitic plutons and charnockites, strongly foliated to almost unfoliated, and considered to have been emplaced during the Pan-African orogeny (Tubosun *et al*.,1984).
iv. Undeformed acids and basic dyke.

2.2.1 The Migmatite-Gneiss Complex (MGC)

About half of the Nigerian Basement Complex consists of the Migmatite-Gneiss Complex (Fig. 6); they are quartzo-feldspathic rocks that often contain hornblende and biotite. They strongly resemble the tonalite trondhjemite- granodiorite (TTG) suites of Archean and Early Proterozoic terrains elsewhere in the world (Dada *et al*., 1993*a*). It has ages ranging from Liberian (2800±200 Ma) to Pan-Africa (600±150 Ma). Metamorphism in this group has generally attained the amphibolites facie grade. The following three lithologic groups characterized the Migmatite complex (Rahaman, 1988):

i) Grey foliated biotite, hornblende, quartz, feldspathic gneiss of tonalitic to granodioritic composition which is now known as the grey gneiss or early gneiss. Alternating mafic and quartzofeldspathic material sometimes define a fine banding.

ii) Mafic to ultramafic components, which were present, often outcrop as discontinuous boudinaged lenses or concordant sheet of amphibolites with minor amount of biotite-rich ultramafite. They are usually strongly foliated which is parallel to that in the enclosing rocks. Except where it constitutes the paleosome to the migmatite, it is present in grossly subordinate amount to the grey gneiss.

iii) The felsic component which is composed of a varied group of rocks consisting of pegmatite, aplite, and quartz-oligoclase vein, fine grained granitic gneiss, and porphyritic granite. The felsic component has largely modified pre-existing structure than in the other two. It occurs as concordant to discordant veins and dykes of pegmatites, swarms of augen-shaped porphyroblasts and indefinite impregnations commonly resulting in destruction of the structure of the host rock.

Depending on the relationship between these three components, the gneisses can be distinguished from the banded gneiss, granitic gneiss and agmatites. 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 (Grant, 1970). Ajibade (1988) distinguished the ancient migmatites in northern Nigeria from the Pan-African migmatites by their complex polyphase deformation and mylonitization. Possibly because of their mixed and therefore complex nature, it has been difficult to define the protoliths of the banded gneisses. Some authors suggested that they were metasediments derived from graywacke and shale (Freeth, 1971; Burke *et al*., 1972), whereas others interpreted them as orthogneisses (Onyeagocha, 1986; Ekwere and Ekwueme, 1991; Imeokparia and Emofurieta, 1991). However, Oyawoye, (1972); Onyeagocha and Ekwueme, (1990), agree that migmatization occurred during upper amphibolite-facies regional metamorphism. There is also consensus that metamorphic segregation, partial melting, and injection of leucogranitic material contributed to the formation of the banded gneisses and migmatites. Truswell and Cope, (1963) and Ajibade *et al*., (1979), recognized that the Migmatite-Gneiss Complex (MGC) was subjected to considerable cataclastic deformation. This provided the first evidence for a structural break between the gneissic complex and the schist belts. Ajibade and Wright, (1989) argued that the Nigerian basement is an aggregation of allochthonous terranes, which explains the relicts of Liberian, Eburnian orogenic events, as well as the spread of radiometric ages within the Pan-African range (750–450 Ma). Dada *et al.*, (1993*b*) and Bruguier *et al*., (1994) were the first to apply modren geochronological methods to unravel the absolute chronology of the Migmatite-Gneiss Complex.

The Migmatite-Gneiss Complex is generally considered as the basement complex "Sensu Stricto" (Rahaman, 1988, Dada, 2006) and it is the most widespread of the component units. It

has a heterogeneous assemblage comprising migmatites, orthogneisses, paragneisses and a series of basic and ultrabasic metamorphosed rocks. Petrographic evidence indicates that the Pan-African reworking led to the recystallisation of many of the constituent minerals of the Migmatite-Gneiss Complex by partial melting with majority of the rock types displaying medium to upper amphibolites facies metamorphism. The Migmatite-Gneiss Complex has ages ranging from Pan-African to Eburnean (600-2000 Ma). The Migmatite - Gneiss 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 Ocan, 1978). These rocks record three (3) major geological events (Rahaman and Lancelot, 1984). The earliest at 2000 Ma involved initiation of crust forming processes (for example the Ibadan banded 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, this was followed by ages ranging from (900 to 450 Ma) which represent the imprint of the Pan-African event which not only structurally overprinted and reset many geochronological clocks (timing) in the older rocks, but 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 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, and 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 the only undisputable event that affected the Nigerian basement. Debate exists on 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), Fitches *et al*., (1985), and Ekwueme, (1987) argued that the Pan-African orogeny did not overprint all traces of earlier events.

2.2.2 The Metasediments (Schist belts)

The Schist belts forms the supracrustals that comprise of low grade, metasediment and metavolcanic-dominated belts trending N–S which are best developed in the western half of Nigeria and are seldom found east of longitude 8º E. According to Wright, (1985), the schist belts of northern Nigeria comprise Zungeru-Birnin Gwari, Kushaka, Karaukarau, Kazaure, Wonaka, Maru, Anka and Zuru belts. These schists are considered to be Upper Proterozoic supracrustal rocks which have been infolded into the migmatite-gneiss-quartzite complex.

The schists are low grade (green schist facie) metasediments assemblages, believed to be Late Proterozoic cover that have in places infolded into the Migmatite-Gneiss Complex. The lithological variations of the Schists include coarse to fine grained clastic, mainly pelitic – semi pelitic schist, phyllites and banded iron formation (Turner, 1964; Ajibade, 1980). Carbonate rocks (marbles/dolomitic marbles) and mafic-metavolcanics (amphibolites), are also prominent members of the schists. Some may include fragments of ocean floor material from small back-arc basins. Rahaman, (1976) and Grant, (1978) for example 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. Grant, (1978), Holt, (1982) and Turner, (1983) based on

structural and lithological associations; suggest that there are different ages of sediments. However, Ajibade *et al.*, (1979) disagree with this view and show that both series contained identical deformational histories. The structural relationships between the Schists and the basement were considered by Truswell and Cope, (1963) to be conformable metamorphic fronts and Ajibade *et al*, (1979) first mapped a structural break. The schists are generally considered to be Proterozoic in age.

2.2.3 The Older Granites

The Older Granites are believed to be pre-, syn- and post-tectonic rocks which cut both the Migmatite-Gneiss complex and the schist belts . The term "Older Granite" was introduced by Falconer, (1911) to distinguish the deep-seated, often concordant or semi-concordant granites of the basement complex from the high-level, highly discordant tin-bearing granites of Northern Nigeria the Mesozoic anorogenic granite ring - complexes known as the Younger Granites. The Older Granites represent a varied and long lasting (750–450 Ma) magmatic cycle associated with the Pan-African orogeny. They range widely in age from 750–450 Ma and in composition from tonalites and diorites through granodiorites to true granites and syenites. Charnockites form an important rock group emplaced during this period. They are generally high level intrusions and anataxis has played an important role (Rahaman, 1981). The Older Granites suite is notable for its general lack of associated mineralization although the thermal effects may play a role in the remobilization of mineralizing fluids. The Older Granites in Nigeria have been dated severally at 750-500 Ma (van Breemen *et al*., 1977; Rahaman *et al*., 1983; Fitches *et al*., 1985; Ferre *et al.*, 1998; Ekwueme and Kroner, 1998).

The Older Granites are the most obvious manifestation of the Pan-African orogeny and represent significant additions of materials (up to 70% in some places) to the crust (Rahaman,

1988). 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 Granites 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; Whalen *et al*., 1987; Maniar and Piccoli, 1989; Frost *et al*., 1999)

Dada, (2006) suggested that the term "Pan-African Granitiods" be used for Older Granites not only on the merit of age which was not available at the time they were named Older Granites, but because it covers several important lithologic groups formed at the same time. (Rahaman, 1988) discarded the earlier classification of members of the Older Granites suite on the basis of their texture, mineralogical composition and the relative timing of their emplacement. In its place, members of the Older Granites suite were classified by Rahaman, (1988) as follows, based mainly on the textural characteristics:

i. Migmatitic granites
ii. Granitic gneiss
iii. Early pegmatites and fine-grained granites
iv. Coarse-grained porphyritic granites
v. Slightly deformed pegmatites, aplites and vein quartz and
vi. Undeformed pegmatites, two - mica granites and vein quartz

McCurry, (1973) divided the granites into two main groups according to their field relationships:

a) Syntectonic group that comprised elongate batholithic sheets that are partly concordant and foliated.

b) Late tectonic group that are made up of poorly foliated discordant bodies, rich in mafic xenoliths and having a lower proportion of potash feldspar. The late granites are considered to be the products of widespread mobilisation and reactivation of older basement rocks during the Pan-African orogeny.

2.2.4 Undeformed acid and basic dykes

The undeformed acid and basic dykes are late to post tectonic with reference to the Pan-African (600±150 Ma) event. The Undeformed acid and basic dykes cross-cut the Migmatites-Gneiss complex, the Schist Belt and the Older Granites. They include:

a. Felsic dykes that are associated with Pan-African granitiods on the terrain such as those of the muscovite, tourmalines and beryl bearing pegmatites, microgranites, aplites and syenites dykes (Dada, 2006).
b. Basic dykes that are generally regarded as the youngest units in the Nigerian Basement such as dolerites and the less common basaltic, felsites and lamprophyric dykes.

The age of the felsite dykes has been put at between 580 and 535 Ma from Rb-Sr studies on whole rocks (Matheis and Caen-Vachette, 1983; Dada, 2006) while the basic dykes have a much lower suggested age of 500 Ma (Grant, 1970).

2.3 TECTONIC SETTING

2.3.1 Pan-African Fracture System

The Pan-African belt of West African was divided into two part (the West African Craton and East Saharan block) bounded by the Kandi fault system (Wright, 1985). The East Saharan block was subjected to important vertical movements (Ball, 1980). However, erosion has removed the sedimentary cover and exposed the underlying Precambrian shield due to uplift

(Ball, 1980). In the Hoggar (Fig. 7) where the maximum uplift is observed, the Precambrian terrain has reached the height of about 3,000 m (Ball, 1980).

The main structures of the block are due to the Pan-African orogenesis (about 600±150 Ma). Bertrand and Caby, (1978) interpreted this orogeny as the result of a continental collision between two blocks, the West African Craton and Congo Craton. This collision may have caused significant crustal thickening which allowed reworking of the crust at depth (Ball, 1980).

According to Ball, (1980) three structural domains (Fig. 8) have been distinguished. From west to east these are:

i. The Pharusian belt, the westernmost domain in which late Pan-African calc–alkaline volcanic material dominates.

ii. The central domain consisting of Eburnean (2000±200 Ma) and Kibaran (1100 Ma) sailic material reworked during the Pan-African event.

iii. The eastern domain composed of probable Pre–Pan-African gneisses and granites on which lies the narrow ensialic tiririne fold belt Fig. 9. The supracrustal rocks in this belt probably lay down and are preserved along a N-S trending shear zone.

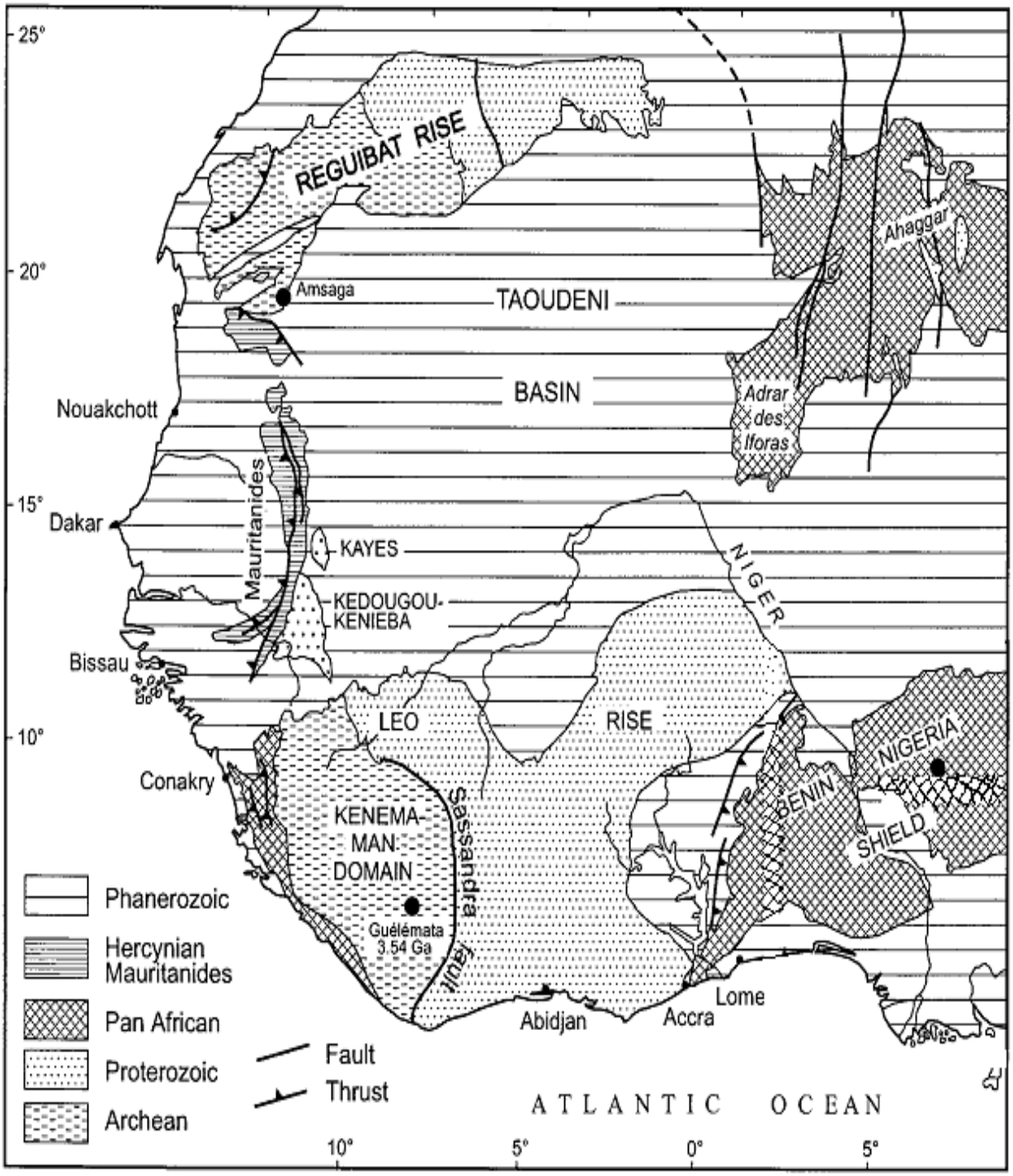


Figure 7: Major tectonic units of the West African Craton and location of oldest rocks in West Africa (after Boher *et al.* 1992)

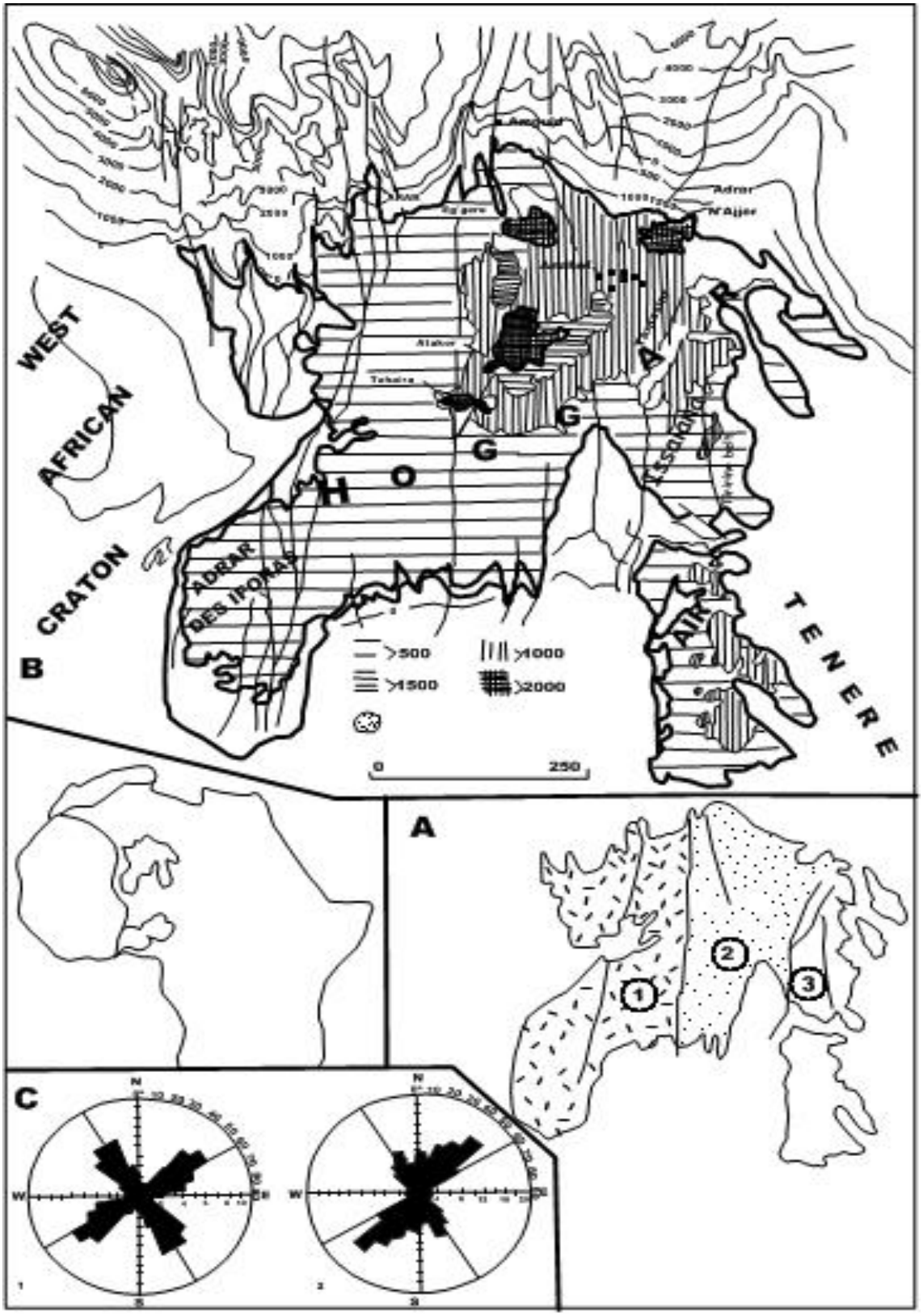


Figure 8: Map of the Precambrian shield of West African and its three structural domains in North–West Africa (A_1), The Pharusian belt, (A_2), The central domain (A_3), The eastern domain (after Bertrand and Caby, 1978)

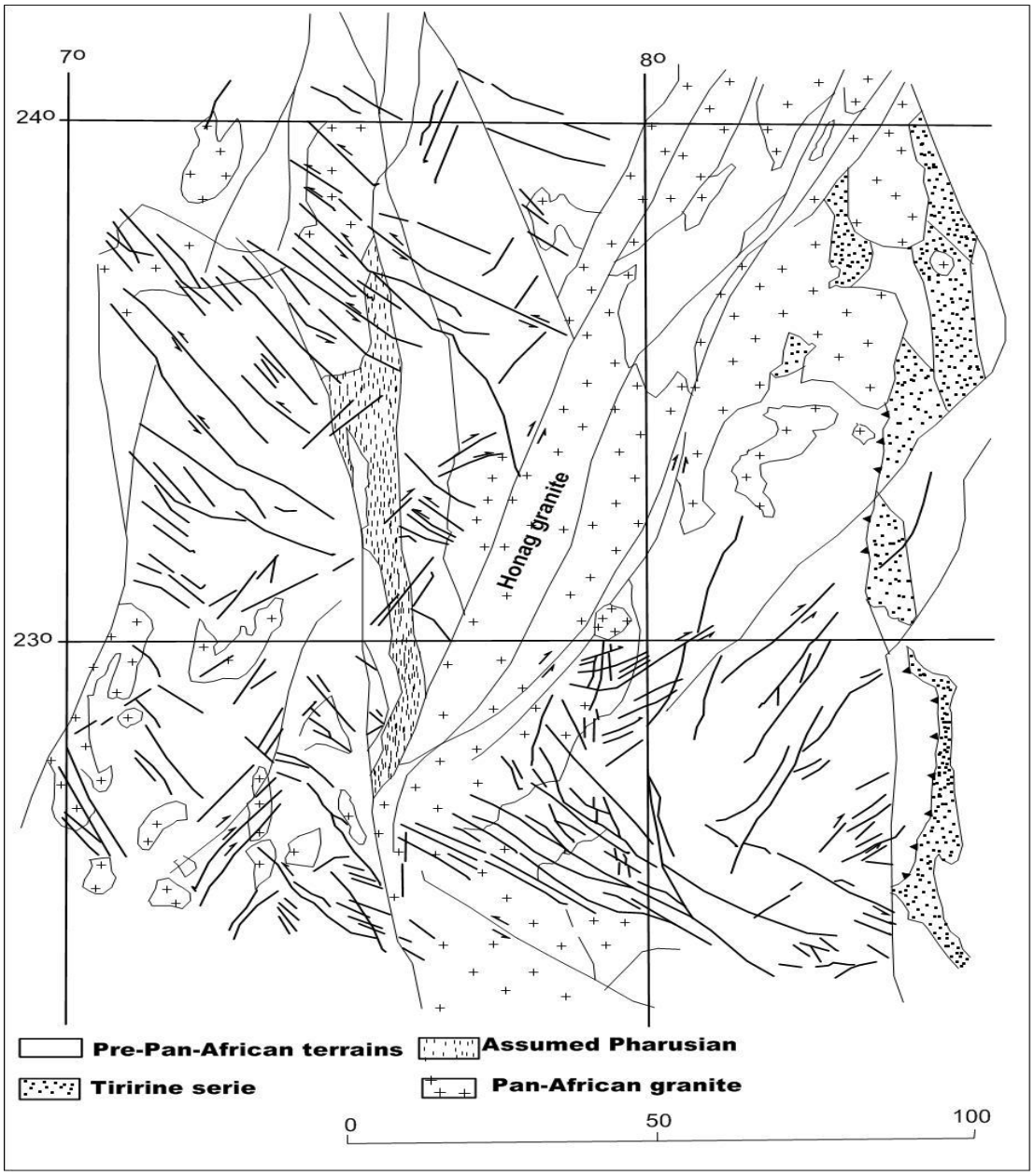


Figure 9: Fracturation of the eastern Hoggar a photo-interpretation (after Ball, 1980).

The Pan-African N-S trending shear zones are mylonitic and generally have a horizontal stretching lineation, implying horizontal displacement. This displacement has been considered as of considerable importance (Caby, 1968; Vital, 1975).

Detailed photo-interpretations (Fig. 9) show that a major conjugates system of strike-slip faults affects the whole area (Ball, 1980). The fault directions have consistent trend and senses of displacement, a NE-SW trending system having a dextral sense of movement and a NW-SE trending system having a sinistral sense. Both sets cut the entire major Pan-African structures, including the N-S trending shear zones and the late orogenic granites. These faults are mainly the result of brittle deformation. Both directions of the conjugate system exist everywhere in the belt. However, one of them is often predominant. This variation of the pattern can possibly be attributed to competency differences. In the central Hoggar the NE-SW dextral system tends towards an E-W direction, whereas in the western Adrar des Iforas, the sinistral system tends towards an N-S trend.

2.3.2 Major fracture system in Nigerian

The Nigerian Pan-African belt has been considered as the southern prolongation of the central Hoggar (McCurry, 1976). It is similarly cut by N-S trending shear zones of Pan- African age, which are displaced by late orogenic slip faults. Like those in the Tuareg Shield the dextral faults display a NE-SW strike and the sinistral faults a NW-SE strike (McCurry, 1971).

In the north of the Nigerian Pan-African belt, the dextral set is the best developed and offsets the mylonites by more than 10 km in some places (McCurry, 1971; 1973 and Ball, 1980). It is important to note that outcropping of rocks in Nigeria is poor compared with the Tuareg Shield, and the number of faults drawn on present day maps is probably a gross under estimation.

Two important NE-SW trending transform faults (Romanche and Chain) (Fig. 10) are define in the Atlantic by Francheteau and Le Pichon, (1972) Ball, (1980) and are situated on the prolongation of two dextral wrench faults of Pan-African age in southern Nigeria (Wright, 1976). According to Ball, (1980) the transform faults may have been formed preferentially on pre-existing zones of weakness.

Important features of the Nigeria fracture systems are

i. A major NE-trending fault cuts the basement in the extreme south west of Nigeria, close to the continuation of the Accra-Lagos sedimentary basin boundary.

ii. The important Ife fault zone, whose extension to the coast beneath younger sediments has been identified by Hubbard, (1975) is also known to continue beyond 8^{o} N.

iii. The only two significant strikes-slip displacements so far mapped in Nigeria occur within these fracture system, both involves dextral movements amounting to about 10 km in the eastern belt (McCurry, 1973) and about 30 km in the western belt (Wright, 1976).

It is considered that the compressional episode which caused folding is the same event which was responsible for the conjugate fault system in the rest of the shield. Thus the brittle deformation must have occurred after 530 Ma (Lancelot and Black, 1978).

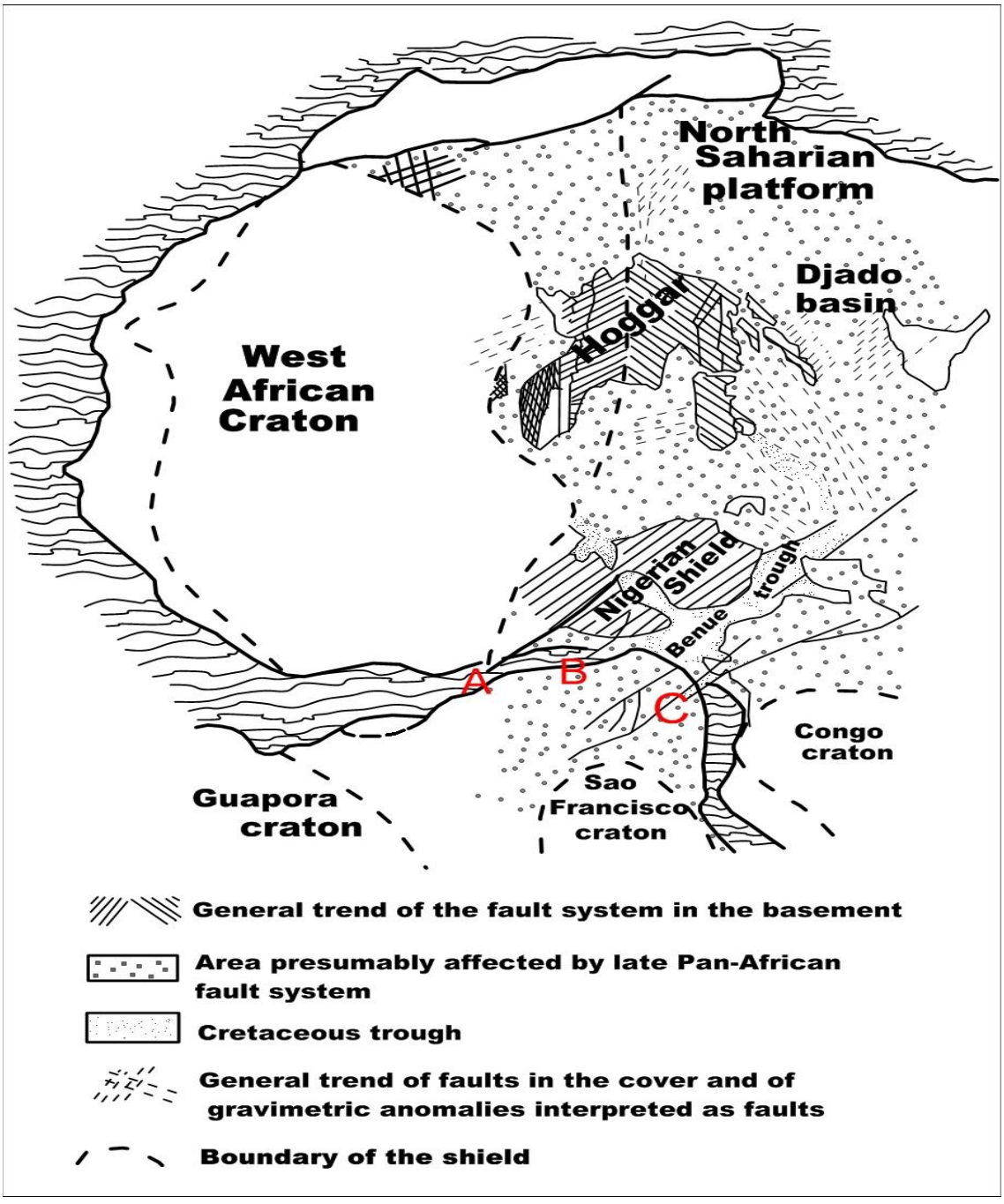


Figure 10: Map of the conjugate fault system in the Tuareg and Nigerian shield (after Almeida and Black, 1967). A-Romanche fracture zone B-Chain zone C-Ngaoundere fault system of Cameroon.

CHAPTER THREE

FIELD GEOLOGY OF THE STUDY AREA

3.1 INTRODUCTION

The study area comprises rocks of the Nigerian Pan-African (600±150 Ma) crystalline basement (Fig. 11, in pocket). It is a highly deformed gneissic terrain, characterized by uplift, fracturing/faulting, intense folding, shearing and sillification resulted to formation of quartz and amethyst at different stages of formation. The shear zone is characterized by extreme ductile-brittle shearing, fracturing and prominent mineralization of milky quartz and amethyst at different stages.

The area is made up of highly fractured and poorly exposed weathered granitic gneiss and sheared gneiss. The granitic gneiss belongs to the Pan-African migmatite - gneiss complex. It also forms the predominant rock unit as observed in the field. Minor lithological units are minor quartz veins and a prominent vein in which amethyst mineralization occurs and aplite dykes. The structural feature of the study area comprises joints, faults and foliations.

3.2 FIELD DESCRIPTION AND PETROGRAPHY OF MAJOR ROCK

3.2.1. Granitic gneiss

The granitic gneiss occurs in Ungwan Rimi, Sabon Kaura, Dutsen Bakura, Gidan Rano and Ungwan Turaki. The rocks outcrops as whaleback at Ungwan Turaki and Sabon Kaura (Plates I) trending N74º E. The granitic gneiss is considered the oldest rock unit in the area. It is variable in colour, generally light to dark grey with an alternating light and dark bands, medium to coarse grained and foliated with parallel thin bands of light and dark coloured minerals. The granitic gneiss displays subtle bands of mafic and felsic minerals. The mineral present are quartz, feldspars, mica (mostly biotite) commonly aligned in a preferred N-S direction. The quartz and

feldspar occur together in layers which are separated from each other by thin drawn-out bands of mica. The foliations are characterized by alternating dark and light coloured band, foliated, layered aggregates of platy or linear grains forming lenses or blades. The colourless to white coloured quartz occurs in granular aggregates and also in lenticular masses with feldspars. Feldspar is white to grey in colour. Both the alkalic and soda-lime varieties of feldspar are present, but they can rarely be distinguished by megascopic means. Feldspars occur as elongated, lenticular, formless grains. This lack of definite form makes it more difficult to distinguish feldspar from quartz. Biotite is dark brown to black, muscovite is white in colour. The mica appears not to have any distinct crystal form, but is in flakes, shreds or irregular leaves, drawn out in bands and sometimes in thin patches. It usually lies stretched out along the gneissose planes of the rocks arranged in one direction.

When observed in thin section the granitic gneiss (Plate II, III) is composed of quartz, plagioclase, biotite, microcline, orthoclase, muscovite and pyroxene. Quartz constitute about 30%, plagioclase 25%, biotite 20% microcline 10%, orthoclase 10%, and of pyroxene 5% (Plate II). Quartz is colourless with no pleochroism, and twinning. Quartz occurs as polycrystalline mineral and display undoluse extinction. The habit is subhedral to anhedral. Birefringence is also 1st order with extinction angle occurring at ~30°, 40° and 80°. The quartz occurs as poikiloblastic crystals defined by inclusion of biotite in quartz. No fractures were seen in quartz an indication that they were form as the alpha or low temperature form of quartz.

Plagioclase is colourless with low relief and anhedral to subhedral crystals. It is grey in cross polarized light and display polysynthetic twinning and oblique extinction.

Microcline is colourless but cloudy in plane polarized light with low relief. It exhibit oblique extinction and characteristic cross hatch twinning.

Orthoclase appears colourless to cloudy with low relief. It is grey in cross polarized light with oblique extinction and exhibits no twinning whatsoever.

Biotite is grey to brownish colour and has prismatic, subhedral to anhedral habit with perfect cleavage (Plate II). It shows no twining and occurs in patches with moderate to high relief. Biotite forms interstitial lamellae with brown pleochroism. Birefringence is 1st order and the mineral possess no extinction angles. Commonly, biotite occurs as poikiloblasts within plagioclase (Plate III).



Plate I: Field photograph of quartz vein within, medium grained grey coloured granitic gneiss exposed in Sabon Kaura.



Plate II: Photomicrograph of granitic gneiss showing essential mineral composition (Qtz = Quartz, Plg = Plagioclase, Bio = Biotite). PPL, Mag. 4mm X40.



Plate III: Photomicrograph of granitic gneiss showing Biotite inclusion in plagioclase. (Oth = Orthoclase, Qtz = Quartz, Mic = Microcline, Plg =Plagioclase, Bio = Biotite) XPL Mag. 4mm X40.

3.2.2 Sheared gneiss

The sheared gneiss occurs within highly fractured uplifted terrain and as scattered outcrops (Plate IV) at Dutsen Bakura HillHill. This rock is strongly foliated, sheared and characterized by intense folding. The sheared gneiss is dark grey in colour. It occurs in an alternating light and dark bands, medium to coarse grained and strongly foliated with intense folding of quartz minerals. The mineral constituents are the same as the granitic gneiss. The quartz and feldspar occur together in layers which are separated from each other by thin drawn-out bands of mica. The foliations are characterized by alternating dark and light coloured band, foliated, layered and aggregates of platy or linear grains forming lenses or blades. The sheared gneiss is highly silicified **(**Plate V).

Thin section study of the sheared gneiss (Plate VI,VII) shows it to be composed of fine grained, scattered cataclastic quartz and mica (mostly biotite). Plate VI, VII shows thin cross-cutting microveins of crystalline quartz and increase silicification.



Plate IV: Highly fractured scattered boulders at Dutsen Bakura Hill.



Plate V: Unmineralised quartz veins, micro folding and sillicification in sheared gneiss.

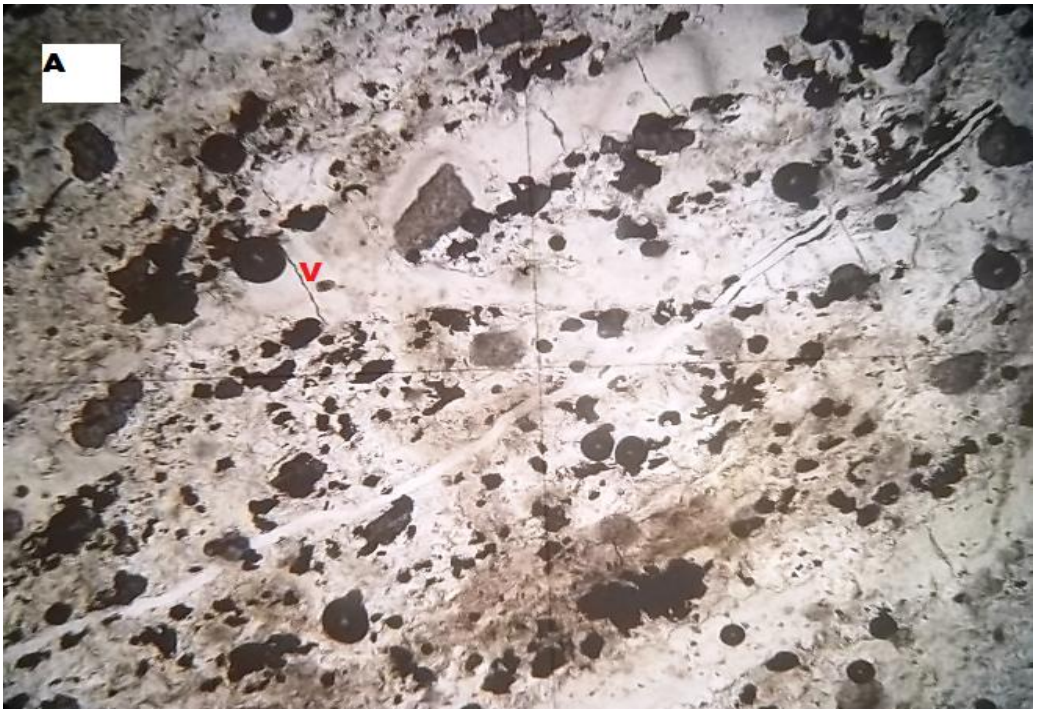


Plate VI: Photomicrograph of sheared gneiss showing thin cross-cutting veins (V) of crystalline quartz and sillification (Mag. X 40).

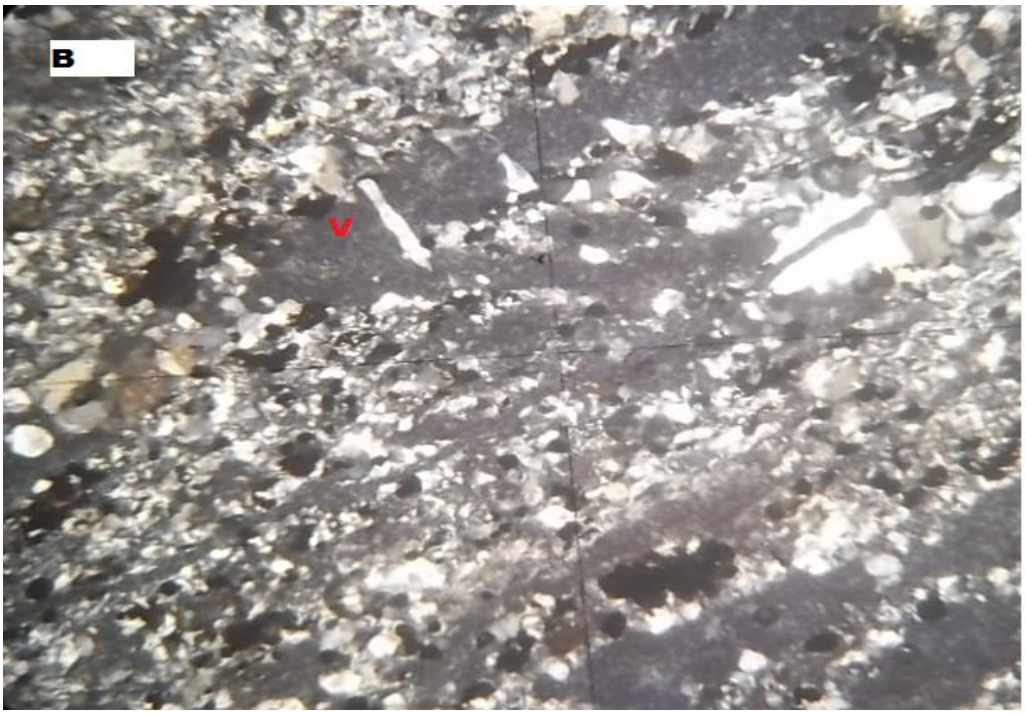


Plate VII: Photomicrograph of sheared gneiss XPL (Mag. X 40).

3.3 FIELD DESCRIPTION OF MINOR INTRUSIONS

3.3.1 Aplite dyke

Aplite dyke about 7 cm in thickness traverses the granite gneiss in the study area. The aplite dyke is light-coloured, composed dominantly of plagioclase feldspar, quartz and mica minerals. It is a uniformly fine-grained intrusive igneous rock of less than 2 mm (0.08 inch) and has a characteristic granular texture (Plate VIII).



Plate VIII: Field photograph of Granitic gneiss showing foliation and equi-dimensional aplitic dyke near Gidan Rano. (Pen is about 6 cm).

3.3.2 Minor quartz veins

Quartz veins occur as fracture and joint fillings in the granitic gneiss and sheared gneiss. Milky quartz is the major mineral forming facture and joint fillings (Plate VIIII) in the granitic gneiss. Most of these veins are crystalline and fine to medium-grained. The veins are of various dimensions ranging from few mm of minute threads in the sheared gneiss to over 10 cm in the granitic gneiss. The quartz veins exhibit pinch and swell, irregular in size some are wide and some thin along their length (Plate VIIII).

Micro-veins of different generations are present and they are observed to offset one another. At least two generations of micro-veins some of which are intensely folded have been observed. Some of the veins are found to coalesce with or intersect each other within the sheared gneiss (Plate V). The Rosette diagram plotted (Fig. 12) for crosscutting veins in the granitic gneiss and sheared gneiss, shows a general NNE-SSW dominant trend consistent with the Pan-African trend. The strike directions of these veins and lineaments are parallel to the trend of the granitic gneiss which is NE-SW.



Plate VIIII: Field photograph of Unmineralised minor quartz veins within the granitic gneiss in Dutsen Bakura Hill.

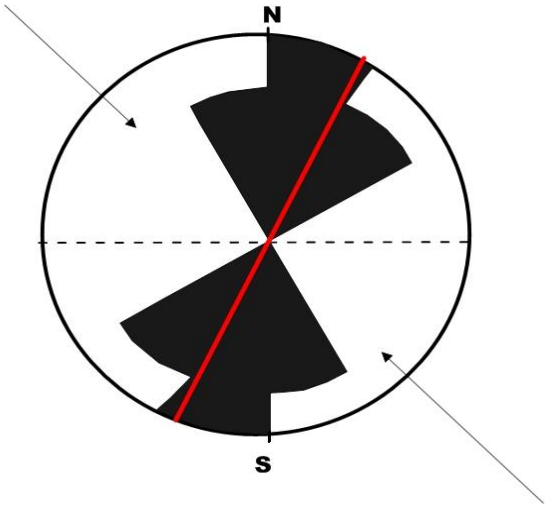


Figure 12: Rosette diagram indicating a dominant NNE-SSW trend of quartz veins in granitic gneiss in Dutsen Bakura Hill.

3.4 THE AMETHYST BEARING VEIN

The mineralization is structurally controlled and trends NE-SW direction and vertical dip with the width varying from 4.3 to 7.3 m following the regional structural trend. The grain size is highly variable. A fractured zone measuring about 1.5 Km (1,519.29 m) long containing a two stage milky quartz and amethyst mineralization occurs in Dutsen Bakura HillHill. The amethyst (quartz) vein is almost entirely made of quartz (>98 wt %) and less than 2 wt% of muscovite and feldspar. It generally occurs where sheared gneiss is the enclosing wall rocks. The intensely sheared gneiss has width ranging between 10 to 12 m. The zone of mineralization is vertical (Plate X) about 5m wide characterized by intense folding. Contact between the amethyst vein and the sheared gneiss is sharp an indication of an open system or channelized flow (Plate XI).

3.4.1 Mineralogy of the amethyst vein

The Dutsen Bakura HillHill vein shows two variations in colour (Plate XII) the veins within the mineralized zone contain almost entirely quartz crystals ranging from 0.5 to 2 cm in width. Quartz appears in milky and different shades of purple colour. The amethyst vein display banding parallel to the enclosing walls (Plate XIII); the banding consisting of alternating amethystine and milky quartz believed to represent, respectively periods of relative quiescence and of active growth. According to Holden (1925), the milky quartz in such an association is the result of direct crystallization from the parent siliceous hydrothermal solution. The residual solution is enriched in iron which may now enter the crystal structure of quartz to give the amethystine colour. Milky quartz and amethyst occur as part of an alternating colour of mineralization sequence involving macro-crystalline quartz. The direction of growth of the amethyst has been controlled to a large extent by the resistance of the granitic gneiss.



Plate X: Vertical section of amethyst mineralization in Dutsen Bakura Hill mine pit. The veins are at various stages of weathering.



Plate XI: Sharp contact between sheared gneiss and the amethyst (V) vein in Dutsen Bakura Hill.



Plate XII: Milky quartz and amethyst mineralization alternation within the sheared gneiss.

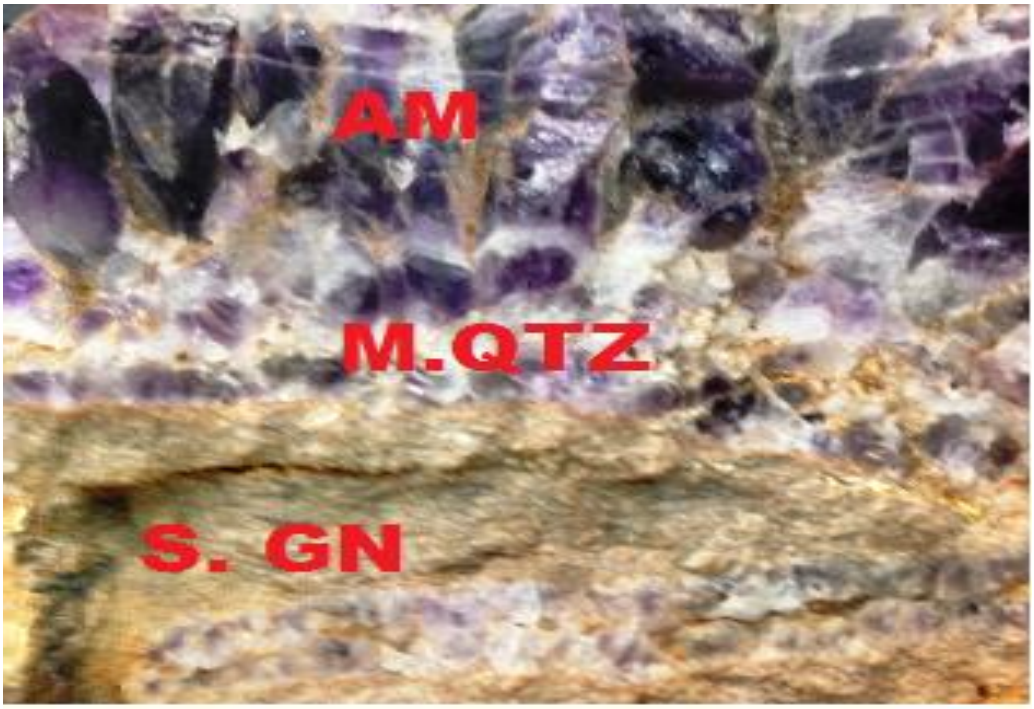


Plate XIII: Zoning as it appears in amethyst. The oxygen isotopes samples were also sampled in the order it it was zoned.

3.4.2 Textu

The amethyst in some places have grown inwards from end to end at right angles to both (Plate XIV) walls of the vein and where the two sets of crystals do not meet the resulting vugs are lined with well formed crystals in a comb (vuggy) texture (Plate XV, XVI) and also in pockets (Plate XVII). The amethyst mineralized zone usually display banded structure parallel to the enclosing walls (Plate XVIII); the banding consisting of milky quartz and amethyst believed to represent, respectively, periods of relative quiescence and active crystal growth.



Plate XIV: Photograph of mineralised zone in Dutsen Bakura Hill showing amethyst crystals grown inwards from end to end at right angles to both walls of the vein.



Plate XV: Amethyst mineralization exbiting geods in Dutsen Bakura Hill.



Plate XVI: Comb texture (Vugs) in amethyst seen in Dutsen Bakura Hill



Plate XVII: Pocket of milky quartz and amethyst deposit in in Dutsen Bakura Hill.

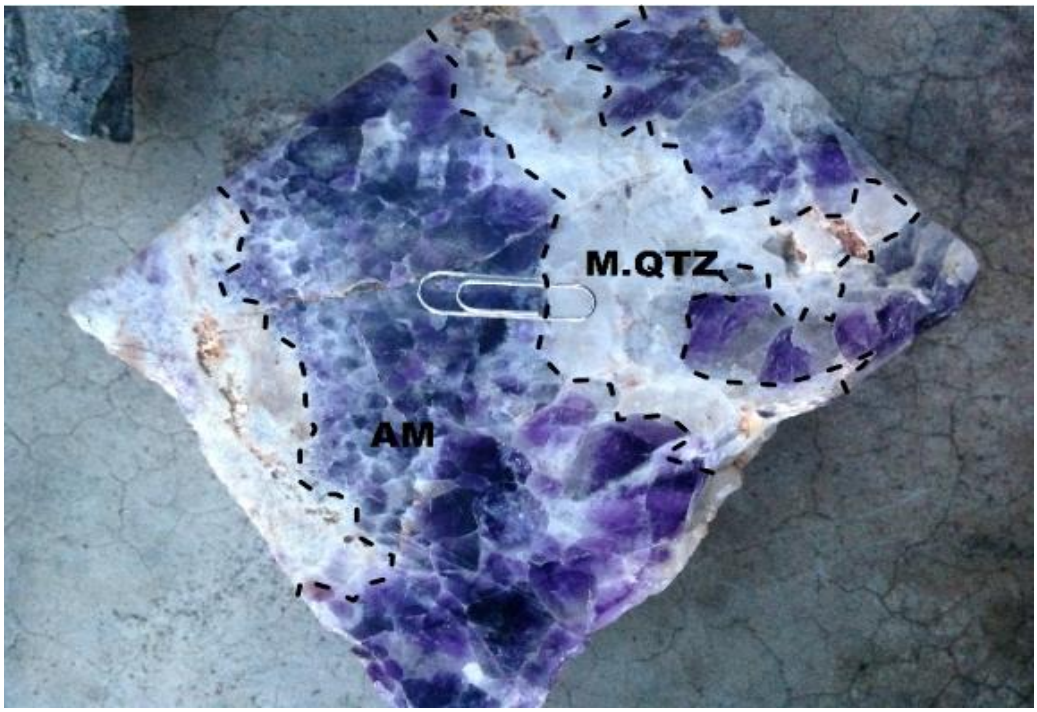


Plate XVIII: Photograph of a polished hand specimen rock showing alternating amethystine and milky quartz (banding) from Dutsen Bakura Hill.

3.5 STRU

Signatures of tectonic activity in the area are seen in the various structural features of the Dutsen Bakura HillHill. They are probably due to impacts of metamorphism and deformation on the rocks. The main structural feature in the area comprises joints, fault and foliation.

3.5.1 Joints

Most of the rocks in the area have well defined cracks and joints. In Dutsen Bakura HillHill, joints exhibit shearing with components parallel to the direction of propagation of the fracture front. Strike measurement of the joints and cracks reveal that they have a general NNE-SSW trend concordant to the general structural trend in the Nigerian Pan-African basement complex which is known to have undergone both ductile and brittle deformation associated with tectonic activity. Joints within the sheared gneiss maintain a constant orientation across the folded rock which is interpreted as have formed after the folding.

3.5.2 Fault

Faulting is the major structural feature in the study area. A NE-SW trending strike-slip fault with a dextral movement was mapped in the area for over 615.70 m terminating at the Dutsen Bakura HillHill. The relative displacement measured averagely is 164.04 m, shearing accompanied the faulting in the area. The fault is clearly represented in the geological map (Fig. 11). The mineralised zone is located within the faulted fractured zone which strikes at N48ºE and dips 68º to the south-east. These fracture zones are filled by amethyst and milky quartz. At least two periods of mineralization occurred. This is evident, as an early generation of amethyst has been distinguished which is clearly sheared. The second generation of amethyst crystallized interchangeably with milky quartz. The timing of mineralization was probably constrained to the closing stages of Pan- African as been shown to be associated with wide spread fracturing and silicification.

3.5.3 Foliation

Foliation in the granitic gneiss show closely spaced compositional layers that are mineralogically distinct and of comparable abundance, defined by the alignments of the mica minerals in NE-SW direction (Plate VIII). It also occurs in the sheared gneiss where the minerals in the sheared gneiss are laminated and aligned in a general NE-SW direction corresponding to the Pan-African imprint.

CHAPTER FOUR

GEOCHEMISTRY

4.1 SAMPLING AND ANALYTICAL TECHNIQUE

4.1.1 Sampling

A total of 16 representative samples were collected along carefully selected traverse lines. These consist of three samples of milky quartz (BK17/14, BK13/14 and BK23/14), three samples of amethyst (BK25/14, BK61/14 and BK3/14), four samples of the sheared gneiss (BK2/14, BK2/15, BK21/6 and BK3/15) and three samples of the granitic gneiss (BK1/15, BK1/14 and BK21/8). The amethyst vein samples were collected at 10 m interval to allow for the determination of spatial variation of elemental constituents.

Thirteen samples were selected for whole rock analysis and three for oxygen isotope analysis. The samples were then broken into smaller chips and handpicked to avoid any contamination and then packaged into plastic containers at the laboratories of the Department of Geology, Ahmadu Bello University, Zaria, Nigeria, and shipped to Activation Laboratories Limited; (ACTLABS), Ancaster, Ontario, Canada, where major, trace and rare earth element (REE) and isotopic analysis were carried out.

4.1.2 Sample Analysis

The whole rock analysis was done using standard analytical procedures named ‘4 Litho’ a combination of packages Code 4B (lithium metaborate/tetraborate fusion ICP whole rock) and Code 4B2 (trace element ICP/MS) by Activation Laboratories Limited (ACTLABS). 4 Litho analyses used $LiBO_2$/Tetraborate fusion ICP for major oxides plus minor elements. Code 4B2

analyses of trace element used ICP-MS. These are packages developed by the Activation Laboratories.

Samples BK34/14, BK1/14*and BK22/14 were treated with BrF_5 at 650^{o}C in nickel bombs following the procedure described in Clayton and Meyeda, (1963) for oxygen ($\delta^{18}O$) isotope analysis. The resulting fluorination reaction, convert oxygen atom (O) in the mineral, to oxygen gas (O_2) which was subsequently converted to Carbon dioxide (CO_2) gas using hot carbon (C) rod. The liberated Oxygen gas (O_2) was then analyzed using a Finigan MAT Delta, which is a dual inlet isotope ratio mass spectrometer. The entire reaction steps are quantitative. Oxygen isotope compositions are given in the standard δ notation, expressed relative to VSMOW in per mil (‰). Replicate Oxygen isotope analyses of the standard used (NBS-28 quartz) generally have an average precision of 0.19‰ (Valley *et al.*, 1995).

The analytical data obtained are presented in Tables 4.1, 4.2, 4.3 and 4.4. Major elements are reported in weight percent (wt %) and trace elements in part per million while value of oxygen ($\delta^{18}O$) isotope is reported as parts per thousand (per mil).

Table 4.1: Major element composition in rocks from Dutsen Bakura HillHill (values in wt %).

Rock type /Sample No/ Oxides	Granitic Gneiss			Sheared Gneiss				Milky Quartz			Amethyst		
	BK1/15	BK1/14	BK21/8	BK2/14	BK2/15	BK21/6	BK3/15	BK17/14	BK13/14	BK23/14	BK15/14	BK51/14	BK3/14
SiO_2	76.77	76.93	79.25	84.32	82.09	83.4	99.21	97.43	98.43	99.22	100.1	98.95	99.74
Al_2O_3	11.61	11.69	11.85	7.42	10.34	8.66	0.61	0.21	0.22	0.05	0.18	0.16	0.06
Fe_2O_3(T)	1.83	2.26	1.49	2.47	1.82	3.9	0.67	0.6	0.66	0.56	0.63	0.65	0.67
MnO	0.019	0.055	0.032	0.011	0.004	0.011	0.01	0.006	0.006	0.006	0.006	0.006	0.007
MgO	0.07	0.06	0.12	0.12	0.01	0.21	0.02	0.01	0.01	0.01	0.01	0.01	0.01
CaO	0.61	0.47	1.15	0.05	0.03	0.05	0.03	0.02	0.02	0.02	0.02	0.02	0.02
Na_2O	2.91	3.92	4.99	0.01	0.02	0.02	0.02	0.02	0.01	0.01	0.02	0.01	0.01
K_2O	5.65	4.29	0.79	0.33	0.06	0.67	0.02	0.01	0.01	0.01	0.01	0.01	0.01
TiO_2	0.102	0.097	0.108	0.84	0.104	0.847	0.015	0.001	0.001	0.002	0.001	0.001	0.001
P_2O_5	0.01	0.01	0.01	0.05	0.06	0.06	0.01	0.01	0.01	0.01	0.01	0.01	0.01
LOI	0.36	0.22	0.27	2.75	4.19	2.97	0.28	-0.02	0.03	0.06	-0.03	-0.04	0
Total	99.93	100	100.1	98.36	98.72	100.8	100.9	98.3	99.38	99.92	101	99.75	100.5

Table 4.2: Trace-Element Abundances in rocks from Dutsen Bakura HillHill (values in ppm).

Rock type	Granitic Gneiss			Sheared Gneiss				Milky Quartz			Amethyst		
/Sample No/ Oxides	BK1/15	BK1/14	BK21/8	BK2/14	BK2/15	BK21/6	BK3/15	BK17/14	BK13/14	BK23/14	BK15/14	BK51/14	BK3/15
Sc	3	3	7	9	3	11	1	1	1	1	1	1	1
Be	3	4	7	2	1	2	1	3	3	1	5	4	1
V	5	12	8	76	9	95	7	5	5	5	5	5	7
Ba	377	382	79	70	22	178	30	7	8	3	7	4	30
Sr	28	27	46	52	35	93	7	2	2	2	2	2	7
Y	163	144	184	24	104	34	3	2	2	2	2	2	3
Zr	574	467	405	246	581	251	4	6	4	4	4	4	4
Cr	20	20	20	290	20	290	20	20	20	20	20	20	20
Cu	10	100	10	10	100	10	10	10	10	10	10	10	10
Zn	100	220	110	30	90	30	30	30	30	30	30	30	30
Ga	21	23	21	22	19	18	2	4	3	1	4	4	2
Ge	3	3	3	1	2	1	1	1	1	1	1	1	1
Rb	274	228	31	24	5	58	2	2	2	2	2	2	2
Nb	67	46	53	21	44	23	1	1	1	1	1	1	1
Ag	3.3	3.3	2.4	1.4	4.1	1.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Sn	13	10	9	13	8	17	1	1	1	1	1	1	1
Sb	0.6	0.5	0.6	0.6	0.5	0.6	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Cs	2.2	1.3	0.5	1.3	0.5	2.3	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Hf	25.8	19.4	16.7	6.2	25.1	6.3	0.2	0.2	0.2	0.2	0.2	0.2	0.2
Ta	5	3.6	4.9	0.8	3.6	0.8	0.1	0.1	0.1	0.1	0.1	0.1	0.1
W	1.99	3.61	1.18	12.1	1.61	8.21	0.86	1.88	0.57	0.44	5.59	0.47	0.86
Tl	1	0.8	0.2	0.1	0.1	0.3	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Pb	35	57	36	70	27	66	6	5	5	5	5	5	6
Bi	0.4	0.4	0.4	1.6	0.4	0.9	0.4	0.4	0.4	0.4	0.4	0.4	0.4
Th	25.8	21.3	68.2	8.9	14.5	8.7	0.3	0.7	0.1	0.1	0.1	0.1	0.3
U	13.6	9.5	9.8	5.4	6.2	10.6	0.6	0.1	0.1	0.1	0.1	0.1	0.6

Table 4.3: REE-Element data in rocks from Dutsen Bakura HillHill (values in ppm).

Rock type /Sample No/ Oxides	Granitic Gneiss			Sheared Gneiss				Milky Quartz			Amethyst		
	BK1/15	BK1/14	BK21/8	BK2/14	BK2/15	BK21/6	BK3/15	BK17/4	BK13/14	BK23/14	BK15/14	BK51/14	BK3/14
La	37.1	58.6	64.4	59.6	64.5	54.5	8.9	1	0.4	0.3	0.3	0.2	0.3
Ce	72.5	105	94.9	97.5	120	65.9	6.3	1.3	0.5	0.5	0.3	1.1	0.4
Pr	8.84	12.3	13.6	13.4	14.4	11.6	1.95	0.18	0.08	0.07	0.06	0.06	0.08
Nd	30.5	45.9	47.3	45.7	52.7	39.1	6.3	0.6	0.2	0.2	0.1	0.2	0.3
Sm	8.1	11.2	12.6	9.7	12.3	7.7	1.3	0.1	0.1	0.1	0.1	0.1	0.1
Eu	0.7	0.98	1.11	1.5	1.17	1.29	0.16	0.05	0.05	0.05	0.05	0.05	0.05
Gd	9.3	13.4	16.2	7	11.9	6.2	0.9	0.2	0.1	0.1	0.1	0.1	0.1
Tb	2.2	2.9	3.6	1.2	2.5	1	0.2	0.1	0.1	0.1	0.1	0.1	0.1
Dy	15.9	20.8	26.3	6.3	16.8	6.4	0.7	0.2	0.1	0.1	0.1	0.1	0.1
Ho	3.5	4.7	5.9	1.2	3.8	1.4	0.1	0.1	0.1	0.1	0.1	0.1	0.1
Er	11.4	14.6	19.1	3.4	12.2	4.3	0.3	0.1	0.1	0.1	0.1	0.1	0.1
Tm	1.99	2.49	3.24	0.58	2.07	0.71	0.05	0.05	0.05	0.05	0.05	0.05	0.05
Yb	14.2	18.2	22.9	4.2	14.9	5.1	0.3	0.2	0.1	0.1	0.1	0.1	0.1
Lu	2.45	3.16	3.91	0.62	2.46	0.85	0.05	0.04	0.04	0.04	0.04	0.04	0.04
Eu/Eu*	0.25	0.25	0.24	0.56	0.3	0.57	NA	1.09	1.54	1.54	1.54	1.54	1.54
LaN/YbN	1.74	2.15	1.87	9.46	2.89	7.12	19.78	3.33	2.67	2	2	1.33	2
LaN/SmN	2.82	3.22	3.14	3.78	3.23	4.35	4.21	6.15	2.46	1.85	1.85	1.23	1.85
CeN/YbN	1.3	1.47	1.05	5.9	2.05	3.29	5.34	1.65	1.27	1.27	0.76	2.8	1.02
CeN/SmN	2.1	2.2	1.77	2.36	2.29	2.01	1.14	3.05	1.17	1.17	0.7	2.58	0.94
EuN/YbN	0.14	0.15	0.14	1.02	0.22	0.72	NA	0.71	1.43	1.43	1.43	1.43	1.43
Σ-REE	218.68	314.23	335.06	251.9	331.7	206.05	26.95	4.22	2.02	1.91	1.6	2.4	1.92

4.2 MAJOR AND MINOR ELEMENTS

The bulk chemical compositions of the rocks/minerals are variable (Table 4.1) to a considerable extent. The most notable characteristic of the granitic gneiss is that it has relatively low SiO_2 content ranging from 76.77 to 79.25 wt% (generally >70 wt %) and high Al_2O_3 content ranging between 11.61 to 11.85 wt% (<11 wt %). Whereas the sheared gneiss has high SiO_2 content ranging from 82 w% to 84 wt % and low Al_2O_3 content ranging from 7 wt%-10 wt % which is slightly lower than the Al_2O_3 content in the granitic gneiss indicating a decrease in Al_2O_3. The Al_2O_3 exhibits a positive correlation with the K_2O content indicating the possible presence of potash feldspar. The major element compositions of the granitic gneiss are predominantly SiO_2, Al_2O_3, and Na_2O, and a small amount of K_2O, consistent with quartz and feldspar as the major constituent minerals.

The SiO_2 content of amethyst range from 98.95 to 100.1 wt%, while that of the milky quartz range from 94.43 to 99.22 wt% revealing that all samples were high purity alpha quartz (content higher than 98%). Na_2O and K_2O values are <0.01 in both milky quartz and amethyst except in a sample which Na_2O has 0.02 wt% (below detection limit of the analytical method employed). There is a general increase in SiO_2 content from the wallrock to the material of the vein.

The total iron (FeO t) contents expressed as FeO is less than 1 wt% in each of the six samples of milky quartz and amethyst, whereas the sheared gneiss has higher Fe_2O_3 content (3.9 wt %) while in the granite gneiss FeO content range from 1.49-2.26 wt%. The sheared gneiss has relatively higher total iron content than the granitic gneiss. Also, there is no exceptional enrichment in the total iron content either in the amethyst or milky quartz and the total iron content do not have correlation with the colour of the samples analysed. The total iron content in

quartz is known to be temperature dependent and its concentration increases with temperature (Holden, 1925). The TiO_2 concentration in the milky quartz and amethyst samples ranges from 0.001 to 1.002 wt%. However, each of the five samples from the milky quartz and amethyst has TiO_2 values of 0.001wt% indicating low content of Ti in the samples. The CaO and MgO concentrations in granitic gneiss and sheared gneiss are less than 1 wt% in each sample. However, sample BK 21/8 have a higher CaO content of 1.15 wt%.

4.3 TRACE ELEMENTS DISTRIBUTION PATTERN

The granitic gneiss is enriched in Ba, Rb, Th, Zn, U, Zr, Y, Hf and Tm when compared to the sheared gneiss but depleted in others namely Cs, Ba, Sr, Ta, W, Pb and Tl (Table 4.2). The bulk continental crust normalized patterns for granite gneiss and sheared gneiss is shown in Fig.13. The granitic gneiss and sheared gneiss both have quite uniform bulk continental crust normalized patterns for incompatible elements except for few discrepancies. Sr and Tl are greatly depleted in the granitic gneiss compared to the sheared gneiss with a pronounced negative anomaly. Ba exhibit negative anomaly in the sheared zone Fig.13 when compared in the granitic gneiss. Cs is depleted in the granite gneiss but enriched in the sheared zone. Rb abundance in the samples BK1/15 and BK1/14 is higher than in sample BK21/8 (Table 4.2, Fig. 13 A, B) and notably depleted in the sheared gneiss. However, it is also worth noting that Ba and Rb are enriched in the granitic gneiss relative to the sheared gneiss.

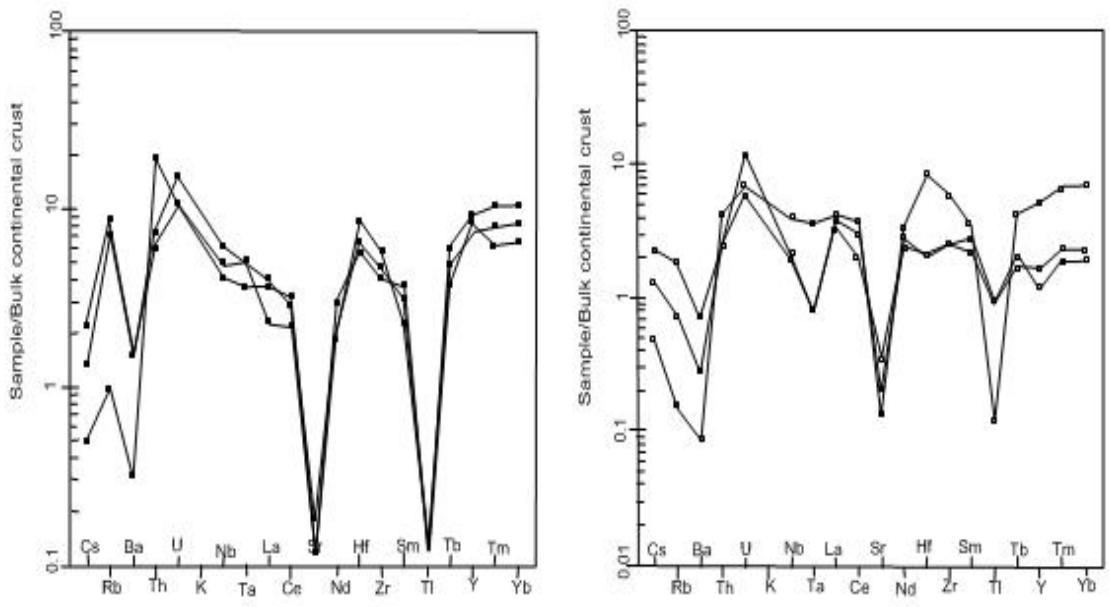


Figure 13: Trace element concentration normalized to the composition of continental crust and plotted from left to right in order of increasing compatibility (A) granitic gneiss (B) sheared gneiss. Normalising values are those of Taylor and McLennan (1995).

The ratio of some incompatible trace and lithophile elements viz: Rb/Ba, Ba/Nb, La/Nb, Nb/Ta, Zr/Hf and Pb/Nd of the granitic gneiss, sheared gneiss, milky quartz and amethyst are presented in Table 4.4. Ba/Nb, Nb/Ta, Zr/Hf and Pb/Nd values in granitic gneiss and sheared gneiss are similar. The Ba/Nb, Nb/Ta, Zr/Hf and Pb/Nd values of milky quartz are similar to that of amethyst. Rb/Ba and La/Nb values in granitic gneiss are similar to that of sheared gneiss while the values of these ratios in milky quartz and amethyst are also similar.

Table 4.4: Incompatible lithophile element ratio

Inter-lithophile ratio	Granitic Gneiss	Sheared Gneiss	Milky Quartz	Amethyst
Rb/Ba	6.36	0.33	3.33	3.75
Ba/Nb	5.05	3.06	6	5.33
La/Nb	9.65	2.83	0.57	0.27
Nb/Ta	12.21	16.95	10	10
Zr/Hf	23.36	28.68	23.35	20
Pb/Nd	1.03	1.19	18.52	25

Selected trace elements are plotted against SiO_2 content in Fig. 14 a-t. Er, Tm, Th, U, Gd, Tb, Dy, Ho, Rb, Nb, Ag, Eu, Y, Zr, Zn and Gn concentration decreases from the granite gneiss towards the sheared gneiss with increasing SiO_2 content. Fig. 14 shows similar trend of depletion of trace elements in the gneisses and quartz veins with respect to the SiO_2 content. There is a general decrease in concentration of some trace and REE elements from the granite gneiss to the material of the vein with increasing SiO_2 content. The degree of depletion is due not only to the degree of dilution factor of quartz, but also to mobility of various elements. In general, the incorporation of trace elements in quartz of hydrothermal origin is dependent on the growth direction and velocity, solution chemistry and P-T condition of its equilibration (Brown and Thomas, 1960; Cohen, 1960; Siebers and Klapper, 1984; Siebers, 1986).

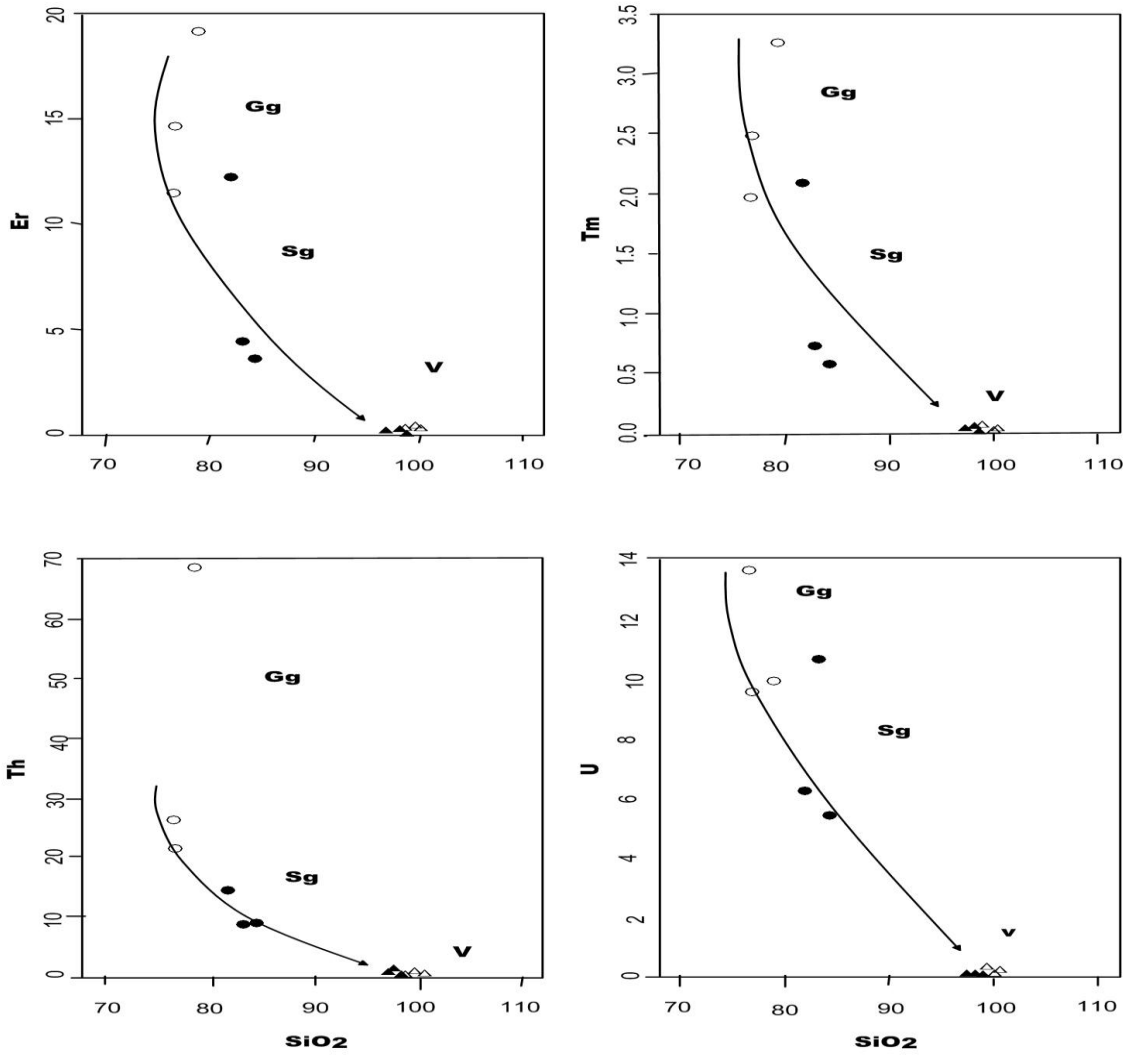


Figure 14: Similar trend of depletion of Er, Tm, Th, U (ppm) plotted against silica content in Dutsen Bakura Hill.

○ = Granitic gneiss

● = Sheared gneiss

▲ and Δ = Vein material

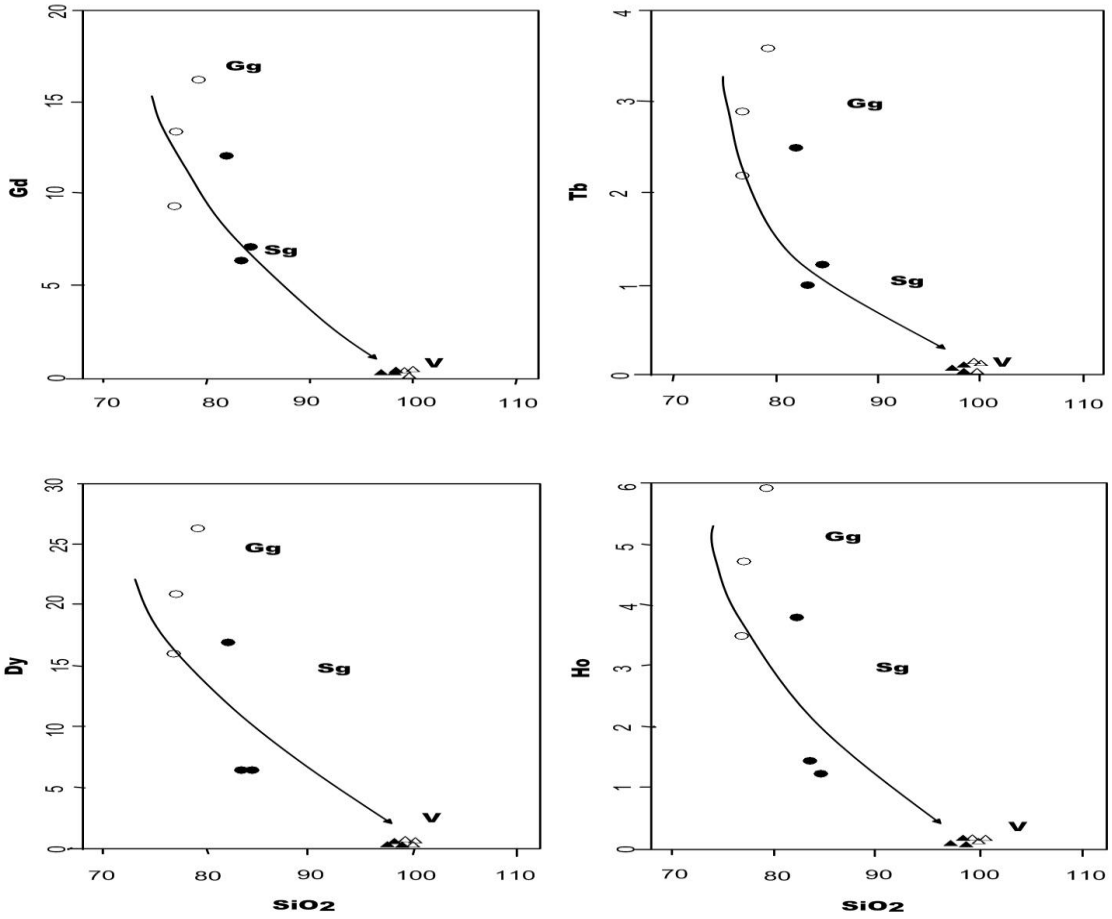


Figure 14: Similar trend of depletion of Gd, Tb, Dy, Ho (ppm) plotted against silica content in Dutsen Bakura Hill.
○ = Granitic gneiss
● = Sheared gneiss
▲ and Δ = Vein material

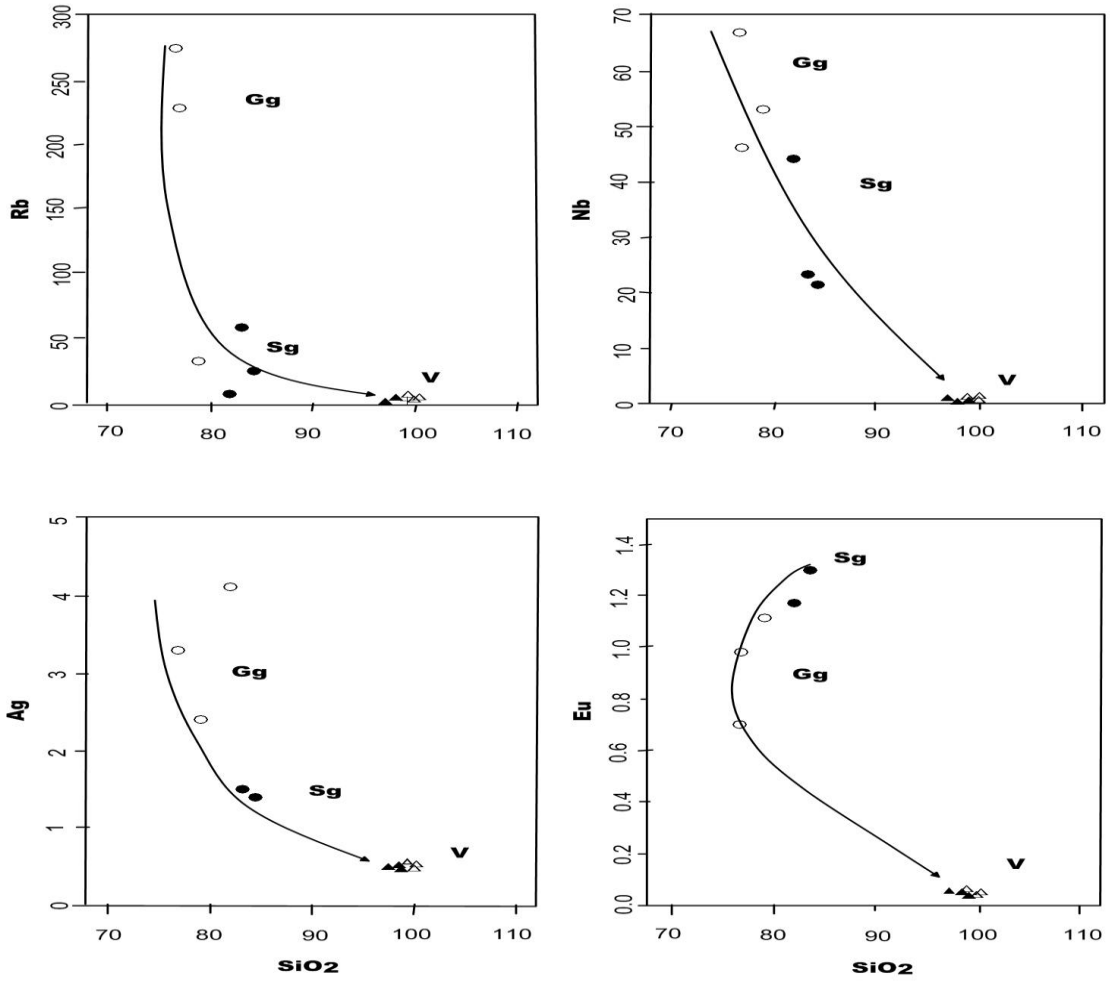


Figure 14: Similar trend of depletion of Rb, Nb, Ag, Eu (ppm) plotted against silica content in Dutsen Bakura Hill.

○ = Granitic gneiss

● = Sheared gneiss

▲ and Δ = Vein material

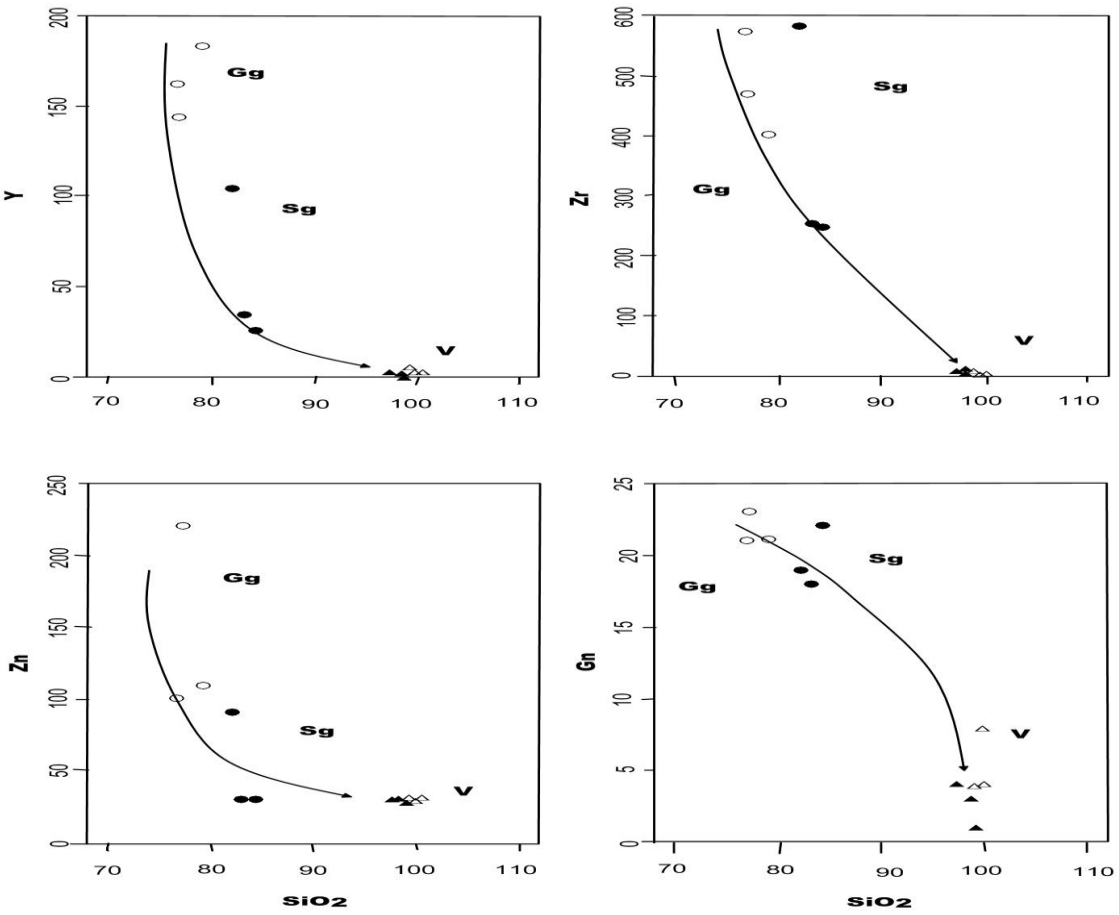


Figure 14: Similar trend of depletion of Y, Zr, Zn, Ga, (ppm) plotted against silica content in Dutsen Bakura Hill.
○ = Granitic gneiss
● = Sheared gneiss
▲ and Δ = Vein material

4.4 RARE EARTH ELEMENT DISTRIBUTION

Chondrite - normalized pattern of the rare earth elements is shown in Fig. 15. The granitic gneiss and the sheared gneiss have high LREE abundances (Σ LREE 157.04) and slightly fractionated REE patterns (La_N/Yb_N = 1.7–9.1) as well as marked negative Eu and weakly negative Ce anomalies. The negative Ce anomaly is typical of Ce^{3+} oxidized by atmospheric oxygen (O_2) to Ce^{4+} under alkaline conditions (ref). Both the granitic gneiss and sheared gneiss have similar negative Eu anomaly though it is stronger (Eu/ Eu* = 0.3) in the granitic gneiss than it is in the sheared gneiss (Eu/Eu* = 0.3– 0.6). However, there is a general slight depletion of the HREE in sheared gneiss relative to the granitic gneiss. Figure 15 also shows that the combined chondrite-normalized REE patterns of the sheared gneiss are parallel to those of the granitic gneiss, but at slightly lower absolute abundances. In contrast, the REE patterns of milky quartz and amethyst (material of the veins) are quite different from those of their immediate wallrocks (Fig. 15). Both milky quartz and amethyst show slight HREE (heavy rare earth element) enrichments relative to the LREE (La_N/Yb_N = 1.3-3.337). They also show negative Ce anomaly except one of the samples which has a positive Ce anomaly, an indication of a reduced condition. It is also worth noting that milky quartz and amethyst have less or no pronounced negative Eu anomalies (Eu/Eu* = 1.09–1.54) and that their REE patterns are irregular, with distinct REE tetrad effect. Individual chondrite-normalized REE patterns of the granitic gneiss, sheared gneiss, milky quartz and amethyst in Dutsen Bakura HillHill is presented also in Fig. 16.

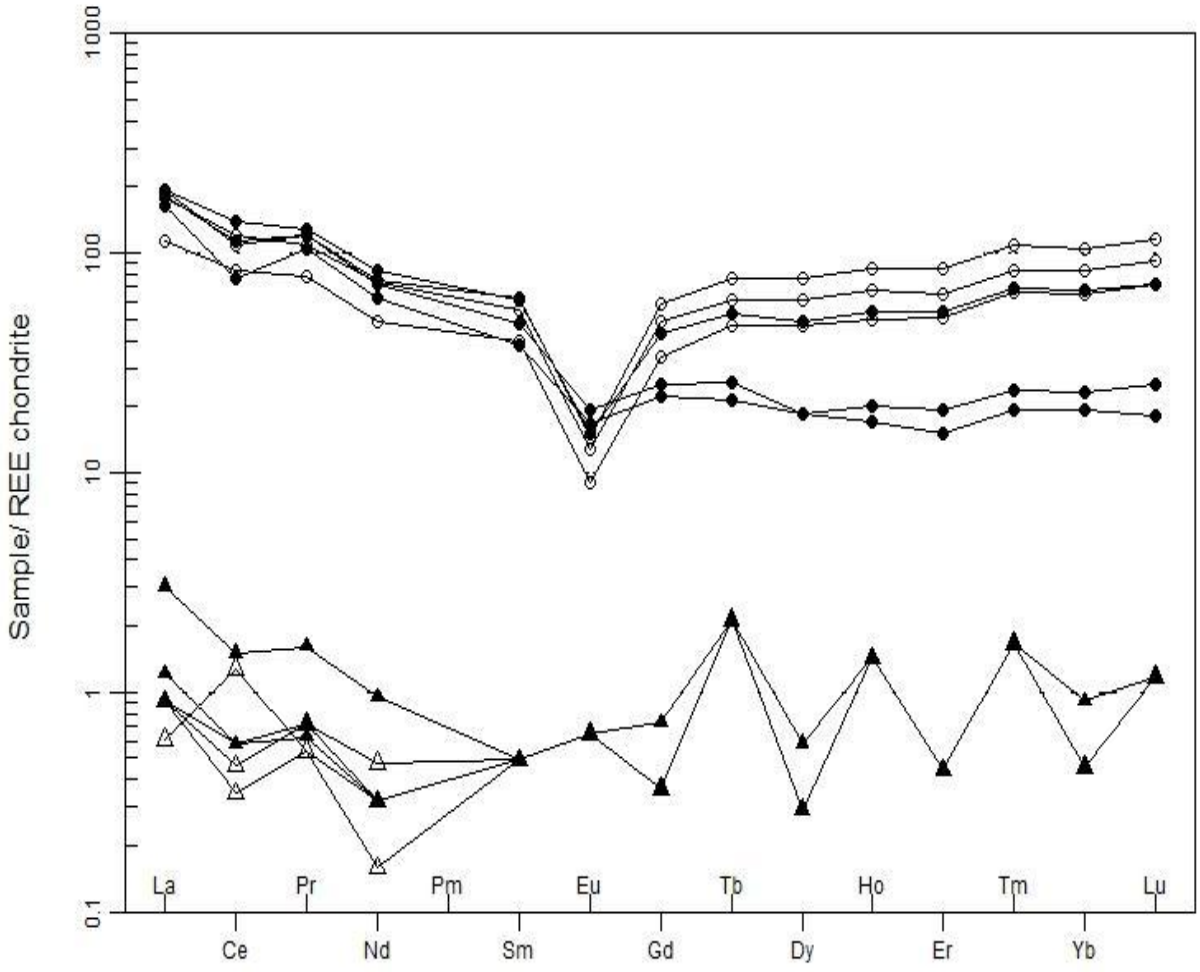


Figure 15: Chondrite-normalised REE patterns of Dutsen Bakura Hill (Normalising values are those of Nakamura, 1974).
○ = granitic gneiss
● = sheared gneiss
▲ = milky quartz
Δ = amethyst

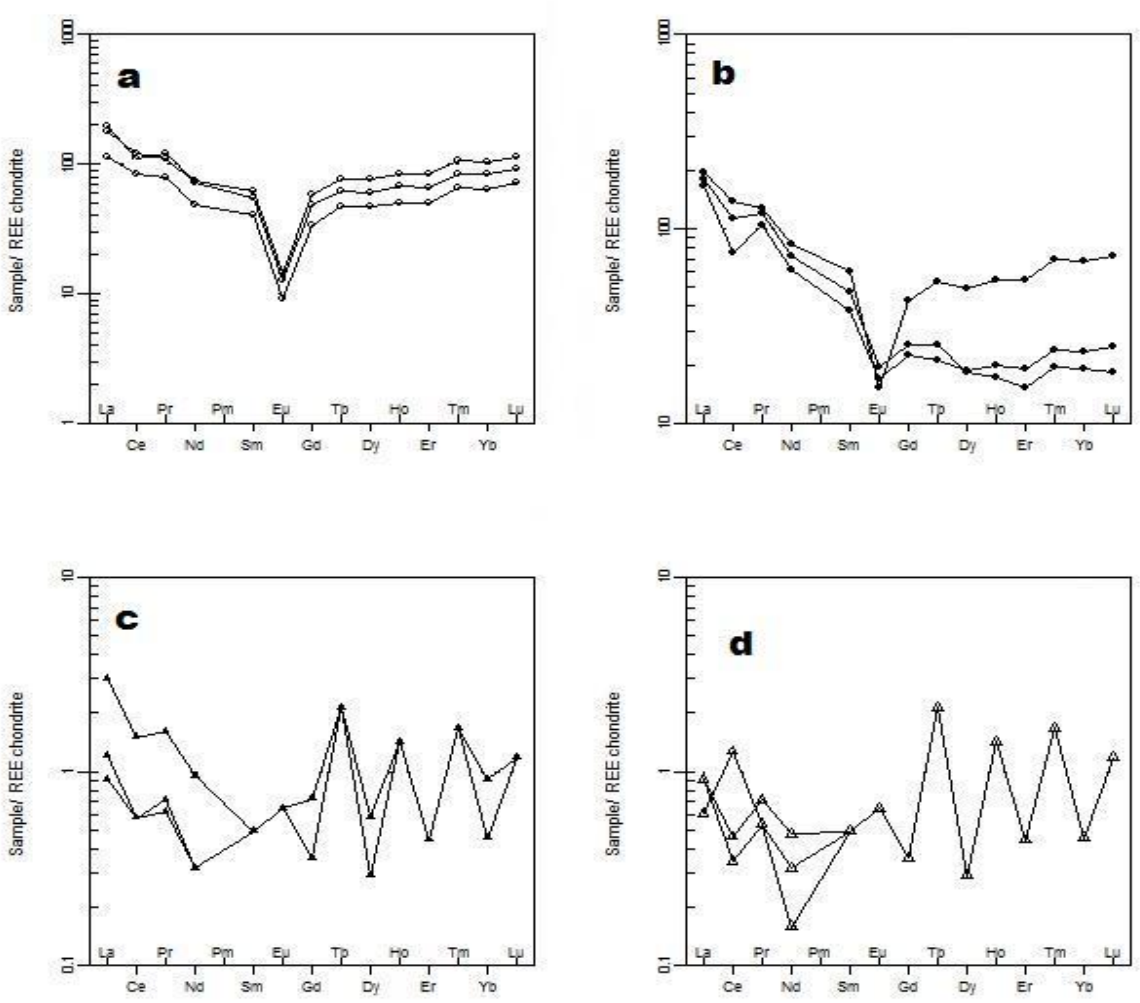


Figure 16: Chondrite-normalized REE patterns of the granitic gneiss (a), sheared gneiss (b), milky quartz (c) and amethyst (d) from Dutsen Bakura Hill. Normalizing values are those of Nakamura, (1974)

4.5 STABLE ISOTOPE RESULTS

The oxygen isotope data of the quartz extracted from the granitic gneiss and that of the milky quartz and amethyst are presented in Table 4.5. Quartz from both the veins and their wallrocks have different $\delta^{18}O$ values. The representative sample of the granitic gneiss has a $\delta^{18}O$ value of 7.1 while the milky quartz and the amethyst from the same vein on the other hand have $\delta^{18}O$ value range are from 12.1 to 17.1‰ with an average of 12.1‰. The oxygen isotope composition of the quartz from the veins and host rock is represented (red box) in Fig 17. There is a trend from low to high values from the granitic gneiss, the milky quartz to the amethyst within a single filling phase. The milky quartz which is probably changed to amethyst variety shows an increase in $\delta^{18}O$ value. In contrast, the amethyst, which usually closes a sequence, has slightly higher $\delta^{18}O$ value relative to the earlier formed milky quartz variety.

Table 4.5: **Oxygen isotope compositions of quartz extracted from granitic gneiss, milky quartz and amethyst in Dutsen Bakura HillHill. (per mil ‰)**

Sample No	Description	Mineral	$\delta^{18}O$
BK1/14	Granite gneiss	Quartz	7.1
BK22/4	Milky quartz	Quartz	12.1
BK34/14	Amethyst	Quartz	17.1

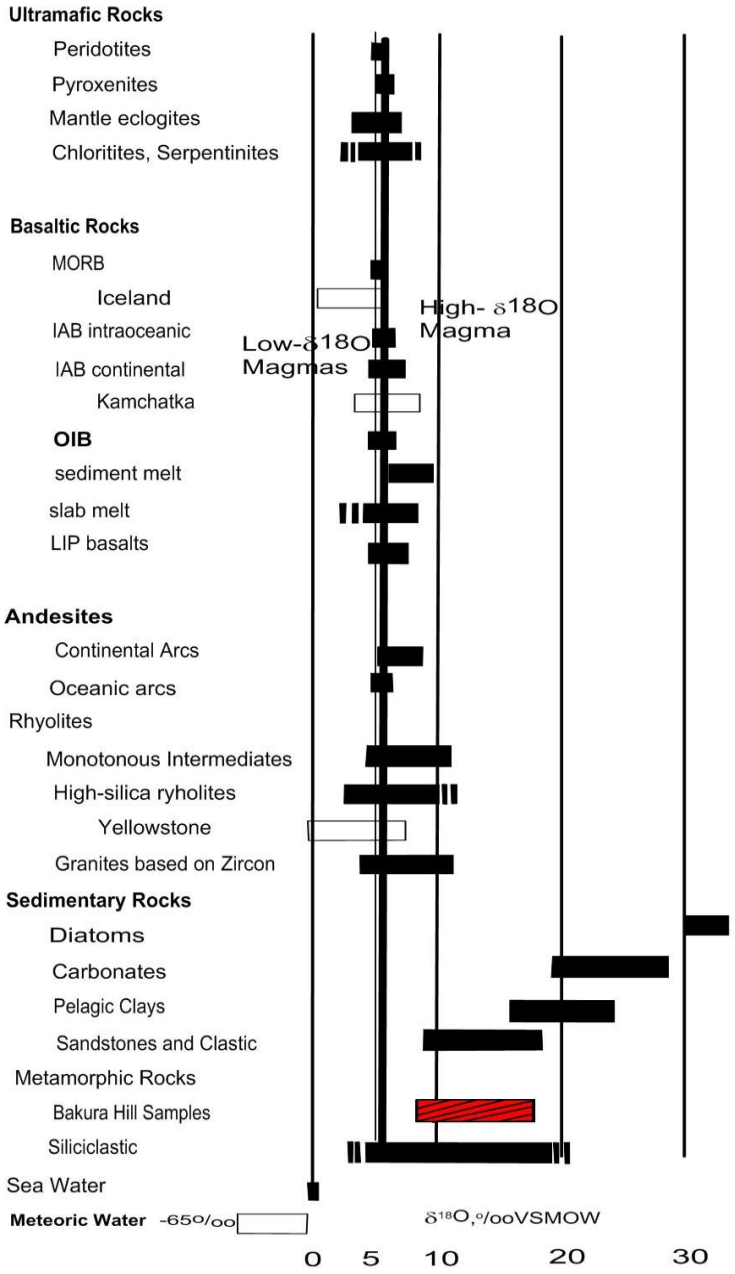


Figure 17: Variation in oxygen isotope composition in magmas and rocks. The range of values obtained from Dutsen Bakura Hill during the present study is indicated as the stifled box. Adapted from Muehlenbachs, (1998); Eiler, (2001); Valley *et al.*, (2005); Hoefs, (2005); Sharp, (2006).

CHAPTER FIVE

DISCUSSION

5.1 DISCUSSION OF FIELD RESULT

Field studies have shown that the study area has undergone tectonic activities and consequently structural displacement of rocks similar to the structural pattern associated with the Pan-African brittle deformation proposed by Ball, (1980). The various structural features in the study area have been described in section 3.4. However the most prominent feature is the dextral strike slips fault that crosses the area with about 168 m displacement. When extrapolated the fault is parallel to the N-S trending fractures. Therefore, it is believed to be related to the general trend. The mineralisation however is constrained in an NE-SW trending vein dipping vertically as a fracture infill by fluids generated by deformation possibly a product of shear zone metamorphism, as earlier on explained by Ajibade *et al*., (1987) Wright *et al*., (1985) and Ball, (1980).

The opening and filling of fractures/cavities in the rocks are the major processes related to the generation and sealing of porosity/fractures in ore deposits (Hartmann *et al.,* 2010a). The amethyst occurring within the vein exhibits comb structure, suggesting precipitation from a fluid (Dong *et al.,* 1995). The vein is characterized by abundance of vugs which indicate near-surface formation of the deposit (McArthur *et al.,* 1993). The filling of milky quartz and amethyst is recognized as a low-temperature (50°C) process (Juchem, (1999), Gilg *et al*., (2003), Duarte *et al*., (2009), Morteani *et al*., (2010), Commin-Fischer *et al*., (2010), which is generally considered to represent hydrothermal event and of an epigenetic origin. The thickness of the veins ranges from 4.3 to 7.3 m. The granitic gneiss surrounding the vein is slightly brecciated (sheared) most probably during the Late Pan-African. The granitic gneiss generally consists of NE-SW and NW-SE trending slightly faulted sheared gneiss. Both the NE-SW and NW-SE trending granitic

gneiss are characterised by quartz veins which are parallel to the general trend of the granitic gneiss. However it is only the NE-SW trending vein that is mineralised. Following the shearing of the granitic gneiss in the NE-SW direction, milky quartz and finally the amethyst were deposited from the migrating hydrothermal solution. Contact between the host rock and vein is sharp. The shearing process possibly brought about the deposition of milky quartz and later amethyst.

5.2 TRACE ELEMENT FRACTIONATION AND REE DISTRIBUTION PATTERN

Fractionation of some incompatible trace and lithophile elements as revealed by the values of Ba/Nb, Nb/Ta, Zr/Hf and Pb/Nd suggests that the sheared gneiss is a derivative of the granitic gneiss. Similarly, the relative similarity in the value of Ba/Nb, Nb/Ta, Zr/Hf and Pb/Nd suggest that the milky quartz and amethyst are probably co-genetic. Further this is suggestive of overriding influence of chemical composition of the fluid relative to fractionation of trace element (Hong-Feng and Cong-Qiang, 2002.). The REE pattern of the granitic gneiss shows slight enrichment of LREE and compared to the HREE with marked negative Eu anomaly thus suggesting crustal origin for the rock. The value of negative Eu anomaly is of gneissic source terrain which resulted from fractionation of plagioclase feldspars in the gneissic protolith (McLennan, 1989).

However, the milky quartz and amethyst (material of the vein) have complicated and irregular REE pattern with characteristic of the so-called REE tetrad pattern (Fig. 18), a phenomenon reported by Peppard *et al*., (1969). Because the REE are group of elements with identical charge (3^+ under most geologically related oxidation conditions) and a relative narrow range of ionic radius (from 1.03 Å for La^{3+} to 0.86 Å for Lu^{3+} in VI coordination (Shannon, 1976), they tend to have almost the same behaviour and exhibit smooth patterns during many

geological processes, especially in the silicate-melt systems. The REE tetrad pattern is, therefore, a rare type of fractionation behaviour, which has attracted the attention of geochemists. According to Hong-Feng and Cong-Qiang, (2002), the unusual REE patterns of some minerals as well as their host rocks cannot be explained by the ionic radius effect, and can only be understood by referring to the electronic configuration of these elements, which plays an important role in the complexes they form in fluid-rich systems. According to McLennan, (1994); Henry *et al*., (1996); Kamber and Collerson, (2000), REE fractionation (tetrad pattern) also exists in synmetamorphic veins which formed during metamorphic dehydration in the western Alps. Thus, it appears that the cases with the tetrad effect are closely related to fluids, and usually accompanied by the fractionation of trace elements with identical charge and similar radius (Liu *et al*., 1993; Bau, 1996; Irber, 1999; Minami *et al*., 1998).

According to Hong-Feng and Cong-Qiang, (2002), most veins have obviously low Nb/Ta and Zr/Hf ratios (Table 4.4). The Zr/Hf ratios of the material of the vein are also away from the CHARAC (charge-and-radius-controlled) field of 26 □ Zr/Hf < 46 (Bau, 1996). Another geochemical pair, Pb and Nd with similar incompatibility and generally no significant fractionation in silicate-melt system, is fractionated during shear zone metamophism (Hong-Feng and Cong-Qiang, (2002). It is clearly shown (Table 4.4) that the material of the vein invariably have much higher Pb/Nd ratios than the granitic gneiss. The large ion lithophile elements, which tend to concentrate equally in the upper continental rocks during mantle/crust evolution due to their similar mineral/melt partition coefficients, show varying behaviour during cataclastic metamorphic deformation (Hong-Feng and Cong-Qiang, (2002). However, a common trend was established from the granitic gneiss to the vein when the concentration of some trace and REE elements were plotted against silica where there is a general decrease in concentration of some

trace and REE elements from the granite gneiss to the material of the vein with increasing SiO_2 content (Fig 14 a-t). This further suggests that the formation of amethyst mineralization is characterised by depletion in the concentration of Er, Tm, Th, U, Gd, Tb, Dy, Ho, Rb, Nb, Ag, Y, Zr, Eu, Gn and Zn in the vein relative to the host granitic gneiss with increase in the concentration of silica. (Silica (SiO_2) concentration increases from the granitic gneiss to the sheared gneiss and the vein).

5.3 OXYGEN ISOTOPE

The oxygen isotope results show that the granitic gneiss has $\delta^{18}O$ value of 7.1 while the milky quartz and the amethyst have $\delta^{18}O$ value of 12.1 and 17.1 respectively. Thus values of $\delta^{18}O$ clearly show in both the granitic gneiss and the vein is higher than established values in granites, rhyolites and andesites but similar to greywackes and siliciclastics rocks (Fig.17). It is therefore proposed that the protolith of the granitic gneiss are greywackes and/or siliciclastic rocks. Moreover, the oxygen isotope result constrained the mineralizing fluid within the range of metamorphic fluids (Fig. 17) with probable involvement of meteoric fluid. This view is supported by (Bindeman, 2008b) who reported that oxygen isotopic variations spans about 100% where half of these variations and nearly all negative $\delta^{18}O$ values are occupied by meteoric water. The $\delta^{18}O$ of each silica phase is a function of the $\delta^{18}O$ of the fluid that deposited the minerals and the temperature-dependent fractionation factor of oxygen isotopes in quartz and water (Duarte *et al.,* 2010). The scattered $\delta^{18}O$ values of silica in the vein represent either variation in the fluid temperature or isotopic composition of the fluid. Trends observed in the isotopic signature of different stages of filling in the amethyst-bearing vein give additional insights into the history of the mineralization. The amethyst mineralized zone usually display banded structure parallel to the enclosing walls; the banding consisting of amethyst and milky

quartz believed to represent, respectively, periods of relative quiescence and active crystal growth. This is well illustrated by the field profiles recorded in Plate III b and V b. The granitic gneiss is depleted in $\delta^{18}O$ relative to the milky quartz which form the beginning of the filling sequence, while relatively higher $\delta^{18}O$ value occur in the amethyst which formed at the close of the sequence. Although this tendency is less evident in pockets with two or three filling sequences; in these also, it can be observed that irrespective of the sequence the amethyst is generally isotopically heavier as compared to the milky quartz formed immediately before it. With a few exceptions, this pattern seems to be a more general feature of the vein formed in the Dutsen Bakura HillHill. The relatively high $\delta^{18}O$ value of the amethyst complies with the expected thermal evolution of the fluid towards decreasing temperature at the final stage of filling (Duarte *et al.,* 2010). And hydrothermal system generally tends to evolve toward heat dissipation during cooling (Duarte *et al.,* 2010).

5.4 GENESIS OF THE AMETHYST MINERALIZATION

A number of studies have shown that quartz veins in metamorphic terrains are precipitated from silica-rich fluids produced by deformation during shear zone metamorphism (Yardley, 1983; Yardley and Bottrell, 1992; Ague, 1991; Henry *et al*., 1996; Wilkinson *et al*., 1996). It might be argued that the milky quartz and amethyst (material of the vein) are derived from the granitic gneiss owing to the fact that all of them have siliciclastic protolith (Fig. 17). However, the differential fractionation of highly incompatible trace element in the material of the vein and the granitic gneiss does not support this consideration. For example in the case of partial melting, it might be expected that Ba would show enrichment in the veins comparable to Rb, Th, and U (Hong-Feng and Cong-Qiang, (2002). This is not the case as can be observed in (Table 4.2). In addition, the fractionation of some geochemical pairs (Nb-Ta, Zr-Hf, Pb-Nd) and

the REE tetrad effect as revealed by the REE pattern in milky quartz and amethyst also argue against this consideration (Hong-Feng and Cong-Qiang, (2002). Bebout *et al*., (1999) have demonstrated that metamorphic fluids have highly fractionated trace element composition. Therefore, from the result obtained it is clear that the materials of the vein, like similar synmetamorphic veins in other terrains were deposited by fluid generated possibly by deformation during shear zone metamorphism (Putlitz *et al*., 2002; Becker *et al*., 1999).

Previous studies of quartz veins occurring in metamorphic terrains suggest that the vein-forming fluids are either derived from the granitic gneiss (Yardley, 1975; Yardley and Bottrell, 1992; Putlitz *et al*., 2002) or partly (~30%) from an external source (Ague, 1994; van Haren *et al*., 1996). In the case of a partly external source, fluids migrate in a channelized way (i.e., the veins are the major conduits of migrating fluids), and are mineralogically and isotopically in disequilibrium with the granitic gneiss host (Ague, 1994; van Haren *et al*., 1996). However, because of the hydrothermal alterations found in the granitic gneiss studied, the vein-forming fluid in the study area were possibly derived from shear zone metamorphism and possibly as the evolution of the fluid is taking place crystallisation front of the metasomatic fluid brings about precipitation of the amethyst.

The source of colouration in the amethyst is due to enrichment in Fe_2O_3 which is higher than the values obtained from amethyst result in Table 5.1 by Holden, (1925). Hence the amethyst mineralization probably precipitated from silica-rich fluids produced by deformation during shear zone metamorphism. Colour in amethyst develops due to substitution of Fe^{3+} for Si followed by natural irradiation producing Fe^{4+} (Gaines *et al.,* 1997). It is possible that the presence of transition elements, impurities, lattice defects and strain have contributed to the variation of colour in the vein quartz. Gaines *et al.,* (1997) have noted that variable amounts of

Al present in quartz may contribute to its colour. In order to determine what impurities were found in amethyst, Holden, (1925) made a detailed analysis on some samples from several localities base on different colours.

According to Holden, (1925) the elements which might possibly enter into the pigments are iron, manganese and titanium (Table 5.1). He noted that the amount of manganese in amethyst does not vary with the depth of colour. He then concluded, therefore, that manganese does not give colour to amethyst. Whereas, the amount of titanium is small and rather uniform from the dark to the pale samples which he concluded was probably due to the small rutile inclusions often present in quartz. The suggestion that an iron compound causes the violet colour in amethyst has been the one most often made (Fernando *et al.,* 2009). The analyses in Table 5.1 show that amethyst contains large amounts of total iron, and that the percentage of Fe_2O_3 with the total iron may have been responsible for the colouration. The average percentage of Fe_2O_3 for each of the three colour-classes is: (i) 0.14 (ii) 0.026 (iii) 0.007. This clearly suggests that some compound of Fe_2O_3 in the total iron may be responsible for the pigmentation of amethyst in the study area.

The analytical data on milky quartz and amethyst from Dutsen Bakura HillHill presented in Table 4.5 reveals that the amethyst contains a relatively high amount of Fe_2O_3 compared to the milky quartz and that the percentage of Fe_2O_3 increases from the milky quartz to the amethyst. The average percentage of Fe_2O_3 for milky quartz and amethyst is: 0.61 and 0.65 respectively. The Fe_2O_3 and TiO_2 content of the amethyst are higher than the values reported by Holden, (1925) while MnO content is similar to that of Holden's (Table 5.2).

Table 5.1: Analysis of amethyst for FeO(T), TiO_2, and MnO (adapted from Holden, 1925).

Color - class	Specimen number	FeO(T)	TiO_2	MnO	Average %Fe_2O_3
i	4	0.335%	trace	0.0002%	0.14
	14	0.24	0.0005%	0.0001	
	3	0.06	trace	none	
	1	0.05	0.001	0.0001	
	7	0.02	trace	none	
ii	19	0.07	0.001	0.0080	0.026
	13	0.03	0.001	0.0011	
	17a	0.02	trace	0.0015	
	18	0.006	trace	0.0002	
	23	0.005	trace	0.0002	
iii	12	0.011	trace	0.0004	0.007
	8	0.005	trace	0.0001	
	9	0.015	trace	0.0002	
	17b	0.004	0.001	0.0021	
	2	0.004	trace	0.0002	

Table 5.2: Relative composition of Fe_2O_3, TiO_2 and MnO in milky quartz and amethyst

Variety	Sample No	Fe_2O_3	TiO_2	MnO	Ave % Fe_2O_3
Milky quartz	BK17/14	0.60	0.001	0.006	0.61
	BK13/14	0.66	0.001	0.006	
	BK23/14	0.56	0.002	0.006	
Amethyst	BK25/14	0.63	0.001	0.006	0.65
	BK61/14	0.65	0.001	0.006	
	BK3/14	0.67	0.001	0.007	

5.5 A PROPOSED MODEL OF ORIGIN

The proposed model seeks to present a conceptual view of the origin of the Dutsen Bakura HillHill amethyst mineralization. The model is based on field, geochemistry and oxygen isotope results illustrated in Fig 18. The latest orogenic event that affected the area was during the late Pan-African 540±40 Ma ago. Metamorphism, uplift, cooling, fracturing and faulting dominated the end of the Pan-African activity. It is also marked by development of a conjugate fracture system of strike-slip faults (Ball, 1980). Fault directions have a consistent trend and sense of displacement which is a NNE-SSW trending system having a dextral sense of movement (McCurry, 1971; Ball, 1980) similar to structural trend of Dutsen Bakura Hill area. The granitic gneiss host was sheared leading to ingress of metasomatic fluid that causes extensive sillicification. The sillicification process was marked by the extensive development of the milky quartz first in the vein. The last episode of the sillification process was marked by the development of amethystine quartz localized at the core of the milky quartz veins.

The oxygen isotope results show that the granitic gneiss has $\delta^{18}O$ value of 7.1 while the milky quartz and the amethyst have $\delta^{18}O$ value of 12.1 and 17.1 respectively. Thus values of $\delta^{18}O$ in both the granitic gneiss and the vein are clearly higher than the established values in granites, rhyolites and andesites but similar to greywackes and siliciclastics rocks. It is therefore proposed that the protolith of the granite gneiss are greywackes and/or silliciclastic rocks. Furthermore, the oxygen isotope result constrained the mineralizing fluid within the range of metamorphic fluids with probable involvement of meteoric fluid. The amethyst mineralization in the study and adjacent areas (Makarfi and Ikara amethyst mineralization) suggested that they are all related to major faults found in the basement complex around north central Nigeria. Silica content increases from the granitic gneiss to the amethyst an indication of sillicification. The

model suggests that the terrain underwent faulting, shearing and finally amethyst mineralization. The opening and filling of fractures/cavities in the rocks are the major processes related to the generation and sealing of porosity/fractures in ore deposits. The amethyst occurring within the vein exhibits comb structure, suggesting precipitation from a fluid. The vein is characterized by abundance of vugs which indicate near-surface formation of the deposit. The filling of quartz and amethyst is recognized as a low-temperature process which is generally considered to represent hydrothermal event and of an epigenetic origin.

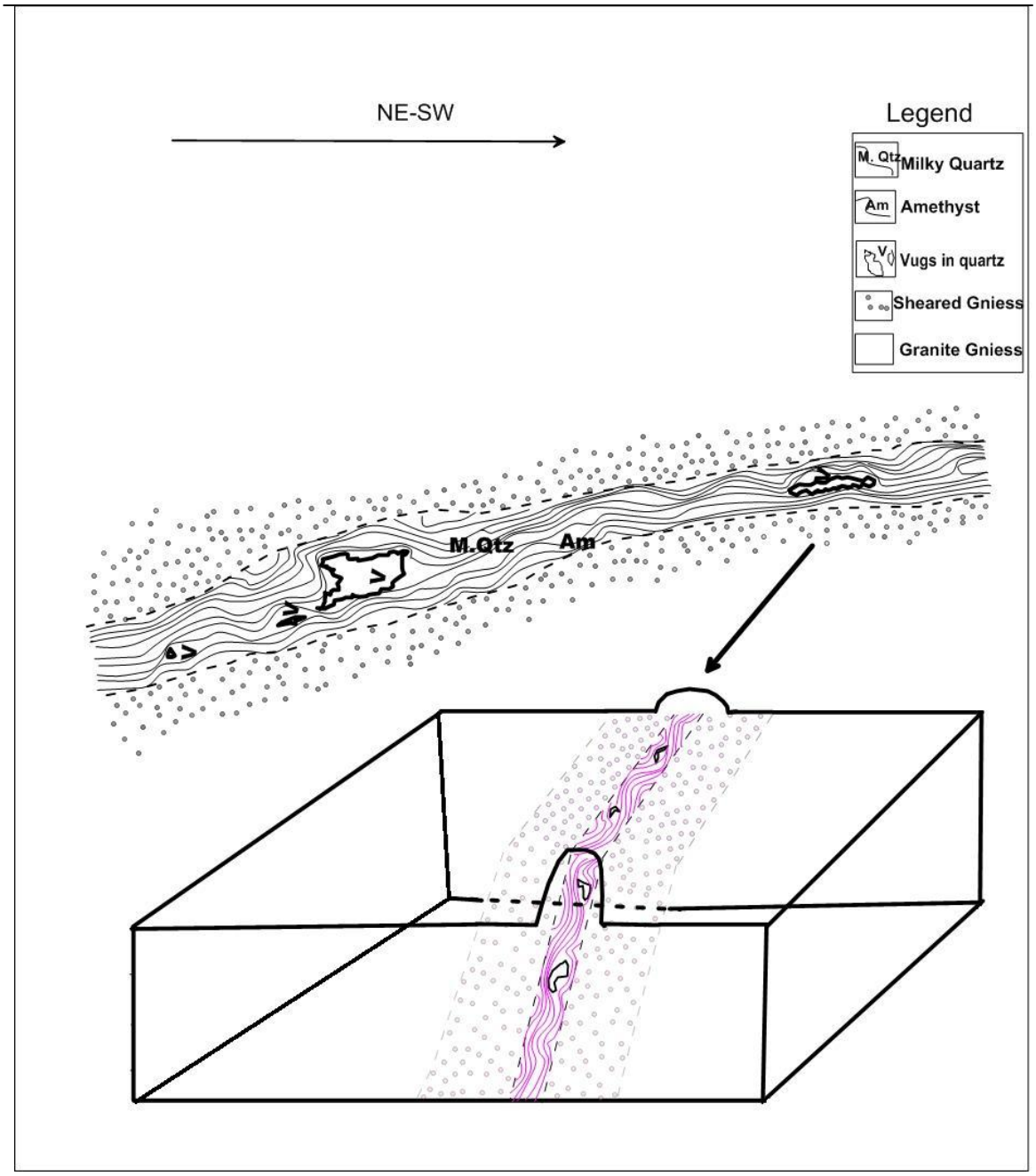


Figure 18: Conceptual model of Dutsen Bakura Hill amethyst mineralization

CHAPTER SIX

SUMMARY AND CONCLUSION

6.1 SUMMARY

The study area is located within the north-central Nigerian Basement Complex which has been affected by the Late Pan-African orogeny. The Nigerian Basement complex evolves by the plate tectonics processes involving collision between a passive continental margin of the West African Craton and the active continental margin of the Tuareg Shield 600 Ma ago.

The mineralisation occur as vein filling and composed almost entirely of silica which appear in alternating purple and milky colours within a slightly faulted sheared gneiss.

Major elements systematic show that the granitic gneiss; sheared gneiss, milky quartz and amethyst samples are variable to a considerable extent. The mineralised veins are enriched in SiO_2, Al_2O_3 and Fe_2O_3.The SiO_2 content increases from milky quartz to amethyst. However, the Ba/Nb, Nb/Ta, Zr/Hf and Pb/Nd values of milky quartz are similar to that of amethyst. Rb/Ba and La/Nb values in granitic gneiss are much higher compared to the sheared gneiss, milky quartz and amethyst. The trace element pattern normalized to bulk continental crust after Taylor and McLennan (1995) shows that incompartible elements in all samples are characterised by high abundance of large ion lithophile elements (LILES), depletion of Nb, Sr and Eu, and enrichment of Pb.

Trace lithophile elements content (Fig. 13) suggest that the granitic gneiss and sheared gneiss have crustal origin. This is further confirmed by the REE pattern. The REE pattern of the milky quartz and amethyst, however, indicate that they form contemporaneously. The milky quartz and amethyst (material of the vein) have complicated and irregular REE pattern with characteristic of the REE tetrad effect. Moreover, a general decreasing trend was established

from the granitic gneiss to the vein when the concentration of some trace and REE elements were plotted against silica. This further suggests that the formation of amethyst mineralization is characterised by depletion in the concentration of Tb, Dy, Ho, Er, Tm, Yb, Lu, Tb, Tl, Ta, Nb, Rb, Eu, Ag and Th in the vein relative to the host granite gneiss with increase in the concentration of silica.

Oxygen isotope data constrained the mineralizing fluid within the range of metamorphic fluids with probable involvement of meteoric fluid. It also clearly shows that both the granitic gneiss and quartz vein have $\delta^{18}O$ values higher than those in granites, rhyolites and andesites but similar to those in greywackes and siliciclastics rocks thus suggesting that the protoliths of the granite gneiss are greywacke and/or siliciclastic rocks. The amethyst mineralization most probably precipitated from silica-rich fluids produced by deformation during shear zone metamorphism.

6.2 CONCLUSION

Field and laboratory studies of the Dutsen Bakura HillHill reveal the following:

1. The basement rocks of Nigeria were affected by the Pan-African orogeny which was fractured paving channels for fluid incursion.
2. The vein hosting amethyst deposits is hosted within NE-SW striking; steeply dipping faulted brecciated granitic gneiss. The vein is characterised by open space, shearing and vuggy textures, thus indicating that the mineralisation is structurally controlled and is epigenetic in origin.
4. Comb structure (vuggy structure) accompanies amethyst deposition suggesting precipitation from a residual/hydrothermal fluid.

5. At least two phases of amethyst crystals separated by milky quartz, during the period of shearing are present. The sequence contains two generations of quartz crystals, due to episodic influx of hydrothermal solutions that deposited the quartz. The sequence contains alternating generation of amethyst and milky quartz. These sequences of deposition are traceable throughout the vein.
6. Geochemical results points to crustal origin for the granitic gneiss and the sheared gneiss and suggests that the sheared gneiss is a derivative of the granitic gneiss. However the milky quartz and the amethyst are probably co-genetic
7. Oxygen isotope signatures of the milky quartz and amethyst constrained the mineralizing fluid to metamorphic with probable involvement of meteoric fluid.
8. Hence amethyst in Dutsen Bakura Hill is precipitated from silica-rich fluids produced by deformation during shear zone metamorphism.

6.3 RECOMMENDATION

The number of samples taken to represent the entire study area is limited hence there is need for a more in-depth studies in other amethyst mineralized shear zones that were recently discovered (Makarfi and Ikara amethyst mineralization). This will enable formulation of a more comprehensive model for the amethyst mineralization in Pan-African basement complex of Nigeria.

There is a need for more in-depth study to constraint the amethyst mineralization episode to general tectonic evolution of the Pan-African basement complex of Nigeria since it is increasingly becoming obvious that most of the sheared zones tend to be associated with the amethyst mineralization.

Furthermore there is the need for XRD studies as this will characterize and provide an insight into the actual cause of the violet colour in amethyst within north-central Nigeria**.**

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APPENDIX I

Quartz Vein Trend Readings within Granitic Gneiss in Dutsen Bakura HillHill

10	336	70	36	280	20
350	300	320	06	54	60
340	360	350	350	40	40
40	326	106	44	106	312
28	44	22	36	68	50
60	14	72	70	46	68
18	18	18	30	14	14
314	328	328	348	06	326
264	340	90	08	20	284
320	180	151	280	61	269
220	240	230	162	27	30
344	26	96	32	98	78
360	276	286	348	52	

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ATTN: Magaji Shehu Suleiman

CERTIFICATE OF ANALYSIS

16 Crushed Rock samples were submitted for analysis.

The following analytical packages were requested: Code 10A 18O Silicates Isotopic Analysis
Code 4LITHO (11+) Major Elements Fusion ICP(WRA)/Trace Elements Fusion ICP/MS(WRA4B2)

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Notes:
We recommend using option 4B1 for accurate levels of the base metals Cu, Pb, Zn, Ni and Ag. Option 4B-INAA for As, Sb, high W >100ppm, Cr >1000ppm and Sn >50ppm by Code 5D. Values for these elements provided by Fusion ICP/MS, are order of magnitude only and are provided for general information. Mineralized samples should have the Quant option selected or request assays for values which exceed the range of option 4B1. Total includes all elements in % oxide to the left of total.

CERTIFIED BY :

Emmanuel Eseme , Ph.D.
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