GEOLOGY, STRATIGRAPHY AND INORGANIC PETROLEUM GEOCHEMISTRY OF THE BORNU BASIN AT ITS BOUNDARY WITH UPPER BENUE TROUGH, NE NIGERIA

BY

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Declaration

I declare that the work in the thesis entitled "Geology, Stratigraphy and Inorganic Petroleum Geochemistry of the Chad (Bornu) Basin at its boundary with Northern part of the Benue Trough, NE Nigeria" has been performed by me in the Department of Geology under the supervision of Prof. H. Hamza, Prof. T. Najime, Prof. U. A. Danbatta and Prof. E. O. Obiosio.

The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this dissertation was previously presented for another degree or diploma at any university/institution.

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Name of Student	**Signature**	**Date**

Certification

This thesis entitled "GEOLOGY, STRATIGRAPHY AND INORGANIC PETROLEUM GEOCHEMISTRY OF THE BORNU BASIN AT IT'S BOUNDARY WITH THE UPPER BENUE TROUGH, NE NIGERIA" by MOHAMMED, Yakubu Bata meets the regulations governing the award of the degree of Doctor of Philosophy of Ahamdu Bello University, Zaria and is approved for its contribution to knowledge and literary presentation.

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Dedication

This thesis is dedicated in memory of my late grandmother Mallama Adama and my late father Alhaji Bata Mohammed and also to my children Mohammed, Hafsat, and Habiba. and Halimatus- Sadiya

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I would like to acknowledge everyone who has assisted me throughout the doctoral study in so many ways. To me, achieving a PhD is a journey with so many hurdles (ups and downs). Without lead stars, it would be very difficult to navigate. I therefore owe my first and foremost gratitude to Chairman of my supervisory committee Prof. H. Hamza for his enthusiasm, guidance and persistent support at all levels of my study. It was a real privilege and honour for me to have a truly inspiring person who allowed me to work with him despite his vast commitments, and who thoughtfully put me on the prospective path of research.

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Abstract

The study area is situated in the southwest part of the Nigerian sector of the Bornu Basin, which falls between latitudes $10^{o}\ 52^{I}\ 30^{II}$ to $11^{o}\ 15^{I}$ N and longitudes $11^{o}\ 37^{II}\ 30^{II}$ to 12^{o} E. A detailed geological mapping coupled with sample collection was carried out within the study area so to analyze the samples. Geological map was produced distinguishing different lithological units on the basis of their field relationships using various geological parameters. Petroleum geochemical analytical methods were employed using AAS and MREAS to determine source rocks maturation level of some selected shale samples for trace elements and transition metals that are usually incorporated into the petroleum charge system. A new proposed stratigraphy from the Chad (Bornu) Basin is here in presented to give a detail and comprehensive outlook of the study area, which in turn reflects a true image of the entire basin. For the first time, the basin is being classified into group and members in order to revise and correct the stratigraphy on the basis of anomalies observed by this work and previous researchers. The oldest unit in the basin Bima Formation is now regarded as a group in the Bornu Basin because of some new field evidences that were found worthy to describe it as Bima Group and subsequently subdivide the lithological units into formations, vis; Lower, Middle, and Upper. Yolde Formation, which is only recognized in the Gongola Basin, has been mapped and now considered to be overlying the Bima Group in the study area. No any report or detail field evidence has ever been presented on the basin to consider the Yolde Formation as part of its stratigraphy; this is the first time it is reported as a stratigraphic unit within the basin. The previously known Gongila and Fika Shale Formations in the basin are now regarded as members within the Pindiga Formation in the Gongola Basin, because field evidence have shown that the Gongila village lies on the boundary between Middle Bima, Yolde Formation and Kanawa Member of the Pindiga Formation. In the present study Fika Shale is considered as a member because of the revised stratigraphy of the Gongola Basin. The Gongila Formation was previously considered to consist of two lithological units, i) the lower shale/limestone unit which is now considered as the Kanawa Member and ii) the upper shale/sandstone unit which is now regarded as the Dumbulwa Member. In the present study both the Gongila Formation and Fika Shale are now regarded as part of the Pindiga Formation. Upper conglomeritic sandstone forming a marked formational boundary was observed within the Kerri- Kerri Formation in the study area. The Chad Formation outcrops in the study area and overlie the Cretaceous sediments extending into the basin blanket over most of the Cretaceous sediments.

Detailed facies analysis revealed facies groups: 1) Gravel Facies, consisting of sub- facies units, i) clast- supported conglomerates (Gcs), ii) clast- supported conglomerates grading into sandstones (Ggs), 2) Sandstone Facies (S) which consists of i) massive sandstones, (Ss) ii) cross-bedded sandstones (Sx), iii) normally- graded sandstones (Sng) and 3) Mudstone Facies (M) which consists of i) silt- clay streaked layers (Msm) and ii) massive mudstone (Mm), and lastly 4) Carbonate Facies (C) mail composed of carbonate- rich layers. Analysis of architectural sedimentary elements also showed five elements which are; channels (CH, HO), sediment gravity- flow deposits (SG), sandy bedforms (SB), downstream- accretion macroforms (DA) and flood plain fines (FF). These elements are defined by their geometries and bounding surfaces.

The overall petroleum geochemical results showed that Fe and Mn (siderophile) elements have the highest concentration value of inorganic geochemistry, which generally does not corresponds with most global results obtained in relation to elemental analysis with regards to crude oils and

source rocks. In general, source rocks have higher geochemical values than crude oil samples if they mature, but in this study the concentration of the elements are mediocre which may be as a result of shallow depth of burial and lack of sedimentary cover over the targeted source rocks. The biophile elements Ni and V which are principal actors used in assessing petroleum potentials have lower values because of exposure and subsequent obliteration of their main constituent. Therefore, it can be concluded that, both the siderophile (Fe, Co, Mo, Cr, and Mn), chalcophile (Cu, Zn, Pb, and Cd) and biophile (V and Ni) elements have relatively low geochemical values for petroleum generation.

Representative sandstone samples from different formations such as the Bima Group, Yolde Formation and Dumbulwa Member of the Pindiga Formation in the study area were classified on the basis of their mineral composition. Samples 4, 5, 7, 24, 27, 28, 34, 35, 36, 38, 40 and 41a are classified as arkosic arenites due to the high percentage of feldspar and quartz than rock fragments in majority of the samples, whereas samples 12, 21, 25 are classed as lithic arenites because rock fragments have higher mineral aggregate than feldspar. The compositional maturity of the sandstones was identified, the matured composed of arkosic arenites and the immature ones are related to lithic arenites. It can therefore be concluded that the Bornu is same as the Upper Benue Trough (Gongola Basin) based on the geological map produced, field relationship and geological setting. The Bornu Basin is no different from the adjacent basin except the sedimentation of the Quaternary Chad Formation

TABLE OF CONTENTS

Declaration ii

Certification iii

Dedication iv

Acknowledgement v

Abstract vi

Table of Contents vii

List of Tables xii

List of Figures xiii

List of Plates xv

CHAPTER ONE

1.0 INTRODUCTION 1

1.1Background 1

1.2 Statement of the Research Problem 2

1.3 Aim and Objectives of the Study 3

1.4 Scope of the Study 3

1.5Justification 4

1.6Location and Accessibility 5

1.7Physical and Human Geography 5

1.8Climate and Vegetation 8

1.9 Previous Works 8

CHAPTER TWO

2.0 GEOLOGICAL FRAMEWORK 10

2.1 Regional Evolution of the Chad Basin 10

2.1.1 Megatectonic Setting and Origin of the Chad Basin 11

2.1.2 Intracratonic Basins 14

2.1.3 Tectonic Setting 16

2.1.4 Lithostratigraphy and Depositional Environments of the Bornu Basin 18

2.1.5 Structural Styles in the Bornu Basin 26

2.2 Structures and Stratigraphy of the Upper Benue Trough (Gongola Basin) 29

2.2.1 Preamble 29
2.2.2 Structures 30
2.2.3 Stratigraphy 32
2.3 Facies Analysis 58
2.3.1 Contextual Background 58
2.4 Petroleum Geochemistry 61
2.4.1 Historic Background 61
2.4.2 Application of Petroleum Geochemistry 64
2.4.3 Organic Productivity and Preservation in Continental Environment 65
2.4.4 The Petroleum System 68
2.4.5 Organic Geochemistry of the Bornu and other related Basins 69
2.4.6 Inorganic Petroleum (Geochemistry) Exploration 73

CHAPTER THREE

3.0 MATERIALS AND METHODS 79
3.1 Materials 79
3.1.1 Field Study and Geological Mapping 79
3.1.2 Logging and Stratigraphic Section 80
3.2 Methods 80
3.2.1 Geochemical Analysis 80
3.2.2 Microwave Plasma Atomic Emission Spectroscopy (MP-AES) 81
3.2.3 Atomic Absorption Spectrophometer (AAS) 81
3.3 Petrography 83
3.3.1 Thin Sections 83

CHAPTER FOUR

4.0 RESULTS 84
4.1 Field Geology 84
4.1.1 Basement Complex rocks 84
4.1.2 Cretaceous Rocks 88
4.2 Facies Analysis 118
4.3 Petrography 121
4.4 Trace Element Geochemistry 129

CHAPTER FIVE

5.0 DISCUSSIONS **130**

5.1 Stratigraphy of the Study Area **130**

5.1.1 Basement Complex Rocks 131

5.1.2 Lower Cretaceous Series (Bima Group) 131

5.1.3 The Upper Cretaceous Series 140

5.1.4 Post-Cretaceous Sedimentation 146

5.2 Facies Analysis **151**

5.2.1 Gravel Facies (G) 151

5.2.2 Sandstone Facies (S) 154

5.2.3 Mudstone Facies (M) 157

5.2.4 Carbonate Facies (C) 159

5.2.5 Analysis of the Sedimentary Architectural Elements 159

5.3 Petrography and Sandstone Classification **162**

5.3.1 Minerals Distribution 162

5.3.2 Sandstone Composition 166

5.3.3 Provenance of Sandstone 167

5.4 Trace Element Geochemistry **168**

5.4.1 Biophile Elements: V and Ni 169

5.4.2 Siderophile Elements: Fe, Co, Mo, Cr, Mn 169

5.4.3 Chalcophile Elements: Cu, Zn, Pb, Cd 170

5.4.4 Distribution Pattern of Trace Elements in Source Rocks 172

5.4.5 Maturity 174

5.4.6 Timing of Hydrocarbon Generation 176

5.4.7 Intrusion Impact on Maturation 178

5.3.8 Reservoir Rocks 178

5.5 Paleogeography Reconstruction **179**

5.6 Sedimentary Structures **180**

5.6.1 Primary Structures 180

5.6.2 Secondary Structures 183

CHAPTER SIX

6.0 SUMMARY, CONCLUSION AND RECOMMENDATION **185**

6.1 Summary **185**

6.2 Conclusion **187**

6.3 Recommendation **187**

REFERENCES **190**

LIST OF TABLES

Table 2.1 - Chemistry of kerogen 67

Table 4.1 – Facies and their codes 120

Table 4.2 - Mineral composition of sandstone of Bima Group, Yolde Formation and Dumbulwa Member of Pindiga Formation 127

Table 4.3 - Percentage of mineral grains for classification of sandstones of the Bima Group, Yolde Formation and Dumbulwa Member of Pindiga Formation in the study area 128

Table 4.4 - Concentration of some trace elements associated with shales of Kanawa Member of Pindiga Formation and Fika Shale of Bornu Basin 129

Table 5.1 - Proposed revised stratigraphic succession for the Nigerian sector of the Chad Basin (modified from Carter *et al*., 1963 in the Chad Basin and Zaborski *et al*., 1997 in the Upper Benue Trough) 150

LIST OF FIGURES

Figure 1 – Topographic map showing the location of the study area 7

Figure 2- Schematic diagram showing African sedimentary basins and swells 11

Figure 3 - Geological map of West Africa between latitudes 10^{o}N and 25^{o}N 12

Figure 4 - Outline geological map showing the main features of the Upper Benue Trough region 31

Figure 5 - Geological map of the Upper Benue Trough region 31

Figure 6 - Geological map of the Tukulma, Pindiga, Yelwa and Futuk inliers 46

Figure 7 - Strcutural features in the Upper Benue Trough associated with Santonian transpressional activity along the faults of the Wuyo-Kaltungo high where deviation of the horizontal stress occurred and originally linear *en echelon* folds developed sigmoidal axial traces. 49

Fig.8 – Geological map of the study area 86

Fig.9 a,b Sections of the Lower Bima Sandstone exposed west of Dutsen Mafurun Lanske 92

Fig.10 – Section of the Lower Bima Sandstone exposed at Skatikume Stream 93

Fig.11 – Section of the Middle Bima Sandstone exposed at the foot of Tangaran Hill 95

Fig. 12 – Section of the Upper Bima Sandstone exposed at the foot of Tangaran Hill 100

Fig. 13 – Section a, b of the Yolde Formation exposed at SE part of Yadi Kukuwa 103

Fig. 14 – Section a, b of the Yolde Formation exposed at SE part of Yadi Kukuwa 104

Fig. 15 – Section of the Yolde Formation exposed at Shishiwaji 105

Fig. 16 – Section of the Kanawa Member of Pindiga Formation exposed at Yadi Kukuwa Stream 110

Fig. 17 – Section of the Kanawa Member of Pindiga Formation exposed at northern art of Gabai 111

Fig. 18 – Section of the Dumbulwa Member of Pindiga Formation exposed along Njibulwa railway crossing 111

Fig. 19 – Section of the Fika Shale exposed along Mutwe 112

Fig. 20 – Lithostratigraphical succession of the Bornu Basin 117

Fig. 21 - Sandstone distribution pattern in Loren (2002) classification scheme 164

Fig. 22 - Plot of concentrations (ppm) against trace metals in 2D pattern 177

Fig. 23 - Plot of concentrations (ppm) against trace metals in 3D pattern 178

LIST OF PLATES

Plate I. Coarse –grained granite exposed along Dokshi road 87

Plate II. Fragments of pegmatite exposed along Dokshi road 87

Plate III. Conglomerate with pebbly sandstone of Lower Bima Sandstone around Dokshi 89

Plate IV. Fragments of quartz, feldspers and conglomerate at Panana Village displaying the alluvial fan of Lower Bima Sandstone around Dokshi 89

Plate V. Co-axial jointed sandstone exposed at Panana Village of Lower Bima Sandstone 90

Plate VI. Tabular cross- bedded sandstone at Panana Village of the Lower Bima Sandstone 90

Plate VII. Stratigraphic section of Lower Bima Sandstone with multiple reactivation surfaces Separating ferruginized sandstones, shale is exposed at the base of the succession in the quarry site 91

Plate VIII Gray shale of lacustrine origin, a deposit of the Lower Bima Sandstone exposed at a Local quarry site near Dokshi 91

Plate IX. Thick clay of Lake Margin of the Middle Bima Sandstone 94

Plate X. Silicified and brecciated sandstones of Upper Bima Sandstone exposed at Wongeri Hills 97

Plate XI. Silicified Tabular cross- bedded sandstone of Upper Bima Sandstone exposed at the foot of Tangaran Hill along stream channel 97

Plate XII Convolute cross- bedded sandstone of Upper Bima Sandstone exposed at the foot of Tangaran Hill 98

Plate XIII Eroded anticline of the Upper Bima Sandstone exposed along Birni Gadam 98

Plate XIV. Tabular- oblique cross- bedded sandstone of Yolde Formation exposed at Yadi Kukuwa 101

Plate XV. Tabular cross- bedded sandstone of Yolde Formation exposed at Yadi Kukuwa 102

Plate XVI. Massive thick sandstone bed with mudstone at its base of Yolde Formation 102

Plate XVII Shale unit of the Kanawa Member of the Pindiga Formation exposed at Yadi Kukuwa Road 107

Plate XVIII. Thick bed of limestone of the Kanawa Member of Pindiga Formation exposed around Yadi Kuuwa towards its boundary with Yolde Formation 108

Plate XIX. Limestone unit of the Kanawa Member fragments turning to yellowish- gray along Kukuwa Gari road 108

Plate XX. Shale unit of the Kanawa Member overlain by alluvial deposit exposed at outskirt of Bara along stream channel 109

Plate XXI. Interbedded sandstone/shale unit of Dumbulwa Member of the Pindiga Formation, with fractured beds trending NW- SE direction 113

Plate XXII. Shale/limestone unit of the Fika Shale exposed along Mutwe Road 114

Plate XXIII. . Ferruginized conglomeritic- sandstone of the Kerri- Kerri Formation 115

Plate XXIV. Red, medium- grained sand of the Chad Formation exposed at eastern Yadi Kukuwa 116

Plate XXV. a- arkosic arenites, b- arkosic arenites, Alt F- altered feldspar, Qz- quartz. Photomicrograph under cross- polars 122

Plate XXVI. c- lithic arenite, d-arkosic arenite, e- lithic arenite, Qz- quartz, Alt F- altered feldspar, Orth- orthoclase, Alb- albite. Photomicrographs under cross- polars 123

Plate XXVII. g- lithic arenites, h- arkosic arenites, i- arkosic arenites, j- arkosic arenites, Qz- quartz, Alt F- altered feldspar. Photomicrographs under cross- polars 124

Plate XXVIII. k- arkosic arenites, l- arkosic arenites, m- arkosic arenites, n- arkosic arenite, Mccl- Microcline, Qz- quartz, Alt F- altered. Photomicrograph under cross- polars 125

Plate XXIX. 29 o- arkosic arenites, p- arkosic arenites, Alt F- feldspar, Qz- quartz. Photomicrographs under cross- polars

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background

The study area, which is part of the Nigerian sector of the Chad Basin (Bornu Basin) is the largest intracratonic basin in Africa (Obaje *et al*., 2004) covering an area of about 2,335,000 km^2. The Chad Basin straddles five countries, namely; Nigeria, Cameroon, Chad, Niger and Central African Republics. Approximately one- tenth of the surface area of the Chad Basin is in northeastern Nigeria, bounded to the east by the Northern Highland (Mandara Mountains) and to the south by the Benue Trough and Biu Plateau Basalts. The Chad Basin lies between Latitudes 11^oN and $13^o43'38"N$ longitudes $8^o21'49"$ and $14^o22"E$. It forms part of the Western and Central African Rift System (WCARS) that was formed during the separation of African crustal blocks in the Cretaceous and belongs to the West African Rift Subsystem (WAS) (Genik, 1992, 1993). The West and Central African Rift Systems have attracted much attention from the oil industry because the Cretaceous sedimentary basins are deep, extensive; have formed along zones with enhanced geothermal gradients, and have been blanketed by thick Cenozoic sediments which might have further aided its hydrocarbon maturation.

Discovery of “oil and gas” in the Chad Basin (Chad and Niger) in the 1970’s have given rise to exploration activities in the Bornu Basin. Such discoveries are based on the occurrences of oil and gas “shows” in the eastern and western parts of the Chad Basin in the neighbouring Chad and Niger Republics (Petters, 1981; Whiteman, 1982; Genik, 1992, 1993). Whiteman (1982) stated that, there might be prospect for hydrocarbons in structures located within the zone of interdigitation between marine and non- marine facies, especially

in Turonian rocks which were laid down when the south of the Bornu Basin was connected via the Gongola Trough with the Benue Trough.

1.2 Statement of the Research Problem

There has been to date, very little comprehensive geology, stratigraphy and petroleum potential of the Bornu Basin at its boundary with the Gongola Basin. The subsurface geology of the study area is not known due little effort by oil companies to provide previous researchers with data, though there was drilling by by NNPC in the 1980's at the shores of Lake Chad (Carter *et al*., 1963; Avbovbo *et al*., 1986; Okosun, 1995; Zaborski *et al*., 1997; Obaje *et al*., 2004; Mohammed 2010, 2012; Hamza *et al*., 2012) about information of the geology of the area. The study reveals whether or not, all the Cretaceous sedimentation is similar to that of the Benue Trough. The stratigraphy of the Bornu Basin is often related to the Upper Benue Trough (Gongola Basin) due to studies carried out by Zaborski *et al*. (1997) which gives room for review. Therefore, this research work is determined to revise the stratigraphic successions in the Bornu Basin from Aptian to Quaternary so as to provide comprehensive document from the field to reveal whether it is a mirror of the Upper Benue Trough or it stands as a separate stratigraphic entity.

No detail inorganic petroleum geochemical studies has been carried out to determine the elemental prospect, therefore, the present study analyzed some shale samples collected from the study area (Kanawa Member of Pindiga Formation and Fika Shale) to determined their prospect for petroleum generation using trace elements such as; Biophiles, Siderophiles and Chalcophiles. The study will also carry out detail facies analysis in order

to classify the facies into groups and sub-groups, as well as conducting microscopic petrographic studies to differentiate the sandstones of the study area into different classes.

1.3 Aim and Objectives of the Research

The aim of the study is to carry out a detailed stratigraphic study of the area based on field mapping so as to ascertain the boundaries of different lithological units in the study area and to also understand the processes of events that took place during and after the deposition of the sediments. In order to achieve this aim, the following objectives have been undertaken;

(i) Ascertain from the geological fieldwork, the different rock types and the structures occurring in the study area so as to produce a geological map.

(ii) Carry- out detail stratigraphic studies so as to correct some stratigraphic misrepresentation based on field evidences.

(iii) Carry- out detail facies analysis of the lithologic units, with a view to interpreting the paleoenvironment.

(iv) Undertake inorganic petroleum geochemical analyses of representative samples and determine from the concentration of transition metals in parts per million (ppm), the petroleum potentials of the argillaceous sediments.

(v) Carry- out detail Petrographic work on sandstones and classified them.

1.4 Scope of the Study

The research work entails mapping on a scale of 1:50,000 and sampling of rocks from different locations within the study area (Mutwe Sheet 110 SE and parts of Mutwe Sheet 110 SW and Gulani Sheets 132 NE and NW), and to use the samples collected for

laboratory analytical work, which include stratigraphy and facies analysis. Both the field observations and the laboratory data would be integrated to come up with a refined stratigraphy and facies analysis

1.5 Justifcation

The stratigraphy, structures and inorganic petroleum geochemistry of the study area has not been extensively studied particularly at the edge of the basin. The study will evaluate the stratigraphy, sandstone classification and inorganic petroleum geochemistry to understand whether the source rocks have generated petroleum or not and to possibly propose a refined lithostratigraphic succession in the area.

Therefore, the research work will provide detail information on the stratigraphy, structure and inorganic petroleum geochemistry of the study area to both researchers and oil companies aimed at understanding the petroleum charge system in the basin. The lithostratigraphic succession will be revised to solve some stratigraphic problem regarding mis-mapping which was raised and corrected at the Upper Benue Trough (Gongola Basin) by Zaborski *et al*. (1997) and identifying Yolde and Kerri- Kerri Formations which were not previously reported in the study area.

Petroleum geochemistry, therefore, plays an important role in enhancing the supply of petroleum, needed to satisfy the ever-growing energy demand as the global population is projected to reach about 10 billion by 2050 (UN-DESA, 2015). In view of this, a challenge that has become apparent concerning the future of petroleum exploration, particularly looking for additional petroleum in less mature or frontier areas, which the Bornu Basin is

an example, would enhance productivity and increase the reserve base of the nation when recovered from new and previously explored areas.

1.6 Location and Accessibility

The study area is located in the southwestern part of the Nigerian sector of the Chad Basin (Bornu Basin) (Fig. 1). The area falls between Latitudes 10^0 52'3"to 11^0 15'N and Longitudes 11^0 37'30"to 12^0 E, Mutwe sheets 110 SW, and part of Mutwe sheet 110 SE and parts of Gulani sheets 132 NW, NE, covering a total area of 1640.5 km^2 insert Fig.1: Location map of the study area. The study area is accessible through tarred and untarred road from Kukuwa Gari to Bara, and most other locations accessible through footpaths and untarred roads.

1.7 Physical and Human Geography

The Chad Basin occupies the semi- arid Sahelian part of eastern West Africa. It is a basin of internal drainage, that is, no river flows out of it. In the Bornu Basin, the relief slopes gently from an elevation of 530m at the western margin to 240m in the Lake Chad (Miller *et al*., 1968). The decline in altitude towards the north is probably as much a matter of climate zoning and the southerly source of sediments resulting from tilting. The generally low- lying topography of the basin is interrupted in the northern part by ridges of sand dunes which may extend for many kilometres (Odusina *et al*., 1983). The Lake Chad lies in a shallow depression and its shoreline changes markedly in response to seasonal fluctuation in lake level. From December to January, the lake reaches its highest annual level owing to the seasonal inflow of the Chari River, which forms the boundary between Cameroon and

Chad Republics to the east. Thereafter, evaporation exceeds river inflow and the level of water in the lake gradually declines until July, when it begins to rise.

The people within the study area are predominantly Babur, Kanuri, and Fulani by tribes; the Babur's being the majority. The people practice subsistence agriculture and nomadic cattle rearing, moving their catties where there is available water, and grazing depends on available land. Most people live in Buni Yadi town in the northern part and around Gujba Village which is more populated.

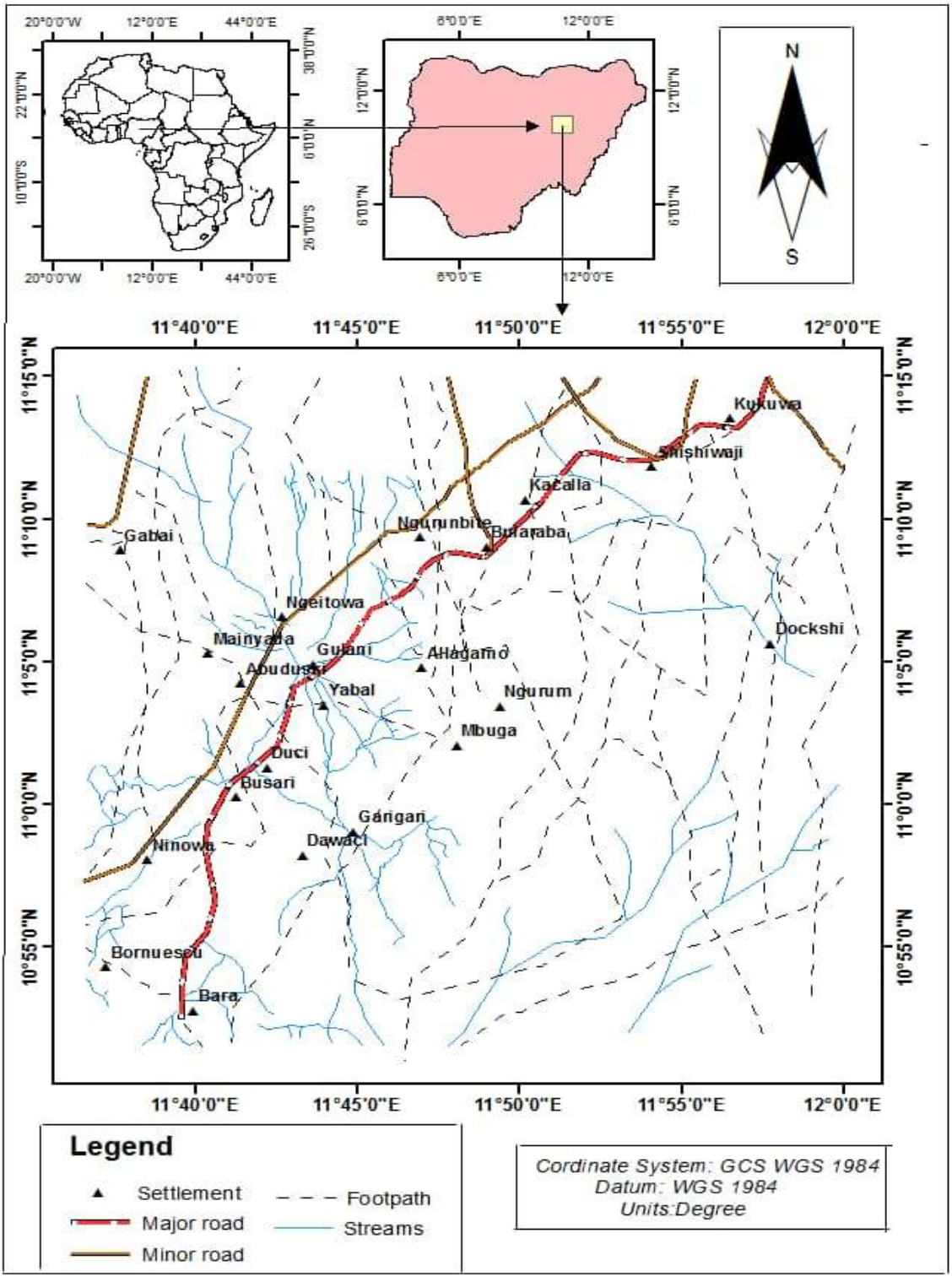


Fig. 1: Topographic map showing the location of the study area

1.8 Climate and Vegetation

The study area lies within the semi-arid climatic zone, characterized by a long dry season (October to April) and a short rainy season (May to September). Goni *et al.* (2005) reported that the rainfall pattern generally shows spatial and temporal variability over the area and has been characterized by single maxima, with a peak mostly around August. The rainfall record in semi- arid region is between 250 mm to 500 mm of annual rainfall, while the temperature over the area may go up to 48^0C and sometimes may come below 10^0C in the months of dry cold weather. Humidity is generally low, except during the brief rainy season. The potential evapo-transpiration is high over the area.

The vegetation in the study area is basically the Sudan Savannah, among the species includes; Acacia, Combretum genus, and sparse short grass cover. The differences in the types of vegetation depend on factors such as soil type, seasonal surface water pools and amount of rainfall. The clay flats which are submerged during the rainy season have predominantly grasses of annual type (Musa, 2007).

1.9 Previous Works

Research on the Chad Basin as a whole date back to early 20th Century. The Bornu Basin was given less attention, partly due to lack of comprehensive knowledge of the petroleum geochemistry and scanty outcrops of Cretaceous sedimentation. The origin of the Chad Basin at large is connected to chain of interior cratonic basins in Africa, whose origin are closely connected to the structural evolution of Africa and especially the separation of the African and South American continents in the Cretaceous, which attracted a lot of attention from many workers. Among the researchers are Furon (1963), Faure (1966), Louis (1970),

Burke and Wilson (1972), Burke and Dewey (1974), Burke (1976), Thiesen *et al*. (1979), Petters (1981), Fairhead (1986), Fairhead and Binks (1991), Guiraud and Maurin (1992), Guiraud *et al*. (1992), Wilson and Guiraud (1992), Genik (1992, 1993), Hartley and Allen (1994) among others. The Chad Basin is believed to be a product of rifting, subsidence and sedimentation accompanied by the separation of African and South American continents.

Pioneer workers, mostly on the geology and hydrogeology of the Chad Basin in Nigeria include Falconer (1911), who made a geological investigation in the northern Nigeria. Raeburn and Brynmor (1934) worked on the geology and water resources in the Bornu Basin. Barber (1965) and Barber and Jones (1960) focused on the pressure (artesian) water and hydrogeology of the Maiduguri and Bornu Provinces in general. Carter *et al*. (1963) carried out detailed geological studies covering Adamawa, Bauchi, and Bornu Provinces in the northeastern Nigeria with some selected boreholes and stratigraphic correlation between Chad Basin and the Gongola Basin. A model of the tectonic setting of the Chad Basin in general was presented by Genik (1992) who proposed four stages to characterize the tectonic framework and evolution of the Basin. These include i) a Pan- African crustal sage; ii) early rift stage; iii) late rift stage; and iv) post- rift stage

CHAPTER TWO

2.0 GEOLOGICAL FRAMEWORK

2.1 Regional Evolution of the Chad Basin

The origin of some African Phanerozoic sedimentary basins is related to the dynamic processes of plate divergence (Petters, 1981). Notable exceptions, however, are the deformed basinal sequences of the Palaeozoic foldbelts of Mauritania and Morocco which resulted from Hercynian convergent plate motion and the collision of Africa and North America, and the Tinouf and Ougarta basins which are Palaeozoic Successor basins (Dillon and Sougy, 1974). The Atlas Foldbelt was caused by the convergence of African and Liberian plates during the Alpine Orogeny.

The African continent provides many examples of rift systems and associated sedimentary basins, for example, the Late Carboniferous- Early Jurassic Karoo Basins of southern and eastern Africa (Kent, 1974). The Triassic- Jurassic Moroccan graben (Van Hautens, 1977) and the Early Cretaceous rift systems extending from the Saharan platform of Algeria and Libya through Central West Africa to the Gulf of Guinea (Burke and Dewey, 1974; Louis, 1970; Radier, 1959).

Another class of sedimentary basins which are indirectly related to continental plate divergence in West Africa is the broad intracratonic epeirogenic basins (Petters, 1981). Among these is the Chad Basin (Fig.2). The Chad Basin is a broad epeirogenic down-warp in the interior of West Africa and was occupied by an epeiric sea from Cenomanian to the Paleocene.

2.1.1 Megatectonic Setting and Origin of the Chad Basin

The interior basins of West Africa occupy broad, shallow, flat- bottomed basement down warps that form a curvilinear system of basins which lie parallel from the continental margin between latitudes 25^0 N an 30^0 S (Petters, 1981) as illustrated in (Fig. 2). Taoudeni, Congo, Cubango and Kalahari Basins are located on Archean Cratonic nuclei, whereas the Chad Basin lie within the belt of Pan- African reactivated basement (500 Ma). The basement arches which surround the West African interior basin north of latitude 10^0 N are the Nubo- Arabian swell to the east, Tibesti, Haggar and Reginsat uplifts to the north, the Kaas and Eastern Senegal Massifs to the west, and the Upper and Lower Guinea Arches to the south (Fig.3.).

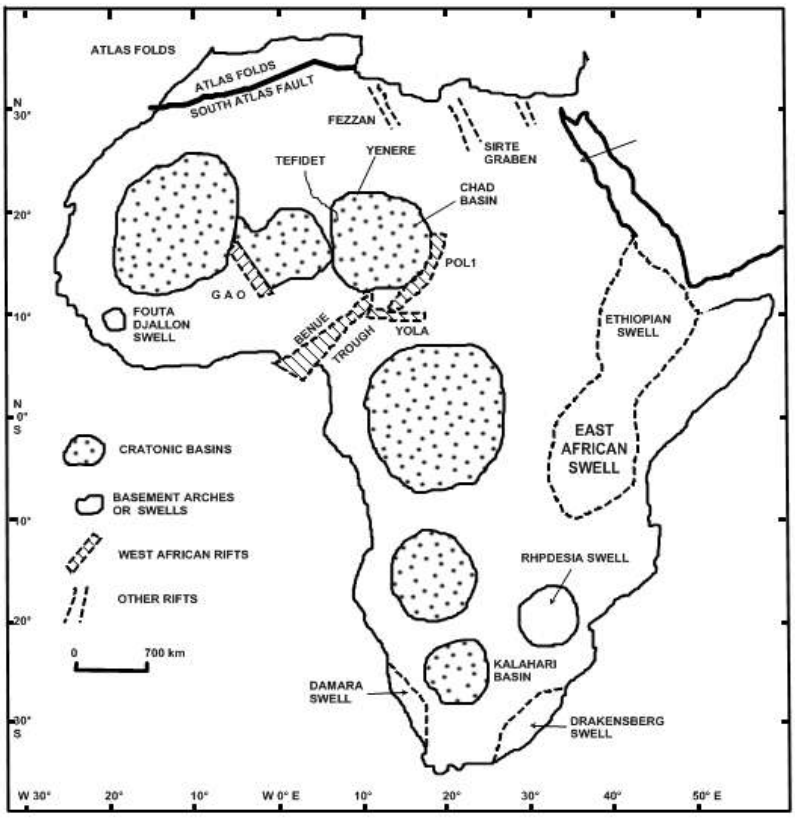


Fig. 2. Schematic diagram showing African intracratonic basins and swells (After Burke and Wilson, 1970)

Theories of the origin of African interior basins have stressed the role of rifting (Furon, 1963; Burke and Dewey, 1974). Rifts have been recognized in the Chad Basin by (Louis, 1970). The Chad Basin lies along the trans- African lineament which was defined by Nagy *et al*. (1976) as a zone of weakness that runs transversely from the Niger Delta to the Nile Delta, and is also occupied by the Benue Trough in Nigeria, the Chad Basin in Niger and Chad Republics, the Kufra Basin in Libya and the Qattara Depression in Egypt.

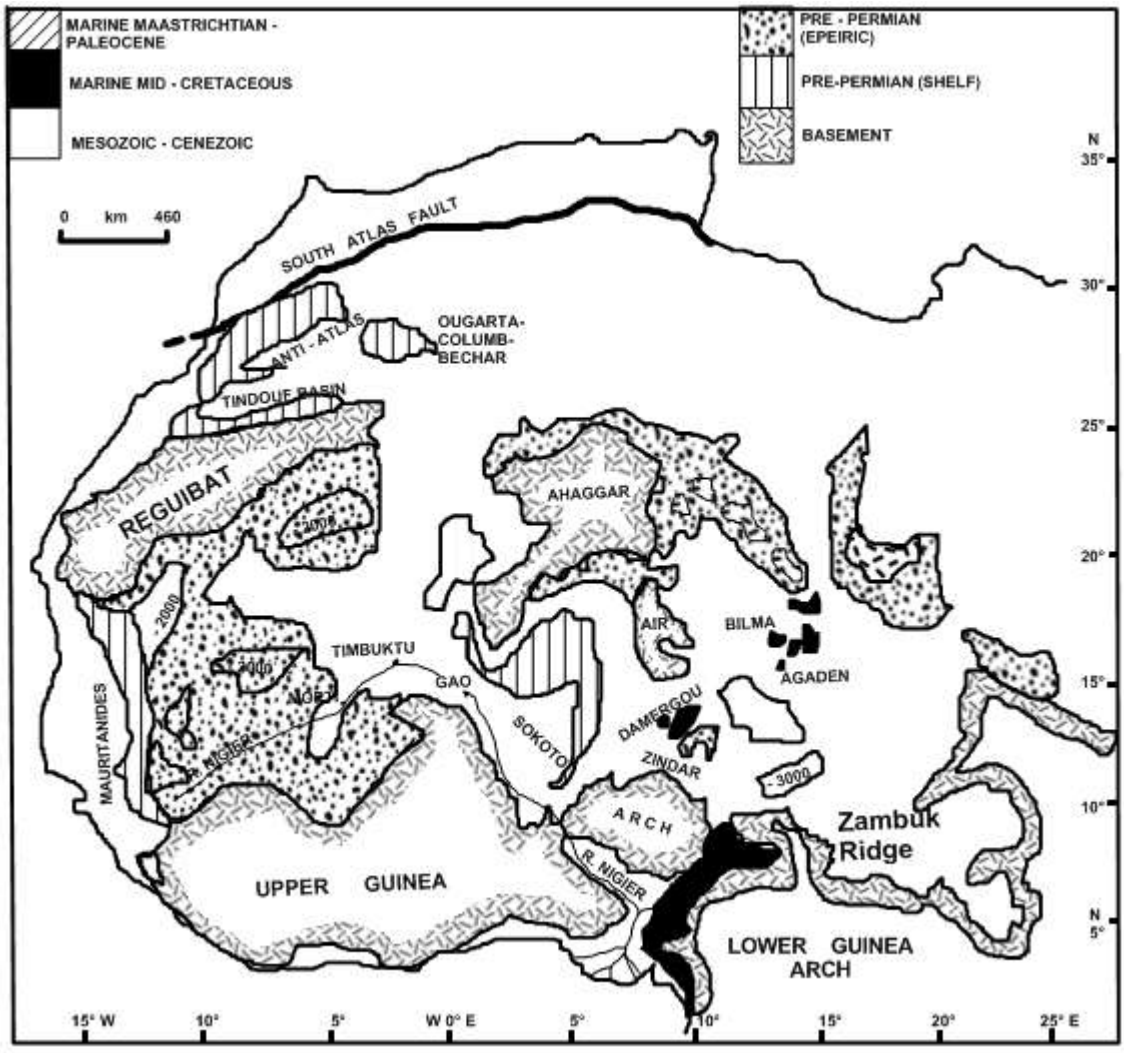


Fig.3. Geological map of West Africa between latitudes 10°N and 25°N (After Petters, 1981)

Theories of cratonic subsidence and basin formation have emphasized the role of changes in mantle regime and subsidence due to flexure of the lithosphere in response to sediment loading (Bolt, 1976). Faure (1973) and Sloss and Spleed (1974) ascribed cratonic subsidence to seafloor spreading, plate tectonics and mantle thermal perturbations. Faure (1973) further stated that the migration of cratonic subsidence and marine sedimentation from the Late Cenomanian in the Chad Basin was attributed to horizontal relative translation between the lithosphere and the asthenosphere. According to Faure, 1973, crustal uplift occurs as continental lithosphere rides over bumps in the asthenosphere while subsidence occurs after the continent moves over the lithospheric bump.

The uplift and subsidence history of the African plate appears to be related to the history of seafloor spreading in the Atlantic Ocean (Faure, 1973; Sloss and Speed, 1974). This model is also similar to the evolution of intracratonic basins resulting from thermal heating and uplift of the lithosphere and thinning due to erosion which result in thinning of the cold lithosphere. Strong evidence of west African intracratonic basins during Mid- Cretaceous phase of active seafloor- spreading in the Atlantic is evident in the widespread Cenomanian- Turonian marine transgression in the Chad, Iullemmeden and Congo Basins (Furon, 1963; Franks and Nairn, 1973. Bond (1978) demonstrated that the African continent has been undergoing stronger uplift than the other continents since the Miocene. Burke and Wilson (1972) argued that the rise of swells in Africa (Fig.3) maybe due to convection plumes in the mantle which by lifting parts of the continent have resisted and halted eastward motion from the Mid- Atlantic Ridge and have held Africa stationary for the past 25 Ma (since Miocene). Renewed subsidence in the Chad Basin during the

Quaternary shows that; intracratonic basins can be reactivated by sediment loading if the surrounding basement areas are uplifted and eroded (Burke, 1970).

2.1.2 Intracratonic Basins

Intracratonic basins occur within continental interior away from plate margins. They are oval in plane and saucer-shaped in cross-section. Intracratonic basins are flowed with continental crust, and in most instances, are also underlain by failed or fossil rifts. Their evolution involves a combination and succession of basin-forming processes, which include continental extension, thermal subsidence over a wide area, and later isostatic readjustments (Busby and Ingersoll, 1995).

Controversy has surrounded understanding of the global origin and evolution of intracratonic basins. Klein (1991) has reported that eleven hypothesis have been proposed by several authors for the formation of intracratonic basins. These are examined.

(i) Increase in density of the crust by an eclogite phase transformation (Michigan basin, Haxby *et al.,* 1976; Williston Basin, Fowler and Nisbet, 1985),

(ii) Rifting associated with impingement of a thermal plume at the base of the lithosphere as in Illinois Basin (Burke and Dewey, 1973),

(iii) Thermal metamorphism of the lower crust to the boundary conditions of the greenschist and amphibolite facies (Australian intracratonic basins, Middleton, 1980).

(iv) Mechanical subsidence caused by isostatiscally uncompensated excess mass of igneous intrusions (Williston Basin, DeRito *et al.,* 1983).

(v) Tectonic reactivation along older structures (Michigan Basin, Howell, 1989; Parama, Maranhao, and Amazonas Basins, Brazil, DeBrito Neves *et al.,* 1984).

(vi) Thermal subsidence (Illinois Basin, Sleep, 1976; Sleep and Snell, 1976; Sleep *et al.,*1980; Heidlauf *et al.,* 1986; Willliston Basin, Ahern and Mrkvicka, 1984; Ahern and Ditmars, 1985; Michigan Basin,Sleep *et al.,* 1980; Nunn *et al.,* 1984; Nunn, 1986; Hudson Bay Basin, Quinlan, 1987; Amadeus Basin, Australia, Lindsay and Korch, 1989).

(vii) Partial melting of lower crust and drainage of resulting igneous melt to mid-ocean ridges by volcanism, resulting in basin subsidence above the zone from which igneous melt was removed (Sloss and Speed, 1974).

(viii) Changes in intraplate stress, assuming a visco-elastic plate (Australian intracratonic basins, Lambeck, 1983a, b or an elastic plate (all intracratonic basins, Karner, 1986).

(ix) Thermal subsidence following intrusion of anorogenic granites in response to changing heat flow during supercontinent breakup (all intracratonic basins, Klein and Hsui, 1987).

(x) Thermal subsidence followed by subsidence caused by an isostatically uncompensated intrusions (Illinois basin, Hamdani *et al.,* 1991), and

(xi) Subsidence caused by tectonic events at adjacent plate margins (Leighton and Kolata, 1990).

The Chad Basin is related in terms of its evolution to type's ii, iv and x. This basically has to do with rifting and thermal subsidence which is key identity to the evolution of the basin (Avbovbo *et al*., 1986, Burke, 1976b)

2.1.3 Tectonic Setting of the Chad Basin (Bornu Basin)

The Bornu Basin is covered by a monotonous basin wide, Quaternary deposit, the Chad Formation. Sediments below this cover are nowhere exposed except at the southern edge where the basin wedges with the neighbouring Benue Trough (Avbovbo *et al*., 1986) and the Biu Plateau Basalts. The Bornu Basin (like the Benue Trough) exhibits platform sedimentation in a geotectonic setting related to rifting. As in most part of Nigeria, there is no record of sedimentation between the Precambrian to Late Mesozoic times (Carter *et al*., 1963).

2.1.3.1 Pan African Crustal Consolidation Stage (750- 550 Ma)

Major basement lineaments and faults were produced within the basin during the Pan African crustal consolidation. The structures formed precursor directions on the "essential structure for the future rift basins". The dominant NE-SW trending fault system (Avbovbo *et al*., 1986; Benkelil, 1989) of the Bornu Basin belongs to this phase.

2.1.3.2 Early Rift Stage (130-98 Ma)

This was the period of the rift basin formation. The Benue Trough and Bornu Basin represent the third and failed arm of the trple junction rift system which was formed during the break- up of the Gondwanaland and the start of the separation of the African and South American continents in the Early- Cretaceous at about 130 Ma (Benkhlil, 1989; Fairhead and Binks, 1991; Genik, 1992). This separation gave birth to the South Atlantic Ocean. According to these authors, the strike- slip movements of wrench fault which originated from South America to Africa in response to the separation of the two continents played a major role in the development of the Chad Basin. The lateral movements of a block relative

to the other crustal blocks at this time resulted in the transtentional opening of the Benue Trough and the Chad Basin.

2.1.3.3 Late Rift Stage (98- 75 Ma)

Rift formation slowed down and a tectonic- eustatic rise in sea level led to epicontinental transgression which causes from the Tethys and the South Atlantic via to meet Algeria, Nigeria and the Benue Trough respectively to the Chad basin. This has been proved from macro- fauna evidences (Reyment, 1980; Allix *et al*., 1981; Benkhelil and Robineau, 1983; Okosun, 1992). According to Genik (1992), the slowdown in the rift development due to changes in the stress regime caused by variations in the spreading rate and direction between the Equatorial and Southern Atlantic plates culminated in a marked tectonic pulse at about 85 Ma. This tectonic pulse was a basin- modifying event, which caused folding and basin inversion in the Benue and Bornu Basins (Avbovbo *et al*., 1986; Genik, 1992; Guirauid, 1993).

The subordinate NW- SE trending fault system which have restricted occurrence in the sediments to where was developed as relief faults in response to changes in the stress regime after the Santonian deformation that belong to this phase. Majority of the faults in the basin are basement involved. Movements along these faults led to high angle faults in the overlying strata. Avbovbo *et al*. (1986) reported that the basement involved faults resulted in the formation of horst, grabens and similar structures. Many of these faults within the basin terminate below the Cretaceous – Tertiary boundary unconformity. The tectonic regime during this phase was probably dominated by tensional movement as indicated by the preponderance of high- angled normal faults and the scarcity of reverse

faults. Folds within the basin are simple and assymmetrical with low fold frequencies and amplitudes which increase towards the centre of the basin. They have spatially restricted occurrence to the southeastern part of the basin (Avbovbo *et al*., 1986). Avbovbo *et al*. (1986) authors stated that numerous faults from the two fault system transgress the folds. The fold axes extend over long distance and in most cases without effective strike closures. The chief fold axes strike NE- SW. The folds are probably flexural which developed from the graben subsidence in the basement. An anticline and syncline at Dumbulwa and Mutwe both of which trend NW-SE constitutes the dominant folds within the basin.

2.1.3.4 Post Rift Stage (66- 0 Ma)

There was no significant tectonic activity during this phase. Earth movements ceased within the basin before 66 Ma which represents the Palaeocene, hence no faulting and significant folding observe in the Tertiary and younger strata. These units have gentle dips to the north and northeast towards the centre of the Chad Basin, which is in conformity with the general slope direction of the basin.

2.1.4 Lithostratigraphy and Depositional Environments of the Bornu Basin

2.1.4.1 Bima Sandstone (Albian- Turonian)

Sedimentation began in the Bornu Basin in the Albian (?) times with a continental, sparsely fossiliferous, poorly sorted, medium to coarse- grained feldsathic sandstone, which unconformably overlies the Precambrian Basement (Carter *et al*., 1963). Okosun (1995) reported that the formation consists of thin to thick beds of fine to coarse- grained sandstone of variable colours ranging from white, brown, reddish brown to gray, and the coarse textures are more common towards the bottom of Kinasar-1 well. Hamza *et al*.

(2012) reported a strata with a thickness of 45m in Tuma- 1 well which corresponds to the Bima Sandstone, while the lower part of "Formation 1" in Murshe- 1 well also related to the Bima Sandstone. Mohammed (2010) reported a thickness of 30m from Kanadi- 1 well which is moderately sorted, fine- medium grained and dark brown in colour. Avbovbo *et al*. (1986) reported seismic sequences to represent the Bima Sandstone. They described sequence la as their lower sequence to be the deepest in the Bornu Basin with upper boundary varying from toplap to concordant, suggesting a variation from an unconformity boundary to a conformable strata surface. The lower boundary which presumably rest on the basement is marked mainly by baselap. A seismically transparent pattern indicative of possible continental fluvial sands with alternating high and low energy suggests paralic deposit.

Avbovbo *et al*. (1986) further stated that the boundary relation between sequences below, especially that of the latter was deposited as a marine onlap on top of sequence 1a which is possible to correlate with the Middle and Lower Bima Sandstone of (Carter *et al*., 1963), sequence 1b is said to have a thickness of 3000m with a monolithic characteristic facies. Sequence 2 of Avbovbo *et al*. (1986) corresponds with the Upper Bima Formation with alternating high and low amplitudes reflection patterns exhibiting divergent configuration indicating active differential subsidence contemporaneous with deposition. There is more than 3000m thick of sediments and seismic data suggests fluvial environment of deposition, but having facies changes towards the edge of the basin and that the sequence is presumed to be dominantly shale with increasing sand to the northeast, they concluded that the apparent lack of feature as in salt tectonics suggest that the sequence to be shale. Carter *et*

al. (1963) reported earlier that the Bima Sandstone is wholly continental in the northern part of the basin, while in the south, shale (marine) occurs in its lower part.

2.1.4.2 Gongila Formation (Turonian- Santonian)

The Gongila Formation is a transitional sequence between the underlying continental Bima Sandstone in the Bornu Basin, stratigraphic equivalent of Yolde Formation in the Gongola Basin which is overlain by the marine Fika Shale. It is a calcareous shale- sandstone unit, deposited in a shallow marine environment and regarded as transitional facies (Avbovbo *et al*., 1986) or passage beds of (Carter *et al*., 1963) accompanying marine incursion (transgression of the Tethys Sea across the Sahara and the northeastern of Nigeria). The marine incursion which started in Late Albian time reached its peak in the Turonian, during which the entire Benue- Chad axis become inundated.

Carter *et al*. (1963) assign Gongila Village as the type locality of the Gongila Formation, which they divide the formation into an upper sandstone- shale member and a lower limestone- shale member. The lower part of the Gongila Formation consists of limestone, shale and marl and has been dated Cenomanian- Turonian (Popoff *et al*., 1988) and Lower Turonian (Barber, 1957; Obi, 1990). Obi (1990) reported that the limestone of the Gongila Formation at Ashaka Quarry from his mineralogical and petrological studies which reveals that the limestone were deposited under low energy, shallow marine to hypersaline. Okosun (1995) reported that the formation consists of thin to moderately thick interbeds of shale, silty sandstone and sandstone. The shale is gray to dark gray, while the sandstone has variable colours ranging from white, brown, yellow, purple and gray, and has fine to coarse- grained texture. He further stated that volcanic intrusive which occur as diorite sills

are seen at several horizons of the formation from Kanadi- 1, Sa- 1, and Wadi- 1 wells. Okosun ((1995) concluded that the shale adjacent to the intrusive have become thermally degraded and are very brittle and soft. Carter *et al*. (1963) reported numerous Cenomanian-Lower Turonian ammonites from the basal limestone facies and dated as Lower Turonian.

The formation corresponds to ("Formation 2") of Hamza *et al*. (2012) which they described as having the first appearance of shaly limestone at a depth of 3240m in Murshe- 1 and 3565m in Tuma- 1 wells, while the upper part of the ("Formation 2") is marked by the first appearance of fine- grained micaceous sandstone or siltstone intercalated with gray to black shale at depths of 3215m in Murshe-1 and 3530m in Tuma-1 wells respectively. Mohammed (2010) reported shale units in Kadaru-1 and Herwa-1 wells which intercalates with silt and sandstone. The formation have thicknesses of 1035m (4705- 3670)m in Herwa-1 and 765m (4980- 4195)m in Kadaru-1 wells with varying colours ranging from blackish brown, dark brown dark gray and grayish black.

Zaborski *et al*. (1997) pointed out that, there is however, some doubt concerning this point while in an event the term "Gongila Formation" is inappropriate for these beds, because they stated that Gongila village itself lies upon the Lower Bima Sandstone. Carter *et al*. (1963) cited the hill near Gongila Village as the type locality of the Gongila Formation. Zaborski *et al*. (1997) went further to say the hill, presumably nearest to the southeast of Gongila village, is made up of Middle and Upper Bima Sandstones overlain by the attenuated Yolde Formation and a sandy limestone, the basal part of the Kanawa Member. This relationship has led to erroneous previous mapping in the Dumbulwa- Bage High. Geological Survey of Nigeria maps {Sheets 25 (Potiskum) and 36 (Gombe)} indicated the

Dumbulwa and Bage Hills consisting of the Bima Group, they are infact made up of Dumbulwa Member of (Zaborski *et al*., 1997).

In the light of criticism concerning the name "Gongila Formation" indicated above, it was proposed by Zaborski *et al*. (1997) that the term "Dumbulwa Member" be used for the sandstone and shale sequence in the middle part of the Pindiga Formation in and around the Dumbulwa- Bage High.

2.1.4.3 Fika Shale (Turonian- Maastrichtian)

During the Turonian, bluish black ammonite rich, open marine Fika Shale was deposited (Carter *et al*., 1963). The formation is occassionally gypsiferous and contains limestone which is very prominent and well exposed around Mutwe Syncline. Okosun (1995) stated that it has a thickness of 890m and that volcanic intrusive (diorite sill) have degraded the adjacent shale to thermally britlle. The sedimentation, resulting from the Atlantic transgression from the south continued into the Senonian. The Turonian- Senonian depositional phase that produced the Gongila Formation and Fika Shale was succeeded by a regressive phase. Marine transgression in the Cenomanian- Turonian inundate large parts of Africa (including Bornu Basin), reaching a maximum extent of about 80Ma (Hartley and Allen, 1994) or approximately 94- 84 Ma (Petters, 1996). The formation is diachronous and has been assigned a Turonian- Maastrichtian age (Carter *et al*., 1963). Mohammed (2010) studied two wells and reported that the formation is moderately sorted with variation in colour ranging from brown, dark brown, dark gray, and black from the top to bottom of Kadaru-1 well and dark brown, dark gray, grayish brown, blackish brown, and black, in Herwa-1 well. They have thicknesses of 1695m (3670- 1995) m in Herwa-1 well and

2550m (195- 1645) m in Kadaru-1 well. The Fika Shale is generally monotonous except where it forms boundary with other formations, or break occurs.

Hamza *et al*. (2012) reported the base of Fika Shale ("Formation 3") which is taken to be the first appearance of whitish gray shaly limestone at depths of 2845m and 2950m in Murshe-1 and Tuma-1 wells respectively. The middle part as "Formation 4" and upper part as "Formation 5" and concluded that the three "Formations" (3, 4, and 5) are the equivalents of Fika Member of (Zaborski *et al*., 1997). Avbovbo *et al*. (1986) reveal from their seismic sections that sequence 4 is characterize primarily by discontinous, low-amplitude seismic facies bounded above and below by conformable strata surfaces. They reported a 500m thickness, with monolithic unit deposited in an environment of uniform energy but increases in sand content to the southwest. Regression led to Maastrichtian-Palaeocene continental sedimentation.

2.1.4.4 Gombe Sandstone (Maastrichtian)

In the Late Maestrichtian time, a phase of tensional deformation occurred in the basin and continued until the end of the Cretaceous, restructuring the basin with a widespread uplift, arching along the basin axis and creation of an elongate NE- SW graben system (Avbovbo *et al*., 1986). The Gombe Sandstone is believed to be a fluvial- lithoral sequence of sandstone, siltstone, shales, clays, and thin coals beds were encountered in Gombe (Upper Benue Trough) from a well sunk near Gombe Sandstone- Kerri- Kerri Formation boundary were observed at several localities by (Carter *et al*., 1963). Such deposits are common shelf or delta platform environments. Zaborski *et al*. (1997) reported that the formation have been folded, faulted and dissected during the deformational episode. Avbovbo *et al*. (1986) stated that sequence 5 has an angular unconformity relationship with the overlying Tertiary

beds while maintaining a conformable boundary with adjacent sequence. They concluded that the sequence is not present everywhere in the basin because of erosion; therefore the thickness ranges from 0- 500m. Similarly, Okosun (1995), Mohammed (2010), and Hamza *et al*. (2012) are of the view that the formation is not present in their studied wells from Maiduguri sub- basin to the shores of Lake Chad.

Folding and deformational events that followed the deposition of the Gombe Sandstone are believed to have commenced in the Late Cretaceous time (Odusina *et al*., 1983) and resulted in the development of large anticlinal and synclinal structures in the Cretaceous rocks. Subsequent erosion removed parts of the Cretaceous- Tertiary boundary (Avbovbo *et al*., 1986; Popoff *et al*., 1986)

2.1.4.5 Kerri- Kerri Formation (Tertiary)

Overlying the Gombe Sandstone is the continental Lacustrine- deltaic deposits refer to as Kerri- Kerri Formation of Palaeocene age. The formation is unaffected by folding, but dips gently to the north and northeast below the Chad Formation. Okosun (1995) reported that the formation consists of thin and thick beds of sandstone, grits and clays in Dawasa and Damagum boreholes. Carter *et al*. (1963) earlier stated that the sandstones is locally cross-bedded and ferruginized, and that laterite capped the erosional surface towards the top of the formation. The Kerri-Kerri Formation developed as a result of E-W extension (Benkhelil, 1986, 1988); NNE-SSW trending faults occur along its western margin and N-S faults to the east (Adegoke *et al*., 1986; Zaborski *et al*., 1997). The formation is more extensive and varied in the Upper Benue Trough where three distinct lithologies; comprising ferruginous sandstone, kaolinitic sandstone and laterites have been recognized.

The formation is regarded as sequence 6 by Avbovbo *et al*. (1986) and dips at low angle toward the northwest and has a thickness of 350m with parallel to sub- parallel reflection characters. The continental clastic nature has also been described by Adegoke *et al*. (1986) and Dike (1995) with a thickness of 320m. The Kerri- Kerri Formation appears to have been derived from Cretaceous sedimentary rocks where relief was much more subdued (Carter *et al*., 1963). Pliocene and Quatenary eruptive and associated volcaniclastic depositional phases were separated by an interval of weathering and erosion (Turner, 1978; Braide, 1994).

2.1.4.6 Chad Formation (Quaternary)

Chad Formation is the youngest stratigraphic succession in the basin. In the Pleistocene and probably Pliocene, fluvial lacustrine clays with diatomite and coarse fluviatile sands were deposited. Okosun (1995) reported variable colours of the formation ranging from white, yellow, brown to gray, and that the clay is massive and locally gritty in texture due to the presence of angular to sub- angular quartz grains. Mohammed (2010) stated that the formation unconformably overlies the Fika Shale in both Herwa-1 and Kadaru-1 wells at depths of 1255m and 1250m respectively, with thicknesses of 975m and 925m, and the thickness of sand increases towards the shores of Lake Chad region. The base of the "Chad Formation" is marked by the appearance of fine to medium grained sandstone or sandy clay at depths of 620m and 706m in Murshe-1 and Tuma-1 wells (Hamza *et al*., 2012). The topmost seismic sequence 7 in the Maiduguri sub- basin is characterized by a lower concordant boundary and parallel seismic reflections that dips from 1^{o} to 2^{o} northwest, and has an approximate thickness of 150m which is neither folded nor faulted (Avbovbo *et al*., 1986). The formation is at least one kilometre thick in the deeper parts of the basin (Wright

et al., 1985) and is a product of erosion from the watershed into the Chad Basin accompanied by episodic and sporadic uplift and volcanism (Burke, 1976).

According to Burke (1976), during the Neogene and Quaternary about 0.5km of sediments over an area roughly 500km in diameter has accumulated in the Chad Basin. Towards the end of the Tertiary and until recent times, widespread volcanic activity occurred in the uplifted southern and central areassuch volcanic activity occurred in the NE- SW and localized on the southern edge of the Bornu Basin and the eastern edge of the Gongola Basin (Saugy, 1987). Today, sand dunes, river alluvium, deltaic and lagoonal clay flat, blanket wide areas to the south and southwest of the Lake Chad.

2.1.5 Structural Styles in the Bornu Basin

2.1.5.1 Structures

The Structural features in the basin are mainly products of structural and tectonic events during the Late Cretaceous times that reshaped the basin (Olugbemiro, 1997). Cratchley *et al*. (1984) recognized an ovoid- shaped negative bouguer gravity anomaly north of Maiduguri, and further identified a "Maiduguri Trough", thought to contain some 300m of Cretaceous and Quarternary sediments, running NNE from near Maiduguri and connects with the Termit rift. On a larger scale, Odusina *et al*. (1983) maintained that geologic evidence points to the fact that the Bornu Basin is a junction of both the Upper Benue Trough and the Manga structural unit of Niger Republic, that is to say, the evolution of both the Bornu Basin and the Upper Benue Trough are ultimately related. Their studies revealed four (4) main structures in the Bornu Basin based on seismic reflections;

i) Intrusive features of either igneous or sedimentary origin

ii) Moved structures with surfaces as possible stratigraphic traps

iii) Graben structures, growth faults and

iv) On- lap sequences

Avbovbo *et al*. (1986) stated that the structures in the Maiduguri sub- basin consist of faults and simple asymmetrical folds, most of which have a dominant NE- SW trend. These features are exhibited best on the NE-SW seismic lines. They further stated that, it is difficult to differentiate these structures with intrusive rocks (especially if the intrusion is diapiric), buried sills and basement horsts.

Avbovbo *et al*. (1986) classified the structural styles in the Bornu Basin into two (2): i) fault- related structures and ii) fold- related structures

Fault- Related Structures

Avbovbo *et al*. (1986) further stated that most of the faults in the sub- basin are basement involve, and results in horst, grabens, and related features. Detached faults, which probably developed in response to basinal deformation and a preponderance of high- angle normal faults and a paucity of reverse faults, are apparent, indicating the dominance of tensional movements within the basin. Cross-sectionally, most of the faults terminate beneath the regional angular unconformity that delimits Cretaceous from Tertiary sedimentation. Two major fault systems were recognized by Avbovbo *et al*. (1986) and these are;

i) Laterally persistent northeast- southwest- trending faults with zig- zag pattern of rift systems (Frewd and Mezzer, 1976) and

ii) Laterally persistent, northwest- southeast- trending faults that are numerically subordinate to the former.

Their investigation additionally reveals that transparent intrusive bodies are virtually restricted to the Cretaceous sediments and are geographically limited in shallow areas of the basin and that these bodies are assigned subparallel to the long axis of the basin and are associated carbonate build-ups.

Fold- Related Structures

Avbovbo *et al*. (1986) confirm from their seismic data that the folds consists simple, folded sediments with low fold frequency and amplitude, the amplitude of the fold increases basinward (toward the southwest) and the frequency decreases toward the shallow parts of the sub- basin (northwest). Stratigraphic units pinch out northwestward toward the basin edge, the southeastern part of the basin has been elevated by the effects of folding that it now rises above the basin edge. A significant part of the folded sediments now sub-crops beneath the Tertiary regional unconformity. The fold regime may be indicative of large regional event and persistent of compressive force which led to the folding. They consider the folds to be flexural that developed as a result of the basement- controlled graben along existing fault/fracture plates, and that the basement is not folded along with the sediments as earlier reported by (Wright, 1970), and also despite the reliability of plate consummation theory of (Burke, 1969) in explaining the origin of the folds.

Nur (2001) reported from his spectral analysis survey over SW Bornu Basin that most of the anomalies from the gravity pattern are trending NE- SW and NW- SE directions. He further explained that sixty percent (60%) of the inferred fractures have NE- SW direction, twenty five percent (25%) trend in the NW- SE direction, while about fifteen percent (15%) have an N- S orientation. Four deep sub-basins were identified by Nur (2001) which are; northeastern Jakusko sub- basin, the second sub-basin is located at Lantewa and extends

southwards for more than 50km. the third is located 40km northeast of Gubio and beyond, while the fourth sub- basin identified is located 35km southwest of Bama.

Nigerian National Petroleum Corporation, Research and Development (NNPC, R & D, 1997) carried out a gravimetric survey over the whole of Bornu Basin and their investigation revealed the existence of three major structural sub- basins thus; I) Maiduguri in the south, ii) Gubio in the west and iii) Lake Chad region in the north. Anakwuba *et al*. (2011) carried out a spectral gravity survey within the Bornu Basin and their investigations revealed two set of faulting and structural trends, which are NE- SW and E- W directions.

2.2 Structures and Stratigraphy of the Upper Benue Trough (Gongola Basin)

2.2.1 Preamble

The Upper Benue Trough comprises the area extending from Bashar- Mutum Biyu line in the south to as far as the "Dumbulwa Bage High" of Zaborski *et al*. (1997) in the north. The "Dumbulwa Bage High" is an anticlinal structure that separates the Gongola Basin from the Bornu Basin. An early study of the Upper Benue Trough and the southern Chad Basin was carried out by numerous researchers such as (Falconer, 1911; Jones, 1932; Raeburn and Jones, 1934; and Barber *et al*., 1954). Carter *et al*. (1963) undertook a regional study covered by Geological Survey of Nigeria 1:250,000 Series Map Sheets 25 (Potiskum), 36 (Gombe) and 47 (Lau), and provided the basis for all later works. The Upper Benue Trough has become known and has been re-mapped by several researchers (e.g. Aliix, 1983; Benkhelil, 1985, 1986, 1988; Popoff, 1988; Guiraud, 1989, 1991, 1993 and Zaborski *et al*., 1997) and documented its structural framework.

The Cretaceous succession in the Upper Benue Trough comprises of Early Cretaceous succession. Late Cretaceous thermo- tectonic sag condition prevailed, while sedimentation processes was strongly influenced by transgressive- regression phase. The Upper Cretaceous may be divisible into discrete pre- Santonian and Campano- Maastrichtian parts; the Latter was deposited during a renewed phase of rifting (Zaborski *et al*., 1997). The Upper Benue Trough includes an E-W trending Yola arm and an N- S trending Gongola Basin (Fig. 4.).

2.2.2 Structures

The Yola arm and the Gongola Basin are separated by an area structurally dominated by four major NE- SW trending sinistral strike- slip faults, the Gombe, Bima- Teli, Kaltungo and Burashika Faults; basement inliers, notably the Kaltungo inlier is associated with them (Zaborski *et al*., 1997). Additionally, Benkhelil (1988, 1989) regarded the median zone as a partially exposed basement high characterizing the axis of the Benue Trough. Carter *et al*. (1963) referred to the area as "Zambuk Ridge". Zaborki *et al*. (1997) stated that this term has frequently been applied to a line marked by a single fault which passes just south of Zambuk Village (Fig. 5.). Guiraud (1993) described the axial zone as "Wuyo Kaltungo Basement High", while Zaborski *et al*. (1997) adopted "Wuyo Kaltungo High" and further stated that the term "Yola" , "Wuyo Kaltungo High" and "Gongola Basin" corresponds to the "Benue Basin", Zambuk Ridge" and southern "Chad Basin" respectively of (Carter *et al*., 1963).

Zaborski *et al*. (1997) reported that a series of N- S to NNE- SSW trending faults controls the trend of the Gongola Basin, while deep- seated E-W trending fractures appear to characterize the Yola arm (Benkhelil, 1988; Maurin and Guiraud, 1989). The depocentre of

the basin occur in the western part of Gongola Basin in which Campano- Maastrichtian and Cenozoic sediments are deposited. More than 5km of sedimentary rocks occur in the "Dukkul", "Akko" and "Bashar" sub- basins, thinner sedimentation occur in the "Lau" and "Numan" sub- basins of the Yola arm (Benkhelil, 1988).

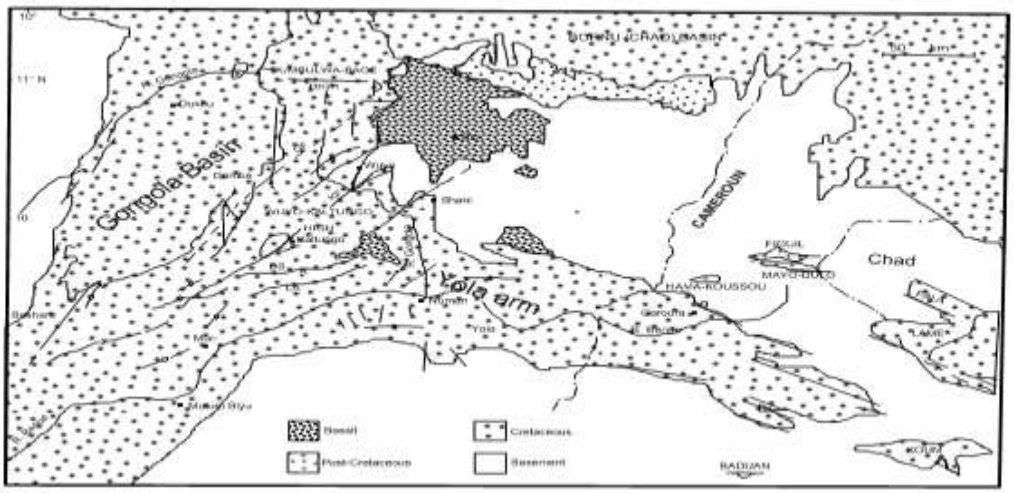


Fig. 4: Outline geological map showing the main features of the Upper Benue Trough region; GF, Gombe-Fault; B-TF, Bima-Teli Fault; KF, Kaltungo Fault; BF, Burashika Fault; DS, Dadiya Syncline; LA, Lamurde Anticline (After Zaborski, 1998).

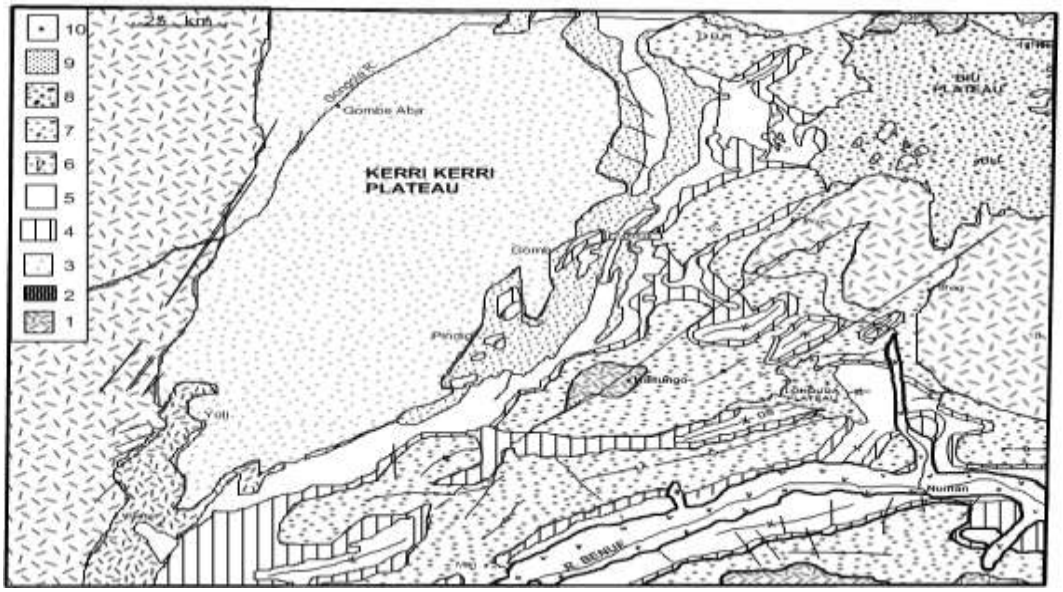


Fig.5. Geological map of the Upper Benue Trough region (based on Benkhelil, 1985; Guiraud, 1989; Zaborski *et al*., 1997). 1, Precambrian; 2, Late Jurassic? To Early Cretaceous volcanic; 3, Bima Group; 4, Yolde Formation; 5, Pindiga Formation and lateral equivalents in the Yola arm; 6, sandy members of the middle part of the Pindiga Formation in the Gongola Basin; 7, Gombe Sandstone; 8, Kerri-Kerri Formation; 9, Neogene to Quatenary basalt; 10, alluvium; D-BH, Dumbulwa-Bage High; BH, Bima Hills; DS, Dadiya Syncline; LA, Lamurde Anticline.

2.2.3 Stratigraphy

2.2.3.1 The Bima Group and Basin Evolution

Bima Group

The Bima Group reaches a thickness of several kilometres and in most places represents by far the greatest proportion of the lithostratigraphical succession present in the Upper Benue Trough (Zaborski *et al.,* 1997). The group is extensively exposed in the eastern and southern parts of the region, it has been studied in detail by some researchers, notably by Carter *et al*. (1963), Allix (1983), Popoff (1988), and Guiraud (1990a, 1990b, and 1991a). The term "Bima Sandstones" was first used by Falconer (1911) for beds occurring at the type locality, Bima Hill, and including the Yolde Formation of later authors. These parts of the "Upper Grits and Sandstones" described by Falconer (1911) from Waja, Ture and Wuyo also belong to the Bima Group and Yolde Formation, as do the "Upper Benue Sandstones" of Longbottom (in Falconer, 1911), all of which were erroneously regarded as post Turonian. The Bima Group includes the greater part of the "Gongola Sandstones" of Jones (1932) and the "Bima Sandstones Group" of Raeburn and Jones (1932) which they encompass the Yolde Formation, the "Guyuk Sandstones" and "Bima Grits" of Barber *et al*. (1954); and the "Bima Sandstone" of Carter *et al*. (1963). Ojo and Pinna (1982) proposed a more complex division of the Bima Group. Regionally, schemes were done by Allix (1983) and Guiraud (1990c, 1991a). Thicker outcrops of the Bima Group occur in the Lamurde Anticline and Wuyo- Kaltungo high and adjacent areas.

Allix (1983) and Allix and Popoff (1983) recognized three formations making up the Bima Group in the Lamurde Anticline, "Formations 1, 2, and 3 with a total thickness of 2265m. From the top, "Formation 3", 1200m thick, made up of three members, an upper member,

220m thick, comprising of alternating fine- grained quartz arenites with disturbed stratification and medium- grained, cross- bedded channel- filling sandstones, a middle member 20m thick, fine to medium- grained sandstones intercalated with silty clays and channel- filling, orange, coarse- grained, cross- bedded sands with pebble horizons; and a lower member, 740m thick, laterally extensive, cross- bedded coarse- grained sandstones also containing white to orange medium to fine- grained sandstones was regarded as almost entirely fluviatile in origin. Dinoflagellates obtained from subsequent Talasse east of Kaltungo revealed slight marine tendencies for its upper part suggesting deltaic deposition. Marine paleoenvironments; a Late Albian to Early Cenomanian age was assigned (Allix, 1983).

"Formation 2", 700m thick, made up of;

iii) An upper member, 125m thick, comprising arkosic sandstones, including cross-bedded channel- filling sediments, and micro- conglomerates.

Iii) A member comprising 65m argillaceous beds with intercalated sandstones, siltstones and limestones.

ii) A member, 260m of arkosic sandstones and granulestones with rare intercalation of fine- grained sandstones, and

i) a lower member, 250m thick arkoses and arkosic sandstones with lenses of cross- bedded, fine to coarse- grained sandstones with pebbles beds and very fine- grained sandstones and siltstones, and the bottom was regarded as medium to proximal fan- delta origin with member iii being perilacustrine ostrocods and polynoflora recovered from subsurface near Kaltungo suggesting an Early

Albian age for the base while K- Ar ages for the intercalated lavas at Bima Hill gave Middle Albian for its upper part.

"Formation 1", 365m made up of

ii) An upper member, 100m thick, comprising medium to fine- grained greenish sandstones intercalated with siltstones and shales.

ii) a middle member, 205m thick, rhythmically alternating gray shales and greenish siltstones; and

i) a lower member of which 60m of fine- grained sandstones, siltstones and violet to greenish shales.

Zaborski *et al*. (1997) reported that Formations "1, 2, and 3" corresponds to the "Lower Bima Sandstone", the "Middle Bima Sandstone" (in broad terms) and the "Upper Bima Sandstone" respectively of (Carter *et al*., 1963).

The Lower Bima Sandstone tt is believed to have been deposited in a distal fan- delta prograding into a lacustrine environment. Freshwater ostracods of Necomanian to Albian age were reported, while a polynoflora suggested a Late Aptian age (Zaborski *et al*., 1997; Allix *et al*., 1983).

Guiraud (1990a,b and 1991a) described the Bima Group in the Wuyo Kaltungo high and adjacent areas, subdividing it into:

iii) "Upper Bima Sandstone" (B3), a fairly homogeneous relatively mature unit comprising coarse to fine- grained sandstones characterized by tabular cross-bedding with laterally extensive sets a few tens of cm to a few m thick.

Convolute bedding and overturned cross- bedding are common. The average thickness is about 500m with a maximum in the Lamurde Anticline of 1200m, the deposits were regarded as distal braided river origin.

ii) "Middle Bima Sandstone" (B2), a widely- distributed, fairly uniform unit made up of fining upward cycles each 5- 10m thick. Trough and tabular cross-bedding characterizes the sandstones in the lower part of each cycle, thin clays and palaeosols occur above. The thickness varies from 100- 500m. These deposits were regarded as of proximal braided river origin. Guiraud (1991a) assign a Late Aptian age.

i) "Lower Bima Sandstone" (B1), a highly variable unit ranging in thickness from 0 to over 1500m. Lithofacies distributions are controlled by syn-sedimentary tectonics which created a number of fault- bounded sub- basins within which marginal alluvial fan/ distal debris flow deposits pass laterally into fining-upward fluvial cycles and, in places into lacustrine deposits comprising interbedded clays, fine- grained sandstones and calcareous beds. Dating from intercalated lavas suggests an age from Necomanian to Late Aptian or probably Late Albian (Guiraud, 1991a).

Regional unconformity was identified between ("B1'') and younger beds by (Guiraud, 1990a). Additionally, on a regional scale the subdivision of Bima Group proposed by Allix and Guiraud do not exactly correspond, possibly due to difference in the location of Bima Group cropping out.

Basin evolution during the deposition of the Bima Group has been examined by numerous authors such as (Allix, 1983; Allix and Popoff, 1983; Allix *et al*., 1984; Popoff, 1988; and Guiraud, 1990a, 1991a).The oldest sediments known from the Upper Benue Trough occur at the northeastern termination of the Wuyo- Kaltungo high, around Burashika, 15km southwest of Shani (Zaborski *et al*., 1997). Popoff (1988) reported about 30m of locally-developed lignitic clast and sandstones of inferred fluvio- lacustrine origin. Towards the top, these beds are associated with lava flows yielding K- Ar ages of 147+/-7 Ma. They were referred to a terminal Jurassic to earliest Cretaceous "pre- rift" stage when local depressions were thought to have developed in association with stretching along NE- SW trending faults.

Popoff (1988) believed a Necomanian to Barremian 'eo- rift" stage followed when "basal conglomerates and sandstones several hundreds of metres thick with very large boulders were deposited in small basins in large parts of the Upper Benue Trough. East- West trending faults were regarded as controlling the sedimentation in the Yola arm while brittle extension took place to the west controlled by NNE- SSW and NE- SW trending strike- slip faults. This stage was also accompanied by magamatism in the Burashika area with lava flows yielding ages close to the Jurassic- Cretaceous boundary.

During a Barremian to Middle Albian "syn rift 1" phase, the rate of subsidence due to crustal extension increased and larger elongate basins developed. They were believed to have been the sites of lakes which temporarily merged to create a system of "great interior lakes" perhaps occupying the entire Benue Trough. "Formation 1 and 2" of Allix (1983) was regarded as the lacustrine and marginal alluvial core facies respectively of this system.

Argillaceous facies similar to “Formation 1” reaching thicknesses nearly 3500m were postulated to exist in the subsurface in the Upper Benue Trough.

Transtensional faults trending NNE- SSW and ENE- WNW parallel to the margins of the Gongola Basin and Yola arm were thought to have been active this time. According to Maurin and Guiraud (1989, 1990), the E- W trending half- grabens controlled by syn-sedimentary faults striking approximately E-W associated with NW- SE trending sinistral strike- slip faults. They were described as having developed in a transtensional stress regime, the extensional component of which had an N 160^0 E orientation. Their origin as reported by Guiraud and Maurin (1991a, 1992) was related to a general N- S extension in Central Africa.

Allix (1983) and Allix and Popoff (1983) have also suggested that the deposition of Formation”1” and “2” in the Upper Benue Trough took place in E- W aligned basins. According to Popoff (1988) a “syn rift II” phase took place during the later part of the Albian in response to further crustal stretching. The NE- SW polarity of the Benue Trough was established at this time. A single regional basin was established in the Benue Trough in which “Formation 3” was deposited. Zaborski *et al*. (1997) stated that palaeocurrent directions indicate a large alluvial plain inclined gently north- westwards for the western Yola arm, and was similarly reported by many workers (e.g. Jones, 1961; Ayoola, 1991; Allix, 1983; Allix and Popoff, 1983; Guiraud, 1990, 1991a). North of the Bima- Teli Fault palaeocurrents flowed in a south- westerly direction ultimately discharging into the sea which by Late Middle Albian times had invaded the Central Benue Trough.

Guiraud and Maurin (1991a) interpreted the lacustrine sediments of "Formation 1" in the Lamurde Antiline as a local facies development of the "Lower Bima Sandstone". Elsewhere the unit is made up of widely variable conglomeratic and sandy facies of alluvial fan to braided river origin.

Guriraud (1993) recognized three stages of basin development during the deposition of the Bima Group.

The first rifting stage was marked by deposition of thin, conglomeritic "pre Bima" deposits around Guburunde, on the southern margin of Wuyo horst, and Burashika. Intercalated rhyolites and basalts yield K- Ar and $^{39}A_R/^{40}A_R$ of 147 Ma- 140 Ma (Guiraud, 1991a; Baudin, 1991; Maluski *et al*., 1995). The pre- Bima deposits may therefore be as old as Late Jurassic but their relationship with the "Lower Bima Sandstone" was not clear. They appear to correspond with the eon- rift sediments of Popoff (1988).

According to Guiraud, a second stage of rifting took place from Necomanian to as late as Early Albian within N 60^0 E extensional regime. The "Lower Bima Sandstone" was deposited in sub-basins of half- graben nature controlled by N 60^0 E trending transtensional faults (including the main faults of the Wuyo- Kaltungo high) and N 140^0 E trending normal faults (Fig. 3). In most of these sub- basin alluvial fan deposits adjacent to the active fault- bounded margins give way to braided river deposits towards the basin axes. In the largest of the basins lacustrine conditions developed, but such a situation is only known from the Lamurde area. Palaeocuurents were under local tectonic control and floored towards the axes of the individual basins. The termination of this stage is marked by a regional unconformity at the top of the "B1" beds.

"The Middle and Upper Bima Sandstones" were interpreted as representing a late rift to early sag stage controlled by sinistral transtensive to extensional regimes with further extension in an N 60^0 E direction. Palaeocurrent directions become more uniform. Synsedimentary tectonic activity continued into "B3 times, although on reduced scale; it has been held responsible for the convolute bedding which commonly occurs in this part of the Bima Group (Jones, 1961, 1962; Braide, 1992b; Guiraud and Plaid, 1993).

Deposition of the Bima Group was accomplished and immediately preceded by the main phase of Cretaceous volcanism in the Upper Benue Trough which occurred between 17 Ma and 106 Ma (Popoff *et al*., 1982; Baudin, 1991; Maluski *et al*., 1995). The oldest volcanic occur in the Burashika and Guburunde areas. Uranium mineralization took place approximately contemporaneously (148 +- 12 Ma) along NW- SE trending dextral shears in the Precambrian basement around Mika to the south of Yola arm (Maurin and Lancelot, 1990). The youngest of the volcanic occur in the Bima- Wade area.

There are two groups of basalts identified; the first comprises sometimes porphyritic varieties of alkaline which is transitional in nature. Flows and dykes occur within and directly upon the basement but mostly are lava flows intercalated with the Bima Group. They are associated with the main NE- SW trending sinistral strike- slip or transtensional faults characterizing the Wuyo- Kaltungo high (Guiraud, 1990b). In the Burashika area, the early volcanism (147 – 143 Ma) is bimodal, the basalts being associated with paralkaline rhyolites and the granophytic Kwaba dome which collectively make up the Burashika Group (Carter *et al*., 1963). According to Baudin (1991), the rhyolites originated by differentiation and contamination of alkaline transitional basalts as they rose slowly through the crust. The second group of basalts is of tholelitic transitional nature. They

occur as lava flows within the Bima Group but are restricted to smaller sub- basins being associated with WNW- ESE to NW- SE trending extensional faults (Baudin, 1991; Guiraud, 1990a). Maluski *et al*. (1995) reported that the magmatism in the Benue Trough can be related to the influence of the St Helena hotspots which progressively shifted south so that by Late Cretaceous times significant volcanic activity wasconfined to the southern Benue Trough.

2.2.3.2 Cenomanian to Lower Turonian Succession

The Upper Cretaceous series in the Upper Benue Trough is mainly of marine origin with argillaceous lithologies being dominant. There is a lithostratigraphical differentiation between the subdivisions in the Gongola Basin and that of the Yola arm (Zaborski *et al*., 1997). The "Upper Bima Sandstone" may be partly of Cenomanian age, the greater part of this is represented in both the Yola arm and the Gongola Basin by the Yolde Formation (Carter *et al*., 1963), "passage beds of Bomanda", 9km south of Muri (Falconer, 1911); "Transition beds of Barber *et al*. (1954); "Formation 4" of Allix (1983); its thickness varies, reaching a maximum of 200m and it wedges out in the western part of the Dumbulwa- Bage high where syn-sedimentary uplift also resulted in the attenuation of the "Middle" and "Upper Bima Sandstone" (Zaborski *et al.*, 1997).

The Yolde Formation has been described in some details in the Yola arm by Carter *et al*. (1963) and Allix (1983) and in the Gongola Basin by Zaborski *et al*. (1997). It consist largely of alternation of coarse to fine- grained, cross bedded or sometimes ripple bedded sandstones and gray to greenish shales. Thin limestones or calcareous sandstones occur, especially in its upper part where oysters beds are common. The formation fine upwards, channel- filling coarse- grained sandstones with trough cross- bedding occur in the lower

part, thinly bedded, medium to fine- grained often bioturbated sandstones appear at the top. The boundary with the "Upper Bima Sandstone" is transitional. Carter *et al*. (1963) defined it as the appearance of "marine shales", while Allix (1983) used the appearance of thick, laterally continues siltstones or silty shales or a base with a marker horizon comprising greenish fine- grained sands with disturbed cross- bedding found in parts of the Yola arm. The Yolde Formation represents fluvial and coastal plain palaeoenvironments in its lower parts and shallow marine conditions higher up. Dating of the formation has been carried out on the basis of pollens; Lawal (1982), Allix (1983) suggested an age between the limits in the Late Albian and Late Cenomanian. According to Zaborski *et al*. (1997), there was an error of dating by Carter *et al*. (1963) of Late Turonian *ammonite coilopceras* from for the Yolde Formation.

The Yolde Formation records the initial stage of the Late Cenomanian to Early Turonian transgression but the overlying beds of Pindiga Formation {lower part of the "Turonian limestones and shales of the Benue Valley" and lower part of the "Turonian limestones of Gongola Valley" of Falconer (1911); "Calcareous Group" of Jones (1932); lower part of the "Lower Shale Group" Raeburn and Jones (1934); "Limestones" and "Calcareous Beds" of Barber *et al*. (1954)} represent its peak. They consist mainly of shales, dark gray when fresh but weathers to blue- green to gray colours which measures from few ten of cm maybe superposed to produce units of upto 2m in the Ashaka area, while in the southern flank of the Dumbulwa- Bage high nearly 10m and disseminated gypsum commonly occurs in exposures. In the Yola arm it is "Formation 5" of Allix (1983) which is about 80m thick at its type locality in the eastern Dadiya Syncline (Zaborski, 1990b).In the Wuyo- Kaltungo high Carter *et al*. (1963) referred the unit to lower "limestone- shale member" of the

Pindiga Formation and in the Gongola Basin to the "limestone- shale member" of the Gongila Formation. Zaborski *et al*. (1997) regarded the Gongila Formation as a synonym of the Pindiga Formation and referred the shale- limestone beds to the Kanawa Member (of the Pindiga Formation) {= Kanawa Formation of Thompson (1958)}. The Kanawa Member range from 120m at Kumo as studied by (Lawal, 1982) to just a few m of condensed limestone- dominated beds at the Dumbulwa- Bage high (Zaborski *et al*., 1997).

The limestone beds of the Kanawa Member are frequently richly fossiliferous and have been extensively studied by researchers such as (e.g. Woods, 1911; Barber, 1957, 1958; Carter *et al*., 1963; Wozny and Kogbe, 1981; Obi, 1990b; Zaborski, 1990b 1996b; Neraudeau and Courville, 1997, Hamidu and Hamza, 2007). Dating is based on the ammonite faunas, these are continues units of the upper part of the Upper Cenomanian and most of all the Lower- Turonian (Zaborski *et al*., 1997).

2.2.3.3 Middle- Turonian Succession

The boundary has been variously placed but coincides approximately with the base of *Nigeriensis zone*. The shale- limestone interval is slightly diachronous and its base appears to be of approximately the same age throughout the Upper Benue Trough. The *Walsi Zone* being the top is only known from the Wuyo- Kaltungo high area and the Yola arm (Zaborski, 1998).

The Middle Turonian regressive conditions affected the Upper Benue Trough, in the Gongola Basin and the Wuyo- Kaltungo high, dominantly arenaceous deposits lie above the Kanawa Member. In the eastern Gongola Basin they make up the Gulani Member of the Pindiga Formation (Carter *et al*., 1963) {= "Upper grits and Sandstones of Gulani" (only)

of Falconer, 1911)}. These probably fluviatile sediments include very large- scale tabular cross- bedded, coarse- grained sandstones and granulestones, individual sets being several m thick (Zaborski *et al*., 1997). Thinner sandstones and mottled or dessicated- cracked clays also occur in the Dumbulwa- Bage high, their lateral equivalent is the Dumbulwa Member (of the Pindiga Formation) (Zaborski *et al*., 1997) {= "sandstone shale member of the Gongila Formation" of Carter *et al*., 1963). The beds referred to the Bima Group in the Dumbulwa and Bage hills by Carter *et al*. (1963) lies upon erosion surface, the Kanawa Member in places having been totally removed. The Dumbulwa Member is largely made up of fining- upwards fluvial cycles when complete each about 10m thick, localized development of persistent tabular cross- bedded sandstones also occur. To the south, the Dumbulwa Member passes laterally into the sandstones of the Deba Fulani Member of Pindiga Formation (Zaborski *et al*., 1997), a unit previously unrecognized on the Geological Survey of Nigeria maps.

The Deba Fulani Member represents a variety of fluvial, coastal plain and shallow sublithoral environments. Coarse- grained pebbly tabular cross- bedded sandstones and fining- upwards channel- filling sandstones occur as do more thinly bedded and sandstones with fish vertebrae, phosphate pebbles and burrows of *Ophiomorpha* (Zaborski *et al*., 1997) and the member wedges out to the south.

These three sandstone masses have not been directly dated but have probable age limits within the range of Early Turonian and Late Turonian. They overlie horizons in the Kanawa Member belonging to the *Nigeriensis Zone* in the north and the *Walsi Zone* in the south. North of the Dumbulwa- Bage high, Coniacian ammonites occur in beds overlying the Dumbulwa Member (Zaborski *et al*., 1997).

Zaborski (1998) reported that the nature of age- equivalent beds in the subsurface of the Gongola Basin is unknown and the Deba Fulani Member is not recognizable to the outcrops of the Pindiga Formation occurring in the Tukulma, Pindiga, Yelwa, Futuk inliers (Fig. 6).

In the Wuyo- Kaltungo high area and the Gongola Basin, the sandy members of the Pindiga Formation are overlain by the Fika Member (sensu Zaborski *et al*., 1997) {= upper part of the "Turonian limestones of the Gongola" of Falconer (1911); "Clay- shale Group" of Jones (1932); upper part of the "Limestones- Shale Group" of Raeburn and Jones (1934); "Shale Member" of the Pindiga Formation and Fika Shales of Carter *et al*. (1963); Jones (1932) used the term "Fika Group" mainly for poorly exposed "Sandstones, muddy sandstones and shabby ironstones" in the southern Bornu Basin which appear to be at least in large part, the lower portion of the Gombe Sandstone of later authors (Zaborski, 1998). Zaborski (1998) went further to say that the Fika Member may represent two distinct depositional phases separated by the Santonian compressional event. Its pre- Campanian part primarily comprises shales indistinguishable from those of the Kanawa Member. From a borehole at Kumo, north- west of Kaltungo, Lawal (1982) and Lawal and Moullade (1986) described over 150m of shales with marine microfossils which they dated Coniacian to Santonian on the basis of pollen. Zaborski *et al*. (1997) reported the Coniacian ammonites *Baroisiceras* and *Forresteria* from limestones in the lower Fika Member on the northern flank of the Dumbulwa- Bage high. Barber (1958) assign a Coniacian age to a thin limestone in the Fika Member of the Pindiga Formation on the basis of bivalves *Astatse nigeriensis Schneegans and Plicatula auressensis Copuand*.

2.2.3.4 Late Turonian to Coniacian Transgression

During the Late Cenomanian a "Trans- Saharan Seaway" reported by Kogbe (1980) and Reyment (1980) was established creating marine connection between the Tethyan region and the Gulf of Guinea which passed through the Benue Trough. According to Zaborski *et al.* (1997); Meister *et al.* (1992, 1994) identified ten ammonite- based biostratigrahical horizons of Late Cenomanian to Early Turonian age in the Iullemeden Basin and western Chad Basin. The oldest horizon contains *Neolobites, Metengonoceras and Thomelites?* ; No ammonite- bearing beds of equivalent age occur in the Gongola Basin. The fourth horizon contains *Nigericeras gadeni; Metengonoceras dumbly Cragin and Metoicoceras geslimanum (d'Orbigny)* which all occur in the basal part of the Kanawa Member, the Gadeni Zone. The nominal species of the succeeding horizon of *Paravascoceras Cauvani* is also found in the Upper Benue Trough while the uppermost horizons in Chad and Niger contain *Pseudotissotia nigeriensis*. There are differences between the ammonite faunas occurring immediately around the Cenomanian- Turonian boundary levels in the two regions (Mesiter *et al*., 1994; Zaborski, 1996, 1998) and may be due to palaeoenvironmnetal factors (Zaborski, 1998). Coniacian marine ostracods and molluscs, with ammonite *Pseudotissotia* occur in the western Chad Basin (Faure, 1966; Bellion, 1989).

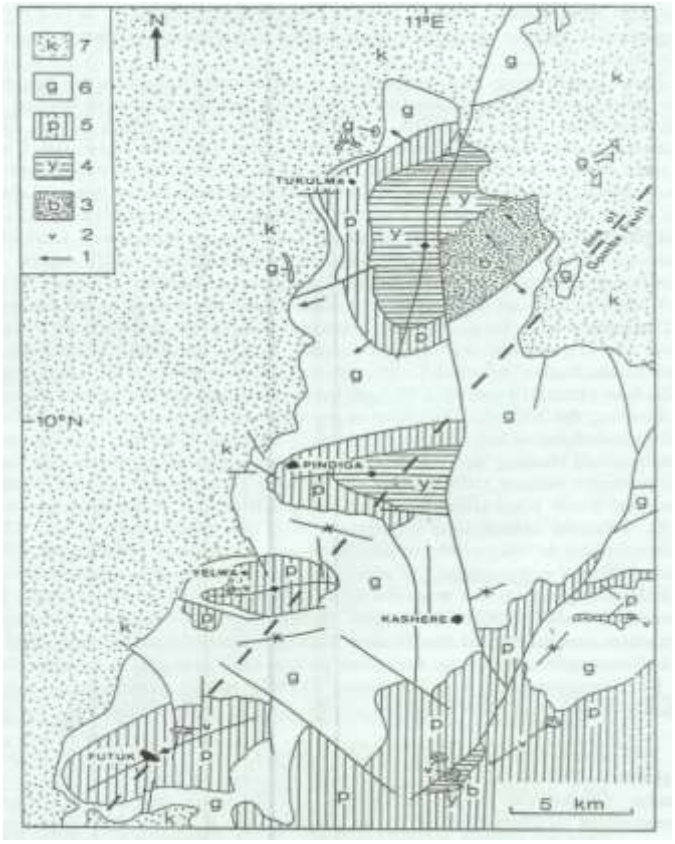


Fig. 6. Geological map of the Tukulma, Pindiga, Yelwa and Futuk inliers. 1, tectonic dip direction; 2, Neogene volcanic; 3, Bima Group; 4, Yolde Formation; 5, Pindiga Formation; 6, Gombe Sandstone; 7, Kerri-Kerri Formation; (Zaborski *et al*., 1997)

Zaborski (1998) reported that there is therefore, good agreement between the Benue Trough, Chad and Iullemeden Basins as regards the timing of the Cenomanian to Coniacian transgressive and regressive episodes. Reyment (1980, 1983) and Reyment and Reyment (1980) have further matched the transgressions with those episodes which occurred at the western U.S.A.

The first exchange of ammonites between Niger and Nigeria took place during the Late Cenomanian (Gadeni Zone). The upper partof the Yolde Formation probably represents the distal part of the earlier "*Neolobites- Thomelites*? Seal" to the north (Zaborski, 1998). Faure (1966) has shown that the Cenomanian Sea advanced slowly from the north over subdued topography in the western Chad Basin. During the Late Cenomanian the sea was

encroaching from the Gulf of Guinea into the Middle Benue Trough, including *Euomhacoceras septenseriatun*. The sea? probably merged during Gadeni Zone {- NW European *Gelinianumm Zone*, western interior of U.S.A Grainh Zone (Zaborski, 1990b)} to complete the trans- Saharan seaway which persisted until Early Turonian. According to Zaborski (1998) there was a faunal exchange restriction, the evidence for consummation is very strong, *Neolobites*, *Nigericeras* and *Pseudotissotia*, along with other Niger and Nigerian ammonites, which occur in southern Algeria (Amard *et al*, 1983 and Amedro *et al*., 1996), whilein the Gongola Basin "vascoceratid" species occur.

The Late Cenomanian to Early Turonian Trans- Saharan Seaway passed to the east of Hoggar through the western Chad Basin and east Niger rifts (Reyment, 1980a; Kogbe, 1980; Pascal *et al*., 1993), (Fig. 7) shows the crustal section along line A-B

From the west to the east, Late Cenomanian to Early Turonian marine formations in the Iullemmeden and Chad Basins gradually increase in thickness from 10m to about 70m (Pascal *et al*., 1983; Mathey *et al*., 1995). Zaborski (1998) stated that there is a lithostratigraphic correlation between the Dukkul Formation of Yola arm and the Kanawa Member in the Gongola Basin, comprising dark gray shales with thin intercalated limestones and that the fauna is largely confined to the limestones but is of low- diversity aspect. The shale horizons represent anoxic and dysoxic bottom waters, while the limestones reresent temporarily oxic condition. Pascal *et al*. (1993) and Mathey *et al*. (1995) related the limestones to peak transgressive pulses during which better circulation pattern were thought to have resulted to oxic bottom water condition.

The Cenomanian to Coniacian foramineferal faunas in the Gongola Basin are dominated by brackish- water arenaceous forms; planktonics (*hedbergellids* and non- keeled *heterohelids*) are rare and mainly occur in the limestones (Petters, 1978a,b; Allix, 1983; Gebhardt, 1997). Gebhardt (1997) suggested a maximum water depth of about 50m for the Kanawa Member and the lateral continuity of individual limestones in this unit cannot be proved. The thick limestone development at Ashaka and over Dumbulwa- Bage high occurs in Late Cenomanian to Early Turonian shoal area (Zaborski *et al*., 1997).

During the Middle Turonian regression the Trans- Saharan Seaway may have been severe in the Gongola Basin- southern Chad Basin region. The link between the Upper Benue Trough and the Chad Basin was re- established during the Late Turonian transgression when faunas took on a cosmopolitan aspect (Zaborski, 1998). Reyment (1980a,b) showed that the Gulf of Guinea "Mungo River association" of molluscs and ostracods extended throughout the Benue Trough and western Chad Basin. Reyment (1980a) concluded that the Coniacian sea occupied the Benue Trough, reached the Bilma area to the north and possibly extended through the Iullemeden Basin as far west as the Gao Trough. A connection with the Tethyan area to the north could not be demonstrated but Reyment (1983) noted similarities between the ostracod faunas of northeastern Nigeria, Niger, and North African countries suggesting at least a brief link.

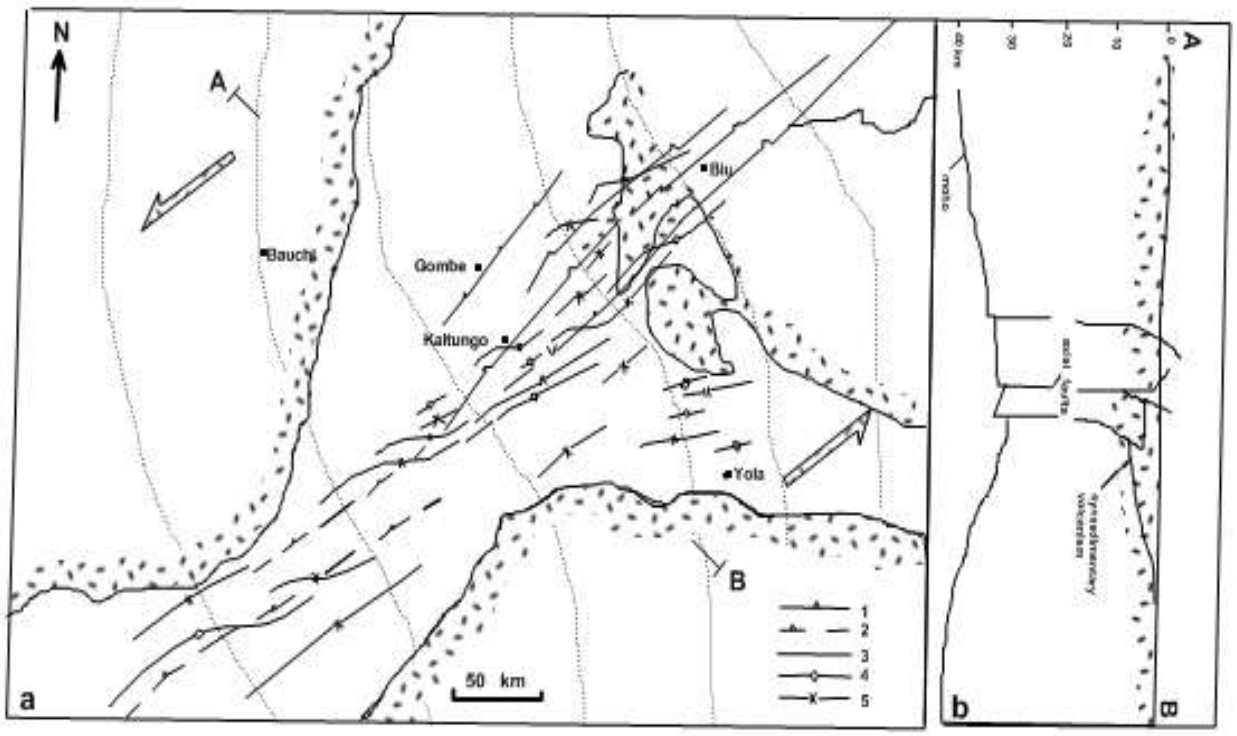


Fig. 7. Strcutural features in the Upper Benue Trough associated with Santonian transpressional activity along the faults of the Wuyo-Kaltungo high where deviation of the horizontal stress occurred and originally linear *enechelon* folds developed sigmoidal axial traces. 1, sinistral reverse basement and cover fault; 2, sinistral reverse basement fault; 3, maximum horizontal stress trajectory; 4, anticlinal axis; 5, synclinal axis. b, Crustal section along line A-B as indicated. (After Guiraud, 1991a).

2.2.3.5 The Santonian Compressional Event

Carter *et al*. (1963) believed that the Pindiga Formation contained a continuous Turonian to Maastrichtian succession. Since the Gombe Sandstone is folded more gently than older rocks, however, they suggested that the main deformation occurred prior to its deposition, this view was held by Whiteman (1982). Allix (1983) noted the thinnest of that part of the Pindiga Formation dated Late Turonian to Early Campanian by Lawal (1982) and suspected that a hiatus might exist within this interval. Guiraud (1993) believed that the main deformation in the Upper Benue Trough occurred during the Santonian. Cratcley and

Jones (1965), Benkhelil (1982, 1988) and Benkhelil *et al*. (1988), on the other hand regarded the folding in the Upper Benue Trough as terminal Maastrichtian. Zaborski (1998) reported that any unconformity at the base of post- Santonian beds would occur within the Fika Member, due to its poorly exposed nature makes clarification of this issue difficult. Zaborski *et al*. (1997) presented some evidence for the Santonian- Campanian folding including the presence of an angular unconformity at the base of Gombe Sandstone in Bashar area. Benkhelil (1982) noted that the compressional deformation in the Upper Benue Trough was concentrated in its axial part where transpressional movements occurred along the main NE- SW trending faults.

Zaborski (1998) suggested that weak folding shown by the Gombe Sandstone was attributed to the Santonian deformational episode on its marginal outcrop location. He further stated that the Santonian sediments occur only along the northwestern margin of the Wuyo- Kaltungo high where clear evidence can be found in the Tukulma inlier. In its southeastern part, the Gombe Sandstone rests directly upon the Bima Group, the contact being a marked angular unconformity (Figures 4, 5). Zaborski (1998) went further to state that a phase of uplift occurred along the line of the Gombe Fault prior to the deposition of the Gombe Sandstone, and that the latter is involved in the later folding, which produced a broad NNE- SSW trending anticlinal structure, and in the Pindiga, Yelwa and Futuk inliers to the south which are arranged in echelon in the sedimentary cover above the Gombe Fault. These relationships demonstrate a terminal Maastrichtian phase of deformation along the fault, and an earlier episode, probably of Santonian age.

Guiraud (1990a) believed that Early Cretaceous sub- basins in the Upper Benue Trough were inverted during the Santonian tectonic event. The main faults of the Wuyo- Kaltungo high were re- activated as reverse or transpressional features over which there were marked deflections of a regional N- S to N 20^0E trending horizontal stress field. Folds arranged *en echelon*, sigmoidal fold axes and positive flower structures were produced along these faults. A similar but less intense style of deformation occurs in association with the N-S trending faults in the Gongola Basin (Zaborski *et al*., 1997); it may also date from Santonian. The major ENE- WSW trending folds of Yola arm, including Lamurde Anticline and Dadiya Syncline, have generally been attributed to terminal Maastrichtian compression but they may be Santonian, more tentatively by Allix (1983). Chanley *et al.* (1978) and Enu (1986) reported that the onset of tectonic activity was reflected in the clay mineralogy of the Upper Cretaceous formations in the Yola arm, a general preponderance of smectite and mixed- layer clays occurs, suggesting poorly drained source area with low topographic gradients. Illite and chlorite appear in the Lamja Sandstone which these authors attributed to uplift of the source areas and active erosion.

Zaborski (1998) states that, although little is known of the subsurface stratigraphy of the Gongola Basin, it is possible that the Upper Cretaceous succession in the Upper Benue Trough is divisible into discrete parts separated by a Santonian- Campanian unconformity, as in the Lower Benue Trough.

2.2.3.6 The Campano- Maastrichtian Succession

Post- Santonian deposition was displaced into the western part of the Gongola Basin. At least 1km of Campano- Maastrichtian age to early Cenozoic sediments is present; the former comprise the upper part of Fika Member and Gombe Sandstone.North and south of

Gombe, major N- S and NW- SE trending faults affect the Gombe Sandstone, the latter features being associated with syn-sedimentary deformation (Zaborski *et al*., 1997) and that slumped horizons and convolute bedding occur in the formation. Renewed rifting appears to have occurred during the Campano- Maastrichtian which is comparable to the Anambra Basin. Genik (1993) described a partly contemporaneous "rift phase III" which took place from 74 Ma to 30Ma in the east Niger rifts.

Allix (1983) described the upper 460m of beds belonging to the Fika Member which were penetrated by a borehole a few kilometres west of Gombe to comprise black shales, silty and sandy shales, siltsones and fine- grained sandstones with carbonaceous beds at various depths. Rare calcareous shales were encountered in the upper part where silty and sandy horizons are most common. On the basis of pollens, a Campanian age was assign to the lower 50m of the strata and a Late Campanian to Early Maastrichtian age to the other beds. Lawal (1982) also dated the upper part of the Fika Member as Late Campanian to Maastrichtian using pollens.

Bioturbated oolitic ironstones a few tens of cm thick occur towards the top of the Fika Member at Pindiga and Gombe while carbonaceous shales are frequent close to the boundary with the Gombe Sandstone (Zaborski *et al*., 1997).

The ammonite *Libycoceras* has been described from both shales near Gombe (Reyment, 1955, 1980) which almost certainly belongs to the upper part of the Fika Member. This occurrence confirms a Late Campanian age, at least in part, for this unit (Zaborski, 1983), and it also has a palaeogeographical implication as regards the Late Campanian transgression. It is possible that the upper part of Fika Member contains beds deposited

during the same transgressive event as the lower Nkporo Shales in the Lower Benue Trough. Brackish water condition, indicated by arenaceous foraminiferal faunas was seen to have extensively developed in the Upper Benue Trough at the same time.

Except in Bashar; the Fika Member passes continuously upwards into the Gombe Sandstone (Sensu Barber *et al*., 1954) = parts of the "Fika Group" and "Kerri- Kerri Group" of Jones (1932), "Upper Sandstone Group" and parts of the "Kerri- Kerri Group" of Raeburn and Jones (1934). The first detailed description of the formation was provided by Carter *et al*. (1963) who designated a type section in Kware Stream on the southern outskirts of Gombe town. It was previously described by Falconer (1911) as "Gombe grits and clays" which has a "characteristic section" occuring at Gombe Abba (Fig. 5) and exposes beds now referred to the Kerri- Kerri Formation**.** Falconer however, referred that portion of the Gombe Sandstone cropping out from Gombe northwards to the Gongola River and parts of the Chad Formation in the southern Bornu Basin to the "Gombe Grits and Clays". The "Kerri- Kerri grits and limestones" of Falconer (1911) included the beds directly underlying the Kerri- Kerri Plateau (sensu strict) in the north- central part of the outcrop of the Kerri- Kerri Formation. The "Duguri sandstone and grits" of Falconer (1911) includes parts of the Gombe Sandstone and Kerri- Kerri Formation.

Carter *et al*. (1963) and Zaborski *et al*. (1997) both reported that in outcrop, the Gombe Sandstone reaches about 300m in thickness, but the units exists in the subsurface beneath most of the area occupied by the Kerri- Kerri Formation. To the southwest, around Bashar and Yuli (Duguri), it overlies the Precambrian basement directly. In the Gongola Basin, the basal Gombe Sandstone consists of white to gray, coarse- grained pebbly sandstones with

distinct cross- bedding but its greater part is made up of tabular cross- bedded gray or brick- red sandstones (Zaborski, 1998).

In most of the Gongola Basin, three main superposed lithofacies were recognized within the formation (Zaborski *et al*., 1997). Its basal part, transitional from the Fika Member, consisting of rapidly alternating shales, often plant- rich, fine- grained sandstones, frequently with *Thalassinoides* burrows, and flaggy ironstones. This facies passes up into one dominated by laminated, fine to medium- grained, white, gray or brown sandstones with interbedded dark gray mudstones or shales, siltsones and flaggy or vesicular ironstones. Bioturbations occurs occassionally as do plant remains, channel- filling sandstones, rarely exceeding 2m in thickness, are common especially around the latitude of Gombe town (Zaborski, 1998). These sandstones may be laminated or cross- bedded and occassionally show convolute bedding. Allix (1983) reported that the genesis of ironstones involved the following;

i) Silicification of fine to medium- grained clay- rich sandstones;
ii) Corrosion of quartz grains and the development upon them of kaolinitic and geothitic envelops; and
iii) The development of massive ferruginous crusts consisting largely of goethite with remnant corroded quartz grains.

Tabular cross- bedding is common, set thickness increasing upwards to reach about 1m. Trough cross- bedding occurs occassionally/infrequently. Very coarse- grained, tabular cross- bedded channel- filling sandstones with pervasive siliceous or ferrigenuous cements are sporadically distributed. The base of the facies at Pindiga is erosional (Zaborski, 1998).

Coals and carbonaceous shales occur within the Gombe Sandstone (Carter *et al*., 1963; Allix, 1983; Dike, 1995).

The general coarsening- upward nature of the Gombe Sandstone, its lateral facies distributions, the presence of coals and the disappearance of marine microfossils in the uppermost Fika Member point to a deltaic origin (Allix, 1983; Zaborski *et al*., 1997) with progradation from southwest (and west?) into a sea receding to the north. The coarse-grained cross- bedded sandstones around Bashar represent a proximal facies. The upper Fika Member may represent the pro-deltaic facies of the system. The post- Santonian part of Fika Member and the Gombe Sandstone may represent a cycle of sedimentation comparable to Late Campanian to Maastrichtian cycle in the Anambra Basin.

On the basis of pollens, Allix (1983) suggested a Maastrichtian age for the Gombe Sandstone; Lawal (1982) and Lawal Moullade (1986) proposed a Late Maastrichtian age.

2.2.3.7 The Terminal Cretaceous Compression

There is no doubt that a compressional episode affected the Upper Benue Trough during terminal Cretaceous (to earliest Cenozoic?) times. A marked angular unconformity separates the Gombe Sandstone from the overlying Kerri- Kerri Formation; the former was uplifted, folded, faulted and deeply dissected prior to deposition of the latter. Numerous inliers of Gombe Sandstone, most representing fault- related hills in the resultant topography, occur towards the eastern margin of the Kerri- Kerri Formation outcrop. A Palaeosols with root casts occurs upon the upper surface of the Gombe Sandstone on the northern Gombe town (Zaborski, 1998).

Benkhelil (1986, 1989) regarded the folding in the Upper Benue Trough as uniquely Maastrichtian; resulting from compression in a N 155^0E direction {(N 160^0E, according to Allix, 1983)} with deviations close to the main faults of the Wuyo- Kaltungo High. Of these, only the Gombe Fault affects the outcrop of the Gombe Sandstone. Sinistral strike-slip movement occurred along this feature during the last Cretaceous compression. The Gombe Sandstone is involved in the *en echelon* folding of the Pindiga- Yelwa- Tukulma inliers which the axes of broad folds in the Gombe Sandstone show deflection in trend south of Gombe (Zaborski *et al*., 1997), and also the major N- S faults of the Gongola Basin also show sinistral strike- slip displacements affecting the Gombe Sandstone.

The Gombe Sandstone folding geometry is similar to that formed during the early stages of the progressive deformation that characterized the Santonian event according to Guiraud (1990a, 1991a, 1991b). The latter resulted from the interplay of approximately N- S regional compression and sinistral faulting which is similar to the stress field that existed during the Cretaceous terminal event. The greater intensity of deformation shown by the pre- Santonian sediments may be due to their location on the Wuyo- Kaltungo high and their involvement in two tectonic events (Zaborski, 1998)

2.2.3.8 The Post- Cretaceous Rocks (Kerri-Kerri Formation)

There is no evidence that the main NE- SW faults of Wuyo- Kaltungo high were active during Cenozoic. The Kerri- Kerri Formation (Fig. 5) developed as a result of E-W extension (Benkhelil, 1988); NNE- SSW trending faults occur along its western margin and N- S trending faults to the east (Adegoke *et al*., 1986; Zaborski *et al*., 1997).

Two main phases of magmatic activity occurred during the Cenozoic (Grant *et al*., 1972). The first is represented by trachytes and phonolites emplaced between 22 and 11 Ma. The second was more widespread and is represented by basalts ranging from 7 Ma to very recent times. This phase included the extrusion of the Biu, Longuda and Song (Libart) basalts which occur at the northern termination of Cenozoic to Recent Cameroon volcanic line (Fitton, 1987; Deruelle *et al.*, 1991). The Biu Basalts range in age from 5 Ma to less than 0.8 Ma (Grant *et al*., 1972). Pliocene and Quarternary eruptive and associated volcaniclastic depositional phases were separated by an interval of weathering and erosion (Turner, 1978; Braide, 1994). From aeromagnetic data, Benkhelil (1986, 1988) identified a concentration of volcanic rocks with a NE- SW alignment north of Bashar. Although mostly concealed, they include basalts dated 41 Ma and 30 Ma which lie upon the Kerri-Kerri Formation.

Adegoke *et al*. (1986) reported that the Kerri- Kerri Formation is composed of flat- lying to gentle dipping basalconglomerate, grit, sandstone, siltsone and clay which unconformably overlies the Maastrichtian Fika Shale and Gombe Sandstone. They describe five stratigraphic sections in their research work (including the type section at Kadi) and six boreholes. Adegoke *et al*. (1986) further stated that the formation attains a thickness of 200m at Duku, they said the rare basal conglomerates, well- bedded siltsones and the presence of shrinkage cracks, clay- supported grits, local channel sandstones and thin horizons of coal and carboneous clay suggest a tpical fluvial, deltaic and marginal Lacustrine environment of deposition. The presence of the pollens S*pinizonocolpites baculatus* and *Monocolpites marginatus* among others confirms a Paleocene age for the formation

2.3 Facies Analysis

2.3.1 Contextural Background

The concept of facies has long been used in correlation and predicting particular rock units. The term “facies” was first introduced by Gressley (1838) and is much debated and described by Teichert (1958), Krumbein and Sloss (1963), Middleton (1973), Reading (1978) and Miall (1984).

A facies is defined on the basis of colour, bedding, composition, texture, structure and fossil content. In biofacies, prime consideration is given to biological contents. In the absence of fossils, emphasis is given to the physical and chemical characteristics of the rocks and the term lithofacies is appropriate (Reading, 1978). Initially the term lithofacies was used in a wide sense, but at present it is considered that each lithofacies represents an individual depositional unit (Miall, 1984). Lithofacies association are assemblages characterizing by particular depositional environments.

Facies analysis is considered in two different levels, essentially following the same approach for turbidite facies developed by Mutti (1992) and later modified by Poyatos-Moré (2014).

The first level considered is mainly descriptive and subdivides sedimentary successions on the basis of readily observable attributes forming single beds and other group of beds. The attributes describe packages of relatively similar beds distinctive units that can be individualized attending differences of lithological properties within a sedimentary succession

The second level goes further and considered a process- oriented approach. In this second level, facies are considered as genetically related units, and it tries to show how a facies form and grades into each other (laterally and vertically). Facies within the second level form genetic facies associations and the section is therefore clearly oriented to interpret their depositional environments and also establish the basic building blocks of stratigraphic framework.

2.3.1.1 Walther's Law of Facies

Walther's Law simply states that both vertical and lateral facies match. A depositional system may contain several environments. Deltas contain channels, mouth bars and prodelta muds and consequently the sedimentary rock types (i.e. facies) in a depositional system may be variables recording to the specific characteristics of their component depositional conditions (e.g. sandy channels and mouth bars, muddy prodeltas). However, these environments can shift laterally causing sediment to stack vertically. As a depositional environment shifts, so also most of the sedimentary facies in any one location change. As time progresses,, the positons of facies also progresses laterally in space and time, hence the laterally- related environments become superimposed forming vertical successions. This process results in deposition of time- transgressive sedimentary formations in which the vertical stacking facies records the originally laterally continuous environments (Middleton, 1973; Reading, 1996).

Sedimentarry environments that were once lying down side- by- side (facies tracts) will eventually end up overlapping one another overt ime, forming vertical facies successions reflecting successive changes in the environments such as marine transgressions and regressions.

2.3.1.2 Facies Associations

A group of sedimentary facies used to define a particular sedimentary environment. Facies association (lateral and Vertical) allow the study of sedimentary facies in space and time, and their relationship with long- term cycles, such as relative sea- level changes and tectonic phases and subsequent accumulation in sedimentary basins (Friedman *et al.*, 1993). The combination of both lateral facies tracts and vertical facies successions can be used to map broader three- dimensional depositional systems that migrate through time and space as a function of cyclic forcing, such as eustasy.

Sobiur (2002) revised the stratigraphy and carried out a facies analysis of Palaeocene-Eocene supra allochthonous sediments in SW Turkey and his research showed that the sedimentary facies in the area is represented by eight facies which were organized into four facies deositional environments: shelf, slope, inner fan and outer fan.

Tamrakar *et al*. (2009) investigated facies associations and depositional environments of fan- delta sequence in SW Kathmandu Basin in Nepal and their studies showed that eight sedimentary facies were recognized in their study araea. They added that facies associations do not contain a sandy facies and concluded that the distribution of the facies associations suggests extensive lake transgression followed by rapid lake regression.

Poyatos- Moŕe (2014) carried out a detail physical stratigraphy and facies analysis of the Castissent Tectono- sedimentary unit of Spain, he classify the facies into four groups on the basis of their grain-size as earlier described by Miall (1996). These are 1) Gravel facies, 2) Sandstone facies, 3) Mudstone facies and 4) Carbonate facies. He first considered packages of relatively similar beds distinctive units that can be individualize on the basis of their

lithological properties with a sedimentary succession. Secondly, he considered facies as genetically related units (both laterally and vertically).

Al Amji (2017) studied the sedimentology, stratigraphy and reservoir quality of Wajid sandstone in SW Saudi Arabia and developed 9 facies associations in his study araea on the basis of unconformities and sedimentary hiatus in the starved successions. He concluded that the Palaeozoic sediments are located in the epicratonal setting.

Puy- Alquiza *et al*. (2017) carried out a detail facies analsis, stratigraphic architecture of Sierra de Guanajuato Basin, Meico to determine the fluvial stratigraphic architecture of the Cenozoic facies and their investigation reveals five architectural elements and facies associations (facies of other researchers) from nine locations.

Shettima *et al*. (2018) carried out facies analysis of Dumbulwa Member of the Pindiga Formation and their research indicated 7 lithofacies, the lithofacies forms 3 facies associations: that consist of delta front sand facies association, pro-delta facies association and estuarine channel facies association. They concluded that the stratigraphic disposition of these facies assocaitons indicated an evolution of lithostratigraphic architecture of the Dumbulwa Member commenced with the development of progradational deltaic packages which was superimposed by transgressive deposition of fluvio- tidal channel sequence.

2.4 Petroleum Geochemistry

2.4.1 Historic Background

Petroleum is a naturally occurring complex mixture of organic compounds essentially of carbon and hydrogen and is found in gaseous, liquid or solid states (Peters *et al*., 2005; Tissot and Welte, 1984). Petroleum is defined here to include crude oil, condensate, natural

gas, rock extract and related bitumen. Petroleum from (seeps) has been known since ancient times and utilized for many purposes including construction, as medicine, for water proofing and adhesive (Connan, 1999). However, exploitation for commercial quantities in relation to fuel for combustion engines began in the 1900 century (Hunt, 1996), as an alternative to another organic substance, coal which was important to the industrial revolution. The use of oil is related both to its high energy content and ease transportation, and also to all its distillation products.

The International Energy Agency (IEA, 2016) predicts an increase in consumption of fossil fuel over the next 20 years, owing in part to a global energy demand which is projected to show a 30% rise in 2040. Finding commercial quantity of petroleum requires the integration of principles from several geoscience disciplines. One such discipline is petroleum geochemistry, which is defined as "*the application of chemical principles to the study of the origin, migration, accumulation and alteration of petroleum and the use of this knowledge in the exploration and recovery of petroleum*" (Hunt, 1979).

Petroleum geochemistry can be traced back to the 19th Century when the significance of petroleum as natural resources was recognized (Hunt *et al*., 2002). They further stated that in the second half of the 19th Century, distillation of petroleum to obtain kerosene was already adopted and the importance of organic matter as a likely source of petroleum was recognized. However, petroleum geochemistry developed in the first part of the 20th Century when organic chemistry became a useful tool in determining the composition of petroleum and was applied to petroleum geology (Hunt *et al*., 2002) and the role of petroleum geochemistry in petroleum exploration became increasingly important only in the 1980s.

In the infancy, the application of petroleum geochemistry was limited to investigating the origin and deposition and to measuring and mapping organic matter of source rocks (Hunt, 1961; Hunt and Jamieson, 1956; Ronov, 1958; Treibs, 1934). The early techniques of petroleum geochemistry include the discovery of porphyrin (Treibs, 1934), the use of carbon isotopes to organic matter in sediments and petroleum (Silverman and Epstein, 1958) and the identification of petroleum compounds (Rossini, 1960). The identification of porphyrins hinted the link between molecules in living organisms and in petroleum. Ronov (1958) noted the relationship between organic rich rocks and the occurrences of oil fields. Correlation of commercial oils with source rock had already been conducted in 1954 when techniques such as fractionation, column chromatography, infrared and elemental analysis (Hunt and Jamieson, 1956; Hunt *et al*., 1954). Carbon isotopic composition was further applied to differentiate between marine and terrestrial derived organic matter as well as correlation studies (Galinov, 1980;Sofer, 1984). Surface prospecting mainly involving the use of oil seeps were among these early recognized applications of petroleum geochemistry (Hunt *et al*., 2002).

Advances in analytical tools such as the use of chromatographics in the early 1960s provided new and more detailed data on organic matter compounds in sediments and petroleum that would form basis for new ideas like biomarkers (Eglinton and Calvin, 1967; Hunt *et al*., 2002; Tissot and Welte, 1978). Coupling of gas chromatography with a mass spectrometry or of gas chromatography with an isotope ration mass spectrometry further enhanced the characterization of organic matter in the 1970s and 1980s (Hunt *et al*., 2002). Rock-Eval pyrolysis instrument was introduced by Espitalie *et al.* (1977) and is now routinely applied in source rock characterization.

The late 1970s saw the emergence of hydrous pyroysis which stimulates the kerogen in the source rock (Lewan *et al*., 1979) and provided data on the behavior of the petroleum products generated from kerogen with increasing temperatures. Prior to the advent of hydrous pyrolysis, several works had already been carried out concerning oil-generation and depth of generation (Lopatin, 1971; Phillipi, 1965; Waples, 1980). However, improved understanding about the generation, expulsion, migration of petroleum and cracking of oil was achieved in the 1980s through the development of models, which are related to improved computer capabilities (Welte and Yuklet, 1981). Basin modeling has since become an integral part of petroleum exploration (Abay, 2017).

Following the early identifications of petroleum compounds, a large number of novel biomarker and aromatic hydrocarbon ratios that are today widely applied in petroleum geochemistry were proposed in the 1970s and the 1980s (Mackenie, 1984; Seifert and Moldowan, 1986). The progressive developments of analytical techniques have broadened the applicability of petroleum geochemistry.

2.4.2 Application of Petroleum Geochemistry

The application of petroleum geochemistry, as a science, to reservoir fluids is relatively been applied, present day; petroleum geochemistry along with other related disciplines is extensively used during exploration, development and production phases of petroleum exploitation activities (Abay, 2017). Geochemical data are needed in the exploration phase to identify a pod of active source and prospects in the production phase, to optimize production and enhance recovery.

2.4.3 Organic Productivity and Preservation in Continental Environment

2.4.3.1 Formation of Kerogen

Organic matter in swamps,, mainly as terrestrial plants, can be preserved. Otherwise, very high rate of oxidation and complete decomposition cause the rate of decay of organic matter to be more than the rate of formation, thus preservation of organic matter could not be achieved. However, accumulation of terrestrial plants in swamps leads to formation of coal, but it is of little concern to formation of fluid hydrocarbons.

What happen to the organic matter preserved in the sediments during burial in a steadily subsiding sedimentary basin? As time passes, burial depth increases, exposing the sediment to increased temperature and pressure. There are three major phases in the evolution of organic matter in response to burial.

i) Diagenesis phase that occurs in shallow subsurface at near normal temperature and pressures. It includes both biogenic decay, aided by bacteria, and abiogenic reactions. Methane, carbon dioxide, and water are given off by organic matter, leaving a complex hydrocarbon called kerogen. The net result of diagenesis of organic matter is the reduction of its oxygen content, whereas the hydrogen/carbon ratio remains largely unaltered.

ii) Catagenesis phase that occurs in the deeper subsurface as burial continues and temperature and pressure increase. Petroleum is released from kerogen during catagenesis, first oil and later gas. The H:C ratio declines, with no significant change in the O:C ratio.

iii) Metagenesis phase that occurs at high temperatures and pressures verging on metamorphism. The last hydrocarbons, generally only methane, are expelled. The H:C ratio declines until only carbon is left in the form of graphite. Porosity and permeability become negligeable.

2.4.3.2 Shallow Diagenesis of Organic Matter

In stratified water an oxygenated zone (+Eh) overlies a reducing zone (-Eh). The interface between oxidizing and reducing zones could be within the water, or coinciding with water sediment interface, or, if the sediments are permeable.

In the upper oxidizing zone, oxidizing bacteria genus *Thiobacillus* oxidizes sulphur, whereas in the reducing zone the bacteria genus *Desulfovibrio* reduces sulphur from sulfate ions releasing free sulphur. This free sulphur might react with organic matter to form hydrogen sulfide (H_2S), or may combine with iron in ferrous hydroxide to produce pyrite (FeS_2). Thus, both hydrogen sulfide and pyrite characterize reduced sediments- rich with organic matter, as known from recent swamps.

2.4.3.3 Chemistry of Kerogen

Kerogen is a term applied to disseminated organic matter in sediments that is insoluble in normal petroleum solvents, such as carbon bisulfide. The soluble fraction of organic matter in sediments is termed bitumens. Kerogen consists of carbon, hydrogen, and oxygen, with minor amounts of nitrogen and sulfur.

Table.2.1 Chemistry of Kerogens (After Hunt *et al*., 2002)

Weight Percent						Ratios		
	C	H	O	N	S	H-C	O-C	Petroleum type
Type I Algal	75.9	8.84	7.66	1.97	2.7	1.65	0.06	Oil
Type II Lipitinic	77.8	6.8	10.5	2.15	2.7	1.28	0.1	Oil and gas
Type III Humic	82.6	4.6	-	2.1	0.1	0.84	0.13	Gas

Three types of kerogen are known, based on chemical composition and the nature of the original organic matter (Yable 2.1). Depending on the type they could generate different types of hydrocarbons. Type I kerogen is essentially of algal origin. It has a higher proportion of hydrogen relative to oxygen than the other types of kerogen (H:O is about 1.2- 1.7). The H:C ratio is about 1.65. Lipids are the major compounds in this kerogen with derivatives of oils, fats, and waxes. The algal type I kerogen is characteristics of many oil shales, source rocks and cannel or boghead coals. Type II, or liptinic, kerogen is of intermediate composition. The original organic matter of this type of kerogen is algal detritus with materials derived from zooplankton and phytoplankton. It has an H:C ration greater than one (1.28). Type III, or humic, kerogen has a much lower H:C ratio (<0.84). It is produced from the lignin of higher woody plants, which grow on land. It is this humic material that, if buried as peat, undergoes diagenesis to produce coal. Type III kerogen tends to generate mainly gas and little, if any oil.

2.4.3.4 Maturation of Kerogen

During the phase of catagenesis, kerogen matures and gives off oil and gas, when kerogen is immature, no petroleum has been generated, with increasing maturity, first oil and then gas are expelled, when the kerogen is overmature, neither oil nor gas remains. The rate of

maturation depends on temperature, time and possibly, pressure. Regarding temperature, significant oil generation occurs between 60 and 120^{o}C, and significant gas generation occurs between 120 and 225^{o}C. Above 225^{o}C the kerogen is inert, having expelled all hydrocarbons, only carbon remains as graphite. The temperatures are only approximate boundaries of the oil and gas windows.

2.4.4 The Petroleum System

The formation and accumulation of petroleum require, as necessary factors, many physical components and processes that can be unified and described under a set of geological situation termed the petroleum system. The petroleum system is defined as a concept, which "*encompasses a pod of active source rock and related oil and gas that includes all the essential elements and processes needed for oil and gas accumulation to exist*" (Magoon and Dow, 1994). The essential elements of a petroleum system include source rock, carrier and reservoir rocks, seal rock or cap rock, and overburden rock. The processes are trap formation and generation-migration-accumulation of petroleum. The order of development in time and space of these elements and processes is fundamental for petroleum accumulation to take place (Magoon and Dow, 1994). Prior to the definition by Magoon and Dow (1994), the petroleum system concept was already described as the "*oil system*" (Dow, 1974), the "generative basin" (Demaison, 1984), the "hydrocarbon machine" (Meissener et al., 1984) and the "independent petroliferous system" (Umishek, 1986).

2.4.4.1 Source Rocks

Source rocks are defined as fine-grained sedimentary rocks containing sufficient amount of organic matter that have the capability to generate and expel enough quantities of

petroleum (oil and gas) under subsurface geological conditions (Hunt, 1996; Tissot and Welte, 1984). The source rock is a prerequisite for every hydrocarbon play and prospect appraisal (Demaison, 1984; Magoon and Dow, 1994). If good source rocks are not present, further prospecting may be abandoned. According to Peters *et a*l. (2012), a source rock is said to be "effective" if it is generating or has generated and expelled, "potential" if it has sufficient organic matter but has not yet expelled, "active" if it is generating and expelling petroleum at the critical moment, "inactive" if it has stopped generating because of uplift and/or "spent" if it is post-mature for oil but can still generate gas methane and wet gas.

2.4.5 Organic Geochemistry of the Bornu Basin

Petters and Ekweozor (1982) carried out a geochemical analysis of Albian to Eocene shales in both Benue Trough and southern Chad Basin and showed that they contain over 0.5% total organic carbon, with values up to 7.4% in anaerobic shales and they show maturity. They further stated that the bituminous zones of the Fika Shale are mature as suggested by their relative Carbon Preference Index (CPI about 1.1) and SOM/TOC and SHC/TOC (up to 271.1 and 41.3 mg/g respectively). These are the principal zones of hydrocarbon generation before the last Santonian uplift and deformation and suggest that the marine facies of the Fika Shale have the capability of generating liquid hydrocarbon.

Preliminary geochemical studies of argillaceous sequences of Turonian-Early Santonian sediments penetrated in some shallow boreholes of 144m in JUM-1 to 456m in Fik-1 in the Southwestern Chad Basin were carried out by Idowu and Ekweozor (1993) and the average results of the total organic content (TOC) of the sampled sections of Gongila and Fika Formations are 1.3% and 0.9% respectively, which exceed the minimum value of (0.5%) usually required for petroleum source rocks. However, they said the content of soluble

organic matter (SOM) and saturated hydrocarbons (SHC) of the same samples are generally low and signify mediocre properties. The organic matter is thermally immature in the up dip perimeter of the basin. Idowu and Ekweozor (1993) concluded that the most promising zone with respect to petroleum potential seems to lie north of their study area where source rocks that have attained optimum levels of maturity for hydrocarbon presumably occur.

The organic matter assessed from vitrinite and T_{max} by Olugbemiro *et al.*(1997) indicates that the Gongila and Bima Formations are within the "oil window", while Fika Shale Formation has best source rock potential in terms of the organic content, but has low thermal maturity. The Gongila Formation is well within the "oil window", but has limited potential as source rock because of the presence of clastic and inert materials.

The "oil window", deduced from the mean vitrinite reflectance profile, occurs between 1270m to 2700m in Kanadi well with respective maturation gradients of 0.5 log% Rm/Km (0.4% Rm/Km) and between 1985m to 3690m in Albarka well with respective maturation gradient of 0.41 log% Rm/Km as analyzed from Fika Shale and Gongila Formation respectively *(*Olugbemiro *et al.,* 1997*)*

A preliminary investigation of the hydrocarbon potential of the southwestern Chad Basin was carried out by Okosun (2000) by the integration of lithostratigraphic, geophysical, organic geochemical and vitrinite reflectance data. The TOC values from Fika Shale and Gongila Formation range from 0.07 to 3.7wt with majority greater than 0.5%. He further stated that the upper part of the Fika Shale is richer in TOC and shows lateral enrichment in organic matter from SW to the NE in the basin accompanied by a corresponding increase in the thickness of the "oil window".

Okosun (2000) concluded that the Gongila Formation has low TOC values and low hydrocarbon potential while the Fika Shale is the better target for hydrocarbon generation and the most promising area for hydrocarbon discovery is the Lake Chad region where the oil window has attained the greatest thickness and also a greater depth of burial.

Obaje *et al.* (2004) carried out organic geochemical studies to assess the qualities of some rocks penetrated by four wells (Kemar-1, Murshe-1, Tuma-1, Ziye-1) in the Nigerian sector of the Chad Basin. Good to fair to poor quality source rocks are inherent in the sequences penetrated by the studied wells. About 80% of the analyzed samples have their total organic contents (TOC) more than 0.5%, the minimum threshold for hydrocarbon generation. Juxtaposition of the hydrocarbon indices against the TOC and T_{max} indicates that the source rocks are entirely gas-prone. Biomarker chromatograms and extract versus TOC plot indicate the presence of oil window in Ziye-1 well at a depth of 1210m, which lies in the upper Gongila Formation and is of the shale unit.

The quality of a source rock is dependent on its total organic matter content ("TOC"), such that clastic sediments with a TOC of about 0.5% are considered potential source rock; however, good source rocks should have a TOC of 1 and above (Waples, 1980).

Obaje *et al*. (2006) studied some wells in the Chad Basin in Nigeria and stated that 80% of the shale samples from the studied wells have TOC values >0.5wt%, the minimum limit for hydrocarbon generation. The HI values indicate gas prone Type III organic matter with possibilities to generate gaseous hydrocarbon when juxtaposed against the T_{max},, S_2 vs TOC plot gave an average Hydrocarbon Index (HI) of 148mgHC/gTOC in some rocks from

Ziye-1 well, indicating a possible oil generating potential (oil was not discovered in this well, but there is such a possibility in prospect that they may generate oil).

Mohammed (2010) carried out a geochemical assessment of some Cretaceous sediments in the Bornu Basin on Kaduru-1 and Herwa-1 exploratory wells and his investigation reveals that between the depth of (1750- 2455)m there is a consistent increase in values of soluble organic matter (SOM), saturated organic matter (SHC) and aromatic hydrocarbon (AHC) and a corresponding increase in the maturation of organic matter within the shale unit, a fair to good petroleum source bed with a general average of fair source rock quality is inherent and is of gas prone.

Alalade and Tyson (2010) investigated hydrocarbon potential of Late Cretaceous Gongila Formation and Fika Shale in the Bornu Basin, they summarily said that there is a low TOC values in most of the shale samples which limits their overall source rock potential. They concluded that the basin has potential for mostly gaseous rather than liquid hydrocarbon.

Mohammed (2012) made an attempt to classify petroleum compounds into hydrocarbon and heteroatomic/nonhydrocarbon compounds on the basis of their implication on organic matter maturation. The hydrocarbon compounds (AHC, SHC) were found to be relatively of low values when compared with heteroatomic/nonhyrocarbon compounds; nitrogen, sulphur and oxygen (NSO), but have mature facies at some horizons which indicate “gas generative window” and show mediocre properties than the heteroatomic/nonhrocarbon compounds.

Mijinyawa *et al*. (2013) evaluated the hydrocarbon potentials, thermal and burial history of Herwa-1 well in the southern Chad Basin and stated that the geochemistry supported a

moderate to good TOC in both Fika Shale and Gongila Formation. HI and T_{max} are above average, S_1 and S_2also suggest good hydrocarbon potentials. They concluded that the oil window begins at a depth of (2000- 3000) m in Middle Cretaceous and gas window starts at Late Cretaceous to Tertiary at a depth greater that (3500) m.

2.4.6 Inorganic Petroleum (Geochemistry)

2.4.6.1 Background

In petroleum exploration, organic geochemistry has been found to be an indispensable tool both at the initial and advanced stage in identifying source rocks and classifying crude oils into families (Ekweozor *et al*., 1979; Doust and Omotsola, 1990). Classification of crude oils into families helps locate hydrocarbons in explored areas at different stratigraphic units of a basin. It is now known that organic geochemistry is also very useful in petroleum production (Karlsen *et al*., 1995; Larter and Aplin, 1995).

Organic geochemical methods of crude oil include biomarker fingerprints, stable isotope ratios and hydrocarbon contents etc, which are fairly expensive (Akinlua *et al*., 2007). Trace elements data of crude oils have been reported to be effective in classifying and correlating oil and are relative to organic geochemical methods (Hitchon and Filby, 1984; Lewan, 1984; Curiale, 1987; Barwise, 1990; Udo *et al*., 1992; Oluwole *et al*., 1993; Akinlua *et al*., 2007 and Abubakr *et al*., 2010).

The nature of occurrence of metals, their distribution patterns and concentrations in crude oils can give information on the origin, migration, environment of deposition and maturation of petroleum (Elirich *et al*., 1985; Barwise, 1990; and Oluwole *et al*., 1993). Trace metals are incorporated into oils in form of porphyrin complexes (species) in

petroleum source rocks and may include direct incorporation from the biomass and formation during sedimentation (Akinlua *et al*., 2007). It may also involve diagenesis from organic molecules as well as metals derived from biogenic (biomass) and abiogenic (weathering of minerals) sources. Lewan (1984) has shown that source rock, type of organic matter and depositional environment have profound effects on the concentration of trace elements in source rocks. There may be difficulty in correlating oils and or/source rocks using trace element contents. However, metals of proven association with organic matter may be used as reliable correlation tools. Nickel, Vanadium, and Cobalt (usually referred to as biophile elements) are such examples.

Concentration of metals in crude oils can be used to classify oils into families. Low V/Ni ratio (<0.5) are expected for petroleum derived from marine organic matter, with high to moderate Sulphur content, while V/Ni ratios (1- 10) are expected for petroleum derived from lacustrine and terrestrial organic matter (Barwise, 1990). Oils from marine organic matter have high concentrations of metals (particularly Ni and V), this is expected since for marine source rocks, there is an abundant input of porphyrin- precursor chlorophylls to the organic matter derived from algae and bacteria (Barwise, 1990). Moderate quantities of metals are found in oils derived from lacustrine source rocks, while little nickel and vanadium are found in land- plant derived. The V/Ni ratios tends to increase with increasing Pr/Ph ratios and 18H- oleanane/17H, C_{30}- hopane ratios, suggesting high terrigenous source input (Udo *et al*., 1992). Lewan (1984) reported that V/(V+Ni) ratio is negatively correlated with the even predominance of n-alkanes and the Pr/Ph ratio, but it is positively correlated with the Ph/nC_{18} ratio, which infers marine organic matter input. Nickel, Cobalt, Strontium, Silver and Bismuth have been found to correlate positively with

the absolute amount of heavy n-alkanes in the petroleum, as these elements are relatively more abundant in parafinic petroleum (Karlsen *et al*., 1995). Enriched V and Ni concentrations greater than 100ppm are observed in bitumens that are associated with Type II and Type I kerogens. Bitumens associated with Type III kerogens contained V and Ni concentrations less than 100ppm (Lewan, 1984).

Lewan and Maynard (1982), and Lewan (1984) have also reported that source rock type and depositional environment have a profound effect on the predicted levels of nickel and in the source rocks. Barwise (1990) also reported that there is a systematic variation in the nickel and vanadium content of crude oils which can be related to depositional environment and source rock types. This implies that the source depositional environment determines the proportion of vanadium to nickel in crude oil. It has been prove that high V/Ni ratio is associated with anoxic palaeoenvironment of deposition ((Lewan, 1984) whilst both V/Ni and Co/Ni ratios have been shown to be anoxic/oxic related parameters (Udo *et al*., 1992).

Chunchan and Goudong (1991) carried out a geochemical analysis on 20 rock samples collected from northeastern China and found that there is a close relationship between contents of V and Ni in organic matter and type of kerogen. Their investigation further revealed that correlations with other elements and the types of organic matter are not so obvious. As the depth increases, the contents of some elements, such as Al, Fe, Mn and Na tend to decrease. But V and Ni contents show good stability with depth and V-porphyrin and Ni-porphyrin in soluble organic matter were identified. Chuchan and Goudong (1991) concluded that chlorophyll eliminates its Mg and combines with V to form V-porphyrin and that both V and Ni in the soluble organic matter come from the organisms according to their close relationships with the types of organic matter

An inverse proportional relationship exists between American Petroleum Institute (API) gravity and the total transition metal contents. The API gravity is also inversely correlated with each of Cu, Ni, V, Se, Mn and Cr (Oluwole *et al*., 1993). These infer that total transition metal content decreases with an increase in oil maturity. Many workers have used the V/Ni ratio as indicator of oil maturity (Barwise, 1990; Udo *et al*., 1992). Udo *et al*. (1992) reported that V/Ni ratio decrease as Pr/nC_{17} ratio decreases and as depth and API gravity of oils increase, thus suggesting that V/Ni decrease with increasing maturation. Barwise (1990) also reported that high concentrations of metals are only associated with oil of low to moderate API gravity. He further stressed that the highest concentrations of metals are found in matured oils.

2.4.6.2 Geochemistry and Application of Trace Elements to Petroleum Exploration

Trace Elementsas Fingerprints

The strict definition of trace elements in geochemistry is that if the contents of elements in the object are so low that their activities could be described approximately by using the Henri law, such elements are called trace elements (Zhao, 2010). More than forty trace elements can be identified in crude oil, with the predominant ones as V and Ni (50%- 70% of the total) (Li *et al*., 2008). Accompanying hydrocarbon, trace elements can travel a long distance (Yang *et al*., 1996; Wen and Purikov, 1999; Qian and Cao, 2001; Jin *et al*., 2006; Sun *et al*., 2009). So they are also known as geochemical indicator, tracer, migration path finder, fingerprint (Mezhibor *et al*., 2009).

Application of Trace Elements to Oil- Source Correlation

Rare Earth Elements (REE)

Their original abundance, distribution form, dispersion or concentration in geological process and migration are all documented by their structure and properties, which make all the REE, co-exist symbiotically in nature, and have the same geochemical behavior (Curiale, 1983).

Transition Metals

Transition metals mainly exist in asphaltene and non- hydrocarbon components in crude oils (Ding *et al*., 1992). Because transition metals have non- occupied electron orbits “d”, which are easy to be hybrid and form combination bond with coordinate bond.

Ni and V

Ni and V are the main trace elements in crude oils which exist in resin or asphaltene as nickel/vanadium porphyrin. During migration Ni and V exchange with surrounding rock; because of the effect of surrounding rock and underground fluid and the sealing ability of the cap rock, the change of absolute amount of Ni and V is difficult to determine, V and Cu usually accumulate in asphaltene, and Ni mainly exist in resin.

Frankenberger (1994) carried out trace element studies of New Zealand crude oils to determine their significance for crude oil classification, geochemistry and analytical chemistry. Frankenberger’s investigation showed that most trace element concentrations are distinctively different in oils derived from terrestrial, lacustrine or marine. Crude oils from marine source contain higher amounts of trace elements than oils of other sources. She further stated that a direct comparison of trace element contents in rock extracts and crude

oils is not possible as element concentrations in extracts are higher due to their different chemical composition. Frankenberger (1994) classicified the trace elements into biophile, chalcophile and siderophile elements and concluded that V and Ni are the most important trace elements for determing maturation, migration and accumulation of crude oils and that Fe tends to have higher value in majority of the analyzed samples.

Akinlua *et al.* (2007) carried out integrated organic and inorganic geochemistry of NW Niger Delta oil sources were discovered to have matured at the same period. The two methods used, showed similarities in maturation and oil source such as Pr/n C_{17} vs Ph/C_{18} and Ni and V, Co/Ni vs V/Ni cross plots and cluster analysis.

Onojiake *et al*. (2010) investigated seven crude oil samples from two wells in the Niger Delta and characterized their trace element ratio using Fe, Zn, Pb, Cu, Cr, Cd, Ni, Mn, V, and Co, these are picked up during migration or in the reservoir and incorporated directly into the oils in form of porphyrin complex (species) in petroleum source rocks from the bitumen and formation during sedimentation (Akinlua *et al*., 2007).

Weiwei *et al*. (2010) uses trace elements to correlate oil source and hydrocarbon migration and accumulation in Tarin Basin in China, their studies reveals that rare earth elements (REE) and transition metals were the elemental tools used to determine the oil sources from formation to formation and block to block.

Wilberforce (2016) studied heavy metals in Bonny Light crude oil in the Niger Delta using Cd, Cu, Ni, V, and Pb, his investigation showed that levels of Pb and Cu were higher than Ni and V possibly as a result of anthropogenic activities.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

3.1.1 Field Study and Geological Mapping

Rock outcrops in the research area were stu died sedimentologically and stratigraphycally from surface and pits (after augering), the augering involves a helical shaft that is used for boring holes in the soil to collect sub- surface samples. The methodology of the study comprises the hardware design and analytical procedures. There are many variables used in the field for the geological mapping. The following materials were employed during the study for effective acquisation of viable information in this exercise;

3.1.1.1 Global Positioning System (GPS)

Locating rocks outcrops on a map can be time consuming, especially where the base map lacks detail such as moorland and deserts. GPS was used to provide multi-satellite- based radio-navigation, timing and positioning system. It also aids data collection in the field and helps in locating points of sampling. Three dimensions were achieved in the field which includes (latitude, longitude and height above a global datum WGS-84). Coordinates were taken at different points of sampling.

3.1.1.2 Sampling

During the mapping exercise, sedimentary rocks were sampled at different locations from both surface and sub- surface using auger and hammer to ensure fresh samples. The samples were then kept in polyethene recording with their coordinates and other physical characteristics such as (e.g. grain-size, structures, and textures) in a field notebook.

Handlens was also used in identifying some of these physical proerties. Some of the rock samples were selected for Petrographic Studies, while others were selected for trace element petroleum geochemistry.

3.1.2 Logging of Stratigraphic sections

Logging of stratigraphic sections was employed in the field to log lithostratigraphic sections and to measure vertical thicknesses of different sequences and their boundaries. Several lithostratigraphic sections were plotted. Rock samples collected in the study area provided sedimentological data that allow their interpretation in terms of transport and deositional processes. Sampling interval depends on the thickness of the sections, mostly it is between 2-5 metres interval. The choice of sampling is based on favourable outcrops that have fresh rock materials that can provide good analytical result.

3.2 Methods

3.2.1 Geochemical Analysis

3.2.1.1 Sample Preparation

Ten (10) shale samples were selected for geochemical studies. The shale samples were used for the analysis to determine the concentrations of V and Mo only with (MP-AES). Detail methodology of MP-AES agilent 4200 application is discussed below as described by (Laura *et al*., 2017). Rock samples used for the analysis were pulverized into fine powder of about 100-mesh size using pestle and mortar. They were grined, washed and dried to avoid contamination.

Sample Digestion

10mL of 1:1 HNO_3 was added to 1.00g of shale sample in a 25x150mm glass digestion tube and the samples were heated to 95+/- 10^{o}C for about 15 minutes. After cooling, 5mL

of HNO_3 was added and heat was applied for another 30 minutes. The digests were allowed to cool, and 2ml of Milli-Q water and 3ml of 30% H_2O_2 was added and heated to 95+/-5^oC. After the digests were cooled, another 1mL of 30% of H_2O_2 was added. Heating continued until the sample volumes reduced to approximately 5mL. The digests were allowed to cool and then diluted to 50ml with Milli-Q water. Prior to analysis, the shale digests were diluted x10 with Mili-Q water to reduce the effect of background emission due the high sample matrix.

3.2.2 Microwave Plasma Atomic Emission Spectroscopy (MP- AES)

The agilent 4200- MP-AES generates a self-sustained atmospheric pressure microwave plasma (MP) using nitrogen gas and a modified inductively coupled plasma torch. Sample introduction to the MP is pneumatic using a concentric nebulizer and cycloric sprey chamber system, and emission line isolation and detection is sequential using a Czemy-Turner monochromator and charge-coupled device system. This method was carried out at the Deppartment of Chemistry, Ahmadu Bello University, Zaria- Nigeria.

3.2.3 Atomic Absorption Spectrophotometer (AAS)

Atomic Absorption Spectrometer AAS is one of the commonest instrument for analyzing metal and metalloids for determination of petroleum geochemistry. This method was described by (Price, 1972). It is used for the determination of light elements with atomic numbers too low. Atomic absorption spectrophotometry was carried out upon the observation of atoms in the elements being studied which absorbs electromagnetic radiation. This occurs when the elements are atomized and the wavelength of light absorped is specific to each element. The rock samples were dried thoroughly.

Sample Preparation

Rock samples used for this analysis were each pulverized into fine powder of about 100-mesh size using pestle and mortar. The samples were washed and dried after grinding so as to avoid contamination. The pulverized samples were carefully kept in test tubes to avoid mixing the samples. Eight trace elements were analyzed using the AAS which includes (Mn, Co, Cr, Pb, Zn, Ni, Cu, and Fe).

Sample Digestion

Wet method digestion in nitric acid was used to determine the trace elements. In wet digestion method, 0.5g of powdered rock sample was weighed into a dry digestion tube. 3 to 4 drops of distilled water was added to the wet samples. 5ml of hydrochloric acid (HCL) was added, and the section was stirred. 5ml nitric aicd were prepared in the ratio of 3:2 and were added and stirred. The tubes were left to stay overnight without heating. The samples were digested at temperature of 120^0C on a hot bath inside a fume cupboard. The solution was heated strongly until there was no fume coming out of the beaker. The samples were leached out with 5ml of 6M hydrochloric acid (HCL) into a graduated test and were made up to 20ml with distilled water. The content was shaken vigorously to avoid caking,and the resulting solutions were referred to as the stock solution. All test tubes were correctly labeled. The solutions were used directly to determine all the selected trace elements using AAS. The analysis was carried out in the Department of Chemistry, Ahmadu Bello University, Zaria- Nigeria.

3.3 Petrography

3.3.1 Thin Sections

A thin slice of (16) samples of sandstone from different formationsin the study area were used; detail procedures have been discussed by (Pettijohn, 1987). In preparing for thin sectioning, a thin slice of rock sample was cut using rock cutter and mounted on a glass slide using araldite. The mounted rocks were then treated gently over the glass slide to remove excess araldite and air present. The rock slice was later scrubbed using abrasive powder and a thickness of 0.3mm is obtained. It was then polished and another glass is used to cover the prepared thin section.

Petrographic microscopy was employed to identify and distinguish different mineral grains within the sandstone slides so as to possibly determine the source area, and compositional maturity level of the rocks. The microscopic determination of minerals used in this study was adopted from previous works such as (e.g.Mackenzie and Adams, 1994; and Scholle; 1979).

Petrographic analysis was carried out using 16 selected sandstones samples from the Bima Group, Yolde Formation and Dumbulwa Member of Pindiga Formation. The study involves examining rock samples with the aid of polarized microscope to obtain mineralogical information on the constituents. The Petrographic view aide in provided information on different minerals based on their physical properties and structure observed on the slides. Quartz, feldspars and lithic fragments all have varying characteristics.

CHAPTER FOUR

4.0 RESULTS

4.1 Field Geology

Geological mapping of lithostratigraphic successions of Bornu Basin was carried out around the southwestern fringes of the basin and a stratigraphy of the area was proposed based on field evidence as indicated in the proposed geological map of the area (Fig. 8)

4.1.1. Basement Complex Rocks

The crystalline basement rocks in the study area can be referred to as inlier because they are surrounded by younger sedimentary rocks.

4.1.1.1 Granites

The granites are low- lying and mappable. The rocks outcropped as scattered boulders in the field were they are exposed. They are exposed in the study area at the basin shoulder, believed to have been uplifted high possibly during the Santonian to Maastichtian deformational episode which restructured the basin, particularly the basement and older Cretaceous sediments.

The granite is coarse- grained in texture, with pink coloured mineral that dominated the groundmass believed to be K- feldspar, while crystals of quartz interlocking other minerals are seen in hand specimen being transparent in colour. Dark ferromagnesian minerals are present. Other accessory minerals might be present, but can not be ascertained because thin section was not carried out on this rock. Plate I shows an outcrop of fragmented boulder of coarse- grained granite along Dokshi road, the granite boulders can be seen to be separated due to the effect of weathering.

4.1.1.2 Pegmatite

The pegmatite which outcrops in the study area can be referred to as a “simple pegmatite” because such granite pegmaties contain only quartz, feldspars and mica. The pegmatite appears low- lying rock in the field adjacent to the granites. It has a limited occurrence in terms of areal coverage. The pegmatite observed in hand specimen is pink to transparent in colour.This is so because quartz, feldspar and mica are the dominant minerals in pegmatites. Quartz is very resistant to weathering and erosion. Plate II shows a pegmatite low- lying that has been fractured.

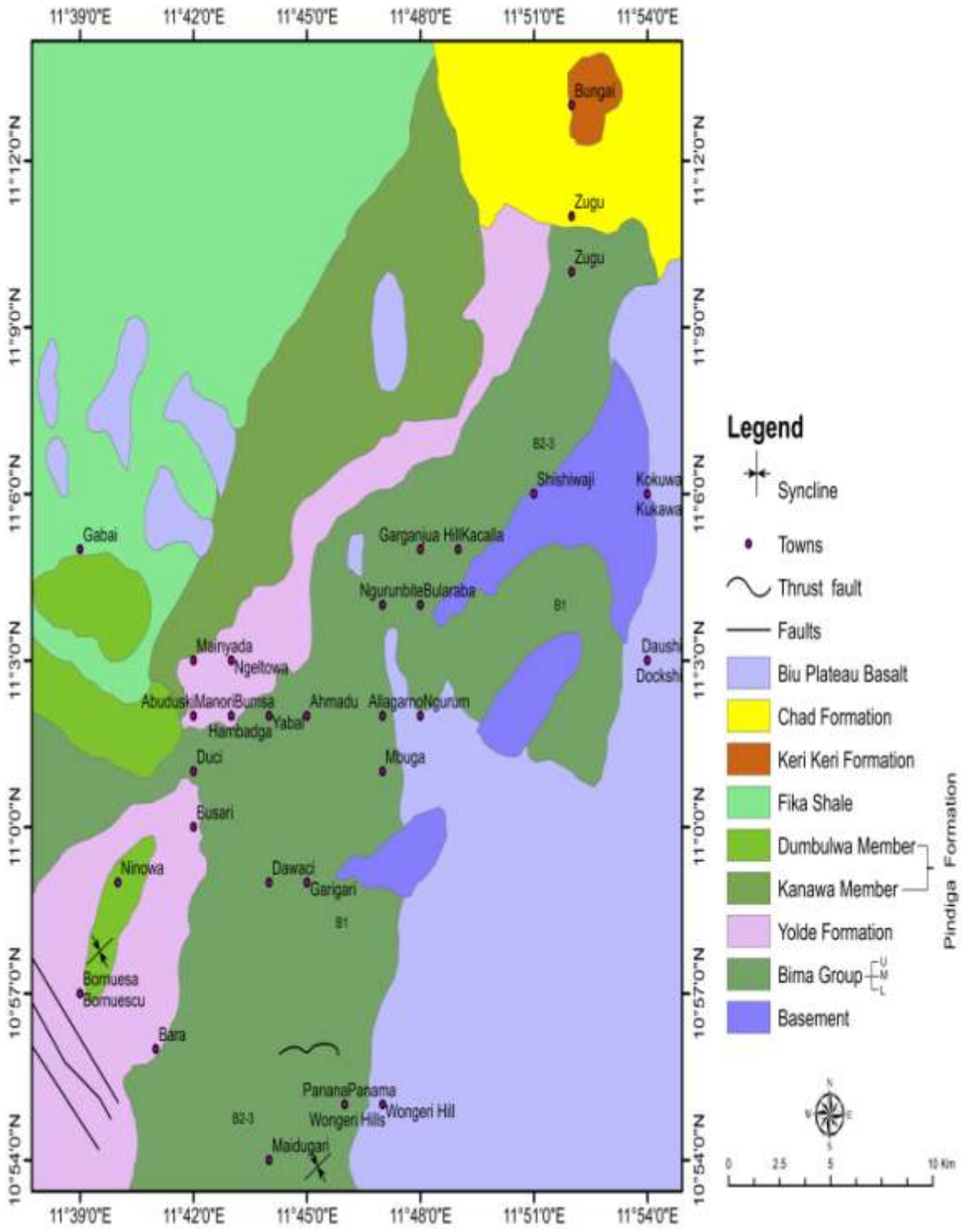


Fig. 8. Geological map of the study area



Plate I. Coarse– grained granite exposed along Dokshi road, (11^0 06.511′ N and 11^0 55.110′ E)



Plate II. Fragments of pegmatite exposed along Dokshi road (11^0 05.527′ Nand 11^0 57.310′ E)

4.1.2 Cretaceous Rocks

4.1.2.1 Bima Group

Lower Bima Sandstone ("B1")

The Lower Bima Sandstone is the oldest sedimentary succession in the basin with different facies types and depositional environments as studied from outcrops. Conglomerate and pebbly sandstone exposed around Dokshi (Plate III), overlies the basement rocks. The formation also consists of fragments of quartz, feldspars and conglomerate, this unit is an alluvial fan deposited at the mouth of the mountain. Plate III shows Lower Bima Sandstone believed to be the oldest sediment deposited in the basin. Co-axial jointing in sandstone was also observed (Plate V), it is exposed at Panana Village; this may be as a result of fluid injection through weaker zone developed along fractures. Tabular cross- bedding is prominent in the Lower Bima Sandstone; the structure can be interpreted as a braided river deposit (Plate VI). Stratigraphic section of Lower Bima Sandstone with multiple re-activation surfaces separating ferruginzed sandstones, and fresh gray shale at the bottom in a quarry site around Dokshi Village (Plate VII) exposed this facies. Fresh gray which was observed around Dokshi is being mined for mud houses within the locality can be interpreted as a lacustrine deposit. This lithological unit has never been reported in any outcrop throughout the Bornu Basin.

Hand specimens of the sandstone showed that it is of different characteristics, such as having clast embedded in groundmass matrix, larger crystals of quartz and feldspars.

Thin section studies of the sandstone samples reveals that the Lower Bima Sandstone consists of various mineral aggregate such as, quartz, orthoclase, albite, altered feldspar, muscovite, microcline, hematite, limonite and zircon



Plate III. Conglomerate grading to sandstone Lower Bima Sandstone around Dokshi, ($11^{0}0.88'$ N and 11^{0} 54.453′ E)



Plate IV. Fragments of quartz and feldspars at Panana Village displaying the alluvial facies fan of Lower Bima Sandstone (10^{0} 55.100′N and 11^{0}46.000′N)



Plate V. Co-axial jointed sandstone exposed at Panana Village of Lower Bima Sandstone (10^0 55.193′ N and 11^0 45.848′ N)



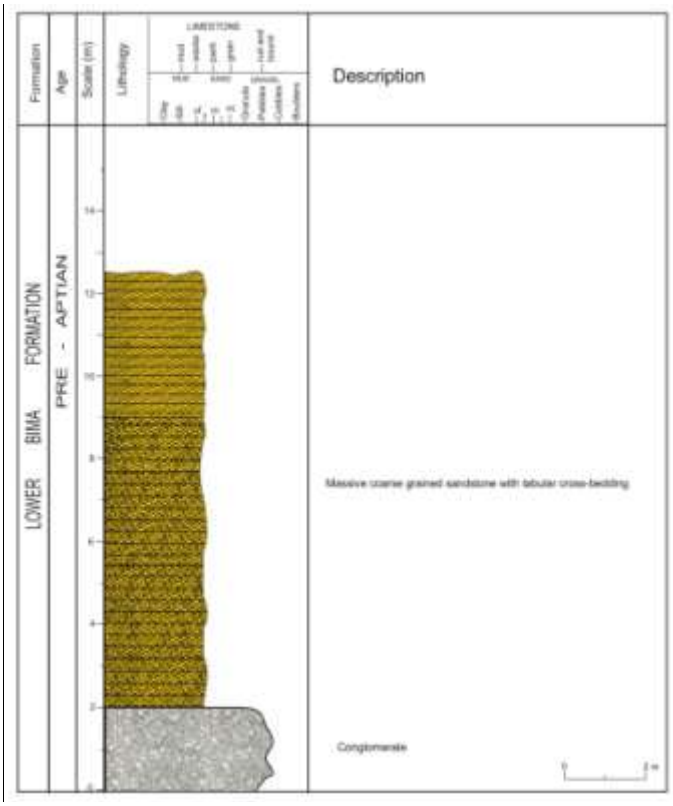
Plate VI. Tabular cross- bedded sandstone exposed at Panana Village of Lower Bima Sandstone (10^0 55.193′N and 11^0 45.848′E)



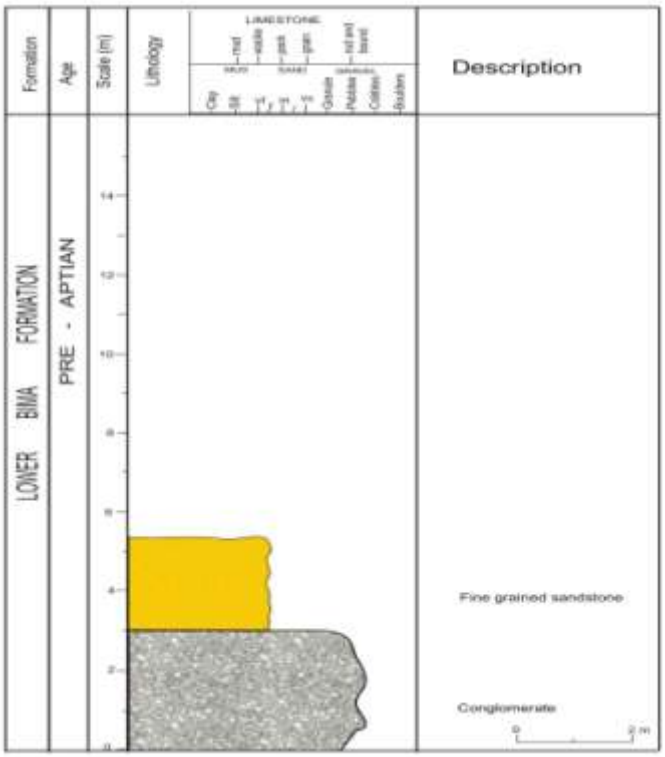
Plate VII. Stratigraphic section of Lower Bima Sandstone with multiple erosional Surfaces separating ferruginized sandstones, shale is exposed at the base of the succession in a local quarry around Dokshi Village(11^0 03.488′ Nand 11^0 55.537′ E)



Plate VIII. Gray shale of the Lower Bima Sandsone exposed at a local quarry site around Dokshi Village(11^0 03.488″ N and 11^0 55.537′ E)



a.



b.

Fig. 9a, b Sections of the Lower Bima Sandstone exposed west of Dutsen Mafurun Lanske (Dandagabal).

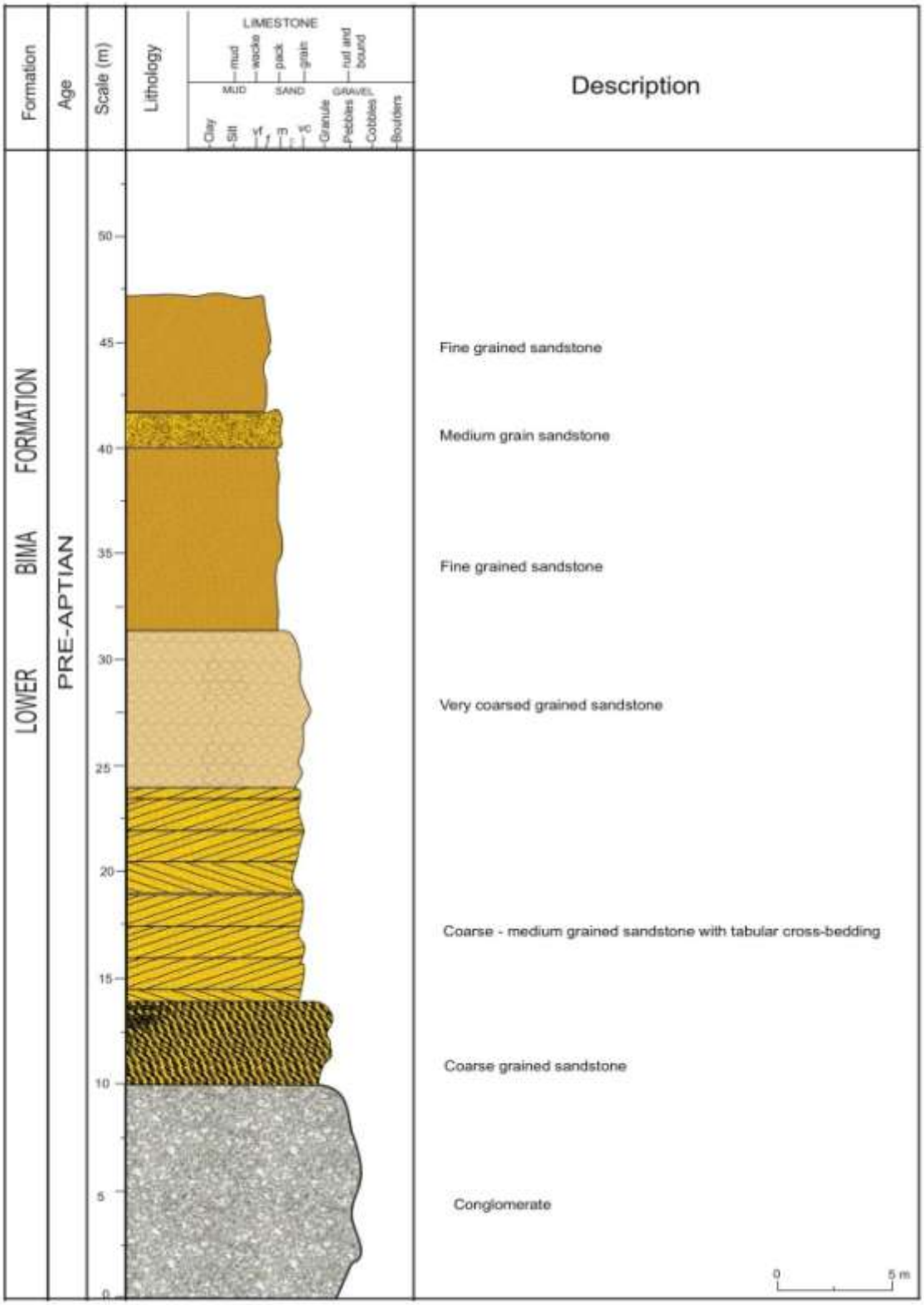


Fig. 10. Section of the Lower Bima Sandstone exposed at Skatikume Stream

Middle Bima Sandstone ("B2")

The Middle Bima Sandsone was mapped at the foot of Tangaran Hill and observed to contain thick clay bed that was deposited at a Lake Margin (Plate IX). This facies is overlain by the Upper Bima Sandstone and is believed to have been thrusted/reverse faulted. This is so because the sandstone of the area have all been crushed and silicified due to strike slip fault movement.

Hand specimen study showed the chipped sample to be clay which is brown in colour. The sample section is very fine- grained stiff, sticky which pliable believe containing silicates of aluminium.



Plate IX. Thick clay of the Middle Bima Sandstone (10^0 54.246′ N and 11^0 47.116′ E)

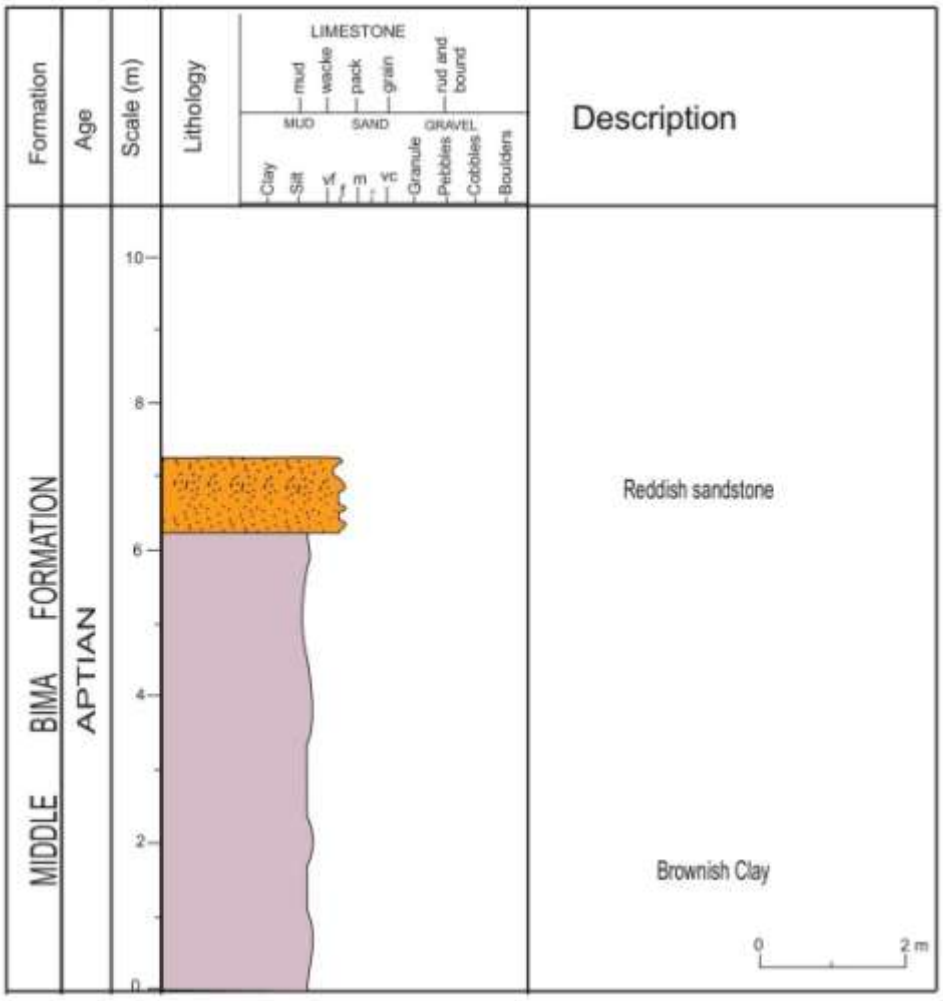


Fig. 11. Section of Middle Bima Sandstone exposed at the foot of Tangaran Hill

Upper Bima Sandstone ("B3")

The Upper Bima Sandstone is more widely distributed and is dominantly of sandstone composition. In most of the outcrops mapped and in particular the Upper Bima Sandstone within Wongeri Hills, the sandstone is silicified and brecciated (Plate X); the sandstones have been crushed and faulted because they occur along fault zone. This is evident by the fine- grained nature of the sandstone resulting from crushing of sediments along fault zone. At the foot of Tangaran Hill, an outcrop of silicified sandstone with tabular cross- bedding

was observed (Plate XI); the sandstone was believed to have been deposited in a fluvial environment. This sedimentary structure (tabular cross- beddeing) was formed mainly by migration of large-scale straight crested ripples and dunes. Silicified convulote cross-bedded sandstone was also observed at the foot of Tangaran Hill (Plate XII), the convulote cross- bed developed as a result of seismic shock on the sediments. Along Birni Gadam road, tilted sandstone bed believed to have been folded and faulted was observed. The anticline is seen very clear; with its sides being eroded possibly due to uplift and abrasion.

Hand specimens of the samples showed that, they are fine- medium grained texture, and silicification is prominent, some show effects of intense crushing and faulting, such as the brecciated sandstone sampled at Wongeri Hill.

Thin section was carried out on some of the samples revealed that, they are composed of quartz, altered feldspar, hematite, microcline, muscovite, andesine, albite, zircon and limonite.



Plate X. Silicified and brecciated sandstones of Upper Bima Sandstone exposed at Wongeri Hills (10^0 55.224′ N and 11^0 46.996″ E)



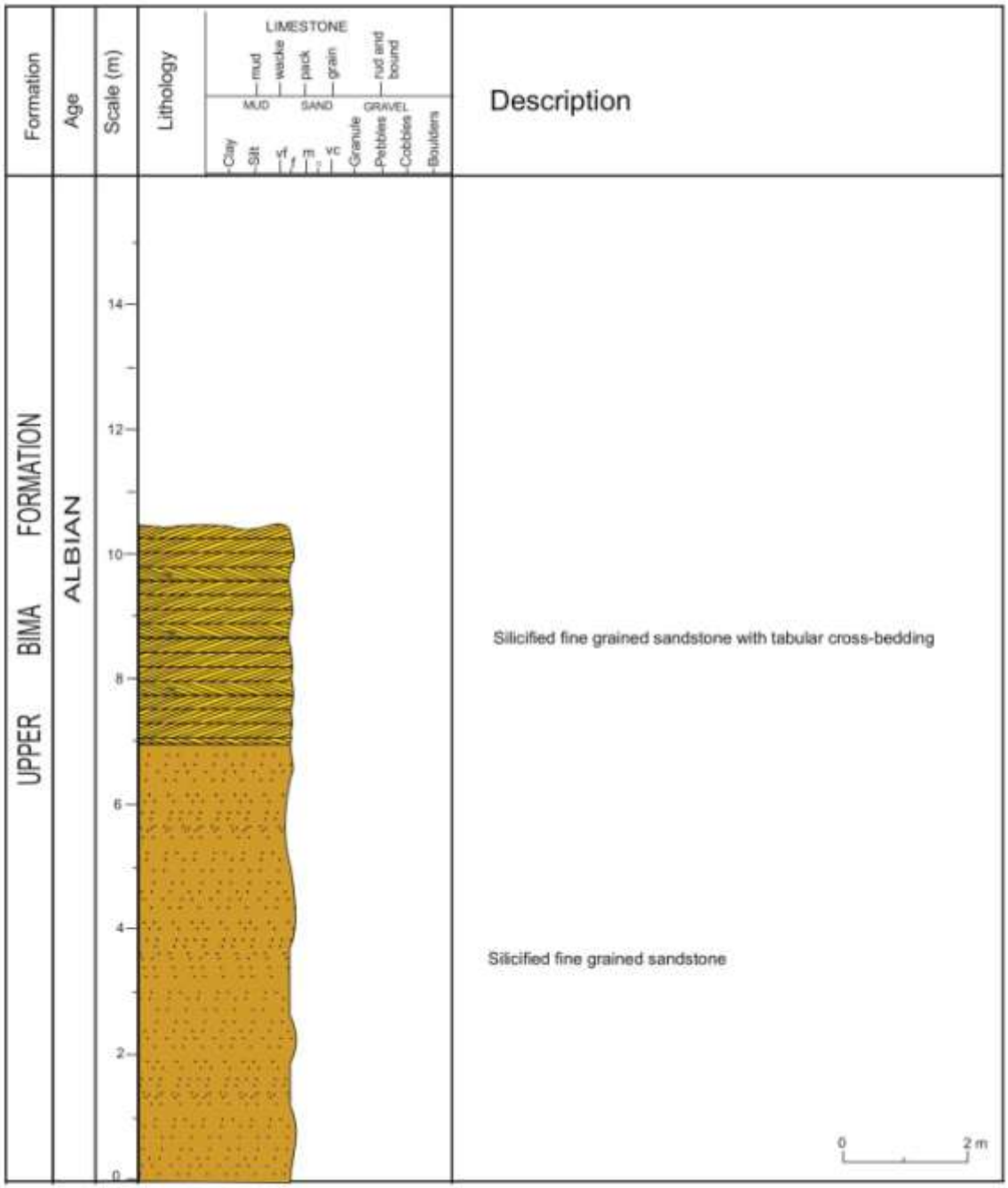
Plate XI. Silicified Tabular cross- bedded sandstone of Upper Bima Formation exposed at the foot of Tangaran Hill along stream channel. (10^0 54.246′ N and 11^0 47.116′ E)



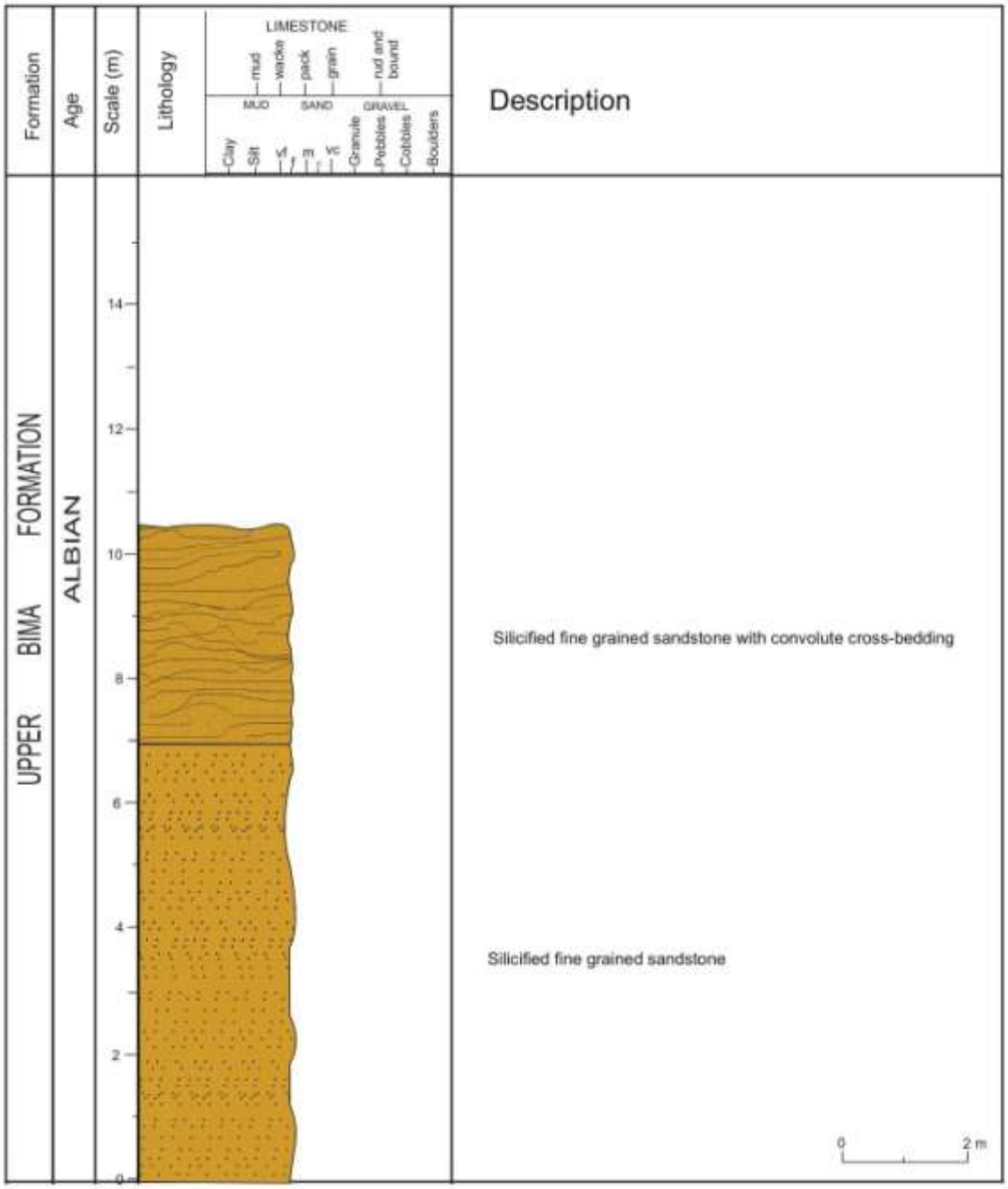
Plate XII. Convolute cross- bedded sandstone of Upper Bima Sandstone exposed at the foot of Tangaran Hill (10^0 54.246′ N and 11^0 47.116^i E)



Plate XIII. A limbof an anticline within the Upper Bima Sandstone exposed along Birni Gadam road, ($10^0$53.700′ N and 11^0 43.587^i E)


Formation
Age
Scale (m)
Lithology
LIMESTONE
mud
wacke
pack
grain
rud and bound
MUD
SAND
GRAVEL
Clay
Silt
vf
f
m
c
vc
Granule
Pebbles
Cobbles
Boulders
Description
UPPER BIMA FORMATION
ALBIAN
14
12
10
8
6
4
2
0
Silicified fine grained sandstone with tabular cross-bedding
Silicified fine grained sandstone
0
2 m

(a)



(b)

Fig. 12. Sections a, b of Upper Bima Sandstone exposed at the foot of Tangaran Hill

Yolde Formation

The Yolde Formation is transitional deposit that indicates the onset of marine incursion into both Bornu Basin and Benue Trough. Various observations and geometry were documented. At Yadi Kukuwa, an outcrop of the Yolde Formation with an oblique- tabular cross- beding was observed within massive sandstone (Plate XIV), it is a coastal unit deposited when the sea was advancing, while the tabular cross- bedded sandstone is fluvial sediment deposited by river (Plate XV). Massive sandstone bed was observed around Shishiwaji with mottled mudstone at its base. Mudstones are formed when very fine-grained clay particles are deposited in water. The tiny particles settle to the bottom of oceans or river as the mud is buried and compacted by overlying sediments, the water is then squeeze out and it turns into a mudstone (Plate XVI).



Plate XIV. Tabular- oblique cross- bedded sandstone of Yolde Formation exposed at Yadi Kukuwa ($11^0$08.97′ N and11^0 55.139′ E)



Plate XV. Tabular cross- bedded sandstone of Yolde Formation exposed at Yadi Kukuwa (10^0 08.380′ N and $11^0$54.351′E)



Plate XVI. Massive thick sandstone bed with mudstone at the base of Yolde Formation exposed at Shishiwaji Village ($10^0$08.380′N and $11^0$54.351′E)

In most of the hand specimens, there are two characteristics facies types in the Yolde Formation, the sandstone, which is medium- grained and purple in colour, it is also very massive. The bottom mudstone was sampled and observed to be also massive and purple in colour.

Thin section analysis of the sandstone showed the presence of the following minerals, quartz, microcline, muscovite, hematite, altered feldspar, orthoclase, and biotite was only observed in the sample of this formation.

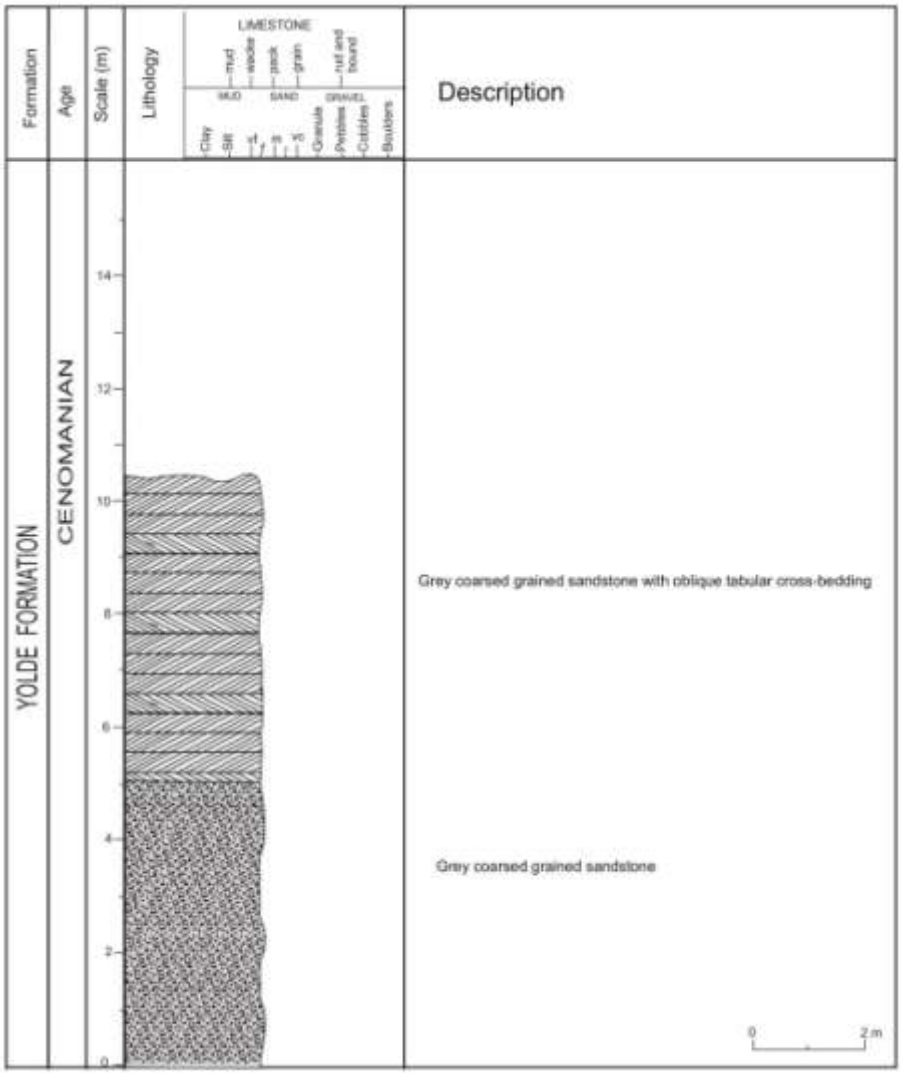


Fig. 13. Section of the Yolde Formation exposed at SE part of Yadi Kukuwa

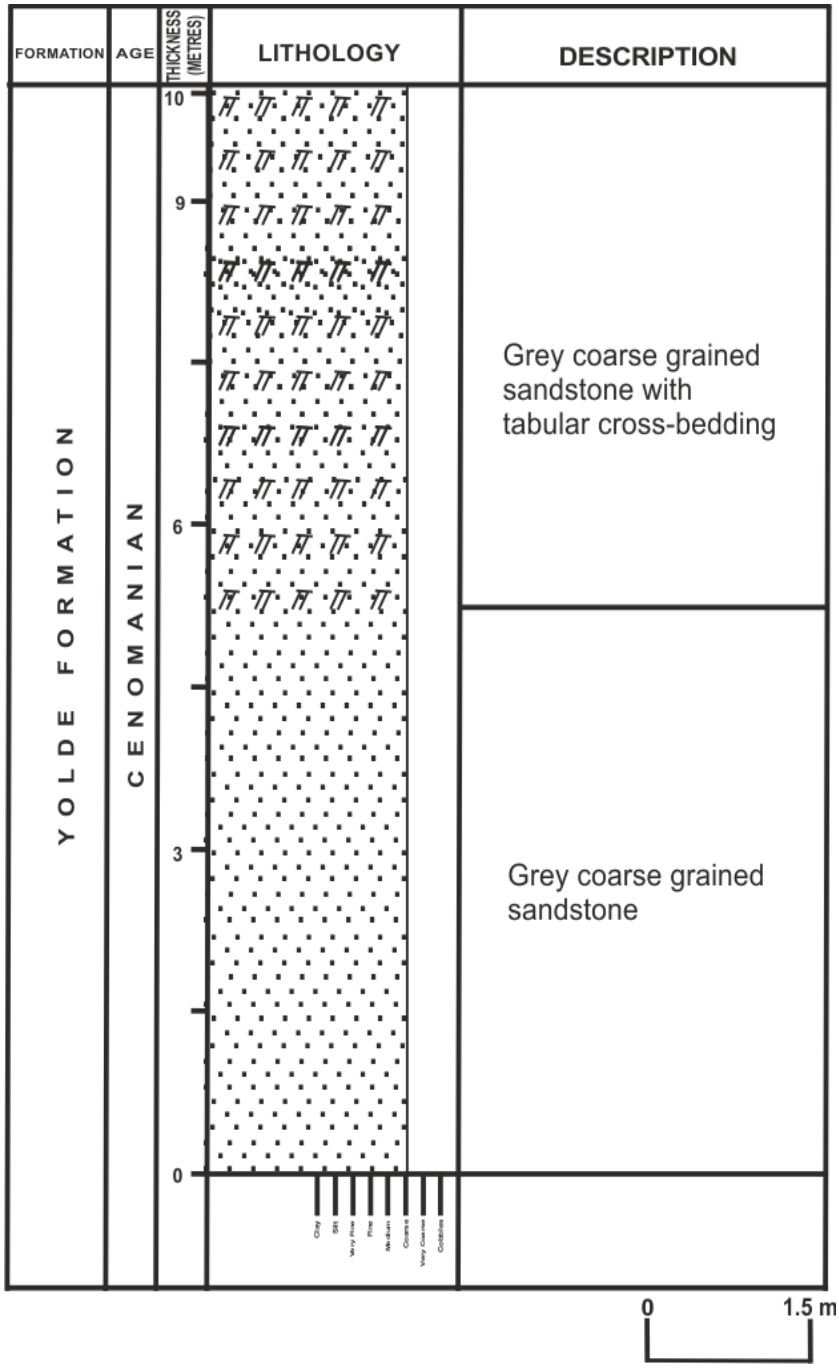


Fig. 14. Section of the Yolde Formation exposed at SE part of Yadi Kukuwa

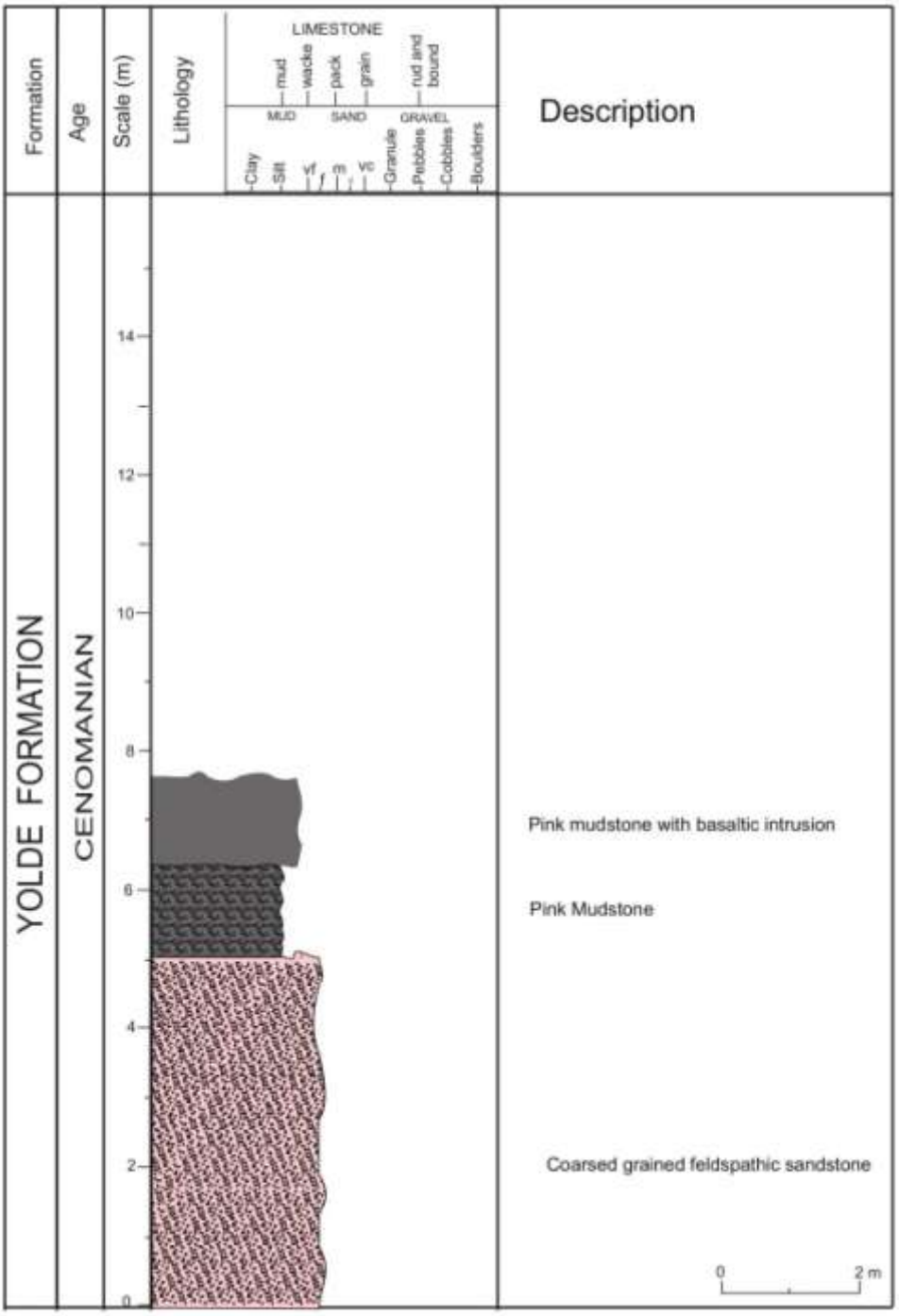


Fig. 15. Section of the Yolde Formation exposed at Shishiwaji

Pindiga Formation

The Pindiga Formation is proposed in this study to be part of the lithostratigraphic succession of the Bornu Basin to replace the previously used Gongila Formation which has some errors in terms of its mapping and naming of type section.

The following are some ethics from the North American Commission on Stratigraphic Nomenclature 2005 (North American Stratigraphic Code)

Article 7 (b) Duplication of names, and

Article 20 – Abandonment and

North American Commission on Stratigraphic Nomenclature (2018)

Chapters 3 Definitions and Procedure,

B. Procedure for Establishing and revising Stratigraphic Codes.

3. Naming of Stratigrahic units

(a) Geographic Component of Names of Stratigraphic units

(iv) –inappropriate Geographic Names

Kanawa Member

The Kanawa Member is the oldest stratigraphic unit in the Pindiga Formation. It is dominantly of shale- limestone unit. The shale unit of the Kanawa Member is exposed at Yadi Kukuwa along stream channel (Plate XVII). The shale is black in colour which is very rich in organic matter. It is hard and jointed due to escape of water. A thick bed of

limestone was observed at Yadi Kukuwa very close to the boundary of the facies with Yolde Formation (Plate XVIII). The bed is more than 5m in thickness and more than 100m wide; it is yellowish in colour as a result of long exposure due to chemical weathering. A yellowish- gray fragment of limestone unit of the Kanawa Member is exposed along Kukuwa Gari road (Plate XIX), the thickness of the limestone cannot be established, and it is more than 50m in length. A shale unit of the Kanawa Member overlain by an alluvial deposit outcropped at the outskirt of Bara along a stream channel (Plate XX). The shale is dark brown to black while the alluvial is fine- grain and brownish in colour.



Plate XVII. Shale unit of the Kanawa Member of the Pindiga Formation exposed at Yadi Kukuwa Stream, (11^0 08.818′ N and 11^0 53.202′ E)



Plate XVIII.Thick bed of limestone unit of the Kanawa Member of Pindiga Formation exposed around Yadi Kukuwa towards its boundary with Yolde Formation, (10^0 08.538′N and11^0 53.223′ E)



Plate XIX. Limestone unit of the Kanawa Member fragments turning to yellowish- gray along Kukuwa Gari road, (10^0 08.538′N and 11^0 53.223′ E)



Plate XX. Shale unit of the Kanawa Member overlain by alluvial deposit exposed outskirt of Bara along stream channel, (10^0 58.480′N and 11^0 40.477′ E)

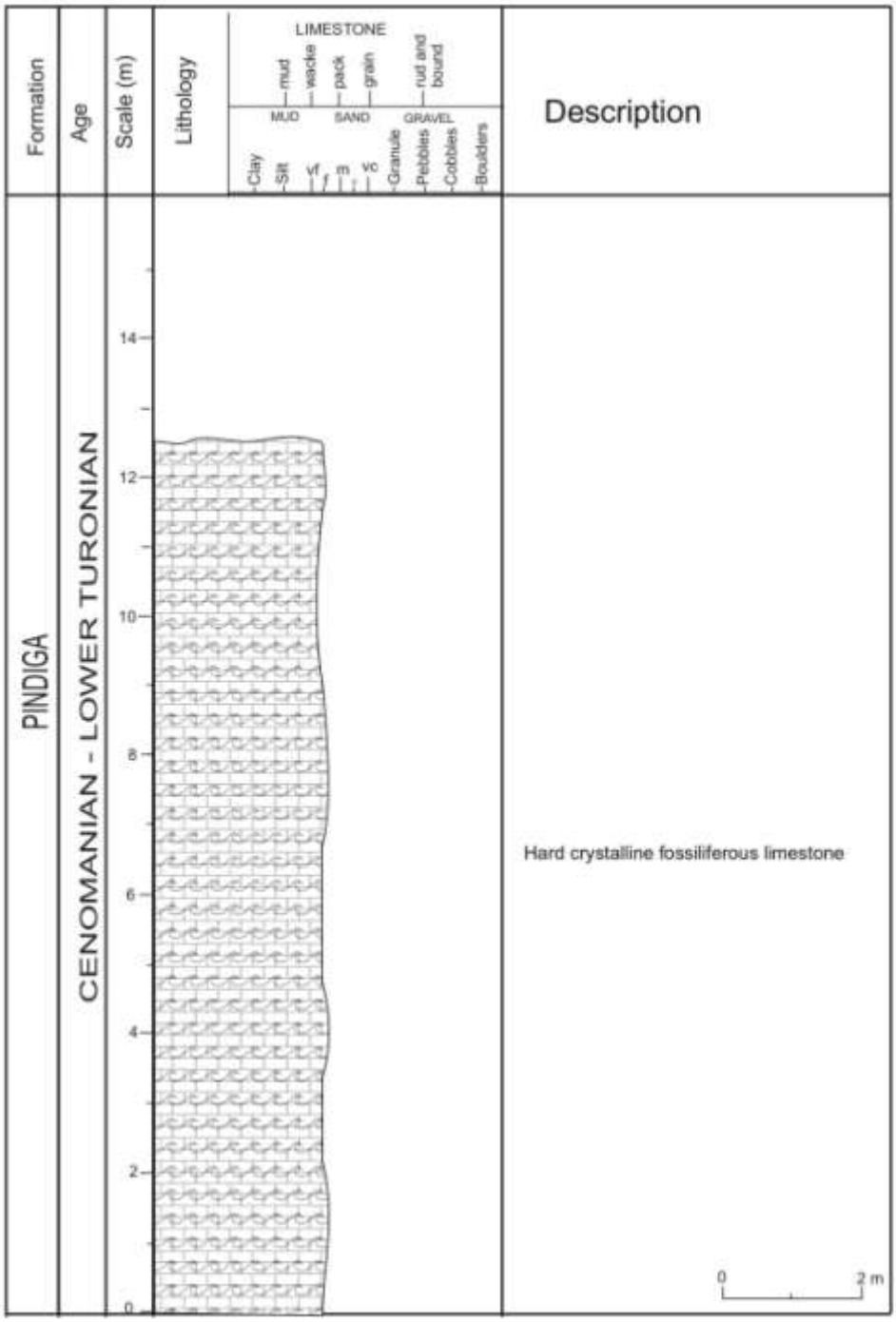


Fig. 16. Section of the Kanawa Member of Pindiga Formation exposed at Yadi Kukuwa stream

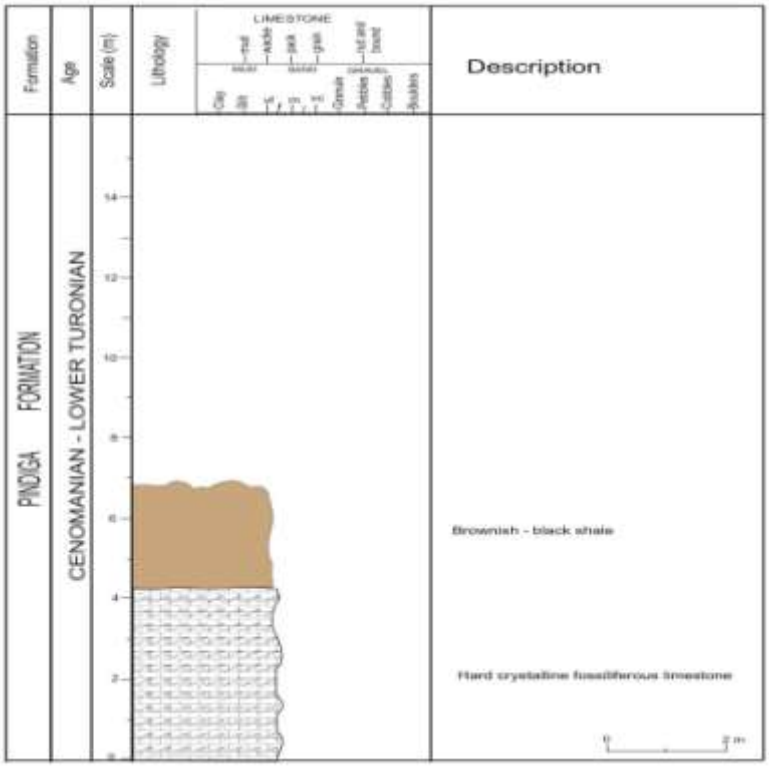


Fig. 17 Section of the Kanawa Member (Pindiga Formation) exposed at northern part of Gabai.

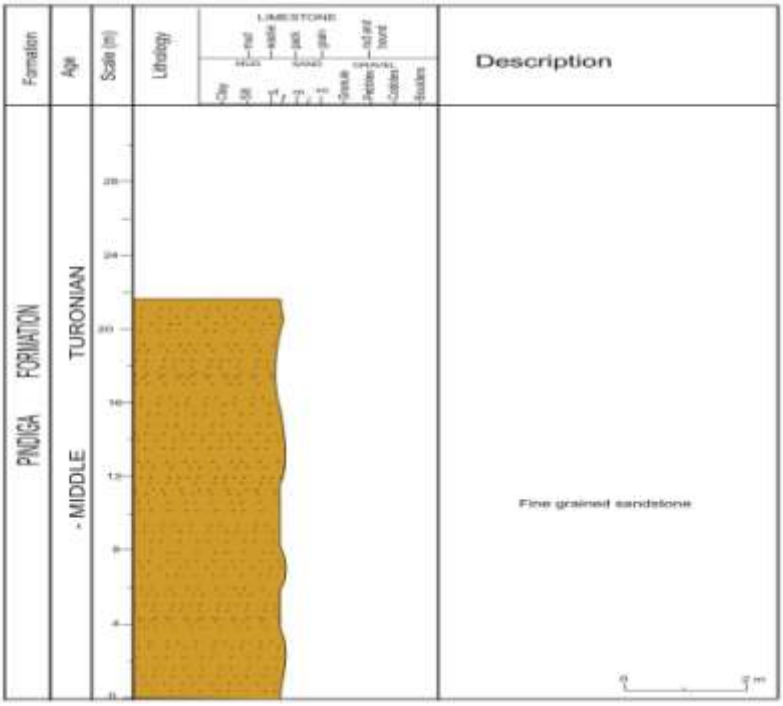


Fig. 18. Section of the Dumbulwa Member of (Pindiga Formation) exposed along Njibulwa railway crossing

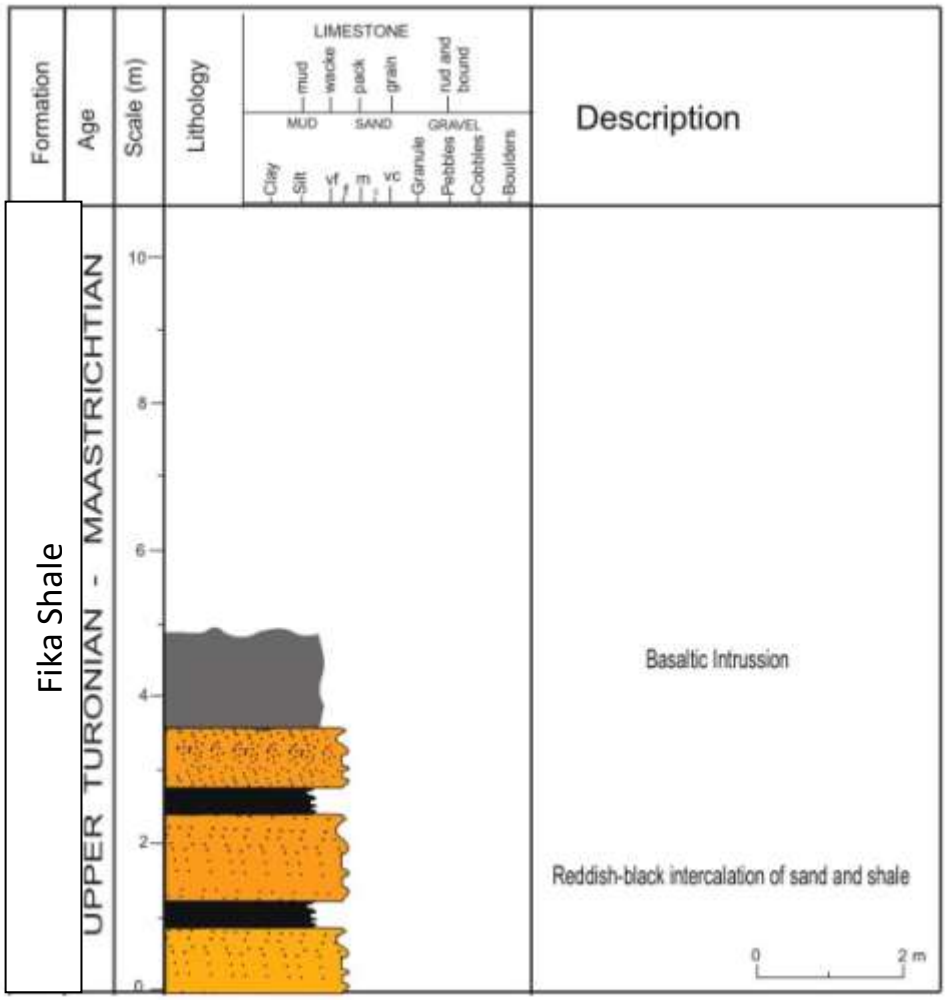


Fig. 19. Section of the Fika Shale exposed along Mutwe road

Dumbulwa Member

Th**e** Dumbulwa Member is the previously **re**cognized sandstone- shale unit of the Gongila Formation that was later assigned the name Dumbulwa Member by (Zaborski *et al*., 1997). The stratigraphic unit was observed along Gabai road, it is interbedded sandstone- shale unit, the samdstone is fine-medium grained and milk colour while the shale is gray to black (Plate XXI). The outcrop is exposed along a fracture plane which trends NW-SE direction.

It is milk colour in hand specimen, and medium- grained sandstone with a massive touch.

Only one sample was analysed for petrograhic study, and showed that it is composed of quartz, altered feldspar, microcline, orthoclase, zircon and andesine.



Plate XXI. Interbedded sandstone/shale unit of Dumbulwa Member of the Pindiga Formation, fractured beds are trending NW- SE direction, (11^0 02.550′ N and 11^0 42.010′ E)

Fika Shale

The stratigraphic unit is exposed along Mutwe road, it was observed as an intercalated limestone/shale bed (Plate XXII), the limestone is massive, gray crystalline with no mega-fossils as observed in the Kanawa Member. The limestone is basically very thin and fragmented in most of the outcrops, unlike the Kanawa Member which has very thick beds measuring upto 7m.

The Fika Shale of Carter *et al*. (1963) was reviewed to Fika Member of the Pindiga Formation in the Gongola Basin by Zaborski *et al*. (1997), but its formation status is maintained in the Bornu Basin.

In hand specimen, the shale is blue- black and some are brownish- black, while the limestone is hard and crystalline, though no macrofossils observed



Plate XXII. Shale/limestone unit of the Fika Shale exposed along Mutwe Road, (11^0 14.176′ N and 11^0 42.95′ E)

Kerri- Kerri Formation

The Kerri- Kerri Formation overlies the Cretaceous sediments in the Bornu Basin unconformably. The outcrop observed is the uppermost part of the formation which is overlain by the Chad Formations. It is a ferruginized clast- supported conglomeritic-sandstone bed (Plate XXIII). Clasts of quartz of rounded to sub-rounded are embedded in

the groundmass matrix. This area was previously mapped as Chad Formation; this is the first time the Kerri- Kerri Formation is recognized and mapped in this study part of the basin of study area. Gombe Sandstone or its equivalent which suppose to overlie the Fika Shale has been observed in the study area. this is because deposition of sediments during Maastrichtian shifted to the west of the basin and no records was reported anywhere even in hand- dug wells or boreholes towards the eastern part of the basin..



Plate XXIII. Ferruginized conglomeritic- sandstone of the Kerri- Kerri Formation exposed in the northeastern part of Yadi Kukuwa, (11^0 09.238′ N and 11^0 55.657′E)

Chad Formation

The Chad Formation covers vast area in the northeastern part of the study area; it unconformably overlies the Kerri- Kerri Formation. It is coarse- medium grained in texture and very loose sand. The outcrop is medium- grained sand, reddish in colour, it is the base of the formation (Plate XXIV), the red colouration may be as a result of weathering and

erosion that have obliterated the feldspar and quartz minerals to geothites (possibly limonite, hemate or magnetite may be present).



Plate XXIV. Red, medium- grained sand of the Chad Formation, exposed at eastern part of Yadi Kukuwa.

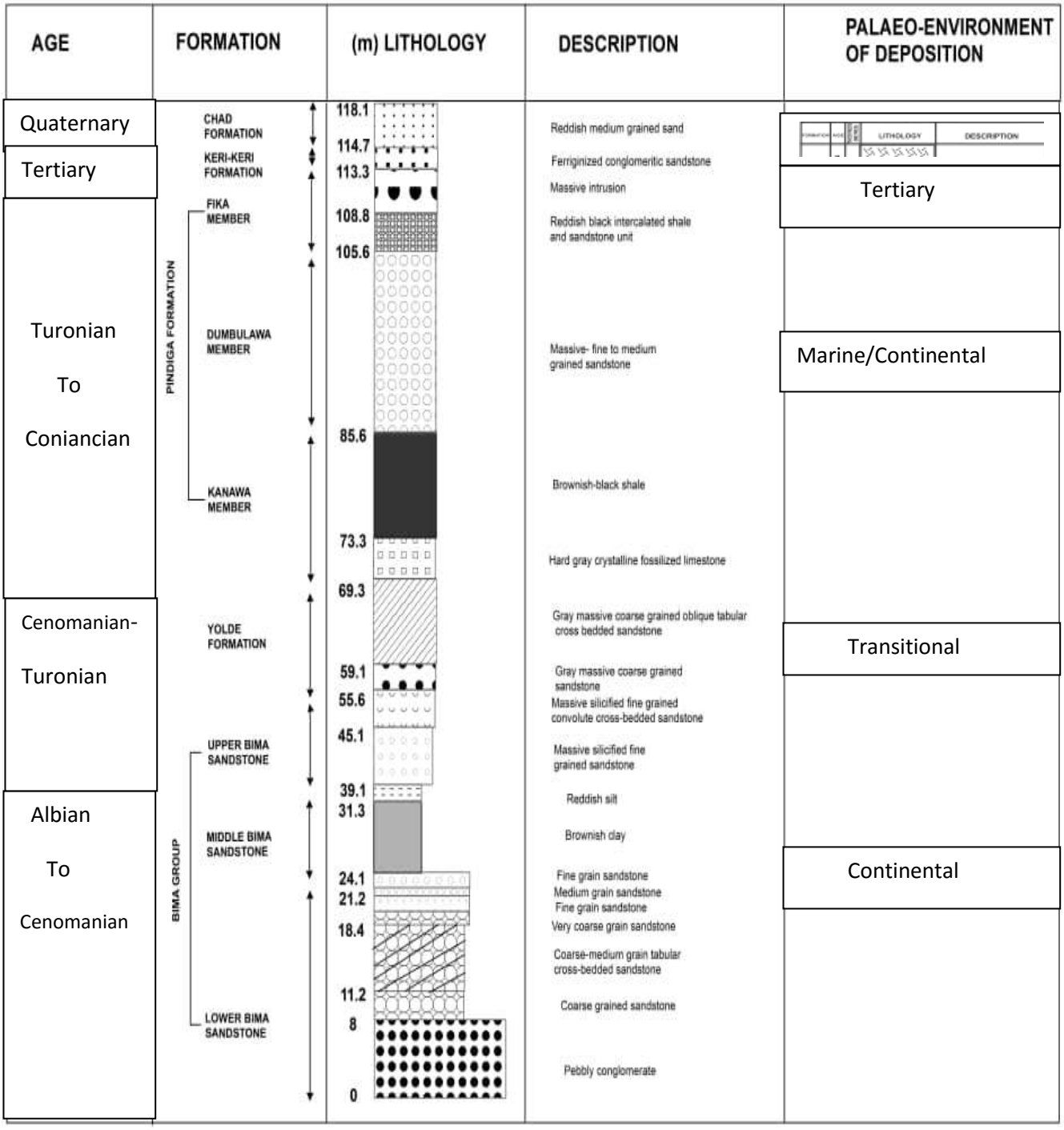


Fig 20: A composite lithostratigraphical succession of the Bornu Basin (This study).

4.2 Facies Analysis

Detail facies analysis was carried out in this work and allows a primary classification based on four groups, mostly according to the grain-size observed within outcrops. This is inspired purely on the descriptive facies classification presented by (Miall, 1978; Ghibaudo, 1992; Miall, 1996; Poyatos- Moré, 2014).

The four main groups recognized in this study are: [a] Gravel Facies, including all beds in the study area containing granules to boulders as the maximum grain-size, and abridged with a code G (first letter of the code); [b] Sandstone Facies, including those beds having very- coarse to very- fine sand as their maximum grain-size, and abridged with a code key S; [c] Mudstone Facies, including the spectrum of grain populations from coarse silt to clay, which is abridged with the code key M, and finally [d] Carbonate Facies, including mixed layers of sandy carbonate as the case may be in some sandstones.

a) G- Facies imclude clast- supported conglomerates (Gcs) of Lower Bima Sandstone and Kerri- Kerri Formation (Plates IV and XXIII), clast- supported conglomerates grading to sandstones (Ggs) of Lower Bima Sandstone (Plate III), grain sizes exceeding 2mm in diammetre.
b) S- Facies include massive sandstones (Ss), of Upper Bima Sandstone (Plate XI), cross- bedded sandstones (Sx), of Lower and Upper Bima Sandstones and Yolde Formation (Plates VI, XI, XII, XIV, XV, XVI), normally- graded sandstones (Sng) of Lower Bima Sandstone, Dumbulwa Member of the Pindiga Formation, and Chad Formation (Plates VII, XXI and XXIV). Sand grain sizes range from 0.0625mm to uo to 2mm in diammetre.

c) M- Facies include silt and clay streaked layers (Msm) of Lower and Middle Bima Sandstones, Yolde Formation, and Kanawa Member of Pindiga Formation (Plates VIII, IX, XVII and XX) and massive mudstones (Mm) of Yolde Formation (Plate XVI), mud grain sizes include silt to clay particles, less than 0.0625mm.

d) C- Facies include carbonate-rich layers (Cl) of Kanawa Member of the Pindiga Formation and Fika Shale of this study. This group of facies is classified according to their lithology and carbonate content.

In the first part of each group within the study area, a descriptive synthesis of all the facies types is presented. Table 4.1 below shows the code assigned to each facies type and then descriptions highlight features as well as brief interpretation of transport and depositional processes involved in the studied sediments. Occassionally, some similarities is established with other facies interpretations proposed by different authors (e.g., Lowe, 1982; Mutti, 1992; Mutti *et al*., 1999; Tinterri, 2007; Zavala *et al*., 2011; Puy-Alquiza *et al*., 2017).

Table 4.1 Facies analysis and their codes used in this study

GROUP CODE	MAXIMIM GRAIN SIZE	LITHOLOGY	FACIES ASSOCIATION CODE
G	Gravel	Clast-supported conglomerates	Gcs
		Clast-supported conglomerates grading into sandstones	Ggs
S	Sandstone	Massive sandstones	Ss
		Cross-bedded sandstones	Sx
		Normally-graded sandstones	Sng
M	Mudstone	Silt clay streaked layers	Msm
		Massive Mudstone	Mm
C	Carbonate	Carbonate-rich layers	Cl

4.3 Petrography

About sixteen (16) rocks samples were analysed to determine their mineral distribution for sandstone classification based on Loren (2002) scheme. Table 4.2 below shows the mineral distribution from sandstone slides and Table 4.3 is a scheme for classification of sandstones.

Point counting method deduced from petrographic studies showed that quartz distribution ranges from 31.20- 67.74%, altered feldsper ranges from 5.37- 34.61%, microcline ranges from 0.97- 3.65%, orthoclase ranges from 17.47- 33.33%, albite ranges from 1.12- 6.66%, zircon ranges from 0.96- 4.34%, limonite ranges from 9.38- 22.21%, muscovite ranges from 2.08- 2.87%, biotite appeared only once and has a percentage value of 0.22. Andesine has a distribution value which ranges from 1.92- 2.66% and hematite ranges from 4.87- 25.64%.

Below are 16 slides 24 a, b, 26 c, d, e, f, 27 g, h, I, j, 28 k, l, m, n, 29 o and p observed under cross- polars. They represent different sandstone groups encountered in the field.

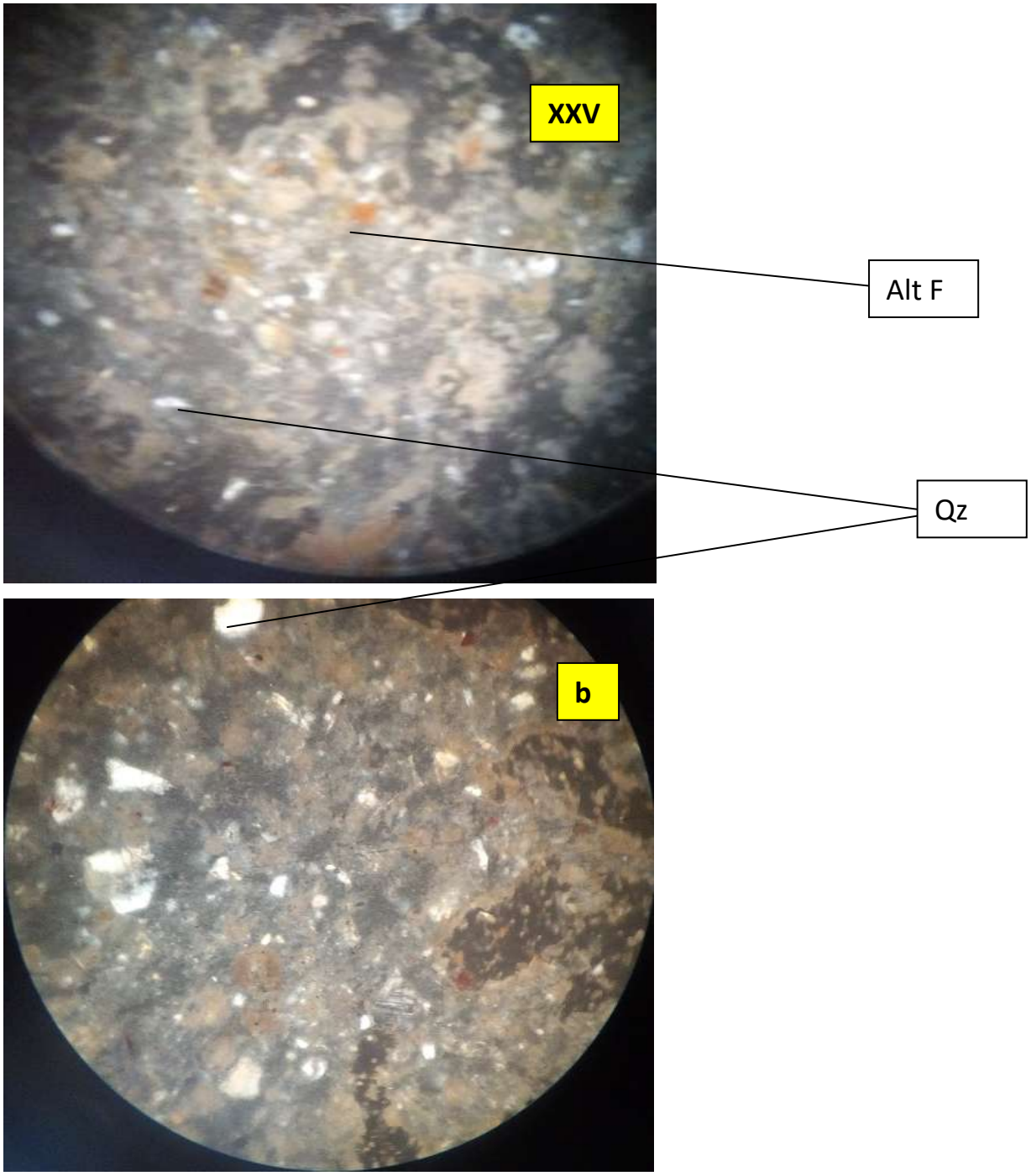


Plate XXV. a- arkosic arenites, b- arkosic arenites, Alt F- altered feldspar, Qz- quartz. Photomicrograph under cross- polars.

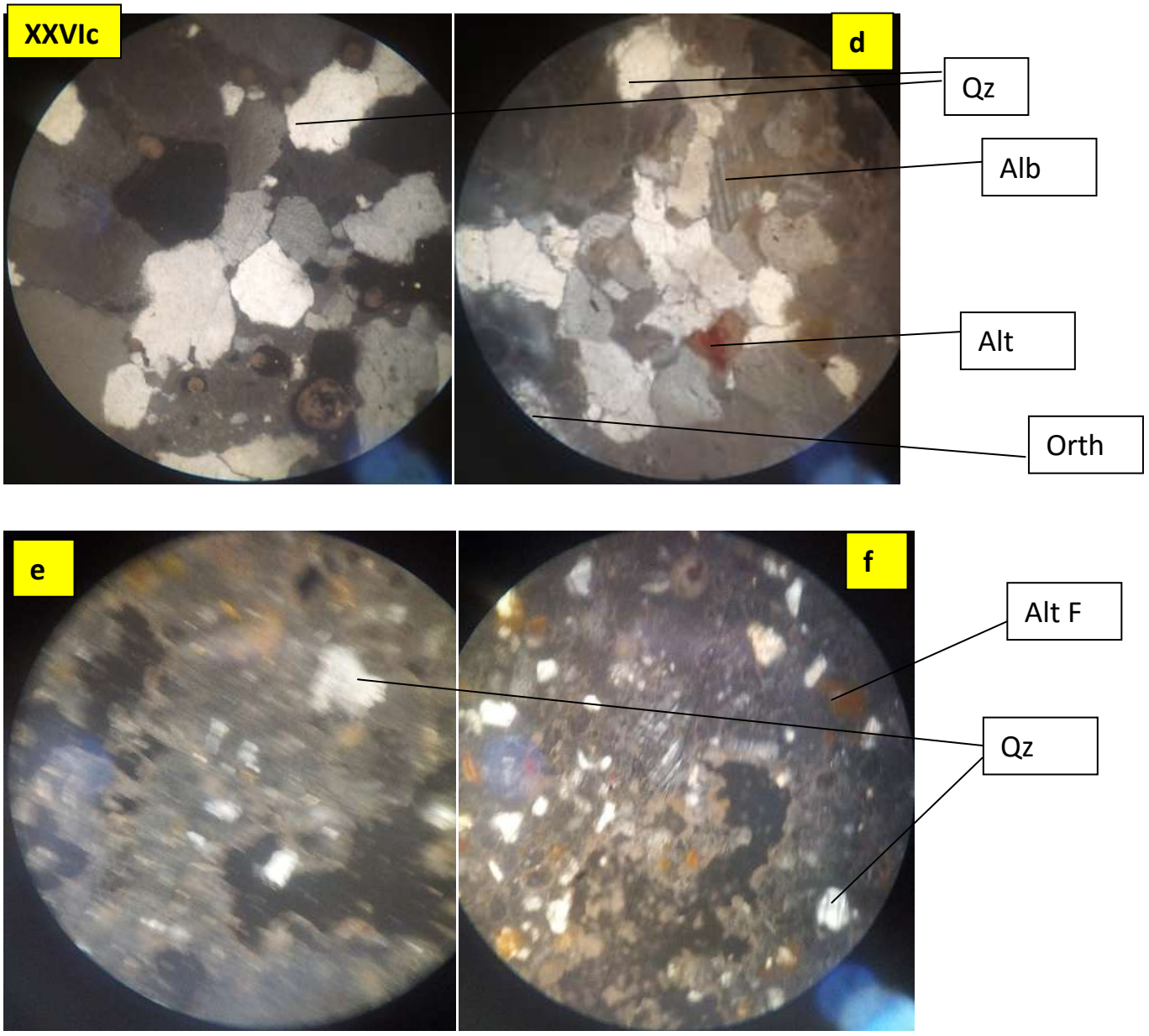


Plate.XXVI. c- lithic arenite, d-arkosic arenite, e- lithic arenite, Qz- quartz, Alt F- altered feldspar, Orth- orthoclase, Alb- albite. Photomicrographs under cross-polars.

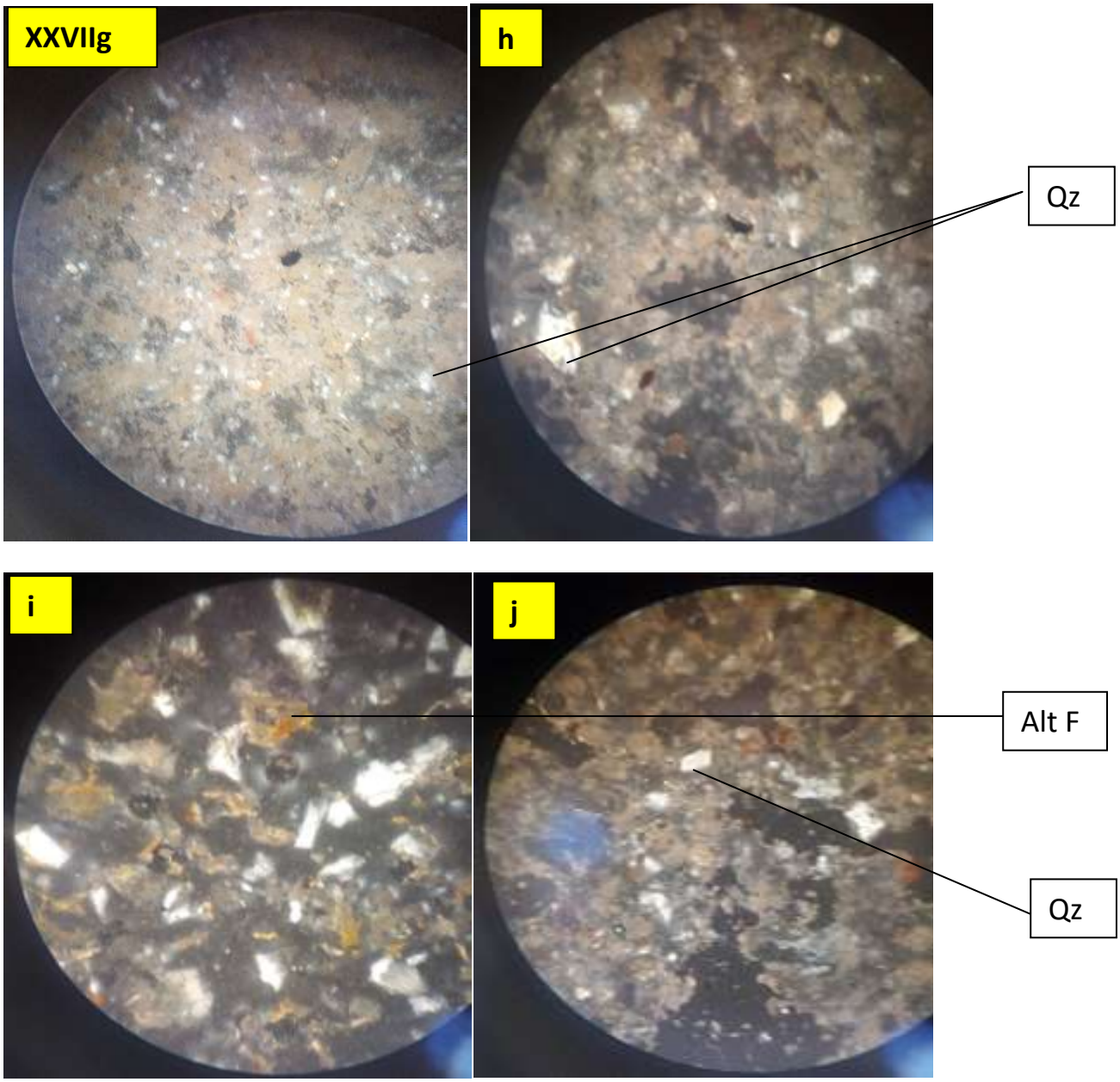


Plate XXVII. g- lithic arenites, h- arkosic arenites, i- arkosic arenites, j- arkosic arenites, Qz- quartz, Alt F- altered feldspar. Photomicrographs under cross- polars

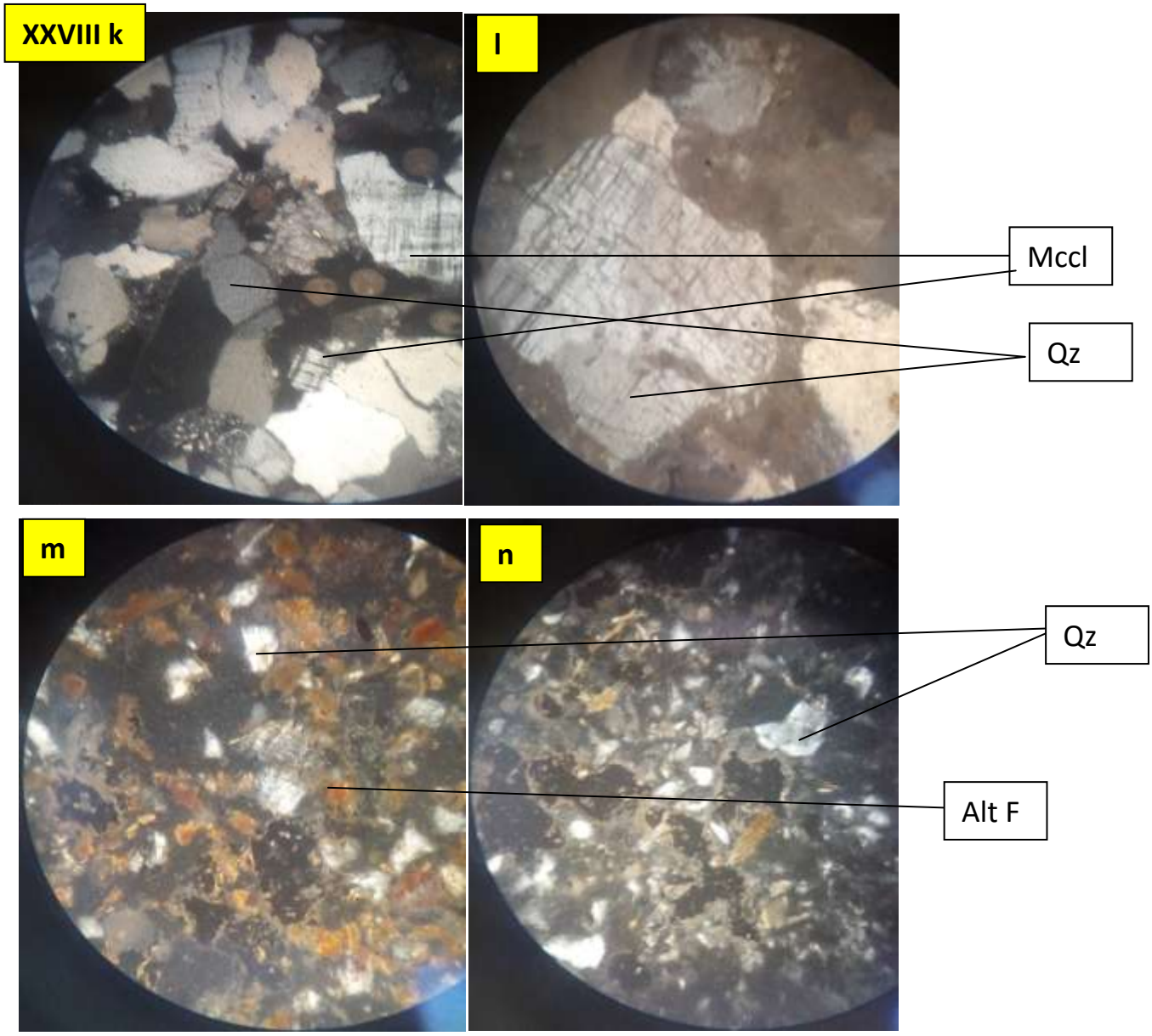


Plate XXVIII. k- arkosic arenites, l- arkosic arenites, m- arkosic arenites, n- arkosic arenite, Mccl- Microcline, Qz- quartz, Alt F- altered. Photomicrograph under cross- polars

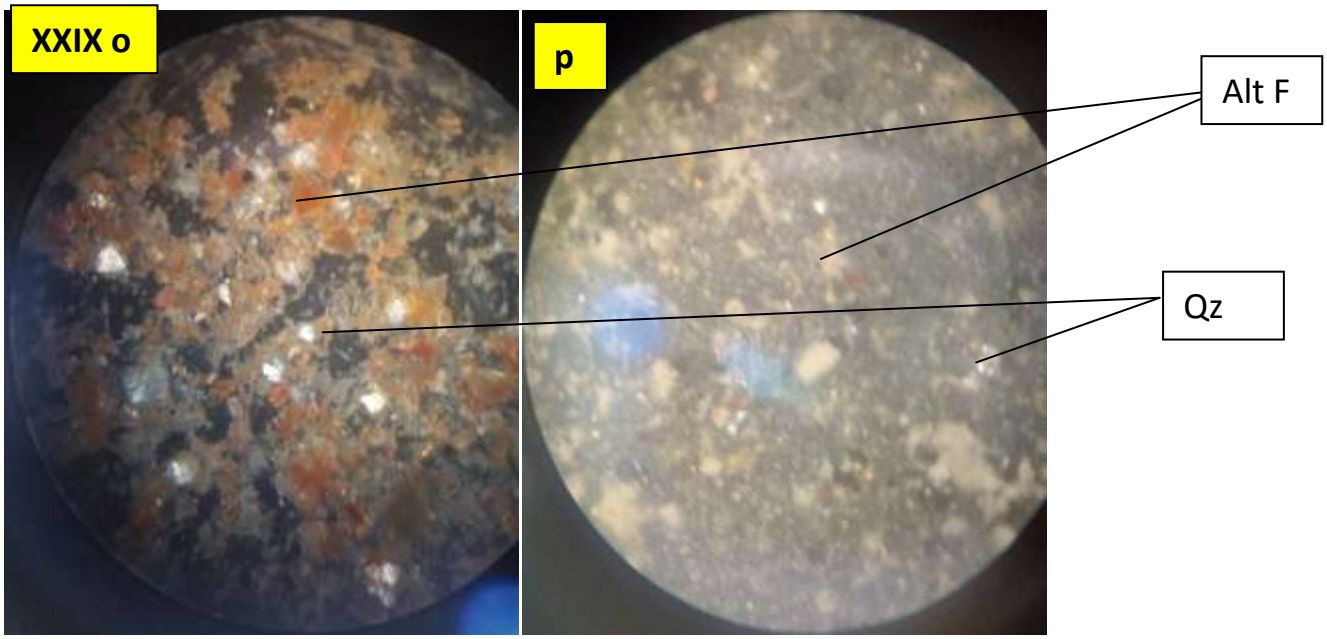


Plate XXIX. o- arkosic arenites, p- arkosic arenites, Alt F- feldspar, Qz- quartz. Photomicrographs under cross- polars

Table 4.2: Mineral composition of Sandstones of Bima Group, Yolde Folde Formation and Dumbulwa Memnber of Pindiga Formation in the study area

Mineral Constituents	**4**	**5**	**7**	**12**	**21**	**24**	**25**	**26**	**27**	**28**	**34**	**35**	**36**	**38**	**40**	**41a**
Quartz	39.02	46.66	67.74	46.15	45.83	39.42	43.43	39.74	35.92	29.56	50	61.11	33.70	49.33	39.13	31.20
Altered Feldsper	18.29	25.33	-	-	17.70	15.38	-	34.61	30.09	22.60	5.37	-	26.96	13.33	24.63	28.80
Hematite	4.87	17.33	-	13.46	17.70	17.30	25.25	25.64	13.59	23.47	8.92	-	16.85	-	-	20.80
Microcline	3.65	2.66	-	-	2.08	1.92	3.03	-	0.97	1.73	-	2.77	3.37	1.33	1.44	-
Orthoclase	28.04	-	32.25	24.03	-	23.07	-	-	17.47	20.86	29.46	33.33	17.97	32	18.84	19.20
Albite	3.65	6.66	-	2.88	3.13	-	-	-	-	1.73	-	2.77	1.12	-	-	-
Zircon	2.43	1.33	-	-	2.08	0.96	1.01	-	1.94	-	-	-	-	1.33	4.34	-
Limonite	-	-	-	13.46	9.38	-	27.27	-	-	-	-	-	-	-	11.59	-
Muscovite	-	-	-	-	2.08	-	-	-	-	-	2.87	-	-	-	-	-
Andesine	-	-	-	-	-	1.92	-	-	-	-	-	-	-	2.66	-	-
Biotite	-	-	-	-	-	-	-	-	-	-	3.57	-	-	-	-	-
Total	**99.95**	**99.97**	**99.99**	**99.98**	**99.98**	**99.97**	**99.99**	**99.99**	**99.98**	**99.95**	**99.99**	**99.98**	**99.97**	**99.98**	**99.97**	**100**

Table 4.3 Percentage of mineral grains for classification of sandstones of the Bima Group, Yolde Formation and Dumbulwa Member of Pindiga Formation in the study area

Mineral Grains	**4**	**5**	**7**	**12**	**21**	**24**	**25**	**26**	**27**	**28**	**34**	**35**	**36**	**38**	**40**	**41a**
Quartz	39.02	46.66	67.74	46.15	45.83	39.42	43.43	39.74	35.92	29.56	50	61.11	33.70	49.33	39.13	31.20
Feldsper	53.63	34.65	32.25	26.91	22.91	42.29	4.04	34.61	48.53	46.92	34.83	38.87	49.42	49.32	44.91	48
Rock Fragments	7.30	18.66	-	26.92	31.24	18.26	52.52	25.64	15.53	23.47	15.16	-	16.85	1.33	15.93	20.80
Name of terrigino us sediment	Arkosic arenite	Arkosic arenite	Arkosic arenites	Lithic arenite	Lithic arenites	Arkosic arenites	Lithic arenites	Arkosic arenites	Arkosic arenites	Arkosic arenites	Arkosic arenite	Arkosic arenite	Arkosic arenite	Arkosic arenite	Arkosic arenite	Arkosic arenite
Total	**99.95**	**99.97**	**99.99**	**99.98**	**99.98**	**99.97**	**99.99**	**99.99**	**99.98**	**99.95**	**99.99**	**99.98**	**99.97**	**99.98**	**99.97**	**100**

4.4 Trace Element Geochemistry

Trace elements analysis of rocks obtained in the study area is shown in Table 4.4. this results shows that among the biophile elements (V, Ni), V concentration ranges from 0.264- 1.288ppm and Ni concentration ranges from 0.298- 0.721ppm, Siderophile elements (Mn, Co, Cr, Fe and Mo) have concentration values as follows, Mn ranges from 0.821-7.567ppm, Co 0.352-0.783ppm, Cr ranges from 0.233- 0.753 ppm, Fe ranges from 1.289-264 ppm and Mo ranges from 0.030- 0.133 ppm, Chalcophile elements (Cd, Pb, Zn, and Cu), Cd concentration ranges from 0.000- 0.012 ppm, Pb ranges from 0.000- 0.339 ppm, Zn ranges from 0.000- 0.425 ppm, and Cu ranges from 0.000- 0.238 ppm

Table 4.4. Concentration of some trace elements associated with shales of Kanawa Member of Pindiga Firmation and Fika Shale of Bornu Basin.

Samples	Mn	Co	Cr	Cd	Pb	Zn	Ni	Cu	Fe	V	Mo
3	3.4	0.362	0.24	0	0.044	0.166	0.37	0	1.289	0.32	0.053
11	2.444	0.508	0.508	0	0.339	0	0.416	0	139.4	0.647	0.133
14	5.809	0.548	0.703	0	0.029	0.22	0.721	0.238	264.8	1.288	0.024
19	7.567	0.497	0.352	0	0	0	0.317	0.01	43.1	0.264	0.041
22	5.4477	0.583	0.33	0	0	0	0.347	0	190.37	0.584	0.038
26	4.629	0.355	0.515	0.009	0	0.145	0.375	0.075	206.3	0.833	0.036
30	2.527	0.783	0.233	0	0	0.084	0.524	0	46.12	0.51	0.05
33	0.821	0.552	0.327	0.004	0.055	0	0.33	0.105	145.78	0.702	0.03
34	2.355	0.532	0.753	0.012	0	0	0.557	0.226	214.86	0.869	0.061
Bumsa	1.805	0.47	0.492	0.02	0.106	0	0.298	0.175	188.53	0.719	0.024
Average	3.692	0.499	0.428	0.004	0.057	0.104	0.425	0.083	144.12	0.6736	0.049

CHAPTER FIVE

DISCUSSIONS

5.1 Stratigraphy of the Study Area

The basic lithostratigraphic succession of the study area which is southwestern part of the Chad Basin (Bornu Basin) was first established by Carter *et al*. (1963) and subsequent modification was carried out by Zaborski *et al*. (1997) in the Upper Benue Trough (Gongola Basin) and the northern part of the Dumbulwa Bage high which affected some of the stratigraphic structure of the Nigerian sector of the Chad Basin. Carter *et al*. (1963) assumed the boundary between the Upper Benue Trough and Chad Basin to be the Zambuk Ridge while Zaborski *et al*. (1997) indicated that the Dumbulwa – Bage High which is an anticlinal structure should be the actual boundary between the two basins. Carter *et al*. (1963) considered Ashaka area as part of the Chad Basin, because they designated the sediments east of Gongila Village as the type locality of the Gongila Formation. Zaborski *et al*. (1997) found out that the sediments east of Gongila Village that was designated as Type Locality for the Gongila Formation by Carter *et al*. (1963) actually belongs to Bima Group (Bima 2 and Bima 3) sandstones. Zaborski *et al*. (1997) re-mapped the area and reviewed the lithostratigraphic succession in the area indicated and included the area as part of the Upper Benue Trough (Gongola Basin). They considered the area north of the Dumbulwa- Bage High as fringe of the Chad Basin and hence form part this study area. Some of the modifications made by Zaborski *et al*. (1997) is hereby adopted in this current study because they have corrected the areas mismapped earlier by Carter *et al*. (1963) in the Uppper Benue Trough (Gongola Basin) and revised the stratigraphic succession. Therefore an attempt is hereby made to update the lithostratigraphic succession in the southwestern part of the Chad Basin (Bornu Basin).

5.1.1 Basement Complex Rocks

Undifferentiated basement rocks outcropped in the study area as inlier and is unconformably overlain by Lower Bima Sandstone. They include pegmatites and low-lying hills of medium- coarse grained granites. The mineralogy of the surrounding sediments reflect the general nature of the basement rocks, which were identified to be of arkosic and lithic arenites, both having high feldspar content.

5.1.2 Lower Cretaceous Series (Bima Group)

The Bima Sandstone of Carter *et al*. (1963) in the Bornu Basin is hereby upgraded to Bima Group, consisting of three basic formations (Lower, Middle and Upper Bima Sandstones) this was done after careful geological and stratigraphic studies of previous reports by researchers (e.g. Allix, 1983; Zaborski *et al*., 1997; and Hamza, 2007) in the Upper Benue Trough and the Bornu Basin.

The continental Bima Group comprises the oldest sediments in the Bornu Basin which directly overlies the crystalline basement rocks, although its type locality is at Bima Hill in the Gongola Basin (Falconer, 1911; Carter *et al*., 1963). The principal reference section is at the Lamurde Anticline in the Upper Benue Trough (Yola Basin). There are several outcrops of the Bima Group in the study area particularly in the southern part where it straddles the Biu Basalts and crystalline granites. The lithostratigraphic succession is presented in Figure 20.

This study is hereby proposing that the lithostratigraphic succession in the Nigerian sector of the Chad Basin (Bornu Basin) for the lowermost unit as previously recognized by Carter *et al*. (1963) to be Bima Sandstone to comprise of three (3) lithological formations regarded or referred to as (Lower, Middle and Upper) Bima Sandstones respectively. Carter *et*

*al.**(1963) in the southwestern part of the Chad Basin (Bornu Basin) which form ppart of this study only described two formations namely; Gongila Formation and Fika Shale.

In order to ahieve one of the objectives of this study following the North American Commission on Stratigraphic Nomenclature (2005) Article 19, which explains how to change a rank of lithological unit with undesirable restriction and Article 28 which described the use of content (Group), change in component formation and International Commission on Stratigraphy (1999) Chapter 3, B5 which clearly explains redefinition and revision of a stratigraphic unit and Chapter 5, C6 which defines what a Group coupled with field observation of the lithostratigraphic succession in the study area, the following proposal is hereby presented.

The proposed revision or redefinition will critically make reference to the Upper Benue Trough in areas where previous researchers have worked and assigned Type Locality, Reference Section/Type Section and any special areas of interest where lithological units were well exposed for detail geological studies.

The Lower Bima Sandstone in the study area was observed to outcrop in locations with its lithological features which have similar characteristics as reported in its outcrops in the Upper Benue Trough (Gongola and Yola Basins) respectively. The lowermost unit of the Lower Bima Sandstone in the study area was exposed around Dokshi comprising of gray shale overlain by fine- grained siltstones (Plate VII) which corresponds to the middle lithologic unit of "Formation 1" of Allix (1983) and Allix and Popoff (1983) at the core of the Lamurde Anticline in the Yola Arm of the Upper Benue Trough and Lower Bima Sandstone of Carter *et al*. (1963) in the same location. Lacustrine gray shale was observed

around Dokshi (Plate VIII) which corresponds with Lower Bima Sandstone ("B1") of Guiraud (1990a, 1990b, 1991) in the Wuyo- Kaltungo High and adjacent areas. Coarse-grained sandstone containing pebble beds was observed at Dokshi Village (Plate III) which corresponds to "Formation 2" of Allix (1983) and Allix and Popoff (1983).

The pebbles consists of fragments of feldspar and quartz were observed at Dokshi Village (Plate IV) which shows that they have been deposited not far away from their source and hence referred to as alluvial fans. This also corresponds with lithologies of Lower Bima Sandstone ("B") of Guiraud (1990a, 1990b, 1991). Middle Bima Sandstone in the Bornu Basin in this study was observed at the foot of Tangaran Hill (Plate IX), a clay unit which is light brown in colour believed to have been deposited at lake margin, is similar to the Middle Bima Sandstone ("B2") of Guiraud (1990a, 1990b, 1991) at the Wuyo- Kaltungo High and adjacent areas, and this also corresponds to the argillaceous beds (iii) of Allix (1983) and Allix and Popoff (1983) in the Lamurde Anticline, and also that of Carter e*t al.* (1963) in the same location.

The Upper Bima Sandstone was observed and studied at different locations with varying characteristics: it was observed at the foot of Tangaran Hill which is a silicified sandstone with tabular and convolute cross- bedding (Plates XI and XII) which are similar to what Guiraud (1990a 1990b, 1991) described as fairly homogenous, relatively mature unit comprising of coarse to fine- grained sandstones characterized by tabular and convolute cross- bedding. Fragments of silicified and brecciated sandstones of the Upper Bima Sandstone were observed at Wongeri Hills (Plate X). Zaborski *et al*. (1997) described it as Upper Bima Sandstone and reported that the area have been affected by reversed/thrust fault. Plate XIII is an eroded anticline section of the Upper Bima Sandstone exposed along

Birni Gadam road, this lithology is similar to the sandstone lithology of the Lamurde Anticline around Tashan Alaja and adjacent areas.

Advantages to Formalize the Bima into Group

There are a number of advantages to the formalization of Group

a) It would permit and encourage increased precision in lithostratigraphic correlation and synthesis and discussions of stratigraphy
b) It would require application of the rules of stratigraphic nomenclature and thus sharpen the definition of otherwise vaguely defined formation units. For example, formally defined and named Group would have to conform to the rules of having a specified type locality (Bima Hill) and a measured and described type section (Lamurde Anticline), and a formal definition in terms of diagnostic features, and incorporate these lithologically distinguishable units in sucession of presently informally and formally defined formations.
c) It would permit improvement of hierachial frameworks by encouraging the recognition and definition of disguishable, albeit currently in this studies informally named, formations as lithologically distinct units within Group.

Proposed Review

The proposal of formal Group requires adopting stratigraphic codes that were published by the North American Commission on Stratigraphic Nomenclature (2005) and International Commission on Stratigraphy (1999) codes are required for the purposed of revising the Bima Sandstone from Formation to Group.

Recommended Changes

International Commission on Stratigraphy (1999)

Chapter 3, B15- Revision or redefinition of previously established stratigraphic units.

Revisison or redefinition of an adequately established unit without changing its name requires a statement of intent to revise the unit, the reasons for doing so, and as much justification and documentation as for proposing a new unit change in rank of a stratigraphic unit does not require redefinition of the unit or its boundaries or alteration of the geographic part of the name. A stratigraphic unit may be promoted or demoted in rank without changing the geographic part of its name

Chapter 5, C6 Group

A Group is a succession of two or more contiguous or associated formations with significant and diagnostic lithologic properties in common. Formations need not be aggregated into groups unless doing so provides a useful means of simplifying stratigraphic classification in certain intervals. Thickness of a stratigraphic succession is not a valid reason for defining a unit as a group rather than a formation. The component formations of a group need not be everywhere the same.

North American Commission on Stratigraphic Nomenclature (2005)

Revision and Abandonment of Formal Units

Articlce 19- Revision. Revision involves either minor change in the definition of one or both boundaries of a unit, or in the units rank

(b) Change in rank- Change in rank of a stratigraphic or temporal unit requires neither redefinition of its boundaries nor alteration of the geographic part of its name. A Member

may become a Formation or vice versa, a Formation may become a group or vice versa and a lithodeme may become a suite or vice versa.

(g) Undesirable restriction- When a unit is divided into two or more of the same rank as the original, the original name should not be used for any of the divisions. Retention of the old name for one of the units precludes use of the name in term of higher rank. Furthermore, in order to understand an authors meaning, a later reader would have to know about the modification and its date, and whether the author is following the original or the modified usage. For these reasons, the normal practice is to raise the rank of an established unit when units of the same rank are recognized and mapped within it.

Rank of Lithostratigraphic Units

Article 28- Group. A group is the lithostratigraphic unit next in rank to formation; a group may consist entirely of named formations, or alternatively, need not be composed entirely of named formations.

Remarks (a) Use of Content- Groups are defined to express the natural relations of associated formations. They are useful small- scale mapping and regional stratigraphic analysis. In some reconnaissance work, the term “group” has been applied to lithostratigraphic units that appear to be divisible into formations, but have not yet been divided. In such cases, formations may be erected subsequently for one or all the practical divisions of the group.

(b) Change in Component formations –

The formation making up a group not necessarily be everywhere the same. However, a formation or its parts may not be assigned to vertically adjacent groups.

(c) When a previously established formation is divided into two or more component units that are given formal formation rank, the old formations, with its old geographic name, should be raised to group status. Raising the rank of the unit is preferable to restricting the old name to a part of its former content, because a change in rank leaves the sense of a wel-established unit unchanged

5.1.2.1 Lower Bima Sandstone ("B1")

The main rock type that characterized the Lower Bima Sandstone in the study area is made up of sand, gravels with poorly defined bedding which is believed to have formed as alluvial fan deposits. The term "Bima Sandstone" was first used by Falconer (1911) for beds occurring at the type locality, Bima Hill, and including Yolde Formation of later authors. The Lower Bima Sandstone consist of alluvial fans occurring in (semi-arid and a humid environment, braided river sandstone, lacustrine deposit, highly arkosic pebbly sandstones, conglomerates and fresh fragments of arkosic basement including feldspar pebbles. Others include gravelly sandstones and boulder orthoconglomerates, conglomerates with pervasive siliceous cement; these sediments are mostly poorly to moderately sorted in some places, though they are arkosic arenites, their mineralogical composition is presented in Tables 4.1 and 4.2. The sandstones of the Lower Bima Sandstone are classified, and their high feldspar content can be attributed to proximity to the basement rocks. The formation contains pebbly conglomerates, with angular fragments of fresh quartz and feldspars believed to have come from the adjacent granites. The thickest section observed in the formation occurs at a quarry site having succession of gray shale at the base with thick bed of sandstones overlying the shale, the sandstones have been

intensely weathered to reddish, and the lithofacies of the sandstones are separated by thin ferruginized bedding planes.

South of Dutsen Mafurun (Lanske), the Lower Bima Sandstone exhibits some NW- SE trend along a fault plane, though the formation is not well exposed as in the Gongola Basin. The fault was measured at a coordinate of N10^{0}55′ 41'' N and 11^0 45^i 23$^{''}$ E. Sandstones with pebbles,, fragments of quartz and feldspars with conglomerates were observed in the Lower Bima Sandstone (Plate III). Co-axial joints, tabular cross- bedding are common primary geological structures observed in the formation. At Dokshi village, gray shale is exposed at the base of a section of the Lower Bima Sandstone (Plate VIII), this is the first report of shale unit within the Bima Group in the Bornu Basin as it also occurs in the Lower Bima Sandstone in the Gongola Basin.

5.1.2.2 Middle Bima Sandstone ("B2")

The Middle Bima Sandstone was described by Carter *et al*. (1963) and subsequently by Allix (1983), Allix and Popoff (1983), and Guiraud (1990a). The formation consists of coarse- grained feldspathic sandstone with tabular and trough cross- bedding, as well as fine- medium grained sandstone. Thick sequence of clay, silts, sandstone, and calcareous sandstones occur in the formation. The formation outcrops in the study area at different locations, but having thin lithological sections, though it passes rapidly into Upper Bima Sandstone such as in the outcrop at Tangaran Hill. The formation varies in thickness at different exposures. The sandstones of the Bima are massive, and range in texture from fine-coarse grained feldspathic, particularly the medium and coarse- grained varieties are more massive. The Middle Bima Sandstone is distinguished from the Upper Bima Sandstone in this study by the yellowish to reddish brown to gray clay that outcropped at

the foot of Tangaran Hill and Bumsa Village with varying colours such as yellow and gray, similar clays of yellow and gray colour was observed at Bursari village measuring up to 4.9m. It occurs as a thin bed. The clay was reported at the middle of the Middle Bima Sandstone stratigraphically by Zaborski *et al*., (1997) in the Gongola Basin, while the massive sandstone of the formation rapidly passes into the Upper Bima Sandstone. At the foot of Tangaran Hill, a mark lateritic facies (diastem) was observed at the upper surface of the Middle Bima Sandstone which probably separates the Middle from the Upper Bima Sandstone as a result of reverse/thrust fault. The clay has been described by previous researchers as a lake margin deposit (Carter *et al*., 1963; Allix, 1983; Allix and Popoff, 1987). The thick clay bed is subsequently overlain by reddish sandstone.

5.1.2.3 Upper Bima Sandstone ("B3")

The formation is well exposed at the foot of Tangaran Hill where a thrust/reverse fault occurs. The formation was observed at Bularafa, Birni Gadam, and Wongeri Hills, Plate X shows a thrusted area of silicified sandstone that has been brecciated into fragments. The best outcrop of this lithological unit in the study area occurs at Tangaran Hill where both tabular and convolute cross-beds are exposed at a stream channel (Plates XI and XII). Its boundary has not been properly reported by previous researchers as observed in this work. It is mostly thinly bedded and poorly exposed in most of the outcrops identified; it varies in thickness from 12m to greater than 15m. The Upper Bima Sandstone is homogeneous, medium-coarse grained sandstone unit which is sometimes difficult to distinguish with upper part of Middle Bima Sandstone as it rapidly passes into Upper Bima Sandstone, except where they show syn- sedimentary structures. The Upper Bima Sandstone is identifiable by its tabular and convolute cross- beddings, while the former is recognized by

trough cross- bed and clay materials, these structures and facies characteristics were used in distinguishing the Bima Sandstones as earlier reported by Zaborski *et al*. (1997) and Carter *et al*. (1963) in the Gongola Basin.

The following are values documented along dip angles on anticlinal folded beds identified close to Birni Gadam.

1) 42^0
2) 56^0 both measurements were taking along E-W direction
3) Plate XIII shows a probable eroded anticlinal surface

The Upper Bima Sandstone is massive, fine- grained sandstone with high feldspar content that is mostly arkosic arenitic sandstone.

5.1.3 Upper Cretaceous Series'

5.1.3.1 Yolde Formation

The name "Yolde Formation" was proposed by Carter *et al*. (1963) for "transitional beds" recognized earlier by Falconer (1911) and Barber *et al*. (1954) between the Bima Group and the Pindiga Formation. This is the first time Yolde Formation is being reported as a stratigraphic unit in the Nigerian sector of the Chad Basin (Bornu Basin) using geological field evidences at various locations and localities within the research area. In some of the localities such as Yadi Kukuwa and Shishiwaji, the lower part of the Yolde Formation was observed with same characteristics and resembles what was earlier reported by Zaborski *et al*. (1997) and similarly, by Carter *et al*. (1963) both in the Gongola and Yola Basins, which composed of alternating sandstone and purple gray mudstone at its base with tabular cross-bedding. In this study, the alternating sandstone/mudstone beds were observed with

both tabular and oblique-tabular cross-bedded sandstone that are very massive in nature. At Bara, the upper part was observed but very poorly exposed, it was observed being overlain directly by the limestone/shale unit of the Kanawa Member of Pindiga Formation. The lower part is interpreted as fluvial in orogin while the upper part is shallow marine with very fine- grain milky argillaceous facies. Plates 14, 15 and 16 are facies of the Yolde Formation exhibiting different geological characteristics.

5.1.3.2 Pindiga Formation

The Pindiga Formation in this study is being contended, suggested and proposed to replace the Gongila Formation earlier considered by Carter *et al*. (1963) as age equivalent beds made up of a lower limestone- shale member referred to as the Kanawa Formation of Thompson, (1958) and upper sandstone- shale member called the Dumbulwa Member (Zaborski *et al.*, 1997). Although in the Gongola Basin, the formation was described to consist of five members including the Fika Shale of Bornu Basin by Zaborski *et al*. (1997) ; considered as a member of the proposed Pindiga Formation: Kanawa, Deba Fulani, Dumbulwa, Gulani and Fika Members.

The Gongila Formation of Carter *et al*. (1963) is hereby proposed to be Pindiga Formation in this study. This is as a result of mis-mapping of the area that make up the boundary between northern part of the Gongola Basin and southwestern Chad Basin (Bornu Basin) by Carter *et al*. (1963), as pointed out by (Zaborski *et al.,* 1997). Zaborski *et al*. (1997) reported that the Type Locality of Gongila Formation near Gongila Village and the reference section south of Shole River were wrongly sited by Carter *et al*. (1963) and that, the lithologies described as limestone/shale and sandstone were not seen at the section, rather sandstone of the Lower and Middle Bima Sandstones were the sediments observed in

the Type Locality referred by Carter *et al*. (1963). Therefore, this study adopts the revised nomenclature by Zaborski *et al*. (1997). Black to dark brown shale was observed at a stream in Yadi Kukuwa in this study (Plate XVII), while thick bed of yellowish limestone was also seen around Yadi Kukuwa which corresponds to the shale/limestone interbedded unit of the Kanawa Member exposed around Kanawa Village as reported by Thompson (1958), Carter *et al*. (1963) and Zaborski *et al*. (1997) within the Gongola Basin which form the lower member of Pindiga Formation. Other similar outcrops of the Kanawa Member were observed at Kukuwa Gari road (Plate XIX) and shale overlain by alluvial deposit exposed at the outskirt of Bara along a stream channel in this study (Plate XX). The Dumbulwa Member which is a new name proposed by Zaborski *et al*. (1997) was mapped at the western part of the study area where it wedges out, this unit was observed to consist of sandstone/shale unit along fractured zone trending NW- SE direction direction in this study (Plate XXI). It is milk in colour in hand specimen and medium- grained massive sandstone which corresponds to the Dumbulwa Member of Zaborski *et al*. (1997) exposed at Dumbulwa- Hills and Upper Sandstone – Shale unit of Carter *et al*. (1963) also in the same location.

General Procedure for Revising the Gongila Formation to Pindiga Formation

Article 7- (b) Duplication of name – Responsibility for avoiding, either in use of the same name for different units (homonymy) or in use of different names for the same unit (synonomy), rests with the proposer.

Chapter 3 Definitions and Procedures

B. Procedure for Establishing and Revising Stratigrapghic Units,

3. Naming of Stratigraphic Units- The names of most stratigraphic units consist of an appropriate geographic name combined with an appropriate term indicating the kind and rank of the unit.

a. Geographic Component of names of Stratigraphic Units

iv. Inappropriate Geographic Names- A geographic name should not be misleading, e.g. London Formation for a unit in Canada.

Article 20- Abandonment

An improperly defined or obsolete stratigraphic, lithodemic, or temporal unit maybe formally abandoned, provided that (a) sufficient justification is presented to demonstrate a concern for nomenclatural stability, and (b) recommendations are made for the classification and nomenclature to be used in its place.

Kanawa Member

The Kanawa Member is now being considered in this study to replace the lower limestone-shale member of the previously described Gongila Formation of Carter *et al*. (1963) by adopting the revised nomenclature of the Pindiga Formation in the Gongola Basin by (Zaborski *et al*., 1997). 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. The Kanawa Member produces a low featureless topography and weathers to a black shale in most of the outcrops in the study area such as in Yadi Kukuwa, at the foot of Manawaji Hill, at Shishiwaji, theree is a marked boundary with the Yolde Formation. The Kanawa Member has an inter-bedded shale/limestone unit with very poor exposures. It indicate the marine incursion into the basin with very thick limestone beds measuring

between 2.5m to more than 10m in thickness as observed in eastern part of Yadi Kukuwa (Plate XVII) and western part of Yadi kukuwa after railway bridge crossing. It also outcrops at Bularafa with thick bed of macroscopic fossils (Plates XVIII and XIX). In some outcrops such as in part of Manawaji village, is an interbedded shale- sandstone unit. It also outcrops at the outskirt of Bara town which is overlain by alluvial sand. The shales of the Kanawa Member are intruded by basaltic flow which forms high hills. Various thick limestone beds occur in numerous areas. In the outskirt of Bara village, a shale- limestone unit outcrops along a narrow stream channel overlain by ferruginized alluvial sand deposit (Plate XIX). No age dating was carried out in this study. The Kanawa Member is exposed at Yadi Kukuwa and parts of Gabai showing the lowermost limestone/shale part of the Pindiga Formation.

Dumbulwa Member

The Dumbulwa Member is a name proposed by Zaborski *et al*. (1997) for a unit of sandstone- shale overlying the previously recognized limestone- shale member of the Gongila Formation of (Carter *et al*., 1963). In this study the upper portion of the Gongila Formation of Carter *et al*. (1963) is regarded as the Dumbulwa Member. Zaborski *et al*. (1997) reported that the term Gongila Formation was inappropriately used for these beds as Gongila village was said to lie on Lower Bima Sandstone and the hill near Gongila village designated as the type locality of Gongila Formation is made up of Middle and Upper Bima Sandstone overlain by the attenuated Yolde Formation and sandy limestone of the Kanawa Member. Though the standard section was said to occur in Shole Stream which corresponds to the sandstone- shale units

related to those at Nguzowa at the foot of Dumbulwa Hills where the type locality of Dumbulwa Member occur as designated by Zaborski *et al*. (1997) In this study area, very few outcrops of the strata were encountered because they have limited occurrence only in the western part and they wedge out in the study area (Fig. 17). Prominent outcrops were seen at Gabai Anticline and northern part of Bara having intercalation of sandstone- shale units. It is fine- coarse grained and feldspathic, the shale units are mostly at the upper part of the facies due to renewed marine incursion that passes into the Fika Shale during the Campo- Maastrichtian global Turonian marine transgression. The sandstone looks milky when fresh and weathers to gray when exposed to chemical action.. No detailed study was carried out because of scanty outcrops. At Bumsa, the shale unit is more dominant covering large areal extent. Outcrop of the Dumbulwa Member was observed at a railway crossing at Njibulwa, showing a relatively thick bed of the sandstone unit of the Dumbulwa Member, the characteristics of the Dumbulwa Member observed is in conformity with same facies reported earlier by (Zaborski *et al*., 1997).

5.1.3.3. Fika Shale

The Fika Shale of Carter *et al*. (1963) is maintained, though it has been downgraded to a member in Gongola Basin by Zaborski *et al*. (1997). The Fika Shale was recognized as a formation in the Bornu Basin by Carter *et a*l. (1963), but was revised and regarded as member of the Pindiga Formation in the Gongola Basin by (Zaborski *et al*., 1997). In the study area, the Fika Shale is featureless and has a very poor occurrence in outcrops, in most of the areas mapped; it is poorly exposed such as in Gabai, Bungai and its extensive occurrence along Mutwe Syncline where interbedded shale/limestone unit occur. This is

distinguishable from the Kanawa Member by its richness in terms of microfossils in the limestone unit and poor in macrofossils as reported earlier by Zaborski *et al*. (1997), as observed in the field. The limestone in the Fika Shale is thin while thick beds occur in the Kanawa Member which measures upto 7m as observed at Yadi Kukuwa. Plate XXII shows interbedded shale with fragments of limestone along Mutwe road.

During the Late Campano- Maastrichtian times in the Gongols Basin the Fika Member which is synonomy of the Fika Shale contains Campanian beds with *dinoflagellates* and arenaceous foraminifera (Lawal, 1982; Allix, 1983). During the Maastrichtian times therefore, the direction of advance of the Saharan seaways switched from east to west of Hoggar Massif, though Genik (1993) reported a final Mid- Eocene marine incursion into the Niger rifts. This

switched was related to approximately N-S oriented terminal Cretaceous compression which brought about ulift in the Benue Trough, the Bornu Basin, the south- eastern Iullemmeden Basin and western Chad Basin (Avbovbo *et al*., 1986; Benkhelil, 1989; Olugbemiro *et al*., 1997; Zaborski *et al*., 1997).

5.1.4 Post- Cretaceous Sedimentation

5.1.4.1 Kerri- Kerri Formation

The Kerri- Kerri Formation is poorly exposed in the study area in the form of thin lens of erosional surface. It occupies a small area in the extreme northeastern part of the study area in the form of indurated, poorly sorted, ferrruginized pebbly sandstone (Plate XXII). It appears as a stratigraphic marker at the boundary with the Chad Formation; and is the uppermost part of the Kerri- Kerri Formation as described by several authors. This is the

first time such formation is reported in the area, because previous workers chers such as Carter *et al*. (1963) mapped it as Chad Formation.

5.1.4.2 Chad Formation

The Chad Formation blanket the northeastern part of the study area (Fig. 20) as it does to most part of the entire Nigerian sector of the Chad Basin (Bornu Basin) with little appreciable information from outcrops, except from drillied logs, this was reported by Carter *et al*. (1963) and Barber *et al*. (1954) from the northern and central parts of the Bornu Basin.

No thick section of the formation was encountered for field detail description in the study area, though several authors have worked extensively on the formation towards the shores of Lake Chad where drilling by NNPC reaching up to a depth of 5010m was reported in which the formation is having a thickness of between 700- 1000m depending on the location of the well (Okosun, 1995; Olugbemiro *et al.*, 1997; Hamza *et al.*, 2002; Obaje *et al*., 2004; and Mohammed, 2010) among others. In this study area, the Chad Formation weathers to reddish medium- coarse- grained sand (Plate XXIV). The dominant feldspathic variety are well exposed along Zugu road, where coarse- grained sand with crystals of quartz and feldspars occur. The sandy unit increased towards the Lake Chad area; while clay unit thinned as one approaches the Lake Chad region. The formation has contact with the Bima Sandstone, Yolde Formation, and Kanawa Member of the Pindiga Formation and Fika Shale in the northeastern part of the study area (Fig. 8).

Relationship of the Chad Basin (Bornu Basin with the Upper Benue Trough (Gongola Basin)

Cratchley *et al.* (1981) reported that the Maiduguri trough represents one continuous fracture extending from the Benue Trough through Lake Chad to the vicinity of Largeau. However, there are numerous positive (+ve) anomaly near Lake Chad area e.g. around Geidam which suggests that the structural history of the area is extremely complex and may well have been modified in the Tertiary Period.

Avbovbo *et al*. (1986) reported that the Chad-Benue Basins are presumed to be related genetically. Knowledge of the Chad Basin geology is deduced primarily from information on the better known Benue Trough (Gongola and Yola Basins), supported by lithologic data obtained from boreholes. Avbovbo *et al*. (1986) summarizes the relationship between structural styles in the Chad Basin and basin configuration. They concluded that folds that developed in the deeper section of the sub-basin are shown to die out in the direction of sedimentary pinchout, this confirming the extension of the Benue Basins geological features into the Chad area.

Matheis (1986) supported the view that the Benue Trough may extend into the Maiduguri sub-basin, while Abubakar *et al*. (2010) reported that the evolution of the Gongola Basin is of rift origin, and Anakwuba *et al.* (2011) stated that this reinforces the idea of similar geodynamic evolution for the region, from the Benue Trough up to the Chad Basin.

In terms of stratigraphic evolution, both the Benue Trough and the Chad (Bornu) Basin are believed to be factors of the third and "failed" arm of a triple junction rift system that formed before opening of the South Atlantic in the Early Cretaceous. The Cretaceous sedimentation and stratigraphic successions of both basins is almost similar as reported by previous researchers. The Bima Group, comprising the Lower, Middle and Upper

Sandstones reported in the Gongola Basin were studied extensively and mapped in the study area including the "pre-Bima" of Avbovbo *et al*. (1986) which consist of Lacustrine shale of Lower Bima Sandstone. The lower section of Yolde Formation was also mapped within a narrow zone, while the middle and upper parts were conspicuously absent, this may not be unconnected to the Santonian- Maastrichtian tectonic deformational episodes which results to uplift and erosion.

The 3 members of the Pindiga Formation which were earlier reported by Zaborski *et al*. (1997) in the Dumbulwa- Bage High were also studied and documented in this study; it consists of the Kanawa and Dumbulwa Members and Fika Shale. The Kerri- Kerri and Chad Formations outcrop extensively in the Bornu Basin. The Chad Formation has been attributed to a thermal sag stage of the basin development subsequent to rifting in the WCAS. Hartley and Allen (1994) believed that uplift of periphery of the Chad Basin, notably of Hoggar, Air, Tibesti and Darfur domes, was the most important control on the Neogene- Recent sedimentation in the Basin.

On the basis of these facts documented by many authors, the Bornu Basin is considered as a continuous basin from Benue Trough to the vicinity of Lake Chad and this study supports the view that, the two basins are geodynamically and stratigraphycally related.

Table.5.1.Proposed revised stratigraphic succession for the Nigerian sector of the Chad Basin [(Modified from Carter *et al*., 1963 and, Zaborski *et al*., 1997 and this study).

AGE		GONGOLA BASIN 1 WUYO- KALTUNGO HIGH Zaborski et al., (1997)		CHAD BASIN 2 Carter et al., (1963)		CHAD (BORNU) BASIN 3 This study	
Quatenary to Neogene		Basalts (Biu)		Chad Formation		Chad Formation/Basalts Biu	
		////////////////////////////		////////////////////////////		////////////////////////////	
PALAEOCENE		Kerri-Kerri Formation		Kerri-Kerri Formation		Kerri-Kerri Formation	
		////////////////////////////		////////////////////////////		////////////////////////////	
MAESTRICHTIAN		Gombe Sandstone		Gombe Sandstone /	Fika		Fika
CAMPANIAN			F				
SANTONIAN		//////////////////	I		Shales		Shale
CONIACIAN			K				
	U	Pindiga	A			Pindiga	
	M		Dumbulwa/Gulani/Deba				
TURONIAN		Formation	Fulani			Formation	Dumbulwa Member
	L		Kanawa Member	Gongila Formation			Kanawa Member
CENOMANIAN		Yolde Formation					Yolde Formation
ALBIAN		BIMA	"Upper Bima Sst"	Bima Sandstones		Bima	"Upper Bima Sst"
APTIAN		GROUP	"Middle Bima Sst"			Group	"Middle Bima Sst"
pre-APTIAN			"Lower Bima Sst"				"Lowe Bima Sst"
		////////////////////////////					
JURASSIC		Volcanics/"pre-Bima deposits"		//////////////////////		//////////////////////	
		////////////////////////////					
PRECAMBRIAN		Crystalline basement		Crystalline basement			Crystalline basement

1= Zaborski *et al*., (1997), 2= Carter *et al*., (1963), 3= This study

5.2 Facies Analysis

Detail facies analysis was carried out in this work and allows a primary classification based on four groups (Table 4.1), mostly according to the grain-size observed within outcrops. This is inspired purely on the descriptive facies and facies association presented by (Miall, 1978; Ghibaudo, 1992; Miall, 1996; Poyatos- Moré, 2014; and Puy-Alquiza *et al*., 2017).

5.2.1 Gravel Facies (G)

These facies deposits formed relatively volumes of sediments within the Lower Bima Sandstone and Kerri- Kerri Formation represented by conglomerate with pebble fragments of quartz, feldspars.They are practically rescricted to the eastern part of the study area. Such deposits are mainly characterized by the presence of very coarse- grained (grains with sizes from 2mm in diametre and above). These gravel deposits are observed in their proximal sections.

5.2.1.1 Clast- Supported Conglomerate (Gcs)

Description

This type of facies is commonly found in the study area, with almost all the facies located in eastern part of the study area. They form relatively small- scale lenticular units in the Lower Bima Sandstone, and are often underyling Clast- Supported Conglomerate Grading into sandstone (Ggs), they are also observed observed in the upper part of the Kerri- Kerri Formation forming a single bed (Plates IV and XXIII).

The facies consist of clast- supported granules, pebbles and cobbles with poorly sorted matrix. Deposits tends to display non- straitfied character and in some cases with normal grading, are commonly made up of pebbles without matrix passing upwards into pebbles with poorly sorted

sands matrix. These facies regularly form the basal deposit of channelized deposits, in overall forming channel- filled accretory units.

Interpretation

As described above, clast- supported conglomerates facies are mainly deposited over basal erosion surfaces, and are often generated by cut and fill processes forming lag deposits.

Deposition of Gcs facies result from frictional freezing of basal gravity portion of a hyperconcentrated flow (Mutti, 1992). These coarse particles are transported as bed load and, once the flow transport capacity is significantly reduced, deposition of the coarser grains occurs by frictional freezing. Poyatos- Moŕe (2014) also states that such deposits are left behind resting as residue and the finer particles are transported in more diluted turbulent suspension, travel further by passing the area of deposition of Gcs facies. Energy dissipation through intense turbulence is the main cause of the extensive and deep scouring (Mutti *et al*., 1999).

5.2.1.2 Clast- Supported Conglomerates Grading into Sandstones (Ggs)

Description

This facies is more common in the study area particularly in the Lower Bima Sandstone. It is restricted to the southwesterrn part towards the boundary of the formation with the basement rocks and Biu Basalt. It is 1 to 3m thick, forming common divisions of gravels and sandstones above erosion contacts earlier reported by previous researchers (e.g. Carter *et al*., 1963; Allix, 1983; and Zaborski *et al*., 1997).

They are normally overlying the Gcs facies.. The Ggs are predominantly conglomeritic with a poorly sorted sandy matrix (Plate III), either displaying discrete gravelly traction carpets or dispersed units of gravels forming the base of sandstone divisions. Grain sizes often decreases

upward, and different grains show no- uniform flow condition forming and overall fining- up trend.

Interpretation

This facies reflect sedimentation in an overall wanning flow, decreasing both velocity and acceleration with time, and deposition by traction processes associated with an increasing fallout. The prevailing sediment transport is bed local, in an either high concentration inertia flow or hyperconcentrated flow (Mulder and Chapron, 2011), with granular interaction of the coarset partices forming inversely- graded bands by dispersive pressure.

The formation of traction carpets may form either by (1) rapid entrsinment of gravel into suspension as rising stage Todd (1989) or “waxing” of a river flood (Pierson and Scott, 1985), followed by settling into the grained traction carpet at flood peak and falling or “waning” stage; (2) and by overconcentration of a “normal”, low- density bedload. Gravel entrainment of the Lower Bima Sandstone in the study is accompanied by suspension and traction carpet development which is significantly easier if the river flood already carries a high concentration of sand and silt in suspension.

Gravelly traction carpets can be maintained in channels or relatively low gradient by the shear stress exerted by overlying high- density, sand- bearing turbulent flows. The tangential shear stress is converted to dispersive pressure within this facies, which aids buoyancy and quesi-static grain- to grain contact in support of the clasts within the gravel carpet to the hindered settling effect (Bagnold, 1954, 1973; Middleton, 1970; Hampton, 1979; Pierson, 1981; Postma *et al*., 1988) among ohers.

The carpet is a quasi- plastic rheology, but behaves much like a viscous fluid at high shear rates. Stress driven gravelly traction carpets produce sheet- like units of clast- to matrix- supported conglomerates, characterized by parallel clast fabric. These units are ungraded or normally graded, depending on the rate of shear, the viscosity of the flow and the celerity of deposition (Todd, 1989).

5.2.2 Sandstone Facies (S)

Most deposits of the Bima Group, particularly the Lower and Upper Bima Sandstones, Yolde Formation and Dumbulwa Member of the Pindiga Formation, forms the bulk of the outcrop belt of the study area, and are constituted by Sandstone Facies, with major and wide extension than the gravel deposits (Table 4.1).

Their field relationships have been discussed in some detail in Chapter IV. Plates V, VI, VII, X, XI, XII, XIII, XIV, XVI, XVII, and XXI and Fig. 10, these are the lithological units comprising the Sandstone Facies association in the study area. The range of sandstone deposits observed, including massive sandstones (Ss), cross- bedded sandstones (Sx), normally graded sandstones (Sng) and finally inversely- graded sandstones (Sig).

5.2.2.1 Massive Sandstone (Ss)

Description

This facies as in Plates V and X occurs within the Lower and Upper Bima Sandstones. They are sharp or erosive- based massive and structureless beds that are generally poor to moderately-sorted, involving grain populations from coarse to medium to fine- grained sandstones.

However, some massive sandstone amongst the Bima Group are, preferentially the silicified variety occuring at fault- zone, generally well- sorted, with grain sizes not exceeding fine to very- fine sand materials. Overall, no internal structure can be recognized among these facies, except water and soft sediment deformation.

Interpretation

The massive character of Ss deposit is produced by rapid “in mass” deposition from high density flow. However, Poyatos- Moŕe (2014) said the flow is more diluted after losing most of the bedload material in proximal settings, and loses the coarsest particles that are transported (coarse to medium sand) after hydraulic jump produced either by a change in the depositional gradient or unconfinement and subsequent expansion of the flow.

The change in flow leads to a rapid aggradation by loss of transport ability, preventing a formation of traction deposits. Additionally, Poyatos- Moŕe (2014) is of the opinion that profusion of water escapement structures and ripped- up mud clasts are also consistent with a sudden deposition and the likely relationship with a hydraulic jump. However, Kneller and Bramay (1995) added that these facies requires flows which are sustainable at a relatively constant discharge for long periods, such as direct fluvial input, either constant or in flood.

5.2.2.2 Cross- bedded Sandstone (Sx)

Description

This have a large facies sub-group with widespread outcrop development in the study area. It includes facies of Lower and Upper Bima Sandstones and Yolde Formation (Plates V, XI, XII,

XIV, XV, and XVI). They display moderately erosive to sharp bases, normally associated with grain size. Geometrics are commonly tabular or low- gradient convolute and oblique- tabular cross- beds.

Interpretation

This facies contain some spectrum of cross- bedded sands, showing sedimentary result if different transport and depositional processes associated with different flow classes. Poyatos-Moré (2014) states that cross- beds are normally related with traction processes exerted by overpassing flows over previously deposited grains, which become imbricated and reworked. Other processes, such as tides and waves, may also affect deposition of grains, and this interaction is subsequently reworked in the resulting bed.

Depositions of bedload grains that overpass the proximal zone dominated by the coarser G-facies form a set of very prograding. Some of these cross- beds are sigmoids, which can evolve downcurrent to tabular and massive sand layers of Ss facies.

The presence of different massive (Ss) to cross- bedded facies (Sx) in the study area represent different processes of decelaration and expansion of flows, considered to be a function between the flow momentum and the water depth (Mutti *et al*., 2003).

Thus, while massive facies are derived from a sudden flow decelaration linked to precipitation that prevent presence of traction processes, cross- bedded facies (Sx) and graded beds (Sng) are more associated to more gradual decelaration and acceleration, allowing an alternation of traction and fallout processes.

5.2.2.3 Normally- Graded Sandstone (Sng)

Description

This facies occurs in the Lower Bima Sandstone (Fig. 10) along Dokshi road. Normally- graded sandstone in the study area are fine- grain layers, mostly >5cm in thickness with sharp erosional (re-activation)) bases. They are normally well- sorted due to uniformity of their particles.

Interpretation

Normally- graded sandstone facies is deposited in a decreasing strength of the transporting medium; it is interpreted by Kuenen and Migliorini (1950) as traction + fallout processes from generally waning flows but still with a high suspension of fine to very- fine sand. Most of turbidites models are interpreted to this type of facies.

Consequently, normally- graded beds are more commonly associated to surge- type currents, generated by "virtually instantaneous events" such as seismogenic slumping (e.g.Garcia and Hull, 1994; Poyatos- Moré, 2014).

5.2.3 Mudstone Facies (M)

Mudstone facies has fewer occurrences in the study area and is restricted to the lower bed of Yolde Formation (Mm) and Middle Bima Sandstone (Msm) Plates VII, VIII, IX, XVII and XX respectively. The range of mudstone facies observed is not very wide, because they are constrained by grain sizes, often contain sand and gravel sizes.

5.2.3.1 Silt and Clay Streaked Layers (Msm)

Description

This type of facies was observed in the northeastern part of the study area (Plates VIII and IX), probably due to scanty and poor outcrop quality of the area been located at the basin shoulder,

particularly the Bima Group. They involve medium silt to clay beds, and are generally well-sorted.

Interpretation

This deposit is believed to have being deposited under low energy condition, while Poyatos-Morć (2014) interpreted them to belong to low- concentration- tail of hperpycnal flows, where fallout processes are dominant, segregating the silt and clay content of suspension load by shear sorting in a kind of "burst and swept" process.

5.2.3.2 Massive Mudstones (Mm)

This facies was observed at the base of Yolde Formation in the study area along Shishiwaji road (Plate XVI). It is underlying the sandstone bed, and is purple (or mottle) in colour, very well-sorted. It is not bioturbated as the case may be for some facies of same formation elsewhere.

Interpretation

This facies correspond to deposition during relative underfeeding of clastics, or very distal positions offshore, with very low contribution rates and sedimentation from the distal terms of hperpycnal flows (Poyatos- Morć, 2014), which previously left its load of flocculated clay, leaving the suspension with residual change that can remain suspended longer, and this travel longer distances from river mouth. It involves settling from a suspension load depleted of clastic content, with enrichment ration of particles by hydraulic selection.

5.2.4 Carbonate Facies (C)

Carbonate facies are present in the study area within the Pindiga Formation (proposed in this study) in the lower limestone/shale bed of the Kanawa Member (Plates XVIII and XIX) and the overlying limestone/shale bed of the Fika Shale (Plate XXII).

5.2.4.1 Carbonate- Rich Layer (Cl)

Description

This type of facies is thick within the Kanawa Member and thin within the Fika Shale in most of the outcrops studied. The thick beds are frequently feasible in the outcrops of the Kanawa Member. They are both fossiliferous with differences in fossils due to time of deposition because the former is older than the latter. Researchers such as (Carter *et al*., 1963; Reyment, 1965; and Zaborski *et al*., 1997) have reported various types of fossil species within these limestone layers.

Interpretation

This facies can be interpreted as being consequence of the colonization of different organisms during period of interruption of fluvial sediment supply.

5.2.5 Analysis of the Sedimentary Architectural Elements

Five architectural elements were recognized in the study area which has been described in some detail by Miall (1996) and subsequently adopted by other researchers such as (Oplustil *et al*., 2005; Puy- Alquiza *et al*., 2017) among others. They are: Channels (CH, HO), sediment gravity-flow deposits (SG), sandy bedforms (SB), downstream- accretion macroforms (DA), and flood plain fine (FF). These elements are defined by their geometries and bounding surfaces (Miall, 1996), forming the basis for interpreting depositional environments.

5.2.5.1 Channels CH, Channels Fills HO

Channel deposits comprise facies of clast- supported conglomerate (Gcs), scour fill sand, equivalent to cross- bedded sandstone of this study (Sx) and normally- graded sandstone (Sng).

These basically include the facies of Lower and Upper Bima Sandstones, Yolde Formation and Kerri- Kerri Formaion. They often erode sand bedform and other channels. Their geometry is of concave- up channel, locally forming multi- story channel geometry. The thickness may vary from 0.5m to 2m in some cases.

Channels comprising facies Gcs, Sx and Sng record channel deposition. The presence of coarse-grained conglomerates may indicate a sudden increase in velocity of the depositional current, high lateral migration of channel is a typical feature, Most channels have a multi- story and multi- lateral nature.

5.2.5.2 Sediment Gravity- Flow Deposits (SG)

Sediment gravity- flow deposits consist of clast- supported conglomerates grading into sandstones (GgS) and massive sandstones (Ss). The facies occur within Lower Bima Sandstone and Yolde Formation. They have sharp erosional bases and geometry of elongate lobes. They are underlain by gravel or sand bedforms, and they occur within channel deposits. Sediment gravity-flow deposits thickness is up to 1m as the case may be in this study.

Sediment gravity- flow deposits indicate non- cohesive gravity- flow deposition. Their presence within the channel fills probably records channel bank instability and slumping

5.2.5.3 Sandy Bedforms (SB)

Sandy bedforms consist of cross- bedded sandstone (Sx) and normally- graded sandstone facies of Lower and Upper Bima Sandstones and Yolde Formation. They have sharp bases and are often eroded by channels. Sand bedforms are usually up to 2m thick. They are intercalated with overbank elements.

Sand bedforms record intra- channel deposition. They were probably produced by migrating ripples within the channel (Miall, 1996).

5.2.5.4 Downstream Accretion Macroforms (DA)

Downstream accretion macroforms comprise facies of clast- supported conglomerate (GcS), cross- bedded sandstones (Sx) and normally- graded sandstones (Sng), which are basically same as the facies enumerated in channels and channel fills (CH, HO). They comprise of the Lower and Upper Bima Sandstones, Yolde Formation and Kerri- Kerri Formation. They are up to 5m in thickness. Downstream accretion macrofroms record channel depsotion.

5.2.5.5 Overbank Fine (FF)

This element consists of massive units tens of metres in lateral extent; it comprsises facies of massive mudstone (Mm) within the Yolde Formation, and presents vertical facies variability, reflecting the fact that the depositional surface was flat and readily susceptible to small changes in depositional process.

Overbank fine record individual flood events, the presence of dessication cracks indicate longer term drying out of floodplain.

5.3 Petrography and Sandstone Classification

5.3.1 Mineral Distribution

Table 4.2 showed the distribution of mineral percentages obtained from point counting deduced from Petrographic examination. The distribution of the minerals from the study area followed the usual trend for classification of sandstones such that quartz and feldspar being the major rock-forming minerals constituting between 47.48% in sample 25 to 99.99% in sample 7 and 35.

Quartz being the most stable and abundant rock- forming mineral occurs in all the samples and have values that range from 31.20% to 67.74%. The presence of quartz is attributed to its resistance to both mechanical abrasion and chemical dissolution. Altered feldspar range from 5.37% to 34.61%, hematite, a class of iron oxide range from 4.87% to 25.64%, such mineral result from dissolution of unstable ferromagnesian minerals. Microcline, a potassic feldspar has values ranging from 0.97% to 3.65%, orthoclase, another potassic feldspar mineral has values ranging from 17.47% to 33.33%, while albite, a plagioclase feldspar series range from 1.12% to 6.66%. Zircon is considered as one of the most stable mineral that is highly resistive and is believed to have undergone several sedimentation cycles, it has values ranging from 0.96% to 4.34%, limonite, a variety of iron oxide that forms from the hydration of hematite or formed from oxidation and hydration of iron rich sulphide minerals and chemical weathering of iron rich minerals like biotite. It range from 9.38% to 27.27%, it is often the major component of lateritic soils. Muscovite is a stable authigenic mineral that is present in samples 21 and 34, this can be attributed to its unstability, it range from 2.08% to 2.87%, biotite being a second variety of mica is only present in sample 34, this showed that sample 34 is composed of both mica minerals and may be close to the source area, it has value of 0.22% which is considered to be the least abundant mineral in all the samples. Andesine, a ca- rich plagioclase which is an unstable mineral is present in samples 24 and 36, its values range from 1.92% to 2.66%.

Therefore, from Table 4.3, shows that mineral abundance tends to obey Bowen reaction series in such a way that most of the mafic high temperature minerals tend to dissolves and weather to secondary minerals, while the low temperature minerals that are more reisistant tends to dominant the sedimentary cycle.

Sixteen (16) samples were used in the point counting procedure carried out with the aim of classifying the sandstones using petrographic examination in distinguishing the sediments into different arenitic groups on the basis of quartz, feldspars and rock fragments distribution as observed under the microscope. From the results obtained in Table 4.2, quartz being the most stable rock- forming mineral tends to have higher percentage of mineral inherent in it. It range from 31.20% to 67.74% with an average 38.44%, sample 1a has the least value when compared to feldspars put together, but higher than the rock (lithic) fragment. Feldspar being the second most abundant rock- forming mineral range from 4.04% to 53.63%, with an average value of 38.25%, it has the highest percentage of 53.63% in sample 4 with least in sample 25 having a value of 4.04%. Rock (lithic) fragments has values ranging from 0.00% to 52.52% with an average of 18.10%, this shows that it has the least value when compared with quartz and feldspars that constitutes the bulk of rock- forming minerals. Additionally, samples 7 and 35 have no occurrence of any rock fragment, while in sample 25 it has the highest percentage of 52.52% more than quartz and feldspar put together. It also has higher value than feldspar in samples 12, 21, and 25, which result in naming the rock samples lithic arenites. Figure 14 below shows the distribution pattern of different sandstones in the study area.

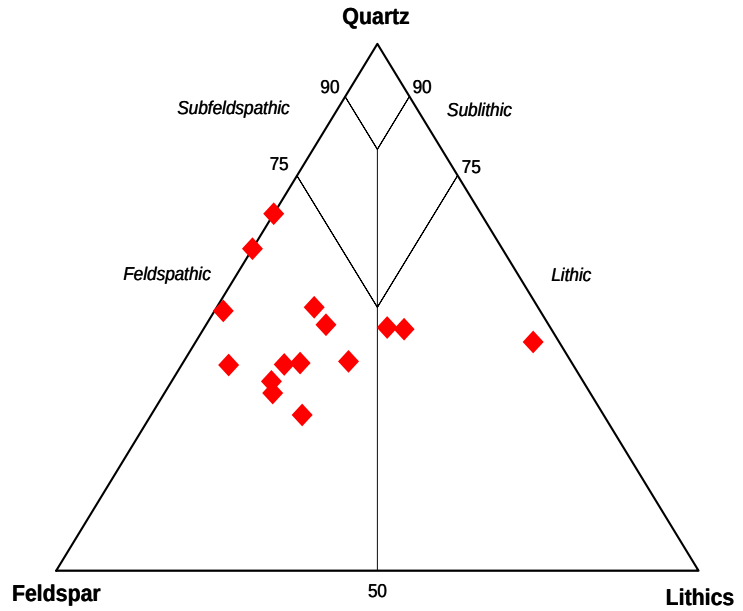


Fig.21. Sandstone types within the study area using Loren (2002) classification scheme

Photomicrographs 25 a and b (Plate XXV) were classified as arkosic arenites based on point count, while photomicrographs (Plate XXVIa, b, c, d, f) are classed as arkosic arenites and lithic arenites, point count from photomicrographs (Plate XXVIIg, h, I and j) consist of 3 arkosic arenites and 1 lithic arenites. All the other photomicrographs (Plates XXVIII k, l, m, and n and XXIX o and p) are arkosic arenites. These photomicrographs were used for identifying minerals for classification of the sandstones studied in the research area.

Sandstones are usually classified according to the relative proportions of the three components;

i) Quartz

ii) Feldspar (Potassium + plagioclases)

iii) Rock (lithic) fragments

Point counting method was employed to classify the sandstones after petrographic microscopic examination has been carried out to identify the mineral composition of the sixteen (16) samples analyzed in order to assign petrologic names for distinguishing them characteristically.

Loren (2002) classification scheme was adopted for the classification using the identified minerals, basically quartz, feldspar (potassium + plagioclase) and rock fragments. Sandstones in the study area were classified as arkosic arenites due to the fact that their quartz content is less than 75% and their feldspar ratio higher when compared with rock fragment, it shows that the appropriate names according to Loren (2002) classification scheme is arkosic arenite for the samples listed above, Table 4.2 distribution supported this scheme. Likewise, samples 12, 21, and 25, are classified as lithic arenites because the quartz constituent is less than 75% as well and have greater percentage of mineral lithic fragments than feldspars put together.

The classification carried out is based on the distribution of the three constituents having higher than 25% between feldspar and rock (lithic) fragment and less distribution of quartz (<75%), the percentage values is responsible for naming the arenites. The percentages of quartz within the mineral grains influence the type of sandstone that would be produced. From the study carried out, quartz has the highest percentage of mineral grains, followed by feldsper (potassium + plagioclase) put together, while rock (lithic) fragment has the least number of mineral grains which can be attributed to the stability of the minerals couple with the resistance from weathering and erosion.

5.3.2 Sandstone Composition

The composition of sandstone is largely a reflection of the geology and climatic condition of the source area. Some grains and minerals are chemically and mechanically more stable than others such as zircon, tourmaline, rutile and quartz.

5.3.3.1 Compositional Maturity

Compositionally, the sandstones from the study area can be said to be matured and immature. These are the two categories of sandstones observed petrographically and are; arkosic and lithic arenites. Mature sandstones from the study area are the arkosic arenites which consist of quartz, some feldspars, and some rock (lithic) fragments, such that the feldspars have higher constituents than the rock fragments, whereas the immature sandstones here are the lithic arenites which basically contain higher percentage of feldspars and rock fragments put together than quartz, but the rock fragment has higher percentage of fragments inherent in it than feldspars. Most immature sandstones as the case may be in this study consist of higher percentage of rock fragments and feldspars put together than quartz.

5.3.3 Provenance of Sandstone

Climate, through the influence on weathering processes, can have a significant effect on the ultimate composition of sandstones and thus on provenance interpretation. Hot, humid climate promote alteration and destruction of less- stable minerals and rock fragments, whereas very cold and very dry climates favour preservation of these less- stable constituents. Furthermore, conditions of low- relief and gentle slopes enhance chemical weathering because particles are eroded from such areas slowly. By contrast, high relief and steep slopes promote rapid erosion of detritus before it is significantly weathered.

Plot of QFRF (Fig. 21) suggests that the Cretaceous sandstones may be derived mostly from provenance which is cratonic interior as well as recycled orogeny (Dickenson, 1985). He states that the main source of the cratonic/continental- derived sandstones is low- lying granitic exposures. These accounts for the study area having low- lying basements around northeastern part of Dokshi Village and Buni Yadi, and the basement complex of northeastern Nigeria might be possible sources. Orogenic recycling occurs in tectonic settings where stratified rocks are deformed, uplifted and eroded (Dickenson, 1985). This is typical of the Lamurde Anticline which is the type section of the Bima Group, it falls within the Yola arm of the Upper Benue Trough formed during the Santonian (compressional phase) thermotectonic event, which resulted in the folding and uplifting of the Lamurde area.. Young *et al*. (1975) studied composition versus size of first- cycle sands released from metamorphic and plutonic rocks in semi- arid and humid climates. They conclude that regardless of crystalline source- rock type, weathering in semi- arid climate generates greater amounts of rock fragments, feldspars and accessory minerals. Weatherimg in humid climate produces relatively more polycrystalline and monocrystalline quatz because less- stable minerals and rock fragments are more easily destroyed by various chemical weathering under humid conditions.

Heavy minerals suites as source- rock indicators, rounded and angular zircon mineral are present within some samples and are believed to have been derived from two sources; igneous and recycled sedimentary rocks. Rock fragments has two sources; volcanic and metamorphic, metamorphic maybe more possible source. Potassium feldspars often suggest sources of alkaline igneous rocks. Quartz is believed to have been sourced from high- grade metamorphic rock or

plutonic source rocks. Continental block provenances: quartzose sand and feldpsars with high ratios of potassium feldspars to plagioclase feldspars and metamorphic and sedimentary rock fragments.

5.4 Trace Element Geochemistry

The shales of the Kanawa Member of the Pindiga Formation and Fika Shale were used for the geochemical analysis as potential source rocks.

Transition metals have been found to be very useful in crude oil maturation, migration and characterization. In this study, special attention is given to the following metals: V, Ni, Mn, Co, Cr, Cd, Pb, Zn, Cu, Fe, and Mo.

The concentration of trace metals in raw shales, extracts and oils can be used to determine their maturity. Table 4.4 showed the concentration of some of the trace metals associated with potential source rocks in the study area, Figures 22 and 23 are plotted in 2D and 3D pattern concentration versus trace metals showing different peaks of the analyzed samples.

5.4.1 Biophile Elements: V, and Ni

The concentration of V ranged from 0.264 to 1.288ppm with an average of 0.6735ppm. The values are higher than those obtained in the Niger Delta crude oils by (e.g. Akinlua *et al*., 2007; Udo *et al*., 1982; Nwachukwu *et al*., 1995; Oluwole *et al*., 1993; Ndiokere, 1983; Onojiake *et al*., 2011) this might be due to different depositional environments and that a direct comparison of trace metal contents in rock extracts and crude oils is not possible, as element concentrations in extracts are, higher due to differences in chemical composition (Frakenberger, 1994) and is a good indication of possible prospect for maturation, since V and Ni are one of the most

important tools for explorarion geochemistry. The concentration of Ni ranged from 0.298 to 0.721ppm with an average of 0.425ppm. The values are lower than some samples of crude oil from the Niger Delta and higher than those obtained by Onojiake *et al*. (2011) whose results showed variation in some samples. This might be as a result of shallow depth for maturation or the organic matter that concentrates Ni porphyrin complexes could have been partially substituted. The values of V and Ni in this study are low and signify the samples being potential source rocks.

5.4.2 Siderophile Elements: Fe, Co, Mo, Cr, Mn

The concentration of Co ranged from 0.352 to 0.783ppm with an average of 0.50ppm. This values are lower than those of Nwachukwu *et al*. (1995), Udo *et al*. (1992), Oluwole *et al*. (1995) and correlated with those of Onajiake *et al*. (2011) who reported an average of 0.52ppm, the values correlate with crude oil data from the Niger Delta, but it is lower for petroleum generation because source rock extracts have higher values under appropriate conditions than crude oils.

The concentration of Fe ranged from 1.289 to 264ppm with an average of 144.12ppm. The values are generally higher than all crude oils reported in the Niger Delta by many researchers and New Zealand by (Frakenberger, 1994), though in most of the trace metals reported Fe tends to have higher concentration in most crude oils, this high value have confirm that Fe might have been mature than other metals since it has the highest concentration in all the analyzed source rock samples.

The concentration of Mn ranged from 0.821 to 7.567ppm with an average of 3.692ppm, this is in conformity with results from previous researchers that reveal extracts have higher concentration

values than crude oils. This values are higher than those reported by (Onojiake *et al.*, 2011) who also used Mn in their research.

The concentration of Cr ranged from 0.233 to 0.753ppm with an average of 0.428ppm, the values are lower than those obtained from the Niger Delta crude oils, though it has been reported by Barwise (1990) that Cr is not detectable, where it is detected, it can be used for oil-oil correlation. In this study, only extracts are used, so there is limitation to its application.

The concentration of Mo ranged from 0.030 to 0.133ppm with an average of 0.049ppm. The values indicate that the roposed source rocks have higher input than crude oils because it is not frequently detectable. Its detection has shown that there is an input of the trace metal.

5.4.3 Chalcophile Elements: Cu, Zn, Pb, Cd

The concentration of Cu ranged from 0.000 to 0.238ppm with an average of 0.0829ppm. The values obtained are lower than those present in most of Niger Delta oils. The low values can be attributed to source and possibly lack of burial depth. Organic matter from lacustrine and terrestrial environments tends to have higher input values than marine.

Concentration of Zn in the analyzed samples ranged from 0.000 to 0.425ppm with an average of 0.140ppm. The values are higher than those reported from the Niger Delta by Udo *et al*. (1992) and lower than those of (Nwachukwu et *al*., 1995; Oluwole *et al*., 1993). This can be attributed to low input from organic matter and shallow depth of burial.

Pb concentration ranged from 0.000 to 0.339ppm with an average of 0.004ppm. The values are lower than those obtained from Niger Delta crude oils by Onojiake *et al*. (2011) who reported an average of 7.94ppm. The low values might be due to temperature and depth of burial which affected the maturation, since incorporation of elements is done during maturation and migration.

Though (Hodgson and Wisher, 1959) have disputed that input of trace metals does not take place during migration.

Cd concentration ranged from 0.000 to 0.020ppm in the analyzed samples with an average of 0.004ppm. The values are lower than those reported by Onojiake *et al*. (2011) whose average value is 0.20ppm. The low values may not be unconnected with time- temperature index of maturity (TTI). The time- temperature index of maturity with regards to this study can be interpreted that the depth of burial is too shallow because as the depth increase the temperature increases as well and so the maturity. The samples were collected at near surface and so the temperature needed for maturity based on Lopatins experiment have not yet entered the onset of oil generative phase.

5.4.4 Distribution Pattern of Trace Metals in Source Rocks

The distribution pattern of some trace metals from the potential source rocks analyzed for biophile, siderophile and chalcophile elements. The trend shows decreasing concentration of trace metals from Fe>Mn>V>Co>Cr>Ni>Zn>Cu>Pb>Mo>Cd.

Fe has the highest concentration values followed by Mn and V, while Cd has the least value in terms of concentration amongst the elements. The presence of V, Ni and Fe in oils is very significant in providing information about its geological history. The high concentration of Fe can be attributed to substitution reaction which might have replaced other metals from the original biological matter or could have been incorporated from the solid or aqueous phases. Some plants are able to concentrate certain trace metals under the right condition (Brooks and

Wisher, 1977) and can tolerate otherwise toxic elements. The high value of Fe is supported in the sense that most source rocks (extracts) have higher concentration values than crude oils. Mn is also related to source rock extracts having higher concentration value. V and Ni are expected to have high concentration than all other trace metals in source rocks and crude oils. This is so because they are the most abundant and important trace metals needed for any petroleum geochemistry. Because plants and animals require trace elements in certain amounts, elements are present in varying concentration which depends on the type of organism and environment. It is known that some marine organisms, such as tunicates, are able to concentrate V as haemovaradin and that could be considered to be one of the elements in petroleum derived organic matter. Lewan and Maynard (1982) said that the enrichment of V and Ni is endemic to organic matter and the difference of the elements from interstitial connate water in the sediments.

The overall results showed that the biophile elements have appreciable values, but lower than the concentrations of Fe and Mn (siderophile) which might be as a result of terrestrial input or have not yet reached the onset of oil generation potential due to shallow burial depth.

Frankenberger (1994) reported that Australian, some China, Nigerian and New Zealand oils have shown low V and Ni contents and are normal in oils derived from land plant matter. So this might not be unconnected to the fact that the organic matter is from terrestrial environment for both Kanawa Member and Fika Shale because they have horizons that are sandy which may contribute to such input.

Mn concentration can also be compared with New Zealand oil as it has the second most abundant trace metal after Fe amongst the analyzed samples, it is said to have higher values than crude oils derived from marine origin. Cu, Cd and Pb are reported with high concentrations by

Frankenberger (1994), they are said to be sourced from marine environment. This can be attributed that, terrestrial input may be responsible for such lower values of these trace metals and that the organic matter might have not reach maturity stage due partial oxygenation

It can further be stated that, the data obtained from the elemental analysis reveals that the trace elements have not yet reached the onset of oil generation simply because of shallow depth of burial. The location of the study area is at the basin shoulder where sediments have been uplifted, thre is the need for renewed sedimentation so as to cover the sediments for possible aid to maturation. In the shores of the Lake Chad, sediments have thickness greater than 4000m with thick Quarternary cover of the Chad Formation. It is expected that source rocks of same Pindiga Formation, comprising of Kanawa Member and Fika Shale can be matured in deeper part of the basin like in Gubio, Baga, Maiduguri and Jakusko sub- basins.

5.4.5 Maturity

The boundary of Bertrand *et al*. (1993) which was also used by Olugbemiro *et al*. (1997) in the Lake Chad region indicates that the "oil window" increases to the north in the study area. This is consistent with the trend of the thickness of Tertiary- Quarternary sediments in the Bornu Basin which increase in northern direction (Petters, 1981).

From reflectance profiles obtained by Olugbbemiro *et al*. (1997) from Albarka and Kanadi wells, their studies implies that eroded sections from the two wells totaly 988km and 987km respectively. The observation follows (Dow, 1977) ascertain that, a Rm value of 0.25% represents the surface value where no erosion has occurred in a uniformly subsiding basin. Although post- Cretaceous erosion, uplift and folding have been reported in the Chad Basin by (Carter *et al*., 1963; Petters, 1981; Avbovbo *et al*., 1986). Olugbemiro *et al*. (1997) further stated

that the magnitude and extent yet to be precisely determined. The top of the Cretaceous sequence reported by Avbovbo *et al*. (1986) measuring about 500m shows an angular unconformity relationship with the overlying Tertiary strata, which further verifies erosional hiatus. This in turn might have eroded sediments at the basin shoulder which also affected the maturity of the shales.

Reburial continued at the end of post- Cretaceous erosion, this might have aided sedimentary cover for better maturation in the Lake Chad area. About 1000m (1km) of sediments have been eroded as reported by Carter *et al*. (1963), and Burke (1976) estimates that the Chad Basin accumulated about 0.5km of sediments in the Maiduguri sub- basin during the Neogene and Quarternary due to peripheral uplift. The eroded sections are yet to be accounted for. Olugbemiro *et al*. (1997) pointed out that the present day estimated eroded section in the Chad Basin is much less than that obtained between the Cretaceous and Tertiary strata. The section can only be considered as remnant of an eroded section that is yet to be "annealed" by reburial.

The "oil window" in some studied wells such as Kanadi (1270- 2600m) and Albarka (1985- 3690m) are not far from those proposed by Genik (1993), who suggested that the "oil window" in the West African Rift Subsystems is around 2500 - 4000m. Thomas (1996) estimated the threshold of the "oil window" in the Bornu Basin to be at a depth of 2000m, or just below the intra- Maastrichtian unconformity. Such thickness reported by several authors is not present in the study area due to lack of reburial of both Tertiary and Quarternary sediments which accounts for about 500m within the Maiduguri sub- basin and virtually increases towards the shores of the Lake Chad where most of the exploratory wells were drilled. Subsequently this and other factors are responsible for the poor source rock quality in the studied area. This is because Olugbemiro *et al*. (1997) and Obaje *et el*. (2004, 2006), Mohammed (2010) and Mjinyawa *et al*. (2012) have

reported fair to good source rock quality within the Fika Shale and Gongila Formation from different exploratory wells reaching a depth of greater than 1500m which is readily not available in the study area.

Overburden thickness increases towards the Lake Chad area (Genik, 1993; Olugbemiro *et al*., 1997), depths to the oil window actually increases in this direction.

5.4.6 Timing of Hydrocarbon Generation

The thermal and burial history as reported by Mijinyawa *et al*. (2012) in the Nigerian sector of the Chad Basin is influenced by the tectonic evolution of the basin. Thermal history and subsidence are important factors used in predicting timing of hydrocarbon generation in the Nigerian sector of the Chad Basin (Bornu Basin) since subsidence have occurred. Mijinyawa *et al*. (2012) used Mckenzie model in the basin within Herwa-1 well which suggest subsidence began from Early Cretaceous around 120Ma at a depth of 2678m which shows a low burial rate, the subsidence trend emded in the Late Miocene around 20Ma at a depth of 5276m which is characterized by a high burial rate, they further stated that the fast rate is confirmed from the burial history plot of Herwa-1 well which indicates maximum burial occurred in the Late Miocene/ from their modeling result, the timing of hydrocarbon generation was deduced from thermal history and temperature of the basin which indicates that oil generation stage falls between (0.45- 0.60%) VRm which began during the Early Cretaceous at a depth of (2000-2200m) the oil window begins at (0.60- 1.3%) VRm at a depth of (2000- 3000m) in the mid-Cretaceous, while the gas window was generated during the Late Cretaceous to Tertiary at a depth of (3500m). The petroleum generative potentials in this study have been characterized to be poor due to lack of reburial and shallow sedimentation within the basin shoulder.

Additionally, the stratigraphic position of the potential source rocks must be taken into consideration, Obaje *et al*. (2006) reported that most of the hydrocarbons in the Nigerian sector of the Chad Basin might have been lost as a result of the Tertiary hiatus (non- deposition), but this contradicted the studies of other researchers such as (Olugbemiro *et al.*, 1997; Mohammed, 2010; Alalade and Tyson, 2010; Mijinyawa *et al*., 2012) who reported quality source rock which have probably exceeded the oil generative window and have and virtually entered the "gas window" because of some reported intrasedimentary intrusives that might raised the temperature and probably have converted the oil to gas or in some parts might have exceeded the dry gas preservation deadline into anthracite/graphite. Figures 22 and 23 are plots of transition metals in 2D and 3D patterns which interprets that Fe has the highest concentratration values amongst all the analyzed elements with an average of 144.12ppm and Cd having the least concentration value with an average of 0.004ppm.

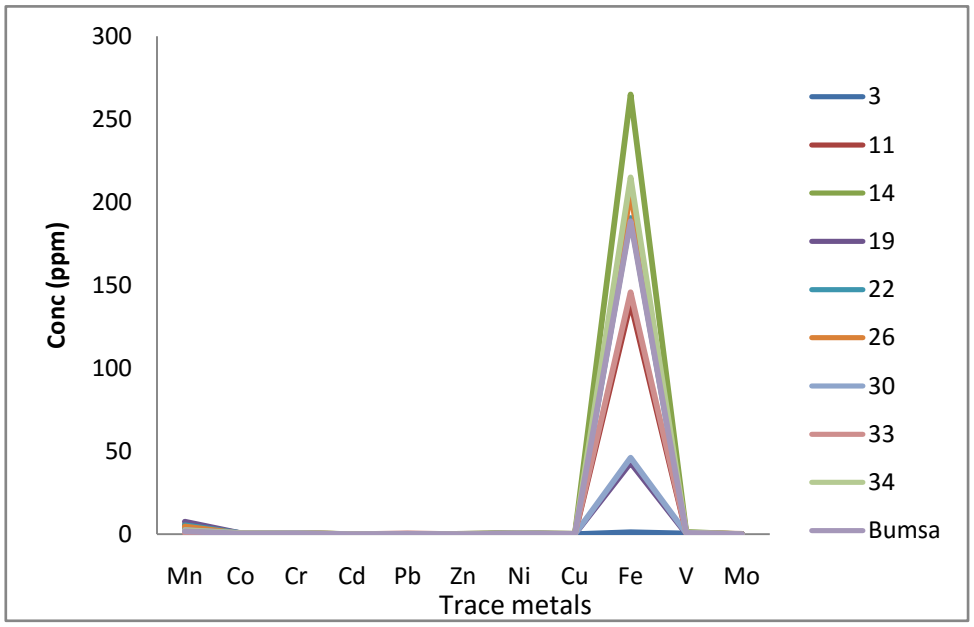


Fig.22. Plot of concentration (ppm) against trace metals in 2D pattern

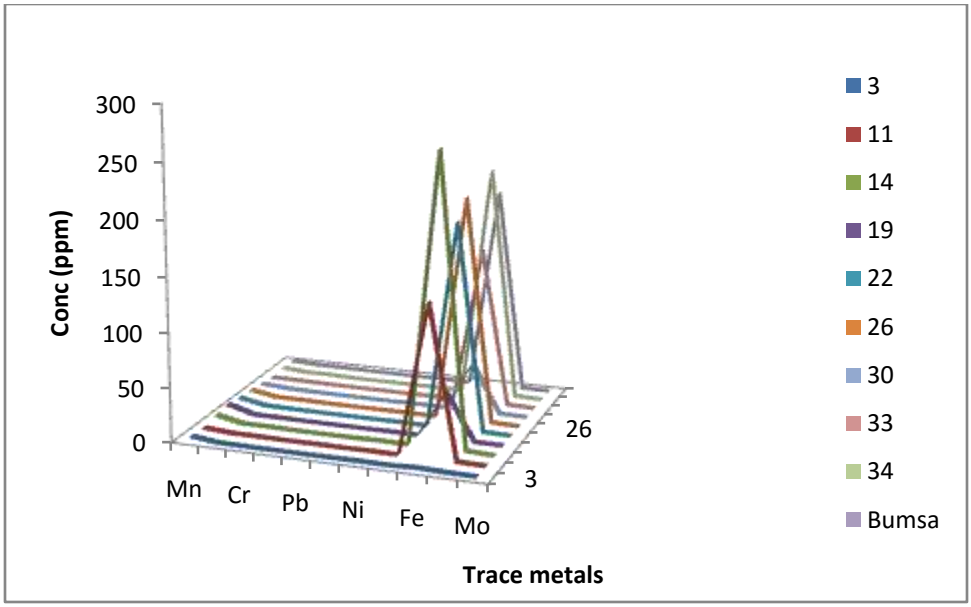


Fig .23. Plot of concentration (ppm) against trace metals in 3D pattern

5.4.7 Intrusion Impact on Maturation

Intrusions can cause heating by contact metamorphism and hydrothermal activity

5.4.5.1 Implications

1) Igneous intrusions can have a major impact on the petroleum system development
2) Positive: e.g., trap development, local heat source to aid maturation
3) Negative: e.g., reduction in reservoir quality, compartmentalization of petroleum systems elements

5.4.8 Reservoir Rocks

Though reservoir studies has not been carried out in this investigation, but previous researchers in the basin such as (Olugbemiro *et al*., 1997; Obaje *et al*., Obaje *et al*., 2004, 2006; Mohammed, 2010, Hamza, 2007) among others have stated that the Bima Sandstone and the sandstone of unit

of the Gongila Formtaion of Carter *et al*. (1963) are possible petroleum reservoirs within the petroleum charge system in the basin.

5.5 Paleogeographic Reconstruction

At the inception of the Chad Basin, Avbovbo *et al*. (1986) stated that shallow marine sediments which are believed to be the lacustrine gray shale of the Lower Bima Sandstone (B^1) reported in this study were deposited over localized fanglomerates and possibly fluvial deposits that were situated unconformably on the basement. They designate the sediments as "pre- Bima" sediments. The succeeding regression resulted in the deposition of a thick sequence of the continental Bima Group (Middle and Upper Bima Sandstones) respectively during the Albian-Cenomanian. The transitional Yolde Formation represents fluvial and coastal plain paleoenvironments in its lower part and shallow marine condition higher up. It is dated Cenomanian- Turonian. The Pindiga Formation recognized in this study was mainly regarded as a purely marine deposit by Carter *et al*. (1963) and Avbovbo *et al*. (1986). The Pindiga Formation in the Bornu Basin was deposited in two different environments. The lower part (Kanawa Member) is composed of limestone- shale unit which is purely marine; this is followed by the Dumbulwa Member which is a sandstone shale unit which lies on an erosinal surface (Zaborski *et al*., 1997) fining- upward fluvial cycles, this was deposited during the regressive phase. Renewed Turonian transgression, during which open marine Fika Shale was deposited. Cretaceous deposition was terminated, and the regressive Gombe Sandstone was deposited (Avbovbo *et al*., 1986). The Cretaceous sediments, which were deformed during the Santonian, presumably formed the detritus for horizontally bedded Tertiary and Quaternary sediemts (Avbovbo *et al*., 1986). They further stated that a relief formed in the basin, locally closed

drainage systems may have developed, and lacustrine sediments of Quaternary Chad Formation may then have been deposited.

They concluded that the Cretaceous may have been intruded by volcanic plugs which are also visible in the study area within the Fika Shale, which terminates below the Tertiary sediments. The plugs therefore, are believed to have formed contemparaneous with the Maastrichtian deformational episode.

5.6 Sedimentary Structures

Sedimentary structures are used to identify the agents of deposition and resulting changes in that depositional environments that the sediments experienced after they were laid dowm. There are numerous primary and secondary structures identified at different locations in the study area.

5.6.1 Primary Structures

Bedding is sometimes used interchangeably with primary sedimentary structures. This is probably the most importsnt feature of a sedimentary rock, and as such is the most widely used term in describing sedimentary sequence.

5.6.1.1 Massive Bedding

Massive beds occur in the study area within the Bima Group (Lower and Upper Bima Sandstones) and Yolde Formation. The origin of such beds is difficult to explain. Presumably, massive beeding is generated in the absence of fluid- flow traction transport, either by some type of sediment gravity flow or by rapid deposition of material from suspension (Plates IV, XII and XV)..

Arnott and Hand (1989) demonstrated experimentally that under upper plane- bed condition of transport in the presence of a heavy rain of suspended sand (typical of turbidity currents) the

formation of lamination is suppressed. This finding suggests that rapid aggradation can account for the massive character of Bouma A divisions of turbidity.

The deposition of some grain flows, fluidized or liquefied flows, and debris flows may also appear massive. Some very thick units may actually be amalgamated units, which are formed by the "welding" together of the deposits of several successive sediment gravity flows consisting of sediments having about the same grain size and general character.

Other massive beds may be of secondary origin, formed either by the homogenizing activities by post-depositional sediment liquefaction owing shocking or other mechanisms.

5.6.1.2 Cross- Bedding

This is the commonest structure in the study area; it is more abundant in sandstones. There are different types of cross- beds that occur in the field of study which include the following;

Tabular Cross- Bedding

This structure occurs in most of the sandstones, comprising of the Bima Group and Yolde Formation (Plates VI, XI, XIV and XV). This type of cross- bed is believed to have been formed in the area mainly by migration in large- scale two- dimensional bedforms (dunes). The geometry of two- dimensional [2-D] bedforms can be described by one transect parallel to flow, whereas three- dimensional [3-D] bedforms must be defined in three dimensions (Ashley, 1990).

Irregular stratification

Several kinds of sedimentary structures are recognized that display features of bedding or stratification but which do not show regular stratification of structures. This type of structure was

observed within the Upper Bima Sandstone (B3) at the foot of Tangaran Hill which resulted from the deformation or alteration during or after deposition but prior to consolidation (penecontemparaneous deformation). Presumably, the deformation might have occurred by physical processes that involve self- sediment aluming, loading, squeezing or partial liquefaction.

Convolute cross- bedding is typical example of this irregular stratification. This in another sense is more applied to completely fold in intricately crumpled beds that are commonly, although not invariably, confined to a single sedimentation unit. Strata above and below this unit may show little or no evidence of deformation; this is typical the case in this study of the Uper Bima Sandstone (Plate XII). Convolute beddings are most common in fine- grained sand to silt size siliclastic sediments.

The origin of convolute bedding is not fully understood, Allen (1982) suggests that they may have formed at three different stages with respect to the time of sedimentation: post- depositional convolute arises sometime after the start of burial, metadepositional convolute arises just before or immediately after deposition ceases, and syndepositional convolute forms episodically to continuously during deposition. Most researchers agree that it is caused in some way by deformation of hydrolastic or liquefied sediment.

5.6.2 Secondary Structures

In the study area, various secondary structures were observed and mostly occur within the Cretaceous sedimentation (Lower and Upper Bima Sandstones) with different structural trends

that conformed to the work of previous researchers. The structures observed includes folds (anticline) at Birni Gadam and (syncline) at Bara and Shishiwaji within the Upper Bima Sandstone. Fault breccias occur at Wongeri and Tangaran Hills, NE- SW, NW- SE were observed, and E-W trending fault was observed at Birni Gadam. Carter *et al*. (1963) and Zaborski *et al*. (1997) reported the NE- SW, NW- SE trending faults (Plates XIII and XXI).

From seismic reflection data Avbovbo *at al*. (1986) inferred a total thickness of over 10km of Cretaceous to Quaternary sediments (was subsequently proved 5km). Two main fault systems were identified in the Bornu Basin, a dominant NE- SW trending and a subsidiary NW- SW trending. They stated that the former involve the Precambrian basement, high angle normal fault delineating horst and graben like features. The latter affects only the sediments. Avbovbo *et al*. (1986) further stated that nearly all the faults terminate at an angular unconformity separating Cretaceous from younger beds. They also reported that folding also affect the Creatceous beds with simple, low amplitude low frequency structures occurring in the deeper parts of the depression.

Three stages in basin evolution were suggested; an Albian- Maastrichtian tensional phase of active rifting, cessation of structural swelling during the Maastrichtian to Danian with concomitant crustal sagging and compressional tectonics, and Cenozoic- Recent quiescent phase. Olugbemiro *et al*. (1997) also reported terminal Cretaceous to earliest Cenozoic folding, uplift and erosion believing that this event has greater importance than any Santonian deformation that might have occurred. The Chad Formation has been attributed to thermal sag of basin development subsequent to rifting in the WCARS.

CHAPTER SIX

6.0 SUMMARY, CONCLUSION AND RECOMMENDATIONS

6.1 Summary

The geological investigation carried in this study shows that there is a regional basin differentiation in terms of facies distribution as observed in the field based on their sedimentary

characteristics. The new revised stratigraphy proposed herein differs with that obtained from NNPC drilled holes towards the shores of Lake Chad and those of previous researchers using North American Stratigraphic Nomenclature (2005) Articles 19b, 19g, 28b and c, and International Stratigraphic Nomenclature (1999) Chatpers 3, B15 and Chapter 5, C6. The stratigraphy of the study area include the following; the Bima Group, consisting of (Lower, Middle, and Upper Bima Sandstones). This is overlain by the transitional Yolde Formation. This is the first time the formation is recognized and reported in the basin based on field evidences. The Yolde Formation is overlain by the newly recognized Pindiga Formation which consists of (Kanawa and Dumbulwa Members). The Pindiga Formation of this study replaces the Gongila Formation of Carter *et al*. (1963) owing to the discovery of mismapping by earlier workers by Zaborski *et al.* (1997) which conform with some of North American Commission on Stratigraphic Nomenclature (2005) Article 7 (b) and Article 20 and International Stratigraphic Nomeclature (1999) Chapter 3 (B,3,a). This is further overlain by the horizontally stratified beds of post-Cretaceous sedimentation consisting of Kerri- Kerri and Chad Formations. The study was able to map most of the Lower and Upper Cretaceous sediments, except Gombe Sandstone which was not encountered in the study area.

Facies analysis carried out revealed four facies groups which are gravel (G), sandstone, (S), mudstone (M) and carbonate (C), and eight lithofacies were identified which are; clast-supported conglomerates (Gcs), clast- supported conglomerates grading to sandstones, massive sandstones (Ss), cross- bedded sandstones (Sx), normally graded sandstones (Sng), and carbonate- rich layers. Analysis of architectural sedimentary elements also showed five facies elements which are; channels (CH, HO), sediment gravity- flow deposits (SG), sandy bedforms

(SB), downstream- accretion macroforms (DA) and flood plain fines (FF). These elements are defined by their geometries and bounding surfaces.

Petrographic analysis carried out was used for classification of sandstone into two classes, viz; arkosic and lithic arenitic sandstones. This was achieved from deducing the percentages of quartz, feldsper, and rock fragments. The classification scheme is based on the distribution of the three constituents, and a compositional maturity was also determined (matured and immature). Matured sandstones contain more quartz with some feldspers, with apppreciable rock fragments, whereas immature sandstones consist of high percentage of rock fragments than feldsper and quartz.

Two geochemical methods were employed for determination of elemental concentration for petroleum geochemical prospecting. The values obtained are not very favourable in terms of distribution in the rocks. This is so because the samples collected are near surface, showing that they have not reached the maximum depth for burial maturity or they have been affected by weathering. Their concentration values are low which mean they are yet to reach the maturation level, such that Santonian deformation activity (uplift) must have affected their thermal maturation. It is difficult to deduced whether or not, if the proposed source rocks have generated oil/gas and expelled ("effective"), or and has stopped generating because of uplift, or thirdly, if it has exceeded the oil/gas generative window due to presence of volcanic intrusives in the study area.

6.2 Conclusion

In conclusion, this study has provided new information on the geology of the Nigerian sector of the Chad Basin (Bornu Basin) at its boundary with the Upper Benue Trough (Gongola Basin)

which highlight the lithostratigraphic succession in the area which hitherto has not been done. The breakthrough was achieved based on field evidences documented in this work, as well as; i) determination of trace element concentrations and distribution related to petroleum geochemistry and geology was discussed; ii) the petrographic analysis carried out revealed two classes of sandstones and their compositional maturity in terms of transportation and provenance, and facies analysis carried out reveals four groups which were used to further classify the sediments into nine facies elements, additionally, architectural elements were also deduced.

6.3 Recommendations

It is recommended that a more detailed geological mapping should be carried out with adequate funding and be supported with seismic survey to reveal buried structures. Also, drilling should be undertaken in areas of source rock sampling points so as to collect mudrocks that are of considerable depth that might have entered the oil generative phase.

Contribution to Knowledge

i) The study was able to map Kerri- Kerri Formation appropriately which was previously recognized as Chad Formation in the study area

ii) The study was able to report Yolde Formation for the first time in the Nigerian sector of the Chad Basin (Bornu Basin) from field evidences

iii) For the first time, using field evidences, the previously recognized Bima Sandstone is now considered as Bima Group with (Lower, Middle and Upper Bima Sandstones). The upgrade was done using both the North American Commission on Stratigraphic Nomenclature (2005) Articles 19 and 28 and International Commission on Stratigraphy Chapter 3, B15 and and Chapter 5,

C6 which clearly supports the revision and redefinition of previously established unit as well as revision and abandonment of formal units (Change in Rank, Undesirable restriction and raising the rank of a unit when desired)

iv) The previously recognized Gongila Formation is now considered as (Kanawa and Dumbulwa Members) of the Pindiga Formatin due to substantial field evidences and revised stratigrahc nomenclature documented. These include Articles 7 and 20 were of the North American Commission on Stratigraphic Nomenclature which clearly supports the review of improperly defined or obsolete stratigraphic unit, and to also avoid duplicating of name which is the case of Pindiga and Gongila Formations in the Nigerian sector of the Chad Basin (Bornu Basin) and the Upper Benue Trough (Gongola Basin)

v) The study was also able to provide a comprehensive facies results which was not adequately available on the Bornu Basin

vi) An attempt is made to use trace elements geochemistry to provide information of the petroleum geology of the basin, particularly at the basin shoulder where thick sedimentary cover is not available.

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