# GEOLOGY, GEOCHEMISTRY AND THE STRUCTURAL CONTROL OF BARITE-ANHYDRITE MINERALIZATIONS IN THE GOMBE INLIER

BY

Iordye Juliet Terhemba
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A THESIS SUBMITTED TO THE APPLIED GEOLOGY PROGRAMME,

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MARCH, 2008

## DECLARATION

I, Iordye Juliet Terhemba declare that this thesis is written by me and has not been presented in part or in whole by anyone for the award of any degree. References made to published and unpublished authors have been duly acknowledged.

IORDYE JULIET TERHEMBA

16-05-2008

DATE

This declaration is confirmed by;

MALLAM AHMED ISAH HARUNA

16th-5-2008

DATE

## CERTIFICATION

I certify that this thesis is an original work done by Iordye Juliet Terhemba with Registration number, 00/9792/1 under my supervision and has met the requirement for the award of Bachelor of Technology in Applied Geology of Abubakar Tafawa Balewa University, Bauchi.

**SUPERVISOR:** MALLAM AHMED ISAH HARUNA

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**DATE:** 16th-5-2008

**CORDINATOR:** PROF. D. M. ORAZULIKE

**SIGNATURE:** ____________________

**DATE:** 26 June 08.

**EXTERNAL EXAMINER:** PROF. E. C. IKE

**SIGNATURE:** ____________________

**DATE:** ____________________

## DEDICATION

This thesis is dedicated to God Almighty who is my pillar of strength, for seeing me through all these years and my dad Mr. M. M Iordye for being there always.

# ACKNOWLEDGEMENT

My profound gratitude goes to God Almighty for giving me the strength and knowledge to go through my academic period. My immense gratitude goes to my dad, Mr. M. M. Iordye for being very sensitive to my needs, my mum, Mrs. P. V. Iordye for her prayers, my siblings Susan, Benjamin, Euphemia, Mark, Lucia my little mama and my cousins Evelyn and Michaella for their support.

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## ABSTRACT

Sixteen veins and other locations were mapped on the Gombe Inlier. Samples were collected and taken to the laboratory for analysis. X-Ray Fluorescence (XRF) analysis was the method employed in order to ascertain the accuracy and reliability of the results. Out of the sixteen veins analyzed, six veins were found to contain mostly Barite ($BaSO_4$), four veins were found to contain mostly Anhydrite ($CaSO_4$), while six other veins contain mainly Silica ($SiO_2$). The structural analysis using the S-pole method produced three main principal planar surfaces (S1, S2, and S3) which collectively trend in NE-SW direction. Each principal planar surface contains either Barite or Anhydrite or Silica. The petrographic studies confirm the presence of the Barite and Anhydrite containing different proportions of Silica which present Silica as the host for the mineralization. The structural and chemical barriers for the mineralizations are the fractures and the silicification process. This research confirm that the fractures hosting the mineralizations conform to the style of opening of the Benue Trough in the NE-SW direction so they also might have been formed during the opening of the Benue Trough in the Cretaceous which coincide with the period of drifting of the Gwondwanaland. The research also confirmed the presence of Barite-cum-Anhydrite mineralizations in the Gombe Inlier and has upgraded the mineralizations from the level of mineral occurrence to the level of mineral resource.

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# CHAPTER ONE

# INTRODUCTION

## 1.1 Statement of Problem

The Gombe Inlier is a basement dome within the Gongola Basin which exposes most of the stratigraphic sequence (Bima Sandstone, Yolde Formation, Pindiga Formation and Gombe Sandstone). Most of the works done in that area are on the exposed stratigraphic sequence at the flank of the inlier.

Barite mineralization was reported from Gombe Inlier but no detailed work has been done to study the Barite alongside other accessory minerals. The fracture systems hosting the Barite on the Gombe Inlier was also least understood because it has not been studied in detail. The chemistry and the economic implication of the Barite mineralization and the accessory minerals were also not understood.

Only unregistered miners patronize the Barite in Gombe Inlier and so the impact of the mineralization on the economy is almost in-assessable.

## 1.2 Aims and Objectives of Study

This research is aimed at determining the origin and economic potentials of the Barite within the Gombe Inlier. Samples from various locations and veins on the inlier have been analyzed to determine the chemical composition of the Barite in order to evaluate its origin and economic potential. Structural analysis of the trend of the Barite veins have been carried out using the stereogram to plot S-pole diagram in order to determine the origin and nature of the structures hosting the Barite.

The research is also aimed at enhancing my library research, field experience and interpretation by means of a detailed macroscopic and microscopic study of the minerals and rocks of the inlier and subsequent production of a geologic map.

It is for the partial fulfillment of the requirement for the award of the degree of Bachelor of Technology in Applied Geology from Abubakar Tafawa Balewa University, Bauchi.

### 1.3 Location and Accessibility

The mapped area is located in Gombe Local Government of Gombe State. It covers an area of 126km$^2$ on the topographic map of Gombe N.W sheet 152 with a scale of 1:50,000 and is located between Longitudes 11°11' 20.4" E and 11°14' 37.4"E and Latitudes 10°16' 20.8"N and 10°19' 16.0"N (Fig. 1).

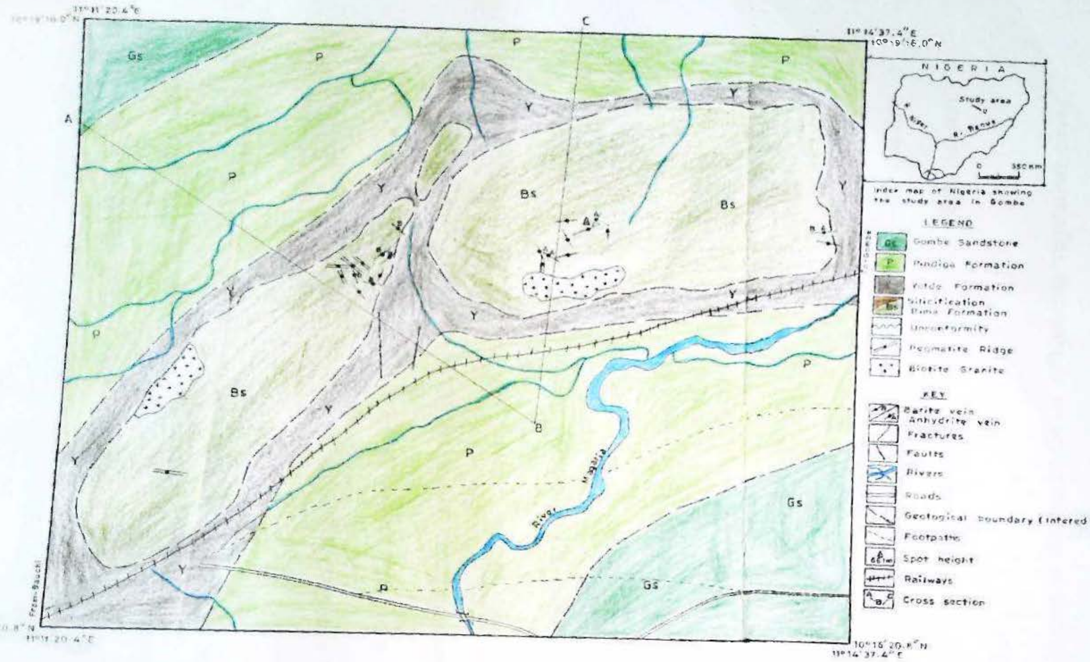
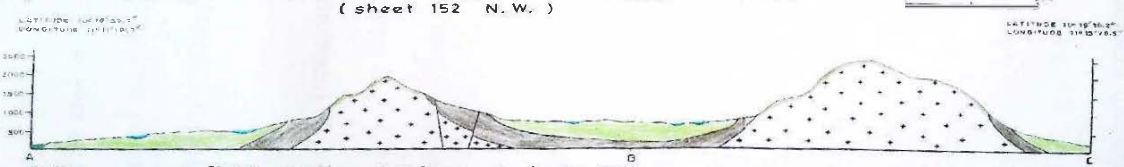



Fig. 1a Geological map of Gombe Inlier showing sample locations (sheet 152 N.W.)



Cross section A — B — C of Gombe Inlier

The area is easily accessible through Dadin Kowa road which is a major tarred road that passes through Gombe town. The untarred motorable road from the railway and foot paths makes the outcrop easily accessible.

## 1.4 Topography and Drainage

The mapped area lies between 29.8704 to 670.5600 meters above sea level based on the contour lines. The topography is defined by the prominent inlier and relatively high hills with gentle and steep slopes and undulating sedimentary rocks surrounding it, making it an inlier.

The drainage of the area is controlled by the inlier. The inlier has no dissections except along the strike – slip fault, water flows down the rock in tributaries, some of which flow into River Magaria (Fig. 1).

## 1.5 Climate and Vegetation

The climate of the study area can be described as bi-seasonal. The dry season is comparatively longer (November – March) than the rainy season (mid-May – September).

Rainfall distribution is the major factor influencing vegetation cover although topography and ground water condition are also significant. In terms of vegetation, the mapped area can be described as exhibiting the characteristics of the Sahel Savannah type of vegetation (Falconer, J.D, 1911). The vegetation comprises mainly of different types of grasses.

The soil type to a large extend controls the type of vegetation that may dominate a given locality.

## 1.6 Scope of the Present Work

The study area has been mapped in detail using the topographic map of Gombe N.W sheet 152 with a scale of 1:50,000. Samples were collected from the veins and from different locations. These samples were studied carefully and noted down in the field notebook. Dip and strike readings were also noted down in the field notebook.

Samples from the field will be studied macroscopically to evaluate texture and colour. Thin sections will be prepared in the laboratory using samples. The slides will be examined with a petrographic microscope and optical characteristics observed in each sample will be noted. The attitude readings of the fractures hosting the veins would be used to plot S-pole on the stereogram to determine the nature and origin of structures hosting the Barite. Geochemical analysis will be carried out on the samples to ascertain their chemical composition.

The S-pole diagrams, the petrographic studies and the geochemical analysis will be used to evaluate the origin of the Barite, the nature and origin of the structures hosting the Barite and the economic potential of the Barite within the Gombe Inlier.

## 1.7 Previous Work

Early studies of the Upper Benue Trough were carried out by Falconer (1911), Jones (1932), Raeburn and Jones (1934) and Barber et al (1954). The basis for all later work was provided by Carter et al (1963) who undertook a regional study of the area covered by the Geological Survey of Nigeria 1/250,000 series map sheet 25 (Potiskum), 36 (Gombe) and 47 (Lau). The Upper Benue Trough has since become known in greater detail and has been almost entirely remapped through the work of Alix (1983), Benkhelil (1985, 1986, 1988), Popoff et al, (1988), Guiraud (1989, 1990a, 1993) and Zaborski et al (1998). There has been detailed research work on the Upper Benue Trough but not Gombe Inlier in particular.

# CHAPTER TWO

# LITERATURE REVIEW

## 2.1 Geological Setting of the Benue Trough

The Benue Trough of Nigeria within which the study area is located is the most important of all the Cretaceous sedimentary basins of Nigeria. It is an elongated rift approximately 1000km long and 50 – 150km wide tending NE – SW and overlying the pre-Cambrian shield of the West African Mobile Belt (Benkhelil, 1989, Guiraud, 1990).

The trough is an elongated partly fault-bounded depression occupied by up to 6,000m of marine and fluvio-deltaic sediments that have been compressionally folded into a non-orogenic shield environment (Carter et al, 1963, Wright, 1976 and 1981).

The northern limit of the trough is the southern boundary of the Chad Basin, which is in turn separated from the trough by an anticlinal feature called the Dumbulwa-Bage Highs (Zaborski, 1997) while the southern limit of the trough is the northern boundary of the Niger-Delta ( Zaborski et al, 1997). Marine and fluvio-deltaic sediments infill the entire Benue Trough ranging from Late Aptian to Paleocene in age (Adegoke, et al, 1978, Allix, et al, 1981).

There has been systematic variation in the depositional environment within the trough over time such that, continental lacustrine or fluviatile sediments occur at the base through various marine transgressive and regressive beds to immature continental sandstones at the top.

## 2.2 Location and Subdivisions of the Benue Trough

The Benue Trough runs through the NE – SW central parts of Nigeria from the Niger Delta in the SW right up to the Bomo Basin in the NE of Nigeria. It is subdivided arbitrarily into lower, middle and upper portions. Although no concrete or clear outline can be drawn to demarcate the individual subdivided portions, some major localities (towns or settlements) which constitute the major depo-centers of the different portions have been well documented by Petters, (1982), Nwajide, (1990), Idowu and Ekweozor (1983) (Fig. 2).

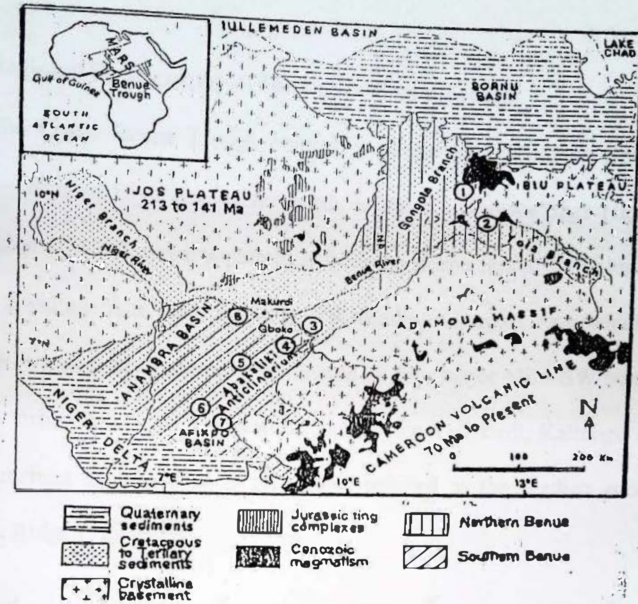



FIG. 2. Geological Sketch Map of Benue Trough (Maluski et al. 1995)

The depo-centers of the Lower Benue Trough comprises mainly of the areas around Nkalagu and Abakaliki, while those of the Anambra Basin centers are around Enugu, Awgu, Akwa and Okigwe. The Middle Benue Trough comprises of areas around Makurdi through Yandev, Lafia, Obi, Jangwa to Wukari. In the Upper Benue Trough, the depo-centers comprise of areas around Tula, Jessu, Dukul, Numanha and Lamja (in the Yola Arm of the trough) and Pindiga, Gombe, Nafada, Ashaka (in the Gongola Arm of the trough).

The study area falls within the Gongola Arm of the Upper Benue Trough. (Fig. 2)

## 2.3 Regional Stratigraphy of the Upper Benue Trough

The Upper Benue Trough comprises of the area extending from the Bashar – Mutum Biyu line as far north as the 'Dumbulwa-Bage High' of Zaborski et al, 1998 which separates it from the Borno Basin. It includes an E – W trending Yola Arm and a N – S trending Gongola Arm which are separated by an area structurally dominated by four major NE – SW trending sinistral strike-slip faults, the Gombe fault, Bima-Teli fault, Kaltungo fault and Burashika fault. Carter et al, (1963) referred to the median zone as Zambuk Ridge (Fig. 3).

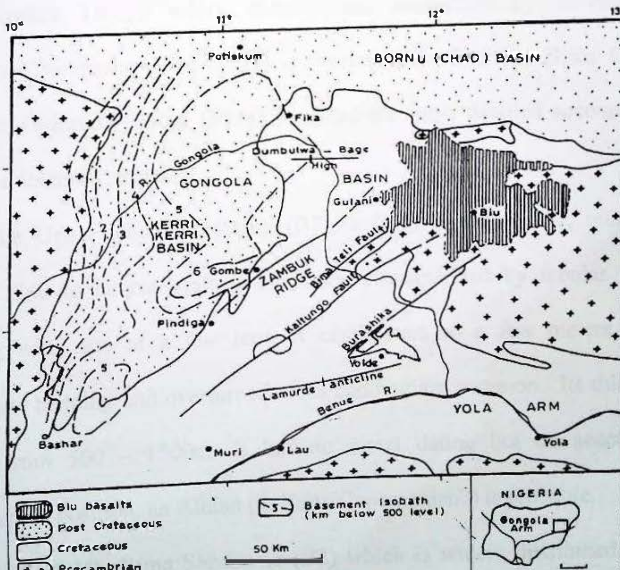



**Fig. 3. Simplified Geological Map of the Upper Benue Trough**
**(after Zaborski et al, 1997)**

The Cretaceous succession in the Upper Benue Trough comprises of Early Cretaceous continental clastics, the Bima Group, Yolde Formation, Pindiga Formation and lateral equivalents in the Yola Arm which are the Dukul Formation, Jessu Formation, Sekule Formation, Numanha Shale and Lamja sandstone, sandy members of the middle part of the Pindiga Formation in the Gongola Basin, Gombe Sandstone, Kerri-Kerri Formation and Neogene to Quanternary Basalts.

### 2.3.1 The Bima Group

The continental Bima Group comprises the oldest sediments in the Upper Benue Trough which directly and unconformably overlie the crystalline Basement rocks. Several workers described the Bima Group however; Guiraud (1990a, 1991a) provided the most detailed account and described its three parts as:

The Upper Bima Sandstone (B3); a fairly homogeneous, relatively mature, fine to coarse grained sandstone characterized by tabular cross-bedding with sets of a few tens of centimeters to a few meters thick. Convolute bedding and overturned cross bedding are common. Its thickness ranges from 500 – 1500m. It has no direct dating but on account of stratigraphic position, an Albian (to Early Cenomanian?) is probable.

The Middle Bima Sandstone (B2) which is widely distributed, fairly uniform unit consisting of fining upward cycles each 5 – 10m thick. It has trough and tabular cross bedding and clays and palaeosols may occur at the top of individual cycles. Overall thickness ranges from 100 – 500m. Guiraud (1991a, 1991b) reported fossil wood, silicified Metadopocarpoxylon libanoticum (Edwards) to which a Late Aptain age was assigned.

Lower Bima Sandstone (B1) is a highly variable unit with an overall thickness of 0 – 1500m. Individual lithofacies distribution was controlled by synsedimentary tectonic activity which created a number of sub-basins with associated volcanism. Lithofacies association within a sub-basin consist of conglomeratic alluvial fan or debris flow deposits, adjacent to active basin – forming faults, grading laterally into fining –upward fluvial sequences into lacustrine deposits with interbedded clays, fine - grained sandstones and calcareous sandstones. In the sector of the Gombe Inlier, the Bima Group is greatly attenuated. It is represented by pebble conglomerates and poorly sorted arkosic sandstone similar to the lower Bima Formation elsewhere. Radiometric ages from intercalated lavas suggest an age from Albian to close to Jurassic- Cretacous boundary, (Guiraud1991a).

### 2.3.2 The Yolde Formation

The name Yolde Formation was proposed by Carter et al, (1963) for the transition beds recognized earlier by Falconer (1911) and Barber et al, (1954) between the Bima Group and the Pindiga Formation. A type section was designated in the Yolde stream in the western part of the Yola Arm. The

Yolde Formation gives rise to a subdued topography often with sparse vegetation cover and is poorly exposed in most part of the Gongola basin.

The Yolde Formation is indeed a transitional sequence between the continental Bima Group and the marine deposits of the lower part of the Pindiga Formation. The lower sandstone - mudstone portion of the Yolde Formation is interpreted to be of fluvial origin, the upper portion with more thinly and regularly bedded bioturbated sandstones and low diversity bivalve faunas at the top is of shallow marine origin. Lawal (1982) and Lawal and Moullade (1986) suggested a Late Albian to Late Cenomanian age for the Yolde Formation on the basis of its palynofossils.

### 2.3.3 The Pindiga Formation

The name Pindiga Formation was proposed by Carter et al. (1963) for the calcareous beds and clay shales previously described by Barber et al, (1954). The nature of the Pindiga Formation is best understood by regarding it as consisting of five members.

The name 'Kanawa Formation' was proposed by Thompson (1958) for a sequence of shales and intercalated limestone outcropping around Kanawa to the east of Gombe. It corresponds only to the lower shale-limestone member of the Pindiga Formation and provides an excellent stratigraphical mark horizon between the sandy units above and below. The Kanawa Member was formed during the Late Cenomanian to Early Turonian transgression, which affected the entire Benue Trough and also the Sahara region of the north (see example, Busson, 1972, Reyment, 1980, Meister et al, 1992). It has a wide spread occurrence in the Upper Benue Trough and a greater part of it consist of shaly mudstone, irregular thin lenses and discontinuous layers of diagenetic gypsum also occur. Its age equivalent in the Yola Arm, the Dukul Formation has similar lithology of shaly mudstone with intercalated limestone. The Kanawa member has been extensively studied due to the rich faunas of its limestone beds.

The name 'Gulani Sandstone' was proposed by Carter et al, (1963, pp. 52 – 53) who regarded it as a member of the Pindiga Formation and provided the only significant previous description. Numerous exposures of the Gulani Member occur in the Gulani-Jang area, where the contact with the Kanawa Member has not been seen but appears to be sharp. The Gulani Member contains relatively thinly bedded coarse to very coarse-grained pebbly sandstones with purple, brown and white laminated mudstone interbeds. The sandstones are frequently ripple-marked and the mudstone occasionally displays desiccation cracks. The age is described alongside with the Dumbulwa Member.

The name 'Deba - Fulani Member' is proposed mainly for the sandy beds occurring in the middle part of the Pindiga Formation. Its unit has not previously been differentiated. The Deba – Fulani Member appears to pass laterally into the Dumbulwa Member, south of the Dumbulwa-Bage High.

Exposures of the Deba Fulani member are rare and no complete section has been found. Limited sections showing sequences of sandstone and siltstone in beds of 5 – 150m thick are present in streams around, especially to the west of Deba Fulani which is proposed as the type area. The age is described along side with the Dumbulwa Member.

The Dumbulwa Member is a new name proposed for a unit which appears to be the same as the upper sandstone-shale portion of the Gongila Formation of Carter et al. (1963). There has been some doubt concerning this view, the term 'Gongila Formation' being inappropriate for these beds because Gongila Village itself lies upon the lower Bima Formation. In the light of the criticism concerning the name 'Gongila Formation', the name 'Dumbulwa Member' was proposed for the sandstone and shale sequence in the middle part of the Pindiga Formation in and around the Dumbulwa-Bage High. The proposed type unit which is in the Dumbulwa Hill consists of fining-upward cycles. The Dumbulwa Member reaches its greatest thickness of about 200m in the Dumbulawa and Bage Hills.

The Dumbulwa, Deba Fulani and Gulani Members are lateral equivalents therefore their ages and environments of deposition can be conveniently considered collectively. No direct dating is currently available for them.

In the Yola Arm, the Dukul Formation which is Early – Middle Turonian at the top is overlain by the Jessu Formation which is interpreted by

Allix (1983) as of a less marine nature than either the Dukul or the overlying Sekule Formation. Ciolopoceras occurs in this area again (Barber, 1957) demonstrating marine Upper Turonian.

The Fika Member comprises of the 'Fika Shales' of Carter, et al, (1963) and the equivalent of the upper shale member recognized by authors in the Pindiga Formation. There was a mis-mapping due to the failure to recognize the Deba Fulani thrust and the subsequent interpretation of the base of the Deba Fulani Member south as the base of the Gombe Formation. The Fika Member produces a low featureless topography and its outcrop can be recognized from the black shrinking clay soil. No type section has been designated, only borehole records provide the nature of the unit. The exposures that occur mostly reveal shaly mudstone, lack macrofossils and contain irregular lenses and bonds of gypsum.

In the Gombe Inlier, three oolitic sandstone beds 40, 15 and 13cm thick from lowest to highest are present in the upper part of the Fika Member which are separated by 1.5 and 1m of shales respectively. Variable thickness of 600m has been reported by authors for the Fika Member and a number of paleontological observations give information on the depositional environment and age. The Fika Member has lower limits around the Middle – Upper Turonian boundary and upper limits close to the Campanian - Maastrichtian boundary. Carter et al, (1963), Lawal (1982) and Allix et al, (1984) believed that it represented a continuous period of deposition from

Turonian to Maastrichtian. Structural dips shown by the Gombe Formation are frequently only about half of those in the nearest exposed pre-Campanian beds. This is not strange since the outcrop of Gombe Formation is same distance from the main deformed zones close to the system of strike-slip faults occurring along the axial part of the Upper Benue Trough. This relationship is also present in the Gombe Inlier where all the Cretaceous sediments have been deformed.

### 2.3.4 The Gombe Formation

The Gombe Formation corresponds to the name 'Gombe Sandstone' which was proposed by Carter et al (1963) for the 'Gombe grits and clays' previously identified by Falconer (1911). A type section was designated by Carter et al, (1963) in the Kware Stream on the southern outskirts of Gombe town. The Gombe Formation is restricted to the western part of the Gongola Basin. It weathers to produce a ferruginous capping. This resistant material, along with ironstone weathered out of the sequence is responsible for the rugged and hilly topography characterizing much of its outcrop. The Gombe Formation has a marked angular unconformity between it and the Kerri-Kerri Formation and is made up of three major lithofacies which may prove recognizable as separate members. At the base, the Gombe Formation consists of rapidly alternating thin beds of silty shales, sometimes with plant remains and fine to medium grain sandstones with some intercalated thin flaggy ironstones. Bioturbation is common in this facies, mainly horizontal feeding burrows of Thalassinoides type. This lithofacies is repeated in the Gombe Inlier above few tens of meters of strata belonging to the bedded facies. Dike (1995) has reported coal horizons in the upper part of the Gombe Sandstone encountered in the boreholes penetrating the subcropping part of the formation.

Gombe Formation was interpreted by Carter et al (1963) as deltaic and estuarine deposits. Lawal (1982) found a marked decrease in marine microfossils (foraminifera, dinoflagellates and acritarchs) at the boundary of the Pindiga Formation and the Gombe Formation, the pollens in the Gombe Formation indicated a Maastrichtian age.

### 2.3.5 The Post-Cretaceous Rocks

The Cretaceous Gongola Basin is concealed to the west by the Kerri-Kerri Formation and to the extreme east by the basalts of Biu Plateau.

The continental clastics of the Kerri-Kerri Formation with thickness of over 320m have been described by Adegoke et al (1986) and Dike (1993). The Formation has scanty age data. Paleocene pollens have been recovered (Adegoke et al, 1979) but Eocene beds may also occur (Adegoke et al, 1986). The irregular topography of the unconformity surface that separates the Kerri-Kerri Formation from the Gombe Formation is exposed on the northern outskirts of Gombe town.

Olivine basalts of the Biu Plateau, described by Carter et al, (1963) occur as extensive lava flows. Associated volcanic cones are arranged along a N – S trending line in the western part of the Plateau (Benkhelil, 1988). These basalts have a net thickness of 250m (Wright, 1989) and radiometric ages which range from 5.0± 0.2 Ma to less than 0.8Ma (Grant et al., 1972).

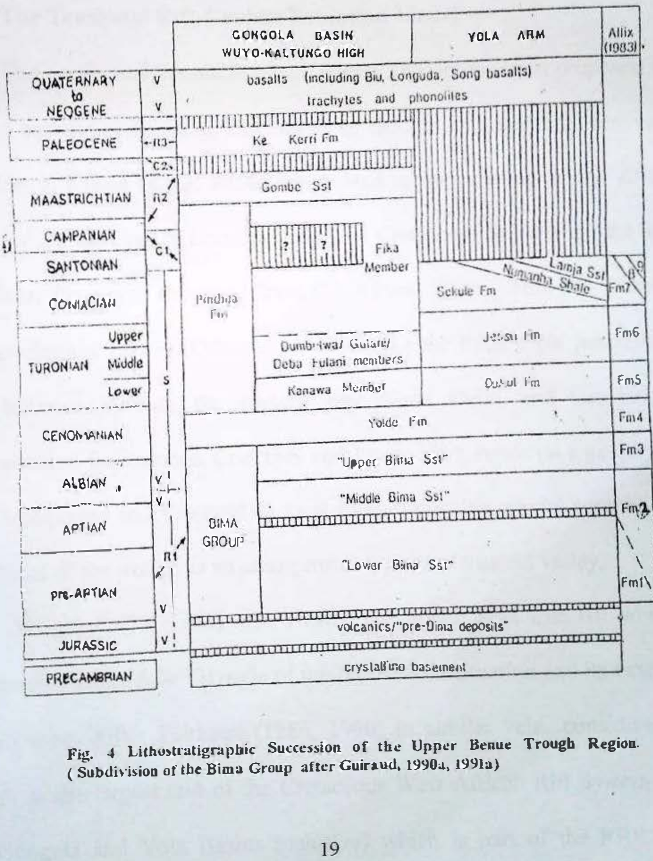



**Fig. 4 Lithostratigraphic Succession of the Upper Benue Trough Region. ( Subdivision of the Bima Group after Guiraud, 1990a, 1991a)**

## 2.4 Origin and Evolution of the Benue Trough

The evolutionary mechanisms of the Benue Trough have been quite controversial within the last fifty years. This has lead to the emergence of two contrasting school of thoughts.

### 2.4.1 The Tensional Rift-Graben Evolution Model

The origin and evolution of the Benue Trough has been proposed by a bulk of authors constituting this school of thought as a tensional movement resulting in rifting (King, 1956) which lead to the opening of the Atlantic ocean (along the Gulf of Guinea) during the Cretaceous times when the South American Plate was separated from the African Plate. This was based on time geological factors (Carter et al, 1963) like the RRR triple junction that was initiated beneath the present day Niger Delta and Gravitational interpretation for instance, Cratchley and Jones, 1965, based on a geophysical data, interpreted and observed an axial zone of positive gravity anomalies on both sides of the trough as an arrangement typical of true rift valley.

Wright (1976, 1981) also viewed the trough as a true rift which is comparable to the Afar Triangle of the NE African situation and its extension to Ethiopian Rift. Fairhead (1986, 1990) in similar vein, considered the trough as the largest arm of the Cretaceous West African Rift System (with the Gongola and Yola Basins inclusive) which is part of the RRR triple junction, initiated at the site of the present day Niger Delta with the other two rift arms subsequently developing into the south and equatorial Atlantic Oceans respectively.

Uma (1998) holds a similar view but stressed the fact that the trough is an intracratonic rift system whose tectonic activities continued beyond the Aptian times, although diachronously in the Turonian through Santonian then culminating in the Maastrichtian at the upper reaches of the trough. In his view, the tectonism accounts for the extreme compaction, fracturing and folding of the pre-Santonian sediments within the trough.

Most of the authors generally argued in favour of a tensional regime of tectonism having been responsible for the origin and evolution of the trough right from the time of its initiation as a triple RRR junction (Burke et al, 1970) throughout its history of sedimentation and deformation. Most of the authors emphasized the wholly ensialic nature of the trough, the thinned crust beneath it and the dominant influence of the vertical movement as a cause of the folding of the Gulf of Guinea alone. They viewed the main boundary rift faults as having been concealed by the Cretaceous-Tertiary sediments owing to the crustal thinning and elevation of the crust-mantle boundary beneath the central parts of the rift.

This view was buttressed and consolidated by some ERTS photographs of the Lamurde Anticline located in the Upper Benue Trough which showed rule-straight, doubly-plunging limbs proving that some of the folding may have been controlled by a system of ENE trending faults in the underlying basement, along which blocks have been differentially uplifted (Fig. 5).

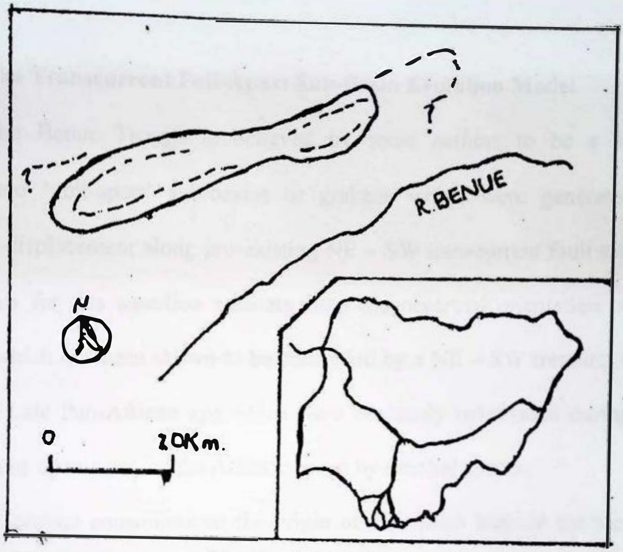



Fig. 5. The Lamurde Anticline from 1:1million ERTS photograph (after Wright, 1981)

Wright (1981) contends that if vertical movement is proved to be the main cause of the folding observed within the trough, then the search for a mechanism of compression will not be required. This is because it is easier to see the successive phase of folding within the trough not as alternations of tensional and compressive phases but as a result of adjustment which have occurred in the trough during the intermitted uplifts of the surrounding broad plateau. He related the way basement surface dip in many places along the boundaries of the trough and related it to the possibility of the underlying basement undergoing down warp towards the trough axis at sometimes during the evolution.

### 2.4.2 The Transcurrent Pull-Apart Sub-Basin Evolution Model

The Benue Trough is believed by some authors to be a set of juxtaposed 'pull-apart' sub-basins or grabens which were generated by sinistral displacement along pre-existing NE – SW transcurrent fault system. The basis for this assertion emanate from the observed orientation of the trough which has been shown to be controlled by a NE - SW trending shear zone of Late Pan-African age which were obviously reactivated during the Cretaceous opening up of the Atlantic ocean by sinistral shears.

Important constraints on the origin of the trough include the tectonic framework, the thermal history and other geological and geophysical considerations.

The first constraint concerns the fault system in the Benue Trough. It is clear that no boundary, N60°E trending fault of major extent has been identified so far. On the other hand, a fault system trending N60°E has been recognized both directly (Maurin et al, 1985, Benkhelil, 1986) and indirectly (Benkhelil in press) along the trough axis. These faults bear the traces of poly – phased tectonic activity and originated as a ductile, dextral shears during the Late Pan – African orogeny (Maurin et al, 1985).

Most recent traces of movement within the trough are due to the sinistral wrenching with the first episode related to the formation of the trough. The youngest movement related to the compressional event (Santonian or Late Cretaceous) are clearly transcurrent with a strong reverse component leading locally to small 'flower structures'. The fault system is not restricted to the Benue trend, and other directions are combined with the main NE – SW set to form the rhomb – shaped sub basins which characterized the deepest structure of the trough.

The second important constraint is the magmatic activity of the Benue Trough which may be locally important. It is restricted to parts of the basin. In the Albian shales of the Abakaliki Anticlinorium, the magmatism is more related to a regional structural control than to a given period of the evolution of the Benue Trough.

Another important constraint is the relationship between tectonics and sedimentation. According to several authors, the numerous transgressions and regressions have to be related to a deformational event (Nwachukwu, 1972, Offodile and Reyment, 1976, Petters, 1978). The fact is that, besides the two well documented major events (Santonian and Maastrichtian), the Benue Trough was an unstable area from the Albian to the end of the Cretaceous.

Considering the tectonic regime, the assumption of Wright (1981) cannot be retained. This is because it is obvious that the origin of the

Cretaceous folding cannot only be related to vertical movements. The folding of a thick volume of sediment accompanied by vertical cleavage, and the determination of the strain ellipsoid corresponding to a horizontal flattening (Benkhelil, 1986), in Abakaliki area are sufficient to prove the compressional nature of the folding.

It is important to note obvious existence of certain peculiarities in a given continental environment. The Benue Trough being an intracratonic basin remains very unique in the West African Rift System. The baseline is that, sedimentary and structural characteristics of the Lower Cretaceous are more satisfactorily explained in terms of extension plus strike-slip movements rather than by extension alone. Hence, compressional movements are responsible for the generalized folding of the Benue Trough but with a noticeable role of wrenching.

# CHAPTER THREE

# METHODOLOGY

## 3.1 Field Work

The Field mapping exercise began on the 23rd of March and ended on the 29th of March, 2007. The reconnaissance survey was carried out using the topographic map of Gombe NW sheet 152 . There was easy accessibility during the field work since the area mapped is situated near Gombe town and is prominent because the main work is on the inlier.

Equipments and materials used in the field include; GPS, hammer, sample bag, compass-clinometer, hand-lens. measuring tape, masking tape, marker, camera, field note book and a pen.

Information acquired from the field includes; spot heights, photographs of some veins (Plates 1,2,3 and 4), and attitude readings of planes, veins and fractures.

### 3.1.1 Sampling

Samples were collected directly from the veins, away from the veins and from certain locations that are not related to the veins within the rock covering the inlier and from the inlier (Plates 1, 2, 3, and 4).

Plate 1. Vein 5

Plate 2. Vein 18

Plate 3. Vein 6

Plate 4. Vein 21

Samples locations were accurately indicated on the geologic map with the aid of the GPS. Dipping directions and strikes of the various veins where samples were collected have also been indicated on the map (Fig. 1).

### 3.1.2 Measurement of Dip and Strike

The GPS and Compass-clinometer were used in the measurement of dipping directions and strikes of the veins. These have been indicated on the geologic map (Fig. 1). Rulers and measuring tapes were used to measure the width of the veins.

## 3.2 Geochemical Analysis

Geochemical analysis is carried out on rocks and minerals to ascertain their chemical composition. The elements and compounds contained in these rocks and minerals are given in weight percentage. Geochemical analysis was carried out with the use of the XRF (X – Ray Fluorescence) machine.

### 3.2.1 Procedure for Geochemical Analysis

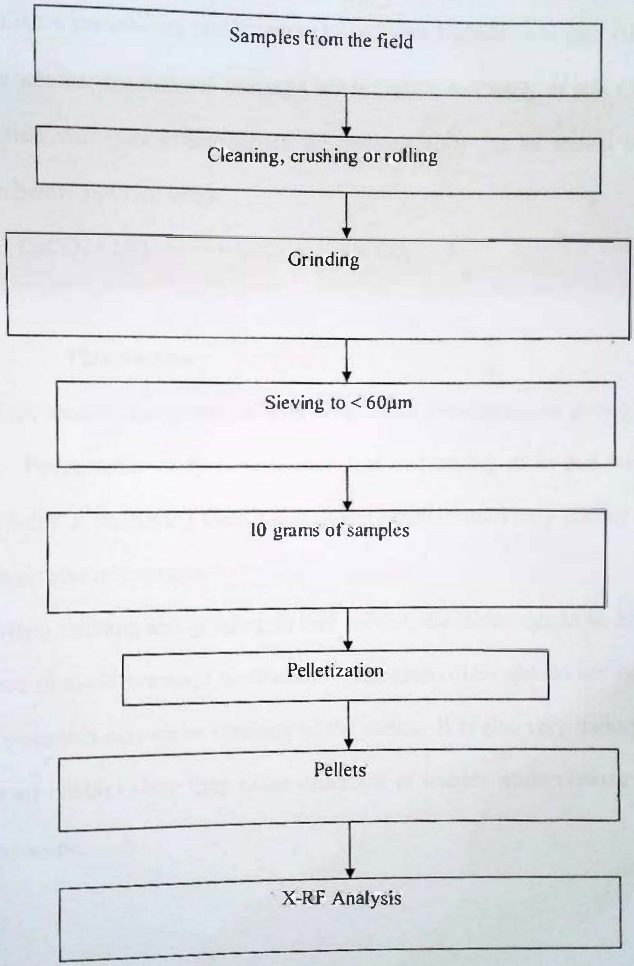



**Fig. 6 Flowchart showing the procedure for geochemical analysis**

### 3.3 Hcl Test

A simple preliminary test was conducted with hydrochloric acid (Hcl) to ascertain whether the mineral bearing CaO is $CaCO_3$ or $CaSO_4$. If it is $CaCO_3$, the reaction will give effervescence by emitting $CO_2$ gas as shown by the equation below and vice versa.

$$CaCO_3 + Hcl \longrightarrow CaCl_2 + Hcl + CO_2 \uparrow$$

### 3.4 Thin Section

Thin section is a process of preparing rocks or minerals for petrographic studies. Petrographic study is very important in studying rocks and minerals since it helps in identifying them based on the characteristics they display under the petrographic microscope.

When thinning and grinding in thin section, the slides should be handled with care to avoid breakage or damage. The glass slides should not be over heated since this may cause cracking of the slides. It is also very important to remove air bubbles since they cause distortion of images while viewing under the microscope.

### 3.4.1 Procedure for Thin Section Preparation

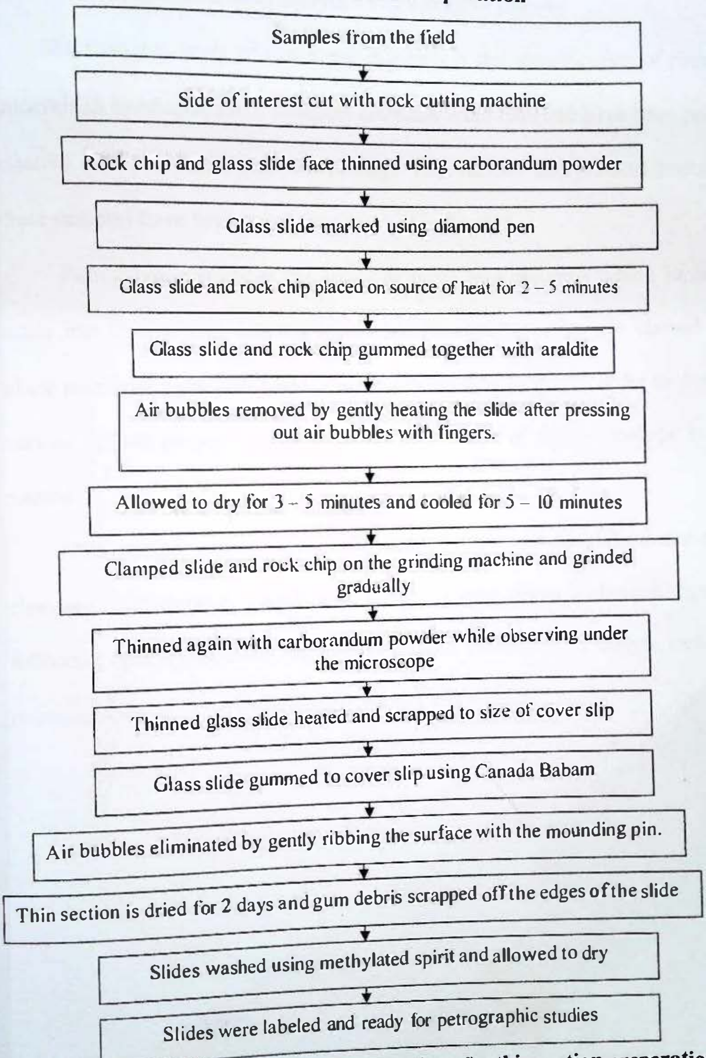



**Fig. 7 Flowchart showing the procedure for thin section preparation**

## 3.5 Macroscopic and Microscopic (Petrographic) Study

Macroscopic study of rocks and minerals is the identification of rocks and minerals in hand specimen. Samples collected from the field have been properly cleaned and examined macroscopically. The various colours and textures of these samples have been carefully observed and noted.

Petrographic study is the study of rocks and minerals which have been made into thin section (slides) in the laboratory. The slides are viewed under plane polarized light (PPL) and cross polarized light (CPL) in order to study the various optical properties they display as the stage of the microscope is being rotated.

The optical properties observed under plane polarized light are colour, cleavage, pleochroism, relief and form. Under cross polarized light, the following optical properties are used in mineral identification; colour, extinction, twinning, cleavage and interference colours and figures.

### 3.5.1 Procedure for Microscopic (Petrographic) Study

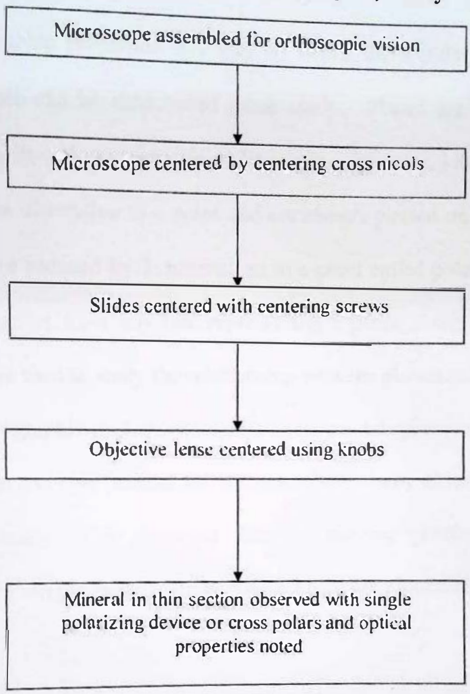



**Fig. 8: Flow chart showing the procedure for microscopic (Petrographic ) Study**

## 3.6 Stereographic Projection

Stereographic projection is a way by which the angular relationships of lines and planes can be determined more easily. Planes are reduced by one dimension to a line, lineaments (lines) like dykes, fractures, joints and veins are reduced by one dimension to a point and are always plotted on the line (plane). Planes could be reduced by 2 dimensions to a point called pole (points counted exactly 90 degrees from any line representing a plane along the East - West line). Poles are used to study the relationship between planes and lineaments.

In stereographic projection, a great circle on the sphere is also a circle on the stereogram and this permits the representation of any structural plane to be constructed easily. The stereonet aids in solving problems of graphic construction by simple manipulation of data which are plotted directly.

### 3.6.1 Procedure for plotting S-pole

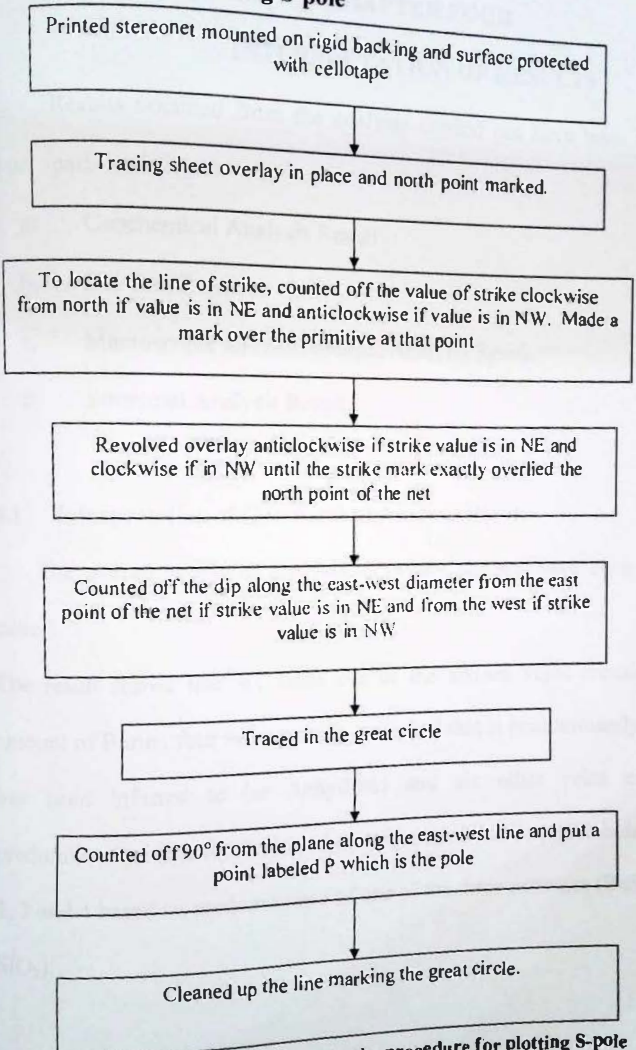



**Fig. 9 Flow chart showing the procedure for plotting S-pole**

# CHAPTER FOUR

# INTERPRETATION OF RESULTS

Results obtained from the analysis carried out have been interpreted in four parts as follows:

a. Geochemical Analysis Result

b. Hcl Test Result

c. Macroscopic and Microscopic Analysis Result

d. Structural Analysis Result

## 4.1 Interpretation of Geochemical Analysis Result

The overall results of analysis of twenty samples have been tabulated on table 1.

The result shows that six veins out of the sixteen veins contain reasonable amount of Barite, four veins contain a mineral that is predominantly CaO (which has been inferred to be Anhydrite) and six other veins contain silica predominantly. The results have been regrouped into 3 and retabulated on tables 2, 3 and 4 based on predominance of one of the three extremes ($BaSO_4$, CaO and $SiO_2$).

**Table 1: Overall Results of Geochemical Analysis**

| Compound (%) | Vein 1 | Vein 2 | Vein 3A | Vein 3B | Vein 4 | Vein 5 | Vein 6 | Vein 7 | Vein 8A | Vein 8B | Vein 9 | Loc 10 | Vein 14 | Loc 15 | Vein 17A | Vein 17B | Vein 18 | Vein 21 | Loc 24 | Loc 25 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $S_iO_2$ | 2 | 37 | 63 | 5 | 50.2 | 27 | 29 | 8.1 | 7.8 | 5.4 | 80.8 | 69.8 | 88.3 | 89.0 | - | 15 | 68.8 | - | 85 | 83 |
| $SO_3$ | 17.6 | 3.1 | 1.5 | 15.8 | 9.44 | 15.1 | 23.9 | 18 | 21 | - | 2.2 | - | 2.2 | 0.3 | - | 0.4 | - | - | - | 1.3 |
| $CaO$ | 10.1 | 36.5 | 11.2 | 15.8 | 9.45 | 3.84 | 8.73 | 3.12 | 0.04 | 51.4 | - | 2.33 | 0.756 | 0.731 | 95.55 | 78.82 | 28.8 | 94.74 | - | - |
| $T_iO_2$ | 0.72 | 0.18 | - | 0.3 | 0.1 | 0.40 | - | 1.0 | - | 0.00 | 0.23 | 0.091 | 0.04 | 0.13 | 0.02 | 0.03 | 0.02 | 0.03 | 0.28 | 0.22 |
| $Fe_2O_3$ | 0.11 | 3.67 | 1.09 | 0.24 | 3.46 | 0.28 | 1.96 | 0.717 | 0.663 | 0.432 | 2.91 | 0.825 | 0.324 | 0.469 | 1.91 | 0.811 | 1.62 | 0.940 | 2.73 | 1.32 |
| $Ga_2O_3$ | 0.07 | - | 0.0086 | 0.17 | - | 0.23 | 0.06 | 0.31 | - | - | 0.04 | 0.11 | 0.04 | - | - | - | - | - | - | - |
| $Ag_2O$ | 0.79 | 0.69 | 0.66 | 0.64 | 0.72 | 0.79 | 0.65 | 1.00 | 0.83 | 0.67 | 1.4 | 1.2 | 0.82 | 1.1 | 1.0 | 0.98 | 0.85 | 0.73 | 1.3 | 1.2 |
| $BaO$ | 63.1 | 14.4 | 4.71 | 58.6 | 22.5 | 50.2 | 33.5 | 64.3 | 67.8 | 0.06 | 1.1 | 0.12 | 5.63 | 1.3 | 0.29 | 2.78 | 0.059 | 1.1 | 0.49 | 1.9 |
| $Ta_2O_5$ | 0.45 | 0.35 | - | 0.40 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - |
| $WO_3$ | 0.78 | - | - | 0.75 | - | - | - | - | - | 0.05 | - | - | - | - | - | - | - | - | - | - |
| $OsO_4$ | 2.2 | - | - | 1.9 | 1.1 | 1.9 | 1.2 | 2.4 | - | - | 1.6 | - | - | - | - | - | - | - | - | - |
| $IrO_2$ | 2 | - | - | - | - | - | 1 | - | - | - | - | - | 0.98 | - | - | - | - | - | - | - |
| $CuO$ | - | 0.02 | - | 0.03 | - | - | - | 0.12 | - | - | - | - | - | - | - | - | - | - | 0.0053 | 0.016 |
| $K_2O$ | - | 3.35 | 3.75 | - | 2.59 | 0.23 | - | - | - | - | 9.68 | 9.06 | 0.850 | 6.40 | - | - | - | - | 10.1 | 11.1 |
| $NiO$ | - | - | 0.0046 | - | - | - | - | - | 0.0085 | - | - | 0.014 | - | - | - | - | 0.001 | - | 0.0069 | 0.0072 |
| $CeO_2$ | - | - | 0.04 | - | - | - | - | - | - | 0.008 | - | - | 0.04 | 0.01 | 0.01 | - | - | - | 0.02 | - |
| $Y_2O_3$ | - | - | 0.077 | - | - | - | - | - | - | - | - | - | - | - | 0.04 | - | - | 1 | 0.10 | 0.097 |
| $Yb_2O_3$ | - | 0.20 | - | - | - | - | - | - | - | - | - | - | - | - | 0.54 | 0.41 | 0.41 | - | - | - |
| $Lu_2O_3$ | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.24 | 0.18 | - | 0.29 | - | - |
| $In_2O_3$ | - | 0.90 | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.54 | 1.0 | - | - |
| $Al_2o_3$ | - | - | 14 | - | - | - | - | - | - | - | - | 16 | - | - | - |  | - | - | - | - |
| $GeO_2$ | - | - | - | - | 0.46 | - | - | - | - | - | - | - | - | 0.40 | - | 0.42 | - | - | - | - |
| $MnO$ | - | - | - | - | - | - | - | - | - | - | - | 0.016 | - | 0.005 | - | - | - | - | 0.068 | 0.009 |
| $Eu_2O_3$ | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.02 | - | - | - | - | 0.01 | 0.005 |
| $Cr_2O_3$ | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | - | 0.022 | - |
| $SrO$ | - | - | 0.11 | - | - | - | - | - | 1.88 | - | - | - | - | - | - | - | - | - | 0.072 | 0.071 |
| $Au$ |  | - | - | - | - | - | - | - | - | 42 | - | - | - | - | - | - | - | - | - | - |

**Table 2: Chemistry of Six Barite Veins**

| Vein | $BaSO_4$ | $SiO_2$ | CaO |
|---|---|---|---|
| 1 (1) | 80.7 | 2 | 10.1 |
| 2 (3B) | 74.4 | 5 | 15.8 |
| 3 (5) | 65.3 | 27 | 3.84 |
| 4 (6) | 57.4 | 29 | 8.73 |
| 5 (7) | 82.3 | 8.1 | 3.12 |
| 6 (8A) | 88.8 | 7.8 | 0.04 |

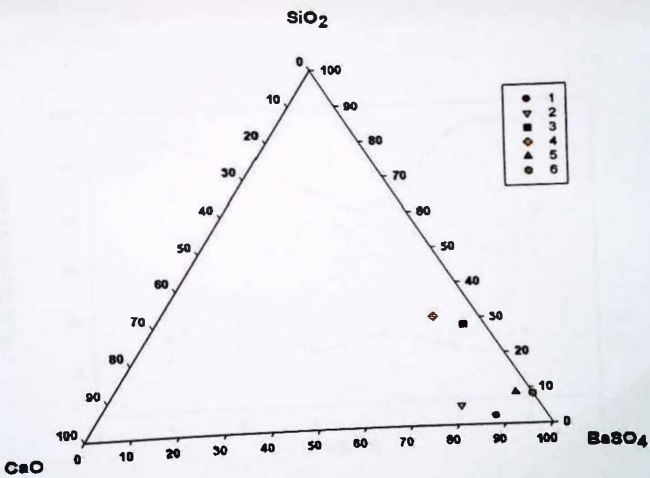



Fig. 10a Ternary Plot for Six Barite Veins

Table 2 shows six Barite veins with the accessory silica and CaO which determines the quality of the Barite. A ternary plot was made for the six veins based on the three parameters (Fig. 10a). The plot shows that veins 1, 2, 5 and 6 contain over 70 wt. % of Barite with the collective impurities constituting less than 30wt. % These are classified as high grade Barite while veins 3 and 4 contain between 57 – 66 wt. % Barite with impurities over 30 wt. % and are as well classified as low grade Barite. The six results were replotted on a binary graph with quantity in wt. % on y axis against the veins on x axis to ascertain their relationship (Fig. 10b)

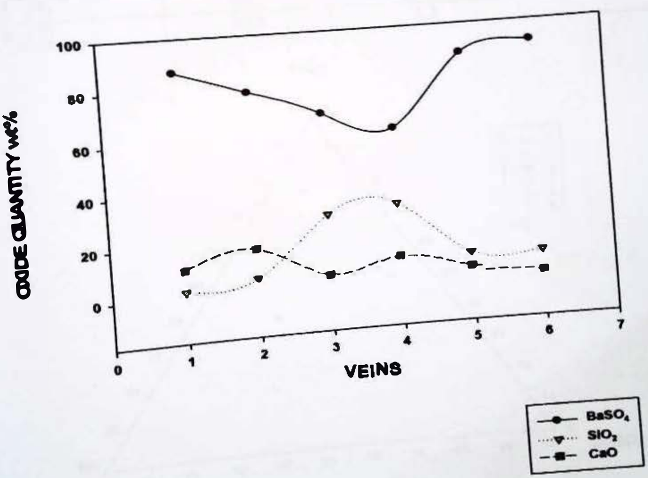



Fig. 10b: Binary Plot for the six Barite Veins

The plot shows a positive correlation between the $BaSO_4$ and $SiO_2$. As the quantity of $BaSO_4$ is decreasing in veins 2, 3 and 4, the quantity of silica is increasing disproportionately while when there is sudden increase of $BaSO_4$ in vein 5 and 6, there is also a sudden decrease in silica content.

**Table 3: Chemistry of the Host rock (Silica)**

| Vein | $SiO_2$ | $BaSO_4$ | CaO |
|---|---|---|---|
| 1 (14) | 88.3 | 7.65 | 0.75 |
| 2 (18) | 68.8 | 0 | 28.8 |
| 3 (2) | 37 | 17.5 | 36.5 |
| 4 (3A) | 63 | 6.21 | 11.2 |
| 5 (4) | 50.2 | 31.94 | 9.45 |
| 6 (9) | 80.8 | 3.3 | 0 |

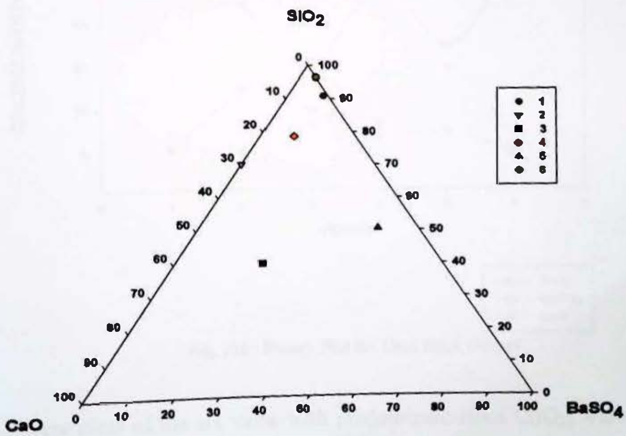



**Fig. 11a: Ternary Plot for Host Rock (Silica)**

Table 3 shows six veins that are predominantly silica. The ternary plot shows that veins 1 and 6 contains over 80 wt. % of silica while others (veins 2, 3, 4 and 5) contain $BaSO_4$ and CaO in different proportions (Fig. 11a). It appears that the silica ($SiO_2$) quantities are indirectly proportional to the Barite ($BaSO_4$).

The same relationship relatively applies for CaO (Anhydrite by inference).

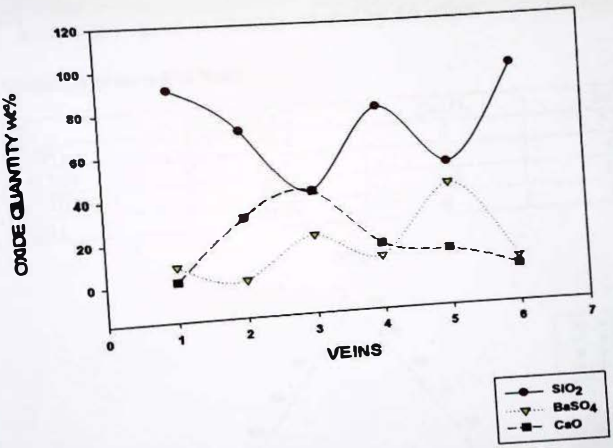



**Fig. 11b: Binary Plot for Host Rock (Silica)**

Binary plots of the six veins with predominant silica ($SiO_2$) were plotted with the quantities in wt. % on y-axis and the veins on x-axis (Fig. 11b). This plot also shows a consistent proportional relationship between the silica ($SiO_2$) and the Barite ($BaSO_4$) in veins 1 and 2 while silica ($SiO_2$) is decreasing in quantity, Barite is also decreasing but there is a sharp increase in CaO. At vein 3, a sharp decrease in silica ($SiO_2$) leads to a sharp increase in both $BaSO_4$ and CaO then another sharp increase in silica in vein 4 leads to sharp fall or decrease in quantities of $BaSO_4$ and CaO. In vein 5, a fall in silica content leads to an increase in Barite ($BaSO_4$) and an increase in silica in vein 6 leads to another fall in Barite ($BaSO_4$) content. There seem to be a competition between $Ba^{2+}$ ions and $Ca^{2+}$ ions in any space or vacuum created by the silica.

**Table 4. Chemistry of Anhydrite Veins**

| Vein | CaO | $BaSO_4$ | $SiO_2$ |
|---|---|---|---|
| 1 (8B) | 51.4 | 0 | 5.4 |
| 2 (17A) | 95.55 | 0 | 0 |
| 3 (17B) | 78.82 | 3.18 | 15 |
| 4 (21) | 94.74 | 0 | 0 |

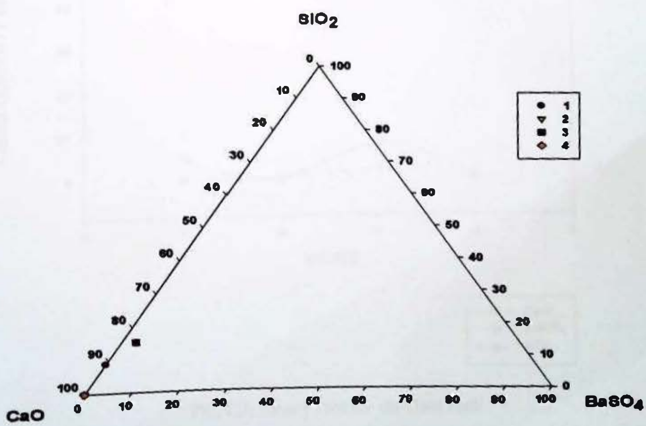



**Fig. 12a Ternary Plot for Anhydrite**

Table 4 contains the composition of the four veins that shows predominance of CaO (Anhydrite ($CaSO_4$) by inference). A ternary plot was also made for the data to ascertain the influence of silica and $BaSO_4$ in this CaO mineralization (Fig. 12a). Veins 2, 3 and 4 show over 70 wt. % of CaO which implies a good grade for any other type of mineralization. It is inferred to be Anhydrite ($CaSO_4$) due to the oxidizing environment of formation and ability to form an assemblage with Barite ($BaSO_4$). Only vein 1 shows a relatively moderate quantity CaO with unspecified impurities constituting above 30% wt. % and silica constituting 5.4 wt. %.

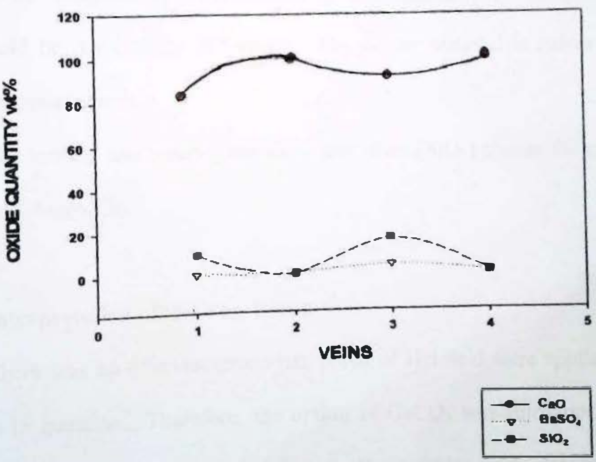



**Fig. 12b Binary Plot for the Host rock**

The binary plot with quantity in wt. % on y-axis and veins on x-axis (Fig. 12b) shows that there is a positive correlation between CaO (Anhydrite) and silica at a very wide range. From vein 1 – 2, as the CaO (Anhydrite) increases, there is a decrease in quantity of silica ($SiO_2$) by same amount. From vein 2 – 3, there is a decrease in quantity of CaO (Anhydrite) and an increase in silica ($SiO_2$) by the same amount.

From vein 3 – 4, there is another increase in quantity of CaO (Anhydrite) and a corresponding decrease in the quantity of silica. Barite ($BaSO_4$) here is permanently relegated to the minimum by high quantity of CaO (Anhydrite). This could be due density difference. The denser material is below and the lighter material above.

The ternary and binary plots show that silica ($SiO_2$) checks the quality of Barite and Anhydrite.

## 4.2 Interpretation of Hcl Test Result

There was no effervescence when drops of Hcl acid were applied on the samples in question. Therefore, the option of $CaCO_3$ was ruled out. $CaSO_4$ became the possible option left. Hence, the samples were inferred to be (Anhydrite) $CaSO_4$.

## 4.3 Interpretation of Macroscopic and Microscopic (Petrographic) Studies Results

Samples collected from the field have been studied macroscopically and the various colours and textures have been observed. The samples made into thin section have been viewed under a petrographic microscope and the characteristics they displayed have been noted.

Macroscopically, Barite samples range in colour from white-gray-brown-red while the texture ranges from very coarse – coarse – medium grain (Table 5) (Plates. 5 and 6)

Table 5. Hand Specimen Description of Barite Samples

| Vein | Texture | Colour |
|---|---|---|
| 1 | Very coarse | Brownish white with tints of green |
| 3B | Fine | Reddish |
| 5 | Coarse | Whitish brown with some grayish colour |
| 6 | Medium – coarse | Whitish gray |
| 7 | Medium – coarse | Light brown – reddish brown |
| 8A | Coarse | Whitish brown |

**Plate 5. Barite Sample**

**Plate 6. Barite Sample**

Microscopically, there are mainly manifestations of Barite on the slides:

a. Coarse interlocking crystals of Barite that are not contaminated by silica (Plate 7) were observed under the petrographic microscope. The Barite crystals show white-cream colours under plane polarized light. The mineral crystal edges become more distinct under cross polarized.

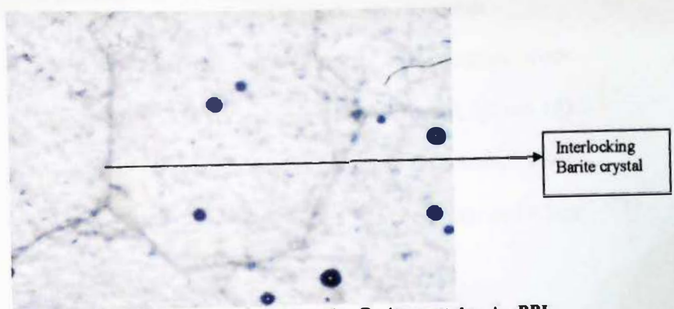



**Plate 7. Outline of Coarse- grain interlocking Barite crystal under PPL**

b. Coarse inter-locking crystals of Barite that have started experiencing dissolution and assimilation along crystal edges indicate traces of silica at the Barite edges. This is an evidence of presence of silica (Plate 8).

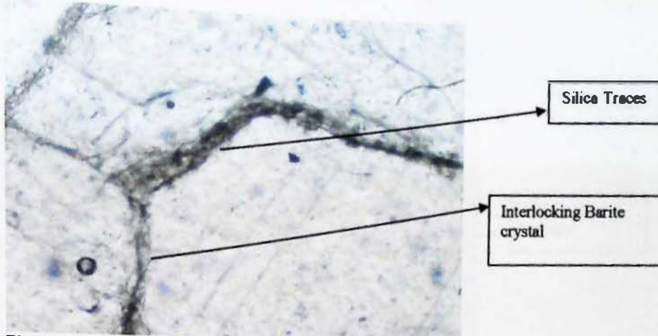



**Plate 8. Alteration along the edges of interlocking Barite crystals**

c. Recrystallized Barite crystal taking a blocky or rectangular shape embedded in fine matrix of silica and fine Barite (Plates 9, 10 and 11). The elongated rectangular crystals are in random arrangements. There seem to be assimilation reaction between fine Barite crystals and Silica within the matrix.

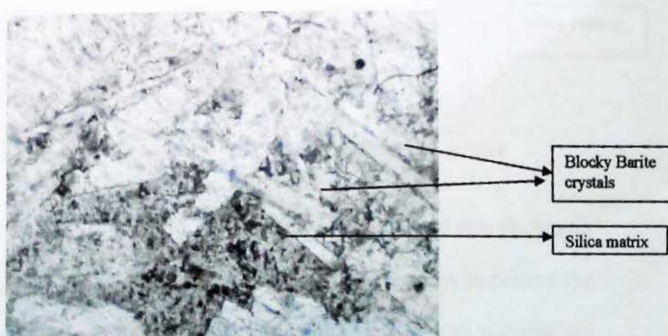



**Plate 9. Recrystallized Barite crystal embedded in Silica matrix taking blocky shape.**

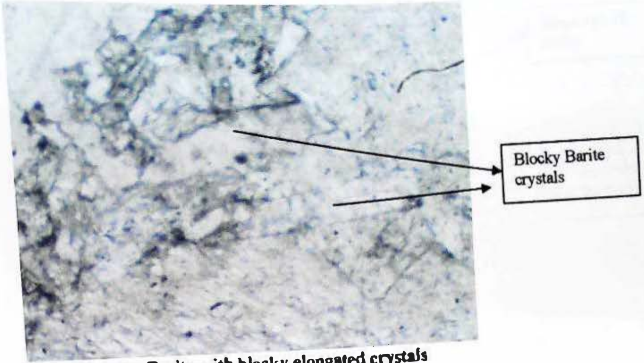



Plate 10. Pure Barite with blocky elongated crystals

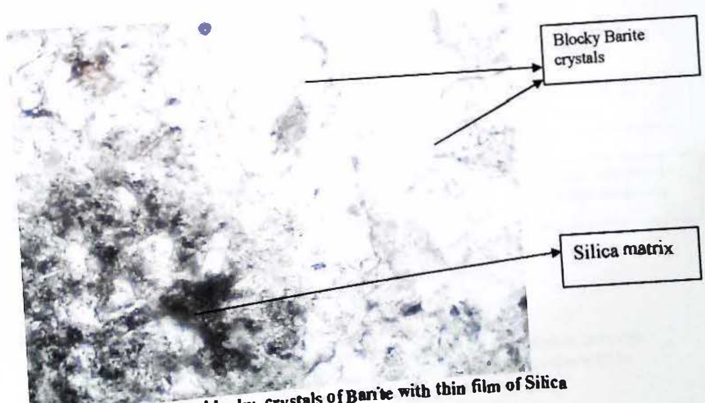



Plate 11. Interlocking blocky crystals of Barite with thin film of Silica

d. Coarse megacryst of Barite being gradually assimilated into the brown fine matrix of silica (Plate 12, 13, 14). Silica appears to present the ideal stable environment for assimilation. Dissolution textures are prominent.

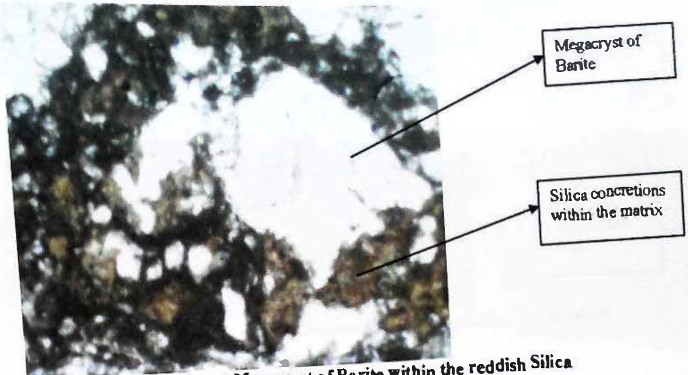



**Plate 12. Disintegration of Megacryst of Barite within the reddish Silica matrix**

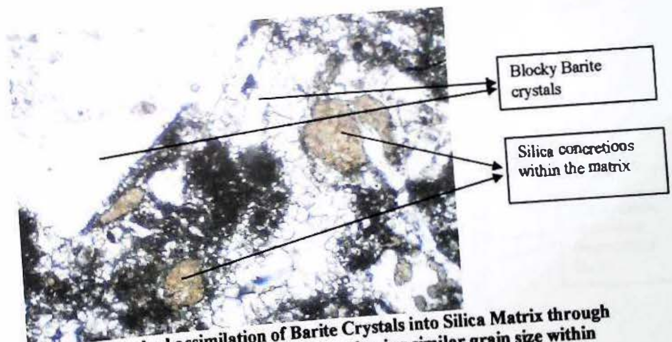



**Plate 13. Gradual assimilation of Barite Crystals into Silica Matrix through recrystallization. Silica and Barite almost having similar grain size within thematrix. Megacryst of Barite partially fragmented.**

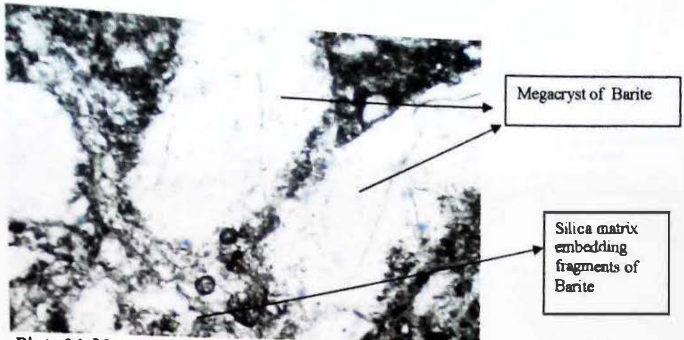



**Plate 14. Megacryst of Barite before fragmentation, assimilation and gradual replacement by Silica in Silica matrix**

e. Coarse megacryst of Barite completely assimilated and recrystallized to fine grain within the matrix of silica (Plate 15). Blocky Barite surface leached by hydrothermal fluid (Plate 16).

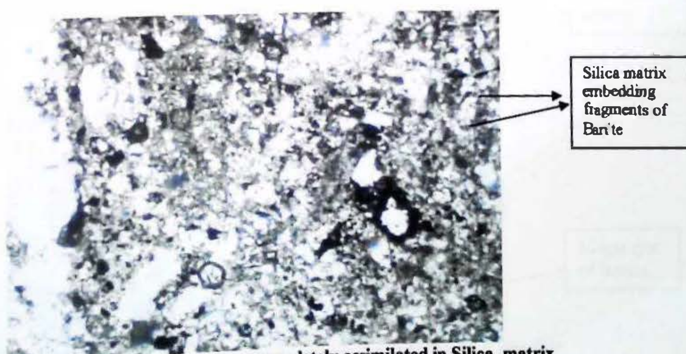



**Plate 15. Barite crytals almost completely assimilated in Silica matrix**

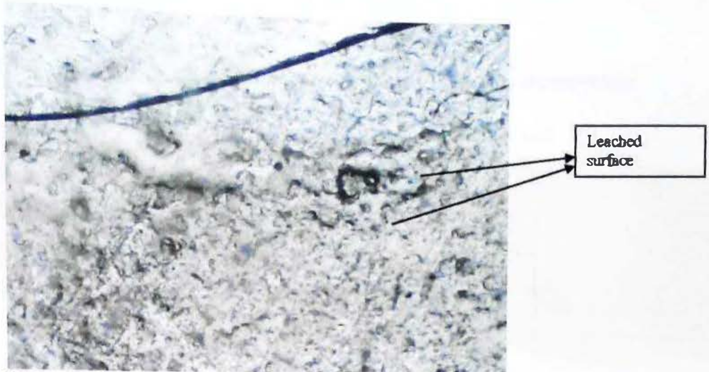



**Plate 16. Leached surface of pure Barite crystals**

f. Fractured megacryst of Barite hosting silica micro veinations as a possible evidence of replacement (Plate 17).

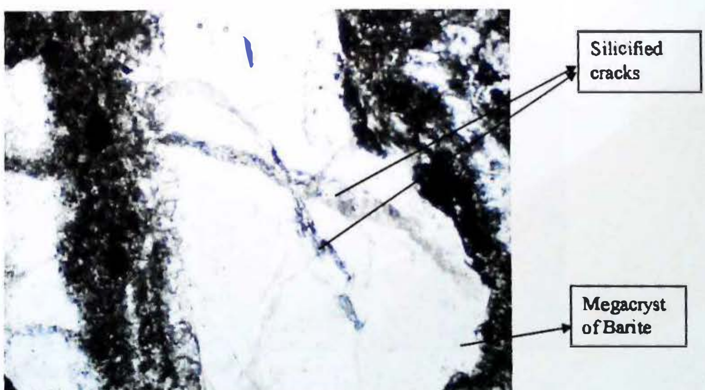



**Plate 17. Megacryst of Barite hosting Silicified cracks as a possible evidence of replacement. The matrix between the megacrysts is that of silica.**

Anhydrite samples have colour range from red-green-brown-white with texture ranging from medium-coarse grain (Table 6) (Plates 18 and 19).

**Table 6. Hand Specimen Description of Anhydrite**

| Vein | Texture | Colour |
|---|---|---|
| 8B | Medium | Reddish brown |
| 17A | Coarse | Greenish red |
| 17B | Coarse | Whitish red – green |
| 21 | Coarse | Greenish – red |

**Plate 18. Anhydrite Sample**

**Plate 19. Anhydrite Sample**

The Anhydrite crystals under Petrographic Microscope also manifest as follows:

a. Fine to medium grain crystals that display shades of white-brown-blue interference colours as the stage is rotated. This is due to different orientation of crystals (Plate 20 and 21).

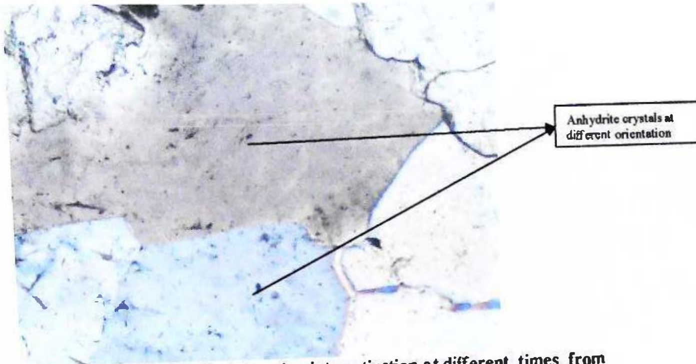



**Plate 20. Crystals of Anhydrite going into extinction at different times from Brown-Blue.**

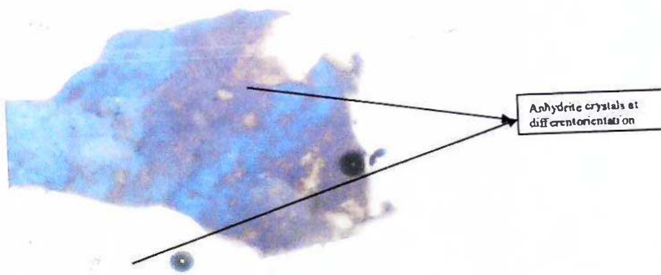



**Plate 21. Crystals of Anhydrite going into extinction at different times from White-Brown-Blue**

b. Elongated spindle crystals of anhydrite that seem to have grown from hydrothermal action through the dissolution and recrystallization of megacryst of Anhydrite (Plate 22). There is a lot of fine brown silica in the matrix which seems to provide the ideal chemical environment for the growth of spindle crystals.

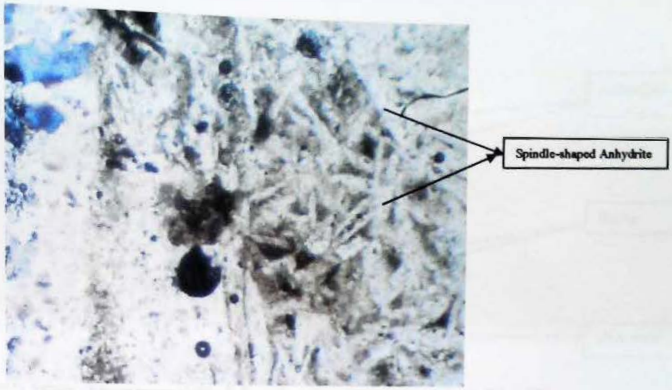



**Plate 22. Megacryst Anhydrite almost completely recrystallized by hydrothermal reaction to spindles of Anhydrite crystals .**

c. Equigrannular crystals of Anhydrite embedded in the fine silica matrix. The equigrannular crystals go into extinction at different times when the stage is rotated. The extinction colour is brownish blue (Plate 23). There are tints of silica within the equigranular Anhydrite crystals that confirmed that the crystal grows in a silica saturated environment. Interference colours are displayed under cross polarized light.

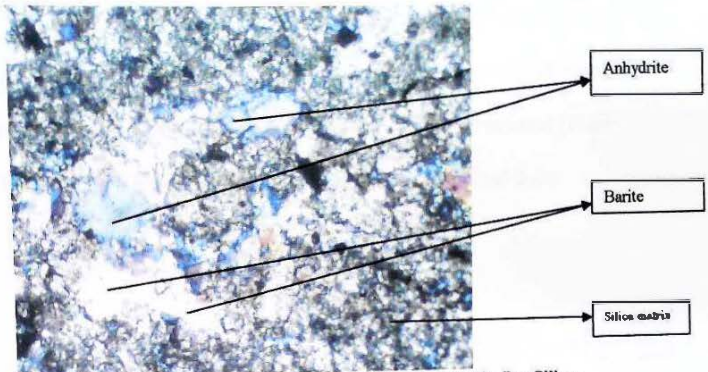



**Plate 23. Granular Anhydrite and Barite crystals embedded in fine Silica matrix. Colouration may be due to assimilation reaction**

The pegmatite sample in hand specimen has a pinkish colour with tints of black and is pegmatitic in texture (Plate 24).

**Plate 24. Pegmatite Sample**

The pegmatite as part of the inlier also displayed some characteristics under the petrographic microscope:

a. Very large crystal of microcline showing the cross hatched twinning (Plate 25, 26). This same pegmatite appeared monomineralic in some slides because the whole slide was occupied by only one mineral (Plate 25). It shows blue interference colour under cross polarized light.

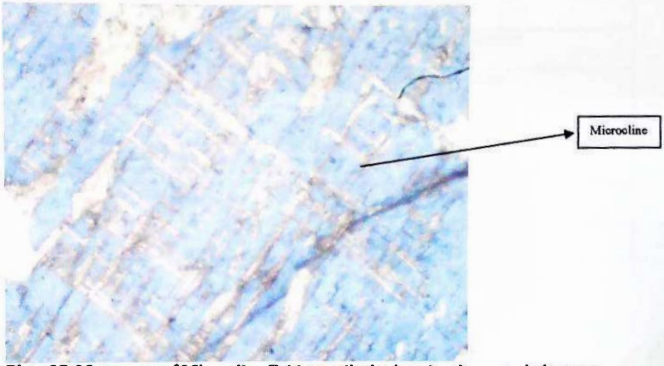



**Plate 25. Megacryst of Microcline Feldspar displaying the characteristic cross hatch twining in Pegmatites**

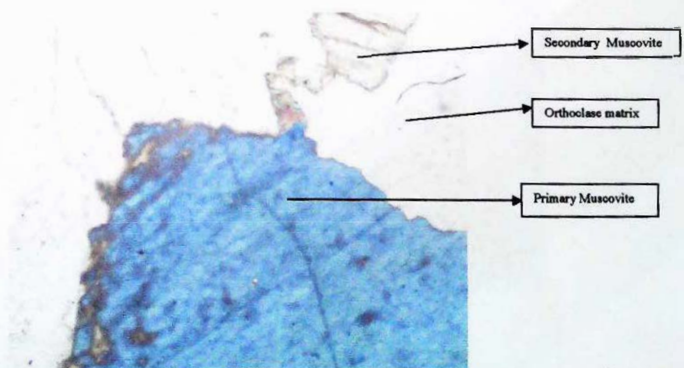



**Plate 26. Unaltered Muscovite fragment in Pegmatite bordering altered Muscovite**

Silica samples range in colour from brown-red-white and have textures ranging from coarse to granular (Table 7, Plate 27).

**Table 7. Hand Specimen Description of Silica (Host rock)**

| Vein | Texture | Colour |
|---|---|---|
| 14 | Coarse | Whitish brown-reddish |
| 18 | Granular | Brownish – white |
| 2 | Medium – coarse | Brownish white |
| 3A | M ium | Brownish with tints of black |
| 4 | Very fine | Reddish brown |
| 9 | Fine | Reddish |

**Plate 27 Silica samples**

The manifestation of silica on the slide was such that:

a. Silica was seen to be incorporating and cementing grains of Barite and Anhydrite within the matrix giving the matrix a multicolour appearance as shown ealier.

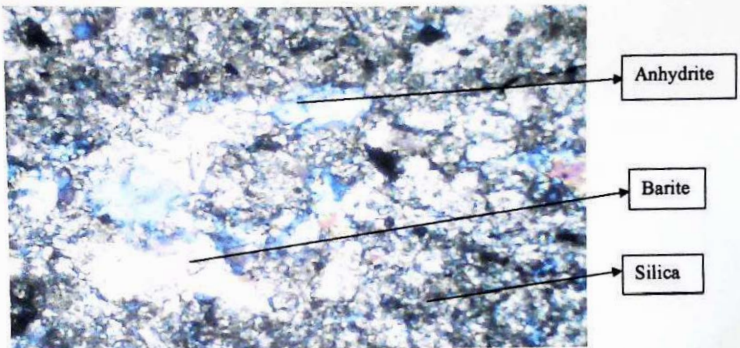



**Plate 28: Granular Anhydrite and Barite crystals embedded in fine Silica matrix. Colouration may be due to assimilation reaction**

The silicified sandstones are brownish in colour and have a fine grain texture (Plate 29).

**Plate29:Silicified Sandstone**

The petrographic characteristics display by the sandstone includes:

Silicified unsorted sandstone with all the intersticia between the sand grains cemented by silica. In the matrix of the silica, we have disseminated fragments of Barite and Anhydite incorporated.

### 4.4 Interpretation Of Structural Analysis Results

Fifteen poles of the attitude of fractures were plotted using the Schmidt Net (Fig. 13) and analyzed using the S-pole method (Fig.14).


**Fig. 13. Schmidt Net for Structural Analysis**

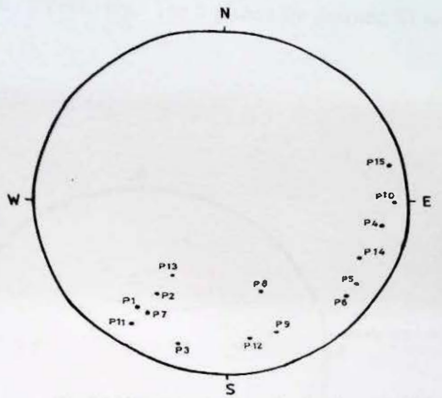


**Fig. 14. Fifteen Plotted Poles for the Trend of Veins**

The poles indicate a general linear trend from North-East to South-West with few of the poles forming subordinate structures to the general structure.

In order to determine the principal planar structure and subordinate linear structure;

a. The overlay carrying the poles is moved and adjusted slowly on the stereonet until the majority or at least a sizeable number of the poles falls on and define a great circle or line of best fit within the poles.

b. Two great circles are identified to carry 5 poles and 4 poles respectively and they intersect at a pole (P3). These 2 great circles define 2 principal planar surfaces with the attitudes N88°E 12°E and

N74°E 20°E respectively. The 2 planes are denoted S1 and S2 (Fig.15 and 16).

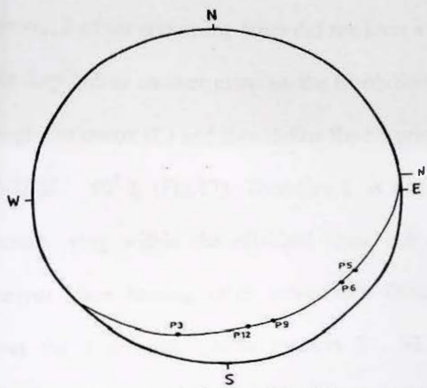



**Fig. 15. Great Circle Fitting Five Poles Giving a Principal Planar Surface (S1)**

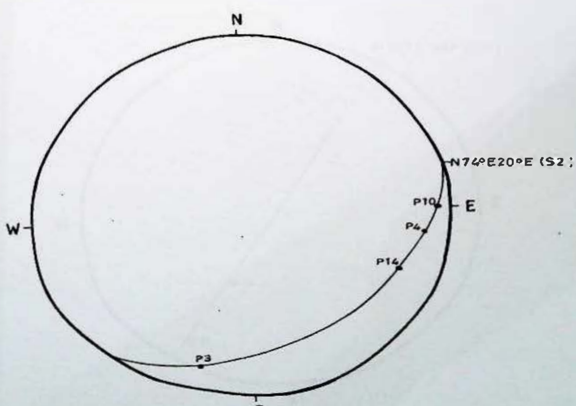



**Fig. 16. Great Circle Fitting Four Poles Giving a Principal Planar Surface (S2)**

c. Majority of the poles that cluster around each of the great circles form subordinate linear structures trending on same strike as the great circle in question.

d. However, 3 of the remaining poles did not form a cluster around centre L but they define another plane on the North-South strike line passing through the centre (L) and then define the S3 principal planar surfaces at N32°E 90° E (Fig.17). Therefore L is not a subordinate linear structure lying within the principal plane but itself define another principal plane bearing other subordinate linear structures. Fig 18 shows the 3 principal planar surfaces S1, S2, and S3 with other subordinate linear structures.

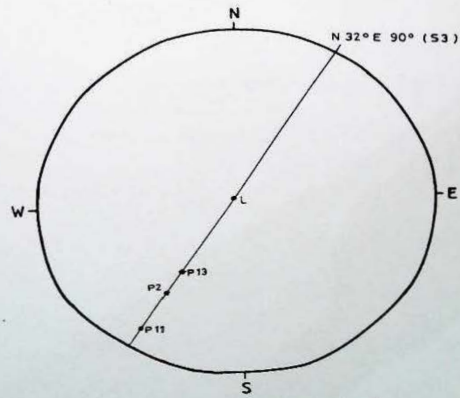



**Fig. 17. Great Circle Fitting Three Poles that pass through Center (L) Giving another Principal Planar Surface (S3)**

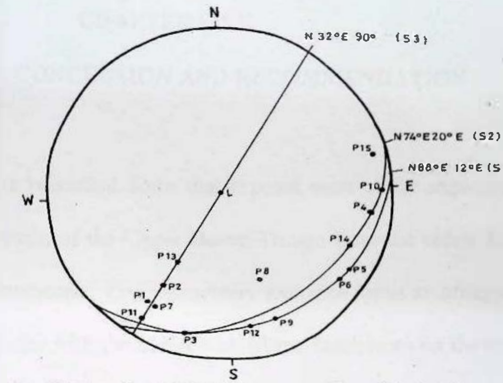



**Fig. 18. Three Great Circles Defining the Three Principal Planar Surfaces (S1, S2 and S3) Defining their collective Attitude readings in NE-SW Direction**

# CHAPTER FIVE

# DISCUSSION, CONCLUSION AND RECOMMENDATION

## 5.1 Discussion

Gombe Inlier is a basement dome that exposes most of the sequence of rocks in the Gongola basin of the Upper Benue Trough from the oldest Bima Sandstone to Gombe Sandstone. The sedimentary sequence forms an offlapping relationship from the inlier with the oldest rock (Bima Sandstone) on the inlier and the youngest (Gombe Sandstone) farther away from the inlier. The inlier was faulted during the division of the Gwondwanaland in the Cretaceous to form a strike-slip fault. The offset of the faulted blocks forms a sinistral strike- slip fault. This movement is consistent with model for the opening ofBenue Trough as a 'pull-apart' basin by many authors notably Benkhelil , 1986 and 1989, Maurin et al, 1985.

A structural analysis of the 15 fractures hosting mineralization on the Gombe Inlier was conducted using the S-pole method. The results show that there are 3 principal planar surfaces (S1, S2, and S3) with the following attitudes (N88°E 12°E, N74°E 20°E and N32°E 90°E). They collectively trend NE-SW and dip eastward. The NE–SW direction is consistent with the direction of movement and sinistral displacement of the strike-slip faults as well as the direction of general trend and opening of Benue Trough. This implies that the fractures were imparted on the Gombe Inlier during the division of Gwondwanaland, when Benue Trough was opening. The silicification and the hydrothermal activities came or started at the beginning of marine condition after the deposition of Bima Sandstone and Yolde Formation because Yolde Formation is partially silicified with Bima Sandstone on the Gombe Inlier especially at the flank. The layer of Bima Sandstone on the inlier is too thin to be classified into Bima 1, 2 and 3 but it is suggestive to say that Bima I unconformably overlies the Basement Complex including the inlier.

The hydrothermal fluid containing the Barium ions ($Ba^{2+}$) and Calcium ions ($Ca^{2+}$) seem to have ascended through the fractures during the silicification process because there is a positive correlation between the Silica and Barite-cum-Anhydrite mineralization. Where the Silica is high in the veins the Barite and/or Anhydrite would be low and vice versa as shown by the ternary and binary plots (Figures,10a, 10b, 11a, 11b, 12a and 12b). The Barite-cum-Anhydrite mineralization took place under oxidizing conditions as a result of reaction between the ascending hydrothermal fluid through the deep-seated fractures and the sea water that flowed into the fractures. The hydrothermal fluid seem to have supplied the Barium ions ($Ba^{2+}$) and the Calcium ions ($Ca^{2+}$) while the sea water supplied the sulphate ions ($SO_4^{2-}$). There seem to have been a very strong competition for sulphate ions ($SO_4^{2-}$) between the Barium ions

($Ba^{2+}$) and the calcium ions ($Ca^{2+}$) because they are in the same group in periodic table; the alkaline earth metals, they are very reactive and so cannot occur free in nature. They all have 2 electrons on their outermost shell. The only difference between them is their density (Ba: 3.51g/cm$^3$ and Ca: 1.55g/cm$^3$) and so their atomic numbers differ also (Ba – 56 and Ca – 20). The most important factors are the valency and ionic radius and based on these, they are all suitable with respect to reacting with sulphate ions ($SO_4^{2-}$). Six veins contain mostly Barite while four veins contains mostly Anhydrite and this shows that there were local saturations of the separate ions ($Ba^{2+}$ and $Ca^{2+}$) with respect to each vein. The ion that is saturated will suppress the unsaturated ion to the barest minimum with silica stabilizing both. While in the silica veins the two ions ($Ba^{2+}$ and $Ca^{2+}$) compete seriously for sulphate ions ($SO_4^{2-}$) to precipitate and that is why the quantities of Barite and Anhydrite fluctuate from one silica vein to another (Tables 2,3 and 4; Figures 10, 11 and 12). Another plausible explanation is that high density of the hydrothermal fluid would favour precipitation of Barite while low density of hydrothermal fluid would favour the precipitation of Anhydrite. This is commensurate with their ionic radius, densities and mobilities.

The petrographic studies shows that the megacryst of the Barite were also recrystallized to blocky rectangular crystals of Barite in the silica medium and in most cases, the megacryst of Barite was assimilated into the matrix of silica either as fine grains or medium grains. This could be seen from the various photomicrographs. The same thing applies to Anhydrite, the megacryst were often times seen to be assimilated into silica matrix. In some other cases, Anhydrite anhedral crystals coexist with anhedral Barite crystals within silica matrix. In some cases Anhydrite megacryst were recrystallized into spindle prismatic crystals in a random pattern. The photomicrograph explains everything. These collectively suggest that there could be another late hydrothermal fluid that invaded the inlier and leached part of the Barite and Anhydrite mineralization and recrystallized them.

The silicified sandstone contains a lot of cemented anhedral crystals of Barite and Anhydrite while the Pegmatite slide shows predominance of microcline feldspars among others. They all show contact relationship with Barite-cum-Anhydrite mineralization.

## 5.2 Conclusion

1. The Bima Sandstone covers most parts of the inlier because it was cemented by the silicification processes so the silicification affects not only the fractures but most of the sedimentary rocks on the inlier.

2. Two mineralizations were discovered to coexist, Barite-cum-Anhydrite. The silicification appears to be the stabilization process for the mineralization.

3. The two barriers for Barite-cum-Anhydrite mineralization which are the structural and the chemical barriers are the fractures and the silicification process. This is consistent with any mineralization in many geological environments.

4. The structural analysis of the fractures carrying the veins identifies three principal planar surfaces (S1, S2 and S3) that trends in NE – SW direction which conform to the direction of the opening of Benue Trough as well as the sinistral displacement of the strike slip fault that displaced the whole inlier. These fractures are believed to have been formed during the division of Gwondwanaland, at the time of the opening of Benue Trough in the Cretaceous. The structural analysis and sinistral displacement support the strike- slip (pull-apart) theory for the origin of Benue Trough.

5. It is rather difficult to suggest any replacement because evidence of replacement is lacking and it's not too clear, but recrystallization in both Barite and Anhydrite were supported by petrographic evidence. There seem to be another late invasion of hydrothermal fluid which affected both Barite and Anhydrite by recrystallizing them. The recrystallization does

Barite and Anhydrite by recrystallizing them. The recrystallization does not seem to be accompanied by any change in chemistry of the minerals as even the recrystallized minerals show total composition of either Barite or Anhydrite well above 70%.

6. The two mineralizations (Barite and Anhydrite) are well within the economic grade of over 70% for each of them. By assessing their chemistry and mode of occurrence, this research has upgraded them from the level of mineral occurrence to the level of mineral resource.

## 5.3 Recommendations

1. Further detailed research should be conducted using isotope geochemistry, trace elements geochemistry and fluid inclusion studies to ascertain the possible number of hydrothermal fluids that invaded the inlier before, during and after the mineralization in order to ascertain the geologic specificity of both the inlier and the Barite-cum-Anhydrite mineralizations.
2. The geological and topographical maps of the area need to be upgraded because some of the positions of rocks and structures in the field do not conform to their actual positions on the map.

3. The registered and unregistered miners and mineral dealers need to be educated on the differences between Barite and Anhydrite coexisting in the same area because they consider everything they mine from the inlier to be Barite which is quite misleading and dangerous.

4. Besides other uses of Barite, both Barite and Anhydrite could be a source of Sulphate, Sulphur, Calcium and Barium for the chemical industries in Nigeria therefore, importation of such chemicals should be checked.

5. A very detailed research should be undertaken to determine the quantity of Barite and Anhydrite in the area.

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