CARBONATE SEQUENCE OF PINDIGA FORMATION IN ASHAKA QUARRY, UPPER BENUE TROUGH, NE NIGERIA.

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NIGERIA

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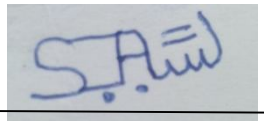
AHMADU BELLO UNIVERSITY, ZARIA

NIGERIA

DECEMBER, 2014

DECLARATION

I declare that the work in this thesis entitled "Carbonate sequence of Pindiga Formation in Ashaka Quarry, Upper Benue Trough, NE Nigeria" has been carried out by me in the Department of Geology under the supervision of Dr. H. Hamza and Dr. T Najime. The information derived from the literature has been duly acknowledged in the text and a list of references provided. No part of this thesis was previously presented for another degree or diploma at this or any institution.

Sa'id Abdulkarim  04/12/2014

Signature Date

CERTIFICATION

This thesis entitled "CARBONATE SEQUENCE OF PINDIGA FORMATION IN ASHAKA QUARRY, UPPER BENUE TROUGH, NE NIGERIA" by Sa'id ABDULKARIM meets the regulations governing the award of the degree of Master of Science in Geology (Stratigraphy and paleontology) of the Ahmadu Bello University, Zaria, and is approved for its contributions to knowledge and literary presentation.

Dr. H. Hamza Chairman Supervisory Committee	Signature	04-12-14 Date
Dr. T. Najime Member Supervisory Committee	Signature	05/12/2014 Date
Dr. H. Hamza Head of Department, Geology	Signature	04-12-14 Date
Dean, School of Postgraduate Studies	Signature	Date

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ABSTRACT

Two lithologic sections of limestone/shale deposits within the Pindiga Formation which is exposed at the Ashaka Cement Quarry which are 4 km apart were studied. The succession is such that the 8-9 m lowermost limestone deposit in the quarry overlies the continental Bima Sandstone, the two being separated by a ferrugineous layer which represents the lower sequence boundary and is characterized by sub-aerial exposure and erosion. The upper part of the section is made up of intercalated limestones and shales representing alternation in the depositional settings with oxic and anoxic conditions for the limestone and the shale deposits respectively. Deposition was in a shallow marine environment which is, in most cases of low energy, although there is evidence of high energy of the depositional medium represented by the cross bedding in some limestone facies,

A transgressive systems tract which is represented by two parasequence sets in the southern section, three parasequence sets in the northern section and a highstand systems tract represented by two parasequence sets in both the southern and northern sections make up the stratigraphic sequence at the quarry; the two systems tracts are separated by a maximum flooding surface. The marine flooding surfaces and minor marine flooding surfaces were identified. The lowstand systems tract is missing in the quarry and the upper sequence boundary is inferred to be within the Deba Fulani Member of the Pindiga Formation. Fossils present in the limestones include bivalves, ostracods, foraminifers, gastropods, and vertebrates. Extraclast such as quartz and feldspar as well as glauconite were also found in some of the limestones. The limestones are generally affected by neomorphism and are mostly wackestone and packston. Porosity is moderate to low, decreasing from top to the base of the profile and is mostly of biomoldic and vuggy type.

Table of Contents

Title page i
Declaration ii
Certification iii
Aknowledgement iv
Abstract v
Table of Content vi
List of Figures viii
List of Plates x

CHAPTER ONE 1

1.0 INTRODUCTION 1
1.1 T**he aim of the study** **1**
1.2 Location, Extent and Accessibility of the study 1
1.3 Relief and Drainage 2
1.4 Climate and Vegetation 3
1.5 Nature of Present Work 4

CHAPTER TWO 5

2.0 LITERATURE REVIEW 5
2.1 An Overview of the Benue Trough 5
2.2 T**he Upper Benue Trough** **7**
2.2.1 Stratigraphy 8
2.2.2 Structure 22
2.3 Previous work in Ashaka area 24

CHAPTER THREE……..……..……..30

3.0 METHODOLOGY 30
3.1 Field Method 30
3.2 Laboratory Method 3**1**

CHAPTER FOUR……..……32

4.0 RESULTS AND DISCUSSION 32
4.1 Microfacies and Microfossils study 32
4.1.1 Microfacies 32
4.1.2 Micropalaeontology 63
4.1.3 Sedimentology 66
4.2 Sequence Stratigraphy 68
4.2.1 Bounding Surfaces of Sequence Stratigraphy 69
4.2.2 The Sequence 71
4.2.3 Stratigraphic Correlation 77
4.3 Depositional Environment 81

CHAPTER FIVE……..83

SUMMARY AND CONCLUSION..... 83

REFERNCES…….…...86

APPENDIX…….……..90

List of Figures

Figure 1: Geological map around Ashaka Cement Quarry……..…2

Figure 2: Map of Nigeria showing the different Sedimentary Basins……..……...…6

Figure 3: Idialised N-S stratigraphic cross-section across the Benue Trough and the relationship to Niger-Delta and the Chad basin……...…7

Figure 4: Geological map of part of the Upper Benue Trough ……..……...…...…8

Figure 5: Spitial relationship within Bima Group along an E-W line from shani.....……11

Figure 6: Early Cretaceous sedimentary environments and structural settings of the Benue Trough, adjoining areas of Africa and north-east Brazil……..……..….13

Figure 7: structural setting for the deposition of "Lower Bima Sandstone" in sub-basins controlled by NE-SW trending strikr-slip and NW-SE trending normal faults…...15

Figure 8: Outline geologic map showing the main feature of the Upper Benue Trough…....23

Figure 9: Section of the Lower Turonian Gongila and Underlying Albian-Cenomanian Bima Formations at the Ashaka Quarry……26

Figure 10: Stratigraphic log of the Gongila Formation at Ashaka Quarry, with subdivision into 20 lithologic levels ……..28

Figure 11: Stratigraphical section in the Pindiga Formation exposed at Ashaka Quarry and in the Pindiga stream ……29

Figure 12: Distribution of constituent in the limestone units of northern section of Ashaka Quarry……....32

Figure 13: Lithostratigraphic section of the northern part of Ashaka Quarry…….....33

Figure 14: Distribution of bioclast in the limestone units of the northern section of Ashaka Quarry……..….34

Figure 15: Northern section of Ashaka Quarry showing the percentage composition, porosity type and rock name…….....47

Figure 16: Distribution of Constituent in the limestone units of southern section of Ashaka Quarry……49

Figure 17: Distribution of bioclast in the limestone units of southern section of Ashaka Quarry……..…..…..49

Figure 18: Lithostratigraphic section of the southern part of Ashaka Quarry……..……..…50

Figure 19: Southern section of Ashaka Quarry showing the percentage composition, porosity type and rock name……60

Figure 20: Northern section of Ashaka Quarry with the foraminifera identified……..…..64

Figure 21: Southern section of Ashaka Quarry with the foraminifera identified..……..……65

Figure 22: Sequence stratigraphic succession of the southern part of Ashaka Quarry……...72

Figure 23: Sequence stratigraphic succession of the northern part of Ashaka Quarry…..…..74

Figure 24: Sequence stratigraphic interpretation of Pindiga Formation (Kanawa Member) at Ashaka Cement Quarry (After Alfarooq 2004)……..76

Figure 25: Lithologic correlation of limestone units in northern and southern section of Ashaka Quarry…….……...……..….78

Figure 26: Sequence stratigraphic correlation of the northern and southern part of Ashaka Quarry……..80

List of Plates

Plate 1: Photomicrograph of sample from unit 1 of the northern section……..35

Plate 2: Photomicrograph of sample from unit 2 of the northern section…….....37

Plate 3: Photomicrograph of sample from unit 7 of the northern section……..…38

Plate 4: Photomicrograph of sample from unit 9 of the northern section…….…39

Plate 5: Photomicrograph of sample from unit 10 of the northern section…..……...41

Plate 6: Photomicrograph of sample from unit 13 of the northern section……....42

Plate 7: Photomicrograph of sample from unit 14 of the northern section……...43

Plate 8: Photomicrograph of sample from unit 18 of the northern section…….…….44

Plate 9: Photomicrograph of sample from unit 24 of the northern section..……46

Plate 10: Lowermost limestone units in the northern section of the quarry ……48

Plate 11: Northern quarry face section ……48

Plate 12: Photomicrograph of Sample from unit 1 of the southern section……..…51

Plate 13: Photomicrograph of sample from unit 2 of the southern section……..…..53

Plate 14**:** Photomicrograph of sample from unit 6 of the southern section……..…..54

Plate 15: Photomicrograph of sample from unit 9 from the southern section…….....55

Plate 16: Photomicrograph of sample from unit 13 from the southern section……..57

Plate 17: Photomicrograph of sample from unit 21 from the southern section……..58

Plate 18: Photomicrograph of sample from unit 23 from the southern section……..59

Plate 19: Lowermost limestone units from southern section of the quarry…..……...61

Plate 20: foraminifera in unit 10, a: *Heterohelix sp*., b: *Lenticulina*..…….....…90

Plate 21: foraminifera in unit 14, a: *Nonium*, b: *Quinqueloculina*……90

Plate 22: foraminifera in unit 18, a: *Quinqueloculina*, b: *Lenticulina*, c: *Elphidium*, d: *Textularia*……91

Plate 23: foraminifera in unit 20, a: *Quinqueloculina*, b: *Lenticulina*..……..…92

Plate 24: foraminifera in unit 7, a: *Lenticulina*, b: *Quinqueloculina*, c: *Heterohelix sp*.....93

Plate 25: foraminifera in unit 9, a: *Quinqueloculina*, b: *Nonium*……..…94

Plate 26: foraminifera in unit 13, a: *Quinqueloculina*, b: *Triloculina*……...…….....……94

Plate 27: foraminifera in unit 17, a: *Quinqueloculina*, *Lenticulina*……..…….....….95

Plate 28: foraminifera in unit 23, a: *Quinqueloculina,* b*: Elphidium*, c: *Textularia*……96

CHAPTER ONE

INTRODUCTION

This project is aimed at studying the microfacies as well as interpreting the sequence stratigraphic framework of the Pindiga Formation exposed at Ashaka Cement Quarry, in North-East Nigeria. Field relationship of the limestone beds and the associated shales was established and the stratigraphic section at the Ashaka Quarry was studied. Samples were taken for further petrographic, micropalaeontological and sedimentological studies.

1.1 THE AIM OF THE STUDY

The aim of this study is to analyze the microfacies and to interpret the stratigraphic sequence of the Pindiga Formation as exposed in the Lafarge Cement Company quarry at Ashaka.

1.2. LOCATION, EXTENT AND ACCESSIBILITY OF THE STUDY AREA

The Ashaka Quarry is located between Ashaka and Bage Villages in Funakaye local government area of Gombe State, northeastern Nigeria. The quarry lies between latitudes 10^{o} $54^{'}$ and 10^{o} $57^{'}$ N and longitudes 11^{o} $26^{'}$ and 11^{o} $29^{'}$ E. It covers an area of about 7.0 km^2 (Fig. 1). The study area is about 100 km NW of Gombe town. It is accessible by major (tar) road from Gombe through Malam Sidi and Bajoga towns. The quarry area is accessible by major roads that aid quarry operations which include the limestone and overburden hauling from the quarry face to the crusher and from the quarry face to the land reclamation site.

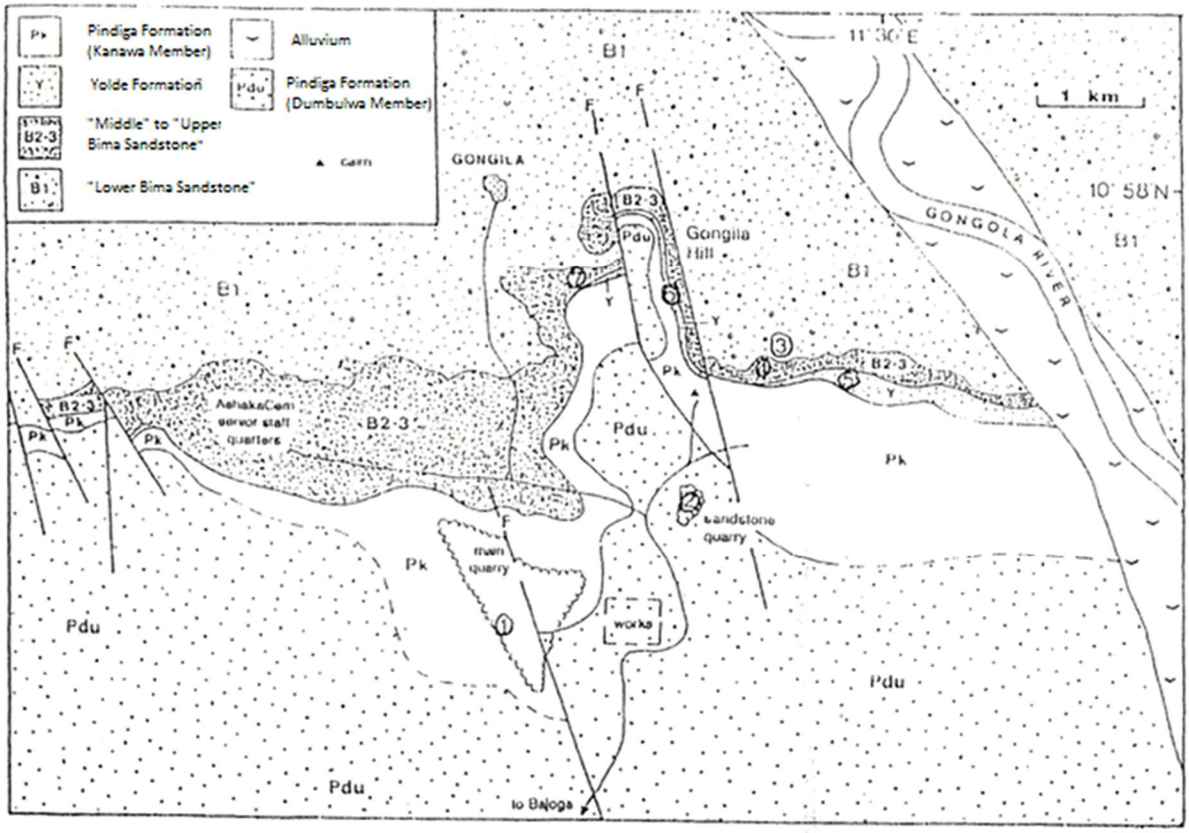


Figure 1: Geological map around Ashaka Cement Quarry. (After Zaborski, 2003).

1.3. RELIEF AND DRAINAGE

Relief at the quarry is generally moderate with elevations ranging between 230 m and 250 m above sea level. After the quarrying, land is reclaimed with fertile soil removed as overburden. Local farmers in the area take advantage of the fertile plain to farm during the rainy seasons; the fertility of the land is due to the liming of the land by the limestone of Kanawa Member, Pindiga Formation. To the northwest and to the northeast of the quarry are areas of higher relief which can be seen at some distance from the quarry. These are the Bage Hills which is 375 m above sea level and a cliff close to the Plain of Gongola River which rises up to 270 m above sea level (Figure 3). The Dumbulwa Member of Pindiga Formation makes up the Bage Hills while Bima Group, Yolde Formation, and

Pindiga Formation (Kanawa and Deba Fulani Menbers) forms the cliff (Zaborski *et al*., 1998). There is no proper drainage system within the quarry; patches of standing water can be seen within the quarry especially during the rainy season. Elsewhere the Gongola River and its tributaries form the main drainage systems in the area. The River Maaza is the main tributary and it flows from northwest to southeast into the River Gongola.

1.4. CLIMATE AND VEGETATION

Generally, Nigeria has a tropical climate with sharp regional variations. The seasons are governed by the movement of the inter-tropical convergent zone, a zone where warm, moist air from the Atlantic Ocean converges with hot, dry, and often dust-laden air from the Sahara desert known locally as the harmattan. During the summer, the zone of inter-tropical discontinuity follows the Sun northward. As a result, more and more of the country comes under the influence of moisture-laden tropical maritime air. Thus, much of the country experiences a rainy season during summer. As summer wanes, the zone shifts southward, bringing an end to the rainy season. Temperatures are high throughout the year, averaging from 25° to 28°C (77° to 82°F). The study area falls within the humid tropical climate zone of Nigeria. The average rainfall varies from 760 mm to 1000 mm annually, with the highest rainfall recorded during the months of July and August.

The study area is characterized by the Sudan Savannah vegetation type which contains predominantly both tall and short grasses with scattered trees and shrubs. The trees are mostly locust bean trees, baobabs and some other forms of deciduous trees. They are heavily cut by inhabitants to make firewood as a source of energy for cooking.

1.5. NATURE OF PRESENT WORK

The present work aims at examining the exposure of limestone/shale units of Pindiga Formation at Ashaka Quarry for the purpose of interpretation of sequence stratigraphy and the microfacies analysis using petrography, micropalaeonotology and sedimentology. The petrography and environment of deposition of the limestones were investigated and related to the previous research work carried out at the quarry. Couville (1992), Couville & Thierry (1993) and Alfarooq (2004) attempted sequence stratigraphic interpretations of the section in southern part of the quarry. The present work will attempt to address some details which were lacking in the earlier works done at the quarry.

CHAPTER TWO

2.0 LITERATURE REVIEW

2.1 AN OVERVEW OF THE BENUE TROUGH

The Benue Trough of Nigeria is a rift basin that extends NNE for about 800 km in length and 150 km in width; its northern limit is the southern boundary of the Chad Basin (Figure 2). The trough contains up to 6,000 m of Cretaceous to Tertiary sediments of which those predating the mid-Santonian have been compressionally folded, faulted, and uplifted in several places. The Benue Trough is sectorially subdivided into a Lower, Middle and Upper portion (Figure 2). Major localities (towns/settlements) that constitute the depocentres of the different portions have been well documented (Petters, 1980; Obaje, 2009; Benkhelil, 1988; Benkhelil, 1989).

Compressional folding during the mid-Santonian tectonic episode affected the whole of the Benue Trough and was quite intense, producing over 100 anticlines and synclines (Benkhelil, 1988). The major deformational structures include the Abakaliki anticlinorium and the Afikpo syncline in the Lower Benue, the Giza anticline, Keana anticline, and the Obi syncline in the Middle Benue, and the Lamurde anticline and the Dadiya syncline in the Upper Benue Trough. Following mid-Santonian tectonism and magmatism, the depositional axis in the Benue Trough was displaced westward resulting in strong subsidence of the Anambra Basin. The Anambra Basin largely contains sediments of Campanian-Maastrichtian to Eocene ages. It is logical to include the Anambra Basin in the Benue Trough, being a related structure that developed after the compressional stage (Akande and Erdtmann, 1998).

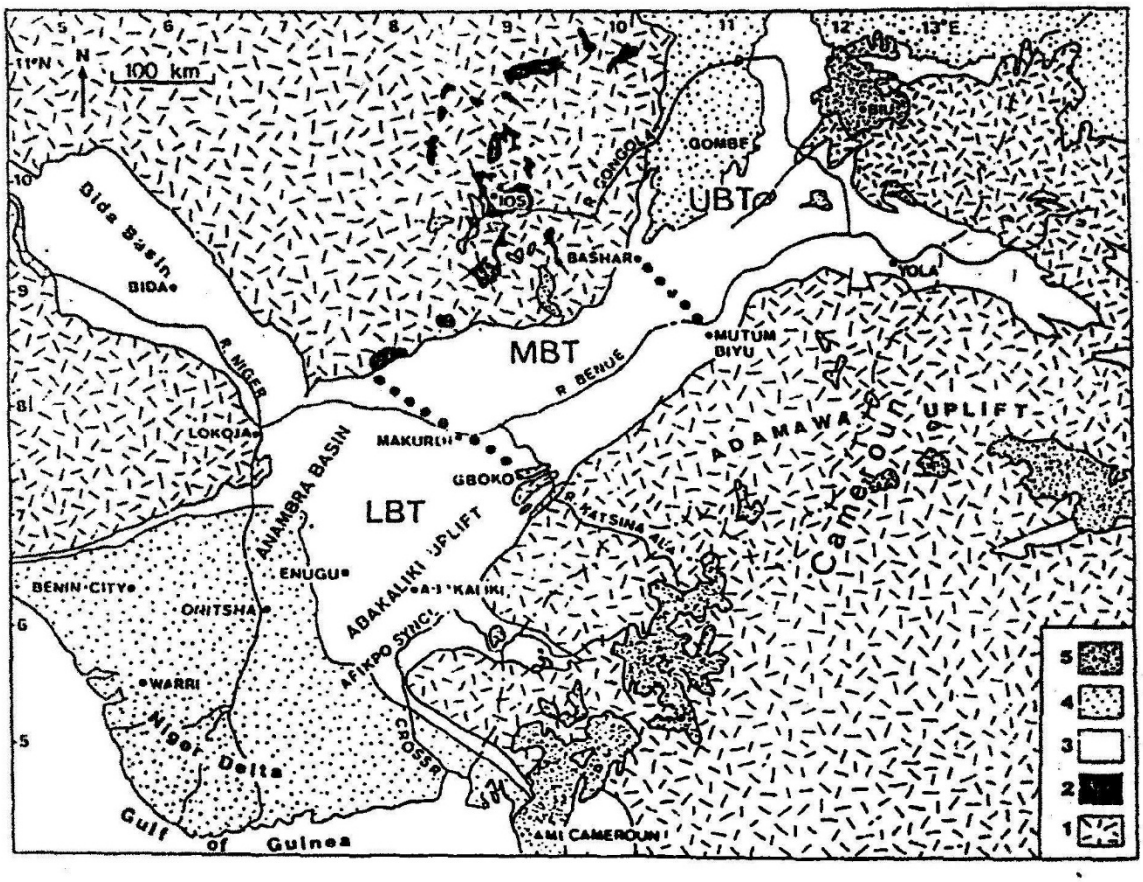


Figure 2: Outline of geological map of the Benue Trough and adjacent areas (after Zaborski, 1998). LBT Lower Benue Trough; MBT Middle Benue Trough; UBT Upper Benue Trough. 1. Precambrian. 2. Jurassic "Younger Granites" 3. Cretaceous 4. Post Cretaceous sediments 5. Cenozoic Recent basalts including those of Cameroon Line.

The depocentres of the Lower Benue Trough comprise mainly the areas around Nkalagu and Abakaliki, while those of the Anambra Basin center around Enugu, Awka and Okigwe. The Middle Benue Trough comprises the area from Makurdi through Yandev, Lafia, Obi, Jangwa to Wukari. In the Upper Benue Trough, the depocenters comprise Pindiga, Gombe, Nafada, Ashaka (in the Gongola Arm) and Bambam, Tula, Jessu, Lakun, and Numan in the Yola Arm.

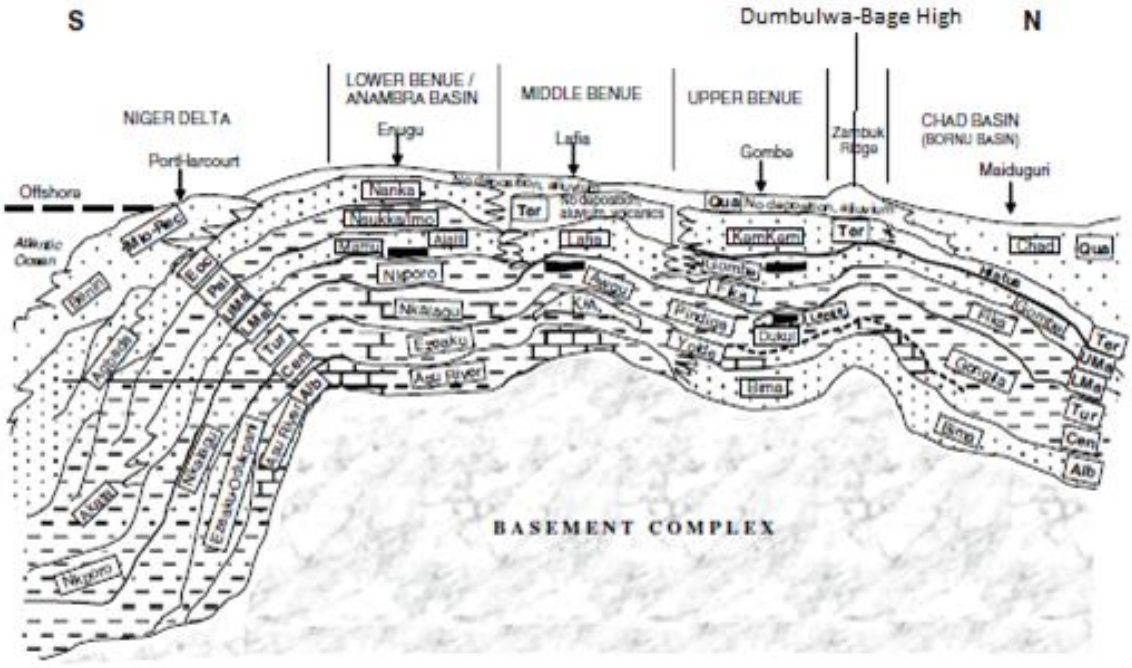


Figure 3: idealized N – S stratigraphic cross-section across the Benue Trough and the relationship to the Niger Delta and the Chad Basin [vertical scale exaggerated: erosion and uplift not considered] (After Obaje, 2009)

2.2 THE UPPER BENUE TROUGH

The Upper Benue Trough comprises the area extending from the Bashar-Mutum Biyu line as far north as the Dumbulwa-Bage high of Zaborski *et al* (1998) which separates it from the Bornu Basin. Important early works on the Upper Benue Trough includes those of Falconer (1911), Barber *et al*. (1954) and Carter *et al*. (1963) who undertook a regional study of the area covered by the Geological Survey of Nigeria. Other workers include Allix (1983), Benkhelil (1988, 1989), Popoff (1988) and Zaborski *et al.* (1998). The Upper Benue Trough is made up of two arms, the Gongola Arm and the Yola Arm (although some authors have sub-divided the Upper Benue Trough to include a third central Lau-Gombe sub-basin.

2.2.1 Stratigraphy

The Cretaceous succession in the Upper Benue Trough comprises Early Cretaceous continental clastics, the Bima Group, and a dominantly marine Late Cretaceous succession. The former includes the oldest sediments known in the Benue Trough, deposited during active rifting. During the Late Cretaceous thermo-tectonic sag conditions prevailed and sedimentation was strongly influenced by transgressive-regressive events.

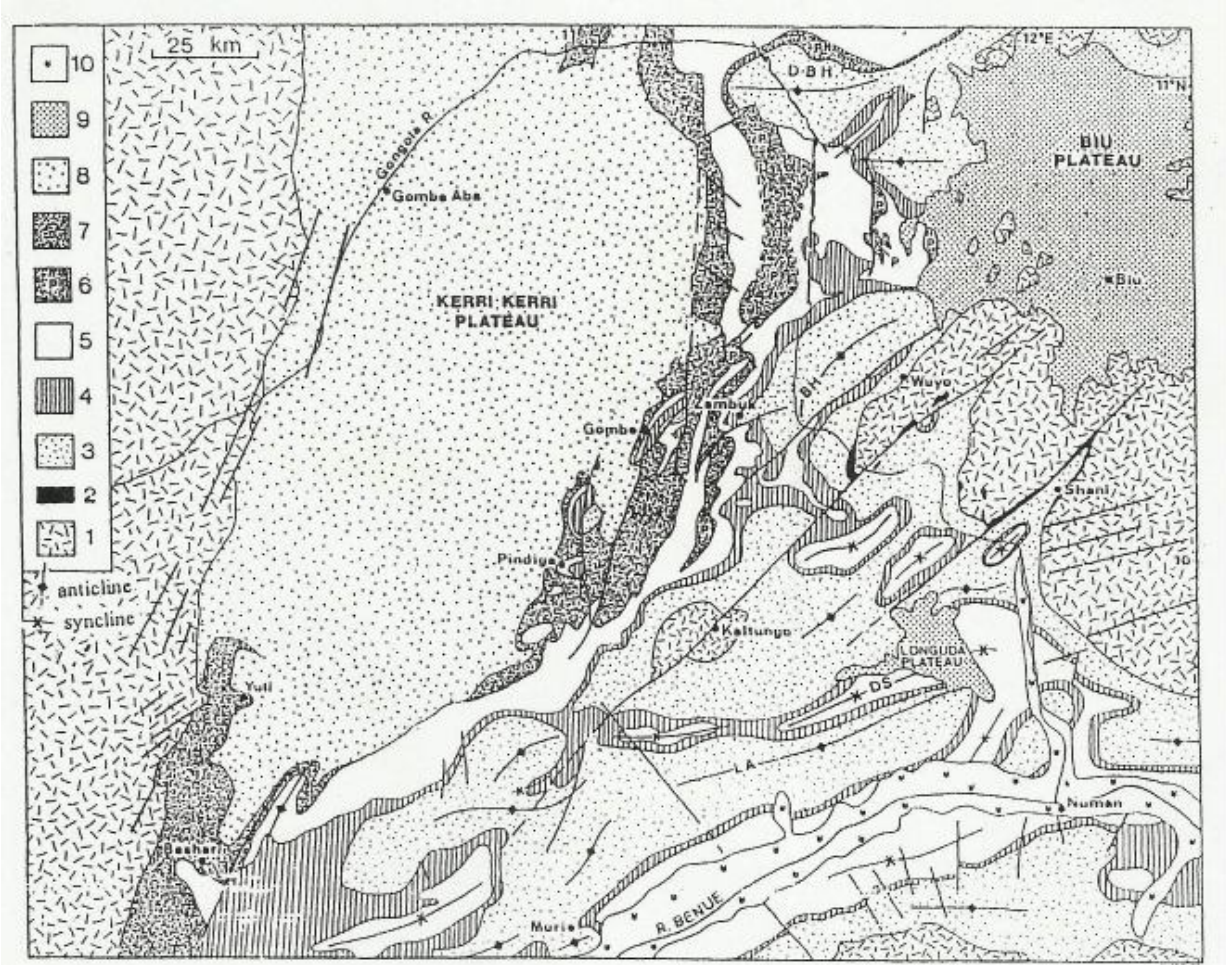


Figure 4: Geological map of the part of the Upper Benue Trough. Explanation [1, Precambrian crystalline basement; 2, Late Jurassic to Early Cretaceous volcanic; 3, Bima Group; 4, Yolde Formation; 5, Pindiga Formation; 6, sandstone members in the middle part of the Pindiga Formation in the Gongola Basin; 7, Gombe Sandstone; 8, Kerri-Kerri Formation; 9, Neogene to Quatenary basalts; 10, alluvium; D-BH, Dumbulwa-Bage high; BH, Bima Hills; DS, Dadiya syncline; LA, Lamurde anticline] (After Zaborski, 2003)

The Upper Cretaceous may be divisible into discrete pre-Santonian and Campano-Maastrichtian parts, the latter deposited during a renewed phase of rifting.

2.2.1.1 The Bima Group

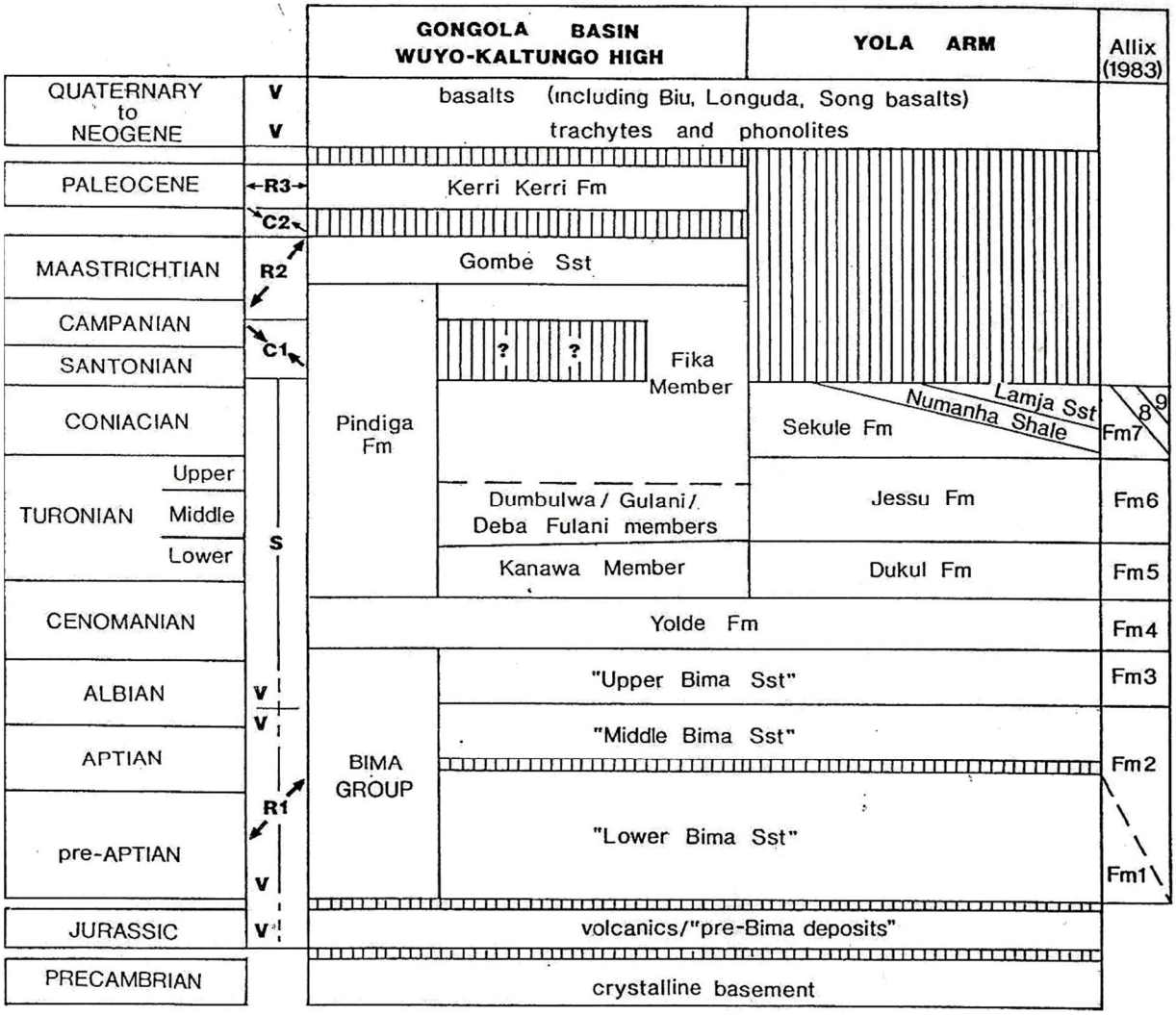
According to Zaborski (1998a), the Bima Group reaches a thickness of several kilometers and in most places represents by far the greatest proportion of the lithostratigraphical succession present in the Upper Benue Tough. Extensively exposed in the eastern and the southern parts of the region, it has been studied in detailed, notably by Carter *et al.* (1963), Allix (1983), Popoff (1988) and Guiraud (1990, 1991). The term "Bima Sandstone" was first used by Falconer (1911) for beds occurring at the type locality in the Bima hills (Figure 4) and including the Yolde Formation of later authors.

Those part 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 "Bima Sandstones Group" of Raeburn and Jones (1934) (which they also encompass the Yolde Formation); the "Guyok Sandstones" and "Bima Grits" of Barber *et al*. (1954); and the "Bima Sandstones" of Carter *et al*. (1963). Ojo and Pima (1988) proposed a very complex subdivision of the Bima Group. More regionally workable schemes were proposed by Allix (1983) and Guiraud (1990, 1991).

The thickest outcrops of Bima Group occur in the Lamurde anticline (Figure 4) where Allix (1983) recognized: at the top, "Formation 3", 1200 m thick, made up of an upper member, 220 m thick, a middle member, 240 m thick, and a lower member, 740 m

thick, "Formation 3" was regarded as almost entirely fluviatile in origin, although the upper part shows some slight marine tendencies suggesting a delta plain paleoenvironment (on the basis of the dinoflagellates from the subsurface at Talasse;) A Late Albian to Early Cenomanian age was assigned to the co-occuring pollens (Allix, 1983).

Table 1: Lithostratigraphic successions present in the Upper Benue trough region {subdivision of the Bima Group after Guiraud (1990a, 1991a)}. V, volcanic episode; RI, Early Cretaceous strike-slip related rifting; S, thermo-tectonic sag phase; C1, first compressional phase, associated with strike-slip movement; R2, Campano-Maastrichtian rifting; C2, terminal Cretaceous compression, associated with strike-slip movements; R3, Paleocene rift stage. (Adapted from Zaborski, 1998a)



In the middle "Formation 2", 700 m thick, made up of four different members which are, from top to bottom; 125 m, 65 m, 260 m and 250 m thick respectively. It was

regarded as of median to proximal fan-delta origin with the upper member being perilacustrine. Ostracods and a palynoflora recovered from the subsurface near Kaltungo suggested an Early Albian age for the base of the formation while K-Ar ages for intercalated lavas at Bima hills gave a Middle Albian age for its upper part. At the bottom, "Formation 1", 365 m exposed, made up of three members; 100 m, 205 m and 60 m thick from top to bottom respectively. It was thought to have been deposited in a distal fan-delta prograding into a lacustrine environment. A Late Aptian age was suggested based on the freshwater ostracods of Neocomian to Albian age reportedly present in the formation. Formations "1","2" and "3" correspond to the upper part of the "Lower Bima Sandstone", the "Middle Bima Sandstone" (in broad terms) and the "Upper Bima Sandstones" respectively of Carter *et al*. (1963).

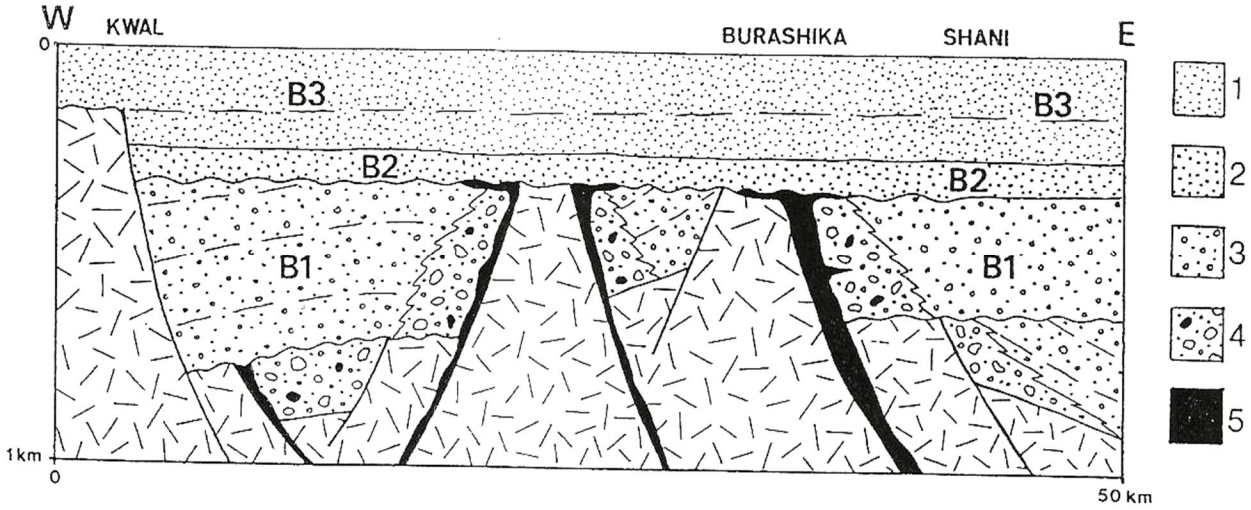


Figure 5: Spitial relationship within Bima Group along an E-W line from Shani (Adapted from Guiraud, 1991). B1, "Lower Bima Sandstone"; B2, "Middle Bima Sandstone"; B3 "Upper Bima Sandstone"; 1, medium to coarse-grained sandstones; 2, coarse-grained sands and gravels of B2; 3, coarse-grained sands and gravels of B1; 4, conglomerates and alluvial fan deposits of B1; 5, basalts and rhyolites.

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

iii, the "Upper Bima Sandstone" ("B3"), with average thickness of 500 m and a maximum of 1200 m.

ii, the "Middle Bima Sandstone" ("B2"), made up of fining upward cycles each 5-10 m thick. The thickness varies from 100-500 m.

i, the "Lower Bima Sandstone" ("B1"), ranging in thickness from 0 to over 1500 m.

A regional angular unconformity was identified between the "B1" and younger beds (Table 1 and Figure 5).

Popoff *et al.* (1988) believed a Neocomian to Barremian "co-rift" begins when "basal conglomerates and sandstones" several meters thick and including boulders of very large size were deposited in small isolated basin in northern Cameroun, and large parts of the Benue Trough. East-west trending faults were regarded as controlling this sedimentation in the Yola arm while brittle extension took place to the west controlled by NNE-SSW and NE-SW trending strike-slip faults (Figure 6). This stage was also accompanied by magmatism in the Burashika area with lava flows yielding ages close to the Jurassic-Cretaceous boundary.

During a Barremian to Middle Albian "syn-rift I" phase (Figure 6b) the rate of crustal subsidence increase and larger elongate basins developed. They were believed to be the sites of lakes which temporarily merged to create a system of "great interior lakes" perhaps occupying the entire Benue Trough. "Formation 1" and "Formation 2" of Allix (1983) were regarded as the lacustrine and marginal alluvial cone facies respectively of this system. Argillaceous facies similar to "Formation 1" and reaching a thickness of nearly 3500 m were postulated to exist in the subsurface Upper Benue Trough. Trans-tensional faults trending NNE-SSW and ESE-WNW parallel to the margin of the Gongola

Basin and Yola arm were thought to have been active at this time. The Barremian-Aptian basins of Cameroun with a fluvio-lacustrine infill belong to this phase.

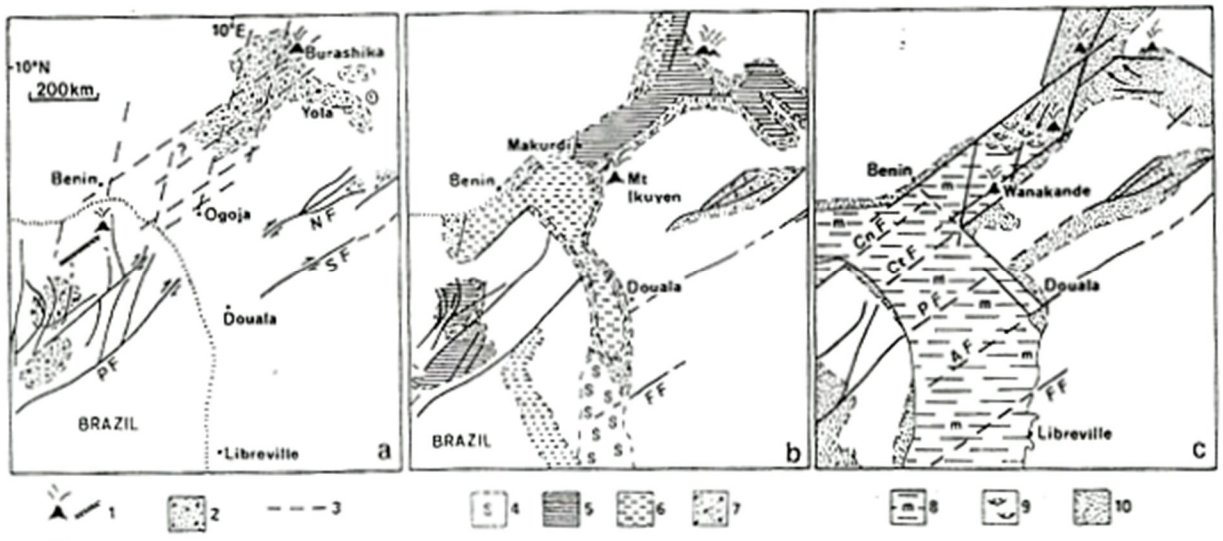


Figure 6: Early Cretaceous sedimentary environments and structural settings of the Benue Trough, adjoining areas of Africa and north-east Brazil (After Zaborski, 1998, After Poppff *et al.*, 1988). a, Neocomian to Barremian. b, Barremian to Middle Albian. c, Late Albian. 1, volcanic flows and dykes; 2, Neocomian conglomerate; 3, gravimetric discontinuity; 4, Aptian salt; 5, lacustrine deposits; 6, probable maximum extent of lacustrine deposits; 7, lacustrine boarder conglomerates; 8, marine deposits; 9, deltaic deposits; 10, fluviatile deposits; PF, Pernambuco fault zone; NF, Ngaoundere (Foumban) fault zone; SF, Sagana fault zone; FF, Fang fault zone; CnF, Chan fracture zone; CtF, Charcot fracture zone; AF, Ascension fracture zone.

According to Popoff *et al*. (1988) a "syn-rift II" phase took place during the later part of 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 Upper Benue Trough (Figure 6c) in which "Formation 3" was deposited. Paleocurrent directions indicate a large alluvial plain inclined gently north-westwards for the western Yola arm (Figure 6c). North of the Bima-Teli faults paleocurrents flowed in south-westerly direction ultimately discharging into the sea which by late Middle Albian times had invaded the Middle Benue. According to Guiraud and Maurin (1992) the Benue Trough was now

subjected to a sinistral transtensive regime in which extension occurred in a N60˚-70˚E direction.

Guiraud (1990, 1991) interpreted the lacustrine sediments of "Formation I" in the Lamurde anticline as a local facies development of his "Lower Bima Sandstone". Elsewhere this unit is made up of widely variable conglomeratic and sandy facies of alluvial fan to braided river origin. Guiraud, (1993) recognized three stages of basin development during deposition of the Bima Group.

The first rifting stage was marked by deposition of thin, conglomeratic "Pre-Bima" deposits around Guburunde on the southern margin of the Wuyo horst and Burashika. Intercalated or superposed rhyolites and basalts occur yielding K-Ar and 39Ar/40Ar ages of 147 Ma - 140 Ma (see also Baudin, 1991). 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 co-rift sediments of Popoff (1988).

According to Guiraud (1993), a second stage of rifting took place from Neocomian to as late as Early Albian during a N60˚E extensional regime. The "Lower Bima Sandstone" was now deposited in sub-basin of half-graben nature controlled by N60˚E trending transtensional faults [including the main faults of the Wuyo-Kaltungo high and N140˚E trending normal faults (Figure 7a)]. In most of these sub-basins alluvial fan deposits adjacent to the active fault-bounded margins give way to braided river deposits towards the basins axes. In the largest of the basins, lacustrine conditions developed but such a situation is only known from the Lamurde area (Zaborski, 1998). Paleocurrents were under local tectonic control and flowed towards the axes of the individual basins. The termination of this stage is marked by the regional unconformity at the top of the "B1"

beds. Deposition of Bima Group was accompanied and immediately preceded by the main phase of Cretaceous volcanism in the Upper Benue Trough which occurred between 147 and 106 Ma (Popoff *et al*., 1986). The oldest volcanics occur in the Burashika and Gubrunde areas.

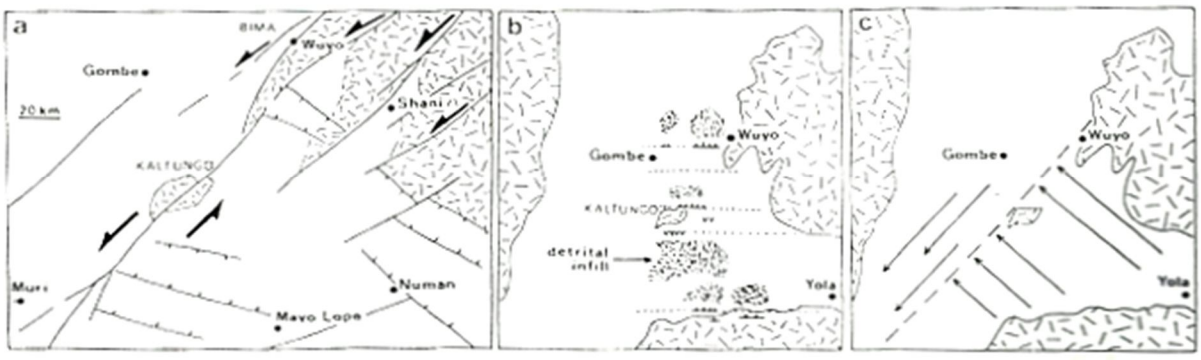


Figure 7: a) Structural setting for the deposition of "Lower Bima Sandstone" in sub-basins controlled by NE-SW trending strike-slip and NW-SE trending normal faults (After Allix, 1983); b) structural settings for the deposition of Formations "1" and "2" in E-W trending trough. c) structural setting for "Formation 3" with north-westrly and south-westerly inclined paleoslopes (After Zarborski, 1998a).

2.2.1.2 Yolde Formation

The Yolde Formation is mainly of marine origin with argillaceous lithologies being important (Zaborski, 1998a). The name "Yolde Formation" was proposed by Carter *et al*. (1963) for the "transitional beds" recognized by Falconer (1911) and Barber *et al*. (1954) between the Bima Group and the Pindiga Formation. The type locality was designated in the Yolde stream in the western part of Yola arm by Carter *et al*. (1963). The Yolde Formation consist largely of alternations of coarse to fine-grained, cross-bedded or ripple-bedded sandstones and grey to green shale. Thin limestones or calcareous sandstones occur, especially in the upper part where oyster beds are common (Zaborski *et al.,* 1998).

The formation fines 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 higher up, Zaborski (1998a); Carter *et al*. (1963) defined the boundary with the "Upper Bima Sandstone" by the appearance of "marine" shales. Allix (1983) used the appearance of thick, laterally continuous siltstone or silty shale or the base of a marker horizon comprising greenish fine-grained sands with disturbed cross-bedding found in parts of Yola arm.

The Yolde Formation was deposited under a coastal marine environment between the continental Bima Formation and the marine deposits of the lower part of the Pindiga Formation. The lower sandstone-mudstone portion of the Yolde Formation was interpreted by Zaborski (1998a) to be of fluvial and coastal plain paleoenvironment and the upper portion with thinly bedded and regularly bedded bioturbated sandstones and low diversity bivalves faunas at the top, of shallow marine origin.

Lawal (1982) and Lawal & Moullade (1986) suggested a Late Albian to Cenomanian age for the Yolde Formation on the basis of its palynoflora. The marine upper part of the Yolde Formation is probably of early Late Cenomanian age according to Zaborski *et al.* (1998) while Popoff *et al.* (1986) suggested an Early to Middle Cenomanian age. Carter *et al*. (1963) reported the Late Turonian ammonite (*Coilopoceras*) in the Yolde Formation. The overall thickness of the Yolde Formation in the Upper Benue Trough is from 140 m to little over 200 m (Thompson, 1958; Carter *et al*., 1963; Lawal, 1982; Allix, 1983; Zaborski *et al.*, 1998).

2.2.1.3 Pindiga Formation

According to Zaborski *et al*. (1998), the Pindiga Formation records the initial stages of the Late Cenomanian to Early Turonian transgression but the overlying beds represent its peak. They consist mainly of shale, dark grey when fresh but weathering to light blue-green to grey colours. Disseminated gypsum commonly occurs in exposures. Sporadic interbedded limestones are also present, most are a few centimeters to a few tens of centimeters thick but they may be superposed to produce unit of up to 2 m and in the Ashaka area on the southern flank of the Dumbulwa-Bage high nearly 10 m. In the Yola arm this shale-limestone unit is refered to as the Dukul Formation (Carter *et al.,* 1963). Here it is about 80 m thick at its type locality in the eastern Dadiya syncline where it also contains sandy and silty intercalations (Allix, 1983; Zaborski, 1990). In the Wuyo-Kaltungo high area, Carter *et al.* (1963) referred to the unit as the 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.* (1998) regarded the "Gongila Formation" as a synonym of the Pindiga Formation and referred the shale-limestone beds to the Kanawa Member of Pindiga Formation. The Kanawa Member ranges in thickness from 120 m at Kumo (Lawal, 1982) to just a few metres of condensed limestone-dominated beds in the Dumbulwa hills (Zaborski *et al.*, 1998).

Zaborski (1998b) described the limestone beds as frequently fossilifereous and the Dukul Formation and Kanawa Member have received considerable attention. Dating is based on the ammonite faunas with five major ammonite zones:

v. a Zone of *Wrightoceras wallsi*; (Reyment)

iv. a Zone of *Pseudotissotia nigeriensis* (Woods);

iii. a Zone of *Vascoceras globosum* (Reyment);

ii. a Zone of *Paravascoceras cauvini* (Chudeau); and

i. a Zone of *Nigericeras gadeni* (Chudeau).

The Cenomanian-Turonian boundary has been variously placed but coincides approximately with the base of the *Nigeriensis* Zone. The Kanawa Member is slightly diachronous. Although its base appears to be of approximately the same age throughout the Upper Benue Trough, the *Wallsi* Zone is only known from the Wuyo-Kaltungo high area and the Yola arm. The Dukul Formation also includes latest Early Turonian beds containing the ammonites *Hoplitoides* and *Kamerunoceras turoniense* (d'Orbigny); the top of the formation approximates to the Lower-Middle Turonian boundary.

During the Middle Turonian, regressive conditions affected the Upper Benue Trough. In the Gongola Basin and Wuyo-Kaltungo high region dominantly arenaceous deposits lie above the Kanawa Member. In the eastern Gongola Basin they make up the Gulani Member (of the Pindiga Formation). These probably fluviatile sediments include very large-scale tabular cross-bedded, coarse-grained sandstones and granulestones, individual sets being several meters thick (Zaborski *et al*., 1998). Thinner sandstones and desiccation-cracked clays also occur. In the Dumbulwa-Bage high their lateral equivalent is the Dumbulwa Member of the Pindiga Formation; it lies upon an erosion surface, the Kanawa Member in places having been removed. The Dumbulwa Member is largely made up of fining-upwards fluvial cycles, when complete each about 10 m thick. Localized developments 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 the

Pindiga Formation (Zaborski *et al.,* 1998). The Deba Fulani Member represents a variety of fluvial, coastal plain and shallow sub-littoral environments. Coarse-grained, pebbly tabular cross-bedded sandstones and fining-upwards channel-filling sandstones occur as do more thinly bedded sandstones with fish vertebrae, phosphatic pebbles and burrows of *Ophiomorpha* type. The Deba Fulani Member wedges out to the south.

According to Zaborski (1998b), these three sandstone members 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 *Wallsi* Zone in the south. North of the Dumbulwa-Bage high Coniacian ammonites occur in beds overlying the Dumbulwa Member (Zaborski *et al.,* 1998).

The nature of the age-equivalent beds in the subsurface of the western Gongola Basin is not known. The Deba Fulani Member is not recognizable in the outcrops of the Pindiga Formation occurring in the Tukulma, Pindiga, Yelwa and Futuk inliers (Figure 8). In the Yola arm, Middle Turonian regression was less pronounced. Here the Middle and Upper Turonian is represented by the Jessu Formation (Carter *et al.,* 1963). It comprises an alternation of shales, siltstones and subordinate sandstones, often calcareous. In the eastern Dadiya syncline 3-4 meters of flaggy ripple-marked sandstones mark the base of the unit while in the Reme syncline to the north fine-grained sandstones are the predominant lithology (Zaborski, 1998a; Zaborski, 2003).

During the Late Cenomanian a "trans-Saharan seaway" was first established creating a marine connection between the Tethyan region and the Gulf of Guinea which passed through the Benue Trough (Zaborski, 2000). The Cenomanian to Conaician

foraminiferal faunas in the Upper Benue Trough are dominated by brackish-water arenaceous forms; planktonic forms are rare and mainly occur in the limestones (Allix, 1983). A maximum water depth of about 50 m was suggested for the Kanawa Member by Zaborski (1998a), Lateral continuity of individual limestones in this unit cannot be demonstrated. The thick limestone development at Ashaka and over the Dumbulwa-Bage high occurs in a Late Cenomanian to Early Turonian shoal area (Zaborski *et al.,* 1998; Zaborki, 1998b). Lithological successions from place to place probably resulted from interplay of both local and regional factors, as well as local water depths. Local areas of freshwater influx may have been important, producing temporary barriers to faunal migration. Such factors may help to explain the difference between the ammonite faunas occurring immediately about the Cenomanian-Turonian boundary in Niger and Nigeria (Zaborski, 1998 b).

2.2.1.4 Gombe Sandstone

The Santonian was a period of folding and deformation in the whole of the Benue Trough. Post-folding sediments are represented by the shallow marine to fluvial Gombe Sandstone of Maastrichtian age. The upper Gombe Sandstone which marks the end of the Cretaceous sedimentation is lithologically similar to the upper part of Bima Sandstone, attesting to the reestablishment of the Albian palaeoenvironmental condition, it lies conformably upon the Fika Member of the Pindiga Formation. The Gombe Sandstone according to Carter *et al*. (1963) is about 300 m thick and is subdivided into three lithofacies (Zaborski *et al.,* 1998):

iii. The “red sandstone facies” which is composed of reddish sandstones and grey to white in some places. Sporadic distribution of coarse to very coarse-grained, cross-bedded channel-filling sandstones within the red sandstone facies,

ii. The “bedded facies”, this consist of regularly bedded, fine to medium-grained white to grey-coloured quartz aranites with interbedded silts, silty clays, flaggy and vesicular ironstones, channel filling sandstones and convolute bedding,

i. The basal “transitional portion” that consist of rapidly alternating thin beds of silty shales with plant remains and fine to medium-grained sandstones with thin flaggy ironstones which is often bioturbated.

The Gombe Sandstone Formation (Obaje, 2009) contains coal, lignite, and coally shale intercalations which in places are very thick. The type locality of the Gombe Sandstone is along the bank of Pantami River in Gombe town. Good exposures are also encountered in many parts of Gombe town and Birin Fulani village. The Gombe Sandstone was interpreted (Zaborski *et al*., 1998) as the proximal part of a coarsening-upward deltaic-like deposit prograding from the southwest into a sea open only to the north based on lithofacies relationships. Hamidu (2012) subdivided Gombe Sandstone into two members:

i). The Arawa Member which comprises the lower and middle parts of the Gombe Sandstone of previous authors and is described as a coarsening-upward, with channel filling sandstone at the lower part and is unconformably overlain by the Kerri-Kerri Formation and,

ii). The Duguri Member for the units that comprises the upper part of the Gombe Sandstone of previous authors, it correspond to the “red sandstone facies” of Zaborski et al (1998) and it is of alluvial depositional environment (Hamidu, 2012).

2.2.1.5 Kerri – Kerri Formation

The Kerri–Kerri Formation which is continental in origin (fluvial to lacustrine) represents Cenozoic sedimentation in the Gongola Basin. According to Adegoke *et al.* (1986), it reaches a thickness of 320 m and is of Paleocene age based on pollens recovered. It is made up of whitish grey sandstones, siltstones, and claystones with the claystones dominating the lithology in most places, typical sections are exposed in Gombe Aba, Dukku and Alkaleri villages. The formation is a post-tectonic sequence within which alluvial fans, fan delta, braided stream, marginal lacustrine and fluvial plain depositional environments were recognized (Dike, 1995).

2.2.2 Structure

The Upper Benue Trough includes an E-W trending Yola arm and a N-S trending Gongola arm or Gongola Basin (Figure 9). These two branches 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, are associated with them (Figure 9), Benkhelil (1988, 1989) regarded this median zone as the partially exposed basement high characterizing the axis of the Benue Trough. Carter *et al*., (1963) referred to it as "Zambuk ridge". This term has frequently been applied to the line marked by a single fault which passes just south of Zambuk village, Guiraud, (1993) referred to the axial zone as the "Wuyo-Kaltugo basement high", and Zaborski (1998a) referred to it as the "Wuyo-Kaltungo high". According to Zaborski (1998a), the terms "Yola arm", "Wuyo-Kaltungo basement high", "Wuyo-Kaltungo high" and "Gongola Basin" correspond to the "Benue Basin", "Zambuk ridge", and "Southern Chad Basin" respectively of Carter *et al.* (1963). A series of N-S to NNE-SSW trending

fault controls the trend of Gongola Basin (Zaborski *et al*., 1998) while deep seated E-W trending fractures appear to characterize the Yola arm (Benkhelil, 1988).

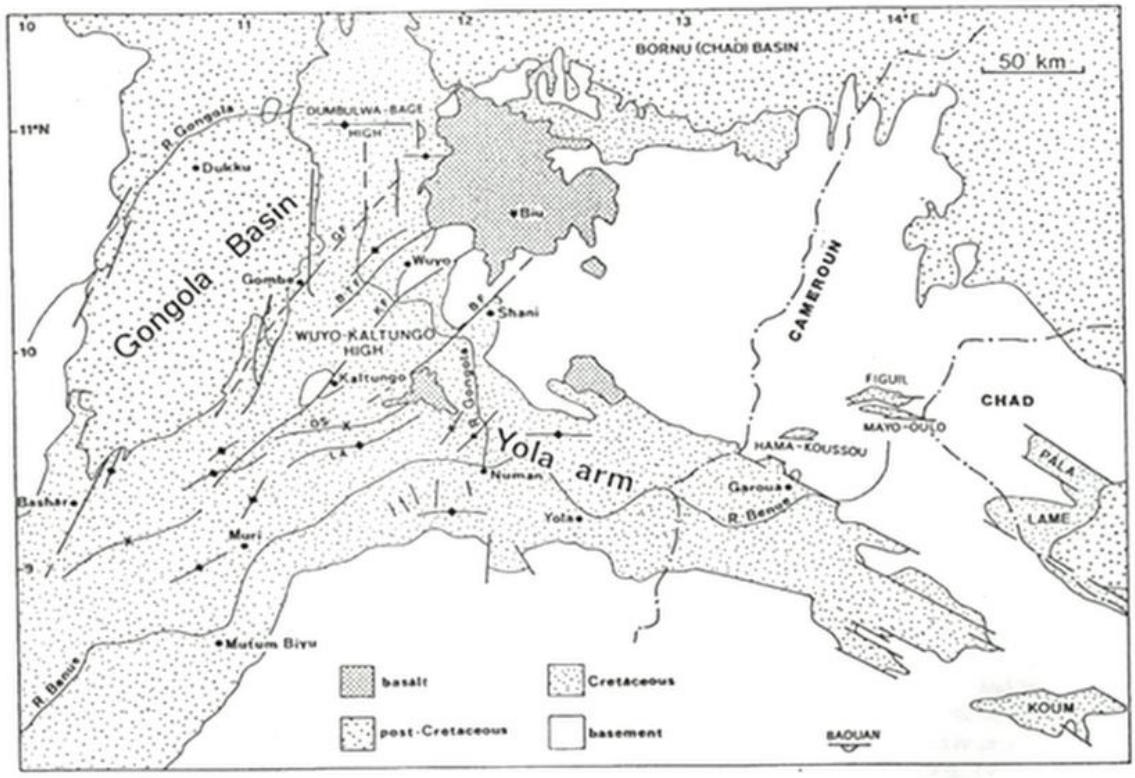


Figure 8: Outline geological map showing the main features of the Upper Benue Trough; GF, Gombe Fault; B-TF, Bima-Teli Fault; KF, Kaltungo Fault; BF, Burashika Fault; DS, Dadiya syncline; LA, Lamurde anticline (After Zaborski, 1998a).

The thickest sedimentary successions occur in the western part of Gongola Basin to which Campano-Maastrichtian and Cenozioc deposits are restricted. Over 5 km of sediment occur in the "Dukku", "Akko and "Bashar" sub-basin; thinner successions occur in the "Lau" and "Numan" sub-basin of the Yola arm (Benkhelil, 1988, 1989). The Yola arm extends eastwards into Cameroun where it is known as the Garoua Basin, bounded on its eastern extremity by NW-SE trending, sinistral strike-slip faults. A number of small Barremo-Aptian, E-W trending half-grabens of transtensional origin also occur in this

region (Zaborski, 1998a), the Hama-Koussou, Figuil, Mayo-Oulo, Koun (Mayo Rey) and Baouan basin, which have a fluvio-lacustrine infill (Guiraud and Maurin, 1992).

2.3 PREVIOUS WORK IN ASHAKA AREA

The first major regional work in Ashaka area was done by Carter *et al.* (1963). They included the limestone-bearing unit in the Gongila Formation with the type locally in the hill near Gongila Village. They also proposed a stream section to the south of Chole as a reference section for the formation. They divided the Gongila Formation into an upper sandstone-shale member and lower limestone-shale member which overlies the Bima Sandstone directly. They defined the base of the formation by the first appearance of marine fossils above the Bima Sandstone. They noted the limestone of the Gongila Formation to be rich in the fossils; 23 species of ammonites, 6 species of bivalves and 4 species of gastropods from both the type locality and reference section were reported. They regarded the faunas as Lower Turonian in age. The limestone – bearing beds of Pindiga Formation have been investigated in more detail. In these later studies, the age of the units was worked out in addition to the lithostratigraphical succession and the structure of the depositional basin.

Wonzy and Kogbe, (1983) noted that the lower part of the Pindiga Formation as represented in the type locality, along the Pindiga stream, corresponds lithogically to the lower part of the "Gongila Formation" exposed at the Ashaka Quarry. They described a 27 m thick section within the Gongila Formation at the quarry and using the abundant ammonite faunas, they proposed four biostatigraphic zones:

d) Zone of *Pseudotission (Bauchioceeras) nigeriensis* (Woods)

c) Zone of *Gombeoceras gongilensis*

b) Zone of *Paravascoceras castatum* (Reyment)

a) Zone of *Paravascoceras bulbosun* (Reyment)

They indicated that Ashaka Quarry section begins with massive light grey limestone about 3.8 m in thickness. The limestone yielded some Upper Cenomanain fossils including *Exogyra columba* (Lamarck), *Exogyra olisiponensis* (Shape) and *Vascoceras bulbosum* (Rayment). This unit is overlain by grey clays and shales with limestone layers containing fossils which belong to the *Paravascoceras castatum* zone. The fossils include: *Paravascoceras costatum* (Reyment); *Vasoceras polygonun* (Barber); *Vascoceras globosum globosum* (Reyment); *Paravascoceras costatum tectiform* (Barber); *Epengonoceras dumbli* (Cragin); *Vascoceras ellipticum* (Barber) *Aphrondina (Mesocallista) quenseli and Gervillaria oliponensis* (Sharpe). Thinly laminated deep blue shales (0.5 m thick) and 0.16 m of light grey hard limestone containing a distinct faunal assemblage were reported to overlie the *Paravascoceras castatum* zone. The fossils in this unit assigned to the *Gombeoceras gongilensis* (Woods) Zone (Wonzy & Kogbe, 1983). Popoff *et al.* (1986) described a 42 m thick section of the Gongila Formation at Ashaka Quarry and observed that the section consist of alternation of marine limestones and shale/mudstone. They indicated that the lowermost 4 m is chert - bearing and was not exposed. Therefore the Gongila-Yolde contact was not visible. The Gongila Formation was subdivided into 18 individual units out of which seven zones were proposed using ammonites.

Meister (1989) studied the section at Ashaka Quarry; this enabled him to establish the vertical distribution of 28 Cenomanian – Turonian ammonites. The biostratigraphic result obtained from his studies made it possible for him to recognize set of 10 biozonation.

Oti (1990) gave an account of the shale – limestone part of the Gongila Formation at the Ashaka Quarry where he describe it to be about 20 m thick and consisting of dominantly shale above and dominantly limestone below (Figure 9).

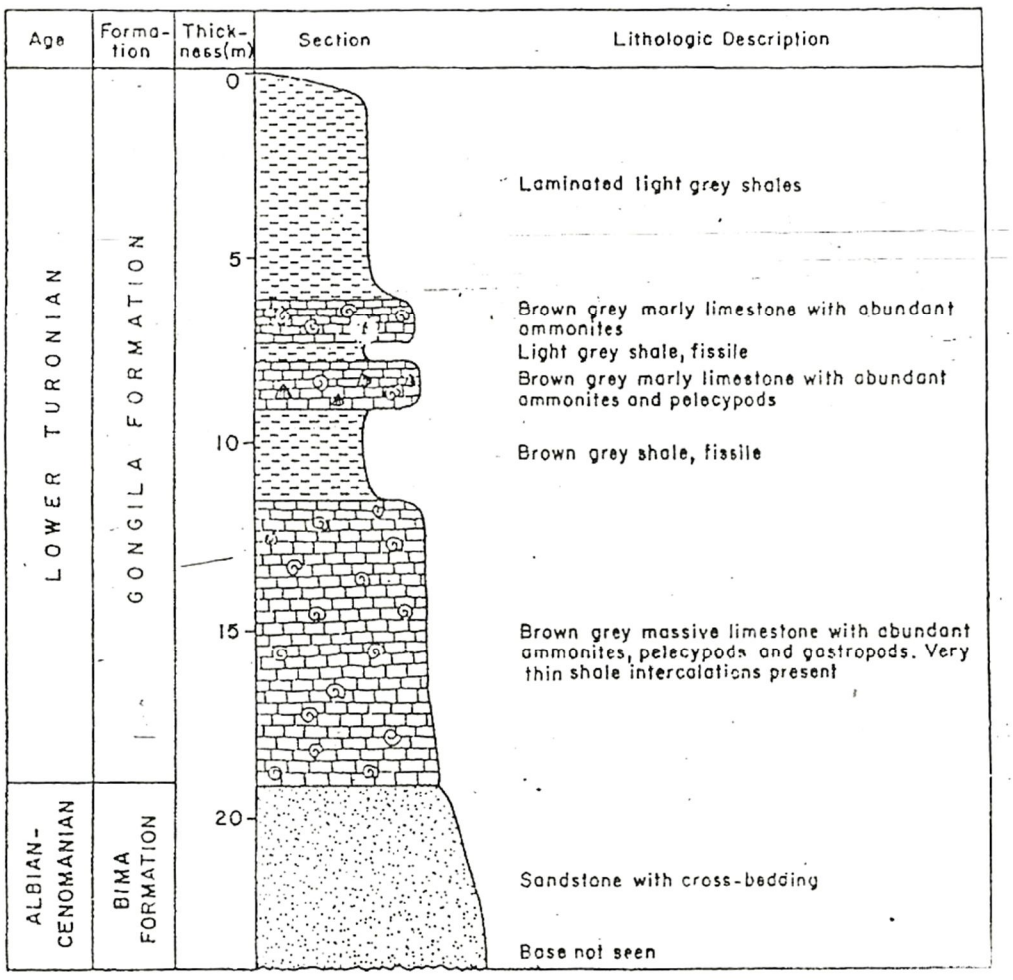


Figure 9: Section of the Lower Turonian Gongila and underlying Albian-Cenomanian Bima Formations at the Ashaka Quarry (After Oti, 1990)

It was reported that the Gongila Formation was resting directly on the Bima Sandstone in the quarry. From the petrographic description of the limestone, the rich fossil content of the limestones was noted to include bivalves, ammonites, arthropods and gastropods. Furthermore, he noted that the Lower Turonian limestones of Ashaka area are resting on the southern flank of the "Zambuk ridge".

Rebelle (1990) worked on the palaeogeographic interpretation of the Gongila Formation, describing the palaeoenvironmental implications of the fossils found in the Ashaka Quarry, as well as the diagenetic reconstruction of the limestones. The Ashaka Quarry deposit was grouped into 20 lithologic units (Figure 10), which he noted was dominantly wackestones and packstones. According to him, the base of the quarry was situated 2 m above the contact with the Yolde Formation and the Cenomanian – Turonian boundary was put at the top of his unit 14.

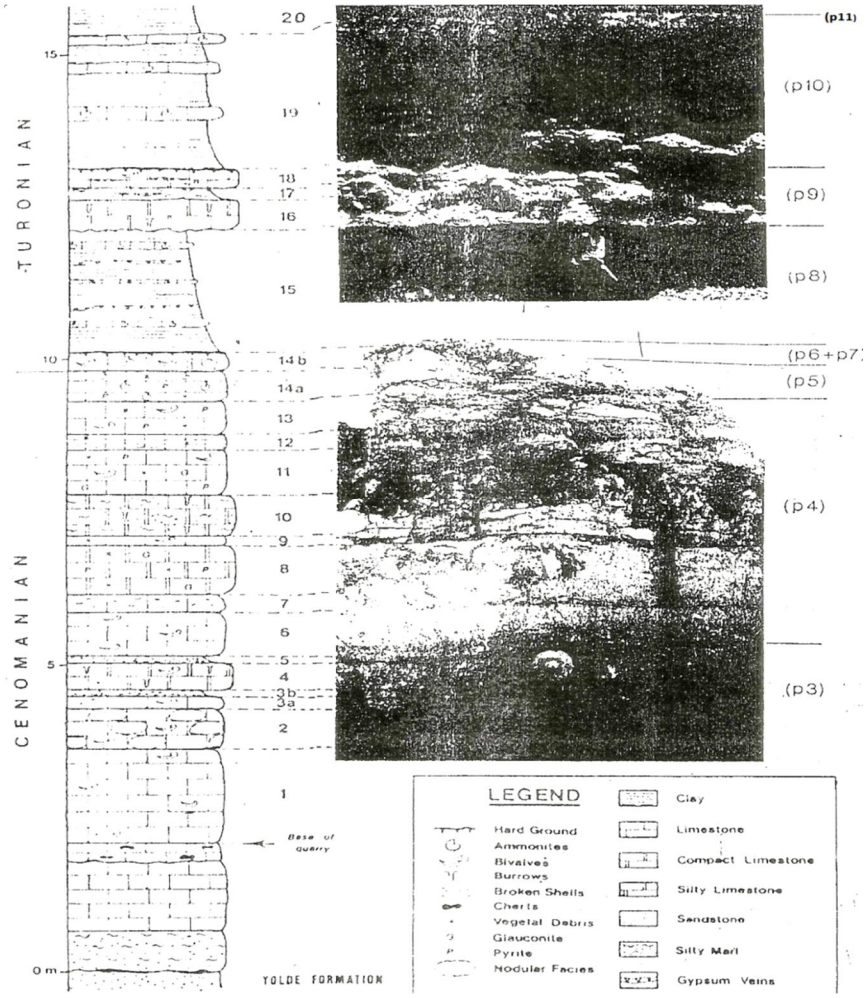


Figure 10: Stratigraphic log of the Gongila Formation at Ashaka Quarry, with subdivision into 20 lithologic levels (After Rebelle, 1990)

Zaborski (1990, 1995, 1998b) worked on the ammonites from the Ashaka Quarry where he used the distribution of the ammonites in the section to construct a detailed biostratigraphy, proposing 5 regional biozones (Figure 11):

5. Zone of *Wrightoceras wallsi* (youngest)
4. Zone of *Pseudotissotia nigeriensis*
3. Zone of *Vascoceras proprium* (Reyment)
2. Zone of *Paravascoceras cauvini* Chudeau
1. Zone of *Nigericeras gadeni* (oldest)

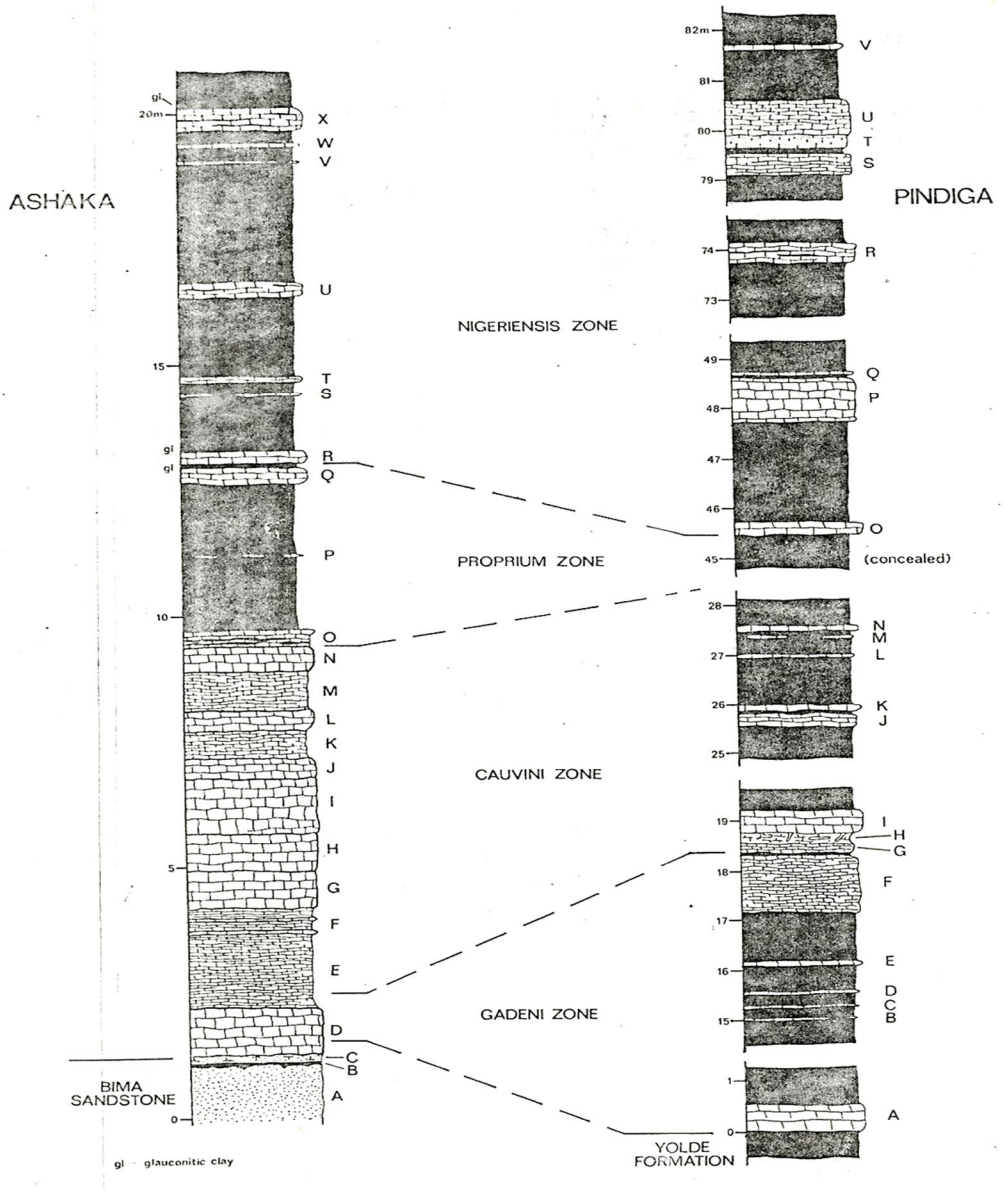


Figure 11: Stratigraphical section in the Pindiga Formation exposed at Ashaka Quarry and in the Pindiga stream (After Zaborski, 1995).

CHAPTER THREE

3.0 METHODOLOGY

Field work was carried-out to determine the field relationship of the limestone beds and the associated shales during which the stratigraphic section at the Ashaka Cement Quarry was studied and sampled for further petrographical and micropalaeontological studies. The northern and southern quarry sections were stratigraphically logged at microfacies levels. Petrographic and micropalaeontological studies of some limestone samples were carried-out.

3.1 Field Method

The lithology, colour, macrofossils and sedimentary structures associated with the sub-facies were identified. The various facies were traced both vertically and laterally to establish the thickness/vertical connectivity and the lateral continuity of the units and to determine if there is apparent truncation of the facies. Care was taken when collecting the samples such that fresh samples were collected in order to avoid distortion of the result by weathering activities. The quantity of samples collected was about 500 g on average from each lithologic unit. Information such as the sample number, the rock unit, horizon description, section of the quarry collected from, locality, and date of the sampling was indicated clearly on the sample bags and at the same time the relevant data was entered into the field notebook. Two sections, one in the southern part of the quarry and the other in the northern part of the quarry, which are separated by distance of 4 kilometres were carefully logged in order to determine if there is lithologic or palaeontologic variation.

Careful examination of the nature of the surfaces separating each unit was also carried out. This was aimed at identifying parasequences, parasequence sets and the

systems tracts, based on the identification of critical surfaces and parasequence stacking pattern. Samples of the various lithologic units were collected with the aid of geologic hammer and chisel, the thickness of each unit was measured using a metre rule, location and elevation readings were obtained using the GPS, and strike and dip of the formation was measured with the aid of compass clinometers. The samples were labeled and kept separately for analysis.

3.2 Laboratory Method

Sixteen thin-sections were prepared from the samples collected from the field. This process was carried out for the different limestone units identified so as to conduct the microfacies analysis and to classify the limestones using Dunham's (1962) and Folk's (1962) classification schemes so as to be able to determine the depositional environment of the sections. The thin section slides were examined both under plane polarized light and cross polarized light and their characteristic features were noted.

Thirty-six limestone samples were first disaggregated using a pestle and mortar so as to increase the surface area for effective penetration of the hydrogen peroxide into the rock samples. The samples collected from the different horizons were placed in different beakers which are labelled with the sample number and name of the horizon from which the sample was collected. Both the limestone and the shale samples were disaggregated, soaked in hydrogen peroxide and water with sodium hypochlorite respectively and then washed through a 63 μm mesh until the water became clear. The residues were oven dried for about two hours. After oven drying, each of the samples was placed into a labelled sample bag for microfossils identification using binocular microscope.

CHAPTER FOUR

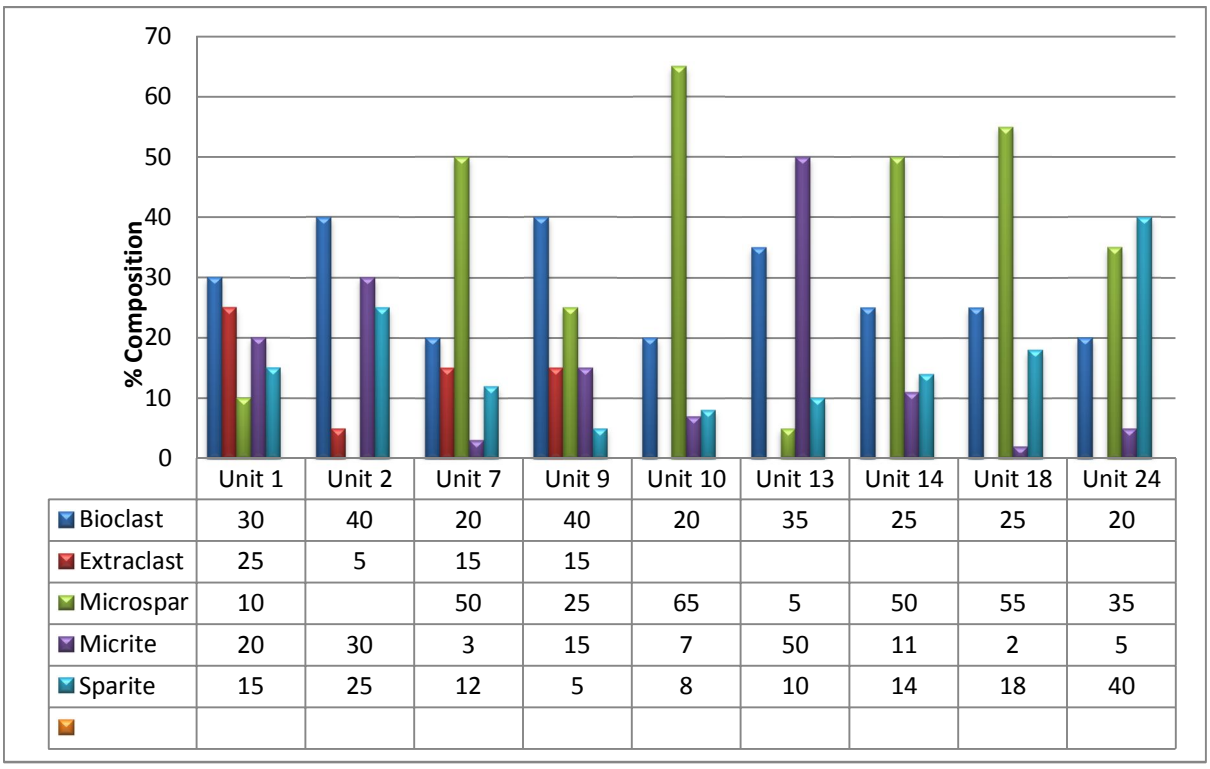
4.0 RESULTS AND DISCUSSION

4.1 MICROFACIES AND MICROFOSSILS STUDY

4.1.1 Microfacies

Diagenetic recrystallization has strongly affected the limestone deposit of the Ashaka Quarry altering most of the microfacies in such a way that they are difficult to recognize in most of the samples, although, the shells of bioclasts especially those of bivalves and ostracods can be observed.

4.1.1.1 *Microfacies analysis of some limestone units from northern section of Ashaka Quarry*



	Unit 1	Unit 2	Unit 7	Unit 9	Unit 10	Unit 13	Unit 14	Unit 18	Unit 24
Bioclast	30	40	20	40	20	35	25	25	20
Extraclast	25	5	15	15					
Microspar	10		50	25	65	5	50	55	35
Micrite	20	30	3	15	7	50	11	2	5
Sparite	15	25	12	5	8	10	14	18	40

Figure 12: Distribution of constituents in the limestone units of northern section of Ashaka Quarry

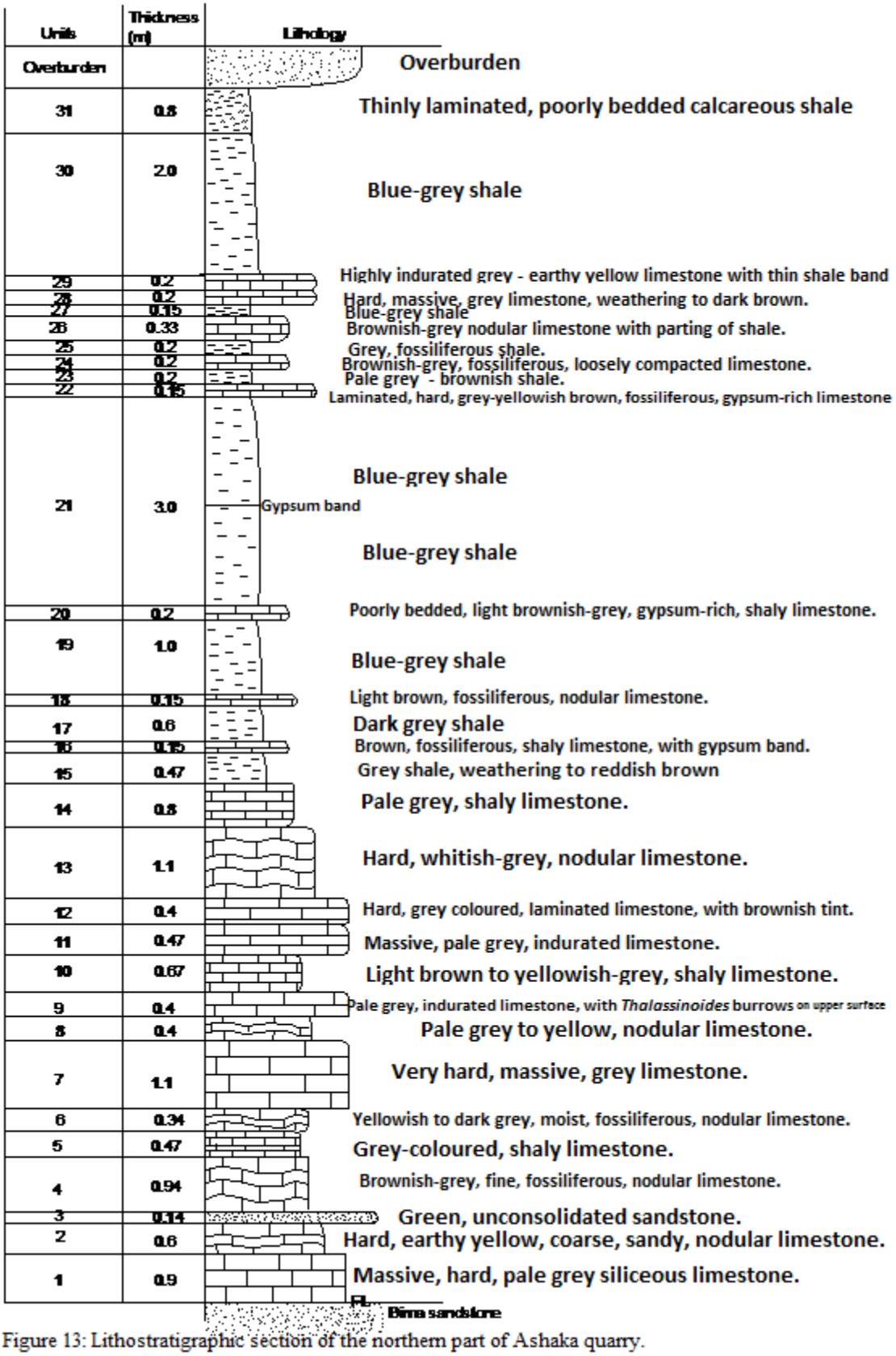
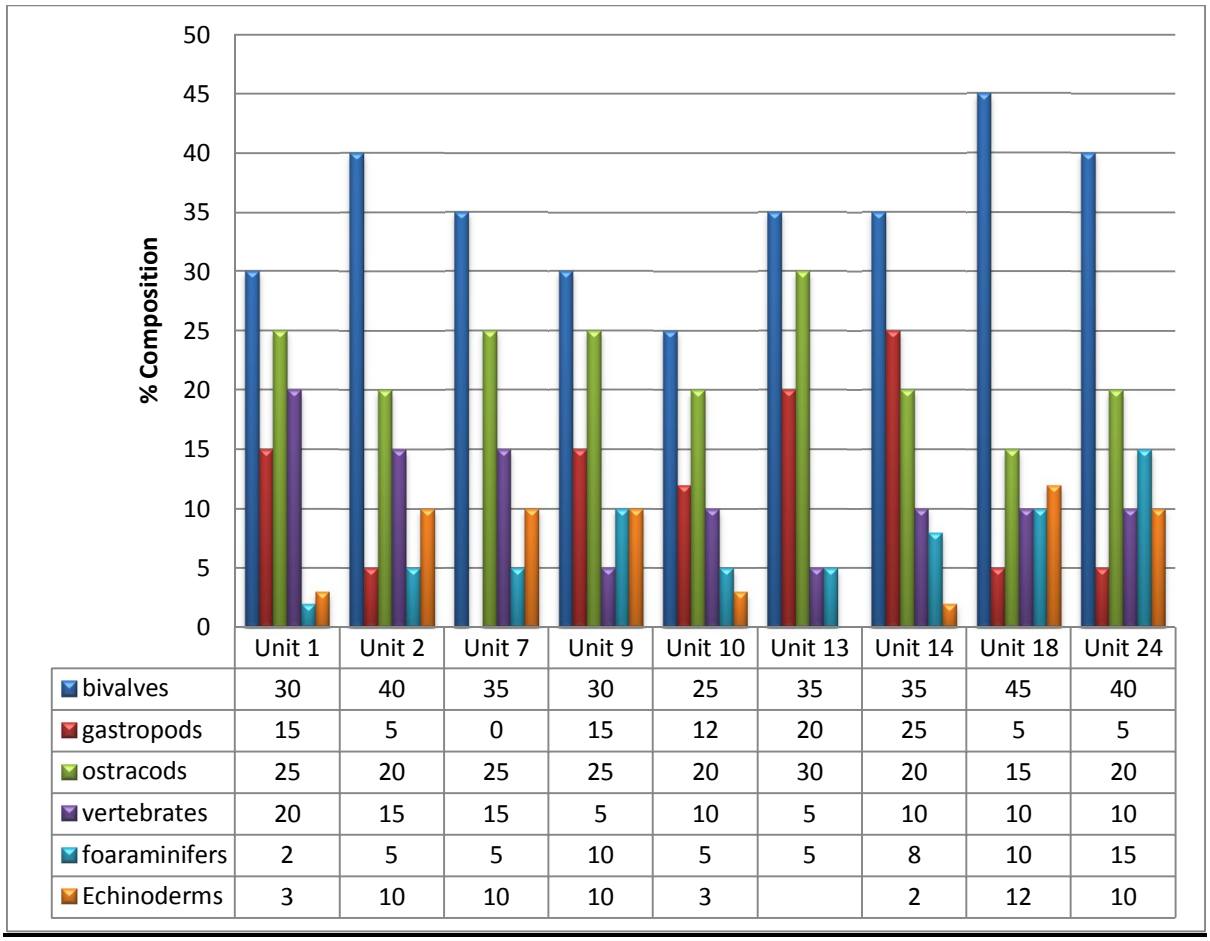


Figure 13: Lithostratigraphic section of the northern part of Ashaka quarry.



	Unit 1	Unit 2	Unit 7	Unit 9	Unit 10	Unit 13	Unit 14	Unit 18	Unit 24
bivalves	30	40	35	30	25	35	35	45	40
gastropods	15	5	0	15	12	20	25	5	5
ostracods	25	20	25	25	20	30	20	15	20
vertebrates	20	15	15	5	10	5	10	10	10
foaraminifers	2	5	5	10	5	5	8	10	15
Echinoderms	3	10	10	10	3		2	12	10

Figure 14: Distribution of bioclast in the limestone units of the northern section of Ashaka Quarry

Unit 1 (Extraclast-rich wackestone/biomicrite)

This is a 0.9 m–thick massive, hard, pale grey-greenish siliceous limestone; bioclasts and extraclast makes up 55% of the total component in this limestone unit and the matrix consist of micrite. It also consists of calcite cement as the important cement binding the rock components with minor sparite which occur as shell replacement. Sparite cement was observed in the aragonitic shells whereas the calcitic shells were not affected. The porosity in the unit is low. Authigenic glauconites occur as relatively round, light green grains.

Bioclasts:

The bioclasts in order of abundance include bivalves (characterized by irregularly foliated shell structure, prismatic shell structure and micrite envelopes filled with sparite cement), ostracods (mostly fragmented and neomorphosed in some places), vertebrates and gastropods.

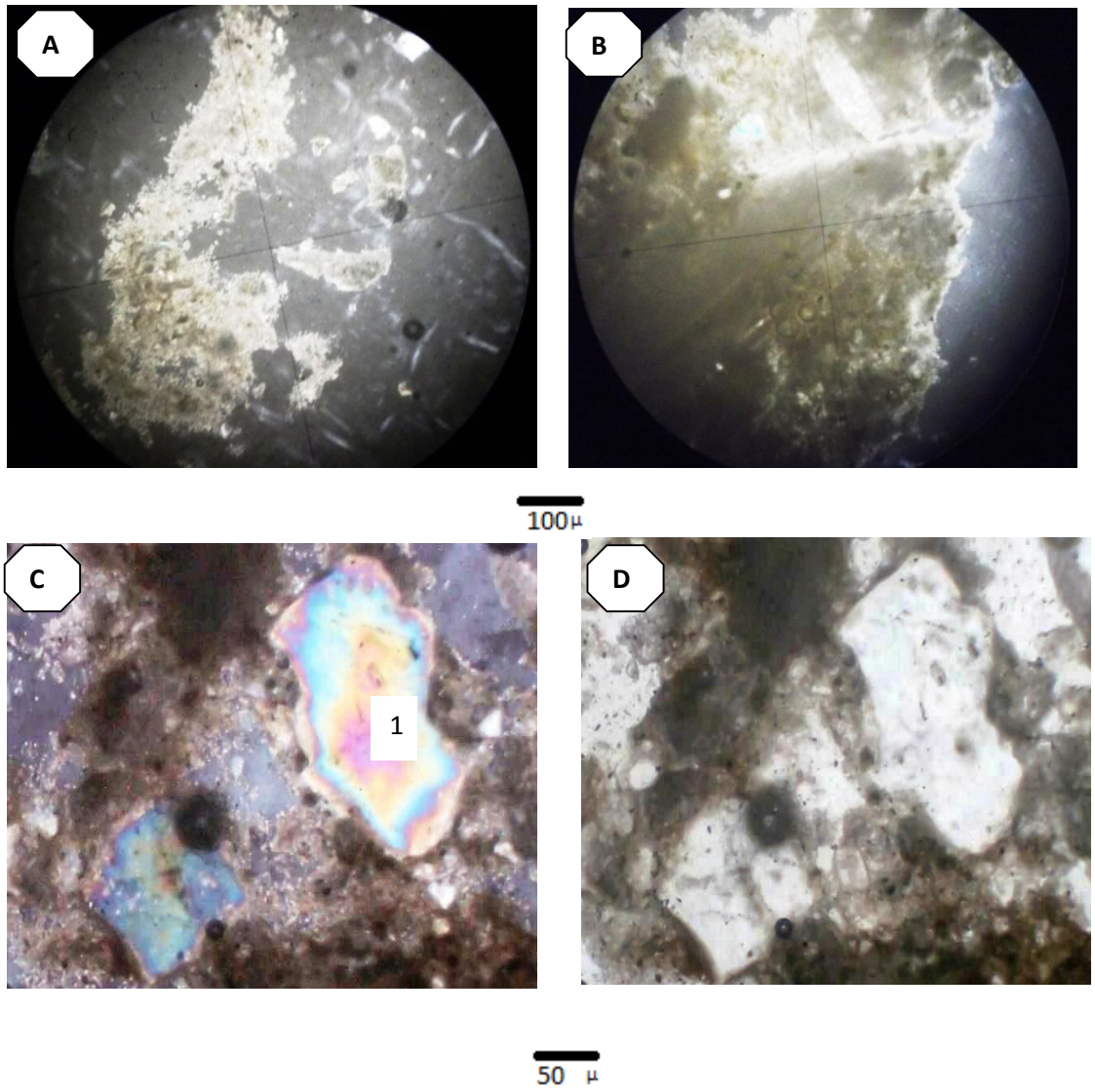


Plate 1: Photomicrographs of extraclast-rich wackestone (biomicrite) from unit 1 (B, C: XPL, A, D: PPL). 1) quartz (extraclast)

NOTE: *Both Dunham (1962) and Folk (1962) classification systems are adopted in this work.*

Extraclast:

The dominant extraclast observed are quartz detrital grains which are corroded and being replaced by calcite and feldspar (plagioclase). This limestone unit may be classified as extraclast-rich wackestone (Dunham's, 1962 classification scheme), or biomicrite (Folk's, 1962 classification scheme).

Unit 2 (Wackestone/biosparmicrite)

This unit is a 0.6 m–thick, hard, earthy yellow, coarse sandy nodular limestone. Allochems (dominantly bioclasts) make up over 40% by volume of the rock, and float or are surrounded by micrite matrix. Sparite cement has filled biomolds formed by dissolution of aragonitic bivalves. The porosity of this limestone unit is low and is restricted to vuggy and biomoldic type. Pyrite occurs as very small cubes disseminated in places and also replaced sparite casts/shell material.

Bioclast:

The allochems present are bioclasts dominatly bivalves (preserved with an irregularly foliated shell structure, an irregularly foliated and homogeneous layer, or a micrite envelopes filled with drusy sparite and biomolds filled with drusy sparite without micrite envelopes). Other bioclasts are ostracods (mostly consisting of single valve, gastropods; vertebrates and echinoderms. The limestone may be classified as wackestone (biosparmicrite).

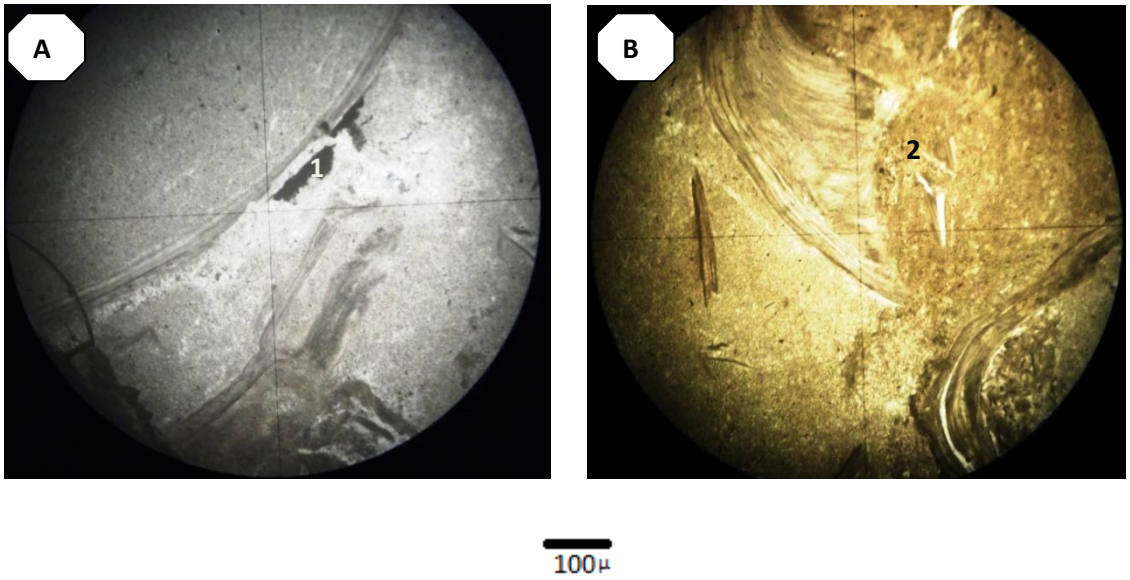


Plate 2: Photomicrographs of wackestone (biosparmicrite) from unit 2 (A: PPL, B: XPL).
1) opaque material, 2) bivalves

Unit 7 (Sandy packstone/sandy biomicrite)

A 1.1 m–thick, very hard, massive, grey limestone, this rock layer consists of a significant amount of insoluble components which are in order of abundance, quartz, feldspar (microcline and plagioclase) and glauconite. The quartz and feldspar extraclasts range in size from silt to sand-sized grains which are rounded in shape. Bioclast and extraclast represent about 35% by volume of this unit, microspar makes up more than 50% while sparite cement compose about 5%. The porosity is relatively higher than the basal limestone unit as a result of aggrading neomorphism of an original micrite matrix; the porosity is the vuggy and biomoldic type.

Bioclasts

Bioclasts include bivalves (characterized by prismatic shell structure, calcitized, and total or partial micritization), ostracods (complete/single valve and are mostly calcitic

valve) and vertebrates, heterohelicids and echinoderms. This unit may be classified as sandy packstone (sandy biomicrite with neomorphic texture).

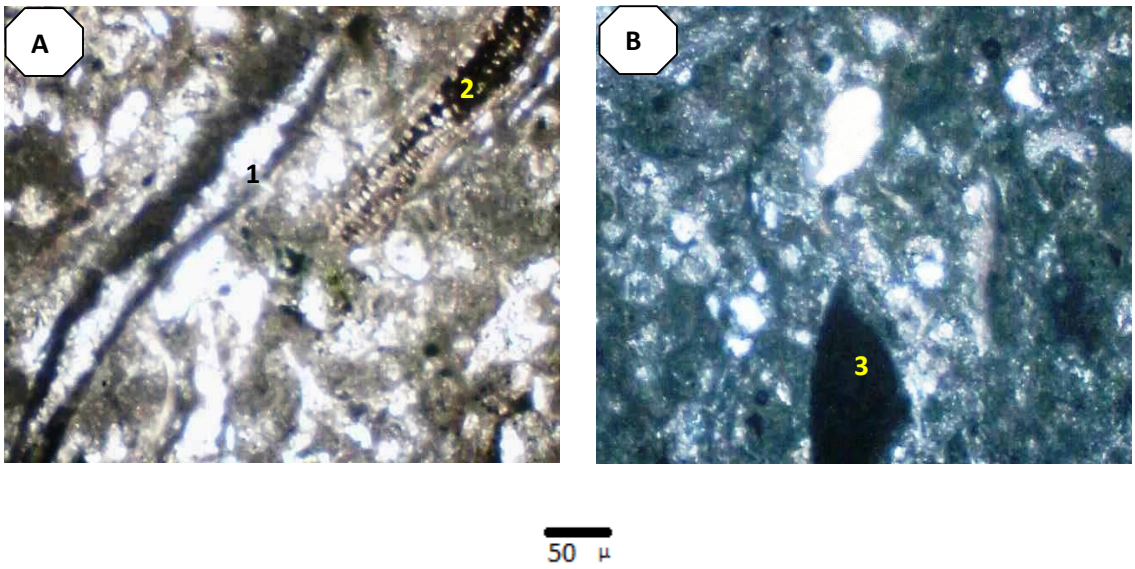


Plate 3: Photomicrographs of sandy packstone (sandy biomicrite with neomorphic texture) from unit 7 (XPL). 1) sparite filled micrite envalope, 2) echinoderm, 3) quartz

Unit 9 (Sandy packstone/biomicrite)

It is a 0.4 m–thick, pale grey, indurated limestone with *Thalassinoides* burrows. Bioclast and extraclast make up about 50% by volume, microspar (originally micrite) about 25%, micrite 15% and sparite cement about 5%. Opaque material is occurring mostly in clusters in euhedral cubic crystal form replaces some shell material. The porosity is moderate and is of biomoldic type. Authigenic glauconite is observed disseminated within the rock.

Bioclasts:

The most abundant bioclasts are bivalves (preserved with irregularly foliated shell structure; as micrite envelopes filled with drusy sparite, and completely micritized, or a drusy sparite casts, micrite envelope). Other bioclasts are ostracods (complete and single valves), gastropods (that are neomorphosed in some places), foraminifers and echinoids.

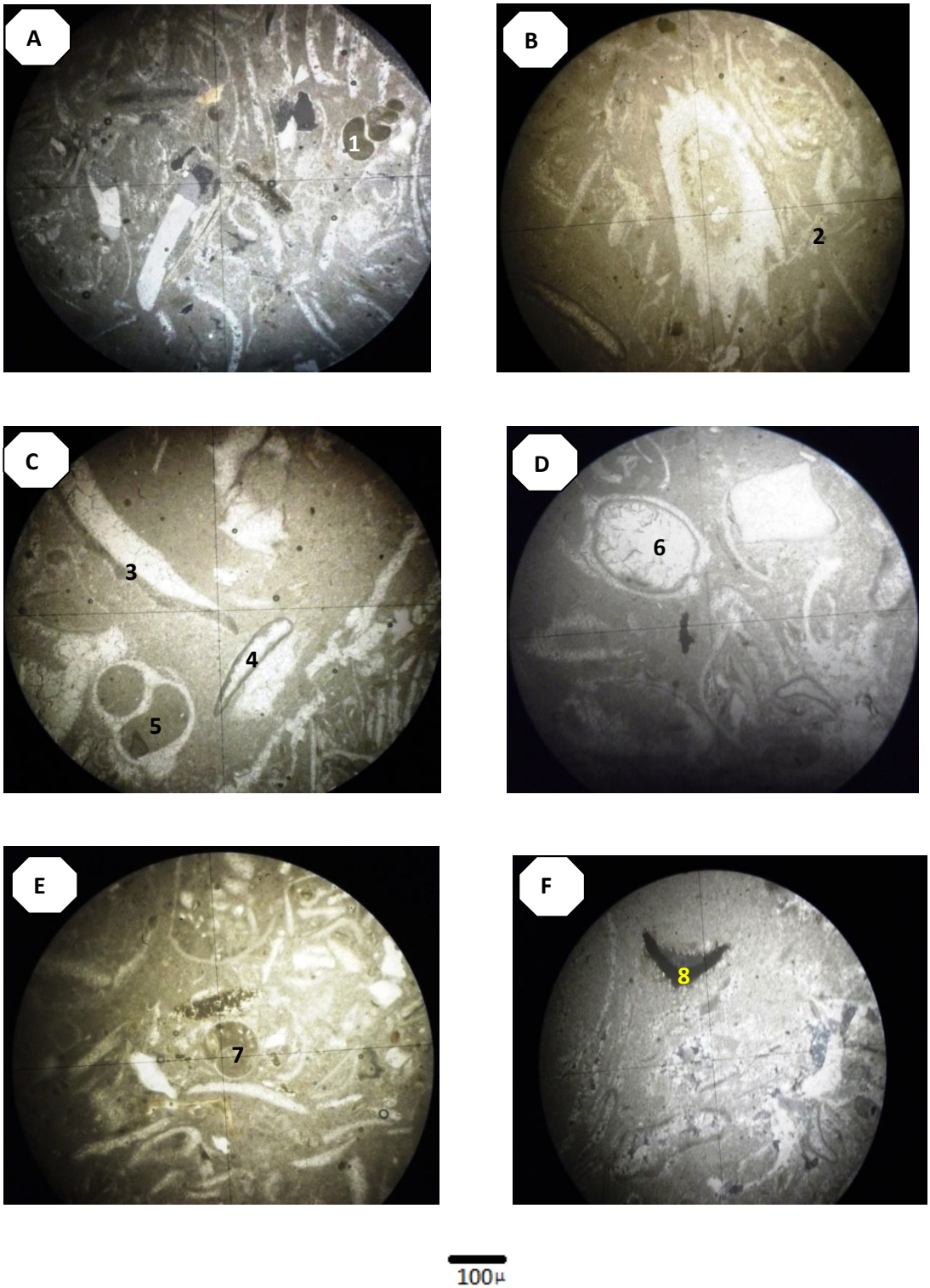


Plate 4: Photomicrographs of packstone (biomicrite) from unit 9 (A, B, C, E: XPL, D, F: PPL). 1) gastropod, 2) ostracod, 3) bivalves with homogeneous shell structure, 4). biomold filled with sparite cement, 5). gastropod, 6). ostracod, 7). gastropod, 8) opaque material.

Extraclast;

Detrital quartz grains form an important part of the extraclasts, their sizes ranges from silt size to sand sized and are corroded. Detrital feldspar falls in the same size and shape category with the quartz and is represented by the albite group. This unit may be classified as packstone (biomicrite).

Unit 10 (Bioclastic wackestone/biomicrite)

This unit is a 0.67 m – thick, light brown-yellowish grey, shaly limestone. Microspar makes up about 65% by volume, bioclasts and extraclast about 20%, while sparite cement and minor micrite constitutes the remainder. The neomorphic sparite occurs mainly as product of replacement of aragonitic shell whereas the drusy sparite occurs as void-filling. The extraclast consist of silt to sand-sized detrital quartz. Authegenic glauconite is also observed in this unit. Porosity is moderate and is restricted to biomoldic and little vuggy type.

Bioclasts:

Fossils include bivalves, brachiopods, ostracods, gastropods and vertebrates in decreasing order of dominance which are set in matrix of microspar. The bivalves are characterized by irregularly foliated shell structure and prismatic shell structure or are preserved as biomolds filled with drusy sparite without micrite envelope and biomold filled with drusy sparite with micrite envelopes. The ostracods occur as isolated valves and articulated carapaces. This unit may be classified as a bioclastic wackestone (biomicrite that has undergone aggrading neomorphism).

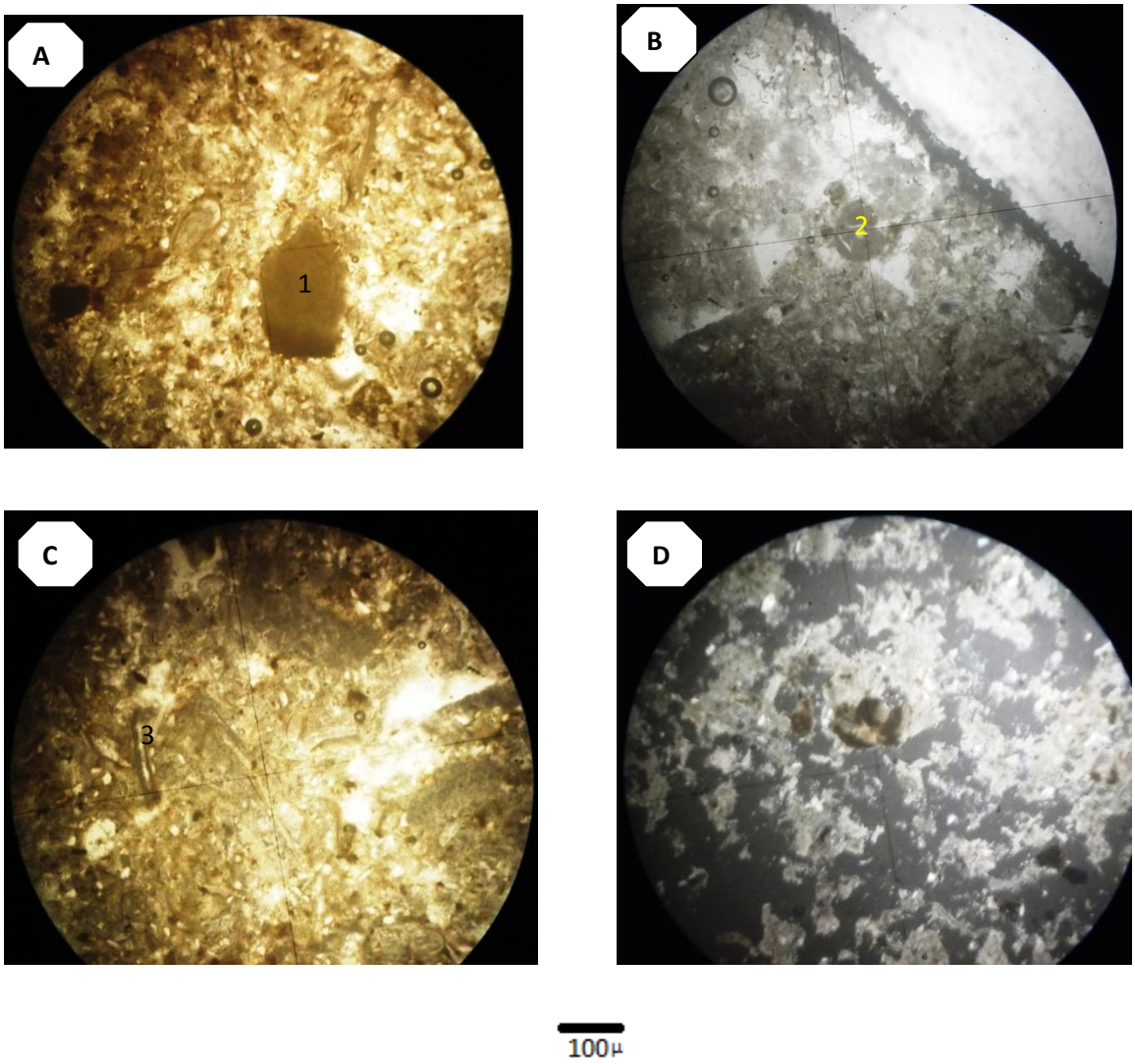


Plate 5: Photomicrographs of bioclastic wackestone (biomicrite) from unit 10 (A, C: XPL, B, D: PPL). 1) quartz extraclast, 2) benthonic foram, 3) void.

Unit 13 (Packstone/biomicrite)

Unit 13 is a 1.1 m-thick, hard, whitish grey, nodular limestone. Micrite comprises about 50% of the total volume; bioclasts make up about 35% while neomorphic sparite makes up for the remaining portion. Some of the biomolds are preserved as sparite cement casts while others were phosphatized. Most of the shells appeared to be bent due to post deposition compaction. Porosity in the rock is mainly biomoldic and vuggy and is moderate.

Bioclasts:

Bivalves are the most abundant bioclasts having irregularly foliated shell structure or preserved as biomolds partially or totally filled with sparite cement, other bioclasts are ostracods (both complete and single valves), gastropods, and hedbergellids. This unit may be classified as a packstone (biomicrite).

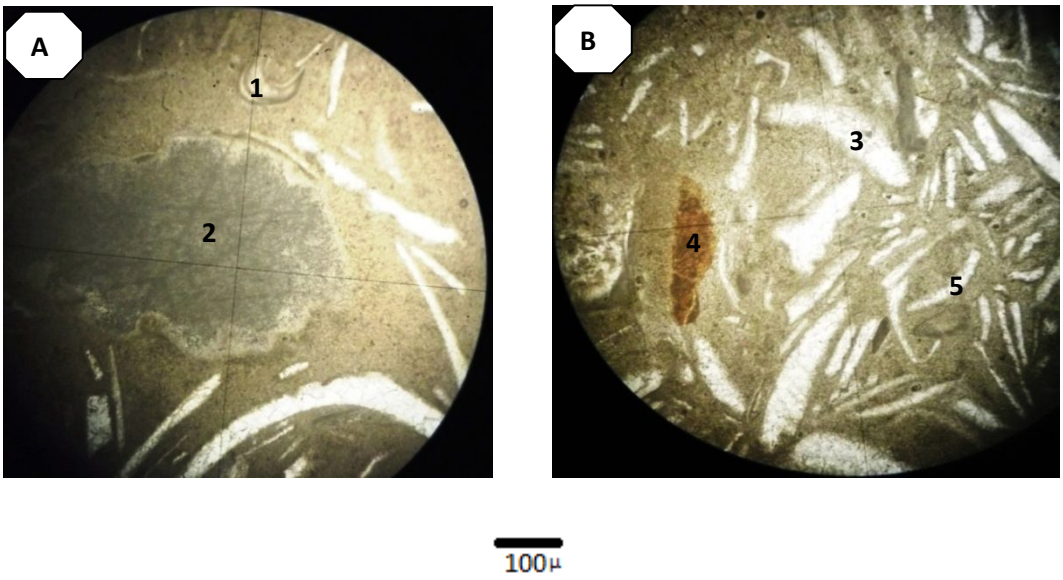


Plate 6: Photomicrographs of packstone (biomicrite) from unit 13 (A, B: XPL). 1) bivalves with irregularly foliated shell structure, 2) gastropod, 3) biomold filled with sparite cement, 4) glauconite, 5) bivalve

Unit 14 (Wackestone/biomicrite)

This unit is a 0.8 m–thick, pale grey, shaly limestone consisting of a microspar matrix which makes up about 50% by volume, bioclasts forming about 25% while micrite and drusy sparite account for the remaining 25%. The bioclasts are bivalves (mostly with homogenous shell structure), gastropods (replaced by calcite in most places), ostracods (mostly of single valve), and vertebrates. Porosity in the limestone deposit is moderate to high, enhanced by dissolution and is both of biomoldic, interparticle and vuggy type in

decreasing order. This unit may be considered to be wackestone based on Dunham's classification scheme or biomicrite according to Folk's classification scheme.

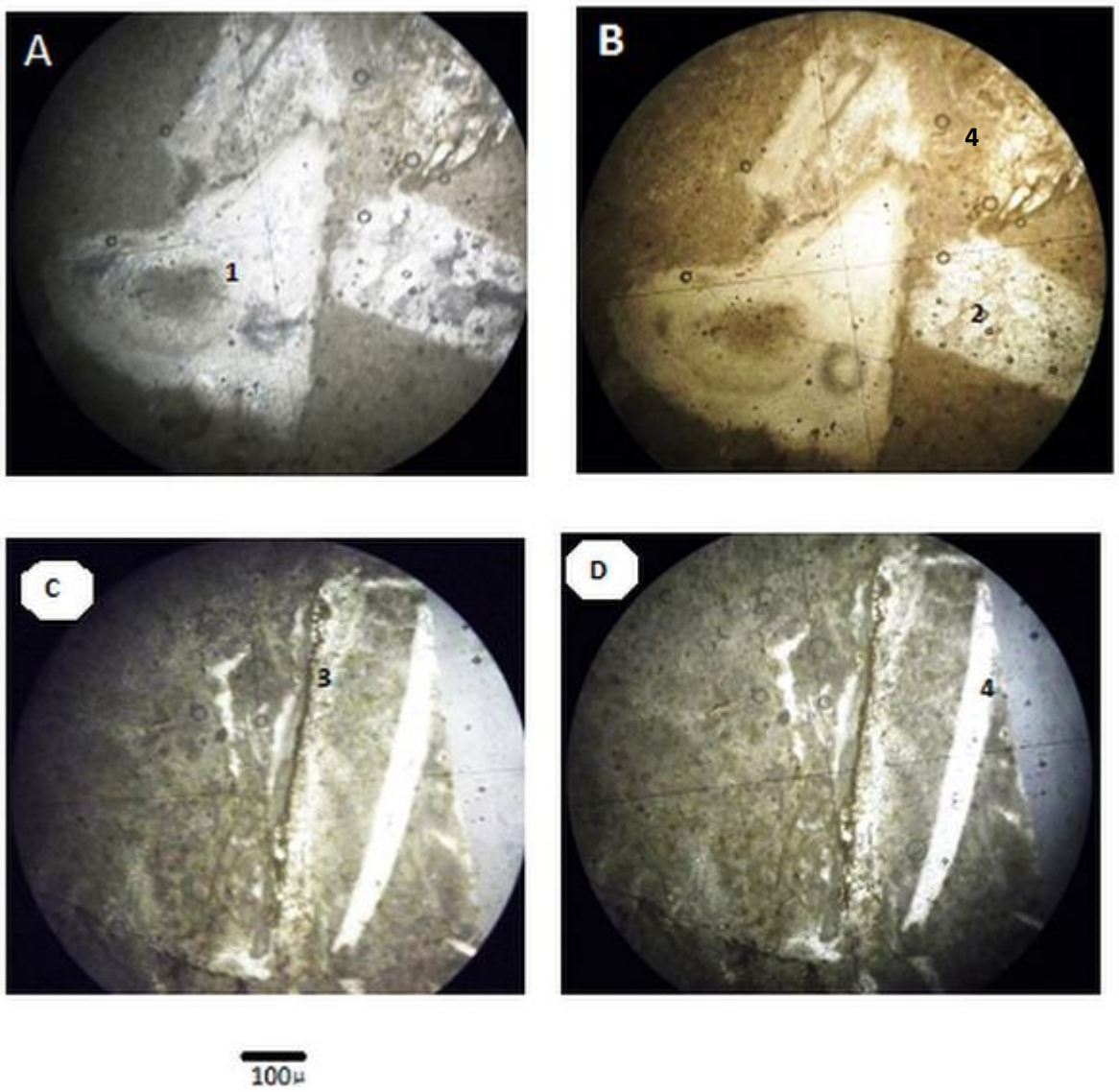


Plate 7: Photomicrographs of wackestone (biomicrite) from unit 14 (A, C: PPL, B, D: CPL). 1) ostracod, 2) sparite, 3) echinoderm, 4) bivalve

Unit 18 (Wackestone/biomicrite)

This unit is a 0.15 m–thick, light brown, fossiliferous nodular limestone. Microspar forms the major part of the matrix comprising about 55% by volume. Bioclasts make up about 25% and sparite cement about 10%. Micrite is of minor importance and opaque

(pyrite) are present, mostly occupying biomolds formed after bivalves. Porosity in this unit is high and is biomoldic, vuggy and interparticle types in decreasing order of importance.

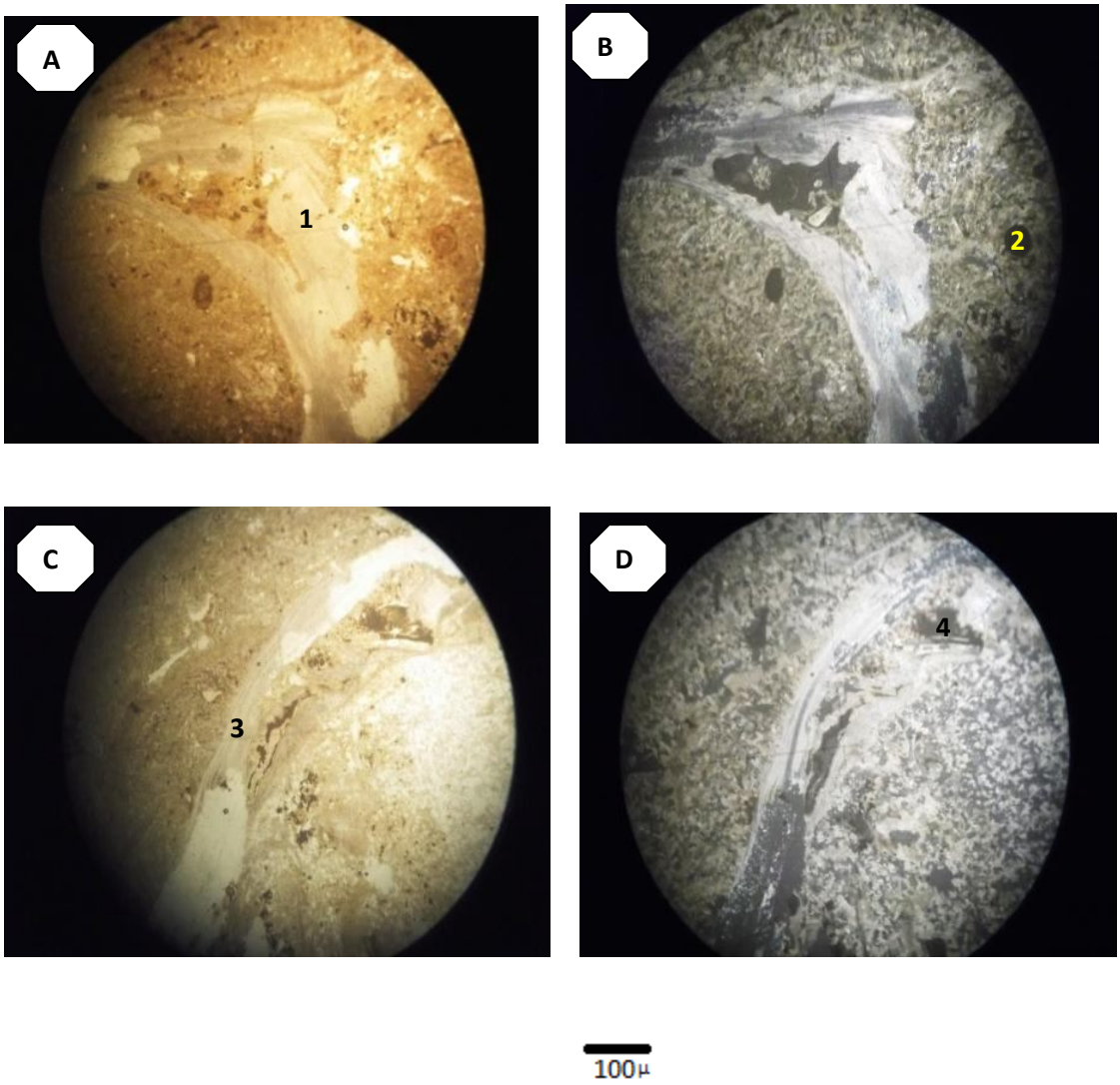


Plate 8: Photomicrographs of bioclastic wackestone (biomicrite) from unit 18 (A, C: XPL, B, D: PPL). 1) bivalve with irregularly foliated shell, 2) foraminifer, 3) bivalve with prismatic shell structure, 4) opaque material.

Bioclasts

Bivalves with irregularly foliated shell structure constitute the most abundant bioclasts in this unit. Others are vertebrates (represented by apatite which is partially replaced by an opaque material), echinoderms, ostracods, foraminifers. This unit may be

classified as bioclastic wackestone (biomicrite that has undergone aggrading neomorphism).

Unit 24 (Wackestone/biomicrite)

This unit is a 0.2 m–thick, brownish grey, fossiliferous, loosely compacted limestone unit. Originally a wackestone with bivalve shell debris, ostracods, gastropods, foraminifers and other allochems floating in micrite matrix, the matrix now consists of microspar and neomorphic sparite in almost the same proportion (about 35% each). The size of the microspar crystals ranges from 5-15μm while that of the neomorphic sparite from 50-70μm. Some of the shells as observed in thin section are micritized. The rock possesses a saccharoidal texture and the porosity is high with vuggy and biomoldic system of porosity. The porosity is fabric selective affecting mostly the aragonitic shell.

Bioclasts:

Bioclasts present in this unit include bivalves with irregularly foliated shell structure (with evidence of dissolution, creating pore spaces that are occupied by opaque materials and some neomorphosed or replaced by micrite), ostracods (complete and single valve), gastropods and foraminifers with globular chambers and vertebrates that are mostly replaced by opaque materials. These together makes up about 20% of the rock composition. This unit may be classified as wackestone (biomicrite).

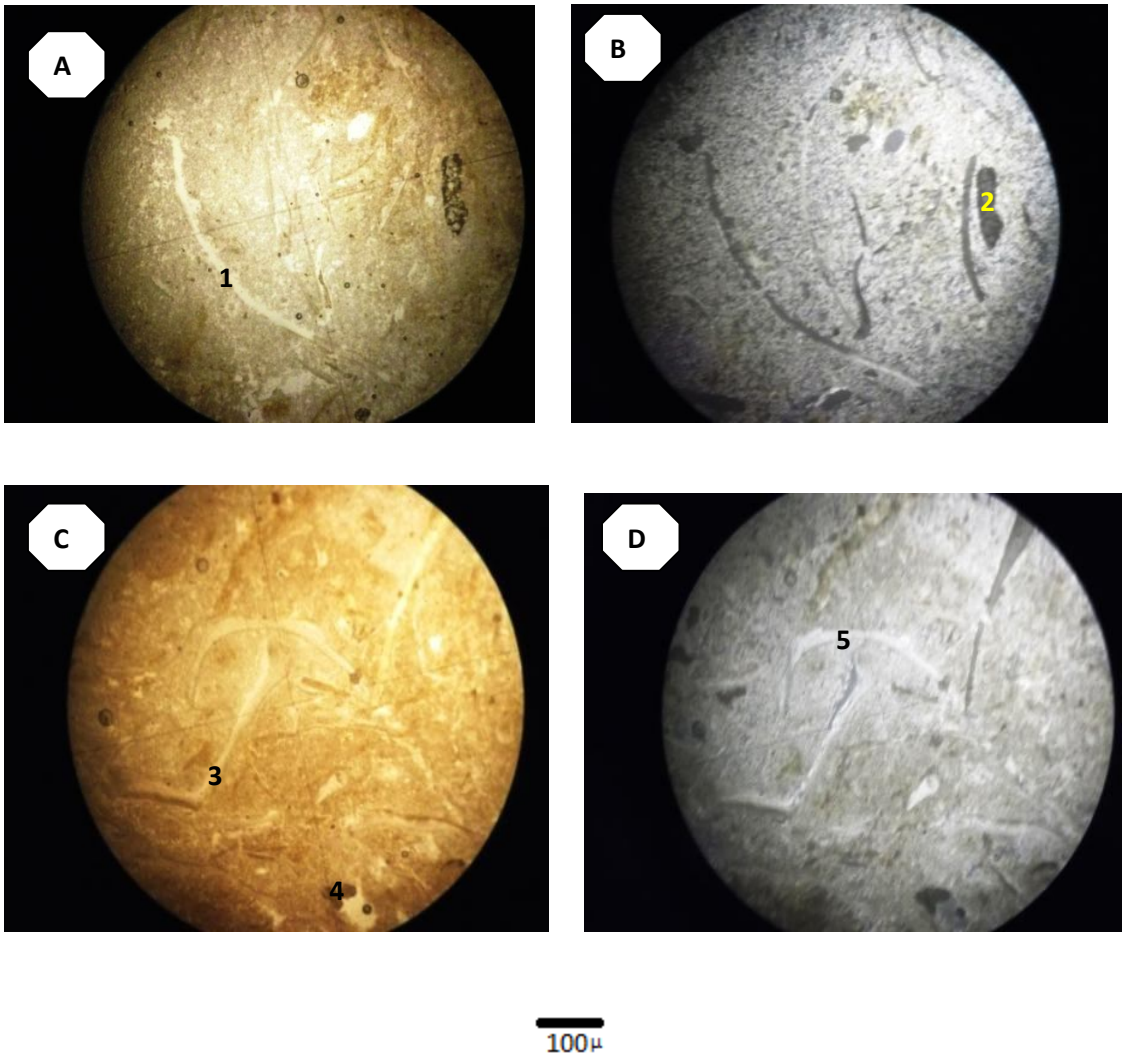


Plate 9: Photomicrographs of wackestone (biomicrite) from unit 24 (A, C: XPL, B, D: PPL). 1) biomold without micrite envalope, 2) foraminifer, 3) bivalve, 4) opaque material 5) ostracod.

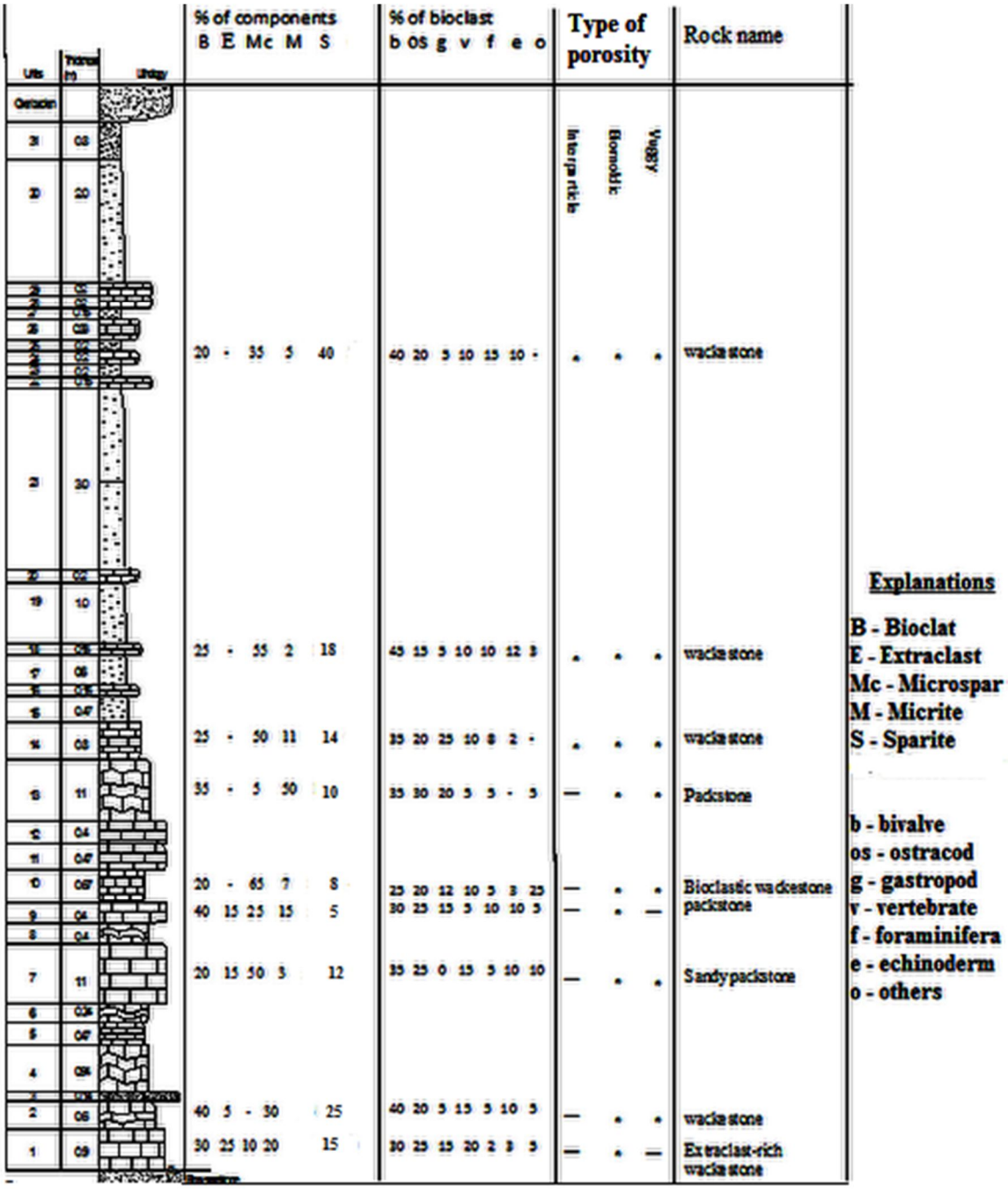


Figure 15: Northern section of Ashaka Quarry showing the percentage composition, porosity type and rock name.

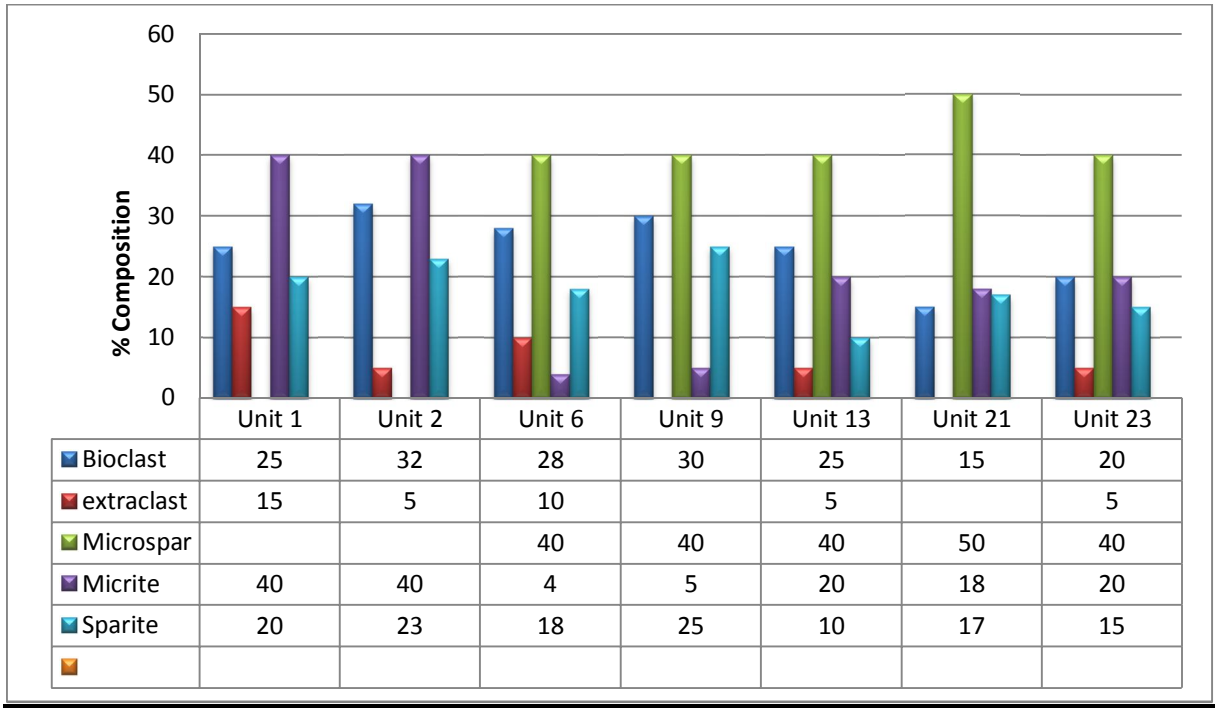


Plate 10: Lowermost limestone units in the northern section of the quarry



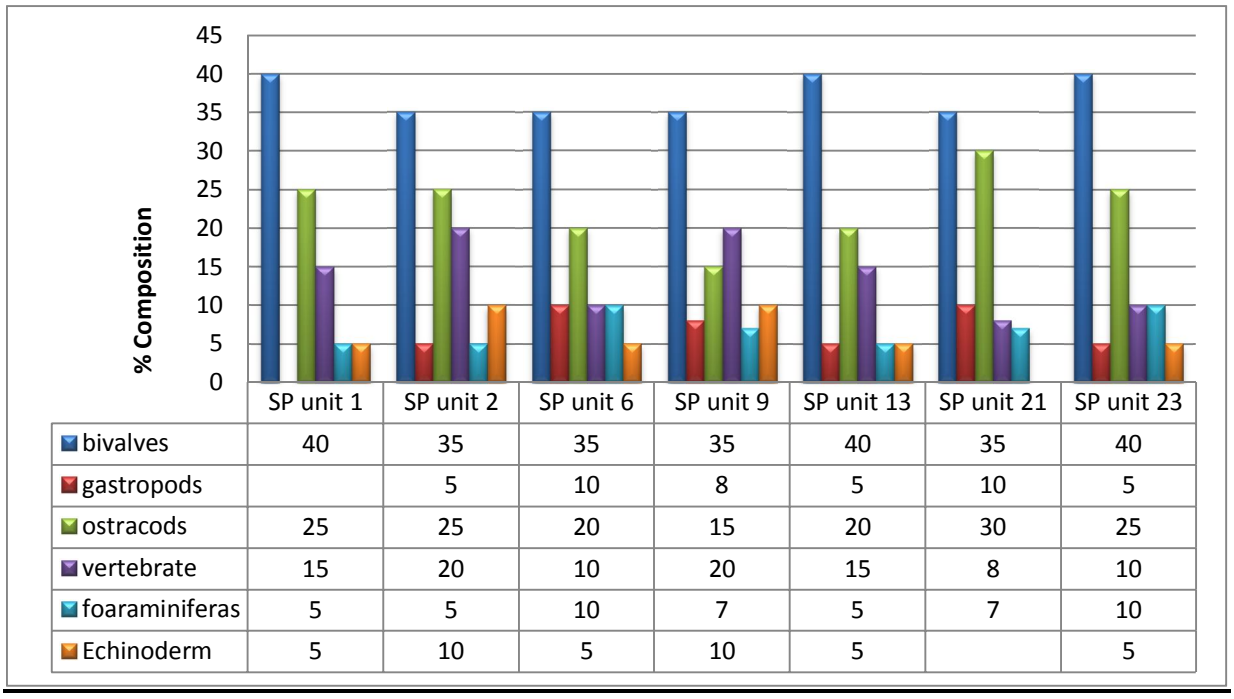
Plate 11: Northern quarry face section

4.1.1.*2 Microfacies analysis of some limestone units from southern section of Ashaka Quarry*



	Unit 1	Unit 2	Unit 6	Unit 9	Unit 13	Unit 21	Unit 23
Bioclast	25	32	28	30	25	15	20
extraclast	15	5	10		5		5
Microspar			40	40	40	50	40
Micrite	40	40	4	5	20	18	20
Sparite	20	23	18	25	10	17	15

Figure 16: Distribution of constituents in the limestone units of southern section of Ashaka Quarry



	SP unit 1	SP unit 2	SP unit 6	SP unit 9	SP unit 13	SP unit 21	SP unit 23
bivalves	40	35	35	35	40	35	40
gastropods		5	10	8	5	10	5
ostracods	25	25	20	15	20	30	25
vertebrate	15	20	10	20	15	8	10
foaraminiferas	5	5	10	7	5	7	10
Echinoderm	5	10	5	10	5		5

Figure 17: Distribution of bioclast in the limestone units of southern section of Ashaka Quarry.

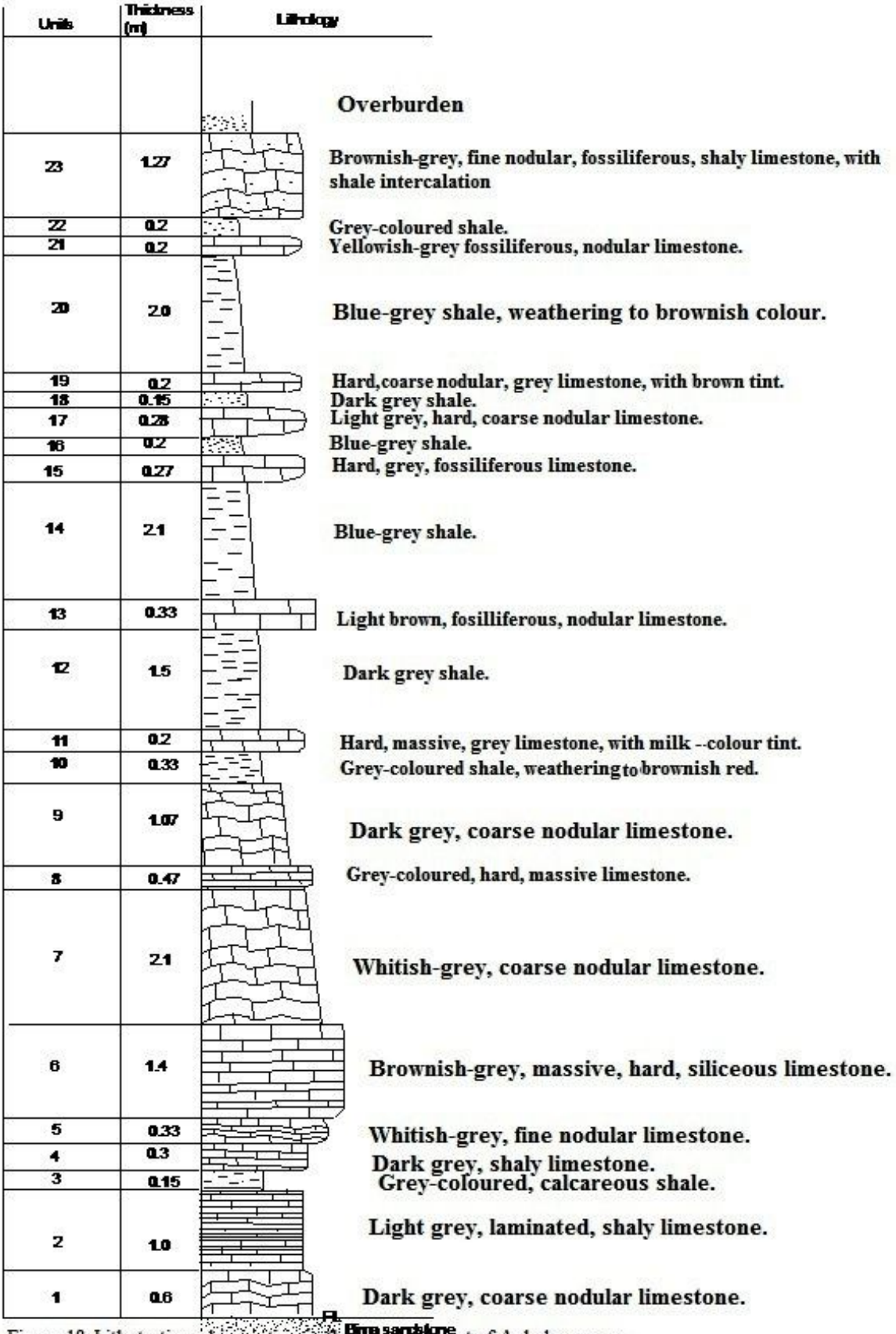


Figure 18: Lithstratigraphic section in the southern part of Ashaka quarry

Unit 1 (Wackestone/biomicrite)

This unit overlies the Bima Sandstone in the southern portion of the Ashaka Quarry. It is a 0.6 m–thick, dark grey, coarse nodular limestone. The matrix consists of micrite (about 40% by volume). It also consists of calcite cement as the major cement binding the rock components with minor neomorphic sparite which occur as shell replacement. Recrystallization fabrics or void filling cement are selective and bias to the aragonitic shells only. The porosity in this unit is low.

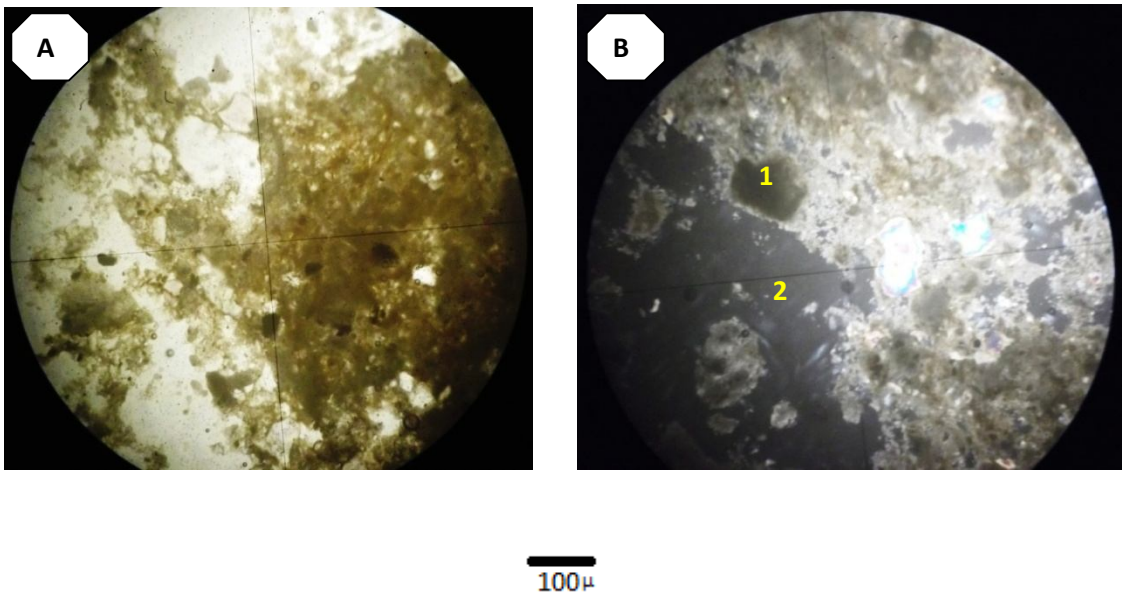


Plate 12: Photomicrographs of extraclast-rich wackestone (biomicrite) from unit 1 of the southern part of the quarry (A: XPL, B: PPL). 1) quartz, 2) solution porosity.

Bioclasts

The bioclasts are bivalves (characterized by irregularly foliated shell structure or prismatic shell structure or preserved in micrite envelopes filled with sparite cement), ostracods (mostly fragmented) and vertebrates.

Extraclasts

The dominant extraclasts observed are quartz grains (corroded and being replaced by calcite), and feldspars. Authigenic glauconite is also present. This unit may be classified as extraclast-rich wackestone (biomicrite).

Unit 2 (Packstone/biomicrite)

This unit is a 1 m–thick, light grey, laminated shaly limestone. Micrite forms about 40% of the unit volume, sparite about 23% and bioclasts about 32%. Opaque material is also seen disseminated within the rock. Porosity is low and mainly biomoldic type. Mechanical breakdown of bioclasts as well as partial to total micritization were seafloor processes that affected the allochems while calcitization of aragonitic bioclasts forming biomold subsequently filled by drusy sparite cement and neomorphism which involved calcitization of the aragonitic bivalves are the internal diagenetic process.

Bioclasts

The bioclasts present include bivalves (with irregularly foliated shell structure, irregularly foliated plus homogeneous shell structure or preserved in micrite envelopes filled with drusy sparite, biomolds filled with drusy sparite without micrite envelop), ostracods (mostly single valve) and vertebrates. This unit is classified as packstone (biomicrite).

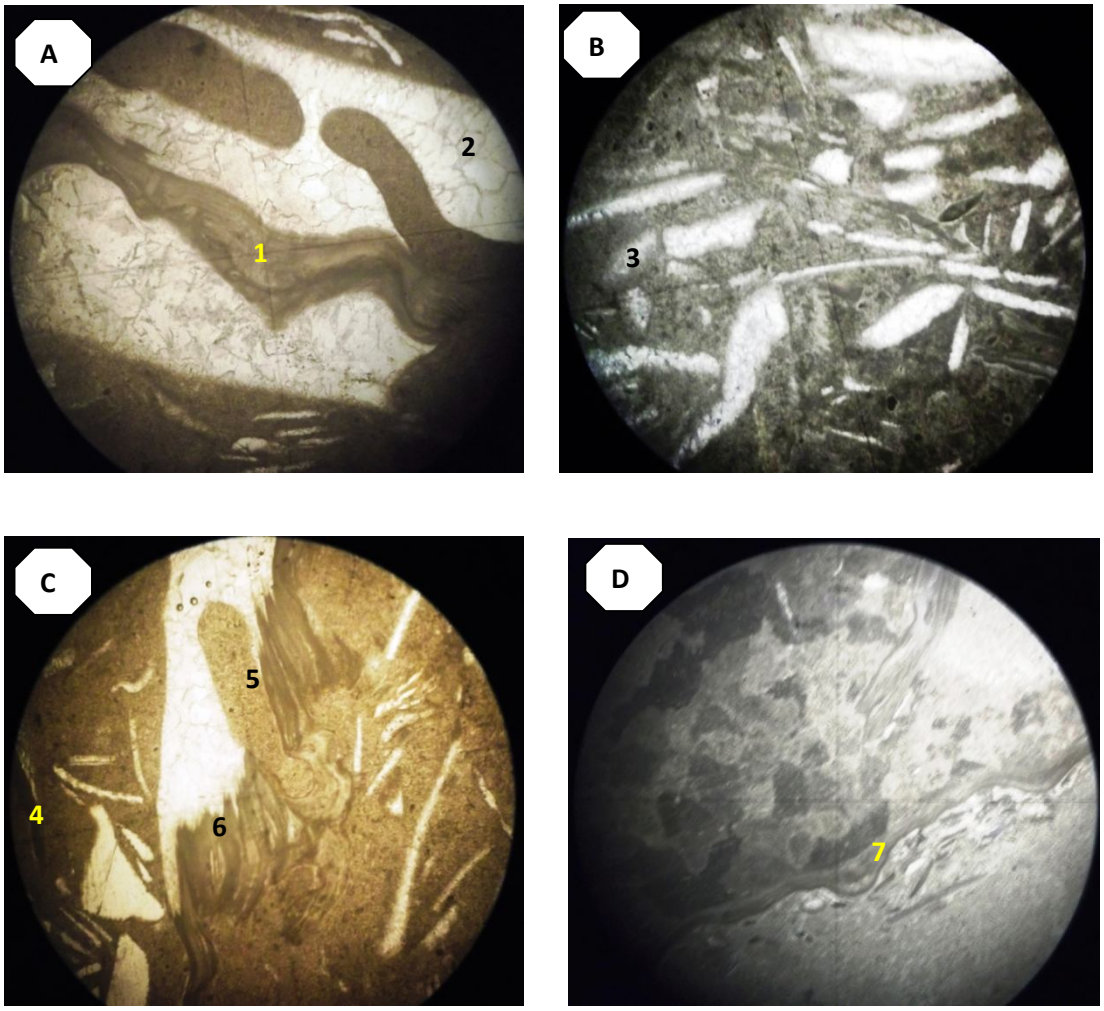


Plate 13: Photomicrographs of packstone (biomicrite) of unit 2 of southern part of the quarry (A, B, C: XPL, D: PPL). 1) bivalve with irregularly foliated shell, 2) sparite cement, 3) biomold of bivalve, 4) bivalve, 5) micrite boring into bioclast, 6) vertebrate, 7) bivalve with homogeneous shell structure.

Unit 6 (Wackestone/biomicrite)

This unit is a 1.4 m–thick, brownish grey, massive, hard siliceous limestone. It comprises a microspar matrix (the result of aggrading neomorphism of original micrite) which is about 40% by volume, bioclasts constitute about 28% by volume while a substantial amount of extraclast (quartz and feldspar – microcline and plagioclase) are

present along with authigenic glauconite about 10%. Micrite and calcite cement makes up the remaining fraction. Bioclasts include bivalves (with irregularly foliated shell structure or prismatic shell structure), ostracods, vertebrates and heterohelicid foraminifers. Porosity is low and is of vuggy and biomoldic type. This unit may be classified as wackestone (biormicrite).

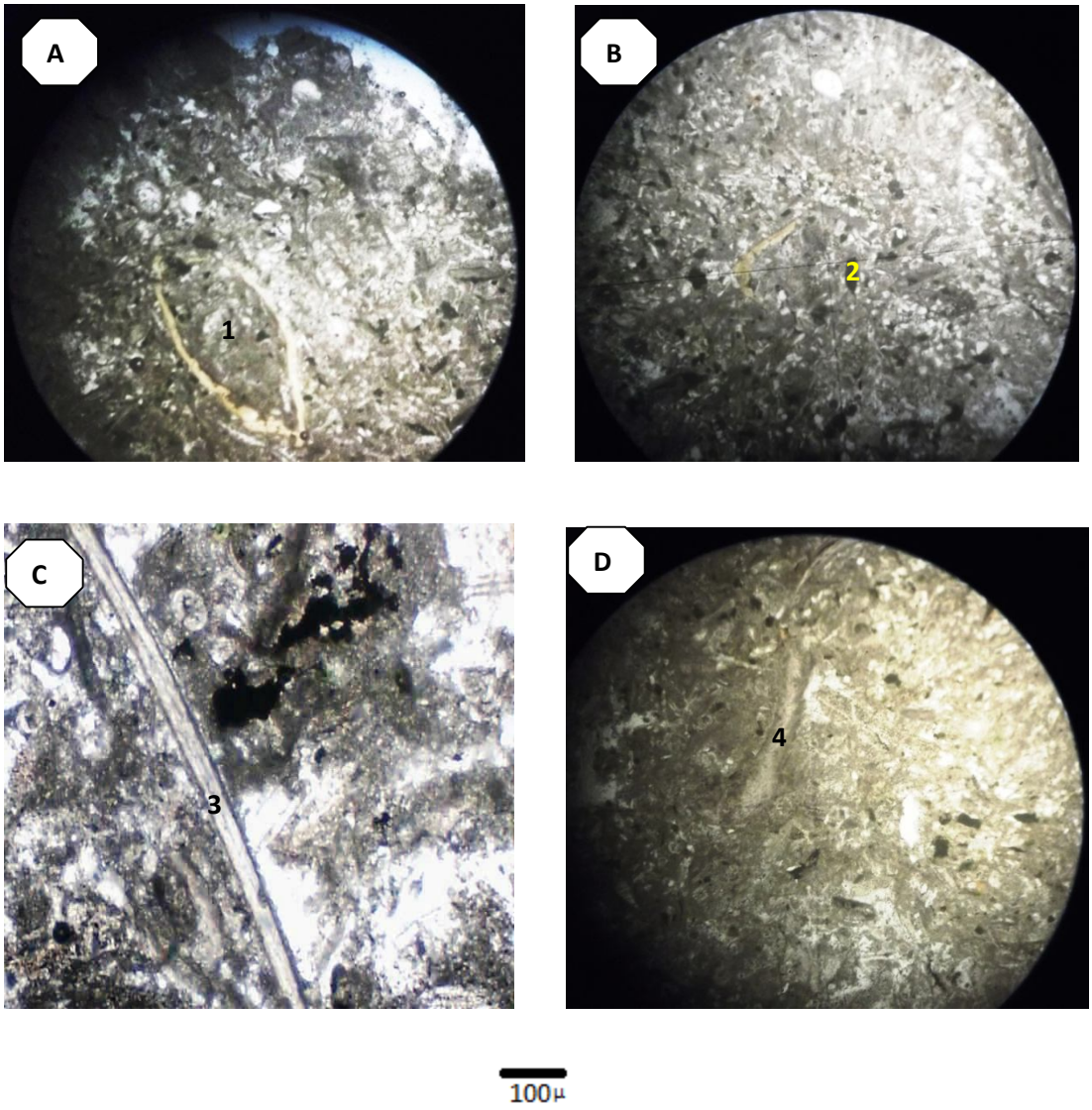


Plate 14**:** Photomicrographs of wackestone (biormicrite) of unit 6 (A, B: XPL, C, D: PPL). 1) ostracod, 2) quartz, 3) bivalve with homogenous shell structure, 4) biomold of bivalve

Unit 9 (Wackestone/biomicrite)

This unit is a 1.07 m–thick, dark grey, coarse nodular limestone. It comprises a microspar matrix (the result of aggrading neomorphism of original micrite) which is about 40% by volume, bioclasts constitute about 30% by volume, sparite about 25% and micrite constitutes 5% by volume.

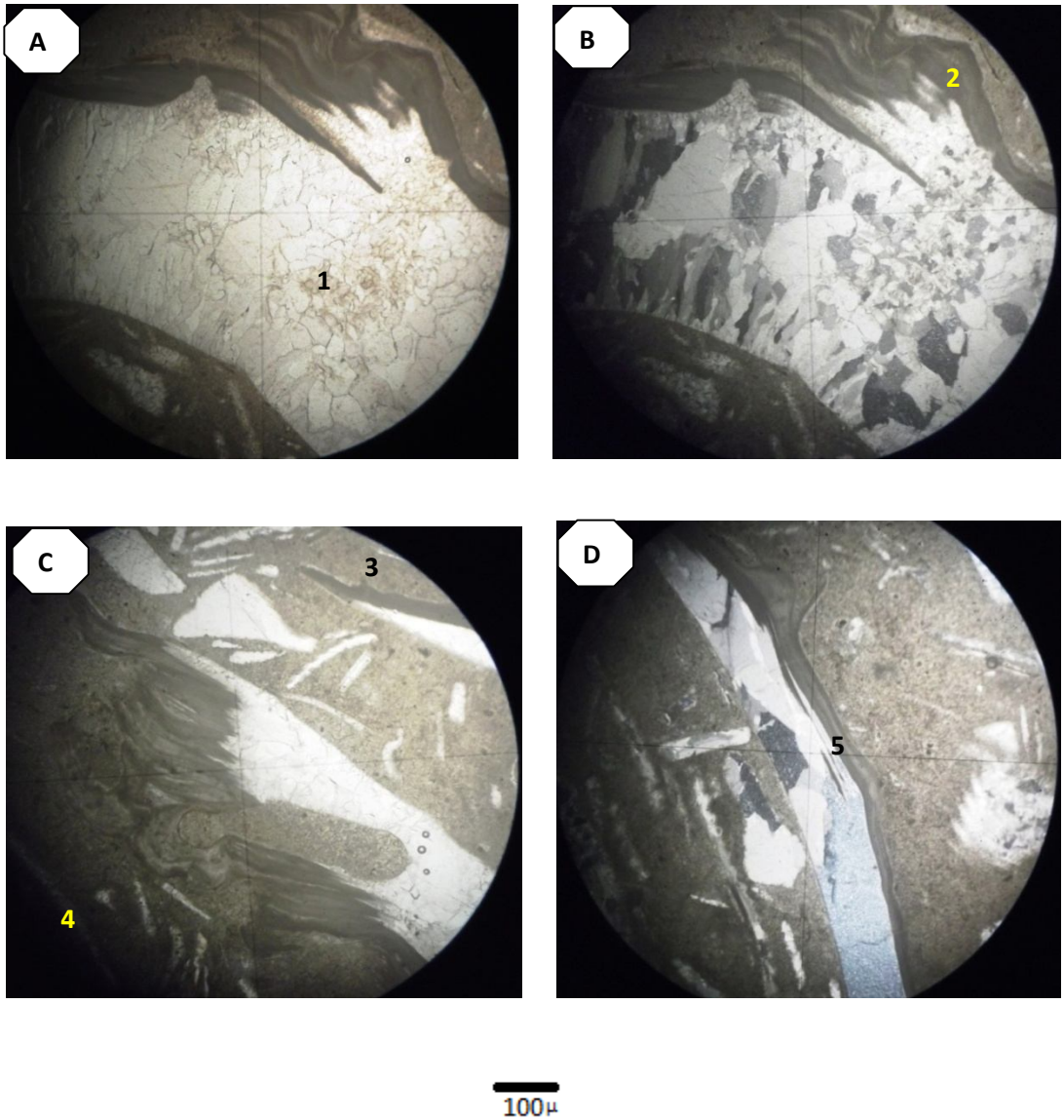


Plate 15: Photomicrographs of wackestone (biormicrite) of unit 9 (B: XPL, A, C, D: PPL). 1) sparite cement, 2) bivalve, 3) microspar, 4) biomold of bivalve, 5) bivalve with homogenous shell structure.

Bioclasts include bivalves (with irregularly foliated shell structure or prismatic shell structure, biomold filled with drusy sparite without micrite envalopes or biomold filled with sparite cement), ostracods (complete and single valve), and gastropods. Porosity is low and is of vuggy and biomoldic type. Diagenesis affected the rock in the form of partial micritization and mechanical breakdown of bioclasts (seafloor process); cementation by drusy sparite cement and neomorphism. This unit is classified as wackestone (biomicrite).

Unit 13 (Wackestone/biomicrite)

This unit is a 0.33 m–thick, tabular fossiliferous limestone containing ammonites, bivalves and gastropods. In thin section, the limestone sample shows some shell fragments which are highly micritized in places. It consist of saccharoidal texture as well as large system of vuggy pores spaces which together gave the rock its unconsolidated nature. There is evidence of compaction as seen from the fracturing of the rock, this affect the rock fabric. Microspar forms about 40% of the rock by volume, micrite about 20%. Pyrite in the form of euhedral cubic crystals was also observed within the rock as seen replacing the neomorphic sparite. Authegenic glauconite with sub-rounded grains is also present.

Bioclasts:

Bioclasts make up about 25% of the rock volume and include bivalves (mostly fragmented and reworked and with irregularly foliated or prismatic structure or preserved in biomolds filled with drusy sparite without micrite envelope or biomolds filled with drusy sparite with micrite envelope), ostracods (complete plus single valves), gastropods, vertebrates, and *Heterohelix sp*. This unit may be classified as wackstone (biomicrite).

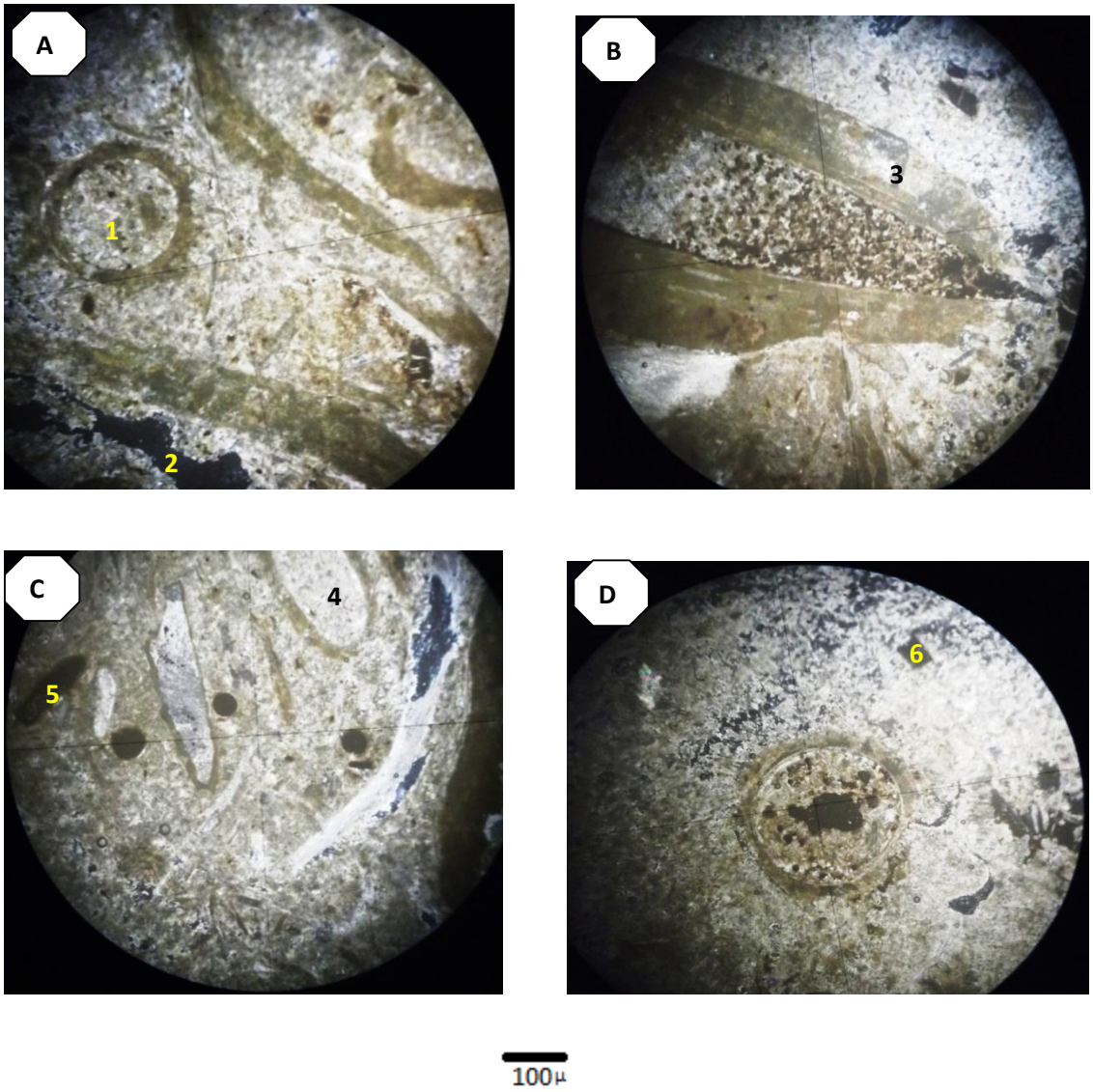


Plate 16: Photomicrographs of wackstone (biomicrite) of unit 13 (A, B, C, D: XPL). 1) ooids, 2) opaque material, 3) bivalve with prismatic shell structure, 4) ostracod, 5) glauconite, 6) quartz.

Unit 21 (Mudstone/biomicrite)

This 0.2 m–thick unit is yellowish grey, fossiliferous nodular limestone. The matrix consists of microspar which is a product of aggrading neomorphism of micrite about 50% by volume, about 18% of the rock volume, however remain in the form of micrite, it also consist of calcite cement about 15%. Porosity in the rock is moderate to high and is of

biomoldic, vuggy and interparticle type. The microfacies characteristics of the bioclasts are fairly observed despite the recrystallization that overprinted most of the signature. Bivalves for instance show irregularly foliated and homogeneous shell structure that is replaced in many places by opaque material, it is also characterized by prismatic shell structure and biomold filled drusy sparite without micrite envelope. Little or no microfacies characteristics are observed in the ostracods and the calcium phosphate (vertebrate) fragments. This unit may be classified as neomorphosed mudstone (biomicrite).

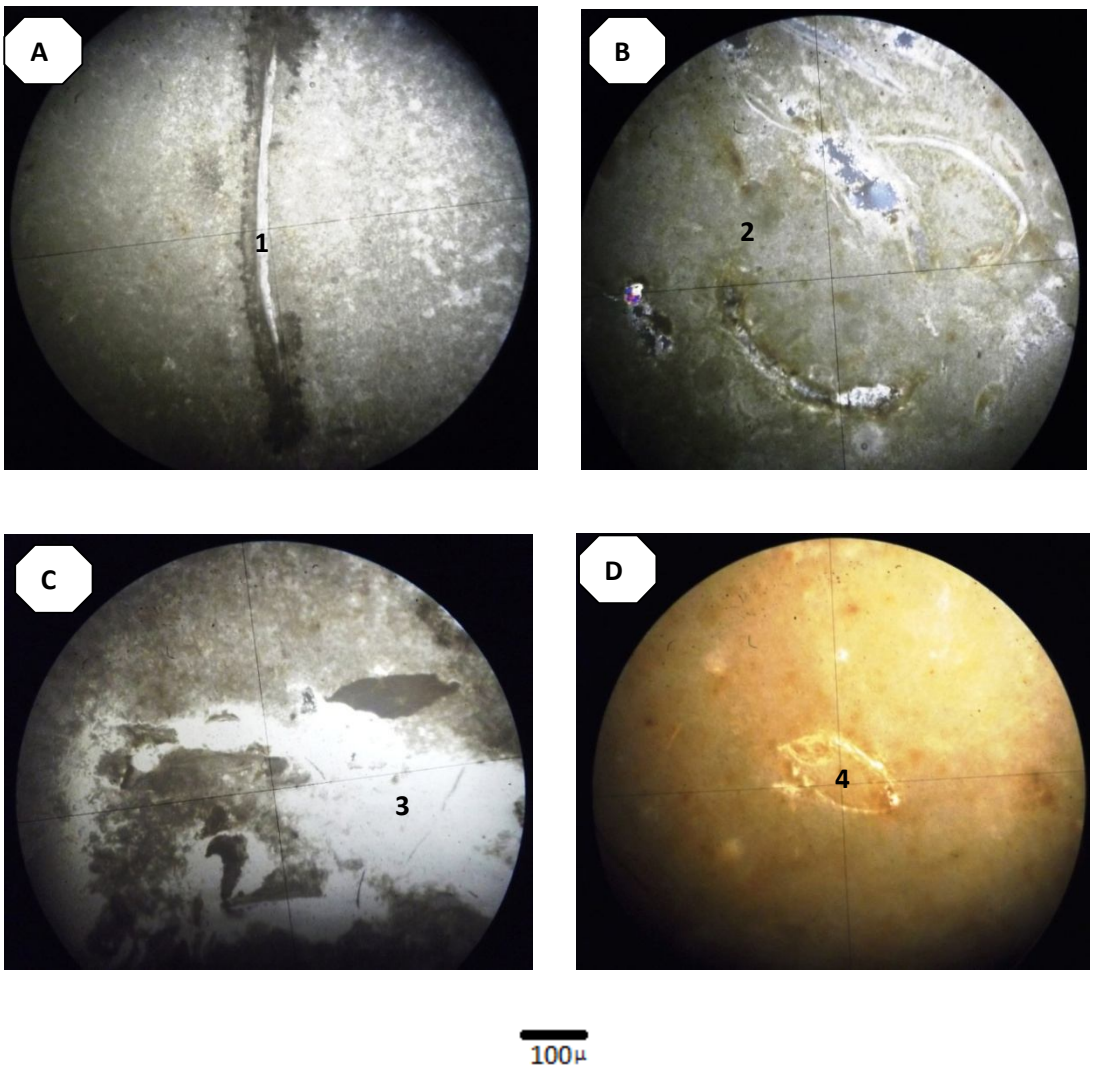


Plate 17: Photomicrographs of neomorphosed mudstone (biomicrite) of unit 21 (B, D: XPL, A, C: PPL). 1) bivalve, 2) microspar, 3) sparite, 4) ostracod.

Unit 23 (Wackestone/biomicrite)

Unit 23 is a 1.27 m–thick brownish grey, fine nodular, fossiliferous, shaly limestone with shale intercalation. Microspar forms the major part of the matrix in this unit (about 40% by volume), micrite which makes up about 20%, and bioclast about 20%. Bioclasts present in the rock include bivalves with irregularly foliated shell structure (some dissolves creating pore spaces that are occupied by opaque materials and some, neomorphosed or replaced by micrite), ostracods (complete and single valve), gastropods, foraminifers with globular chambers and vertebrates that are mostly replaced by opaque materials. Solution porosity caused by dissolution that is fabric selective, mostly affected the bivalves and the foraminifers. Opaque materials occur in the rock mostly as replacement material and occupied the pore space created by dissolution, fracturing in the limestone deposit occurs due to compressive action. The rock may be classified as wackestone (biomicrite).

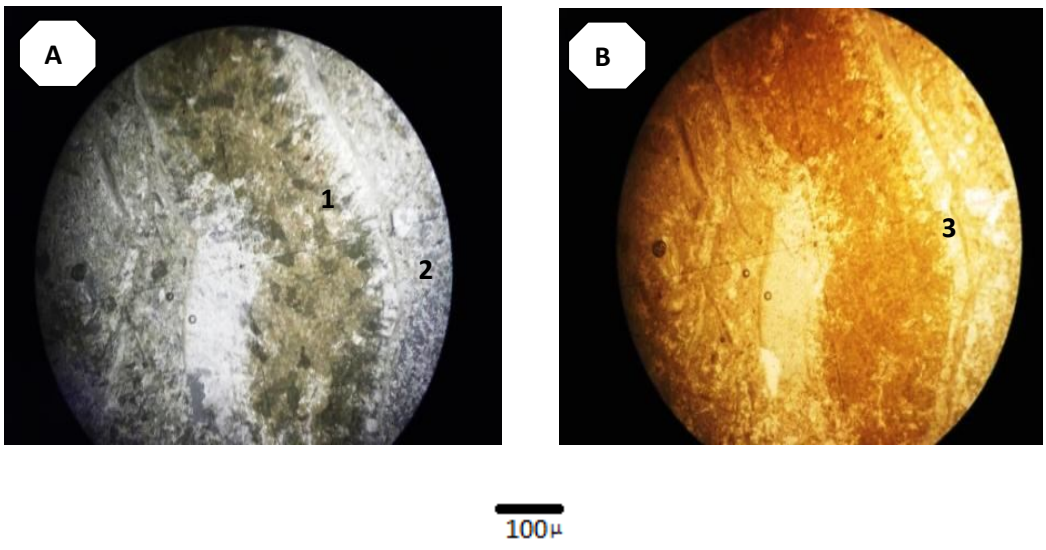


Plate 18: Photomicrograph of wackestone (biomicrite) of unit 23 (B: XPL, A: PPL). 1) sparite cement, 2) micrite, 3) bivalve.

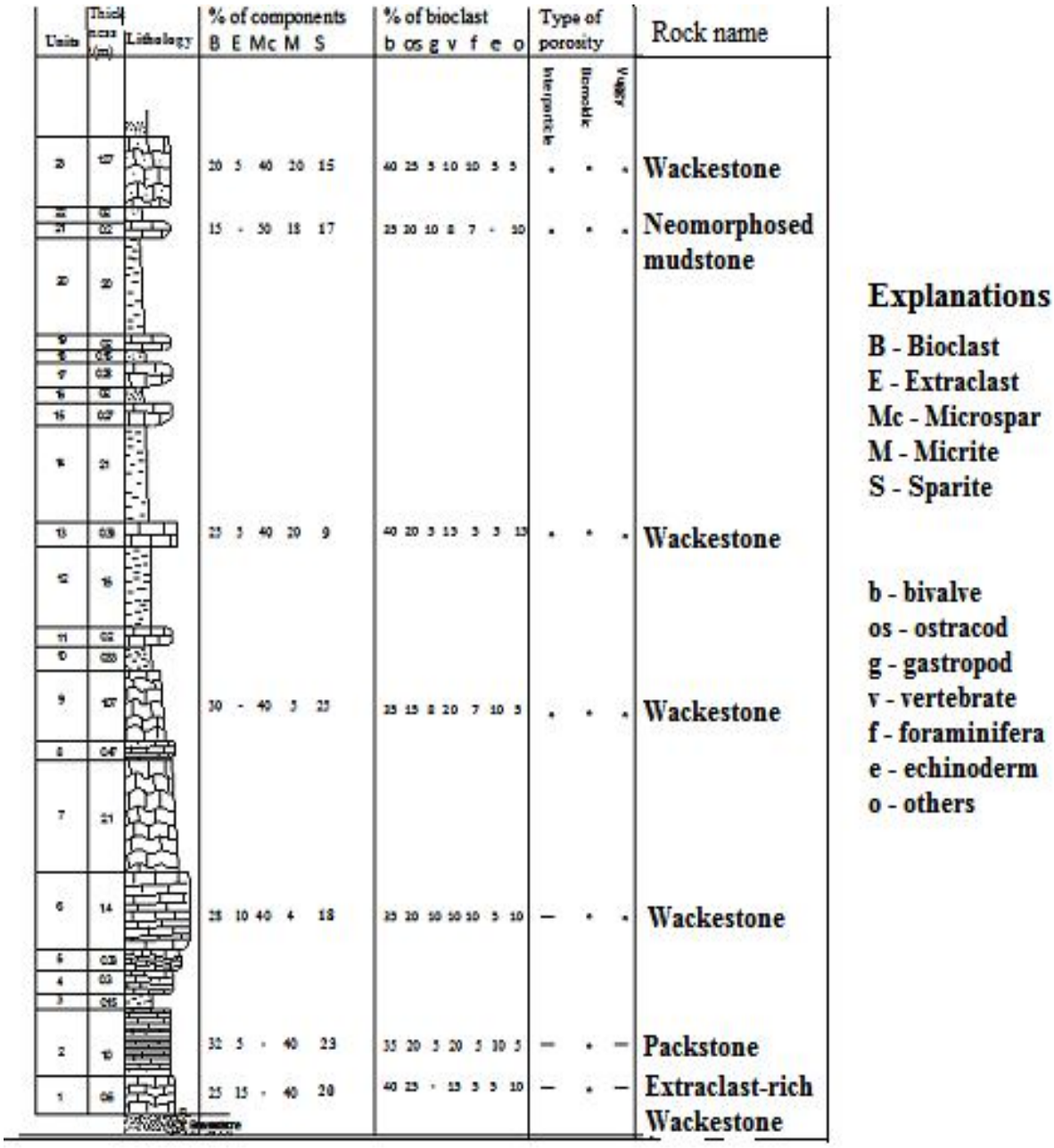


Figure 19: Southern section of Ashaka Quarry showing the percentage composition, porosity type and rock name.



Plate 19: Southern section of the quarry showing the lowermost limestone units

4.1.1.3 *Diagenetic Features*

The Ashaka Quarry limestones show some diagenetic features among which are compaction features, porosity (both loss and creation), neomorphism and cementation. In most of these deposits, diagenesis can be categorized into two broad groups; seafloor diagenesis which involved mechanical breakdown of bioclasts as well as partial and total micritization, and subsurface diagenesis involving dissolution of the aragonitic bioclasts forming biomolds, cementation by drusy sparite cement and neomorphism.

i. **Compaction:** the limestone deposits depict some features of compaction which are mainly fracturing of the rock layer. The fracturing of the limestone is partly due to the weight of the overlying layer and partly due to tectonic activities that took place in the past (Oti, 1990). Evidence of compaction can be observed in plate 13d where a bivalve shell is fractured. It can also be observed in Plates 1 and 3 where there is selective enrichment of the more resistance particles such as quartz and feldspar along a specific plane.

ii. **Porosity:** development of pore spaces as well as its trend can be observed in plates 12, 14 and 17. Biomoldic porosity and vuggy porosity are the most common porosity type observed in the limestone deposit of the Ashaka Quarry, which according to Choquette and Pray (1970) originates on account of late diagenetic processes. Biomoldic porosity results from dissolution of shell leaving behind the biomold while vuggy porosity, from meteoric vadose diagenetic processes". Interparticle porosity was also observed but is of little significance as seen in Plates 8, 9 and 15. It was generally observed that porosity increase from bottom to the top of the profile.

iii. **Neomorphism:** the occurrence of neomorphic microspar in the limestone deposit of the Ashaka Quarry is one of its diagenetic features. These can be seen in Plates 2, 4, 5, 6, 7, 11, 13. The micrite matrix is the one mainly affected by this process.

iv. **Cementation:** the cementing materials that were documented in the history of Ashaka Quarry include blocky cement which are large crystals that usually fills up residual pore spaces, syntaxial overgrowths of calcite cement which are normally found around echinoderm fragments. Also quartz and feldspar overgrowths were

observed on quartz and feldspar grain respectively and both are in optical continuity with the original grain.

4.1.2 Micropalaeontology

Most of the limestones are highly indurated, as such it became difficult to get and identify microfossils in the limestone samples after washing. Microfossils were observed in four limestone units in the northern section of the quarry which are: units 10, 14, 18 and 20. For the southern section, microfossils were noted in five limestone units which are: units 7, 9, 13, 17 and 23. The microfossils observed are mostly benthonic foraminifers with lesser planktonic forms.

In the northern section, unit 10 contains a *Heterohelix* sp. (a planktonic foraminifera) and *Lenticulina* (a benthonic foraminifera), unit 14 contains *Nonium* and *Quinqueloculina,* unit 18 contains *Quinqueloculina*, *Triloculina*, *Elphidium* and *Textularia,* unit 20 contains *Quinqueloculina* and *Lenticulina*. In the sounthern section, unit 7 contains *Lenticulina, Quinquelocula,* and *Heterohelix* sp. (a planktonic foraminifera), unit 9 contains *Quinqueloculina* and *Nonium*, whereas *Quinqueloculina* and *Triloculina* were observed in unit 13. Unit 17 contains *Quinqueloculina* and *Lenticulina* while *Elphidium* and *Quinqueloculina* were observed in unit 23 as shown in Figures 20 and 21 and in Plates 20-28 (in Appendix I). Depositional environment and the palaeoenvironmental condition such as paleotemperature can be determined from the foraminiferal assemblage mentioned above.

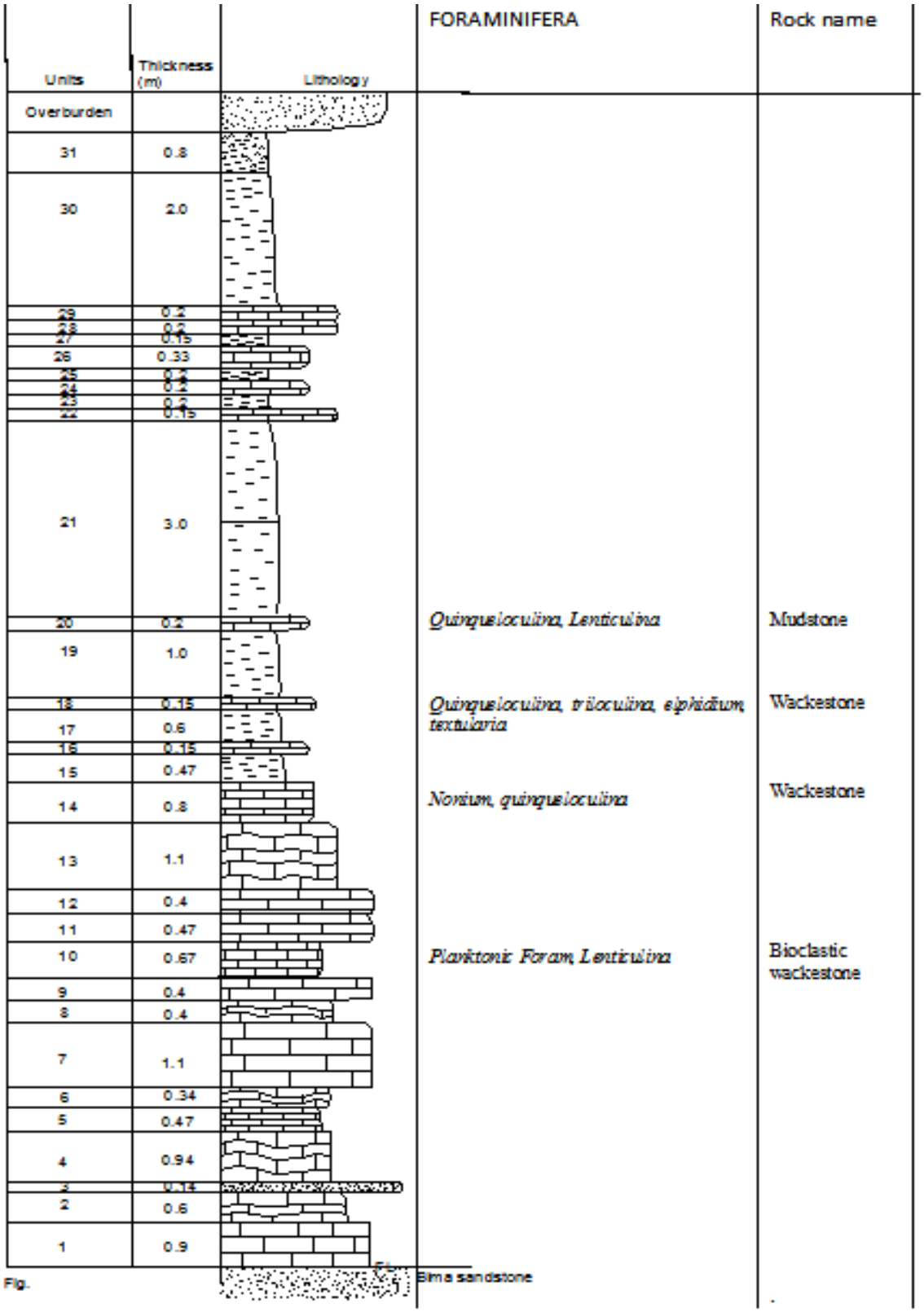


Figure 20: Northern section of Ashaka Quarry showing the distribution of identified foraminiferal taxa.

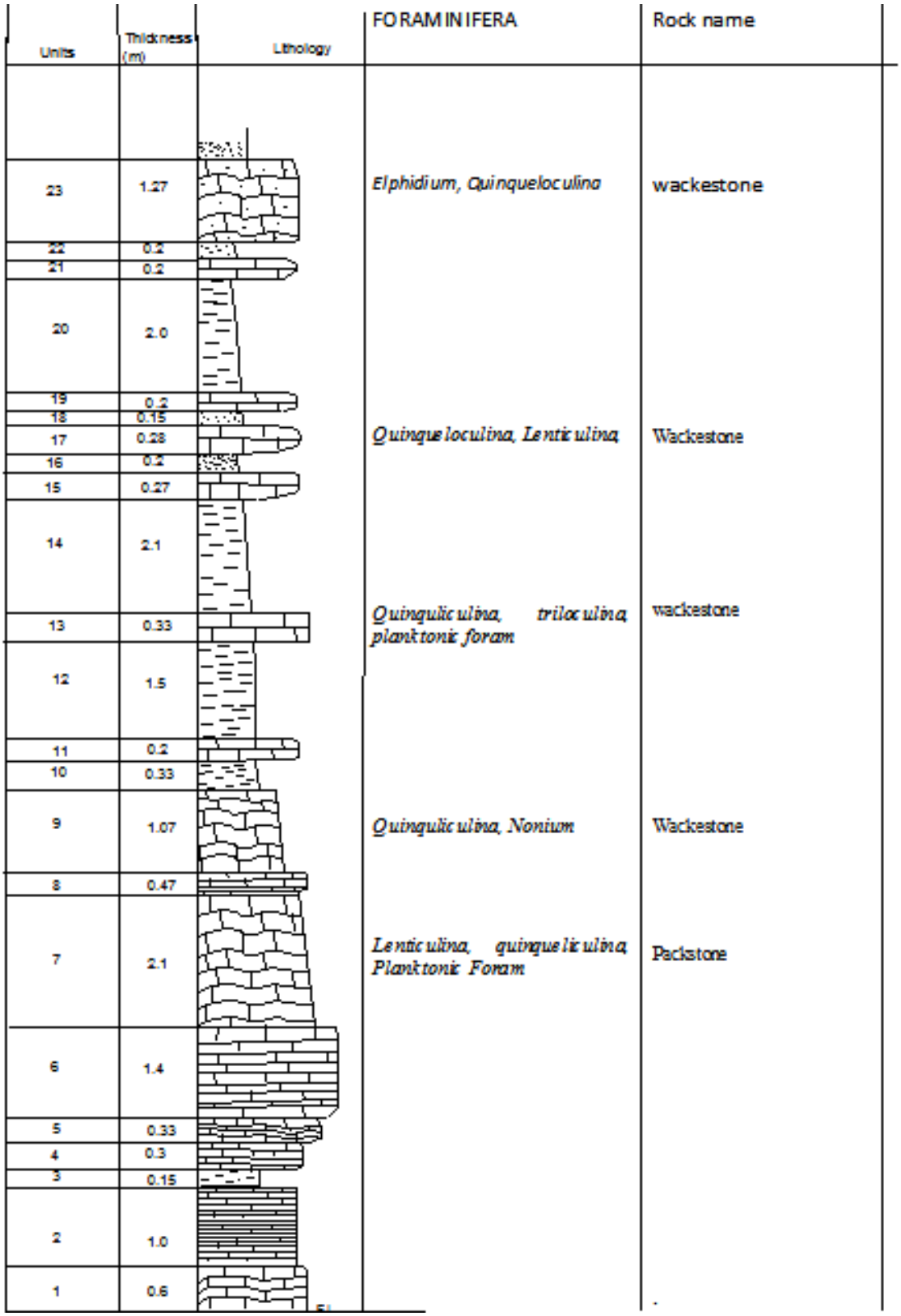


Figure 21: Southern section of Ashaka Quarry showing the distribution of identified foraminiferal taxa

4.1.3 Sedimentology

The limestone – shale units of the Ashaka Quarry is made up of directly superposed limestones below which are about 9 m and 8 m - thick in the northern and southern section of the quarry respectively, and shale with limestone intercalation above. The superposed lower limestones are often hard and grey when fresh but weather to cream-brown colour. These limestones which are mostly wackestone and packstone are made up of 13 units and 8 units in the northern and southern quarry respectively and in both cases each unit rarely exceed 1m in thickness. The contacts between the units are usually sharp depicting minor intermittent break in sedimentation. Structures such as cross-bedding were observed within some of the hard limestone units. The upper surface of the limestones in some cases shows *Thalassinoides* burrows especially the nodular units.

Above the lower superposed limestone units is the limestone-shale intercalations. The shales are dark grey when fresh and light blue to greenish-grey when weathered. Thin band of gypsum often occur within the shales and the limestones units. Glauconite occurs as grains at specific horizons. The colours varies from grey, earthy yellow, brownish-grey, yellowish-brown and pale grey for the limestone deposit and grey, dark grey, blue-grey for the shale deposit in the Ashaka Quarry. The texture is fine grain for the shale whereas the limestones are mostly indurated and nodular with few units that are loosely compacted. The structures observed range from planar bedding (in units 3 and 6), tabular cross bedding on unit 8, *Thalassinoides* burrows in unit 9 and bioturbation surface in units 18 and 29 (Figures 22 and 23). Stacking pattern of the parasequence sets is retrogradational and aggradational. Retrogradational parasequence pattern was observed in the lower unit of the section (Figures 22 and 23) which is characteristic of the transgressve systems tract. The

upper part of the section is observed to be made up of an aggradational stacking pattern which is an indication of the early part of the highstand systems tract. The stacking patterns are given below.

Retrogradational stacking pattern

For northern section, units 1 to 9 forms the parasequence set 1, it has the thickness of 5.29m, units 10 to 14 forms the parasequence set 2 with the thickness of 3.44m whereas units 15 to 18 constitute the parasequence set 3 with thickness of 1.37m (Figure 23). The parasequence sets becomes progressively thinner from set 1 to set 3 and individual parasequences within each of the parasequence set are progressively thicker than the older ones, this is an indication of retrogradational stacking pattern. For the southern section, units 1 to 9 forms the parasequence set 1 with thickness of 7.42m, and units 10 to13 forms the parasequence set 2 with thickness of 2.36m (Figure 22), this also show decrease in thickness from parasequence set1 to parasequence set 2. The parasequences in each of the parasequence sets also shows increase in thickness from the older to younger ones. This is an indication of retrogradational parasequence set stacking pattern which is characteristics of the transgressive systems tract.

Aggradational stacking pattern

For northern section, units 19 to 22 forms the parasequence set 1, it has a thickness of 4.35m, and units 23 to 31 forms the parasequence set 2 with a thickness of 4.28m (Figure 23). The two parasequence sets have approximately the same thickness; this is an indication of an aggradational stacking pattern. For the southern section, units 14 to 19 forms the parasequence set 1 with a thickness of 3.2m and units 20 to 23 forms the

parasequence set 2 with a thickness of 3.67m (Figure 22), this shows no much difference in the thickness from parasequence set1 to parasequence set 2. It shows a repetition of the first parasequence set which together forms an aggradational stacking pattern. This is an indication of the early part of the highstand systems tract.

4.2 SEQUENCE STRATIGRAPHY

Based on the study of the field relations of the lithological units and laboratory analysis, the Pindiga Formation at the Ashaka Quarry may be considered to comprise a single sequence made up of a transgressive systems tract and the highstand systems tract (Figures 22 and 23) lacking the lowstand systems tract. Parasequences and parasequence sets occur within these parts of the sequence.

The lower sequence boundary is the thin ferruginous crust which marks the top of the Bima Sandstone (Zaborski *et al,* 1998). The Pindiga Formation lies unconformably on the Bima Sandstone, the Yolde Formation being absent. This unconformity surface coincides with the transgressive surface, and also the lower sequence boundary.

It was deduced from Zaborski (1998a, 2000), that the upper sequence boundary is at the base of unit 34 of the Deba-Fulani Member which is thought to be "the correlative conformity of the erosional unconformity at the base of the Dumbulwa Member in the Dumbulwa-Bage High area" (Alfarooq, 2004). "The erosional contact was a result of erosion of the Kanawa Member at the beginning of the Middle Turonian regression during which the Dumbulwa and Deba-Fulani Members were deposited".

4.2.1 Bounding Surfaces of Sequence Stratigraphy

Sedimentary sections are subdivided by a variety of surfaces that envelope and enclose genetically related stratigraphic units which may be distinguished on the basis of its geometry, thickness and facies. The framework of some of these surfaces or boundaries is used to define sequences, systems tracts, parasequence sets and parasequences. The surfaces identified in this work are the lower sequence boundary, transgressive surface, maximum flooding surface, marine flooding surfaces and the minor marine flooding surfaces.

4.2.1.1 Sequence boundary and the transgressive surface

At the Ashaka Quarry, the sequence boundary coincides with the trangressive surface which is the ferrugeneous layer on top of the Bima Sandstone. It is characterized by subaerial exposure, weathering and erosion of the Bima Sandstone; it is also an unconformity surface which is marked by the erosion of the Yolde Formation in the area. The surface is said to be a transgressive surface because it underlie a retrogredational stacking pattern of parasequence set and indicates deepening in water level as the limestone deposit which are of marine origin directly overlie continental Bima Sandstone. This surface is seen at the base of unit 1 in both the southern and the northern section of the quarry (Figures 22 and 23).

4.2.1.2 Maximum flooding surface

This is the surface that separates the transgressive systems tract from the highstand systems tract, it is commonly represented by a condensed section where there is high fossils content indicating low rate of sediment accumulation. It also indicates a change

from a retrogredational to an aggredational parasequence set stacking pattern. These surfaces were observed in units 13 and 18 of the southern and northern sections respectively (Figures 22 and 23). These units are characterized by bioturbation, hard ground, presence of glauconite, reworked fossils, bone fragments and phosphetic matter, their upper surfaces also marked the end of retrogradational stacking pattern of parasequence set as well as the beginning of the aggredational stacking pattern of the subsequent parasequence sets.

4.2.1.3 Marine flooding surface

These are the surfaces that separate younger strata from older ones, across which there is evidence of an abrupt increase in water depth. They are planar and commonly exhibit only very minor topographic relief and minor submarine erosion as well as a minor hiatus may be indicated. This study identifies marine flooding surfaces at units 9 and 19 on the southern section of the quarry (Figure 22) and units 9, 14 and 22 on the northern section of the quarry (Figure 23). These units are characterized by bioturbations and nodular surfaces and particularly unit 19 of the southern section and unit 22 of the northern section are rich in glauconite. The marine flooding surfaces here demarcate the boundary between two parasequence sets.

4.2.1.4 Minor marine flooding surface

These surfaces were formed in response to an increase in water depth and typically bound parasequences, like the marine flooding surfaces, they are commonly planer, separating older parasequence from younger ones. These surfaces were identified in this work at units 3, 6, 7, 11, 15, 17, 21 and 23 of the southern section of the quarry (Figure 22)

and units 3, 6, 12, 16, 20, 26, 29 and 31of the northern section of the quarry (Figure 23). Some of these units are rich in glauconite and are nodular, indicating increase in water depth.

4.2.2 The Sequence

The limestone-shale units at the Ashaka Quarry form part of sequence which contains only the transgressive systems tract and highstand systems tract. The sequence is bounded below by a surface characterized by subaerial exposure (the ferruginous layer on top of the Bima Sandstone). The shallow-marine limestone at the quarry which is deposited on the sequence boundary, directly overlie the continental Bima Sandstone, the limestone formed during the transgression period.

4.2.2.1 The Transgressive Systems Tract

The base of the transgressive systems tract coincides with the base of the sequence. The first deposit in this systems tract is unit 1 in the southern and the northern section of the Ashaka Quarry which is massive, hard, pale grey to green limestone in the northern section and dark grey, coarse nodular limestone in the southern section both of which are rich in extraclast. The presence of the extraclast may be attributed to the marine erosion at the transgressive surface which recycled sands from the upper parts of the Bima Sandstone.

The section from the southern part of the quarry contain six (6) parasequences each of which are separated by a minor marine flooding surface. The six parasequences are grouped into two parasequence sets on the basis of their lithological character variation, surfaces separating them and variation in thickness: the parasequence set 1 comprises four parasequences in which limestone units 1 – 9 is constituted, after this, begins the deposition of shale indicating deepening in water level as well as great reduction in the

energy of the depositional medium; Parasequence set 2 consists of two parasequences with the second parasequence bounded at the top by a condensed section that is considered to be the maximum flooding surface at the base of the highstand systems tract, the parasequnce set 2 therefore has shale deposit of units 10 and 12, limestone deposit of units 11 and 13 as

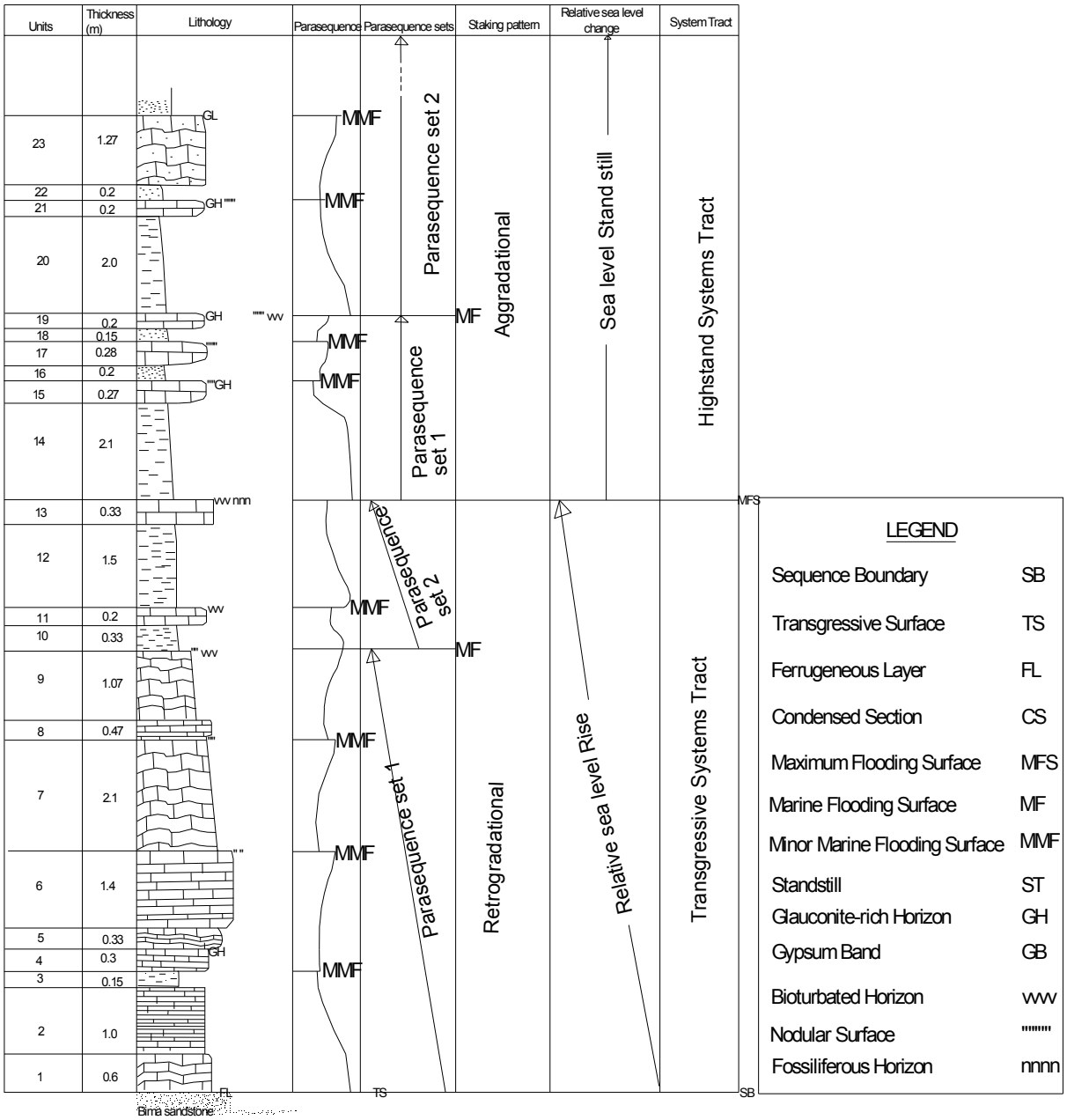


Figure 22: Sequence stratigraphic succession of the southern section of Ashaka Quarry

its constituents. This transgressive systems tract recognized by the retogradational stacking pattern of its parasequence sets in that parasequence set 1 is thicker than paraseuence set 2 due to sediment starvation, and also the younger parasequences in the sets becomes progressively thicker than the older parasequences. This is said to "represents limestone and shale deposited during the period of relative sea level rise" and hence corroborate the evidence given by Alfarooq (2004).

For the northern section, the three parasequence sets recognized in the transgressive systems tract contains seven (7) parasequences with the first three parasequences belonging to the parasequence set 1, the next two parasesequences belong to the parasequence set 2 and the remaining two parasequences belonging to the parasequence set 3. The paraseuence set 1 consist of limestone units 1, 2, 4 – 9 and sandstone unit 3. Parasequence set 2 consists exclusively of limestone units 10 – 14 whereas parasequence set 3 is having limestone/shale intercalations of units 15 – 18 (Figure 23). It can be observed that the younger parasequences within a particular parasequence set are progressively thicker than the older ones, and overall the younger parasequence sets becomes consecutively thinner than the older ones, this typified a retrogradational stacking pattern whereby the parasequence set become progressively thinner due to sediment starvation. This transgressive systems tract is recognized by the retrogradational stacking pattern of its parasequence set and it represents deposition in period of relative rise in sea level.

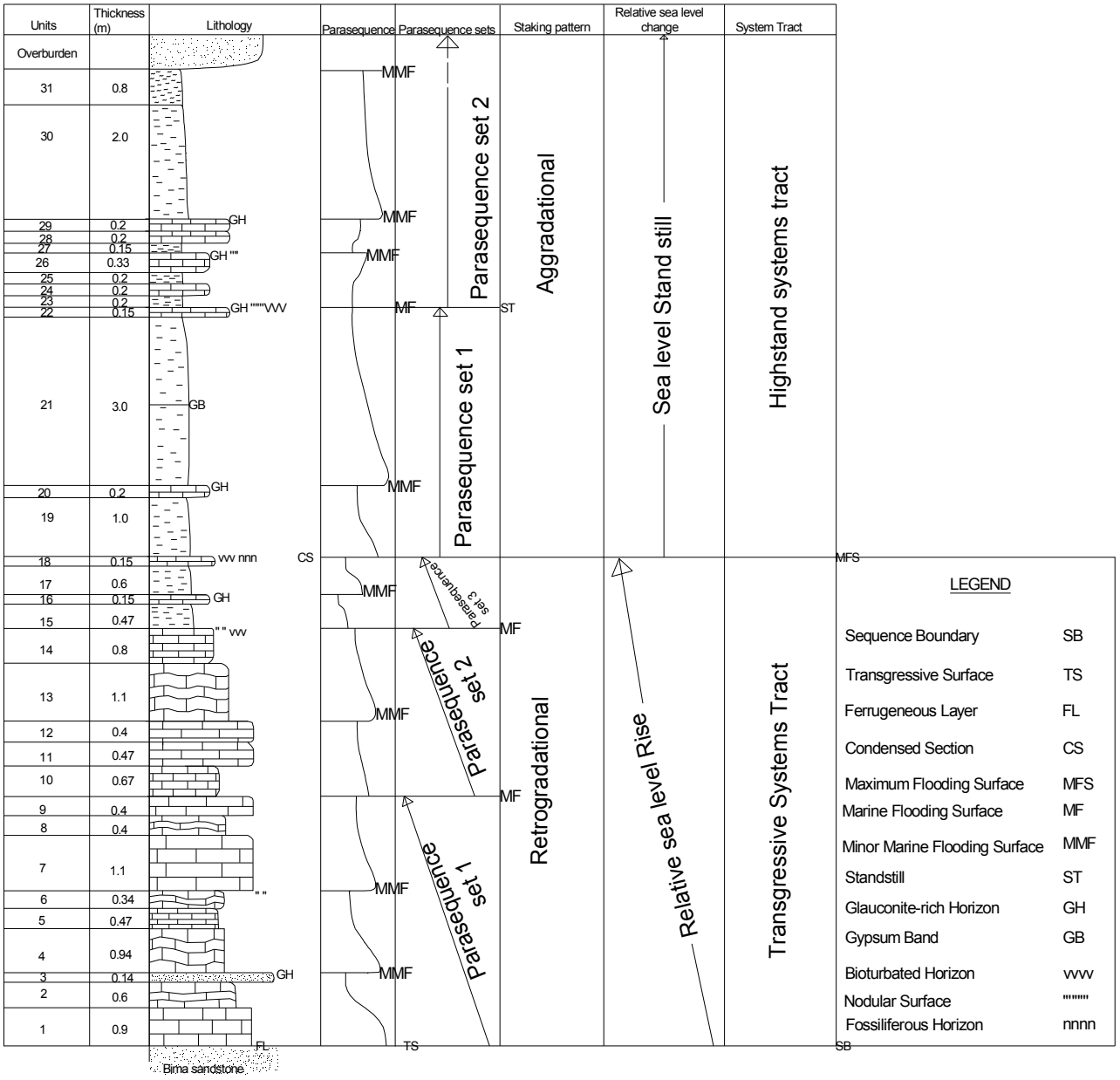


Figure 23: Sequence stratigraphic succession of the northern section of Ashaka Quarry

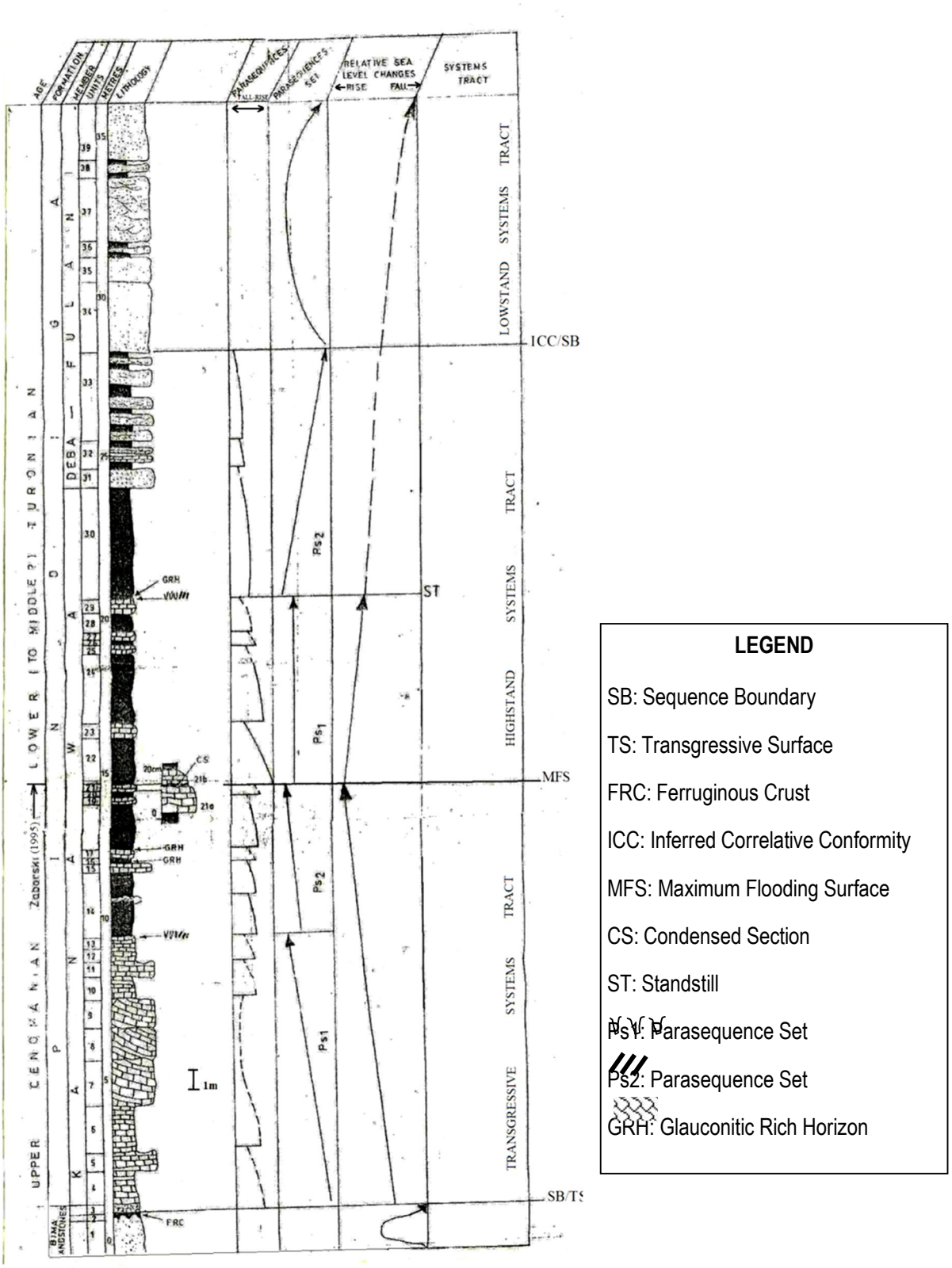
4.2.2.2 The Highstand Systems Tract

Highstand systems tract are recognized by the initial aggradational and subsequent progradational stacking pattern of the parasequence sets, and it position in the depositional sequence. Two parasequence sets were identified both in the southern and northern section

of the quarry on the account of lithological and structutural similarity and the occurrence of diagenetic glauconite on the horizons which indicates period of standstill in sedimentation and this is often the beginning of the highstand systems tract, these two parasequence sets in each case form aggradational stacking pattern.

The lower limit of the parasequence set 1 of the southern section is the maximum flooding surface at the top of the transgressive systems tract. It contains three parasequences (units 14 - 19). The top of unit 23 is heavily bioturbated and rich in glauconite, this together with condensed section at the base of the parasequence set 1 represents the period of standstill. Parasequence set 2 in the southern section contains two parasequences which consists of units 20, 21, 22 and 23 (Figure 22). The remaining parasequences in this highstand systems tract is said to be within the lower part of Deba-Fulani Member (Figure 24) of the Pindiga Formation (Zaborski, 1998a, Alfarooq, 2004).

The northern section of the quarry also consists of two parasequence sets within the highstand systems tract. The parasequence sets forms an agradational stacking pattern with most of the units rich in authegenic glauconite, indicating period of standstill in sedimentation. Parasequence set 1 contain two parasequences consisting of units 19 - 22 (Figure 23). The parasequence set 2 is bounded below by the highly bioturbated, loosely compacted limestone, which is at the upper part of the first parasequence set representing marine flooding surface, it contain three parasequences consisting of units 23 – 31 (Figure 23).



LEGEND

SB: Sequence Boundary

TS: Transgressive Surface

FRC: Ferruginous Crust

ICC: Inferred Correlative Conformity

MFS: Maximum Flooding Surface

CS: Condensed Section

ST: Standstill

Ps1: Parasequence Set

Ps2: Parasequence Set

GRH: Glauconitic Rich Horizon

Figure 24: Sequence stratigraphic interpretation of pindiga formation (Kanawa Member) at the Ashaka Cement Quarry (After Alfarooq, 2004)

4.2.3 Stratigraphic Correlation

This part of the study deals with the examination of the lithology from the two quarry sections and comparison between them as well as comparing the two sections in terms of the sequence stratigraphy.

4.2.3.1 Lithostratigraphic Correlation

Two sections of the quarry were studied in detail: one in the north and the other in the south. The two sections are separated by a distance of approximately 4 km. There are lateral variations in the stratigraphic succession from the north to the south. The limestones at the lower part of the northern section of the quarry which is about 9 m thick can be correlated with the 8 m thick limestones of the lower part of the southern section. As a matter of fact, Ashaka Cement Company uses this grade of limestone for their cement production not the upper limestone units.

Thirteen different limestone facies were identified for the lower limestone deposit in the northern section of the quarry (Figures 13, 23 and 26). Some of these facies merge laterally to form a single limestone facies in the southern section. This accounts for the reduction in the number of facies in the southern section to eight limestone facies. The limestone deposits of unit 4 and unit 5 in the northern section of the quarry give rise to the limestone deposit of unit 4 in the southern section with a reduced thickness owing to the decrease in the rate of sedimentation, as they posses similar lithofacies and structures. It can also be observed that the limestone facies of units 8, 9 and 10 in the northern section are similar to the limestone facies of unit 7 in the southern section due to their common fossil content typified by the presence of *Lenticulina* (Figures 20 and 21), bivalves and ostracods.

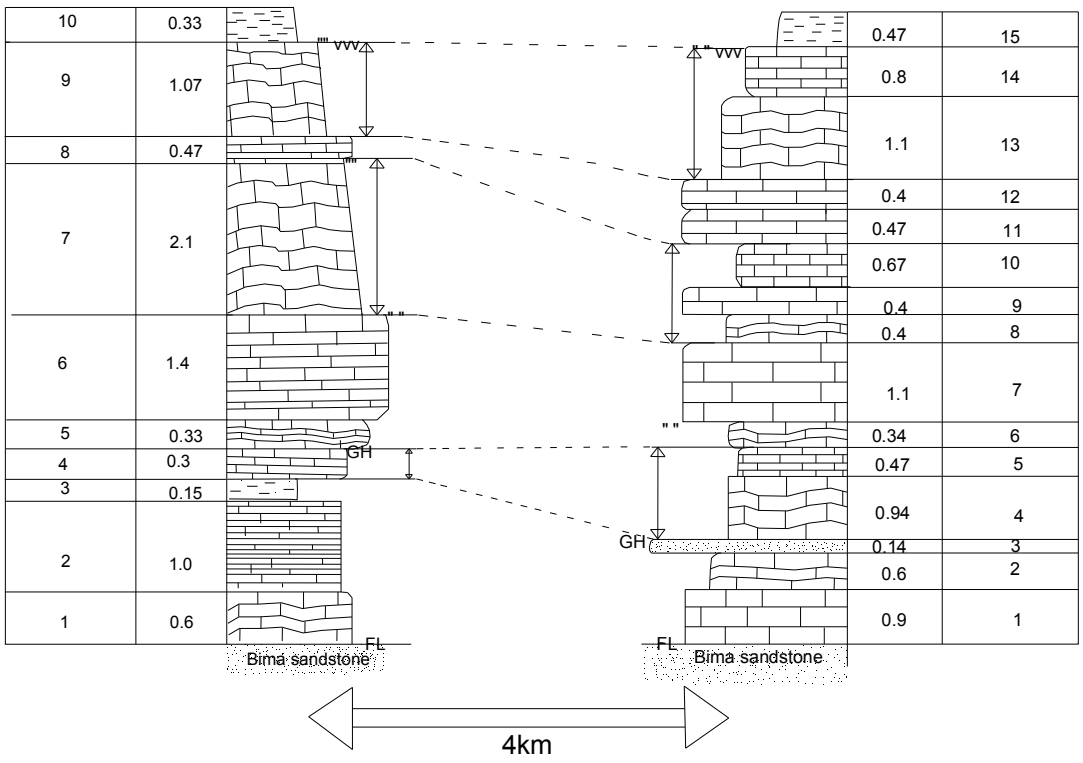


Figure 25: Lithologic correlation of limestone units in the northern and southern section of Ashaka Quarry

Units 11 and 12 in the northern section also merge laterally to form unit 8 in the southern section. This is inferred as a result of the similarity in their physical (colour and texture) as well as fossil contents. Units 13 and 14 in the northern section merge into unit 9 in the southern section due to the similarity in their fossil contents (both having *Nonium* and *Quinqueloculina*). In most of these cases, reduction in the thickness of the beds from north to the south may be attributed to the decrease in the rate of sedimentation, and/or erosion.

4.2.3.2 Sequence Stratigraphic Correlation

The two sections of the quarry studied can be correlated as far as sequence stratigraphy is concern. The guiding principle is based on the stacking pattern of their parasequence sets as well as the bounding surfaces. The ferrugineous sandstone layer on top of the Bima Sandstone coincides with the Lower sequence boundary; this sequence boundary extends throughout the entire quarry area covering both the northern and the southern part of the quarry. The maximum flooding surface that separates the transgressive systems tract from the highstand systems tract and which is characterized by a condensed section was observed in unit 18 in the northern section of the quarry (Figure 23), whereas the surface was observed in the 13 of the section exposed at the southern part of the quarry (Figure 22).

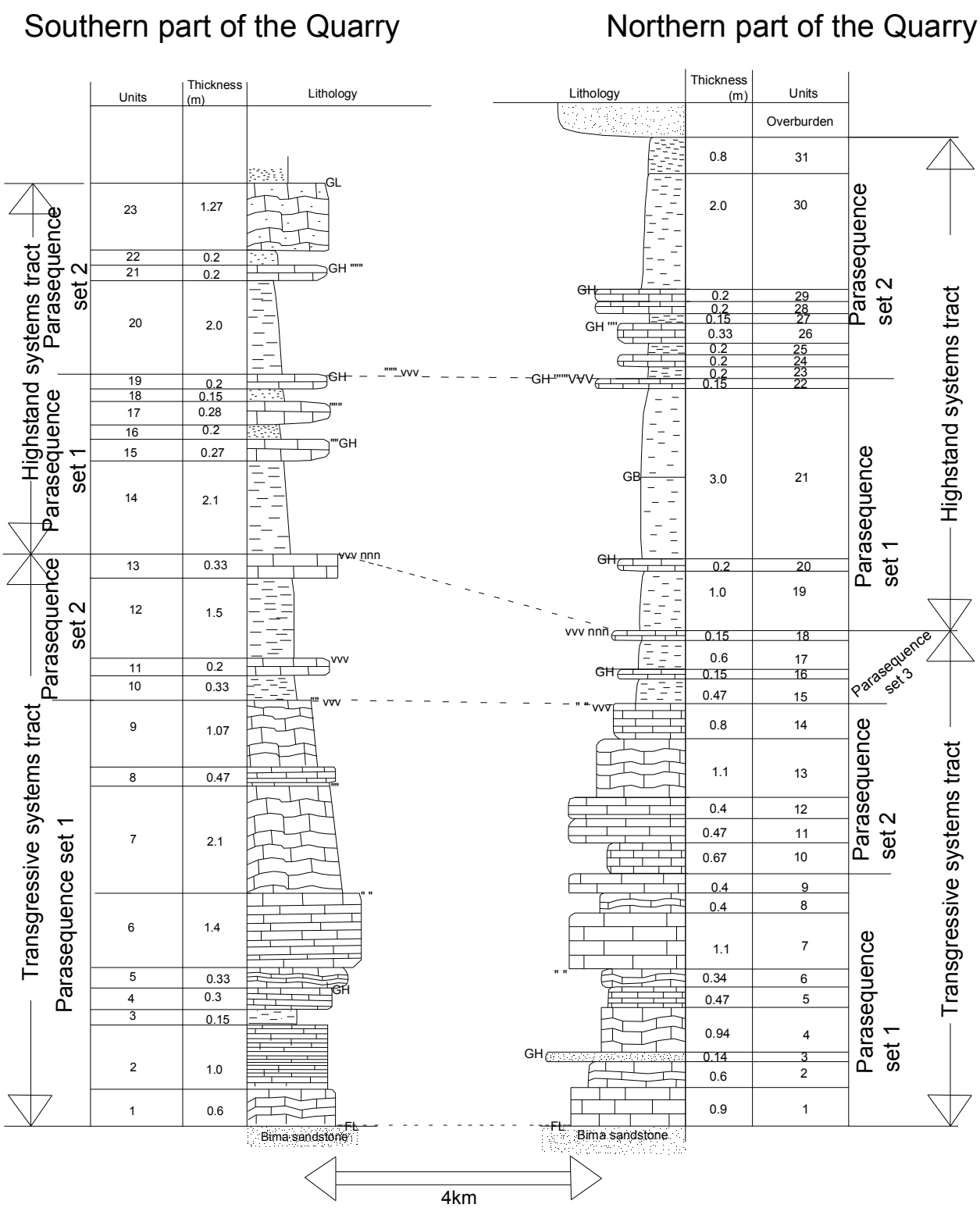


Figure 26: Sequence stratigraphic correlation of the northern and southern section of Ashaka Quarry

4.3 DEPOSITIONAL ENVIRONMENT

The Pindiga Formation at Ashaka Quarry is of marine depositional environment as indicated by the rich marine fossils both macrofossils and microfossils occurring in the limestone units. The dominance of *Quinqueloculina* in the limestones indicates normal marine lagoons while the presence of *Elphidium* is a pointer to outer shelf depositional environments and *Triloculina* indicates hypersaline condition.

The dominantly limestone part of the two sections studied indicates well oxygenated shallow marine environments as shown by the presence and dominance of the shallow marine ammonites such as *Vascoceratid* which are known to be shallow water dwellers and also thrive in oxic environment. Fossils such as bivalves, benthonic foraminifers, gastropods, and echinoderms indicate oxygenated bottom conditions. This evidence is complemented by the frequent bioturbations (Gebhardt, 1997) on the upper surface of some of the limestone units examined. The occurrence of non-keeled planktonic foraminifers also indicates a fairly oxygenated condition. The temperature under which the limestone of the Ashaka Quarry were deposited range between 24□ C to 30□ C which are the tropical temperature range within which *Quinqueloculina* strive (Brasier, 1980).

Extraclasts such as detrital quartz and feldspar are common towards the base of the sections. According to (Oti, 1990) the extraclast have been transported into this area and mostly as a result of erosion of the pre-existing sandstone deposits. Most of the limestone units are marly and contain ammonites while others are cross-bedded without ammonite. The cross-bedded limestone units that lack ammonite are presumed to have been formed under shallow well agitated water conditions, whereas the marly limestone units that contains ammonites are attributed to low energy, slightly deeper waters and are said to be

deposited under normal open marine, sometimes agitated water conditions that is typical of marine shelf. This part has been referred to as a lagoon-shelf environment with normal marine salinity and a non-stratified water body (Gebhardt, 1997).

Going up the lithologic unit in the two sections considered, the marine environment shows progressively quiet and deeper water as indicated by grain size reduction (packstone-wackestone-mudstone) as well as lithologic variations of typically laminated shale with little limestones intercalations. Here benthonic foraminifers were restricted to the limestone and it was reported by Gebhardt (1997) that the population of the planktonic foraminifera increases at this part of the section. Some of the units contain glauconite and glauconite rich horizons were observed to mark water deepening and at this point extraclast (quartz and feldspar) disappeared.

There was an alternation in depositional settings as shown by the limestone/shale intercalation. This alternation involved that of normal marine oxic environment for the limestone and dysoxic or anoxic and in some cases brackish bottom water condition for the shale. This might be attributed to the fluctuation in sea level (sea level rise and fall) and stratification resulting from fresh water influx. Based on the above deductions, field observations and the laboratory analysis, the limestone and shale units in the Ashaka Cement Quarry can be attributed to lagoonal/shelf environment with periodic changes in both the oxygen availability and salinity concentration.

CHAPTER FIVE

SUMMARY AND CONLUSIONS

The limestone and shale lithologic units at the Ashaka Quarry section have considerable variations in thickness, this range from 0.14 m to 3.0 m, although the thickest unit is that of shale. The thickness of limestone units ranges from 0.15 m to 2.2 m. The lower 8 and 9 m thick part of the two sections consists of different facies of limestone while the upper part consists of alternating limestone and shale units. Petrographic studies of some of the limestone units reveals that bioclast such as bivalves, ostracods, foraminifers, and gastropods are the most common, it also reveal the diagenetic characteristics of the limestone which include compaction, solution porosity as well as the matrix/cementing materials most of which are microspar, sparite, micrite and calcite cement. The limestone units being affected by aggrading neomorphism are dominated by wackestone, packstone and mudstone.

The section at the Ashaka Quarry may be considered to be of shallow marine depositional environment and in most cases of low energy, (although there are few instances of agitated high energy condition as indicated by the cross-bedded part of the sections). This is also indicated by the rich marine fossils such as the *Quinqueloculina* and *Triloculina* occurring in some of the limestone units. However, outer shelf depositional environment may be deduced when considering the *Elphidium* present in some units. The basin experienced terrigenous influx at its early stage which account for the extraclast present in the basal units of the sections. The dominantly limestone parts of the sections indicates well oxygenated shallow marine environments as shown by the presence and

dominance of the shallow marine ammonite such as *Vascoceratid,* and molluscs which are known to be shallow water dwellers and thrive well in oxic environment (Gebhardt, 1997). The upper limestone/shale units indicate alternating oxic and anoxic conditions (which may be attributed to fluctuation in sea level as well as distortion of water stratification resulting from fresh water influx). This has also caused salinity change and reduced oxygen levels that led to the death of the rich marine fauna. This stage has also shown that the basin experienced calmness and water deepening conditions marked by the glauconite-rich horizons.

There are some post-depositional characteristics of the limestones unit in the Ashaka Quarry which are revealed by microfacies analysis. It is evident that the original deposits were mainly wackestone and packstone. Fracturing occur in some of the bioclasts due to compaction. Biomolds were observed which were caused by the dissolution of aragonitic shells. Porosity varies from high to low from the upper to the basal limestone units respectively and are restricted to vuggy and biomoldic types of porosity. The muds originally forming the rock fabric were largely affected by aggrading neomorphism producing a microspar matrix. The biomold were in most cases filled with clear drusy sparite.

The ferruginous crust at the top of the Bima Sandstone coincides with the lower sequence boundary while an inferred correlative conformity at the base of unit 34 within the Deba-Fulani Member (Alfarooq, 2004) is the upper sequence boundary. At the Ashaka Quarry, the lowstand systems tract preceding the transgressive systems tract is lacking. This is a pointer to the shallow water marginal position of the Ashaka area. The transgressive systems tract were identified by the retrogradational stacking pattern of their

parasequence sets, wherein three parasequence sets were identified in the northern section of the quarry and two parasequence sets for the southern section in this study (Figures 22 and 23). The early part of the highstand systems tract were also identified in the quarry by the aggredational stacking pattern of the two parasequence sets (Figures 22 and 23). The two quarry sections examined in this study together with the section considered by Alfarooq (2004) which is mid way between these two sections, show that there is a trend of decrease in the number of parasequences from the northern to the southern part of the quarry for the transgressive systems tract. There is also a decrease in the number of parasequence sets from three in the northern section to two in the southern section.

In general, this study agrees with the study carried out by Alfarooq (2004), although only the early part of the highstand systems tract was established in this study as oppose to the complete highstand systems tract that was reported by Alfarooq (2004) in which his upper sequence boundary was placed within the Deba Fulani Member of the Pindiga Formation.

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APPENDIX

A: Photograph of fossils obtained from northern section of Ashaka quarry

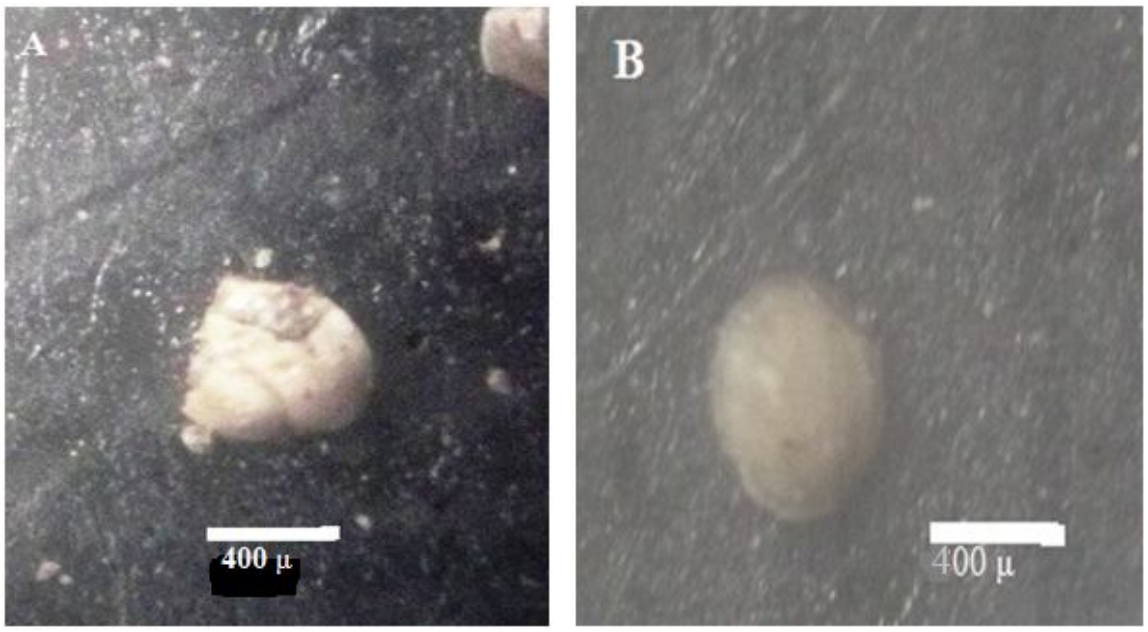


Plate 20: foraminifera in unit 10, a: *Heterohelix sp.*, b: *Lenticulina*

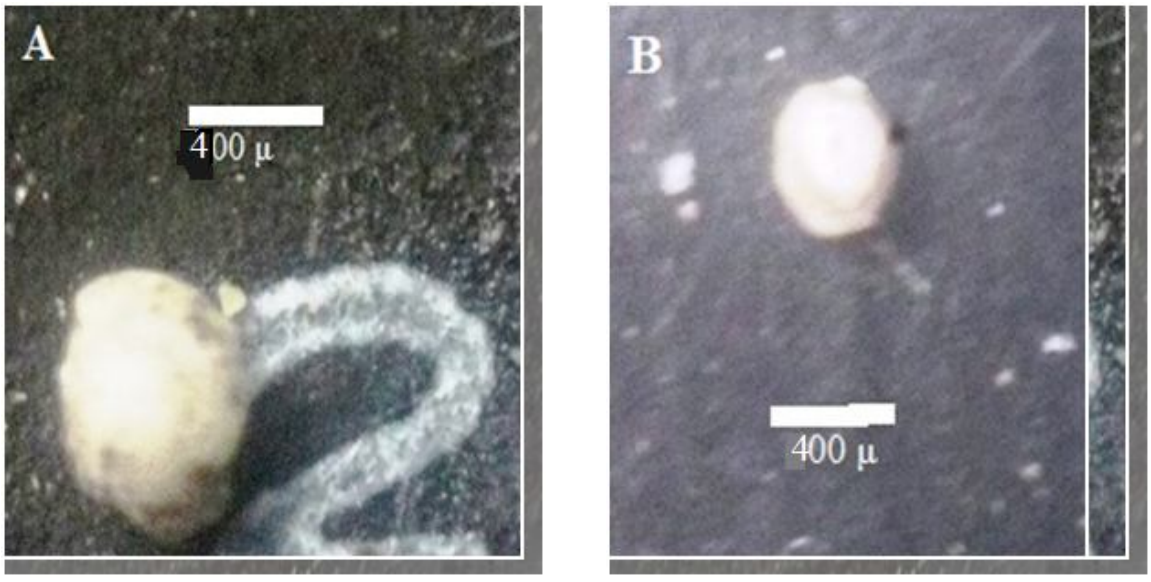


Plate 21: foraminifera in unit 14, a: *Nonium,* b: *Quinqueloculina*

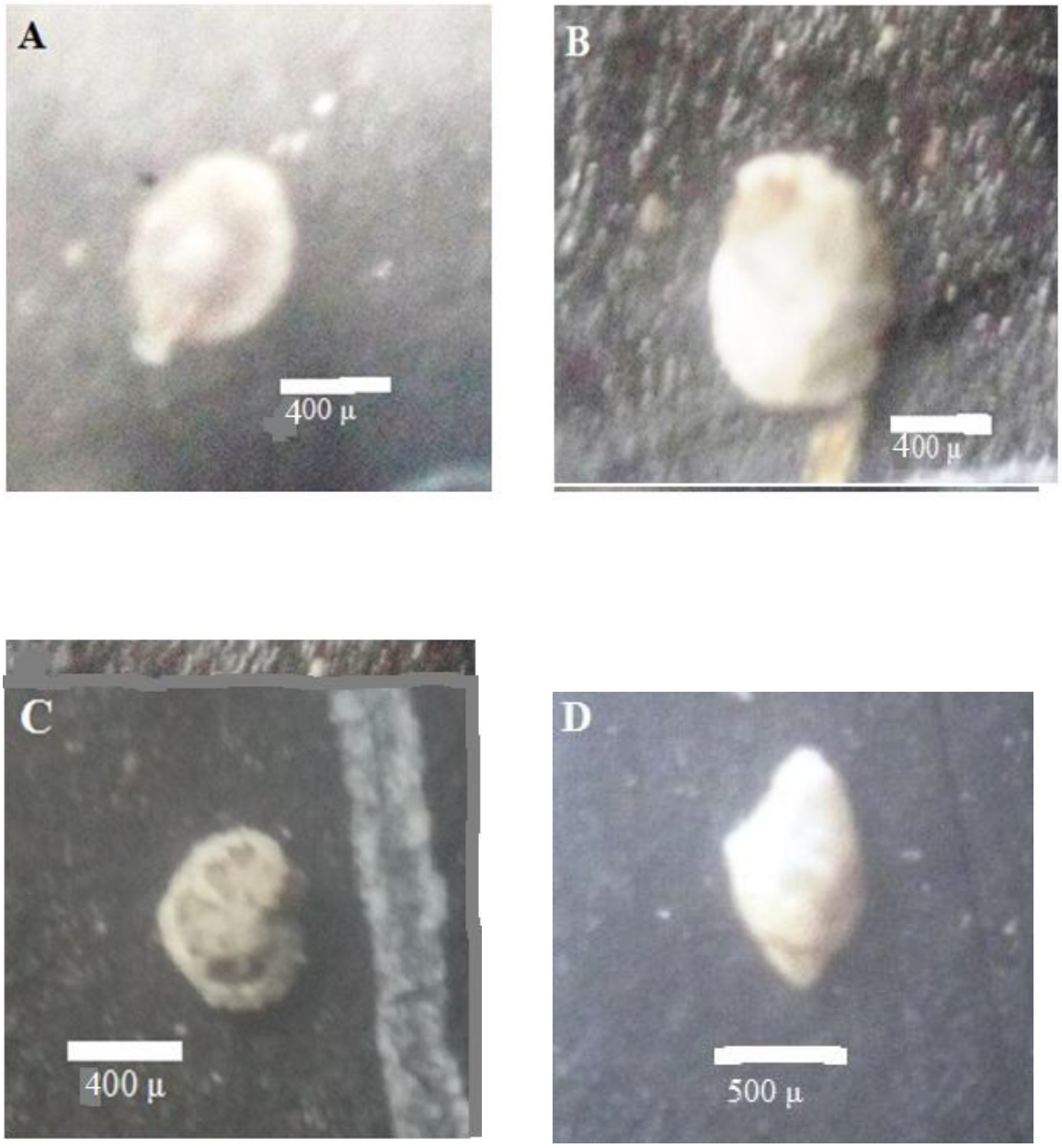


Plate 22: foraminifera in unit 18, a: *Quinqueloculina,* b: *Lenticulina*, c: *Elphidium*, d: *Textularia*

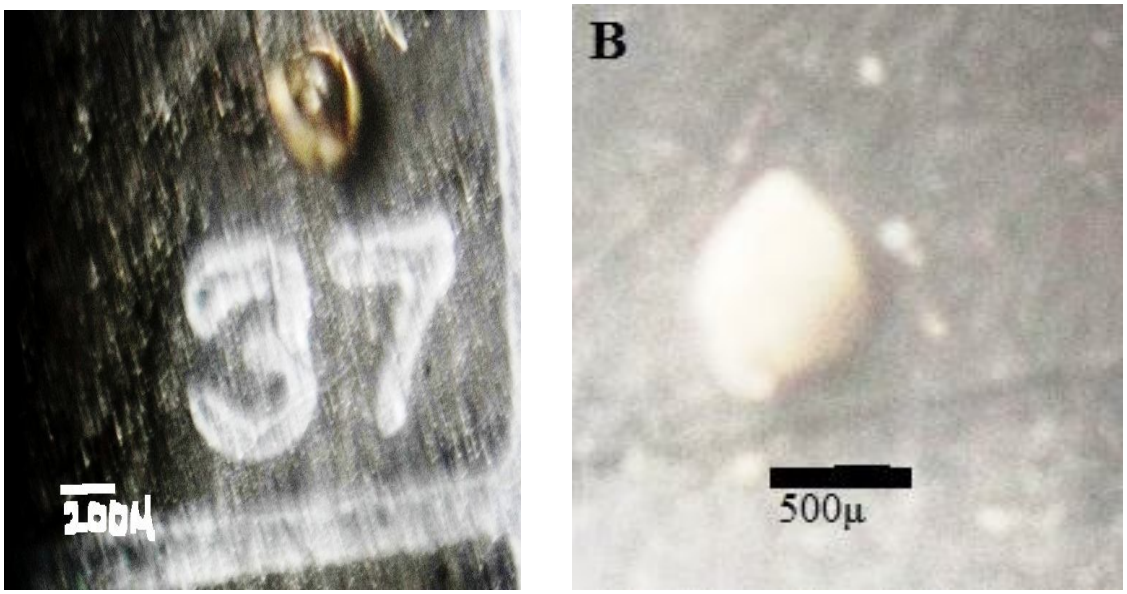


Plate 23: foraminifera from unit 20, a: *Quinqueloculina,* b: *Lenticulina*

B: Photograph of fossils obtained from southern section of Ashaka Quarry

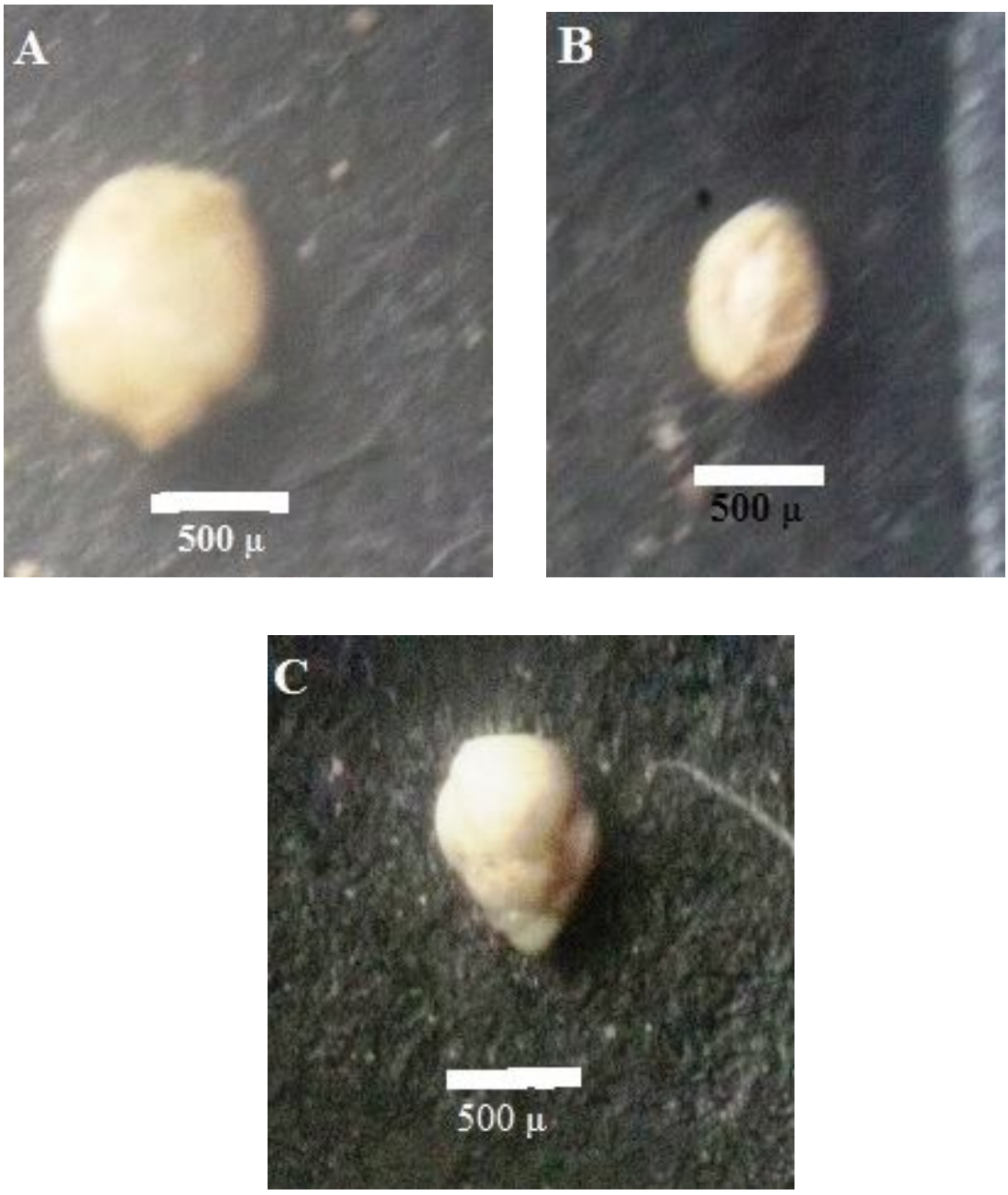


Plate 24: foraminifera from unit 7, a: *Lenticulina*, b: *Quinqueloculina*, c: *Heterohelix sp.*

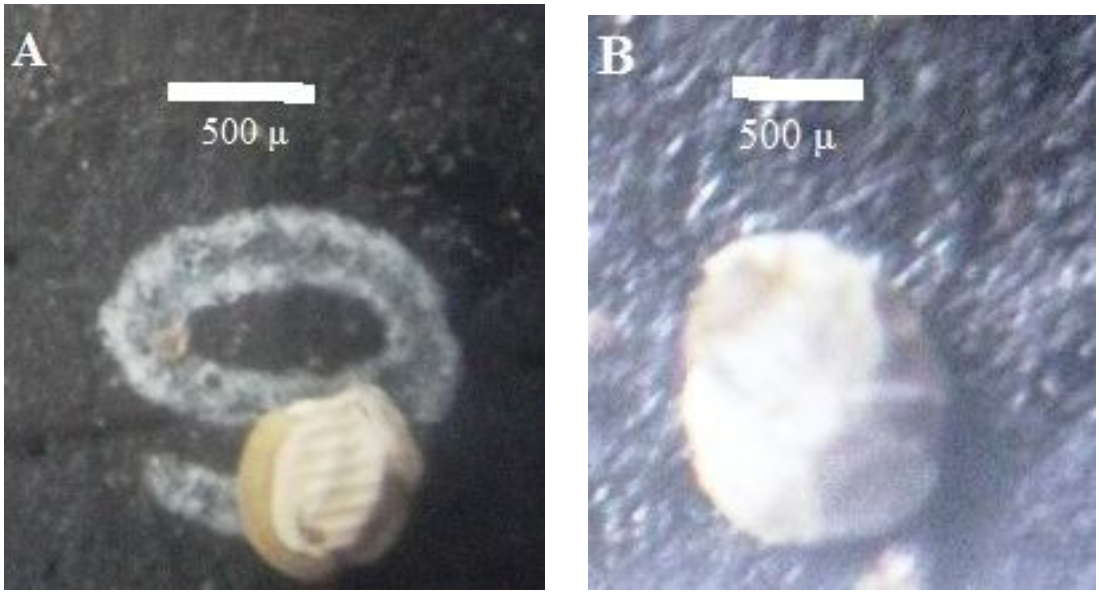


Plate 25: foraminifera from unit 9, a: *Quinqueloculina,* b: *Nonium*

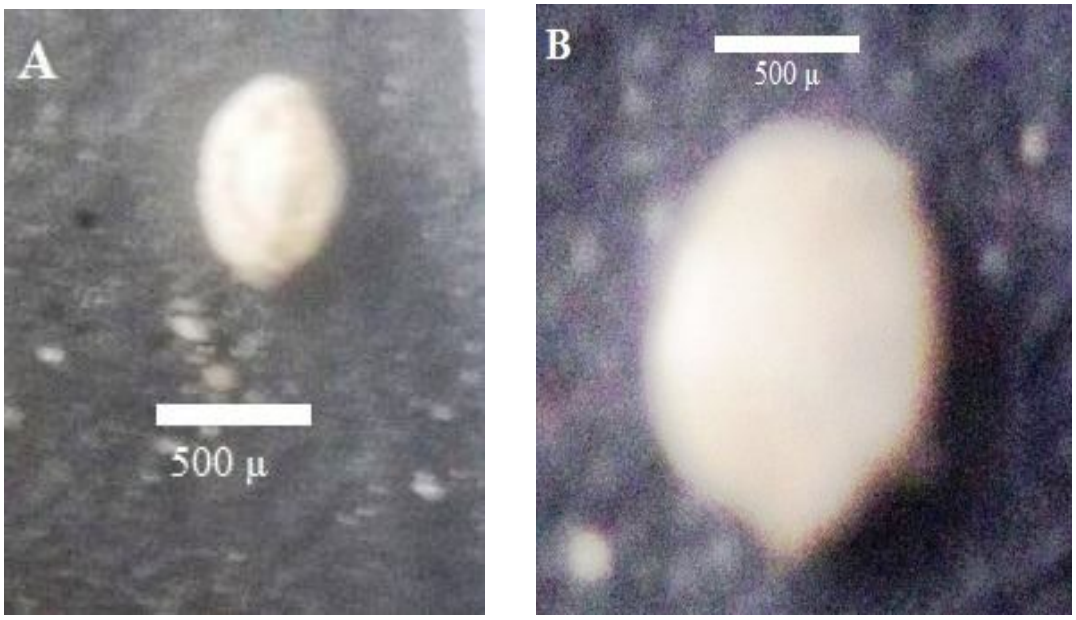


Plate 26: foraminifera from unit 13, a: *Quinqueloculina,* b: *Triloculina*

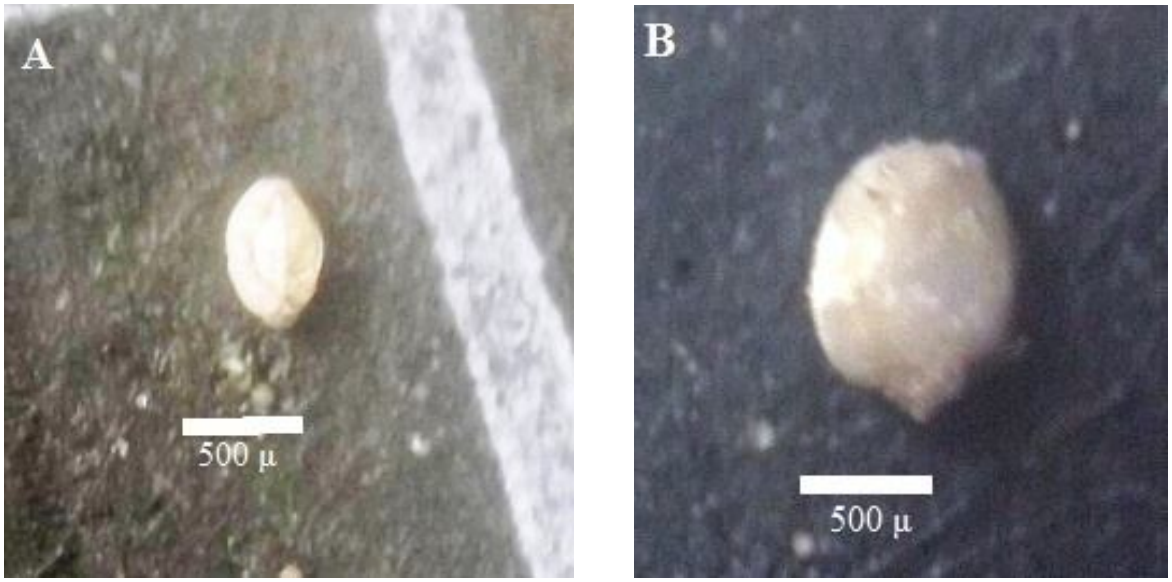


Plate 27: foraminifera from 17, a: *Quinqueloculina*, b: *Lenticulina*

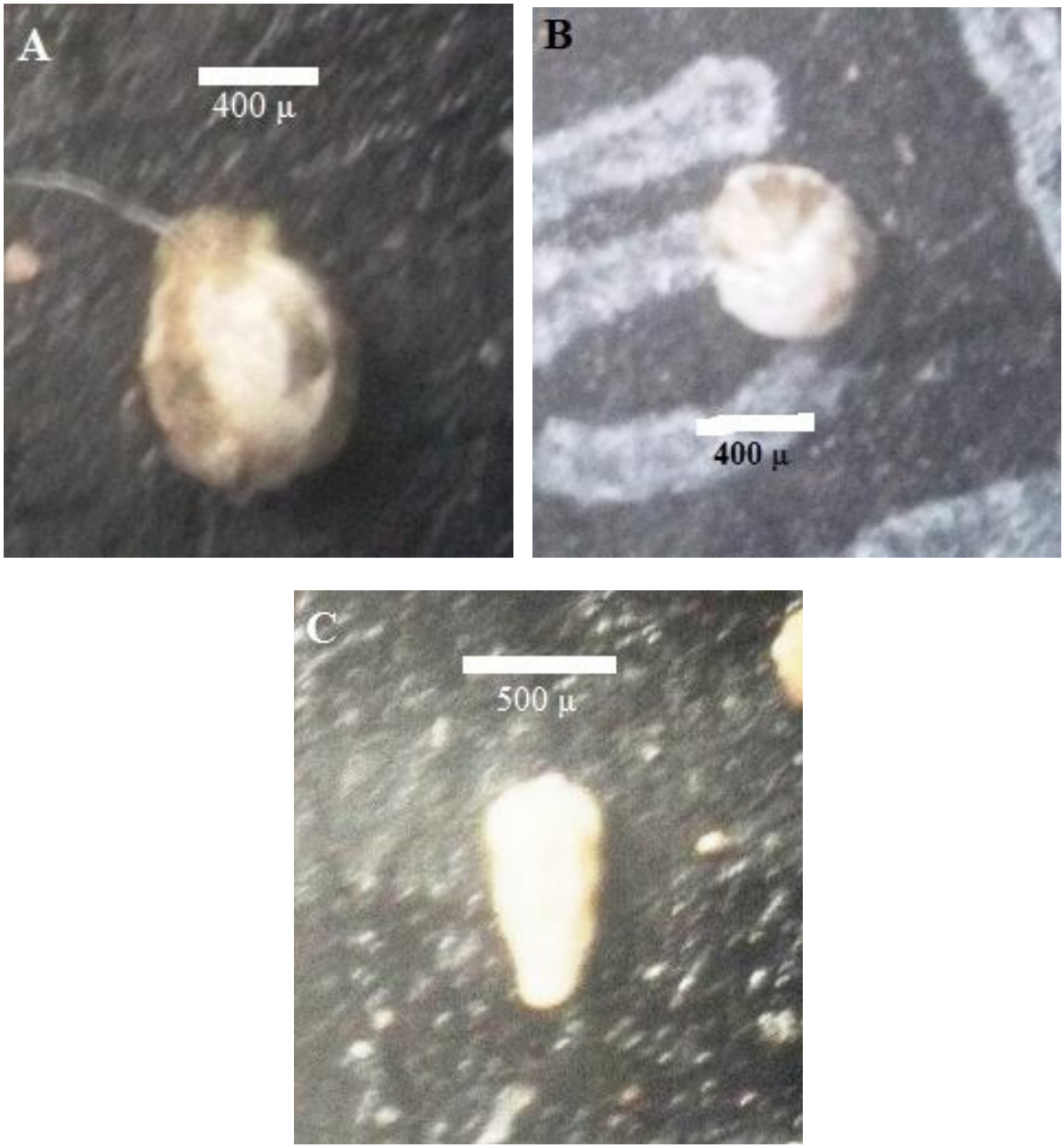


Plate 28: foraminifera from 23, a: *Quinqueloculina*, b: *Elphidium,* c: *Textularia*