THE GEOCHEMISTRY, PALYNOLOGY AND PALYNOFACIES CHARACTERISTICS OF MAIGANGA COAL DEPOSIT, UPPER BENUE TROUGH, NIGERIA

Geochemical, palynological and palynofacies studies had been carried out on samples from 24 boreholes that penetrated Gombe Formation around Maiganga coal mine. The aim of the study was to establish their microfloral assemblages, age, paleoclimate, paleoenvironment and biozonation as well as evaluating the petroleum generative potentials of the Formation. The standard maceration and Rock Eval 6 methods were employed for the palynological/palynofacies and organic geochemical analyses respectively. The studied boreholes are considerably rich in palynomorphs which permitted some adequate deductions, such as the age, paleoclimate and paleoenvironment of the formation. Majority of the pollen and spores observed from the study area included *Proteacidites sigalii, Retidiporites magdalensis, Monoporites annulatus, Cingulastisporites ornatus, Rugulatisporites caperatus, Scabratriporites annellus, Proteacidites longispinosis, Distaverrusporites simplex and Foveotrilete margaritae.* The recovered marker species have been used to date the studied sections Maastrichtian age. Palynomacerals types I, II and III were found in the studied sections with little type – IV and Armophous Organic Matter (AOM). The analyses of these palynofacies were used to interpret the paleoclimate and paleoenvironment of the studied sections as well as zoning the sections into two palyzones, namely, *Proteacidites sigalii – Echitriporites trianguliformis* zone and *Cyathidites* spp-*Laevigatosporites haardtii* zone. The analyzed palynoforms showed that the paleoenvironment of the study sections were swamps and flood plains while the coal seam intercalation was an indication of swampy environment under anoxic condition. The paleoclimatic conditions were inferred to belong to the Late Cretaceous Palmae province based on the analyzed palynomorphs. The geochemical analyses showed that the analyzed samples were organic rich and contained kerogen types (II and III). They were however considered thermally immature based on the analyzed Tmax values which were considered low. The results of the Rock-Eval analyses showed that the samples in boreholes BA-7 and BA-16 contain Type II kerogen while those from borehole BA-17 contain Type III kerogen. This study also revealed that the analyzed samples especially those from boreholes BA-7 and BA-16 may constitute a good source rocks capable of generating petroleum and gas. The Rock-Eval Tmax data available for thermal maturity assessment of the samples suggest that the analyzed samples from the three boreholes are thermally immature. This assessment was consistent with the immaturity status of their coeval formations in other part of the Benue Trough. These contemporaneous formations may be related in depth and/or have experienced similar geothermal gradient with those of the Gombe Formation.

CHAPTER ONE

1.0 INTRODUCTION

1.1 Background of the Study

Palynological and Geochemical studies (Rock Eval and TOC determinations) have become valuable tools and universally practiced methods of evaluating the stratigraphy and source rocks potentiality of sedimentary basins. While palynology deals with the study of plant remains in the sedimentary successions and their applications in biostratigraphy, Rock Eval and TOC studies deal with organic geochemical evaluation of sediments for the purpose of evaluating their source rocks potentials.

A lot of contribution to the understanding of depositional environments and stratigraphy of the Gombe Formation have been made by several previous workers (Ojo and Akande, 2004). The previous studies indicated a wide range of Late Senonian to Maastrichtian age for the Gombe Formation. In another study, Lawal and Moulade (1987) assigned an Upper Maastrichtian age to the Gombe Formation.

Several geochemical studies using Rock Eval and TOC determination methods have been carried out on samples from the Gombe Formation with the principal aim to evaluating the source rocks potentiality of the formation (Idowu and Ekweozor, 1989; Obaje and Abaa, 1996; Obaje, Funtua, Ligouis and Abaa, 1998; Obaje, 2000; Obaje and Hamza, 2000; Ojo and Akande, 2002, Obaje, Attah, Opeloye and Moumouni, 2006; Tukur, Samaila, Shettima and Jauro, 2006).

Despite the work by earlier workers, there exist some stratigraphic and geochemical evaluations gaps that require further studies to be filled up. These gaps include the non inclusion of the coal facies in the stratigraphy of Gombe Formation and the analysis of these coal facies and the subsurface Formation samples to ascertain their geochemical characteristics. These gaps may be attributable to lack of subsurface samples and data which were not available to the earlier authors as occasioned by lack of available boreholes that penetrated Gombe

Formation as at the time of their studies. The search for coal and its subsequent mining in the Maiganga area has however paved way for access to subsurface samples and data from the Gombe Formation. Hence, this study is undertaken to fill the missing stratigraphic and geochemical gaps.

It is therefore justified for the continous study on the Gombe Formation to improve on the stratigraphic and source rocks prospectivity of the Formation. Gombe Formation belongs to the Cretaceous period and forms part of the Nigerian inland basins.

Apart from the Cenozoic Niger Delta which have been studied in detail because of its presumed potentiality for source rocks, other Nigerian inland basins have not been studied intensively which could also be prospective for mineral resources. These inland basins should also be explored since their coeval basins of the world have proved to be viable geologic province for mineral resources.

Among the list of composite methods for stratigraphic and source rock evaluation of an area, Rock Evaluation method using Rock Eval and Palynological studies remain leading and of priorities in Sedimentary basin studies (Obaje *et al*. 2006). While Rock-Eval provides information on the quality and quantity of the organic components of the source rock and its potentiality for oil and gas generation, palynology provides basis for dating the formation, their paleoclimatic conditions, paleoenvironments and possible correlation with known Formations.

1.2 The Study Area

The area chosen for this study is located within the Maiganga coal mine, Gombe state. Maiganga coal mine falls within the Gombe Formation in the Upper Benue Trough of Nigeria. The core samples used for the analyses were collected from the core store room at Ashaka Cement Factory, Ashaka. Twenty-four (24) exploratory boreholes with about 400 samples were collected for the studies. Out of these, three (3) boreholes (BA–7, BA–16 and BA–17) with seventy-three (73) samples were collected and used for the study. Borehole BA–7 penetrated to a depth of 48 m, BA–16 to a depth of 60 m and BA–17 to a depth of 45 m. The Maiganga coal mine is bounded by latitudes 009°N to 12°N and longitudes 10°E to 12°E (Figure 1.1). The Maiganga coal mine is accessible through the Gombe–Yola Road. The mine is located at 8 km, off the 22ND km Gombe – Yola Road in Akko Local Government Area of Gombe State. The villages in the vicinity of the mine include Kumo, Duba Fulani, Kalshingi and Pindiga.

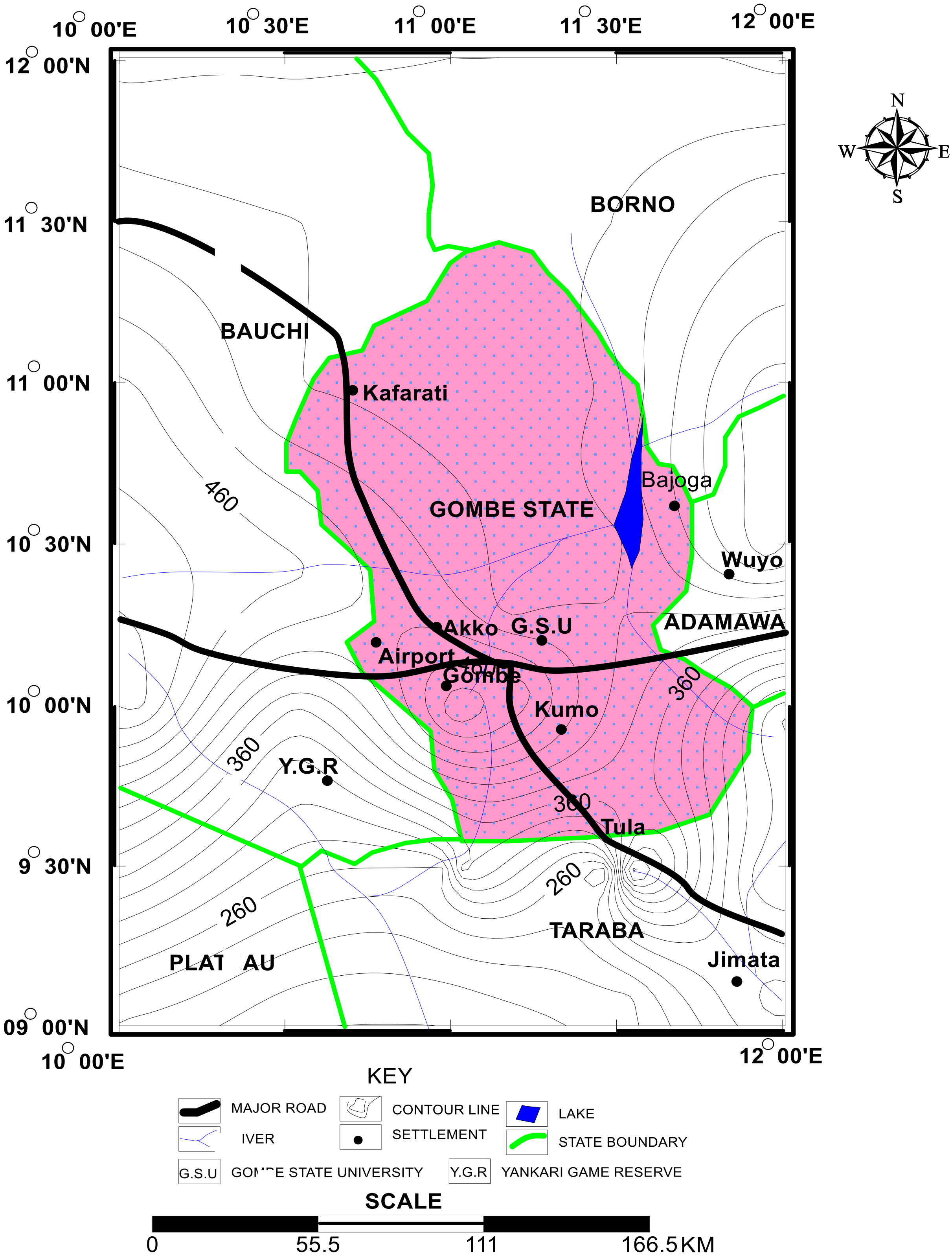

Figure 1.1: Topographical Map of Gombe State.

1.2.1. Climate, relief, drainage and hydrology

Gombe state which hosts the study area is part of Central Nigeria, but the flat landscape in the northern and southern parts of the state have isolated hills (Gombe State, 2013). While the elevation of the plain is at about 600 m above sea-level, the hills reach between 700 m and 800 m. This relief is typically displayed by the Killang Hills at Kaltungo. The Gongola River is the main drainage system in the area, running approximately north south towards the Benue River Basin, but with principal tributaries draining from west to east into river Gongola. Gombe state lies mostly within the poor groundwater provinces in the Gombe sandstones, the Pindiga shales, Kerri-Kerri Formation of Tertiary age and the isolated hill region of the northern central and southern parts (Zaborski, 1997). Groundwater occurs between 180 m depth on the sandstones. In the Gongola River Basin, because of the Cretaceous sandstones and shales, groundwater is generally erratic and meager.

Indeed, dams from suitable surface drainage systems are more favoured than groundwater and boreholes as sources of water for domestic, agricultural and industrial uses (Gombe ADP, 2013). River Gongola is the only major river that flows through the state in the north and east through Dukku, Nafada and all the eastern LGAs, to join the River Benue at Numan. At Nafada, the River Gongola bends southwards and flows through the eastern boarder of the state before it joins River Benue at Numan. It is the sixth longest River in Nigeria, stretching about 530 km much of which lies in Gombe state (Gombe ADP, 2013). It has numerous tributaries and smaller streams including Rivers Dukul, Ruhu, Guji, Balanga and Dadin Kowa.

1.2.2 Soils, vegetation and land use

The topography of Gombe state has exerted an enormous influence on soil development; hence over half of the state (central) that is underlain by the Kerri-Kerri Formation has shallow to moderate impoverished soils, with sandy loams on iron pan. In the Chad Formation in the northern part of the state, the soils are deep but sandy and clayey, but are mostly blanketed by sand dunes. Soils in the eastern parts of the state are shallow to deep loamy, sandy clay, loam and vertisols with cracking clays that have weathered from shales (Gombe ADP, 2013).

According to Reyment (1965), vegetation in Gombe state is predominantly wooded shrub land in the central part, with the plant community comprising *Anogeissus/Combretum/ Afrormosia/ Detarium.* The northern part of the state exhibits a mosaic of shrubbed grassland and grassed shrubland with the preponderance of Acacia. In the hilly southern areas, the vegetation is shrubbed woodland with mostly *Afrormosia* and *Detarium.*

Gombe state has the cultivated and urban areas constituting over 35 % of the land use/land cover. Agricultural land uses include planting of cereals, fruit crops and graze lands for pastoral farming.

1.3 Statement of the Problem

According to Obaje *et al*. (2006), current production of oil and gas in Nigeria comes entirely from the Niger Delta onshore and offshore. Some palynological and geochemical studies have been undertaken in other sedimentary basins of Northern Nigeria including Gombe sub-basin with the aim to have a better understanding of the stratigraphy and geochemistry of the basins which could boost the oil and gas knowledge and production base of the Country.

Also as earlier stated, Ojo *et al*. (2004) have posited that a lot of contributions to the understanding of the stratigraphy of Gombe Formation have been made. However, these inland basins (Upper Benue Trough which host Gombe Formation inclusive) have proved to have a missing gap in terms of palynological and geochemical data. This has left the detailed understanding of the stratigraphy and geochemistry of the inland basins unaccomplished.

Gombe Formation have been chosen for this research work for two reason;(i) Discovery and mining of coal in the area and (ii) access to core samples from the boreholes drilled in the area for coal exploration. The results obtained from this study will complement the existing knowledge about the stratigraphy and geochemistry of the Gombe Formation especially with the use of subsurface samples from the area as against the previous surface outcrops used for similar studies in the area.

1.4 Aim and Objectives of the Research

1.4.1 Aim

The primary aim of the research is to carry out the Palynological, Geochemical and Palynofacies analyses of Gombe Formation. This is with a view to elucidate more on the stratigraphy and source rocks prospectivity of the formation.

1.4.2 Objectives

The objectives of the study therefore include;

(i) To determine the paleoclimate and paleoenvironments of the Gombe Formation based on the palynological and palynofacies analyses.

(ii) To evaluate the source rock prospectivity of the Maiganga coal and the shale strata.

(iii) To compare and correlate the Gombe Formation with other coeval formations such as Patti Formation, Bida Formation and Mamu Formation based on the analyzed palynomorphs.

(iv) To fill the missing stratigraphic gap in the Gombe Formation by the inclusion of the coal facies in the stratigraphy of the formation.

1.5 Justification for the Research

Previous workers have carried out stratigraphical studies of the Nigerian Benue Trough (Reyment, 1965; Lawal, 1982; Adegoke *et al.*, 1986; Popoff *et al.*, 1986; Lawal *et al.*, 1987; Nwajide, 1989; Dike, 1995; Zaborski *et al.*, 1997; Zaborski *et al.*, 1998; Ojo *et al.*, 2004; Ojo, 2009; Odedede *et al.*, 2011; Olaburaimo *et al.*, 2011; Adebanji, 2012). These previous authors have dated the Gombe Formation to range from late Senonian to Maastrichtian. This wide range may be attributed to the use of outcrop samples for analyses as basis for the dating rather than the use of subsurface samples.

It is also on record that many authors have carried out geochemical analyses on samples from the Gombe Formation and their results well documented (Idowu *et al.*, 1989; Obaje *et al.*,2000; Akande *et al.*, 2002; Ojo *et al.*,2002; Akande *et al.*, 2005; Obaje *et al.*, 2006 Moumouni *et al.*, 2007;). Their works were carried out on outcrop samples. However, the advent of Maiganga Coal Mine have given rise to the drilling of some coal exploratory boreholes which gave rise to core samples which are curiated at the Ashaka Cement Factory. These core samples have afforded this study the relative advantage of analyzing subsurface samples as compared to the outcrop samples analysed by the previous workers, hence a perceived more accurate results.

The Gombe Formation in the Upper Benue Trough was chosen for this study for two reasons as earlier stated.The present study, is aimed as an input to the understanding of general stratigraphy and organic geochemical data of the Upper Benue Trough.

CHAPTER TWO

2.0 LITERATURE REVIEW

The knowledge and studies of Gombe Sandstone (now Gombe Formation) dated back to the early 20th century (Reyment, 1965). The geological sediments termed the Gombe Sandstone were discovered as a sequence of estuarine and deltaic sandstone, siltstone, shale and ironstones which overlie the sediments of the Zambuk ridge and the Chad basin in the western part of the region. This was later renamed Gombe Formation due to its heterogeneous rock group as against the earlier monolithic sandstone constituent of the mapped unit (Zaborski, 2003). The restricted outcrop of the Gombe Sandstone suggests that these rocks were deposited in the basin which lay to the west of the ridge in the late Cretaceous time (Reyment, 1965). Falconer (1911) assigned the Gombe Sandstone near Gombe and to the west of Tilde and Dukul to the Eocene Formation termed the "Gombe Grits and Clays". Raeburn and Brynmor (1934) included the Gombe Sandstone in the "Upper Sandstone Group", describing it from the country near Fika.

According to Reyment (1965), siltstones and flaggy sandstone formed the greatest part of the Gombe Sandstone. He observed that the rocks were soft and light grey in colour when fresh, but on exposure gave rise to dark red, flaggy debris which characteristically mantle the Gombe Sandstone hills. He positioned the Gombe Sandstone as the top member of a folded and eroded sedimentary sequence hence not possible to determine its original thickness, but assumed a sedimentary pile of at least 1000 ft (304.8 m) in the area. An unconformity separates the Gombe Sandstone from the underlying Pindiga Formation and Fika shales (Reyment, 1965). The presence of an unconformity was suggested by differences in structure between the Gombe Sandstone and the Older Cretaceous rocks; the Gombe Sandstone is neither strongly folded nor does it reflect the east-west trends which are imposed on the earlier Formations (Falconer, 1911). It was reported that borehole 1504 drilled at Gombe (by the defunct Geological Survey of Nigeria, (GSN) in the early sixties penetrated 98 ft (29.87 m) of the lower beds of the Gombe Sandstones and proved about 10 lithological sections above the Pindiga Formation on which the Gombe Sandstone overlies (Reyment, 1965).

The Gombe Sandstone sediments form the range of hills which runs northwest from Tilde to Biro Golewa and Nafada where the sequence is similar to that of the type Locality at Gombe. About 130 ft (39.62 m) cliff section were reportedly exposed 2 miles (3.22 km) to the South-West of Tilde, near Jigawa. Similar formation was reportedly well exposed near Fika, though complete sections were rarely found (Zaborski, 2003). Here, the Gombe Sandstone consists of flaggy sandstone with interbedded shales, and at highest level, coarse, cross bedded sandstone which forms the Fika hills. Coals, which are more fully described under Economic Geology, have been recorded from boreholes sunk near the Gombe Sandstone-Kerikeri Formation unconformity at several localities (Reyment, 1965). According to him, the coal seams have not been seen to outcrop and some doubt exists as to their precise stratigraphical position but doubt as regards the coal mineralization have now been resolved by the current mining of the coal deposit at Maiganga. Palynological determination by Shell Petroleum Development Company of Nigeria Limited indicated an Upper Senonian to Maastrichtian age for the coals, and on this evidence they are assigned to the Gombe Sandstone coals which occur to the North of Fika at Pokitau, near Molko and to the south of Gombe-Maigunga (now Maiganga) where the coal mine is sited and this constitute the project area for this study. At Pokitau, about 198 ft (60.35 m) shaft indicated a coal seam at the base of the Gombe Sandstone section. It was also reported that coal occured near Molko, close to the Gombe Sandstone–Kerikeri Formation unconformity. A number of shafts were sunk and they showed that the coal occur in small discrete lenses. Coal seams were also reported to have penetrated into the GSN borehole No. 970 at Kolori and in a nearby borehole at Kurugu. At Kolori, 5 ft (1.52 m) of coal with clay and sandstone were intercepted at a depth of 440 ft (134.11 m) and at Kurugu about 2 ft (0.61 m), a dull powdery coal was exposed at a depth of 55 ft. At Garin Maiganga (Maiganga), an old native well was reported to have intersected 10 ft (3.05 m) of coal at a depth of 92 ft (28.04 m)

Paleontologically, apart from few indeterminate lamellibranchs found near Pindiga and plant remains, chiefly roots, collected from a number of localities, coals represent the sole useful fossil material yielded by the Gombe sandstone (Reyment, 1965). In fact, Shell-BP (Reyment, 1965), palynologists have dated the coals as Upper Senonian – Maastrichtian, even though the Gombe Sandstone overlies the shale member of the Pindiga Formation which is Maastrichtian in age. The Kerikeri Formation lies unconformable on the Gombe Sandstone and has been dated as Paleocene by the palynologists of Shell-BP (Reyment, 1965). The Gombe Sandstone is thus regarded as Upper Maastrichtian to Pre-Paleocene in age and represents, therefore the highest horizons of the Cretaceous system.

According to Reyment (1965), coal accumulating condition developed in Nigeria towards the close of the Cretaceous period. He asserted that coal accumulation became most important in the Upper (?) Maastrichtian Mamu Formation, in which all the economical coal seams lie. There are coal deposits in the Maastrichtian-Paleocene Nsukka Formation and this marked the termination of the Cretaceous coal-forming environment in Nigeria. The Gombe coal formation belonged to this period. According to Whiteman *et al*. (1972), the coals of southern Nigerian are black to brownish black and have a dark brown streak; their calorific value is usually between 10,000 and 13,000

B. TU/b; have high volatile content which places the Nigerian coal in group A and B of the sub-bituminous class of the American Society of Testing Material (ASTM, 1951) and in the “Lignitous division” of the Seyler’s classification. He further stated that the Nigeria coals are of the medium quality, non-coking, friable and weathers readily. It has high ash and low fixed-carbon. The above, he asserted makes Nigerian coals compare unfavorably with many overseas coals. The rich resins and wax contents of the Nigerian coals and their self binding under pressure qualifies them as potential sources of chemicals. Carter *et al.* (1963) mapped the northeastern part of the Benue Trough and he assigned the Gombe Sandstone to a Maastrichtian age. According to Carter *et al.* (1963), the Gombe Sandstone rests unconformably on the older folded rocks. Contrary to the above, mapping revealed that the strong folding that affected the Upper Benue Trough is pre-Gombe Formation i.e. pre-Maastrichtian and that, as in the Abakaliki and Lower Benue Troughs, the main folds were generated in Santonian times (Whiteman 1982).

Obaje *et al*. (1994, 1996, 1998, and 1999) had discussed extensively the petrography and organic geochemistry of Benue Trough. Their studies were however concentrated on the middle Benue Trough, with emphasis on Lafia-Obi coals, while the Gombe coal of the Upper Benue Trough was given little attention. This may be due to inaccessibility of the coal as the newest coal mine in the country. These authors have however made significant impact on the understanding of Nigerian coals and their various applications based on their characteristics. Apart from the physical uses of coals, their studies have shown that coals are now better used as oil and gas exploration guides. According to these authors; “coal beds are now widely known to be major source of associated and non- associated gases and are increasingly exploration targets for gas accumulation in most part of the world”. Idowu and Ekwezor (1989) carried out a comparative geochemical study of the argillaceous sequence of Turonian – Conacian age from part of the Upper Benue Trough with a main objective of eludating the origin, nature and thermal evolution of the organic matter in the area. From the study, the authors concluded that geochemical indicators of paleoenvironments confirm anoxic shales of early Turonian age within the Upper Benue Trough and that the shales are potential gas producers in terms of hydrocarbon source potential.

The lithostratigraphy of Benue Trough, with emphasis on Upper Benue Trough has been discussed extensively (Zaborski *et al.,* 1997 and Zaborski, 2003). They subdivided the Gongola arm of the Upper Benue Trough to which the Gombe Formation belongs into the Lower and Upper Cretaceous Series. The Lower Cretaceous Series is made of the Bima Group which was also subdivided into the Upper, Middle and Lower Bima Sandstones while the Upper Cretaceous Series is said to consist the Yolde Formation, Pindiga Formation and the Gombe Formation. Obaje *et al.* (2006) carried out a geochemical evaluation of the northern Nigerian basins and concluded that there exist potential source rocks within the basins based on the analytical results. Gombe Formation was included in their work and the results show that the sediments of the Formation (shale and coals) are potential source rocks due to their high TOC values. Lawal (1982) in his PhD thesis; carried out the palynological analysis of cuttings and core samples from water boreholes in the Upper Benue Trough. He reported a rich assemblage of 245 palynomorphs species comprising 135 pollen and spores species and 110 dinoflagellate and Acritarchs species. Based on the palynomorph associations, he proposed six biostratigrahpic zones (palyno-zones) and dated the sediments Late Albian to Late Maastrichtian. Lawal *et al*. (2004) also carried out the palynological biostratigraphy of Cretaceous sediments in the Upper Benue Basin and their results agreed with that of Lawal (1982). Akande *et al*. (2005) studied the microfloral assemblage, age and paleoenvironments of the Upper Cretaceous Patti Formation, Southeastern Bida Basin and concluded that the abundance of Palmae pollen (*Echitriporites and Longapertites*) and the Pteridopytes suggest a humid climate and Maastrichtian ages for the Formation. Other marker species identified by these authors include *Buttinia andreeve, Retidiporites magdalensis, Echimoncolpites, Echitriporites trianguliformis, Cristaeturites Cristatus* which support the Maastrichtian age of the formation. Odedede *et al.* (2011) carried out the sequence stratigraphic analysis of the Gombe Sandstone and the Lower Kerri-Kerri Formation exposed around Fika-Potiskum in the Upper Benue Trough. They concluded that the Formations were of type 1 sequence, deposited in high stand systems tract (HST) and minor amount of low stand systems tract (LST) with minor components of fluvial deposition. The authors asserted that the predominance of high stand system tracts in the Gombe Sandstone may be attributed to high rate of tectonics and sediments supply, while climate and tectonics exert a strong control on the Kerri-Kerri Formation. Their findings equally revealed three lithofacies of distinct grain sizes and structures for the Gombe Formation viz bioturbated gritty clay, silty clay and well bedded sandstone. Obianuju (2005) and Obianuju *et al*. (2007, 2008) undertook the study of the palyno-stratigraphy and paleoenvironments of the Nsukka Formation of Anambra Basin, Southeastern Nigeria and the Okaba Coal mine respectively. Their studies discovered a lot of palynomorph species and agreed with Maastrichtian – Paleocene age assigned to the formation by previous workers (Simpson, 1954; Reyment, 1965). Ojo *et al.*, (2004) reported two informal palynomorph assemblage zones for Gombe Formation based on the stratigraphic range of pollen and spore species. These proposed zones were referred to as assemblage zone I (*Spinizonocolpites – Echitriporites – Milfordia sp.* Assemblage Zone) and the assemblage zone II *(Proxapertites operculatus – Retidiporites* *echimonocolpites* Assemblage Zone). They concluded that based on the microfloral assemblage, the Gombe Formation was deposited in a marine to continental environment and dated the formation as Maastrichtian in age. Ojo (2009) reported the occurrence of some Maastrichtian, marine dinoflagellate cysts and terrestrial pollen and spores from Upper Cretaceous sediment in Southeastern Bida Basin and used them to infer the ages and paleoenvironments of the Upper Cretaceous Patti Formation as Maastrichtian and continental with marine intervals respectively. He concluded that the palynomorph assemblages from the Patti Formation indicated a predominance of terrestrially derived pollen and spores and some significant marine dinoflagellate correlated with part of Nkporo shale in Anambra Basin and Gombe Formation in Gongola Basin.

Oloto (1994) carried out a study on the Nigerian Maastrichtian to Miocene dinoflagellate and miospore biozonation and concluded that the Nkporo Shale in Anambra basin to the Benin Formation in the Niger delta are made of nineteen dinoflagellate cyst and seventeen miospore assemblage biozones. Adegoke *et al.* (1986) from a study of the palynology and age of the Keri-Keri Formation, Upper Benue Trough, concluded that the formation was of doubtful age. Based on the recovered palynomorphs, they however assigned the Formation a Paleocene age with the description of eight new species as recorded from the Formation. Jan Du Chene *et al.* (1978) in their studies discussed extensively the systematic palynology of several Cretaceous palynomorphs in Nigeria. Whiteman (1982) in a book titled Nigeria: Its petroleum geology, resources and potential discussed in detail the stratigraphy and the petroleum systems within the Benue Trough. In (1960), Gutjahr wrote on the applications of palynology in petroleum exploration and concluded that palynology appears next in rank to Rock-Eval in petroleum exploration studies. Nwajide (1989) wrote on the paleogeographic setting for coal sequences in the Benue Trough Complex but the author did not include Gombe Formation as containing coal. David *et al.* (2005) discussed palynofacies analysis and its stratigraphic applications and the methods of preparing palynofacies samples. Shemang *et al*. (1998) studied the structure of the Gongola arm of the Upper Benue Trough using gravity and magnetic methods and their results were well documented. Adebanji (2012) had also discussed the biostratigraphy and depositional environment of Borno Basin (Gombe Formation inclusive) and had concluded like the previous authors that the Gombe Formation is of Maastrichtian age based on the analysed palynomorphs.

Just like the review of several works on the palynological studies in the Nigerian basins, several works have also been carried out on the organic geochemical studies of the basins using Rock Eval analytical method and TOC determination method principally to evaluate the petroleum potentials of the formations as possible source rocks. Some of these papers are mentioned below.

Akande *et al*. (2002, 2005) carried out the paleoenvironments, organic petrology and Rock-Eval studies on source rock facies of the Lower Maastrichtian Patti Formation, Southern Bida Basin. The authors concluded that the analyses of the formation indicated a mean average of 66 % vitrinite, 18 % of liptinite, 16 % inertinite and 2.1 wt% TOC. These results suggest that most of the samples from the formation are thermally immature to marginally mature with vitrinite reflectance ranging from 0.4 to 0.6 % Ro, Tmax values of 407 – 426 ^{o}C coupled with the prevalence of humic Type III kerogen. Based on the above, the authors concluded that the Patti Formation source rock facies have moderate to fair potential for gaseous hydrocarbons which have not yet been generated. Moumouni *et al*, (2007) in a paper titled "Bulk geochemical parameters and biomarker characteristics of organic matter in two wells (Gaibu -1 and Kasade -1) from the Bornu Basin: Implications on the hydrocarbon potential", gave an indication that two potential gas source intervals (1120 – 1180 m and 1285 – 1405 m) with the possibility of an oil source at about 1300 m depth were found within the Fika–Gongila lithology in Kasade -1 and however concluded that these intervals are too shallow for significant gas generation. No potential gas/oil source intervals were encountered in the Gaibu -1 well despite the vitrinite reflectance values of 1.17 – 1.45 % which is an indication of maturity in the oil to gas window. The authors recommended the investigation of more wells coupled with the incorporation of 3D seismic survey in order to have a better understanding of the subsurface geology of the basin.

Obaje *et al*. (1998) asserted that coal beds are now widely known to be a major source of associated and non-associated gases and are increasingly becoming exploration targets for gas accumulation in most parts of the world. Their work was on the organic maturation and coal-derived hydrocarbon potentials of Cretaceous coal measures in the middle Benue Trough of Nigeria. From their study, they established three coal facies within the Turonian Agwu Formation and these are (i) the vitrinite – fusinite coal facies, (ii) the trimaceritic coal facies and (iii) the shaly coal facies. Boboye *et al.* (2009) carried out a study on the hydrocarbon potential of the lithostratigraphic units in the Late Cenomanian – Early Paleocene shale, Southwestern Chad Basin and concluded as follows; that the organic matter in the formation is predominantly gas prone (Type III kerogen), that the assessed thermal maturation indices within the formation is an indication of the presence of an "oil window", that the Fika shale and Gongila Formations have good source-rock potential in terms of its organic carbon content but have low thermal maturity and that the Bima Formation is not within the "oil window" hence have limited potential as source rock. Obaje *et al.* (2006), in their study titled geochemical evaluation of the hydrocarbon prospects of the sedimentary basins in

Northern Nigeria concluded that organic geochemical and organic petrologic study have indicated the existence of potential source rock in the Benue Trough and the Chad Basin, with coal beds constituting major potential source rocks in the whole of the Benue Trough and that although TOC values and liptinite contents are relatively high in the Bida Basin, their Tmax value and biomarker data show that hydrocarbons are probably just being generated in the basin and may not yet have been expelled or migrated in large quantities. However their work was based mostly on outcrop samples due to the inaccessibility to borehole samples hence this study which employed core samples from the Gombe (Maiganga) coal mine exploratory project will provide clearer and additional Information on the petroleum potential of the Gombe Formation. Obaje (2000), in a paper titled "Biomarker Evaluation of the Oil-Generative Potential of Organic Matter in Cretaceous strata from the Benue Trough", concluded that the long/short ratios of the n-alkanes distribution, the pristine/phytane ratios and the regular sterane percentages indicate that the organic matter is predominantly of terrestrial origin and deposited in suboxic to anoxic environment. The n-alkane odd/even ratios and the hopane transformation indices indicate that only the organic matter in the sediment of the Dukul and Agwu Formations are mature with respect to oil generation. Again, the possible limitation to this study was the use of surface outcrop samples. Ojo *et al.* (2002), in a paper titled Petroleum Geochemical Evaluation of the mid Cretaceous sequence in the Dadiya syncline, Yola basin, Northern Nigeria used Rock-Eval pyrolysis, infrared spectroscopy and organic petrographic technique to characterize the source rock and evaluate the hydrocarbon potential of the sequence. Their findings were as follows, TOC value of 0.2 to 12.9 %, which indicate low concentration of organic matter, <2000ppm hydrocarbons indicating poor potential for commercial hydrocarbon generation, terrestrially derived type III kerogen which is an indication of gas generation, Tmax value of 431ºC - 442ºC and measured vitrinite reflectance (Rm) of 0.51 to 0.77 % which is an indication of matured basin. Ehinola *et al*. (2006) carried out the Organic Geochemistry and Biomarker Evaluation of shale units of the Maastrichtian Patti Formation and their result quite agree with that of previous authors.

Lafargue *et al*. (1997) discussed extensively the application of Rock- Eval 6 in hydrocarbon exploration, production and in soil contamination studies. Their paper described how the new functionalities of the latest version of Rock-Eval apparatus (Rock Eval 6) have expanded applications of the method in petroleum geosciences which include source Rock characterization, reservoir geochemistry and environmental studies, including quantification and typing of hydrocarbons in contaminated soils. In Rock Eval 6 oxygen index detection, residual petroleum potential (S_2), High Tmax, now increased temperature range for pyrolysis and oxidation oven and continuous on-line detection of CO and CO_2 with infra-red detectors with newly improved functionalities as against the Rock Eval 2. However, the Rock Eval 2 still rate popular in use due to non-widespread availability of Rock Eval 6 and its cost of purchase/ analysis. Imogene (1980) and Vidal (1988) discussed in detail the palynomorph/micropaleontology preparation procedures currently used in the Paleontology and Stratigraphy Laboratories, U.S. Geological Survey and Micro paleontological Laboratory, University of Lund, Sweden respectively. The manuals were compilation of procedures currently in use at the U.S. Geological Survey pollen Laboratory and at the micro paleontological Laboratory, Geology Department, University of Lund, Sweden respectively.

Okosun (1995) in a paper titled “Review of the Geology of Bornu Basin” highlighted the geology of the southern Bornu Basin which overlaps the Northern part of the Gongola Basin and his work agreed with earlier authors.

2.1 Origin and Geological Setting of Benue Trough (Upper Benue Trough)

2.1.1 Origin of Benue trough

Unlike the other basins of Nigeria which overlie either the continental margin or lie directly on a continental basement, the Benue Trough is entirely intracontinental with some relationships with the margin of the Gulf of Guinea (Zaborski, 2003). Its formation and evolution were, at least partly, controlled by the nascent oceanic structures of the Equitorial Atlantic.

The Benue Trough of Nigeria is an elongate Cretaceous sedimentary basin, that extends NNE-SSW for about 800 km in length and 150 km in width and it is often described as a failed arm (aulacogen) of a Cretaceous triple junction, located on the site of the present day Niger Delta, with the other two rifted arms having subsequently developed into South Atlantic Ocean and the Equitorial fracture zone (Figure 2.3 a) (Guiraud, 1990).

Geological studies indicate that sedimentation was predominantly of marine origin before been terminated by a period of deformation in the Santonian. And since these sediments pile are up to 5000 m to 6000 m (5 km – 6 km) thick and must have developed over a computed period of 30 Ma, there is good evidence that the Benue Trough was a site of sustained surface subsidence. The deformation in the Santonian caused faulting and folding of the Cretaceous sediments along the axis of the present day sedimentary basin with the regional dipping rarely in excess of 30^o (Zaborski, 2003; Zaborski *et al.*, 1997; Zaborski *et al.*, 1998).

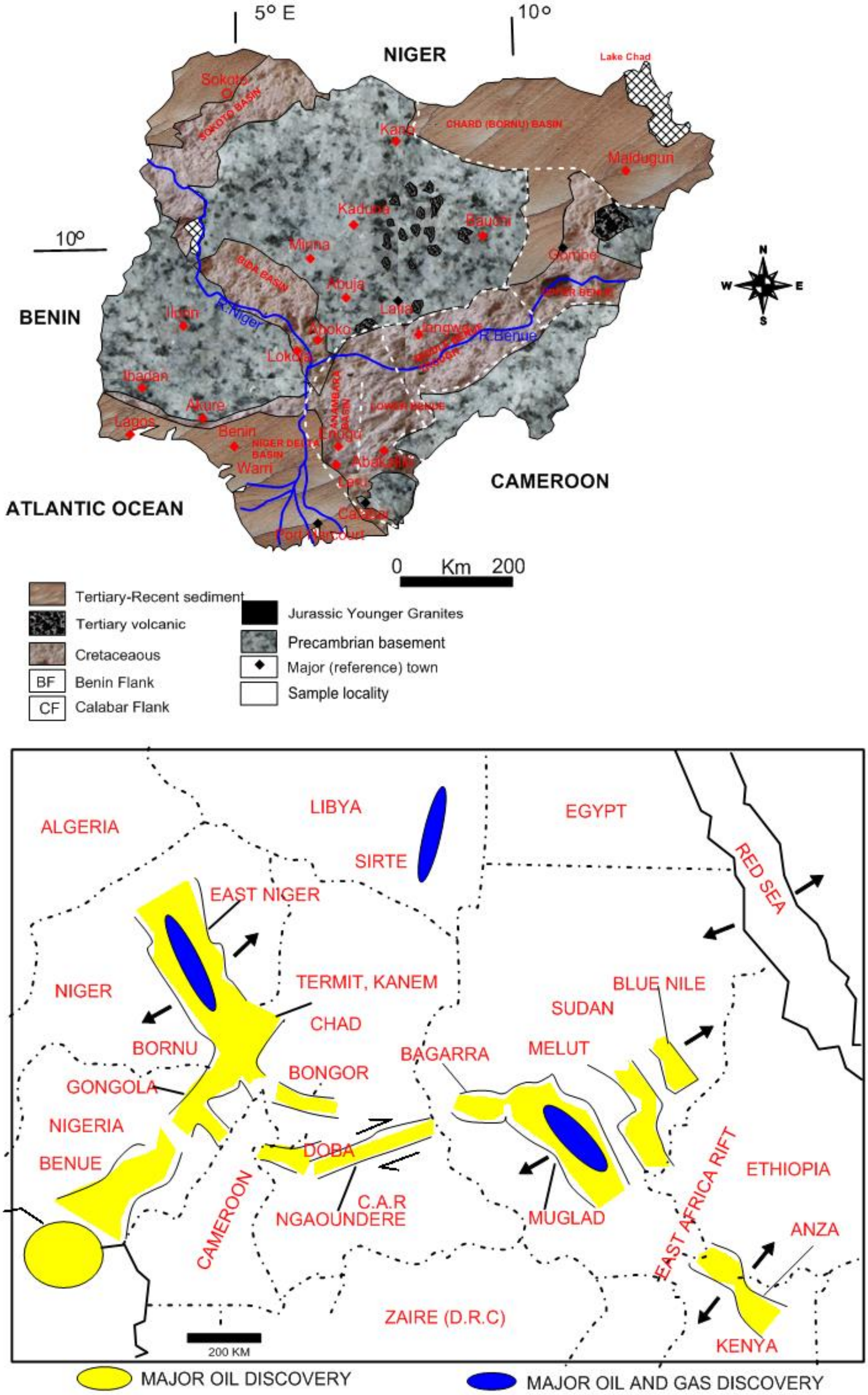

Figure 2.1 Regional tectonic map of western and central African rifted basins (Modified after Obaje *et al.*, 2006).

The en echelon arrangement of fold axes in the middle Benue Trough has been interpreted as an evidence of sinistral movement along NNE shear faults which is supported by field evidence (Zaborski, 1997) (Figure 2.2).

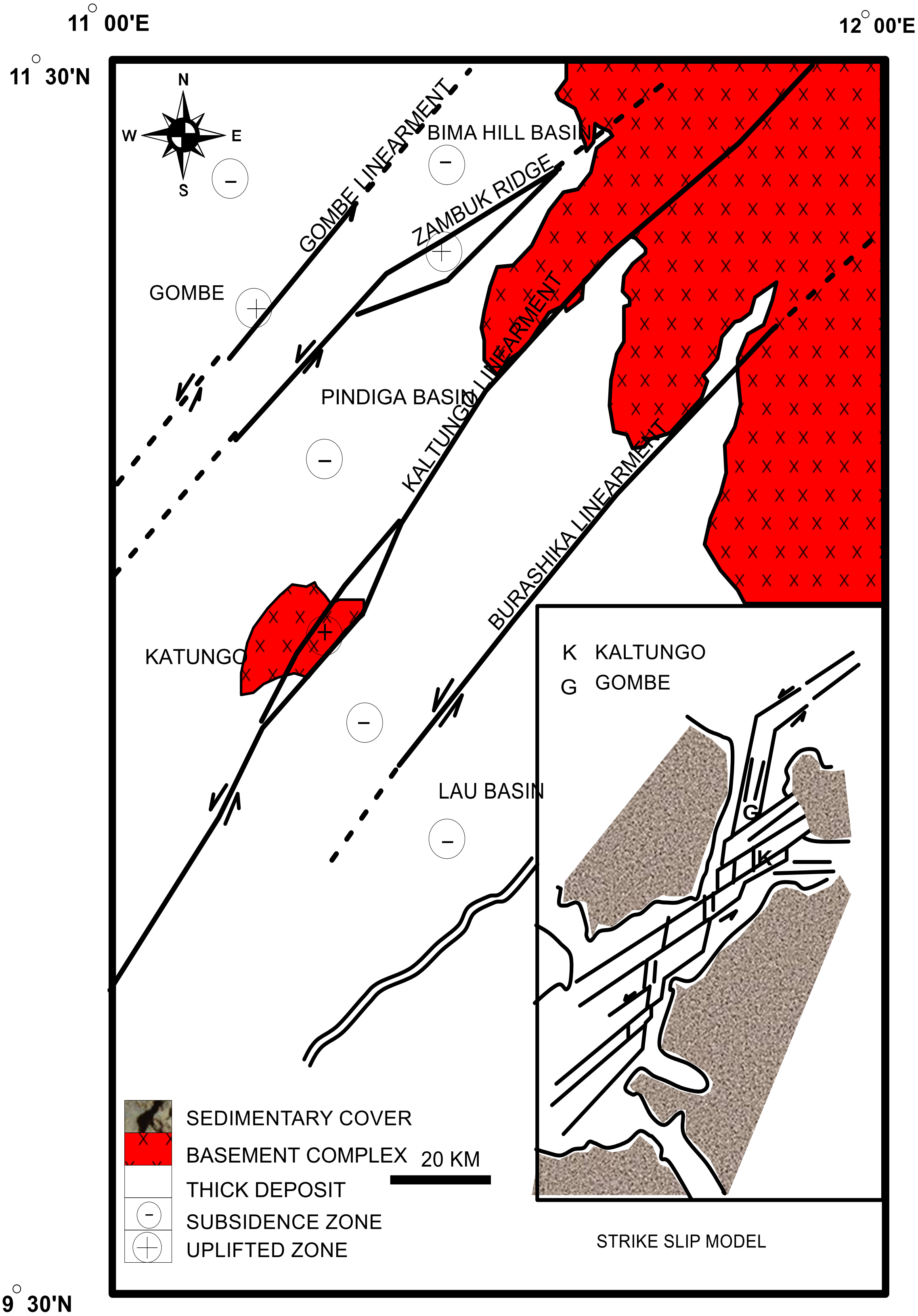

Figure 2.2: Interpretative model of the structure of the Upper Benue Trough (Modified after Zaborski *et al*., 1997).

Geologic and geophysical data analysis have to a great extent assisted in the understanding of the main stages involved in the evolution of the Benue Trough as well as the characteristics that define every stage of the formational history of the Trough (Guiraud, 1991). The basement of the Benue Trough is entirely constituted by a continental crust. In the Lower Benue Trough, this crust was thinned beneath "Abakaliki" during the Albian (c.199 Ma) (Zaborski *et al.*, 1998). However, no oceanic crust was created in the Lower Benue Trough. Moreover, pieces of underlining crust have been uplifted and enclave of gneiss in the basalt in parts of, "Abakaliki". In the Upper Benue Trough, the crustal thinning remains relatively small. The Cretaceous magmatism is restricted and the metamorphism is completely absent.

The oldest sediments (Upper Aptian, c.112 Ma) within the Benue Trough, infill small grabens which are considered as the extension of the E-W tending Trough created sediments outcropping in northern Cameroon, though concealed by the Late Cretaceous in Nigeria (Zaborski *et al.*, 1998).

2.1.2 Structures within the Benue Trough

According to Zaborski *et al.*, (1997, 1998), Zaborski (2003), the Benue Trough is characterized by series of structures as consequence of the tectonic and deformational activities that succeeded the depositional cycles of the Trough. The structures stretch over 120 km in a mean N50E direction. To the northeast, the anticlinal structures are relayed by parallel folds which form a continuous set up to the Upper Benue Trough. At Keana area the structure is cut by a set of brine mineralized veins. They form perfectly straight ridges running over a maximum of 10 km and consisting of quartz, calcite and barite. In the Upper Benue Trough, the main structural feature is the wide spread folding which, in the thick clastic Albian series, result in striking structural reliefs. The present structure in the Upper Benue Trough results from the association of two major events. The first corresponds to the formation of the basin itself and its infilling by thick continental then marine sediments. The second event is responsible for its uplift and the deformation thereof (Shemang *et al.*, 1998). The study of the relationship between the basement and the cover and the role of the important fault zones which control the formation of the basin and the early deformations, definitely led to the preposition of a tectonic mechanism that has been responsible for the formation of the trough.

2.2 Geological Setting (Stratigraphy) of Benue Trough

The Benue Trough is considered most important and hence, the most studied of all the Cretaceous sedimentary basins in Nigeria probably due to its peculiar formational history and its potentiality for hydrocarbon generation, ranking second to the oil prolific Niger Delta (Obaje *et al.,* 1994). At its northeastern end which conforms to the segment commonly known as the Upper Benue Trough, it bifurcates into an E-W tending Yola arm and an N-S trending Gongola arm (Figure 2.3 c) (Zaborski *et al.,* 1997).

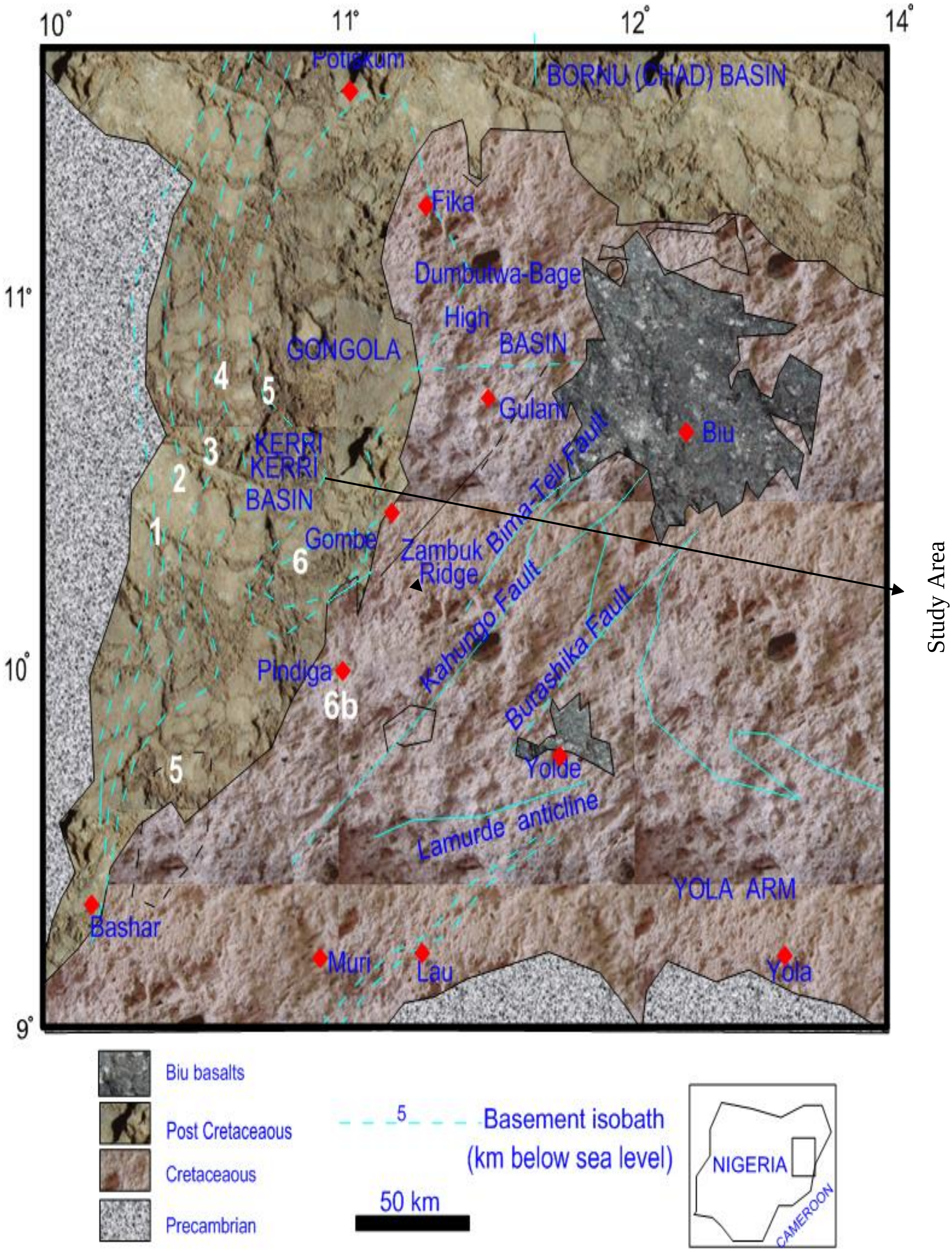

Figure 2.3 a: The two arms of Benue Trough (Modified after Zaborski *et al.*, 1997)

The Benue Trough is geographically divided into three; The Upper, Middle and Lower Benue Troughs (Figure 2.3 b). The geology and stratigraphy of the three sub-basin segments have been well described and documented (e.g. Obaje *et al.*, 2006, Zaborski *et al.*, 1997).

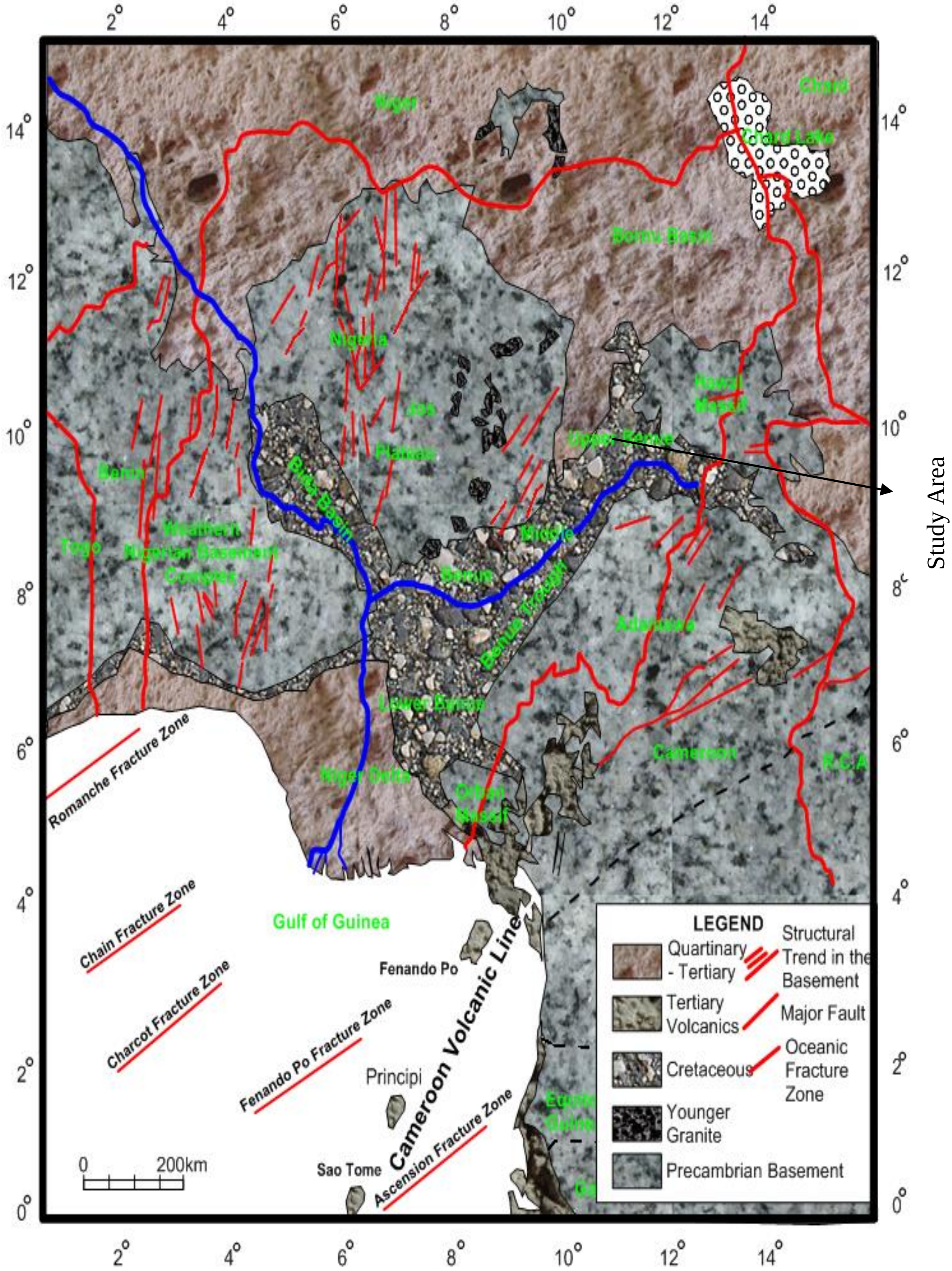

Figure 2.3 b: Geological sketch map of the Benue Trough. (Modified after Odebode, 2010).

For the purpose of this study, the stratigraphy of the Gongola sub-basin that hosts the Gombe Formation will be discussed and this is adopted from the work of Zaborski *et al*. (1997), Carter *et al.* (1963) and Popoff *et al*. (1986). The lithostratigraphic successions for the Gongola basin have been established by these workers. Their schemes are as shown in Figure 2.4.

2.2.1 The Lower Cretaceous series (Bima Group)

The Bima Group consists of the oldest sediments in the Upper Benue Trough and it is referred to as the Lower Cretaceous series in the area. It directly overlies the crystalline basement rocks. It is made of three-fold subdivisions (Guiraud 1989, 1990, 1991), and these include the Upper Bima Sandstone, the Middle Bima Sandstone and the Lower Bima Sandstone. The series as described below are adopted from the work of the previous authors as cited earlier. A simplified geological map of the Upper Benue Trough showing its stratigraphy and the structural elements as adopted from Benkhlil (1989) is as shown in Figure 2.3 c.

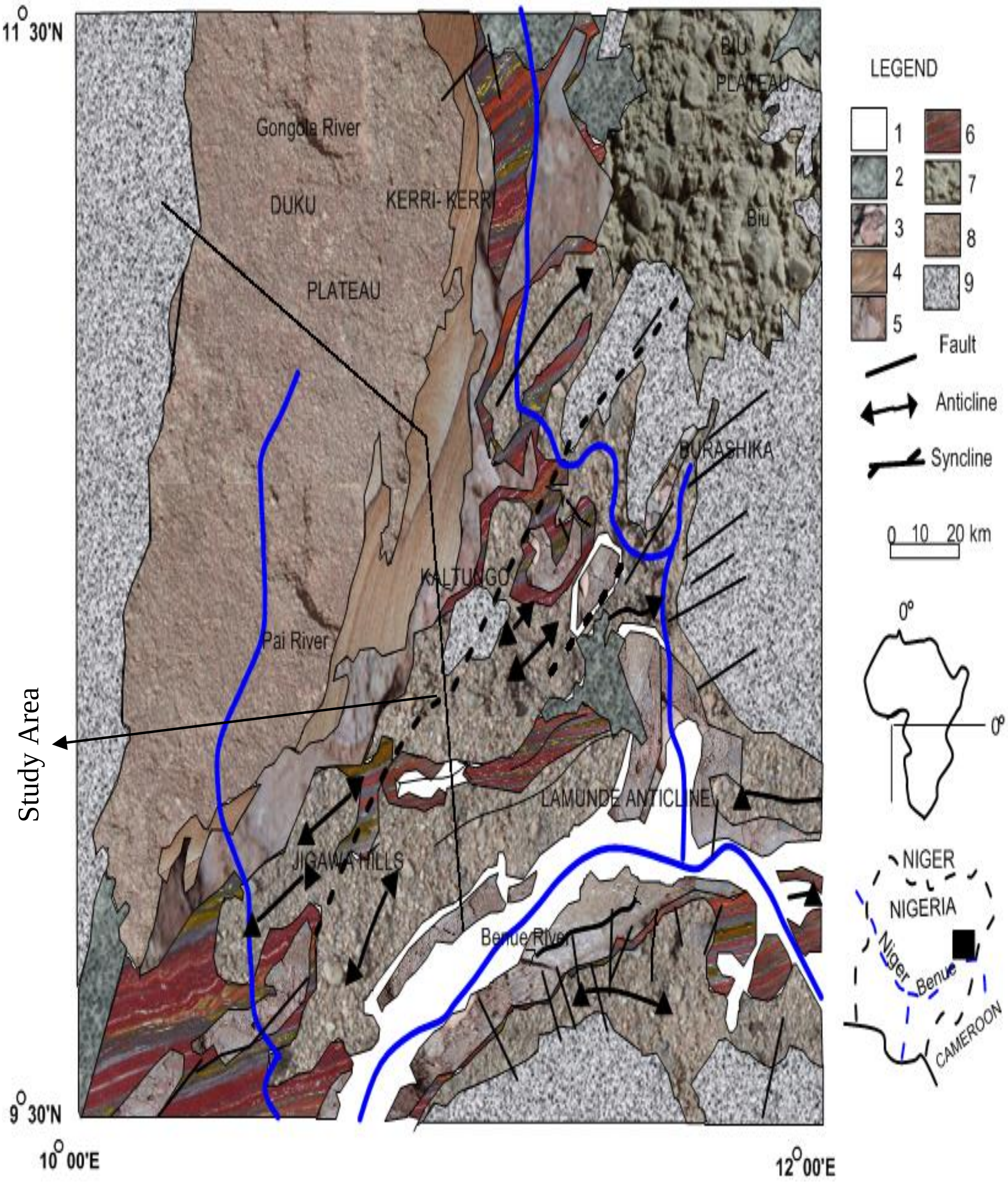

Figure 2.3 c: Stratigraphy of the Upper Benue Trough (Modified after Benkhlil 1989)

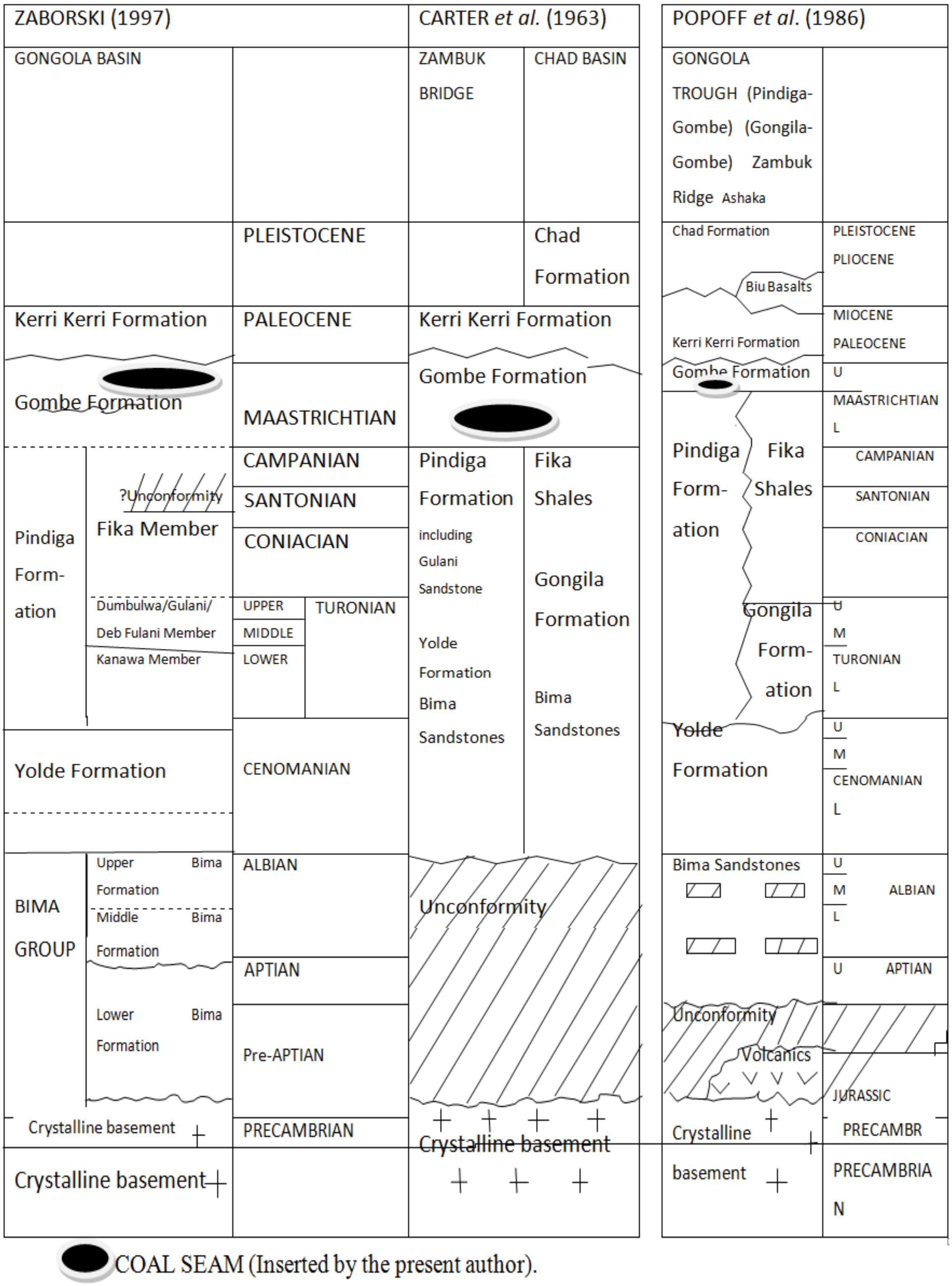

Figure 2.4: Lithostratigraphic successions for the Gongola sub-basin (Modified after Zaborski, 1997)

2.2.1.1 The Upper Bima sandstone

This series is fairly homogenous, relatively mature, fine to coarse-grained, characterized by tabular cross-bedding of few tens of centimeters to a few meters thick, convolute bedding and overturned cross-bedding are common. The average thickness of this unit is 500 m with maximum of 1500 m and represents a distal braided river environment, probably of Albian age (Zaborski *et al.*, 1997).

2.2.1.2 The Middle Bima sandstone

This unit is widely distributed, fairly uniform in content and consists of fining-upward cycles, each 5 to 10 m thick. Trough and tabular cross-bedding characterize the unit. Clays and palaeosols occur at the top of individual cycles. The overall thickness is about 100 to 500 m and dated Late Aptian or Albian age by Guiraud (1991).

2.2.1.3 The Lower Bima sandstone

The Lower Bima Sandstone is a highly variable unit ranging in thickness from 0 to over 1500 m and dated Jurassic to early Albian. It represents an active rift stage of basin development. Its lithofacies distribution were controlled by synsedimentary tectonics which created a number of fault boarded sub-basins within marginal, boulder conglomeritic alluvial fan/debris flow deposits which pass laterally into proximal braided river gravely arkoses and locally into perilacustrine and lacustrine deposits towards the centers of the sub-basins (Zaborski *et al.*, 1997).

2.2.2 The Upper Cretaceous series

This consists of the Yolde Formation, the Pindiga Formation, the Gombe Sandstones (Formation) and the Kerikeri Formation. These Formations are as discussed below

2.2.2.1 The Yolde Formation

The name “Yolde Formation” was first proposed by Carter *et al.*, (1963) for the “transition beds” recognized earlier by Falconer, (1911) and Barber *et al.*, (1954) between the Bima group and the Pindiga Formation. A type section has been shown along the Yolde stream (Zaborski, 2003). This Formation gives rise to subdued topography usually with sparse vegetation. It is poorly exposed in most parts of the Basin. Most of the exposures or outcrops are seen at east of Gongola River, between Kubtogana, Alhaji Ruhu and Ruwan Kuka (Zaborski *et al.*, 1997). The formation occupies the core of a gentle anticlinorium structure in which good exposures occur. The most complete section of the Yolde Formation is found at northwest of Ruwan Kuka, adjacent to Jana-Ruwan Kuka fault where feldspathic Yolde sandstones contain siliceous cement in contrast to their poorly consolidated nature elsewhere in the basin (Zaborski *et al.*, 1997).

According to Zaborski *et al.*, (1997), nearly 150 m of the Yolde Formation have been exposed around Ruwan Kuka, with the Lower part of the formation made up of alternating sandstones and dark grey mud stones which is characterized by desiccation cracks. The sandstones vary from coarse-grained through cross-bedded reaching a thickness of over 5 m in parts. South of Kubtogana and West of Bangade (Figure 2.3c), channel filling sandstones are exposed which reach thickness of 6 m and width of over 50 m. In most places, the uppermost part of the Yolde Formation contains regularly bedded sandstones with argillaceous intercalations, bioturbations (planolites), and calcareous sandstones. South of Titeba (Figure 2.3c), a horizon containing calcareous nodules (approx. 3 m diameters) mark the boundary of the Yolde and the overlying Pindiga Formation. Bivalves are equally present in several parts of the Formation (Reyment, 1965).

The Yolde Formation is up to 200 m at Ruwan Kuka exposure but ranges in thickness between 140 m to a little over 200 m elsewhere across the basin. This formation was reported nonexistent at Gombe hill (Zaborski, 1997). The Yolde Formation was indeed regarded as a transitional sequence between the Bima Group and the Pindiga Formation. The Lower part of the formation is interpreted to be of alluvial origin while the Upper part is considered to be of marine origin. Lawal (1982) dated the formation Late Albian to Late Cenomanian based on palynofacies analyses.

2.2.2.2 ` The Pindiga Formation

The name of this formation was also proposed by Carter *et al*. (1963) for the "Cretaceous beds" and "clay shales" previously described by Barber *et al*. (1954). Its type locality is in the Pindiga stream, to the southwest of Gombe (Figure 2.3c) (Zaborski *et al.*, 1997).

Here, the formation attains up to 80 m thickness. It consists of shales, mud stone and limestone intercalations. It is considered as an equivalent of Gongila/Fika Formation. This Formation is divided into five members, namely the Fika member, the Dumbulwa member, the Deba Fulani member, the Gulani member and the Kanawa member (Hamidu, 2012).

The Fika member is equivalent of the Fika shales of Barber *et al*. (1954), the Dumbulwa has equivalent of Gongila Formation of Carter *et al*. (1963), the Deba Fulani unit equivalent of previously unrecognized unit, the Gulani member being the equivalent of the "Gulani sandstone" of Barber *et al*. (1963) and Kanawa member being the equivalent of "Kanawa Formation" of Thompson (1958). The Gulani, Deba Fulani and Dumbulwa members are lateral lithofacies equivalents occurring in the middle part of the Pindiga Formation.

The Kanawa member is made of shales and intercalated lime stones. Its best outcrops are located at Pindiga stream and Ashaka Quarry. It was dated late Cenomanian to early Turanian. Its age equivalent is the Dukul Formation in the Yola arm. The Dumbulwa member has been correlated with the Gongila Formation and concluded to be coeval in age based on lithostratigraphical study by Zaborski (1997). The Gulani member was proposed by Carter *et al* (1963). Its type localities are at Bara, Gulani and Balbaya (Figure2.3c).

The Deba Fulani member was proposed by Zaborski (1997) for the sandy beds occurring in the middle of the Pindiga Formation which was hitherto undifferentiated. The defunct Geological Survey of Nigeria had earlier mapped the unit as part of Gombe Formation and Gongila Formation. Its type locality is at Deba Fulani at Deba Fulani and Kumo.

The Fika member comprises the "Fika Shales" of Carter *et al*. (1963). The formation is topographically not too prominent and consists of shaly mud stones, lace macrofossils and contains irregular bands and lenses of gypsum. It equally contains beds of lime stones, iron stones, sand stones and plant-rich shales.

2.2.2.3 The Gombe Formation

The present study area is located within the Gombe Formation, precisely at Maiganga coal mine, near Kumo in Akko LGA. The Gombe Formation had been mapped as a unit by several workers (e.g. Falconer, 1911; Berber *et al.*, 1954; Reyment and Barber, 1956 and Carter *et al.*, 1963). The Formation consists of estuarine and deltaic sandstones, siltstones, shales and limestones. There are thin coal beds reported by the above earlier workers and this has been confirmed by the successful exploration and on-going exploitation of the coal deposit at Maiganga coal mine which serve as the source of samples for this study. The exact age of the formation as at that time is unknown but a tentative assignation of Upper (Campanian) Senonain-Masstrichtian has been suggested. Its type locality is Gombe according to the earlier workers.

Carter *et al.* (1963) mapped the northeastern part of the Benue Trough and stated that the Maastrichtian Gombe Sandstone rests uncomformably on the older folded rocks of the Upper Benue depression and that the Maastritchtian rocks are themselves folded. However, mapping reveals that the strong fold which affected the Upper Benue Trough is pre-Gombe, i.e. probably pre-Maastritchtian and that, as in the Abakaliki and Lower Benue Trough, the main folds were generated in Santonian times (Murat, 1972; Burke *et al.*, 1972; Whiteman, 1973). The Gombe Formation is restricted to the western part of the Gongola basin. It weathers to produce ferruginous capping. The weathering is responsible for the rugged hilly topography that characterizes most of the outcrops.

The Gombe Formation is made of 3 major lithofacies which were later proved as separate distinguishable members. At its base, the Gombe Formation consists of rapidly alternating thin beds of silty shales, sometimes with plant remains and fine to medium-grained sand stones with some intercalated thin flaggy Ironstones. Passing upwards, the Gombe sandstone beds become more persistent and make up the greater of what was referred to as “bedded facies” by Zaborski (1997). South of Gombe, the Upper part of the Gombe Formation was termed “Red Sandstones Facies” by Zaborski (1997) probably due to its reddish colouration. Dike (1995) had reported coal horizons within the Gombe Formation and this was later proved by other workers. Infact, the coal seams are presently being mined by the Ashaka Cement Company.

According to Hamidu (2012), the type locality of the Gombe formation was designated as the “Kware Stream” by Carter *et al*. (1963) which is about 3 km south of Gombe where 300 m of sediments were described as exposed. He however asserted that the 1:250,000 scale geological map (sheet 36 Gombe) provided in Carter *et al*. (1963) is inadequate to determine with certainty which of the "Kware" streams in the area actually contains the type section. He concluded, based on his field findings, that the type section for the Gombe Formation proposed by Carter *et al*. (1963) actually belongs to the Arowa member (a member of the Gombe Formation).

Below is the modified lithostratigraphical subdivision of the Gombe Formtion after Hamidu (2012).

Age	Formation	Members
Paleocene	Keri-Keri	
Maastrichtian	Gombe	Duguri member
Campanian		Arowa member

Figure 2.5: Lithostratigraphical subdivision of Gombe Formation. After Hamidu (2012).

2.2.2.4 The Kerikeri Formation

This formation overlies the Gombe Formation. The formation is characterized by cross-bedded quartz arenites. It is believed to be deposited in fluvial channel fill based on its grain sizes, textures and sedimentary structures (Zaborski *et al.*, 1997). According to Adegoke *et al*. (1986), the Kerikeri Formation is dated Early Tertiary.

2.3 Specific Geology of the Study Area

The studied area is an integral part of Gombe state; hence its geology will be discussed within the context of the geology of the state. Gombe state is geologically a part of the Upper Benue Trough, although the state is an entity of its own, the Gongola Trough. As such, the state constitutes a major sedimentary basin, with a fill of about 6,000 m of Cretaceous-Tertiary sedimentary rocks. These rocks are well exposed throughout the state. The eastern part of the state is geologically older than the west (Gombe state, 2012).

Exposures of the non marine Bima Sandstone, a sequence of Albian coarse sandstone, occur extensively in the south eastern part of the state, succeeded westwards by the transitional beds of the Cenomanian Yolde and Jessu Formations (Zaborski *et al.*, 1997; Shemang *et al.*, 1998). These are overlain by the marine Cenomanian to Conacian shales and limestone of the Pindiga Formation, followed by the Gombe Sandstone of Late Cretaceous age. Half of Gombe state is underlain by the Early Tertiary Kerri-Kerri Formation of estuarine origin comprising sandstones and ironstones (Adegoke *et al.*, 1986). The southern Chad Basin covers the northern one third of the state. Figure 2.6 is a sketch of the synthesized geological map of Gombe State, indicating the predominant Gombe Formation that covers the studied area.

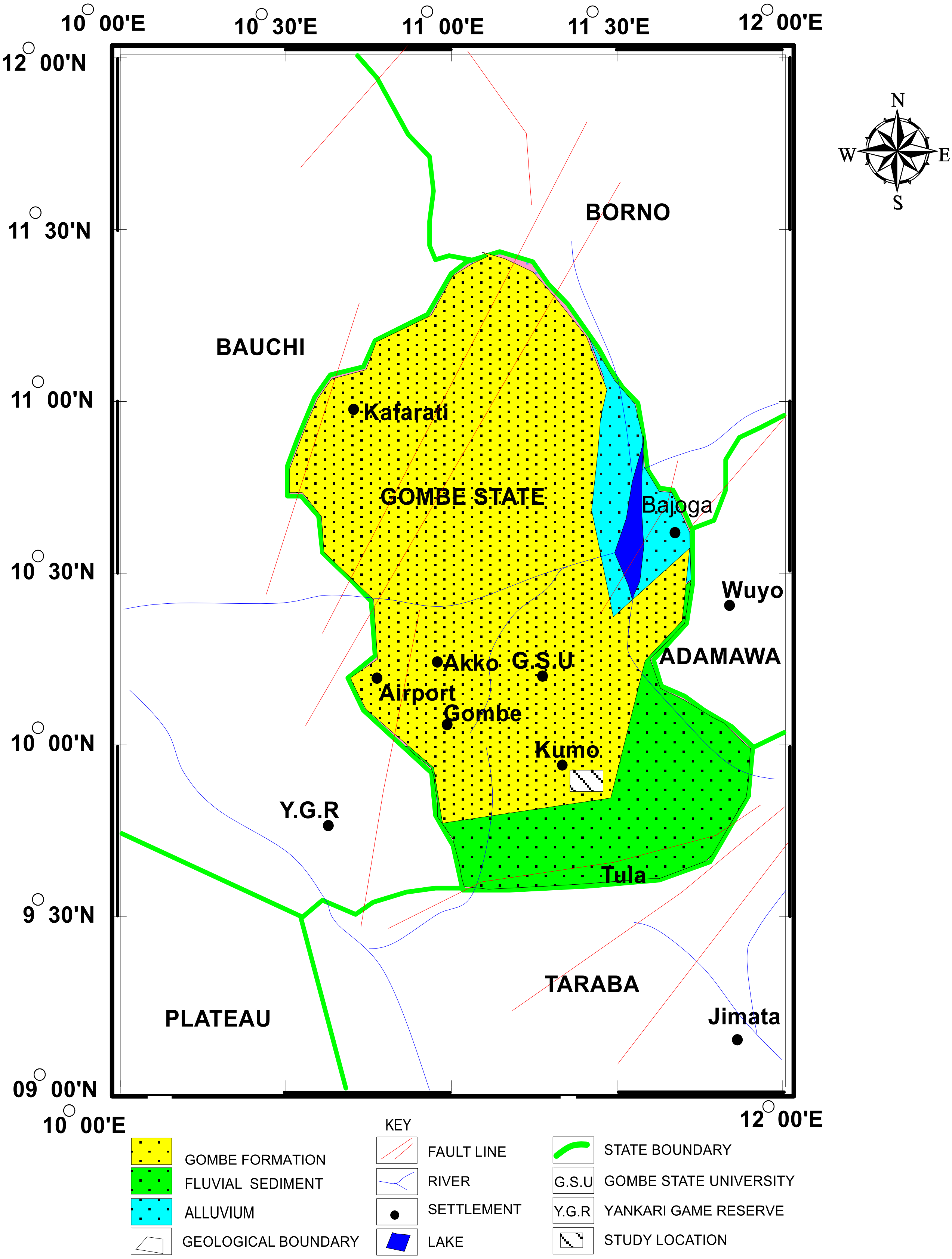

Figure 2.6: Synthesized Geological Map of Gombe State.

2.4 Rocks-Eval Studies

Rock-Eval pyrolysis is used to identify the type and maturity of organic matter and to detect petroleum potential in sediments. (Lafargue, Espitalie, Marquis & Pillot, 1997; Peters, 1986; Obaje *et al*. 2006). Rock Eval pyrolysis is done using the Delsi-Nermay Eval II or 6 plus TOC module. According to Lafargue *et al*, (1997), samples chosen for Rock Eval analysis are usually sub sampled from the freeze-dried material previously crushed for analyses. The method of Rock Eval consists of a programmed temperature heating in a pyrolysis oven in an inert atmosphere of helium of a measured sample (approx. 100mg) to quantitatively and selectively determine the free hydrocarbons contained in the rock sample and the hydrocarbon and oxygen-containing compounds (CO_2) that are volatilized during the cracking of unextractable organic matter in the sample (kerogen).

The pyrolysis oven temperature program is as follows: For three minutes, the oven is kept isothermally at 300^{o}c and the free hydrocarbons are volatilized and measured as the peak (S1) (detected by Flame Ionization Detector (FID)). The temperature is then increased from 300^{o}c to 550^{o}c (at 25^{o}c/ min). This represents the phase of volatilization of the very heavy hydrocarbon compounds (> C_{40}) as well as the cracking of non-volatile organic matter. The hydrocarbons released from this phase of thermal cracking are measured as the S_2 peak (by FID). The temperature at which S_2 reaches its maximum depends on the nature and maturity of the kerogen and is called Tmax (Peter, 1986).

The CO_2 issued from kerogen cracking is trapped in the 300^{o}C-390^{o}C range. The trap is heated and CO_2 is released and detected on a FID during the cooling of the pyrolysis oven and this represents the S_3 peak.

According to Tissot and Welte (1984), the four basic parameters obtained by Rock-Eval pyrolysis are as follows:

S_1= the amount of free hydrocarbons (gas and oil) in the sample (in milligrams of hydrocarbon per gram of rock). If S_1>1mg/g, it may be indicative of an oil show. S_1 normally increases with depth. Contamination of samples by drilling fluids and mud can give an abnormal high value for S_1.

S_2= the amount of hydrocarbons generated through thermal cracking of non-volatile organic matter. S_2 is an indication of the quantity of hydrocarbons the rock has the potential of producing should burial and maturation continue. This parameter normally increases with burial depths >1km.

S_3= the amount of CO_2 (in milligrams CO_2 per gram of rock) produced during pyrolysis of kerogen. S_3 is an indication of the amount of oxygen in the kerogen and is used to calculate the oxygen index (OI). Contamination of the samples should be suspected if abnormally high S_3 values are obtained. High concentration of carbonates that break down at lower temperatures than 390^{o}c will also cause high S_3 values than expected.

Tmax= the temperature at which the maximum release of hydrocarbons from cracking of kerogen occur during pyrolysis (top of S_2 peak). Tmax is an indication of the stage of maturation of the organic matter.

The Rock Eval 6 (RE - 6) apparatus can also be used to determine the TOC of the sample by oxidizing (in an oxidation oven kept at 600^{o}c) the organic matter remaining in the sample after pyrolysis (residual organic matter) (Emeis & Kvenvolden, 1986; Tissot & Welte, 1984).

The TOC is then determined by adding the residual carbon detected to the pyrolyzed organic carbon, which in turn is measured from the hydrocarbon compounds issuing from pyrolysis. The type and maturity of organic matter in petroleum source rock can be characterized from Rock Eval pyrolysis data (Emeis and Kvenvolden, 1986) using the following parameters:

HI= $[100*S_2]/TOC$. HI is a parameter used to characterize the origin of organic matter. Marine organism and algae, in general are composed by lipid and protein – rich organic matter, where the ratio of H to C is higher than in the carbohydrate-rich constituents of land plants. HI typically ranges from approx 100 to 600 in most geological samples

OI= $[100*S_3]/TOC$. OI it is a parameter that correlates with the ratio of O to C, which is high for polysaccharide-rich remains of land plants and inert organic material (residual organic matter) encountered as background in marine sediments. OI value ranges from near O to approx 150.

PI (Production Index) = $S_1/ [S_1+S_2]$. It is used to characterize the evolution level of the organic matter.

PC (pyrolyzable Carbon) = $0.083*[S_1+S_2]$. PC corresponds to carbon content of hydrocarbon volatilized and pyrolyzed during the analysis.

According to Peters and Cassa (1994), maturation of the organic matter can be estimated by;

I. The location of HI and OI on the HI vs OI plots on the Van Krevelen diagram which indicate hydrocarbon generative (kerogen) types and

II. Tmax range. Tmax= 400^{o}C-430^{o}C represent immature organic matter; Tmax = 435^{o}C-450^{o}C represent mature or oil zone; Tmax > 450^{o}C represent over mature zone.

It is pertinent to note that Rock Eval pyrolysis is not normally used to make real-time drilling decisions because of its lengthy sample preparation, running and interpretation time (Lafargue *et al*, 1997). The method is of more research than production application.

2.5 Palynology and Palynofacies Studies

Palynology is the study of the entire acid-resistant microscopic organic matter (OM) recovered from a sediment or sedimentary rock. These can be recent or fossilized material, which has been deposited in a variety of environments that range from terrestrial to the aquatic realm (Andrew, 2004). Palynofacies studies, a term first formulated by Combaz (1964) attempt to qualify and/or quantify the assemblage of the OM particles that typically have a diameter of 5 - 500µm, (Batten, 1996 a as quoted by Andrew, 2004). Hence, these OM particles include pollen, spores and prostistan or algae cysts as well as plant debris (woody and cuticular materials), amorphous matter and other miscellaneous materials. These palynological residues can be extracted from the sediment through a series of chemical digestion technique and then mounted on microscope slides for analysis. Traditionally, palynological samples are manually analysed with a microscope by a trained human palynologists, employing the visual characteristics i.e morphology and textures of the palynomorphs. For the successful biostratigraphic, paleoecological or paleoenvironmental interpretations to be derived in any palynological studies, the accurate identification of sedimentary OM is fundamental (Andrew, 2004). If the significance of the composition of different assemblages is well understood, minor as well as major changes in salinity, levels of oxygenation, water depth, temperature and other environmental parameters in the aquatic realm may all be detectable.

Misidentification can so easily lead to misinterpretation. Ideally, for best results, the entire assemblages (not just selected parts), and the fragmentary and even minutely particulate OM remains associated with these, should be examined (Batten, 1992).

Palynological study has recently embraced more than the study of pollen and spores. Its scope includes all kinds of microscopic organic particles termed Phytoclasts. Phytoclasts range from entities with well defined morphology, such as dinoflagellate cysts, microforaminiferal linings, fragments of woods and cuticle, structured and unstructured plant remains, as well as tissues whose origins are uncertain and are also not easy to categorize (the palynomacerals or palynodebris). Until about three decades ago, the biostratigrahpic applications of palynomorphs have formed the most important area of activity for most professional pre-quaternary palynologists, and even now constitute the engaging aspect of paleopalynology by most oil production companies because of its inherent application in dating sedimentary strata and also deducing their environment of deposition.

Unfortunately little or no attention is usually paid to other disseminules (component) which are present on palynological slides along the palynomorph (Oyede, 1992). Quite often, these neglected components are destroyed by oxidants during the maceration process, because the focus was to concentrate the pollen and spores to the exclusion of other phytoclasts that may obscure them from direct study. Since the formal introduction of the term “palynofacies” in 1964 by Combaz, increase awareness on palynofacies have developed in the oil industries. This is because of its value in the determination of petroleum source potential from the amount, composition and colour of organic matter present in a sedimentary rock.

Palynofacies study is equally applicable to the petroleum geology because it contributes to the identification of depositional environments, thus elucidating the general evaluation of the hydrocarbon potential of a sedimentary basin. Palynofacies refer to the microscope organic constituent of a sedimentary rock after its concentration and mounting under standard conditions of preparation. Palynofacies is very useful for environmental studies, biostratigrahpic analysis, maturation and source rock potential studies hence its important can be overwhelming in earth science studies (Batten, 1996).

However, palynofacies studies are not without shortcomings. One of the obvious problems associated with the discipline is the standardization of terminologies and agreement on nomenclature. This lack of uniform, widely accepted terminology, has negatively affected the dissemination of information among research groups. This is because the terminologies used by various authors and research group are not compatible. They often reflect the authors' biasness (Christopher and Goodman, 1996). The guides and codes of stratigraphic nomenclature are discussed under biostratigraphy just for record purpose because it is not the intention of this author to review these terminologies. An open workshop on organic matter classification was held at the University of Amsterdam in June, 1991 to address the issue of uniformity in organic matter classification. The report of that workshop was however not available to the author, but it was asserted that the workshop addressed the first level of classification using white transmitted light and was able to present four categories of organic matter classification based on their visible structural component (Oyede, 1992). These include;

(I)- Palynomorphs

(II)- Structured debris

(III)- Amorphous debris and

(IV)- Indeterminate.

According to Oyede (1992), palynofacies analysis has been pursued within Shell international for over fifteen years and results have been integrated with sedimentological, seismic stratigraphy (sequence stratigraphy) and traditional palyno-stratigraphic techniques, in order to have a holistic approach to basin analysis. He mentioned that the classification system adopted by Shell was primarily based on extensive detailed study of Jurassic sequences in the North Sea by some authors. The scheme of classification had been adopted on the pilot study carried out on some EA-13 core samples for Shell Oil Company and had proved very useful. Consequently, this scheme has been accepted widely by several authors and has been employed in this study.

2.5.1 Organic matter types and classification

As previously mentioned, four major classes of organic matter are suggested and distinguished by the Amsterdam's Open Workshop on organic matter classification. These include

1. Palynomorphs -These are identifiable plant and animal remains such as spores pollen grains, dinoflagellate cyst, acritarchs, foraminiferal wall linings, fungal spores and pediastrum.
2. Structured debris -These are organic remains that clearly show at least partial preservation of original biological structure e.g. epidermis, cuticle, wood

remains (tracheides and sieve plates), fungal tissue, animal tissue and other plant tissues.

3. Amorphous debris-These are organic remains of uncertain biological affinity, usually not showing visible or well defined structure. They could be homogenous, heterogeneous or opaque.
4. Indeterminate –These are organic matter that do not fall into any of the three categories above and cannot be determined due to its uncertain features.

The Structured debris are grouped into palynomacerals 2 and 3, other plant tissues, fungal matters, animal matters and other indeterminate structured matter. The Amorphous debris includes the palynomacerals 1 and 4, other stuctureless organic matter (homogeneous and finely dispersed) and other indeterminate organic matter.

2.5.2 Description of organic matter types

Organic matters are grouped into four types and these are based on their general appearance and characteristics. These, according to Oyede, 1992 include the followings;

2.5.2.1 Type I

This organic matter may be orange – brown or dark-brown, more or less, stuctureless organic matter, and irregular in shape, variable in preservation and dense in appearance. It is of heterogenic origin, and may include plant debris. Palynomaceral type-1 appears not so resistant to physical abrasion and may be destroyed or degraded in high energy oxidizing environments. It is mainly of higher plants origin, and some may be exudation products, probably the result of jellification of plant debris in the sediment. Palynomaceral type-1 varies in size and shapes. This variation to some extent is a function of the depositional environment, for example, in a high energy environment; there is a complete winnowing of the medium to large-sized forms.

2.5.2.2 Type II

Palynomaceral-2 types are often brown to orange in color and have irregular shape. It may include structured plant material like leaf, stem, rootlets debris, and algal detritus and to a lesser extent humic gels and resinous substances. They are less dense, often thinner and lath-shaped. Their buoyancy is considered higher relative to palynomaceral type-1.

2.5.2.3 Type III

These are usually pale, relatively thin, irregularly shaped and mostly structured materials, occasionally bearing stomata, sometimes with guard cells. They include structured plant materials, mainly of cuticular origin and degraded aqueous plant materials. They are considered the most buoyant of organic matters 1 to 3.

2.5.2.4 Type IV

These usually appear black, equidimensional, bladed or needle-like shape, which is uniformly opaque and stuctureless. It may also occasionally show cellular structure or appear filamentous. The constituents which make up palynomaceral type-4 are of many different origins and they include compressed humic gels, charcoal (resulting from forest fires), reworked charcoal and geothermally fusinized materials. Graded-shaped palynomaceral type-4 is destructive in appearance and reflects the break- up of larger, oxidized wooden debris parallel to the long axis of cellular structure, typical in stem material.

2.5.2.5 Amorphous organic matter (AOM)

This group of organic matter is made up of essentially of stuctureless material, materials bearing a granular appearance. They have variables composition but consist generally of a bacterially reworked biomass composed of dispersed residual fragments of the original constituents. AOM is preserved generally under anoxic (oxygen-depleted) environments. Fine grained sediments can be expected to contain large quantities of stuctureless organic matter, provided that they are deposited under anoxic conditions.

Palynofacies analyses are in general, comparative. As such consistency in sample preparation and analyses techniques is very vital (Imogene, 1980). For reliable palynofacies results, side wall or core samples are preferably used. Core samples were used in this study. Ditch-cutting samples are considered less reliable because of the inherent problem of caving during their sampling. They also result in high rate of contamination.

Palynofacies analysis is more suitable in argillaceous lithology such as shale, argillaceous sandstone and siltstone. It does not allow a build-up of frame work of "background" shale sedimentation, thereby limiting the interpretation of sand bodies developed in the frame work. Hence, as a consequence, the results obtained from palynofacies analysis must be complimented by sedimentological analysis.

Oyede (1992), asserted that as a consequence of the open workshop on organic matter classification as earlier mentioned, Shell Petroleum Development Company (SPDC), Warri had evolved a palynodebris analysis sheet which recognizes two categories of matter; structured organic matter (which includes tracheid/sieve plates, epidermis/cuticle, other plant tissues, fungal matter, animal matter and indeterminate) and Amorphous/ Unstructured organic matter (which includes palynomacerals 1 and 4, discrete and indiscrete stuctureless organic matter and indeterminate). This had been employed in the palynofacies analysis of EA-13, Egbema West-21 and Orogho-2 cores of SPDC.

2.6 Spores and Pollen

2.6.1 Spores

A spore is a reproductive structure, some of which are adapted for dispersal and summing for extended periods of time in unfavourable conditions. The spores of seed plants, are produced internally and its structure derived from the spores that disperse (the spores of bacteria, fungi, algae and protists are rarely preserved but those of terrestrial plants are very common fossils (Playford and Dettmann, 1996). Spores form part of the life cycles of many bacteria, plants, algae, fungi and some protozoa. They are usually haploid and unicellular and are produced by meiosis in the sporangium of the sporophyte and once there are favourable conditions, the spores can develop into a new organism using mitotic division, producing a multicellular gametophyte, which eventually produce gametes. Two gametes fuse to produce a new sporophyte through alternation of generation. Spores are units of asexual reproduction whereas gametes are units of sexual reproduction as two gametes need to fuse to produce a new organism.

2.6.2 Pollen

Pollen is a fine to coarse powder containing the microgametophytes of seed plants, which produce the male gametes (sperm cells) (spores and pollens, 2012). Pollen grains have a hard coat that protects the male gametes during the process of their movement from the stamens to the pistil of flowering plants or from the male cone to the female cone of coniferous plants. When pollen land on a compatible pistil or female cone (i.e when pollination has occurred), it germinates and produces a pollen tube that transfers the sperm to the ovule (or female gametophyte).

The diversity of pollen, especially of the angiosperms from the Mid-Cretaceous, provides the palynologists with an abundance of palynoforms that can be used to determine biostratigraphic sequences establish correlations between geographically separated regions and make paleoenvironmental reconstructions (Jarzen and Nicholas, 2006).

2.6.3 Geological time range for spores and pollen

The earliest terrestrial plants are recorded from the late Silurian (c.420/my) and were homosporous (similar spores) (Herland, 1978). By the end of the Devonian(c.360/my), heterospory had appeared, this still involved dispersal by spores only but both microspores (held in a microsporangium) and megaspores (held in megasporangium) were produced. Both these forms of plants relied on water (or at least damp conditions) to allow transport of the spermatozoid to the egg. The earliest gymnosperms appeared in the very latest Devonian and rapidly become diverse and important during the Carboniferous. The angiosperms did not appear until the early Cretaceous and diversified rapidly from the mid Cretaceous. Table 2.1 shows the geological time scale and the period of plant evolution (spores and pollen) is as indicated by letter ‘P’ based on the author’s modification.

Table 2.1: Geologic Time Scale (Modified after Herland, 1978)

Eon	Era	Period	Epoch	Age (Ma)	
Phanerozoic	Cenozoic	Quaternary	Holocene	0.01	
			Pleistocene	1.64	
		Neogene	Pliocene	5.2	
			Miocene	23.3	
		Palaeogene	Oligocene	35.4	
			Eocene	56.5	
			Palaeocene	65.0	
	Mesozoic	Cretaceous		145.6	
		Jurassic		208.0	
		Triassic		245.0	
	Palaeozoic	Permian		290.0	**P**
		Carboniferous		362.5	
		Devonian		408.5	
		Silurian		439.0	
		Ordovician		510.0	
		Cambrian		570.0	
Proterozoic				2500	
Archean				4000	

P is Period of Plant Evolution

2.6.4 Classification of spores and pollen

2.6.4.1 Classification of spores

Spores can be classified in several ways and these are based on several criteria. The classification of spores and the various criteria used are discussed as follows.

Based on spores – producing structure

In fungi and fungus – like organisms, spores are classified by the structure in which meiosis and spore production occurs. Based on this, spores are classified into:-

a. Sporangiospores – spores produced by a sporangium e.g in fungi (zygomycetes)

b. Zygospores – spores produced by a zygosporangium e.g zygomycetes

c. Ascospores – spores produced by ascus e.g ascomycetes

d. Basidiospores – spores produced by basidium e.g basidiomycetes

e. Aeciospores – spores produced by aecium in some fungi e.g rust, smuts

f. Urediospores – spores produced by uredinium e.g rusts and smuts

g. Teliospores – spores produced by telium e.g rusts and smuts

h. Oospores – spores produced by an oogonium e.g oomycetes

i. Carpospores – spores produced by carposporophyte e.g red algae

j. Tetraspores – spores produced by tetrasporophyte e.g red algae

Based on function

a. Chlamydospores – thick-walled resting spores e.g fungi; produced to survive unfavourable conditions.

b. Parasitic fungal spores – these are classified into internal spores, which germinate within the host, and external spores, also called environmental spores, released by the host to infest other host

Based on origin during life cycle

a. Meiospores – spores produced by meiosis

b. Microspores – miospores that give rise to a male gametophyte (pollen in seed plants)

c. Megaspores (or macrospores) – miospores that give rise to a female gametophyte.

d. Mitospores – these are also known as conidia or conidiospores. They are spores produced by mitosis e.g ascomycetes

Based on mobility

These spores can be differentiated based on their ability to move. They include

a. Zoospores – mobile spores that move by means of one or more flagella e.g some algae and fungi

b. Aplanospores – immobile spores that may nevertherless potentially grow flagella

c. Autospores – immobile spores that cannot develop flagella

d. Ballistospores – spores that are actively discharged from the body of the fungal fruiting body e.g spores of pilobolus.

e. Statismospores – spores that are not actively discharged from the fungal fruiting body e.g puff balls

Based on anatomy

Based on anatomy, spores can be categorized as either monolete spores or trilete spores. In monolete spores, there is a single line on the spores indicating the axis on which the mother spore was split into four along a vertical axis. In trilete spores, all four spores share a common origin and are in contact with each other. So, when they separate each spore shows three lines radiating from a center pole.

2.6.4.2 Classification of pollen

Classification of pollen, like that of spores is based on morphology. Morphological features used in pollen classification include apertures, which represent the pollen tube that passes through its wall by way of structures. Pollen apertures serve as exit for the pollen contents and allow shrinking and swelling of the grain caused by changes in the moisture content. The elongated apertures/furrows in the pollen grain are called colpi (singular – colpus), which along with pores are a major criterion for the classification of pollen. The orientation of the furrows (relative to the original tetrad of microspores) classify the pollen as colpate or sulcate.

Pollens having 3 colpi are said to be tricolpate, while those having one sulcus are said to be monosuclate.

2.6.5 Applications of the study of spores and pollen.

The study of spores and pollen is used for a diverse range of applications (spores and pollen, 2013). These include the followings:

i. Biostratigraphy and geochronology – Geologists use palynological studies in biostratigraphy to correlate strata and determine the relative age of a given bed, horizon, formation or stratigraphical sequence.

ii. Paleoecology and climate change – Palynology can be used to reconstruct past vegetation (land plants) and marine and freshwater phytoplankton communities, and so infer past environmental (paleoenvironmental) and paleoclimatic conditions.

iii. Organic palynofacies studies – This examines the preservation of the particulate organic matter and palynoforms, provide informations on the depositional environment of sediments and depositional paleoenvironments of sedimentary rocks.

iv. Geothermal alteration studies – Examine the colour of palynomorphs extracted from rocks to give the thermal alteration and maturation of sedimentary sequences, which provide estimates of maximum paleotemperatures.

v. Limnology studies – Freshwater palynomorphs, animal and plant fragments, including the prasinophytes and desmids (green algae) can be used to study past lake levels and long term climate change.

vi. Taxonomy and evolutionary studies – Taxonomy attempts to give the hierachial (biological) classification of palynomorphs which can be used in the grouping of plants. Taxonomy include, in ascending order of taxonomic ranks. These are modern biological classification that has its root in the work of Carolus Linnaeus (1735), who grouped species according to their common physical characteristics.

- Life
- Domain
- Kingdom
- Phylum
- Class
- Order
- Family
- Genus
- Species

Evolutionary studies on the other hand deals with how plants and animals evolve from the minutest life form into a more complex life form. The study of spores and pollen can be used to infer the taxonomy and evolution of past plant life.

vii Forensic palynology – This is concerned with the study of pollen and other palynoforms for evidence at a crime scene.

viii Alergy studies – Studies of the geographic distribution and seasonal production of pollen can help sufferers of allergies such as hay fever e.g allergic rhinitis which is an allergic inflammation of the nasal airways caused by grass pollen. Pollinosis causes sneezing, itchy and watery eyes, swelling and inflammation of the nasal passages and an increase in mucus production.

ix Melissopalynology – This is the study of pollen and spores found in honey, especially as regards their source. By studying the pollen in a sample of honey, it is possible to gain evidence of the geographical location and genus of the plants that the honey bees visited. Although honey may also contain airborne pollen from anemophilous (wind pollinated) plants, spores and dust due to direction by the electrostatic charge of bees. Generally, melissopalynology is used to combat fraud and inaccurate labeling of honey. Information gained from the study of a given sample of honey (and pollen) is useful when substantiating claims of a particular source for the sample. Monofloral honey derived from one particular source plant may be more valuable than honey derived from many types of plants.

x. Archaeological study – Archaeological palynology examines human uses of plants in the past. This can help determine seasonality of site occupation, presence or absence of agricultural practices or products and plant related activity areas within an archaeological context.

xi. The distribution of pollen and spores provides evidence of stratigraphical correlation through biostratigraphy and paleoenvironmental reconstruction hence its application in oil and gas exploration.

xii. Palynology also allows scientists to infer the climatic conditions from the vegetation present in an area thousands or millions of years ago. This is fundamental part of research into climate change.

2.6.6 Biological features of spores and pollen

Spores, in the broadest sense, are produced in the cycles of so called “lower plants” or cryptograms, comprising algae, fungi, bacteria and the extensive array of seedless metaphytes. Two basic forms of spores are recognized based on the original relationship of the spore’s tetrad when in the sporangium (Playford and Dettmann, 1996). In tetrahedral tetrads each of the four spores was in contact with all three of its neighbors on its proximal faces, this gives each spores a distinctive trilete or Y- shaped mark. In the tetragonal tetrads, each of the four spores was in contact with only two of its neighbors on its proximal faces, this gives each spore a distinctive rectilinear scar and typically bean- shaped outline. An important point to remember when studying preserved spores is that they are generally compressed proximal- distally, that is along the polar axis, so care is required to differentiate between folds and trilete or monolete mark (Christopher and Goodman, 1996). Further subdivision of spores is based on wall structure and ornamentation. Figure 2.1 shows the terminologies used in the description of the biology of spores and pollen.

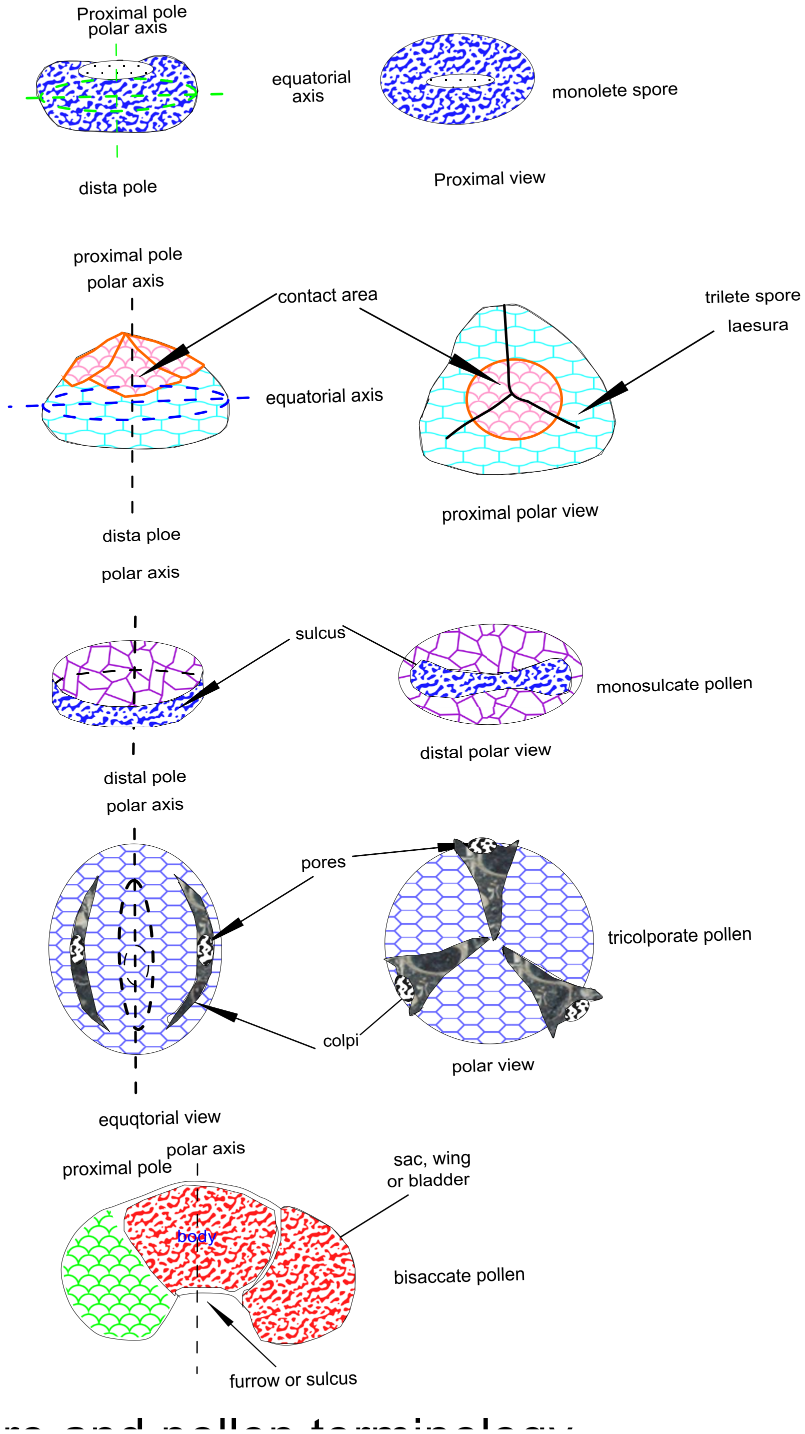

Figure 2.7: Spore and pollen terminology (Redrawn from Playford and Dettmann, 1996).

Pollen is produced by seed plants, both angiosperms and gymnosperms. Pollen has a cellulose wall around the protoplasm called the intine, outside this is the sporopollenin layer which is inert, very tough and resistant to bacteria attack, this layer is called the exine. The pollen of several gymnosperm genera is saccate; that is, grains bear one, two or rarely three air sacs attached to a central body or corpus. Angiosperm pollen is extremely diverse and covers a multitude of combinations of features. Individual pollen grains may be inaperturate, or provided with one or more pores (monoporate, diporate, triporate), slit-like apertures or colpi (monosuclate, tricolpate), or a combination of spores and colpi (tricolporate, syncolporate).

2.6.7 The concept of biostratigraphy

According to Christopher and Goodman (1996), biostratigraphy is defined as "the organization of rock strata systematically into named unit based on content and distribution of fossils". Biostratigraphy and correlation have remained the primary applications of Palynology. Stratigraphic palynology is regarded very important because of the fact that palynomorphs, unlike most of other fossils, are commonly recovered from both marine and non-marine rocks, which provides the potential of correlating terrestrial deposit with those of marine origin.

Reliable biostratigrahpic correlation is dependent on the ability to define, differentiate and recognize biostratigrahpic units. Numerous local, national and international guides and codes have been published that define stratigraphic (including biostratigrahpic) units, more than 35 such codes have been identified by the International Subcommission on Stratigraphic Classification (ISSC) (Christopher and Goodman, 1996). There are three major types of biozones (Salvador, 1994) and these include

(I) the strata between the stratigraphically highest and/or lowest occurrence of taxa referred to as range zone and interval zone

(II) those strata characterized by the association of distinctive assemblages of taxa called assemblage zone and

(III) those characterized by maxima of relative abundance of one or more texa called acme zones or abundance zones.

Lineage Zone has also been recognized by some scheme (NACSN, 1983) as a body of strata containing specimens representing a specific segment of an evolutionary lineage. Some authors however believed that it is better incorporated in either range zone or the interval zone (Hedberge, 1976). A biozone that include the interval of overlap of the ranges of the defining taxa is refered to as concurrent range zone (NACSN, 1983).

Several Criteria are considered in proposing biozones (Christopher and Goodman, 1996) and these criteria include;

(i) the category and rank of the unit,

(ii) its name,

(iii) reference to stratotype,

(iv) a description of the unit (including the criteria that define the unit's boundary),

(v) regional aspects,

(vi) historic background,

(vii) correlation with other units,

(viii) its age and

(ix) a statement of intent to propose a formal unit, published in a recognized scientific medium.

In this study, two (2) biozones are proposed for the stratigraphic column of the studied section of Gombe Formation.

CHAPTER THREE

3.0 MATERIALS AND METHODS

3.1 Materials

The equipment and methods used in this study are based on procedures from Mosunmolu and Getame laboratories where the palynological/palynofacies and Rock Eval analysis were carried out respectively. The core samples used were gotten from Maiganga coal mine. The core samples include shale, siltstone, sandstone and coals and they were recovered from the exploratory boreholes drilled for the coal mining project at Maiganga. For the field work and sample collection, the equipments used were hammer, topographical map of Gombe sheet, Camera, sample bags, masking tape and labeling pen.

For the palynological analysis, the following equipments were used. These include fume cupboard, Branson sonifier 250, Plastic cups, Hot plate, Beakers, Test tubes, warmer, Distilled water, Glass slides, Water distiller, Hydrochloric acid (HCl), Hydrofluoric acid (HF),Hydrogen peroxide(H_2O_2), Palynological microscope, palynological standard album and England finder. For the geochemical analysis, the Rock Eval-6 apparatus was used, while binocular microscope was used to carry out the lithostratigraphic study of the samples.

3.2 Methods

3.2.1 Field work and sample collection

A two-week field exercise was carried out at the project site at Maiganga coal mine and the core samples curiation site at the Ashaka Cement Factory Ashaka, for the purpose of sample collection. A total of 400 core samples collected from 24 exploratory wells (labelled BA 1 – 23 and BA 44?) were sampled, bagged and labelled. The samples were sorted out according to their borehole numbers and depths range and stored in separate bags.

3.2.2 Lithostratigraphic analysis

The core samples were manually crushed to small sized mass and lithologically analyzed under a stereo binocular microscope by comparing the sediment characteristics with Standard Comparative Chart. During the analysis, emphasis was placed on the dominant and secondary rock types, colour, and texture of constituent grains, accessory materials, and fossil contents, nature of cementing material and stage of diagenesis. The lithologic description was routinely complemented by log analysis. The lithologic data are as plotted alongside the range chart using the Stratabugs software.

3.2.3 Palynological analysis

Sample preparation for the palynological analysis were done using the usual acid treatment method as well the newly introduced but yet to be well adopted method of using hydrogen peroxide (H_2O_2) as the maceration medium. However, the use of hydrogen peroxide had two advantages over use of acid viz minimized fear of destroying the palynomorphs as a result of over cooking and complete elimination of possible acid attack in the course of the laboratory work. The hazards of acid inhalation and external destruction to human body as associated with the use of acids in palynomorphs preparation have well been discussed by several authors. In this study, acid was used for BA-7 and BA-16 samples while hydrogen peroxide was used for the preparation of BA-17 samples.

A constant weight (20 g) of each sample was treated with hot hydrochloric acid/hydrogen peroxide to remove carbonates prior to complete digestion in hydrofluoric acid (HF)/hydrogen peroxide solution in a fume cupboard. Gentle agitation of the acid/ hydrogen peroxide / mixture was carried out to aid digestion.

The sample was heated to boiling in hydrochloric acid (HCl)/hydrogen peroxide (H_2O_2) and wet sieved over a 5 micron mesh polypropylene sieve. The sieve was constantly cleaned with iron brush after each usage before it was used for another sample solution to avoid sample contamination. The Branson sonifier 250 was routinely used during sieving to facilitate the complete removal of silt and clay particles. The sieved residue was given controlled oxidation by boiling briefly in concentrated nitric acid (HNO_3). The sample residue was then prepared for microscopic study in the form of strewn mount on glass slide. The mounting medium used was LOCTITE (impruv) manufactured by Loctite corporation, USA. Staining of the slide using infranin O was done in order to enhance the appearance of any dinoflagellate cysts under the microscope most of which are usually fairly transparent in routine (unstained) preparations. Two palynological slides were prepared for each sample (horizon) and analyzed microscopically in order to ensure a complete coverage of the palynomorphs present.

The slides were studied under the binocular microscope, moving north-south, east-west until the whole slide was studied and all taxonomic forms present identified and counted. Stratigraphic markers were noted, their coordinates taken with the aid of England Finder and their photomicrographs also taken. Identification of the palynoforms was aided by the use of standard palynomorph album and some photomicrograph of previous workers.

During the microscope studies, for taxonomy comprising more than 15 % of the flora, only 20 % of the first slide was examined and projected to 100 %. All other taxas were counted completely until the slide is completely analyzed.

3.2.4 Palynofacies analysis

Samples for palynofacies analysis (Visual Kerogen) were prepared in the same way as for palynological analysis. However, the oxidation process with HNO_3 was omitted in order not to bleach the palynodebris (Imogene, 1980). The prepared slides were subjected to the quantitative analysis of palynomacerals (Type I, II, III and IV) as well as the Armophous Organic Matter (AOM).

The whole data generated from the palynological and palynofacies analyses were plotted on STRATABUG with emphasis on palynomorphs of environmental and stratigraphic significance as well as ecological groupings. The LOM and percentage of the different maceral groups were also plotted on the STRATABUGS.

3.2.5 Microscopic analysis

The Palynological slides were examined using transmitted light microscopes commonly under times forty (X 40) dry and times one hundred (X 100) oil immersion objective lenses. Accurate co-ordinates of individual palynomorph on a slide were often given with the aid of either the graduated scale on the traversable slide table of a particular microscope or, preferably, by the use of England Finder co-ordinates.

An England Finder is a specially made slide which is divided into a grid of segments, each one given an alphanumeric reference. When a specimen is located on a slide, slide is carefully removed from the microscope and replaced by the England Finder and the co-ordinates marked down, as long as the orientation of the slide is also noted. It is then possible to relocate the specimen using the England Finder on any microscope. These co-ordinates were taken for marker species mostly during the microscopic work in this study.

3.2.6 Geochemical (Rock-Eval 6) analysis

Fifteen (15) core samples were selected from the 3 out of 24 boreholes (5 samples per borehole) for the Rock-Eval 6 analysis. The selection of the horizon sample was based on the analyzed palynomorph data. Richer palynomorphs horizons were preferentially selected and sampled for the analysis because of their anticipated good results. Also the huge cost of geochemical analyses played a role in the choice of 15 samples out of the lot for the analysis.

The following procedures were systematically observed at the Getame Geochemical Laboratory, PortHarcourt for the analysis.

3.2.6.1 Sample cleaning

The core samples were initially cleaned by seeping in 100 % dichloromethane with shaking followed by decanting of the solvent until the samples were clean. After drying, the samples were washed under running tap water and then dried again in an oven at a pre-set temperature of 30^{o} C.

3.2.6.2 Total organic carbon analysis

Total organic Carbon (TOC) analysis was performed by means of the LECO CS 125 carbon analyzer according to the following procedure.

About 200 mg of the pre-cleaned samples were crushed and accurately weighed into clean LECO crucibles. The rocks were then de-mineralized by hot 10 % HCl and afterwards repeatedly with distilled water. After drying at 60^oC, the crucibles were automatically introduced into the furnace for combustion and measurement of the organic carbon content.

3.2.6.3 Rock-Eval pyrolysis

Rock Eval pyrolysis was performed by means of the Rock – Eval 6 pyrolyser as follows:

Each pre- cleaned portion of the samples were crushed in mortar using pestle and weighed accurately (100 mg approx.) into the sample holder. All the sample holders were transferred into pre-numbered slots in the sample carousel. A commercial standard rock sample was then similarly weighed into other sample holders and slotted into the carousel after every 10 rock samples. Thereafter, the carousel was placed into appropriate location in the instrument and the analysis **START** program button was activated, from then on, the instrument operated automatically until the last sample in the carousel was analyzed.

The analysis process involved the transfer of each sample into the furnace where it was heated initially at 300^0C for three minutes in an atmosphere of helium to release the free hydrocarbons (SI). Pyrolysis of the bound hydrocarbons to give S2 peak followed immediately as the oven temperature was ramped up rapidly to 550^0C at the rate of 25^0C/min. Both the S1 and S2 hydrocarbon peaks were measured using a Flame Ionization Detector (FID). A splitting arrangement permitted the measurement of S3 peak (carbon dioxide) by means of a Thermal Conductivity Detector (TCT).

The instrument automatically recorded the temperature corresponding to the maximum of the S2 peak i.e. Tmax. An in-built computer processed the raw data to afford the values corresponding to the respective Rock – Eval indices. The parameters of rock-eval analysis include the direct measurements (S_1, S_2, S_3, TOC and Tmax) and the derived measurements (HI, OI and PI).

CHAPTER FOUR

4.0 RESULTS AND DISCUSSION.

4.1 Lithostratigraphy

The lithologic analysis of the core samples shows that the entire intervals in the boreholes belong to the Upper Gombe Formation due to its lithological characteristics. The Upper Gombe Formation is made of sand, shale, mudstone and coal facies. The descriptions of the lithostratigraphic units are as described in Figure 4.1 and Appendix F (F.1 to F.3). The lithological logs for other boreholes are as shown in Appendices D (D.1 to D.7).

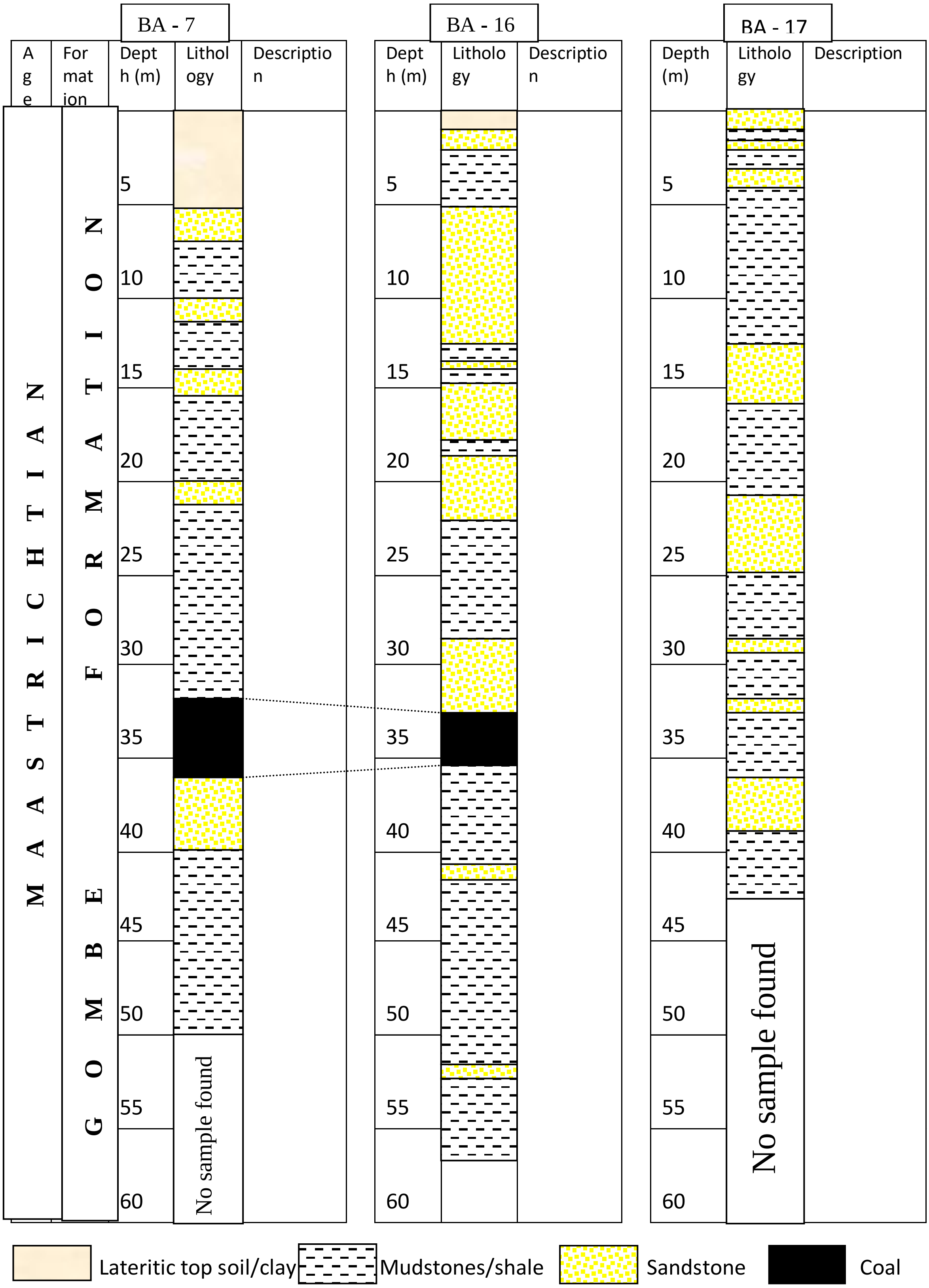

Figure 4.1: Lithology logs for the studied boreholes (BA-7, BA-16, and BA-17).

The analysed boreholes are lithologically made of admixture of sands, shales or mudstones with intercalations of coal seams. Appendix E (E.1 to E.10) shows the photographs of the samples.

4.1.1 Coal seams

Coal seams are encountered in boreholes BA – 7 and 16, 20 as shown in Figure 4.1. The coal seam occur between 33.75 – 36.50 m in borehole BA – 7 and between 33 – 36 m in borehole BA – 16 i.e an inferred thickness of coal seam of 2.75 m and 3 m respectively in boreholes BA – 7 and BA – 16. There are actually two distinct seams of coal within the Maiganga coal mine as observed during the field work and these two seams are currently being mined. The coal seams are intercalated in between an upper sandstone and mudstone facies in all the boreholes where they exist. The above geological setting as typified by Maiganga coal appears similar and correlated with other Nigeria coeval coal deposits (Obaje *et al.,* 1996 a and 1996 b, Obianuju, 2000). The coals found in Gombe Formation are usually dark, hard, striated and crumbles into concoidal fragments when broken.

4.2 Palynomorphs

The results of the palynological analysis are as shown in the form of distribution charts and are contained in the envelope at the back of the thesis (Appendix G) while Figures 4.2 to 4.4 show the interpretational charts for the analyzed palynoforms. Microphotographs of some of the palynomorphs are shown in Appendix A (A.1 to A.7).

The interpretations of the palynomorphs follow the style of several previous authors, e.g (Lawal and Moullade, 1987; Lawal, 1992; Ojo and Akande, 2004; and Ojo and Akande, 2006).

4.2.1 Microfloral assemblage and biostratigraphy

The palynological results presented show the abundance and diversity of the recovered palynomorphs. The boreholes (BA-7, BA-16 and BA-17) that penetrated the Gombe Formation within the studied area (around Maiganga coal mine) are considerably rich in palynomorphs as to permit adequate quantitative analysis and reasonable deductions. The pollen and spores assemblage include angiosperms, gymnosperms and fungal spores.

There are total of 1,151 palynomorph counts within the studied samles, out of which pollen account for 62.29 %, spores, 35.88 % and algae 0.87 %.

Majority of the pollen and spores observed from this study area such as *Proteacidites sigalii, Retidiporites magdalensis, Monoporites annulatus, Cingulatisporites ornatus, Rugulatisporites caperatus, Distaverrusporites simplex, Foveotriletes margaritae, Scabratriporites annellus and Proteacidites longispinosus* have been recorded from the Maastrichtian sediment of Nigerian Basins and other part of west Africa like Senegal, Ivory Coast, Brazil, Gabon, Angola, Egypt and Morocco (Jan Du Chene, 1978; Lawal *et al.*, 1986; Salard- Cheboldaeff, 1990; Oloto, 1994; Ojo & Akande, 2004 and Akande *et al.*, 2005). On the basis of the recovered palynoforms especially the marker species such as listed above and in conjuction with the work of Lawal and Moulade (1987) and Ojo and Akande (2004), the studied boreholes have been rezoned into two assemblage zones as described below (Figures 4.2 to 4.4). These zones, based on their microfloral contents can be correlated with those of Lawal and Moullade, 1987 and Ojo and Akande, 2004. *Retidiporites magdalensis* was also reported from the Late Maastrichtian shale near Auchi in the Anambra Basin (Okosun, personal communication, July14, 2012).

Ojo *et al*. (2004) identified and listed two palyzones for the Gombe Formation based on their study. These are the Assemblage Zone I (S*pinizonocolpites-Echitriporites-Milfordia* sp. Assemblage zone) and the Assemblage Zone II (*Proxapertites operculatus-Retidiporites echimonocolpites* Assemblage Zone). Lawal and Moullade on the other hand named the whole section *spinizonocolpites-baculatus* Zone. In this study, the analysed section of the Gombe Formation have been dated Early Maastrichtian to Late Maastrichtian.

4.2.1.1 Assemblage Zone I (*Proteacidites sigalii – Echitriporites trianguliformis* Assemblage Zone)

Interval: 47 – 23.22 m (BA-7), 57 – 22 m (BA-16), 46 - 21 m (BA-17)

Age: Early Maastrichtian

Diagnosis: This zone is defined by the basal and abundant occurrence of *Proteacidites sigalii, Retidiporites magdalensis* and *Echitriporites trianguliformis* (Figures 4.2 – 4.4).

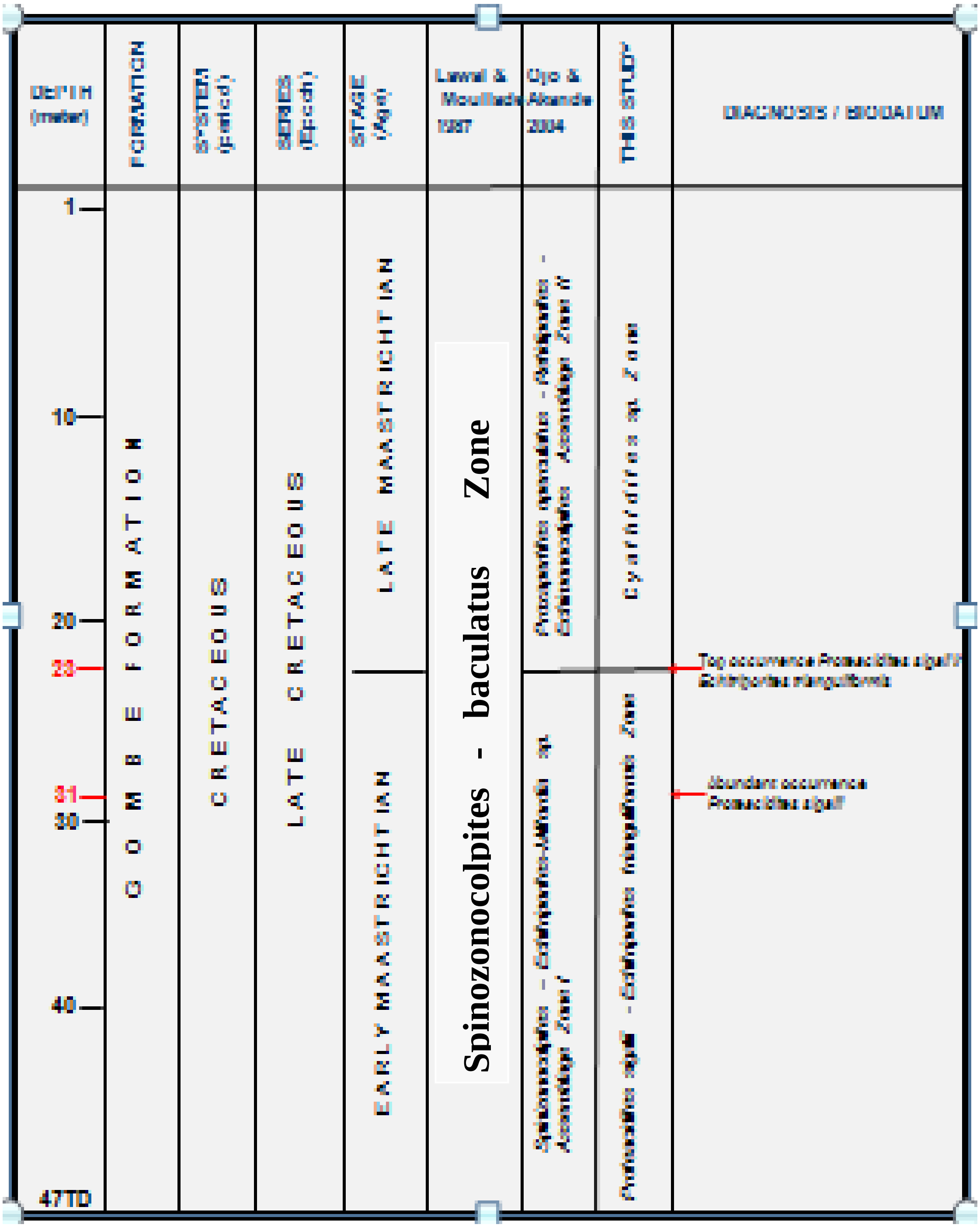

Figure 4.2: Palynomorph Zones recognized in BA – 7 Borehole

The upper limit of this zone coincides with the disappearance of *Retidiporites magdalensis*, *Monoporites annulatus* and *Brevicolporites guinetii* and the abundance top occurrence of *Cyathidites* sp. This zone is also associated with *Perfotricolpites digitatus, Retibrevitricolpites triangulatus, Ctenolophoridites costatus, Retitricolporites irregularis, Proxapertites cursus, Psilamonocolpites marginatus, Psilatricolporites crasus, Proteacidites* sp, *Rugulatisporites caperatus, Sapotaceoidaepollenites* sp, *Proxapertites cursus and Auriculiidites* sp. (Appendix G1 to G3). This zone corresponds to the lower part of the *Spinizonocolpites baculatus* zone of Lawal and Moullade (1987) and the Spinizonocolpites – Echitriporites – Milfordia sp. assemblage zone of Ojo and Akande (2004). Majority of the palynoforms that constitute this zone have been reported by the above earlier workers and have dated the lower part of the Gombe Formation Early Maastrichtian and accordingly, based on the similarity of the palynoforms that constitute the study area with those of the earlier workers, the present study zone is dated Early Maastrichtian.

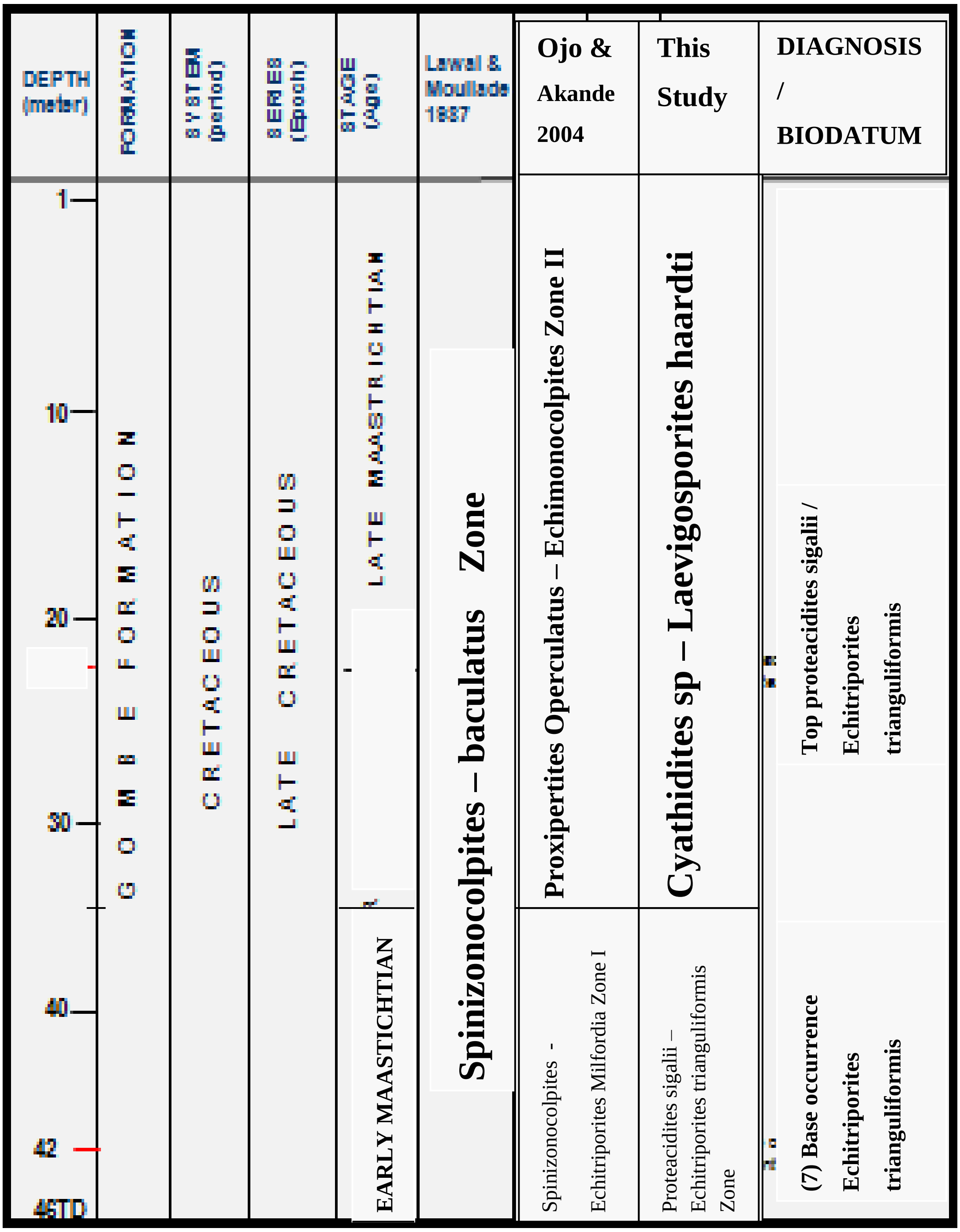

Figure 4.3: Palynomorph Zones recognized in BA – 16 Borehole

4.2.1.2 Assemblage Zone II (*Cyathidites* sp – *Laevigatosporites haardtii* Assemblage Zone).

Intervals: 23.22 – 4 m (BA-7), 22 – 1.0 m (BA-16) and 21 – 1.0 m (BA-17)

Age: Late Maastrichtian

Diagnosis: This zone is defined by the occurrence of *Cyathidites* sp. and other palynoforms that range from the lower zone such as *Longapertites* sp, *Longapertites vandeenburgii, Tricolporopollenites* sp, *Sapotaceoidaapollenites* sp, *Acrostichum aureum, Proxapertites cursus, Laevigatosporites* sp and *Inaperturopollenites* sp. This zone is generally not rich in palynomorphs as the lower zone. This may probably be due to the relative sandy nature of the zone as compared to the lower shaly/mudstone zone which is rich in palynomorph content. This zone is equivalent of the upper *Spinizonocolpites baculatus* zone of Lawal and Moullade (1987) and the *Proxapertites operculatus – Retidiporites echimonocolpites* assemblage zone of Ojo and Akande (2004). On the basis of the correlateable palynomorphs observed in this zone with those of the earlier workers, the zone have been dated Late Maastrichtian.

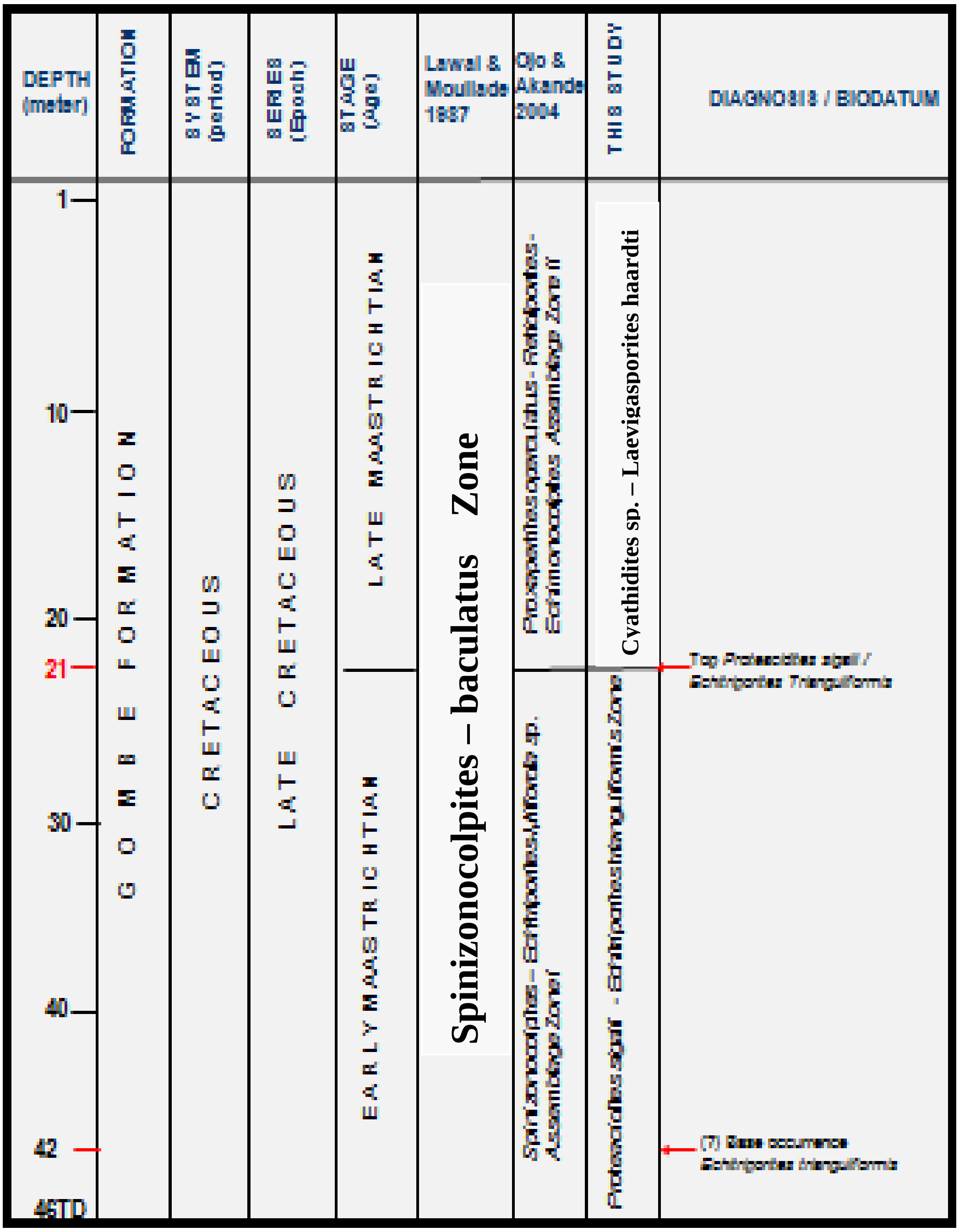

Figure 4.4: Palynomorph Zones recognized in BA – 17 Boreholes

4.3 Systematic Palynology

The systematic palynology adopted in this work generally follows the patterns of Potonie` (1956, 1958, 1960), Dettmann (1963) and Atta-Peters and Salami (2004). Other relevant previous works by Salami (1983), Van Hoeken-Klinkenberg (1964), Ojo (2009), Obianuju (2008) and Aboul Ela (1978) were also consulted especially for synonyms and general descriptions of forms. Finally, the work of Ames and Spackman, 1985 on the catalog of fossil spores and pollen, was widely consulted for species names, general description, authors and references. All species magnification is X 1000.

In this work, the analyzed palynomorphs have generally been grouped into three, namely Pollen, Spores, and Fresh Water Algae. For easy and less cumbersome systematic, the palynomorphs have further been grouped and described under palyno-designated headings such as sporites and pollenites divisions (Aboul Ela, 1978), Pteridophyte spores, Gymnosperm pollen, Angiosperm pollen and Dinoflagellates. Pteridophyte spores will be discussed under sporites while gymnosperm pollen and angiosperm pollen will be discussed under pollenites.

Division: Sporites Potonie`, 1956

Family: Pteridophyte spores

Subdivision TRILETES

A.Genus Cyathidites (Couper, 1953).

Cyathidites minor Couper, 1953

BA – 7, 32.7 m

Appendix A.3, Fig. 6

Description Trilete spore, amb triangular with straight to slightly concave sides and rounded apices. Exine psilate and thick

Age Cretaceous

A. **Genus** Rugulatisporites (Pflug and Thomson, 1953).

Rugulatisporites caperatus Van Hoeken-Klinken-berg, 1964

BA – 7, 35 m

Appendix A.4, Fig. 5

Description Trilete microspore, amb sub-triangular, triangular or spherical, sides convex, radial corners round triangular or sub-triangular forms, trilete mark thin, arms moderate, slightly raised but without margo, exine moderate, rugulate and cavaliculate, both proximal and distal surfaces are sculptured.

Age Cretaceous

B. **Genus** Foveotriletes (Van der Hammen, 1954, ex Protonie, 1956).

Foveotriletes margaritae (Van der Hammen) Germeraad *et al.*, (1968) BA – 7, 32 m

Appendix A.3, Fig. 5

Description The species has foveolate distal surface, thin wall and short less pronounced trilete mark

Age Cretaceous

C. **Genus** Osmunda (Martin and Rouse, 1966).

Osmunda cidites sp. Martin and Rouse, 1966

BA – 16, 40 m

Appendix A.3, Fig. 7

Description Trilete spores, sub-spherical in outline, folded and crumpled. Laesurae faint, thin margo subtending the commissure. The ornamentation consists of slender bacula which are slightly clavate. The bacula are straight and relatively uniform in size, shape and spacing.

Age Cretaceous

D. **Genus** Gleicheniidites (Potonie,1956)

Gleicheniidites senonicus Potonie, 1956

BA – 16, 37m

Appendix A.4, Fig. 4

Description Trilete microspore, trilete mark, thin, amb triangular to sub-triangular, sides moderately concave, corners round, tricrassate but crassitudes are compressed as to appear cicatricose.

Age Cretaceous

E. **Genus** Cingulatisporites (Van Hoeken-Klinken-berg, 1964).

Cingulatisporites ornatus Van Hoeken-Klinken-berg, 1964

BA – 16, 37 m

Appendix A.4, Fig. 2

Description Trilete microspore, amb triangular-round, sides convex, central body surrounded by a distinct ornamented cingulum, trilete mark thin, arme long and extended to the margins of the central body, not bordered by margo, proximal surface convex, smooth but covered by low vernicae, cingulum split into several clavate structures

Age Cretaceous

Subdivision MONOLETE (Potonie, 1956).

F.Genus Laevigatosporites (Protonie, 1956)

Laevigatosporites haardtii Protonie and Venitz

BA – 17, 3 m

Appendix A.2, Fig. 1

Description Monolete spore, posses limited sculptures and usually appears as tiny particles

Age Cretaceous

Subdivision CINGULATISPORATES

G.Genus Zlivisporites (Pacltova, 1959)

Zlivisporites blanensis (Pacltova, 1959)

BA – 17, 27 m

Appendix A.2, Fig. 6

Description Specimen posses' cingulated sculptures which appear to represent residual perisporal membranes.

Age Cretaceous

Subdivision VERRUCATI (Muller, 1968).

H.Genus Distaverrusporites (Muller, 1968)

Distaverrusporites simplex (Muller, 1968)

BA – 16, 29 m

Appendix A.4, Fig. 9

Description Trilete microspore, amb triangular, sides convex, trilete mark thin, arms long and extend to the equatorial margin, not bordered by any margo, exine thick.

Age Cretaceous

Division: Pollenites Potonie, 1956

a. **Class** Gymnospermae

Genus Ephedripites (Boltenhagen and Azema, 1974)

Ephedripites ambigus (Boltenhagen and Azema, 1974)

BA – 7, 32 m

Appendix A.1, Fig. 1

Description The Ephedripites is regarded as a taxanomic synonym of Equisotosporites (Singh, 1964, 1971), multicostate oval in outline, twice as long as broad, narrow ridges, covering the colpi.

Age Cretaceous

b. **Class** Monocolpates (Iversen and Troels-Smith, 1950).

Genus Auriculiidites (Elsik, 1964, Elsik and Thanikaimoni, 1970)

Auriculiidites sp.

BA – 7, 32 m

Appendix A.4, Fig. 7

Description Oval monosulcate pollen grain with auriculate structures at the extremities of the grain. Sulcus long, extending to diameter of the grain, exine thin, and microreticulate. The microreticulate ornamentation and the overall smaller size differentiate this species from A. reticulatus.

Age Cretaceous

c. **Genus** Spinizonocolpites (Muller, 1968).

Spinizonocolpites echinatus (Muller, 1968)

BA – 16, 42 m

Appendix A.5, Fig. 8

Description *S. echinatus* has smooth to finely reticulate ornamentation, closely spaced processes and expanded or bulbous bases.

Age Cretaceous

d. **Genus** Longapertites (Van Hoeken-Klinkenberg, 1964).

Longapertites microfoveolatus (Jan du Chene and Adegoke, 1978)

BA – 16, 47 m

Appendix A.4, Fig. 3

Description Palm pollen, fine foveolate sculpture.

Age Cretaceous

e. **Genus** Longapertites (Van Hoeken-Klinkenberg, 1964)

Longaoertites chlonovae (Boltenhagen, 1978)

BA – 16, 53 m

Appendix A.4, Fig. 8

Description ?

Age Cretaceous

f. **Genus** Monocolpites (Van der Hammen, Pierce, 1961).

Retimonocolpites sp. (Pierce, 1961)

BA – 7, 22 m

Appendix A.1, Fig. 7

Description Intectate reticulate, monocolpate pollen grain, endocolpi only. The lumina of the reticulum vary in size, appearing smaller on the two extremes of the pollen grain.

g. **Class** Porosa (Potonie, 1970).

Sub-class Triporines (Potonie, 1956)

Genus Proteacidites (Cookson, 1950)

Proteacidites sigalii Boltenhagen, 1978

BA – 17, 20 m

Appendix A.3, Fig. 9

Description Pollen sub-isopolar, oblate, angularperturate, triporate. Amb angular, sides nearly straight, apertures sub-circular, exine slightly thicker in the equatorial inter-aperturate regions, sexine about half as thick as nexine, ornamented with reticulum.

Age Cretaceous

h. **Sub-class** Triporines (Potonie, 1960).

Genus Echitriporites (Van Hoeken-Klinkenberg, 1964)

Echitriporites trianguliformis (Van Hoeken-Klinkenberg, 1964)

BA – 17, 21 m

Appendix A.5, Fig. 2

Description It is characterized by fine echinate or spinose form. Triporate, triangular in polar view, pores circular, thick wall, structureless, surface psilate, rather densely and even covered with spines, conical shaped with fairly sharp points.

Age Cretaceous

i. **Class** Tricolpates (Iversen and Troels-Smith, 1950).

Genus Retitricolpites (Van der Hammen, 1956a)

Retitricolpites irregularis (Van der Hammen, 1956b)

BA – 7, 47 m

Appendix A.4, Fig. 6

Description Tricolpate pollen grain, probably iso-polar, radially symmetrical, colpi short, exine thick and coarsely reticulate.

Age Cretaceous

j. **Class** Psilatricolpates (Van der Hammen and Wymstra, 1964)

Genus Psilatricolpites (Van der Hammen and Wymstra, 1964)

Psilatricolporites crassus (Van der Hammen and Wymstra, 1964)

BA – 17, 38 m

Appendix A.2, Fig. 2

Description Psilate tectate pollen grain with clearly visible collumellae, tricolpate,

constricticolpate, constriction indistinct and short.

Age Cretaceous

k. **Class** Proxaperturates (Van der Hammen, 1956).

Genus Proxapertites (Van der Hammen, 1956b)

Proxapertites cursus (Van Hoeken-Klinkerberg, 1966)

BA – 17, 37 m

Appendix A.2, Fig. 7

Description Proxaperturate pollen grains, reticulate, under the muri of the reticulum are columellae, but most of the lumina are without columellae, semi-tectate

Age Cretaceous

l. **Class** Stephanocolpates

Genus Tubistephanocolpites (Salami, 1983).

Tubistephanocolpites cylindricus (Salami, 1983)

BA – 7, 33 m

Appendix A.1, Fig. 8

Description Stephanocolpate pollen, it is circular to sub-circular in outline, encircled by meridionally arranged colpi with pores. Exine is smooth.

Age Cretaceous

m. **Class** Droseraceae

Genus Droseridites (Cookson, 1950 ex. potonie, 1956).

Droseridites senonicus (Cookson, 1950)

BA – 7, 23 m

Appendix A.3, Fig. 4

Description The species is characterized by inaperturate and spinose pollen grains that are united in loose tetrahedral tetrads. The grains are prolate, striate and tricolpate. The colpi are slender and long, the striae are very fine, densely packed and situated parallel to the polar axis.

Age Cretaceous

n. **Class** Monoporates

Genus Monoporites (Cookson, 1950)

Monoporites annulatus (Van der Hammen, 1954)

BA – 17, 23 m

Appendix A.5, Fig. 1

Description The species consists of a spherical, often thin-walled and rather large grain, with a single pore. They are characteristics of grasses.

Age Cretaceous

o. **Genus:** Monocolpopollenites (Pflug and Thomson, 1953).

Monocolpopollenites sphaeroidites (Pflug and Thomson, 1953)

BA – 7, 29 m

Appendix A.1, Fig. 3

Description Monocolpate copus, spherical in shape.

Age Cretaceous

4.4 Statistical Analyses of the Palynomorphs

Various statistical analytical methods have been employed by several previous authors in palynological data analyses and these analytical methods includes; pie charts, bar charts, principal component analysis and average linkage cluster analysis (multivariate statistical analysis) (Clapmam, 1972; Spicer and Hill, 1979; Kovach, 1986, 1988 and 1989;Francisca, 1992; Obianuju and James, 2008; Ojo, 2009). These statistical analytical methods give visual quantitative impression of the palynomorphs as well as their associative tendencies. According to Francisca (1992), the use of multivariate analytical methods in palynological and paleobotanical studies has become more wide spread. The choice of methods depends on the type of data and the specific problems being solved (Kovach, 1989, Fracisca, 1992). Bar charts and multivariate analytical methods (principal components analysis and average linkage cluster analysis) were employed in this study in order to have a quantitative view of the palynomorphs as well as to identify the groups of palynomorphs types which are associations of the variables contained within the data available.

4.4.1 Bar charts

The computed various components of the palynomorphs from the three boreholes analysed are as shown in the form of bar chart in Figures 4.5 to 4.7. Pollen appears most abundant in BA – 7 borehole samples, followed by spores while algae are in negligible quantities.

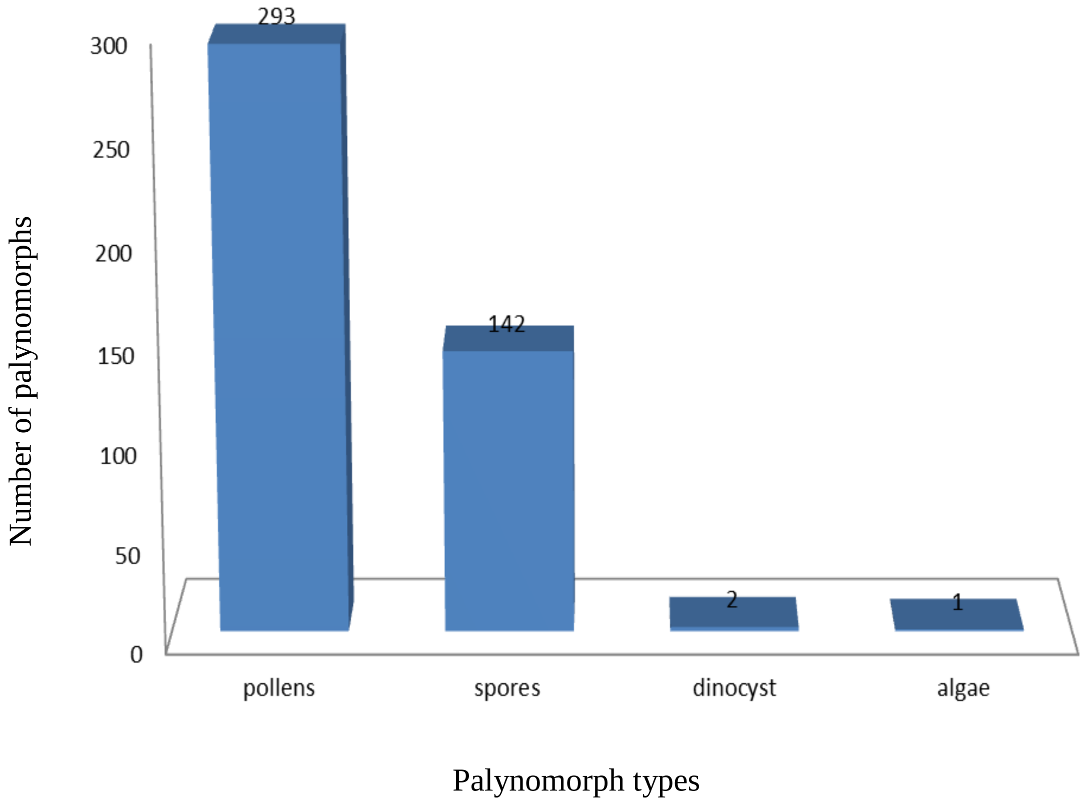

Figure 4.5: Palynomorph distribution for BA – 7

Conversely, in BA – 16, spores appear most abundant, followed by pollen. Algae are also insignificant quantitatively.

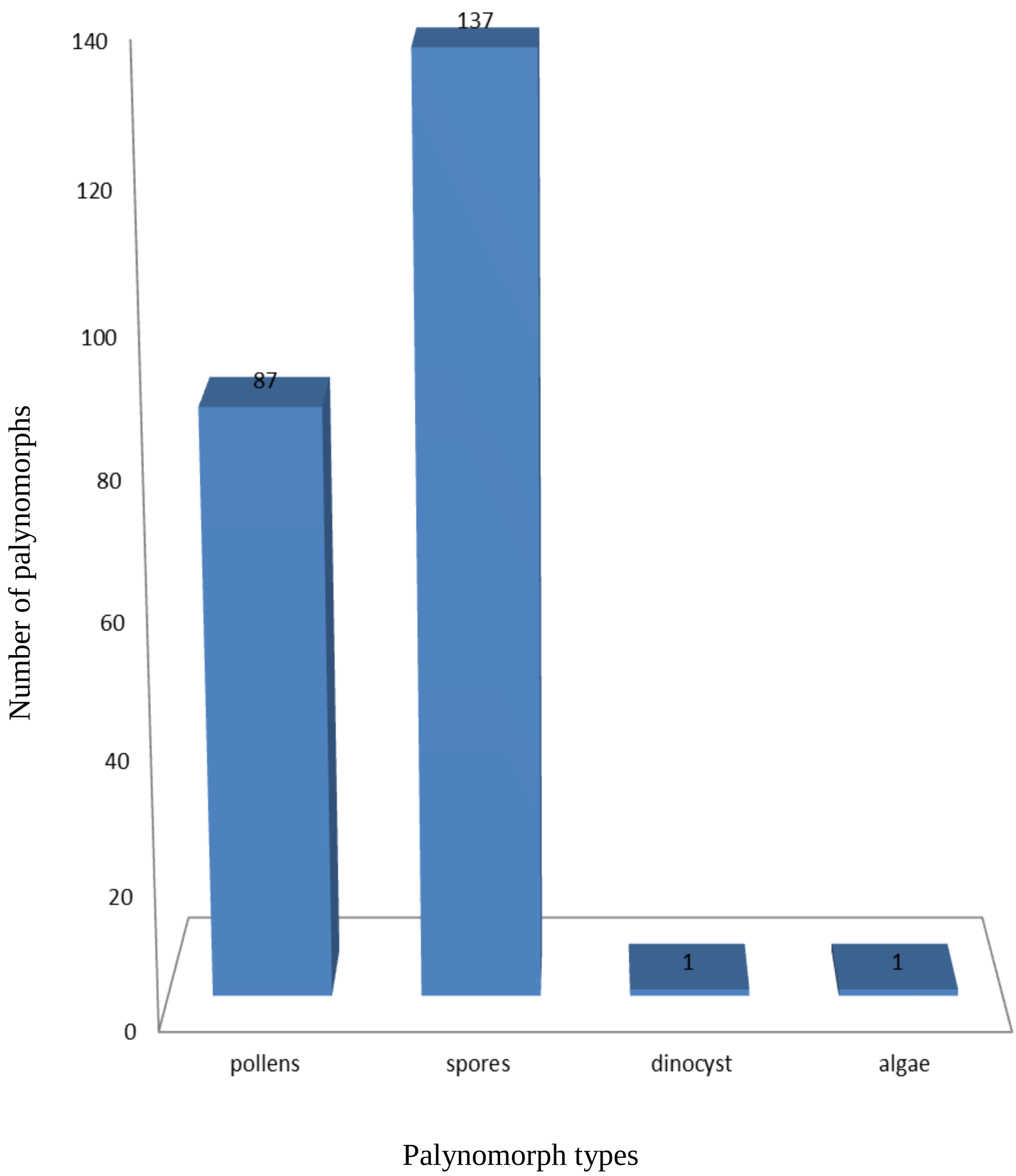

Figure 4.6: Palynomorph distribution for BA – 16

Also in BA – 17, the percentage abundance of the palynomorphs are similar to those of the BA – 7 with pollen dominating, followed by spores and fewer algae.

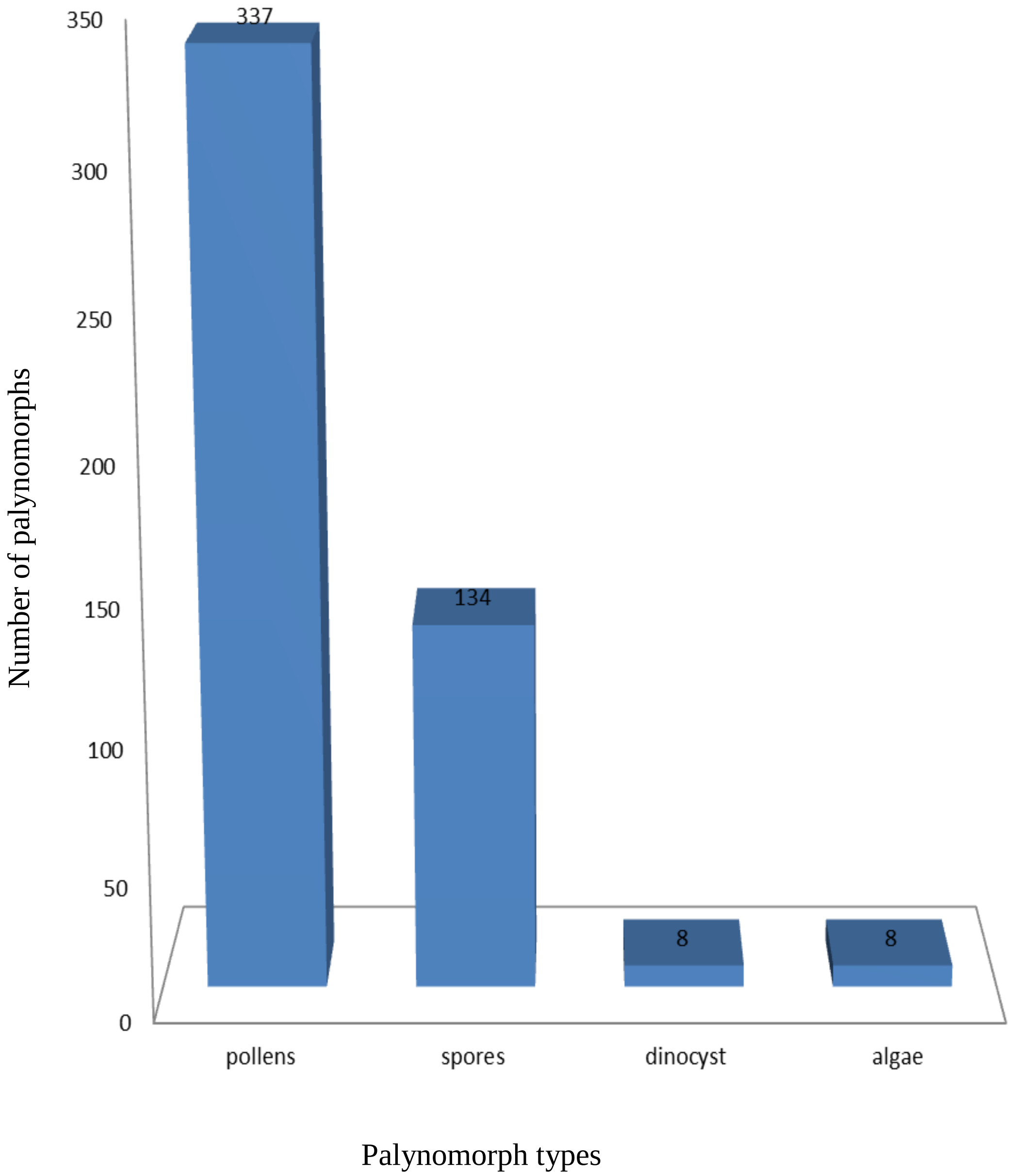

Figure 4.7: Palynomorph distribution for BA – 17

4.4.2 Multivariate statistical analyses

These methods include principal components analysis and average linkage cluster analysis and their results are as discussed below. The style of analysis and interpretation adopted here was taken from the work of Francisca (1992).The software application used for this analysis is SPSS (Statistical Package for Social Sciences).

4.4.2.1 Principal components analysis

From the analysis carried out using the principal components analysis method, it is evident that one principal component account for more than 75 % of the total variance of a centered correlation matrix based on log transformed palynomorphs data (Tables 4.1).

Table 4.1 : Correlation matrix[a]

Eigenvectors (component loadings)				
	PC 1	PC 2	PC 3	PC 4
Pollen	1.000	-.022	.732	.636
Spores	-.022	1.000	-.697	-.786
Dinocysts	.732	-.697	1.000	.991
Algae	.636	-.786	.991	1.000

a. This matrix is not positive definite.

When the palynomorphs with high component loading within each component are identified, four possible palynomorph associations could be defined. From Table 4.1, in principal component 1 (PC 1), pollen, dinocysts and algae have high positive loadings while spores have a high negative loading. Principal component 2 (PC 2) is characterized by high positive loading for spores and high negative loadings for pollen, dinocysts and algae. In principal component 3 (PC 3), pollen, dinocysts and algae have high positive loadings while spores have high negative loadings. Principal component 4 (PC 4) is characterized by high positive loadings for pollen, dinocysts and algae and high negative loadings for spores.

According to Francisca (1992), the ordination by principal components analysis is most affected by palynomorphs occurring in high abundances and those with low abundances are not distinguished. Since some of the low abundance types might be environmentally significant, the method of principal component analysis does not give a very satisfactory interpretative result. In this study, pollen and spores have high abundances while dinocysts and algae have low abundances, hence the use of cluster analysis method which gives a more prescise details of the variables.

4.4.2.2 Average linkage cluster analysis

The unweighted pair group average linkage cluster analysis on a matrix generated by the Spearman rank –order correlation coefficient is comparatively more suitable for multivariate analysis of palynological data (Francisca, 1992). However, other known orders of correlation coefficient exists e.g Pearson and Kenel-al which are mostly used for bivariate analyses. The length of the branches of the dendogram presented in Figure 4.8 depends on the average similarity of each group as they are fused. Since the clusters in the palynomorphs are derived from a single similar analysis, they can be said to be mathematically related. With the data matrix displayed in the dendogram, the structure of the original data can be seen along with the dendogram.

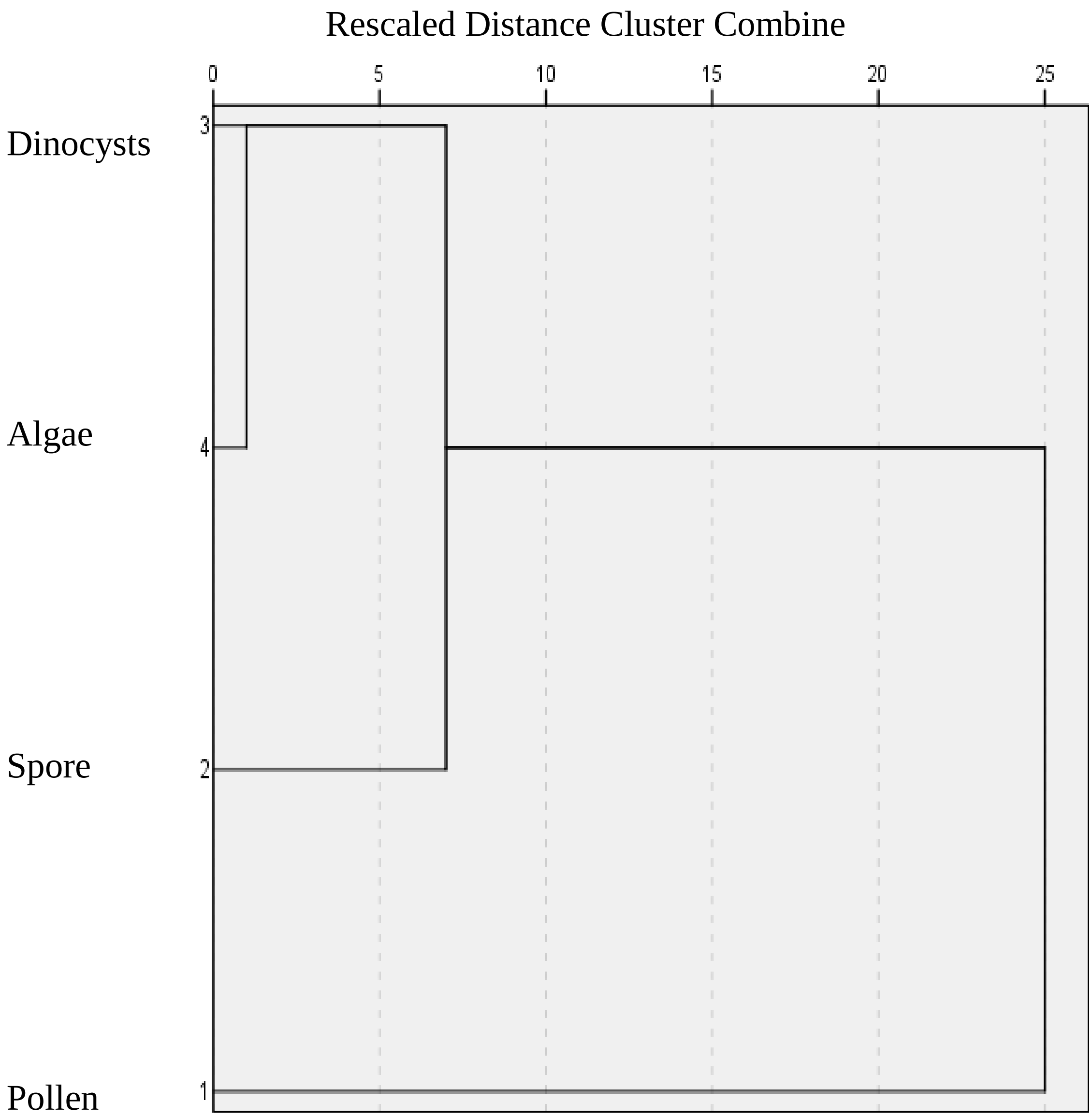

Figure 4.8: Dendrogram using Average Linkage Cluster Analysis.

From the dendogram, two groups or assemblages of palynomorphs can be characterized in the left-hand dendogram by the presence of certain dominant palynomorphs. Pollen and spores occur in high frequencies throughout the boreholes while dinocysts and algae spores are of low frequencies in the boreholes. Generally, low frequency palynomorphs have little effect on the formation of the main groups, particularly where they occur in low abundances in samples.

The dendogram for the palynomorphs components shows two associations with one sub-cluster. The first association has a strong linkage of pollen and spores association which is obvious from the microscopic analysis counts. Dinocysts and algae spores show the weakest linkage in the second sub-cluster. The occurrence of the pollen/spore association is an indication of terrestrial environment.

4.4.3 Palynoform associations

The two assemblages in the sample dendogram in Figure 4.8 can be treated as indicators of palynoforms because they also confirm most of the observations made from the microscopic analysis work. Consequently, the assemblages have been grouped into two associations.

Pollen / spore association: - This palynomorph association is dominated by two palynoforms: pollen and spores, with each of them accounting for more than 40% of the palynomorphs.

Dinocyst / algae / spore association: - This association is characterized by the presence of dinoflagellate cysts and algae, with each accounting for less than 10% of the total palynomorphs. This association has very low species abundances and rarely more than one biodiversity.

4.5 Paleoenvironment and Paleoclimatic Deductions

4.5.1 Paleoenvironment interpretation

Paleoenvironments of the studied borehole sections of the Gombe Formation are discussed based on their lithological and palynofloral characteristics. The predominance of argillaceous strata (shale or mudstone) in the studied sections (Figures 4.1) suggests deposition largely by suspension setting mode in quiet energy setting, probably, swamps and flood plains (Akande *et al.,* 2005). On the other hand, the sandstone deposition phase must have represented a more agitated environment, probably paralic environment whilst the coal seam intercalation is an indication of swampy environment in an anoxic condition during which the environment of deposition was highly depleted in oxygen supply. The abundance of woody and vegetal materials e.g. *Acrostichum aureum, Retitricolporites* which are land derived in the Formation indicates prevalence of fresh water conditions. According to Akande *et al*. (2005), Palynological data is useful tool in Paleoenvironmental analysis and he posited that Palynomorph assemblage with a higher content of large land derived pollen and spores indicate terrestrial source and vice versa. Carter *et al*. (1963) interpreted Gombe Formation as a deltaic and estuarine deposit.

Recently, Zaborski *et al*. (1997) suggested a deltaic – like deposit on the basis of Lithofacies relationships.

4.5.2 Paleoclimatic interpretation

The Paleoclimatic scenario of the studied section of the Gombe Formation is examined based on the pollen/spores data which offer clues for paleoclimatic deductions. Several studies have indicated that the major differences in vegetation across the globe at various geological times are due to variation in climates (Akande *et al*., 2005). According to Akande *et al*. (2005), Hergreen and Chlonova (1981) established eight microfloral provinces, the pre-Albian West Africa- South America province **(WASA**), the boreal Lower Cretaceous province of the north hemisphere, the middle Cretaceous (Albian to Cenomanian) Africa- South America province (ASA), the Upper Cretaceous Normapolles Province and Aquillapollenites province , the late Cretaceous Palmae province of Africa and northern south America, the Godwana province and Senonian Northofagidites province. The Cretaceous microfloral province as discussed by Hergreen and Chlonova (1981) show that West Africa belongs to the late Cretaceous Palmae province. The position is supported by the recovered pollen and spores in the studied area. Palmae pollen and spores such as *Acrostichum aureum, Proxapertites cursus, Retidiporites magdalensis, Longerpertites, Auriculidiites reticulatus, Echitriporites trianguliformis, E. longispinosus, Gleicheniidites senonicus* in the studied section of Gombe Formation microfloral is a strong indication that the sediments belong to the Late Cretaceous Palmae Province. This correlates strongly with the Maastrichtian Patti Formation of the Lower Bida Basin and the Maastrichtian sediments of the northeastern and southern Nigeria (Jan Du Chene, 1980; Ojo & Akande, 2004; Ojo *et al.*, 2004), based on pollen and spores, suggested a tropical climatic condition for the Gombe Formation.

4.6 Comparison of the Palynomorph in Gombe Formation with some Coeval Formations in Nigeria

The present study have revealed some biostratigraphic significant spores and pollen that can permit reasonable correlation with other known coeval Formations in Nigerian sedimentary basins such as Patti Formations (Bida Basins), Nkporo, Nsukka and Mamu Formations (southeastern Nigeria) as well as some adjacent sub-Formations within the

Benue Trough (Table 4.2). Some of the biostratigraphic significant forms recovered from the study area include *Proteacidites sigalii, Retidiporites magdalensis, Monoporites annulatus, Cingulatisporites Ornatus, Rugulatisporites caperatus, Distarerrusporites simplex, Foveotriletes margaritae, Scabratriporites annellus and Proteacidites longispinosus*.

The above marker species have been employed as the basis for the biozonation of the study area (Maiganga coal mine, Gombe Formation) and have also been used to infer the paleoenvironment and paleoclimate of the Formation.

The inferred assemblage zones for the studied area have been dated Early Maastrichtian to Late Maastrichtian. From the above, it is evident that the studied boreholes which penetrate the Gombe Formation are mostly characterized by Maastrichtian palynoforms and their paleoenvironments have been inferred to be swampy and flood plain environments.

Paleoclimate of the studied section on the other hand have been interpreted to belong to the late Cretaceous Palmae province of Hergreen and Chlonova (1981) based on the recovered pollen and spores. Comparatively, the analyzed palynoforms from the studied boreholes of the Gombe Formation are similar and correlate chronologically with similar coeval formations across Nigeria.

According to Okosun (personal communication on July 14th 2012), *Retidiporites magdalensis* was reportedly observed in the Maastrichtian Auchi sediment in the Anambra Basin. Also, Ojo and Akande (2006) have reported the presence of *Echitriporites trianguliformis, Longapertites and Monocolpites magnatus* in the Lower Bida Formation and have dated the Formation Maastrichtian just like the Gombe Formation. Lawal & Moullade (1987) and Salami (1990), have also reported similar microfloral content as described in Gombe Formation in the Lower Coal Measures (Mamu Formation) of the Anambra Basin which were also dated Campanian to Maastrichtian age.

Furthermore, Akande *et al.* (2005) have equally reported similar microfloral assemblage like those of the Gombe Formation within the Patti Formation in the southern Bida Basin and have dated the Formation Maastrichtian based on the recovered forms. The authors have reported forms such as *Buttina andreeri, Retidiporites magdalensis, Echitriporites trianguliformis, Echimonocolpites, Cristaeturites cristatus* and *Longapertites* which are similar to those of the Gombe Formation.

Obianuju (2005) had also reported the presence of similar palynoforms as in Gombe Formation from the Okaba Coal Mine (Mamu Formation) and had dated the Formatiom Maastrichtian-Danian age. Similarly, Obianuju and Nwajide (2007) have reported several similar palynoforms as in Gombe Formation within the Nsukka Formation of Anambra Basin. The authors dated the Nsukka Formation late Maastrichtian to Danian based on the analyzed palynoforms. Similar forms that can be used to correlate the Gombe Formation and the Nsukka Formation include *Echitriporites spinosus, Scabratriporites simpliformis Verrucatosporites* sp., *Monoporites annulatus and Proteacidites dehaani*.

Table 4.2: Comparison of Gombe Formation with some coeval formations in Nigeria

FORMATION	SED. BASIN	NAME OF PREVIOUS WORKERS	MICROFLORAL SPECIES (MARKER FORMS)	DEDUCED AGE
Gombe (Present Study Area)	Benue Trough	Ojo and Akande (2004), Lawal (1982), Lawal and Moullade (1986)	*Proteacidites sigalli, Retidiporites magdalensis, Monoporites annulatus, Cingulatisporites ornatus, Proteacidites dehaani, Foveotriletes margaritae, Proteacidites longispinosus, Dinogymnium* spp, *Cyathidites* sp, *Echitriporites trianguliformis,*	Campanian-Tharentian
Nkporo Shale Formation	Anambra Basin	Obianuju (2005, 2008)	*Echitriporites trianguliformis, Longapertites, Monocolpites magnatus*	Maastritchtian
Mamu Formation	Anambra Basin	Obianuju (2005, 2008), Salami (1990)	Similar to those of Gombe Formation	Campanian-Maastritchtian
Patti Formation	Bida Basin	Ojo and Akande (2006), Ojo, (2009)	*Dinogymnium* sp, *Retidiporites magdalensis, Retimonocolpites, Echimonocolpites, Echitriporites, Monocolpites marginatus*	Campanian-Maastritchtian

4.7 Discussion of Palynofacies

The palynomaceral recovered from the processed BA-7, BA-16 and BA-17 core samples were studied with a view to knowing the palynodebris types, their distribution and the environments of deposition for these three boreholes. In this study, the establishment of the palynofacies is only based on the organic content (palynomacerals) in conjuction with the detailed palynological analyses carried out which were used in the paleoenvironmental interpretation. The descriptions of the various palynomacerals observed are discussed as follows. The plots of the charts for the palynofacies are contained in an envelope at the back cover of the thesis and labeled Appendix H.

In this study, the palynofacies observed from the three studied boreholes are grouped into 4; namely Amorphous Plant Matter (PM I), Vitrinitic Brown and Black Wood (PM II), Curticle and Membraneous Debris (PM III) and Platy Tricheidal Debris (PM IV). The fift group, Structureless Organic Matter (SOM) is considered to be same with the Amorphous Organic Matter and hence, have been treated as one in this study.

4.7.1 Amorphous plant matter (PM I)

These palynofacies types occur as irregularly shaped, brown masses with no cellular details. They appear like jelly material and exhibit clotted appearance and are believed to be alteration products of bacterial and thermal degradation rather than primary material (Oboh, 1992). Thus, it can be inferred that the above reason account for the presence of the Amorphous Plant Matter judging from the immature status of the boreholes sediments analysed (cf. thermal maturity of the analysed samples). The brownish colour of the organic matter suggest terrestrial source as against the gray-coloured marine source. The Amorphous Plant Matter is present in high amount in the three boreholes analysed (Appendix H.1 to H.3)

4.7.2 Vitrinitic brown and black wood (PM II)

These palynofacies group show some cellular structures, appear brown to black and sometime opaque in colour and dense. They are lath-shaped with some showing equidimensional appearance.Their sizes vary from sample to sample, but generally appear like well preserved word. These categories of palynofacies are variously called black wood, charcoal or inertinite by several authors (Oboh, 1992). These fragments are more common in the shales and coal samples and are next to PM I in abundance.

4.7.3 Cuticles and membraneous debris (PM III)

This class of palynofacies appears pale yellow to light brown in colour and range in size from 20μm to over 150 μm. They are more prevalent in the shales and mudstones than the sandstones. These fragments are generally less abundant in the samples analysed across the three boreholes. According to Oboh (1992), curticles are thin, platy epidermal fragments from non woody organs such as leaves and roots. Their buoyant nature ensures their easy dispersedal by water.

4.7.4 Platy tricheidal debris (PM IV)

This class of palynofacies is well preserved woods, with some black and brown stripped tricheidal debris. They are lath-shaped and vary in sizes. They are elongated, tapering cells in the xylem having woody, pitted and intact walls adopted for conduction and support in plants. These palynofacies are well distributed across the three boreholes sampled.

4.7.5 Environmental significance of the palynofacies

An integration of the palynofacies characteristics with lithofacies and palynoforms results of the studied samples suggests two sub-environments. These are terrestrial and coastal depositional environment characterized by the common to abundant occurrence of fungal spores and poorly sorted palynomacerals I and II.

By inference therefore, the studied sections of the Gombe Formation around Maiganga Coal Mine can be interpreted as aproduct of terrestrial/coastal and paralic depositional interplay. The above is supported by the analysed palynofacies and palynoforms and their associations.

The sandstone facies of the Gombe Formation are most likely deposited in high energy environments as compared to the shale/mudstone facies which are likely deposited in a relatively lower energy environment. The plant debris associated with the sandstone facies are usually dense, larger and more equidimensional than those of the shale/mudstone facies which are mainly lath-shaped which usually allow them float on water for a longer period before deposition (Oboh, 1992).

4.8 Presentation and Discussion of Geochemical (Rock-Eval) Analysis Results

The results (TOC; SI; S2; S3; Tmax) obtained from the Rock–Eval 6 pyrolysis are tabulated in Tables 4.3 a, b and c. Also, in these tables are the HI; OI; PP; and PI. Some important plots derived from the Rock - Eval data are S2 vs. TOC; HI vs. OI and Tmax vs. HI are shown in Figures 4.9 to 4.19.

Table 4.3 a: Rock- eval pyrolysis result of samples from borehole BA-7

	a	b	c	d	e	f	g	h	I	j	k	l	m
BOREHOLE													
BA – 7													
BA 7a	31.32	10251	Shale	4.27	0.77	9.82	3.78	430	230	88	10.59	2.60	0.07
BA 7b	32.70	10252	Shale	4.23	0.75	9.88	3.80	431	234	90	10.63	2.60	0.07
BA 7c	34.60	10253	Shale	4.20	0.72	9.80	3.78	430	233	90	10.52	2.59	0.06
BA 7d	19.36	10254	Shale	4.25	0.76	9.77	3.81	433	230	90	10.53	2.56	0.07
*BA7e	36.34	10258	Coal	47.10	1.70	123.02	18.66	426	261	40	124.72	6.59	0.01

Where

a: Depth (m) **b:** Lab. No **c:** Lithology **d:** TOC (w %) **e:** S1 (mg/g)

f: S2 (mg/g) **g:** S3 (mg/g) **h:** Tmax ^{0}C **i:** HI (mgHC/gTOC) **j:** OI (mgCO_2/gTOC)

k: S1 + S2 (mgHC/g rock) **l:** S2/S3 (mg/g) **m:** PI S1/ S1 + S2 (wt ratio)

Table 4.3 b: Rock- eval pyrolysis result of samples from borehole BA-16

	a	b	c	d	e	f	g	h	I	j	k	l	m
BOREHOLE													
BA – 16													
*BA 16a	33.75	10256	Coal	47.07	1.72	122.04	18.63	422	259	40	123.76	6.60	0.01
*BA 16b	35.12	10257	Coal	47.00	1.68	120.10	18.60	430	256	40	121.78	6.45	0.01
BA 16c	22.71	10255	Shale	4.26	0.81	9.81	3.78	427	230	89	10.62	2.59	0.07
BA 16d	41.42	10259	Shale	3.50	0.45	2.50	2.10	420	259	38	2.95	1.19	0.01
BA 16e	54.40	10260	Shale	3.55	0.43	2.61	2.01	431	262	40	3.04	1.29	0.01

Where

a: Depth (m) **b:** Lab. No **c:** Lithology **d:** TOC (w %) **e:** S1 (mg/g)

f: S2 (mg/g) **g:** S3 (mg/g) **h:** Tmax ^{0}C **i:** HI (mgHC/gTOC) **j:** OI (mgCO_2/gTOC)

k: S1 + S2 (mgHC/g rock) **l:** S2/S3 (mg/g) **m:** PI S1/ S1 + S2 (wt ratio)

Table 4.3 c: Rock- eval pyrolysis result of samples from borehole BA-17

	a	b	c	d	e	f	g	H	I	j	k	l	m
BOREHOLE													
BA – 17													
BA 17a	37.26	10261	Shale	2.21	0.24	2.03	1.46	429	92	66	2.27	1.40	0.11
BA 17b	39.34	10262	Shale	2.00	0.24	2.03	1.50	426	102	75	2.27	1.35	0.10
BA 17c	19.25	10263	Shale	2.22	0.22	2.06	1.47	425	93	66	2.28	1.40	0.09
BA 17d	16.74	10264	Shale	2.24	0.27	2.07	1.44	430	92	64	2.34	1.43	0.11
BA 17e	23.05	10265	Shale	2.18	0.28	2.04	1.44	430	94	66	2.32	1.41	0.12

Where

a: Depth (m) **b:** Lab. No **c:** Lithology **d:** TOC (w %) **e:** S1 (mg/g)

f: S2 (mg/g) **g:** S3 (mg/g) **h:** Tmax ^{0}C **i:** HI (mgHC/gTOC) **j:** OI (mgCO_2/gTOC)

k: S1 + S2 (mgHC/g rock) **l:** S2/S3 (mg/g) **m:** PI S1/ S1 + S2 (wt ratio)

4.8.1 Organic matter concentration

The amount of organic carbon (TOC) is a measure of the quantity of organic matter in the source rocks (Tissot and Welte, 1984). A rock that is organic matter lean is automatically excluded from further screening for hydrocarbon source potential. As shown in Table 4.3 a, b and c, the Total Organic Carbon (TOC) for boreholes BA – 7, BA – 16 and BA – 17 vary from 4.20 to 4.27, 3.50 to 4.26 and 2.00 to 2.24 % respectively with the exception of the coal samples whose TOC values vary from 47.00 to 47.10 % in boreholes BA-7 and BA – 16 where the coal seams were penetrated. These TOC values indicate a moderate organic matter concentration (Tissot and Welte, 1984) except for the coal samples that the TOC values are considered high. A minimum of 0.5 % TOC is required for a good source rock (Peters, 1986; Obaje *et al.*, 2006).

The Hydrogen index (HI) value ranges from 230 to 261 mg HC/ g TOC in samples from borehole BA – 7, 230 to 262 mg HC/ g TOC in BA – 16 and 92 to 102 mg HC/g TOC in BA - 17 with overall average HI of 195.13 mg HC/g TOC for the three studied boreholes and this represents the measure of hydrogen richness of the source rock. These HI values are considered adequate for a good source rock (Tissot and Welte, 1984).

The oxygen Index (OI) measured in mg CO_2/gTOC vary from 40 to 90 in BA – 7, 38 – 89 in BA – 16 and 64 – 75 in BA – 17 with a general average of 65.47 mg CO2/gTOC for the fifteen samples analyzed from the Gombe Formation. The OI is measure of the oxygen richness of the source rocks. High OI value (>50mg CO2/gTOC) indicate immature sediment (Peters, 1986). Hence the average analyzed value of 65.47 mgCO2/gTOC of OI for the samples is an indication of immature sediment within the Gombe Formation, though other parameter will have to be considered in adjudging the formation for hydrocarbon generation. Figure 4.24 shows the distributions (trends) of the TOC values of the analysed samples in boreholes BA-7, BA-16 and BA-17. Note: The coaly samples in boreholes BA-7 and BA-16 are excluded in the plot as their values seem to obscure the trends.

4.8.2 Type and quality of organic matter

The quality of organic matter in the source rock facies of the Gombe Formation was from the Rock – Eval generated data (HI and Tmax). The analyzed samples from the Gombe Formation plot mainly along the type II and III kerogen evolutionary pathway as indicated by the plot of HI against Tmax (Figures 4.9 to 4.11).

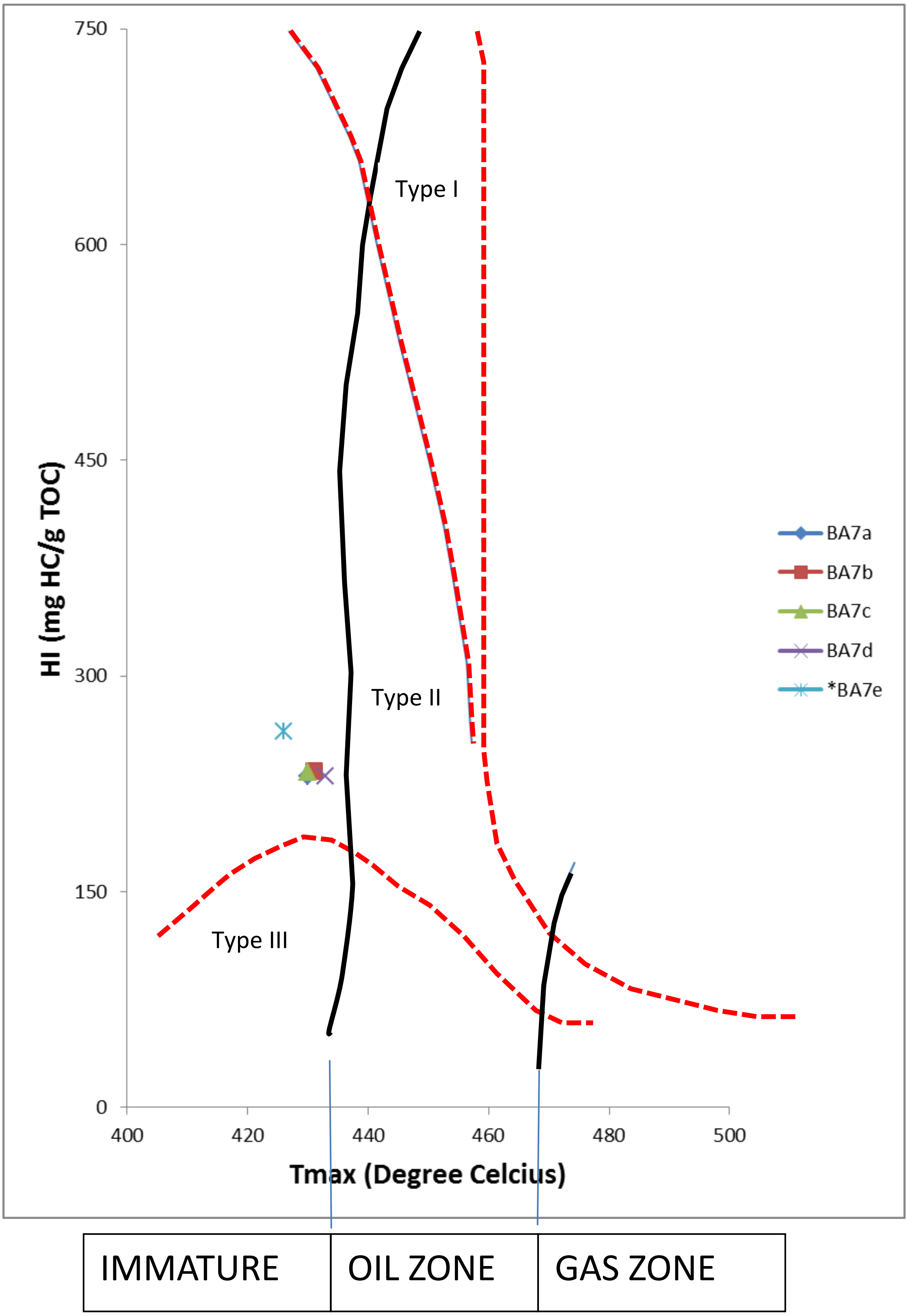

Figure 4.9: Plot of HI vs. Tmax for BA – 7 Borehole

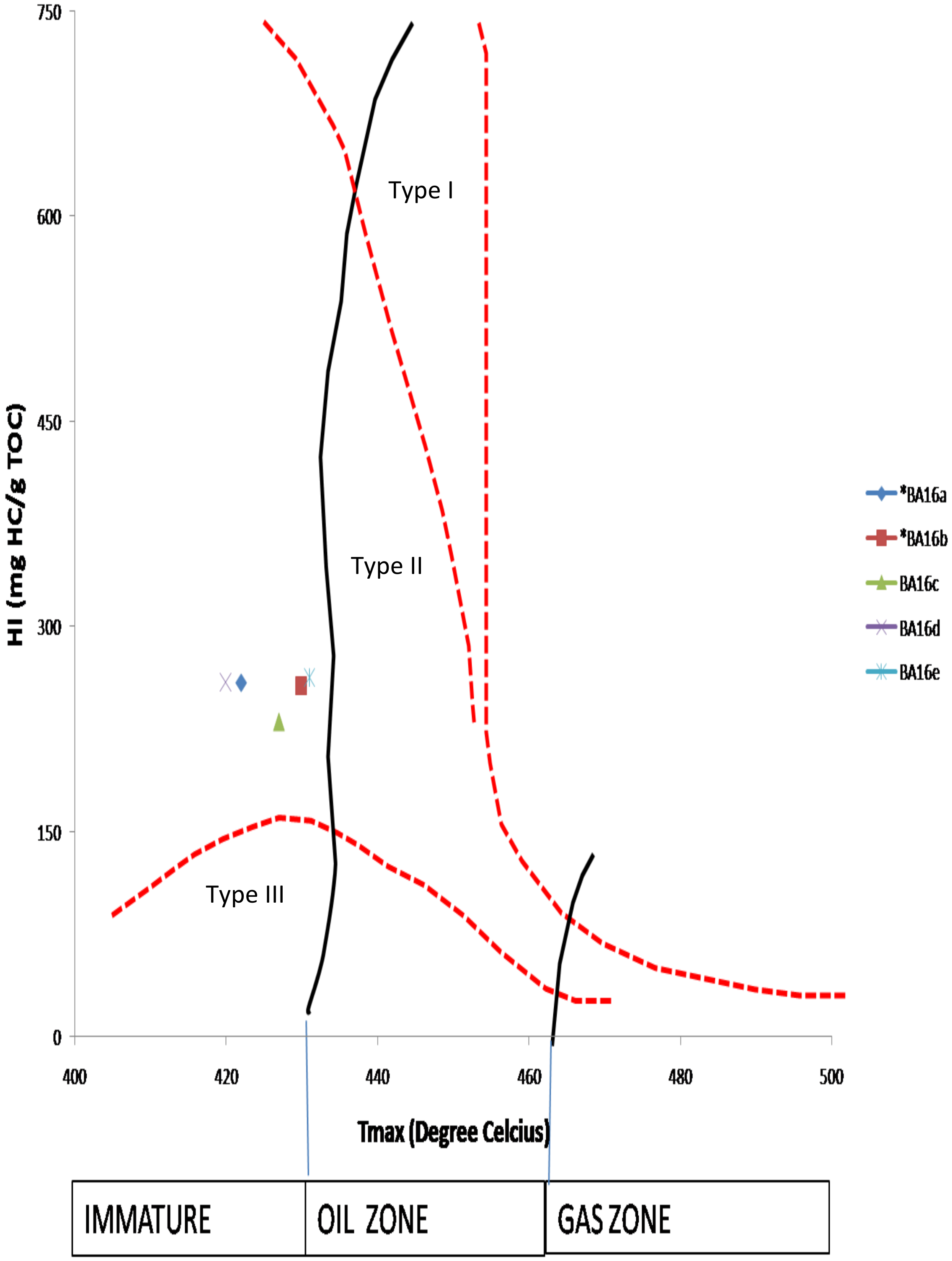

Figure 4.10: Plot of HI vs. Tmax for BA – 16 Borehole

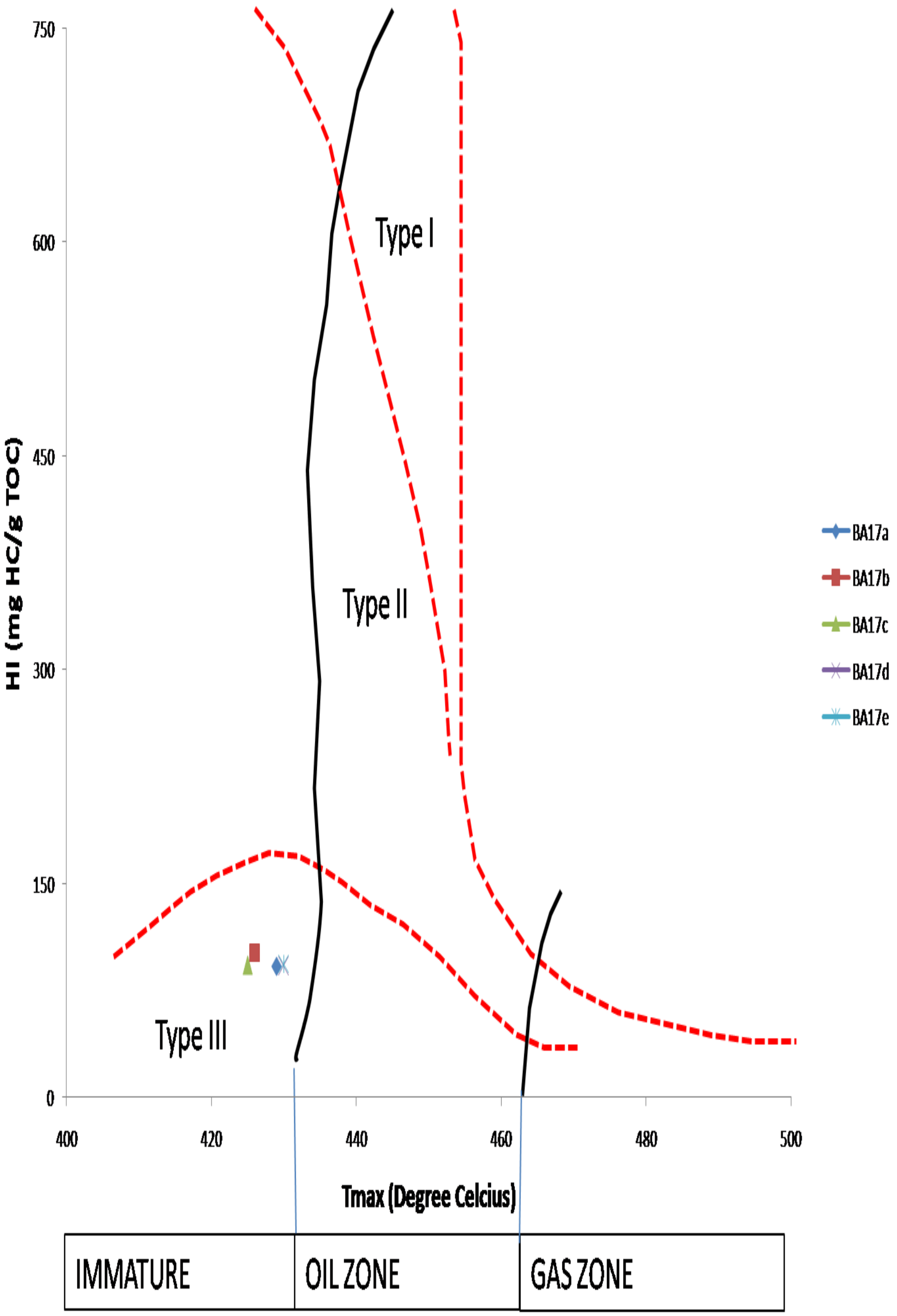

Figure 4.11: Plot of HI vs. Tmax for BA – 17 Borehole

The plots, HI vs. OI on the modified van Krevelen diagram for the analyzed samples (Figures 4.12 to 4.14) indicate mainly Type II kerogen for boreholes BA – 7 and BA - 16 and Type III for BA – 17. This confirms that the source of the organic matter for the Gombe Formation is from terrestrial source with gas/oil potential.

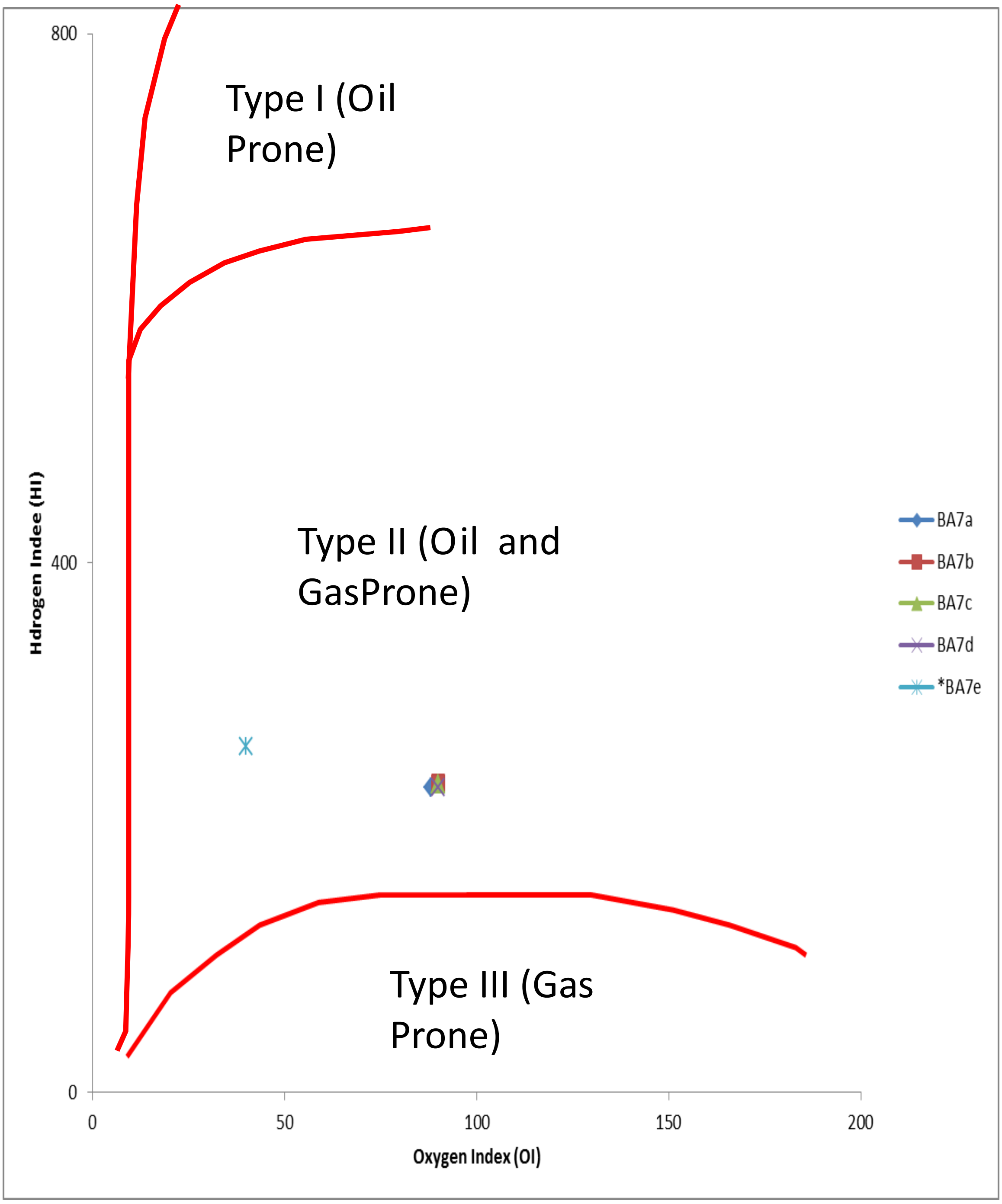

Figure 4.12: HI vs. OI plots on the modified Van Krevelen diagram of samples from (BA-7) Borehole.

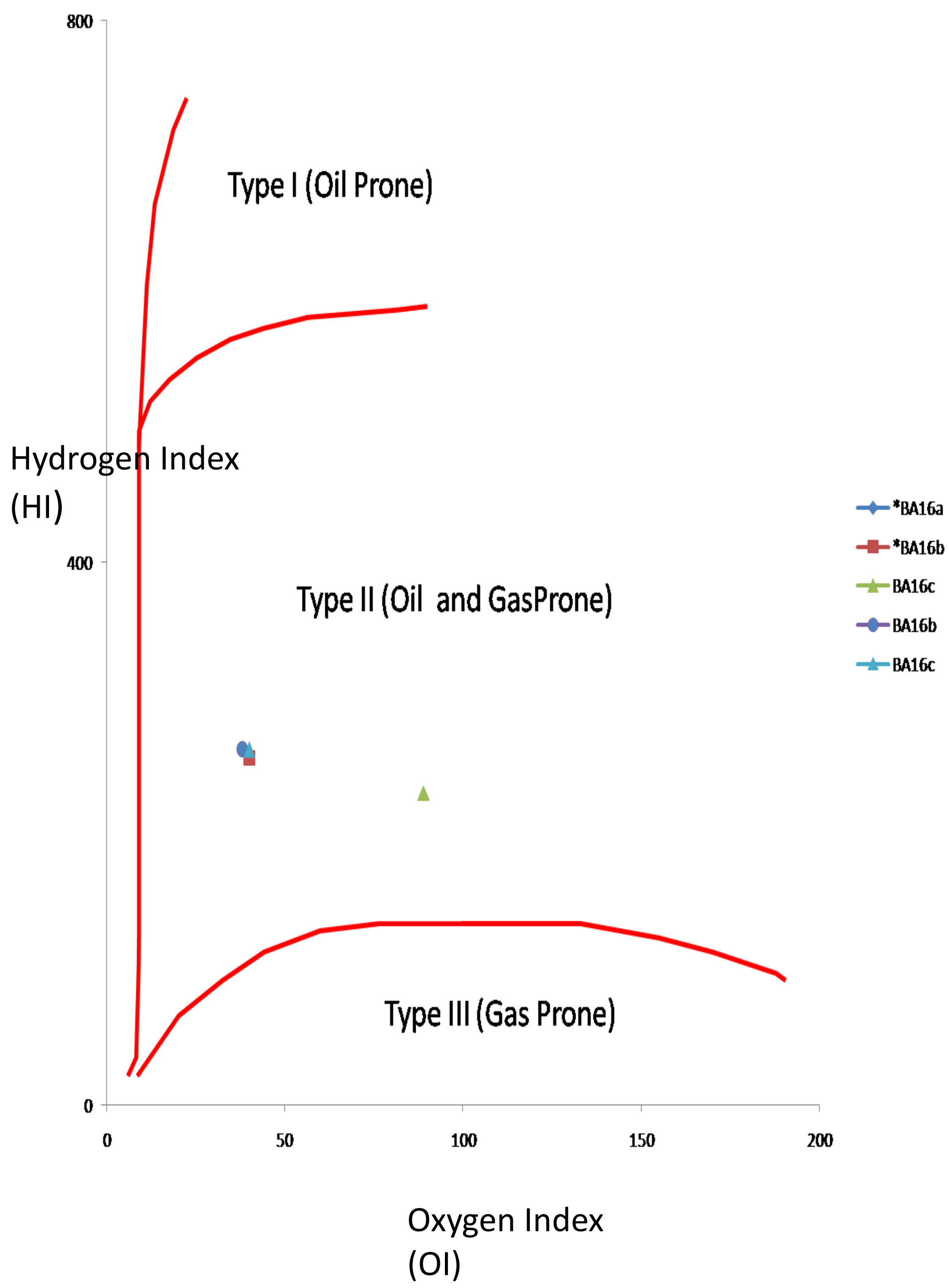

Figure 4.13: HI vs. OI plots on the modified Van Krevelen diagram of samples from (BA-16) Borehole.

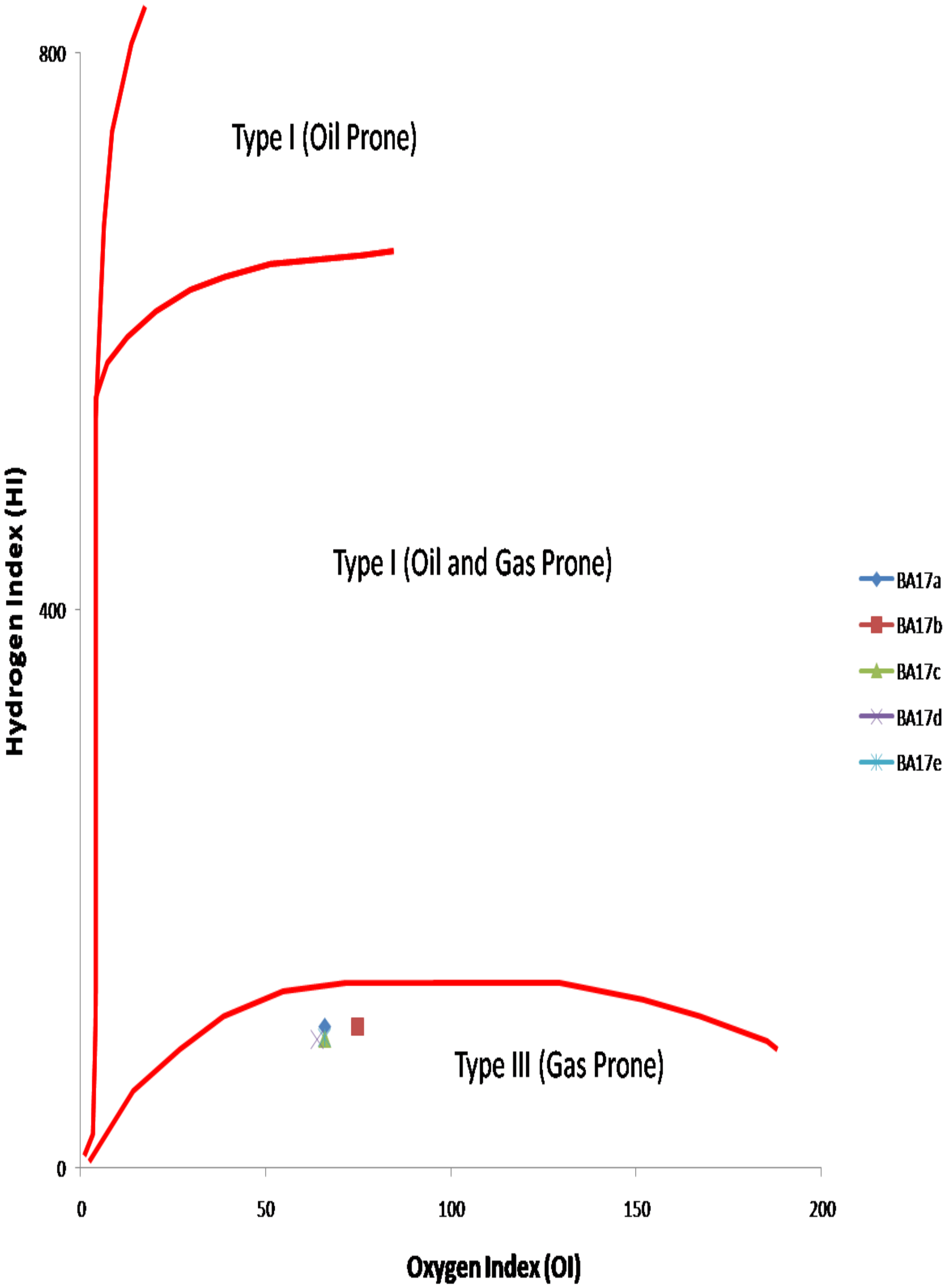

Figure 4.14: HI vs. OI plots on the modified Van Krevelen diagram of samples from (BA – 17) Borehole

In a bid to display the distributions (trends) of the TOC values of the samples, TOC versus depth plots are generated for the three (3) boreholes and presented in Figure 4.15, in order to characterize the organic matter type (kerogen type) of the samples.

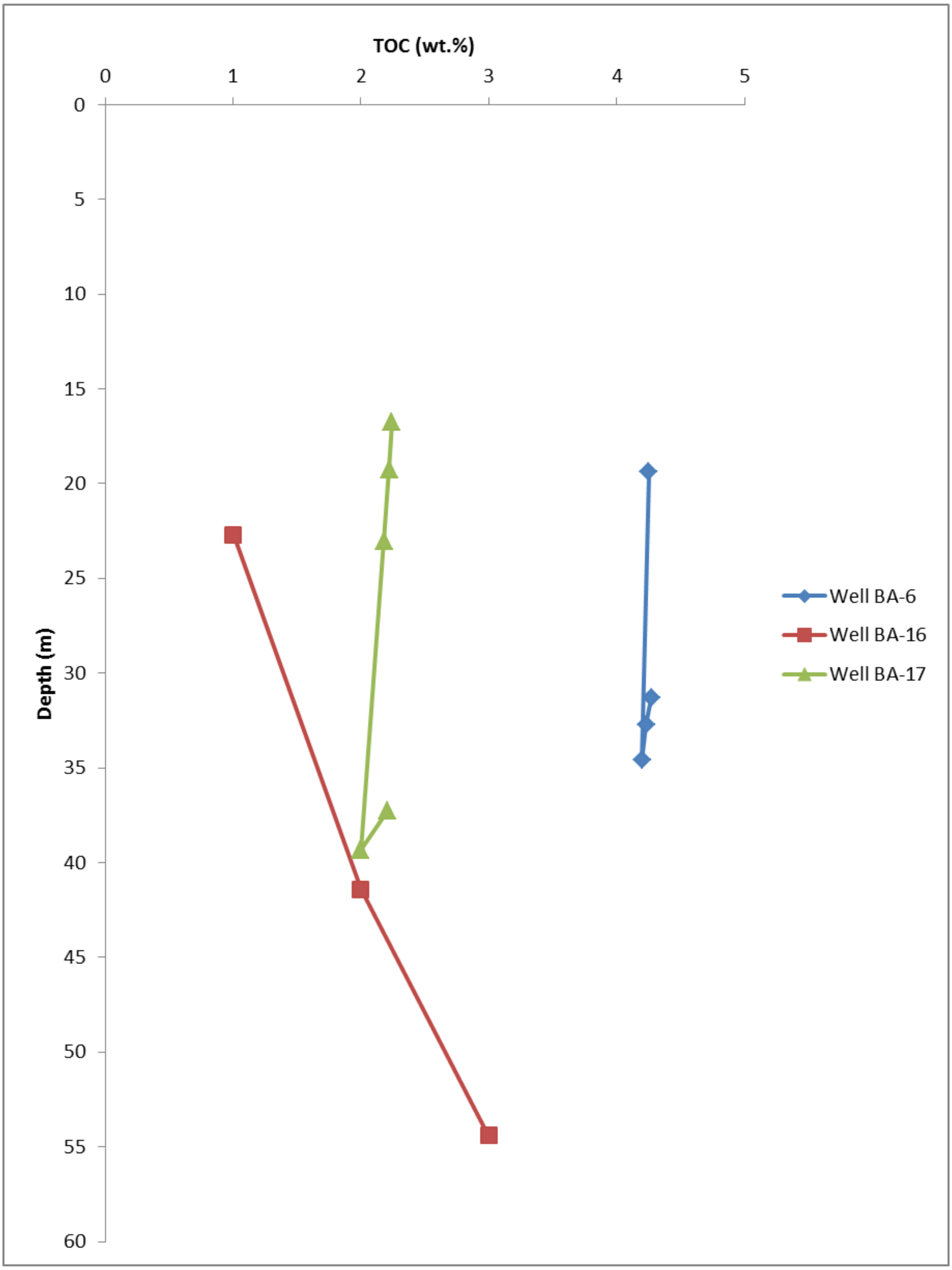

Figure 4.15: TOC versus depth plot

For the evaluation of the generation potential and quality of the analysed samples, plot of (S_1 + S_2) against TOC and the Rock-Eval HI versus TOC were plotted in similar way to that of Ghoria (1998) and these are presented for the three boreholes in Figure 4.16.

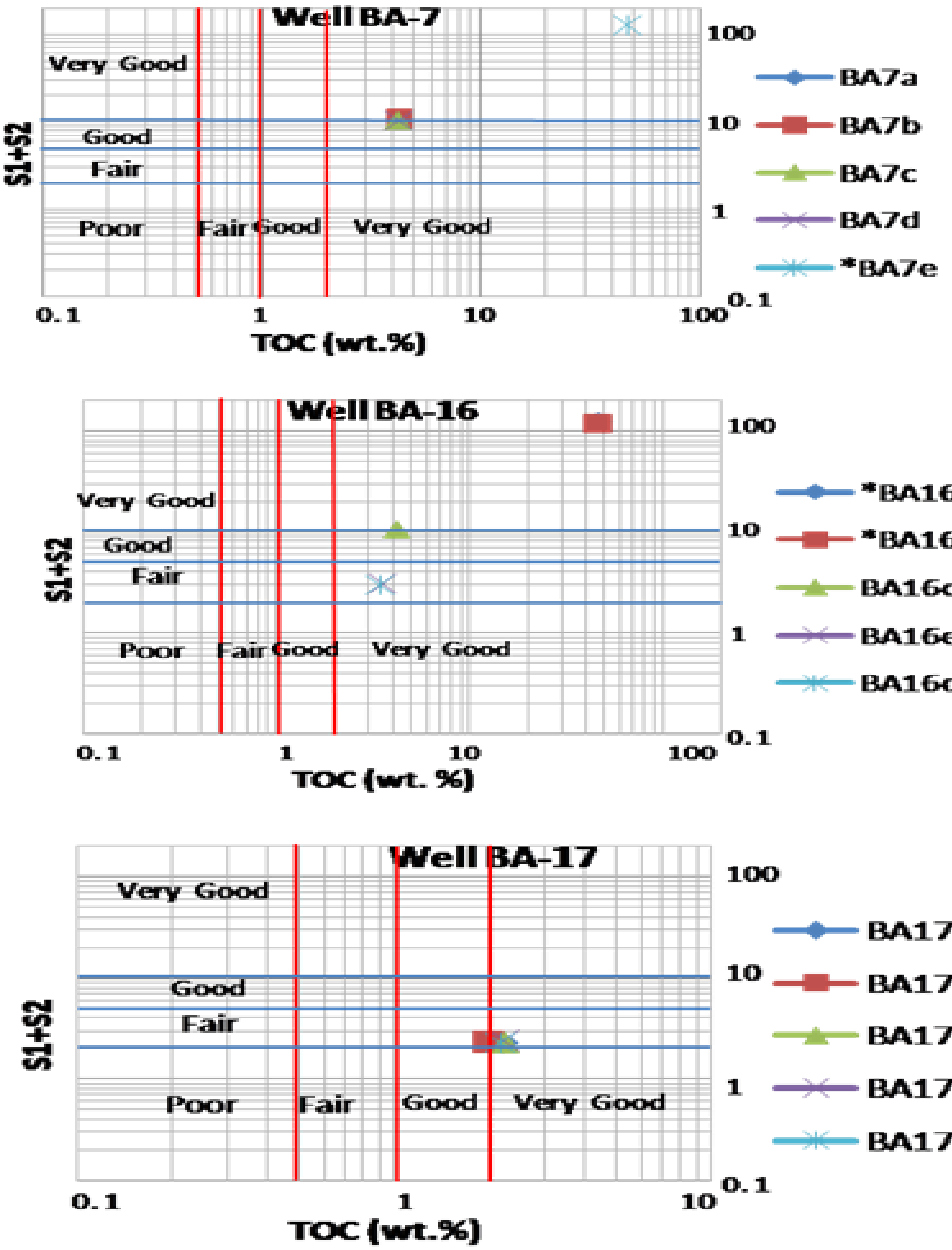

Figure 4.16: Generation potential for the studied samples of borehole BA-7 (top), BA-16 (middle) and BA-17 (bottom) (After Ghori, 1998)

The HI versus Tmax plots were also generated so as to show the level of thermal maturity of the samples in the three wells as shown in Figures 4.9 to 4.11.

4.8.3 Thermal maturity assessment

Thermal maturity of potential source rocks or oils can be evaluated by a number of parameters (vitrinite reflectance, R_o; spore colouration; Thermal Alteration Index, TAI; Rock-Eval Tmax). However, only Rock-Eval Tmax data are available to evaluate thermal maturity of the selected samples of the three boreholes considered in this study. The Tmax values for the three boreholes are generally less than 435 ^{O}C (426 – 431^{O}C for borehole BA – 7, 420 – 431^{O}C for borehole BA – 16 and 425 – 43^{0}C for borehole BA – 17), averaging 431, 426 and 428^{0}C for boreholes BA-6, BA-16 and BA-17 respectively (Table 4.3 a, b and c). These values suggest that the analysed samples from the three boreholes are thermally immature (Figures 4.9 to 4.11). The thermal maturity levels attained by the source rock facies in the studied boreholes compared favourably with the immaturity status of their coeval formations in the Benue Trough (Pindiga and Gongila Formations), suggesting that these contemporaneous formations may be related in depth and/or have experienced similar geothermal gradient.

4.8.4 Organic matter richness and hydrocarbon generative potential

The assessment of source rock potential in the study area is based primarily on the TOC, genetic potential (S_1, S_2) and organic matter maturity. The amount of organic carbon (TOC) is a measure of the quantity of organic matter in the source rocks (Tissot and Welte, 1984). By and large, the higher the TOC, the better the chance and potential for hydrocarbon generation (Akande, 2012).

According to Obaje *et al*. (2006), at the core of any petroleum system is a good quality source (TOC > 0.5%, HI > 150 mgHC/gTOC, Tmax ≥ 430°C and biomarker validation). They posited that other petroleum system elements must include, apart from established source rocks, also reservoir and seal rock, established trapping mechanisms and favorable regional migration pathways. In this study, with average TOC values of 4.24 % for borehole BA – 7, 3.77 % for borehole BA – 16 and 2.17 % for BA – 17 excluding the average value of 47.06 % for the two coal samples analyzed respectively, which indeed meet the minimum of 0.5 % TOC required for petroleum source beds, the analyzed source rock units within the Gombe Formation are considered rich in term of organic matter concentration as to warrant petroleum formation. The high TOC value for the coal samples are expected since these samples are purely made of organic matter derived from plant remains. in general, the rich organic matter concentration in the analyzed samples may be attributed to the deposition of the sediments under anoxic conditions in the Maastrichtian age compared to the oxic event model suggested for Cenomanian to Turonian times in the adjacent Yolde, Dukul and Jessu Formations (Ojo and Akande, 2002) which were considered to be organically lean.

The genetic potentials (S_I+S_2 >1.0 mg HC/g rock) of the analyzed samples are generally high (Figure 4.16). The coal samples have abnormally higher values (Table 4.3 a, b and c). The above data indicate that the Gombe Formation has a good potential for generating economic amounts of petroleum. Tissot and Welte (1984) stated that if the sum of S_1 and S_2 is less than 2.0 mgHC/g rock, the rock is said to be gas prone, or non-generative, 2 – 6 mgHC/g rock indicates moderate source rock while > 6 mgHC/g rock indicates good source rock.

A quick look at TOC versus depth plot in Figure 4.24 shows that the TOC content steadily increases with depth in borehole BA – 16 whereas boreholes BA – 7 and BA –

17 have a similar trend as TOC decreases with depth but suddenly reverse the trend at approximately 35 m and 40 m respectively, although the coaly samples in boreholes BA-6 and BA- BA-16 are excluded in the plot as their values tend to obscure these trends. As shown in Table 4.3 a, b and c, the Total Organic Carbon (TOC) contents for boreholes BA – 7, BA – 16 and BA – 17, averaging 4.24, 3.77 and 2.17 wt. %, vary from 4.20 to 4.27 wt. %, 3.50 to 4.26 wt. % and 2.00 to 2.24 wt. % respectively; with the exception of the coaly samples whose TOC values are in order of few tens of wt. % varying from 47.00 to 47.10 % in boreholes BA – 7 and BA – 16 where the coal seams occur.

The high TOC values generally suggest that the condition during sediment deposition was favourable for organic matter production and preservation. The analysed samples may have been deposited under anoxic conditions in the Maastrichtian time compared to the oxic event model suggested for Cenomanian to Turonian times in the adjacent Yolde, Dukul and Jessu Formations (Ojo and Akande, 2002) which were considered to be organically lean.

According to the guidelines of Peters (1986), the TOC values between 0.5 and 1.0 % indicate a fair source-rock generative potential, TOC values varying from 1.0 to 2.0 % reflect a good generative potential, TOC values between 2.0 and 4.0 % refer to a very good generative potential, and rocks with TOC greater than 4.0 % are considered to have excellent generative potential. In line with the above criteria, the TOC results of rock samples in this study show that the analysed samples from boreholes BA – 7 and BA – 16 have very good generative potential while those from borehole BA – 17 have good to very good generative potential respectively. This is demonstrated in the plot of the S_1 + S_2 versus TOC (Figure 4.16). It is suffice to say that in term of generation potential, boreholes BA – 7 and BA – 16 are more promising than BA – 17 and this is underpinned by the presence of type II kerogens in the former and type III kerogen in the latter (Figures 4.12 to 4.14).

Tissot and Welte (1984), also proposed a genetic potential (SP = S1 + S2) for the classification of source rocks. According to their classification scheme, rocks having SP of less than 2 mg HC/ g rock correspond to gas-prone rocks or non-generative ones, rocks with SP between 2 and 6 mg HC/ g rock are moderate source rocks, and those with SP greater than 6 mg HC/ g rock are good source rocks. Based on the above criteria, the analysed samples of borehole BA – 7 are good source rocks; those from borehole BA – 16 are moderate to good source rocks while samples from borehole BA – 17 are considered to be moderate source rocks. They added further that those rocks with exceptionally high SP values in order of 100 or 200 mg HC/ g rock may provide either an excellent source rock, if the burial depth is sufficient, or an oil shale, if the burial depth is shallow. Thus, the analysed samples especially those from boreholes BA – 7 and BA – 16 may constitute a good source if the burial depth is sufficient or oil shale at shallow depths.

Using Espitalie *et al*. (1984) classification, the plots of HI versus Tmax show that the source rocks of Gombe Formation are of type I/II (oil prone) and type III (gas prone) kerogen derived from marine and terrestrial plants respectively (Figures 4.12 to 4.14). These further buttress the earlier proposed paleoenvironments for the Gombe Formation.

Also, an assessment of the HI versus OI for the three wells indicates that organic matter is predominantly of Type II and Type III kerogen (Figures 4.12 to 4.14). Juxtaposition of the HI vs. T_{max} and HI vs. OI plots indicate that the samples from Gombe Formation have both gas and oil generative potentials. Obaje *et al*. (2006) and Peters (1986) stated that a thermal maturity Tmax rocks with HI above 300 mg HC/gTOC will produce oil; those with HI between 150 and 50 will produce only gas; and those with HI less than 50 are inert.

However, Sykes and Snowdon (2002) and Obaje *et al*. (2006) proposed that coaly source rocks are sufficiently different from marine and lacustrine source rocks in their organic matter characteristics to warrant separate guidelines for their assessment based on Rock – Eval pyrolysis. Using data from some New Zealand coals, they concluded that the threshold for oil generation in coal occur at Tmax of 420 – 430 ^{O}C and the threshold for oil expulsion is at Tmax of 430 – 440^{O}C. It is pertinent to note that comparing the above Tmax threshold values with the value analyzed for the Gombe coals (422 – 430^{O}C), it is evident that the Gombe coals have the capacity to generate oil and may be able to expel same due to its attainment of the minimum Tmax required for oil expulsion as quoted above.

A plot of S2 vs. TOC for the analyzed samples gave an average HI value of 264,261 and 115 mg HC/gTOC for BA – 7, BA – 16 and BA – 17 samples respectively (Figures 4.17 to 4.19). It should be noted that the average hydrogen index of 115 mg HC/gTOC in Figure 4.34 for BA – 17 is not reliable because of the high scatter of the points (the regression coefficient is 0.386).In this case, the Rock-Eval pyrolysis generated hydrogen indices in Tables 4.3 a, b and c are more reliable and hence should be adopted. Contrarily, those of BA – 7 and BA – 16 (Figures 4.17 and 4.18) are reliable because of their non – scattering. The regression coefficients for these two other boreholes are 1 and 0.999 respectively.

According to Langford & Blanc–Valleron (1990) and Obaje *et al*. (2006), hydrogen indices obtained from Rock–Eval Pyrolysis can be misleading, as much of the hydrocarbons may be absorbed by the rock matrix, the analyzed source rocks may therefore yield Rock–Eval Pyrolysis – generated HI values that are less than the true average hydrogen index, while the coaly source may have HI values that are higher than the true average. They therefore proposed the use of S2 versus TOC plots and believed that the regression equations derived from these plots were the best method for determining the true average hydrogen index (Av. HI) and measuring the absorption of hydrocarbon by the rock matrix as discussed above.

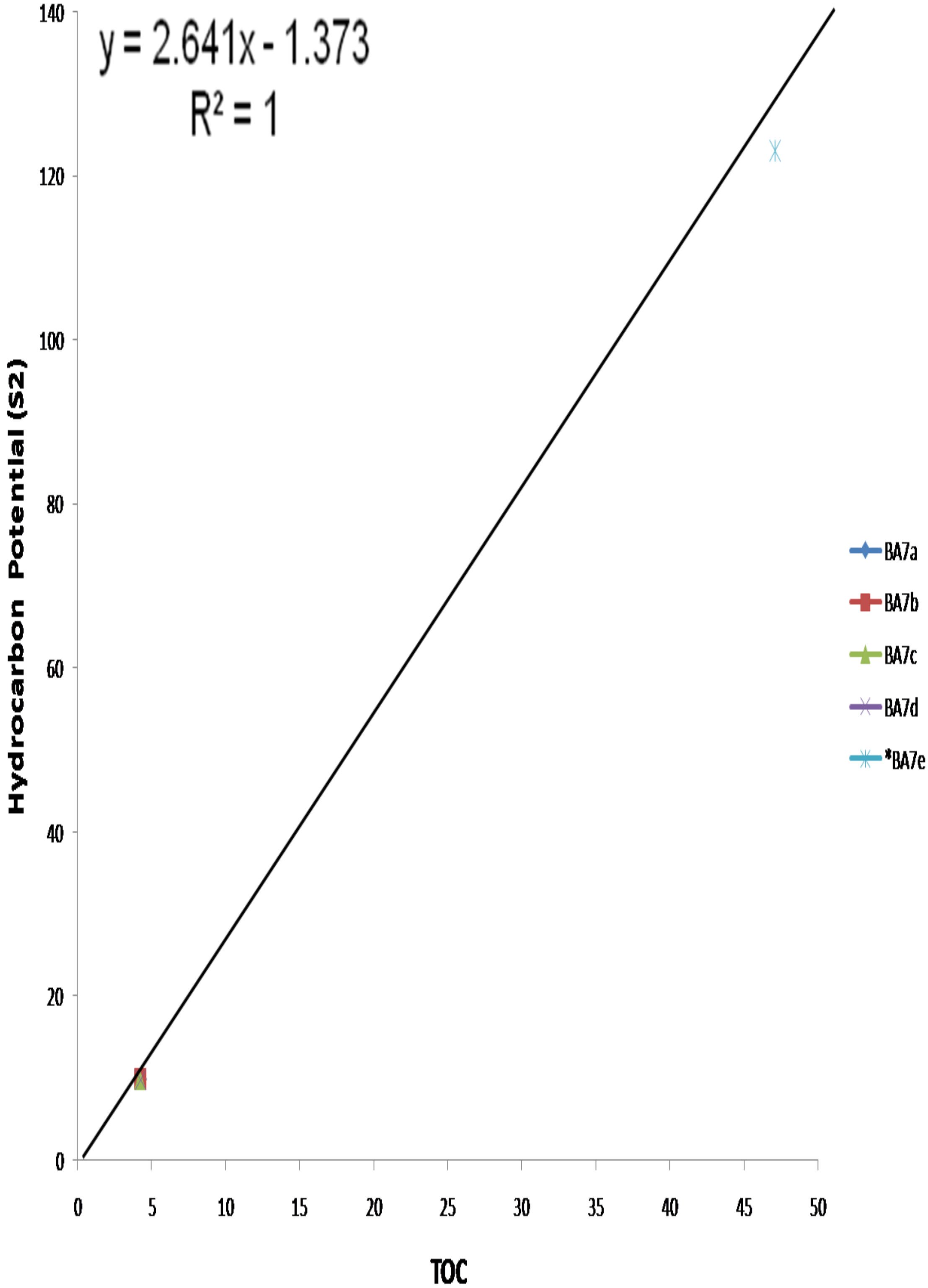

Figure 4.17: Plot of Hydrocarbon Potential (S2) vs. TOC for BA – 7 Borehole

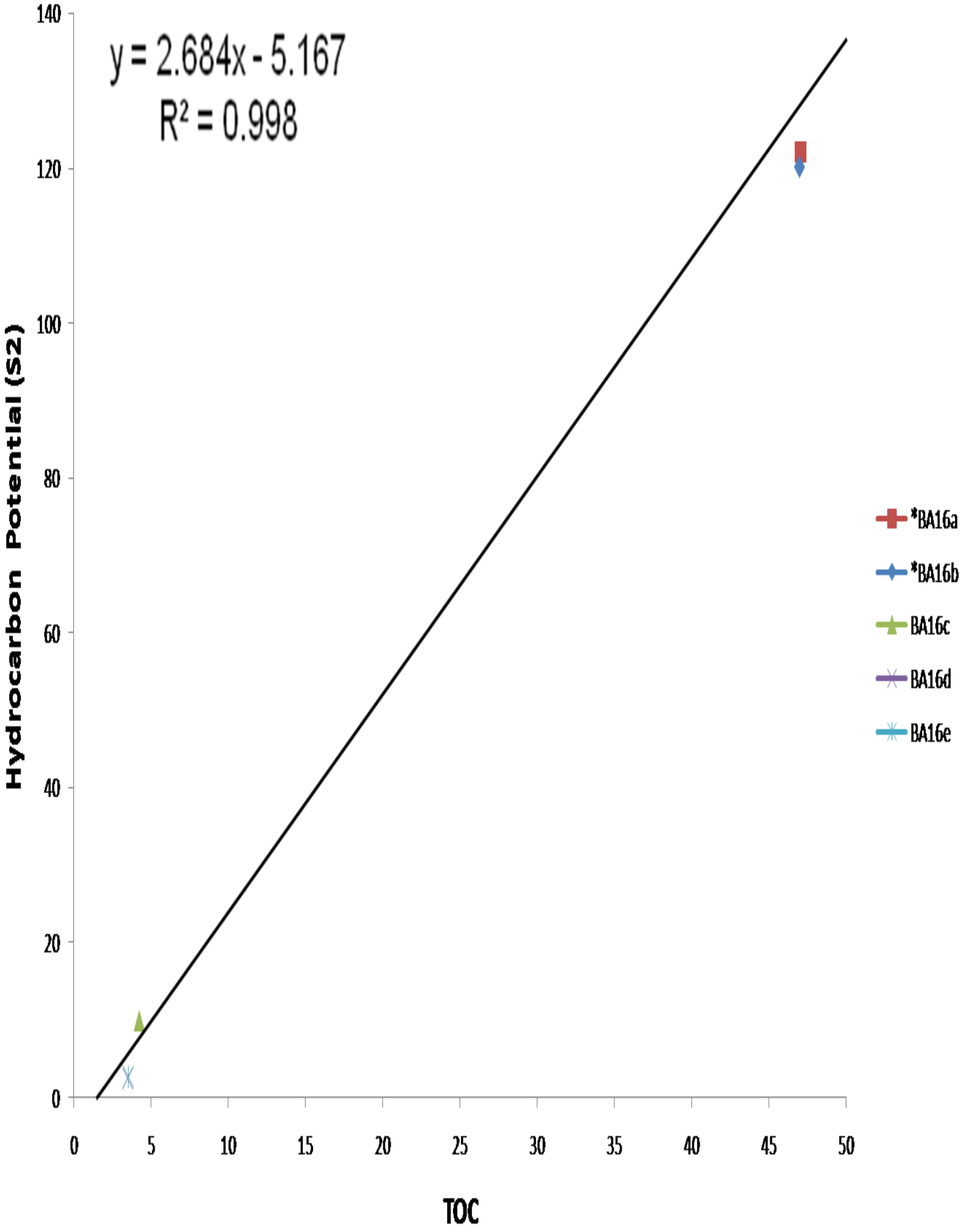

Figure 4.18: Plot of Hydrocarbon Potential (S2) vs. TOC for BA – 16 Borehole

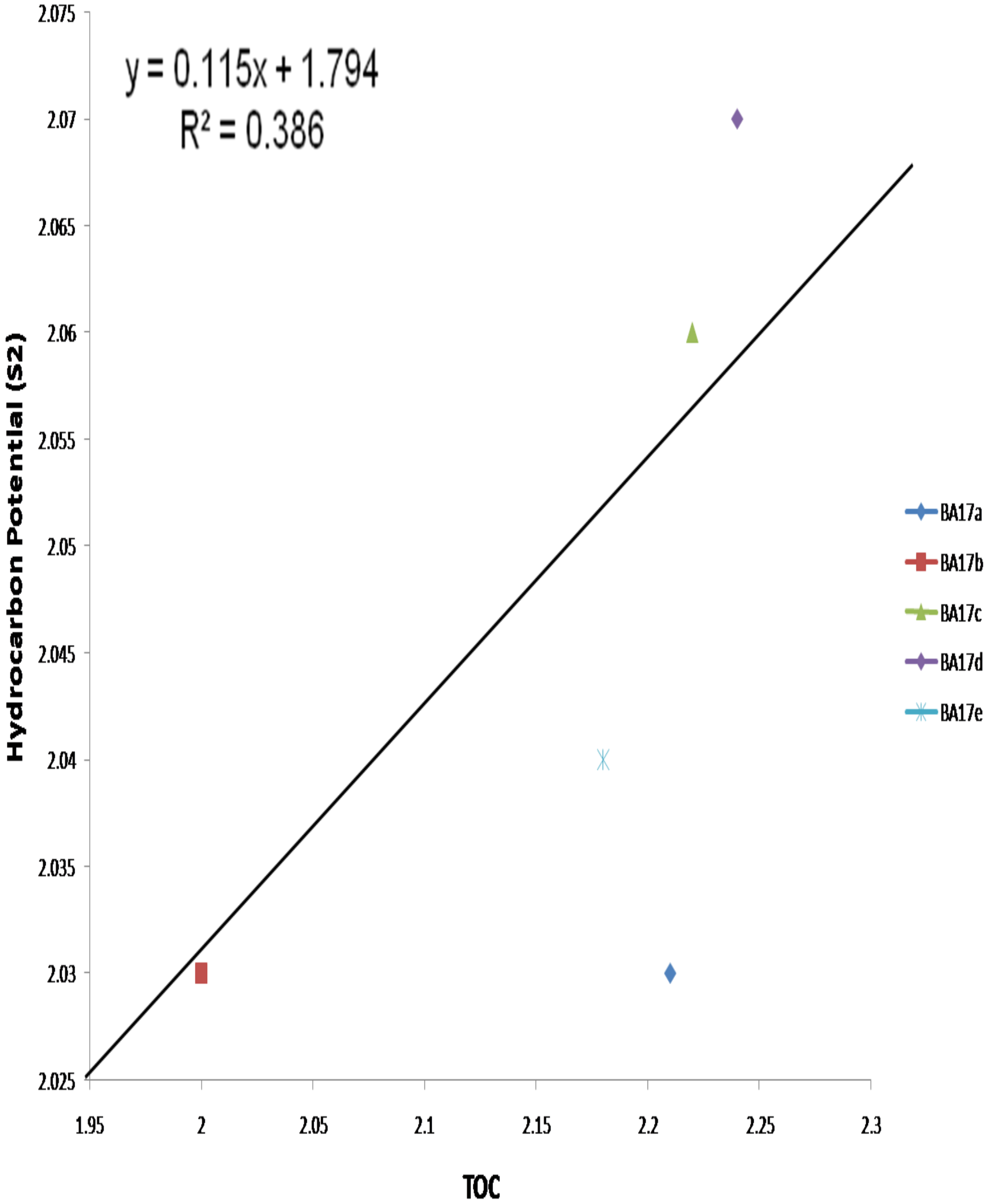

Figure 4.19: Plot of Hydrocarbon Potential (S2) vs. TOC for BA – 17 Borehole

CHAPTER FIVE

5.0 CONCLUSION AND RECOMMENDATIONS

5.1 Conclusion

This study had carried out geochemical, palynological and palynofacies analyses of parts of the Gombe Formation at Maiganga coal mine. The results of the analyses have shown that the Gombe Formation is a heterogeneous unit characterized by sand, shale, siltstone and some coaly intercalations and these sub-lithological units are characterized by diverse palynomorphs and palynomacerals. The formation was dated Early Maastrichtian to Late Maastrichtian on the basis of the palynomorphs. The Gombe Formation around Maiganga coal mine is characterized by two distinct coal seams which are intercalated between an upper sandstone and lower mudstone facies. This geological setting appeared similar and correllateable to other Nigerian coeval coal deposits. The coals are usually dark, hard, striated and crumble on hitting to coincoidal fragments. The inferred paleoenvironment of deposition for the Gombe Formation based on the analyzed palynomorphs ranges from swamps through flood plains to brackish – water environment. Paleoenvironmentally, the pollen and spores belong to the Late Cretaceous Palmae Province based on the available palynoforms analyzed.

The studied boreholes are considerably rich in palynomorphs that permitted adequate interpretations such as the age, paleoclimate and paleoenvironment of the studied sections. The microfloral content and diversity of the studied boreholes were essentially similar and found to contain similar assemblage zones. Analyzed palynomorphs included pollen, spore and few fungi. The presence of some marker species have aided in the delineation of the studied borehole sections into two biozones. The marker palynomorphs included *Proteacidites sigalii, Retidiporites magdalensis, Proteacidites* *dehaani, Distaverrusporites simplex, Foveotriletes margaritae* and *Echitriporites trianguliformis*. The newly proposed palyzones are the *Proteacidites sigalii – Echitriporites trianguliformis* zone and the *Cyathidites* spp – *Laevigatosporites haardtii* zone.

The suggested paleoenvironment of the studied section was based on their lithological and palynofloral characteristics; the predominance of argillaceous strata suggest deposition largely by suspension settling mode in low energy level environment, such as lakes, and flood plains. On the other hand, the sandstone deposition phase is an indication of more agitated environment of higher energy.

From the results of the palynofacies analyses, four palynomaceral types were observed and these included the Amorphous plant matter (PM I), Vitrinitic brown and black wood (PM II), Curticles and membraneous debris (PM III) and the Platy tracheidal debris (PM IV). These palynofacies characteristics coupled with the lithofacies and palynoforms analyses results of the studied sections of the Gombe Formation suggested two sub-environments for the deposition of the formation sediments; the terrestrial and coastal deposition environments. By inference therefore, the studied sections of the Gombe Formation around Maiganga coal mine can be interpreted to have been formed under terrestrial and parallic conditions of deposition.

Geochemically, the Gombe Formation is considered to have potential for oil and gas generation based on the type II and III kerogens observed and the TOC values. The geochemical data indicated that the Gombe Formation showed a fair to good source rock quality and has potential for gas and oil generation. The coaly source rocks have higher potential for petroleum generation based on their analyzed data, namely high TOC and S2 values. The plots of HI versus OI on the modified Van Krevelen diagram for the Gombe Formation indicated types II and III kerogen for the formation and this was an indication of the potential to generate gas and oil. The analysed relatively low Tmax values showed that the formation was relatively thermally immature.

Also, the geochemical analyses results showed that the TOC values across the analysed sections of the Gombe Formation varies from 2.00 to 4.27 % which is an indication of moderate organic matter richness of the formation. However, these TOC value ranges from 47 to 47.10 % for the coal samples obtained from the same sections of the Gombe Formation. These exceptional high TOC values are indication of the more organic content within the coal samples than the sandy/shale samples.

Other geochemical parameters derived from the analyses of the formation samples included hydrogen index (mean value of 195.3 mgHC/g TOC) which were considered adequate for good source rocks, oxygen index (mean value of 65.47 mgCO_2/g TOC) which was an indication of immature sediments, Tmax of generally less than 435^0C implying thermally immature sediments and the high generative potentials (S_1 + S_2) which ranged from 2.27 to 124.72 mgHC/g rock. All the above were indications of good petroleum and gas source rocks but of relatively immature status that would have upgraded into a matured source rocks if burial had continued.

5.2 Recommendations

The following recommendations are hereby made in view of the results obtained from this research and various limitations encountered in the course of the research work. These recommendations include:

1. More research work should be carried out within the Gombe Formation especially when there are deeper boreholes in the area that can produce core samples from deeper part of the formation.

2. The above research should focus on Gc – Ms, Vitrinite reflectance measurements and biomarker evaluations in order to ascertain the thermal maturity of the formation.

3. Government and relevant multinational oil companies should work out the possibility of sinking deep exploratory boreholes in each of the Nigerian sedimentary basins and the core samples curiated. This will afford prospective researchers ready materials for analysis.

4. If researches are to be conducted meaningfully, modern laboratory facilities and equipment should be provided to the Tertiary Institutions for easier analyses and data management.

5. Other aspects of micropaleontology e.g foraminifera, ostracods and nanofossils should also be used to study the Gombe Formation for an integrated approach for a better understanding of the formation interms of age, paleoenvironment and paleoclimate.

REFERENCES

Aboul Ela, N. M. (1978). The Palynological Characteristics of the Upper Cretaceous Sediments in Abu Tarkur Plateau, Kharga Oasis, Egypt. *Revista Espanola de Micropaleontologia*. X, (3) 421 – 442.

Adebanji, K. A. (2012). Biostratigraphy and depositional environment of the Sediments in Borno Basin, North Eastern Nigeria. *Indian Journal of Science and Technology,* 5, (6) (June 2012). 2800 – 2809.

Adegoke, O. S., Jan Du Chene, R. E. & Agumanu, A. E. (1986). Palynology and Age of the Kerri-Kerri Formation, Nigeria. *Revista Espanola De Micropaleontologi:* X. (2). 267 – 285.

Akande, S. O. & Olusola, J. O. (2002). Organic Petrology and Rock-Eval studies on Source Rocks Facies of the Campanian-Maastrichtian Patti Formation, Southern Bida Basin, Nigeria *Nigerian Association of Petroleum Explorationist Bulletin,* 22 – 29.

Akande, S. O., Ojo, O. J., Erdtmann, B. D. & Hetenyi, M. (2005). Paleoenvironments, Organic Petrology and Rock-Eval studies on source rock facies of the LowerMaastrichtian Patti Formation, Southern Bida Basin, Nigeria. *Journal of African Earth Sciences* 41 (2005). 394 – 406.

Akande, W. G. (2012). Evaluation of Hydrocarbon Generation Potential of the Mesozoic Organic-Rich Rocks Using TOC Content and Rock-Eval Pyrolysis Techniques. *Geosciences* 2012, 2(6): 164 – 169.

Ames, H. T. & Spackman, W. (1985). Catalog of fossil, spores and pollen. Tertiary and Upper Cretaceous Spores and Pollen from Africa, Europe, Canada, Australia and New Zealand. 44, *University Park, Pennsylvania*. 182.

Andrew, F. W. (2004). The semi – automated classification of sedimentary organic matter and dinoflagellate cysts in palynological preparations. An unpublished PhD thesis 1 – 4.

Atta-Peters, D. & Salami, M. B. (2004). Late Cretaceous to Tertiary Pollen grains from Offshore Tano Basin, Southwestern Ghana. Instituto *Geologico Minero de Espana* 451 – 465.

Bankole, S. I; Schrank, E; Dominik, W. & Erdtmann, B. D. (2007). Palynology of the Cenozoic Oshosun Formation, Dahomey Basin, Southwestern Nigeria: Age and Paleoenvironmental Implications. *Revista Espaniola de Micropaleontologia,* 39(1 – 2). 29 – 44.

Barber, W., Tait, E. A. & Thompson, J. A. (1954). The Geology of the Lower Gongola. In: *Annual Report of the Geological Survey of Nigeria*. 1952 – 53, 18 – 20.

Batten, D. J. (1992). Stratigraphic and Paleoenvironment analyses continue to demand the inclusion of high quality Paleontological data. *Cretaceous Research*, 13. 591 – 595.

Batten, D. J. (1996). Palynofacies and paleoenvironmental interpretation in:Jansonius and D. McGregor, eds. palynology principles and applications: *American Association of Stratigraphic Palynologists Foundation*. ; Publishers Press, 1996. 1011 – 1065.

Benkhelil, J. (1989). The Origin and Evolution of the Cretaceous Benue Trough (Nigeria). *Journal of Africa Earth Science*, 8: 251 – 282.

Boboye, O. A. & Abimbola, A. F. (2009). Hydrocarbon Potential of the lithostratigraphic Units in Late Cenomanian – Early Paleocene Shale, Southwestern Chad Basin. *World Applied Sciences Journal* 7 (5): 563 – 573.

Boltenhagen (1978). Introduction a la palynology stratigrapique du basins sedimentaire de Afrique equitoriale, *Memoire du Bureau de Researches de Geologique et Mineres*, 32, 305 – 327.

Boltenhagen, E. & Azema, A. (1994). Spores et pollen du Cretace Supericur du Gabon: *Pollen et Spores*. 9, 191 – 199.

Burke, K. C., Dessauvagie, I. F. J. & Whiteman, A. J. (1972). Geological History of the Benue Valley and adjacent areas In: Dessauvagie, T. F. J. and Whiteman, A. J. (Eds). *African Geology, Ibadan University Press*, Ibadan. 187 - 205

Carolus Linnaeus (1735). The Systema Naturae. Retrieved on 18th Feb. 2013, at 6pm. from www.systemanaturae.com

Carter, J. D., Barber, W. and Tait, E. A. (1963). The Geology of parts of Adamawa, Bauchi and Bornu Provinces in North – Eastern Nigeria. *Geological Survey of Nigeria Bulletin*. 56 – 59.

Christopher, R. A. & Goodman, D. K. (1996). Introduction to Biostratigraphy and Time Scales. In Palynology: principles and applications, *Journal of Jansonius and D. C Mcgregor (eds)*, 2. 463 – 468.

Clapham, W.B.J. (1972). Numerical analysis and group formation in palynology: *Geoscience and Man*, 4, 73 – 85.

Combaz, A. (1964). Les Palynofacies. *Revue de Micropaleontologie*, 7, (3). 205 – 218.

Cookson, I. C. (1950). Fossil pollen grains of the protaceous type from Tertiary deposits in Australia. *Australian Journal of Scientific Research*. B. 3.

Couper (1953). Uppermost Cenonian-basal Turonian ammonites from Salinas, Angola. *Annals of South.Africa Museum*, Cape Town, 75, 51 – 152.

David, J. B. & Darrin, T. S. (2005). Palynofacies Analysis and its Stratigraphic Application. E. A. M. Koutsoukos, (ed.), *Applied Stratigraphy*, *Springer Publishers,* Nertherlands. 203 – 226.

Dettmann, M. E. (1963). Upper Mesozoic Microfloras from Southeastern Australia. *Proceedings of the Royal Society of Victoria*, 77, 1 – 148.

Dike, E. F. C. (1995). Stratigraphy and Structure of the Kerri-Kerri Basin, Northeastern Nigeria. *Journal of Mining and Geology*, 29 (2). 77 – 92.

Ehinola, O. A., Sonibare, O. O., Falana, A. M. & Jarvie, D. (2006). Organic Geochemistry and Biomarker Evaluation of Shale Units of the Maastrichtian Patti Formation, Bida Basin, Nigeria. *Nigerian Association of Petroleum Explorationist Bulletin*, 19 (1). 78 – 88.

Elsik, W. C. (1964). New Sporomorph genera from the Upper Cretaceous of Peru. *Pollen et Spores* 6 (2), 553 – 564.

Elsik, W. C. & Thanikamoni, L. (1970). Palynology of Paleocene Rockdale Lignite, Milan County, Texas. II Morphology and Taxanomy. *Pollen et Spores*. 10 (3), 599 – 664.

Emeis, K. C. & Kvenvolden, K. A. (1986). Shipboard organic geochemistry on JOIDES Resolution. *ODP Tech*. 7.

Espitalie, J., Marquis, F. & Barsony, I. (1984). Geochemical Logging. In: Voorhees, K. J. (Ed.), Analytical Pyrolysis – Techniques and Applications. *Butterworth*, *Guildford*, 276 – 304.

Falconer, J. D. (1911). The Geology and Geography of Northern Nigeria. *Macmillan London*, 295.

Germeraad, J. H., Hopping, C. A. and Muller, J. (1968). Palynology of Tertiary Sediments from Tropical areas. *Review of Paleobotany and palynology*, 6: 189 – 348.

Ghori, K. A. R. (1998). Petroleum source-rock potential and thermal maturity of the Officer Basin, Western Australia. *Geological Survey of Western Australia*, 52 (Unpublished)

Gombe, 2013 – Climate, Relief, Drainage and Hydrology of Gombe State. Retrieved from www.gombestategov.com on 10 January, 2013 at 5.55pm

Gombe ADP. 2013 –Soil, Vegetation and Land Use in Gombe State. Retrieved from www.gombestate.gov.ng on 10 January, 2013 at 6.08pm

Guiraud, M. (1989). Geological Map of the part of the Benue Valley, 1:50,000 (with explanatory note). *Elf Nigeria Ltd*, Lagos.

Guiraud, M. (1990). Tectono-Sedimentary Framework of the Early Cretaceous Continental Bima Formation (Upper Benue Trough. NE Nigeria). *Journal of African Earth Sciences*, 10: 341 – 353.

Guiraud, M. (1991). Mechanisme de formation du basin Cretacesur decrochement. Un examples des decrochements senestres NE – SW du basin dela Itaute – Benoue (Nigeria). *Bulletin de Centres des Recherches Exploration Production Elf – Aquitaine*, 15: 11 – 67.

Gutjahr, C. C. M, (1960): Palynology and its application in petroleum exploration. *Gulf Coast Association Geological Society Trans*. 10. 175, 187.

Hamidu, I. (2012). The Campanian to Maastrichtian Stratigraphic Succession in the Cretaceous Gongola Basin of North-East Nigeria. Ph.D thesis A.B.U, Zaria. 41.

Hedberg, H. D (ed) (1976). International stratigraphic guide; *John Willey and Sons, Ltd*, New York, 200

Hergreen, G. F. W. & Chlonova, A. F. (1981). Cretaceous Microfloral Provinces; *Pollen et Spores*, 23, 441 – 556.

Herland, R. (1978). Dinoflagellate Cysts and Architarchs from the Bearpaw Formation (Upper Campanian) of Southern Alberta, *Canada Paleontology* 16: 665 – 706.

Idowu, J. O. & Eweozor, C. M. (1989). Petroleum Geochemistry of some Upper Cretaceous Shale from Upper Benue Trough and Southwestern Chad Basin, Nigeria. *Journal of Mining and Geology*, 25(1 & 2) 131 – 149.

Imogene, D. L. (1980). Palynomorph Preparation Procedures Currently used in the Paleontology and Stratigraphy Laboratories, *United States Geological Survey Circular*. 830. 1 - 29.

Iversen, J. & Troels-Smith, J. (1950). Pollen morphologische Definitionen Und typen. *Denmark Geologische Unders*. IV Rackke Bd. 3.8 Copenagen.

Jan Du Chene, R. E., Adegoke, O. S., Adediran, S. A. & Peters, S. W. (1978). Palynology and Foraminifera of the Lokoja Sandstone (Maastrichtian), Bida Basin, Nigeria. *Revista Espanola de Micropaleontologia* 10: 379 – 393.

Jarzen, D. M. & Nicholas, D. J. (2006). Pollen in Palynology, Principles and Applications. *Jansoniums, Journal and McGregor, D. C (eds).* 1, 261 – 291.

Kovach, W. L. (1986). Multivariate statistical package for the IBM-PC now available: *Plant Science Bulletin*, 32, 2.

Kovach, W. L. (1988), Quantitative paleoecology of a Cretaceous megaspore flora, using multivariate methods: *Cretaceous Research*, 9, 255 – 282.

Kovach, W. L., (1989). Comparisons of multivariate analytical techniques for use in pre-Quarternary plant paleoecology: *Review of Palaeobotany and Palynology*, 60, 255 – 282

Lafargue, E., Espitalie, J; Marquis, F. & Pillot, D. (1997). Rock-Eval 6 Applications in Hydrocarbon Exploration, Production and in Soil Contamination Studies. *In Revue de L'Institut Francais' du Petrole*, 53, (4) 421 – 437.

Langford, F. F. & Blanc-Valleron, M. M. (1990). Interpreting Rock-Eval Pyrolysis data using graphs of pyrolyzable hydrocarbons versus total organic carbon. *American Association of Petroleum Geologist Bulletin* 74, 799 – 804.

Lawal, O. (1982). Biostratigraphie, Palynologie et Paleoenvironments des Formation Cretaces de la itaute Benoue; Nigeria – North-Oriental. *Doctorat de Specialite*. *Universite de Nice.* 198.

Lawal, O. & Moullade, M. (1987). Palynological Biostratigraphy of Cretaceous Sediments in the Upper Benue Basin. *Revue de Micropaleontologie*, 29: 61 – 83.

Martin, H. A. & Rouse, G. E. (1966). Palynology of Late Tertiary Sediments from Queen Charlotte Islands, British Colombia: *Canadian Journal of Botany*; 44, 171 – 208.

Moumouni, A. Obaje, N. G., Nzegbuna, A. I. & Chaanda, M. S. (2007). Bulk Geochemical Parameters and Biomarker Characteristics of Organic Matter in Two wells (Gaibu – 1 and Kasade –1) from the Bornu basin: Implications on the Hydrocarbon Potential Science and Engineering (2009).

Muller, J. (1968). Palynology of Pedawan and Plateau sandstone formation (Cretaceous – Eocene) in Sarawak, Malaysia. *Micropaleontology*, 14 (1), 1 – 39.

Murat, R. C. (1972). Stratigraphy and Paleogeography of the Cretaceous and Lower Tertiary of Southern Nigeria. In T. F. J. Dessauvagie and Whiteman (Eds), *African Geology*, *Ibadan University Press*, Nigeria. 251 – 266.

North American Commission on Stratigraphic Nomenclature (NACSN, 1983) – North American Stratigraphic Code. – *Bulletin of American Association of Petroleum Geologists*, 67, 841 – 875.

Nwajide, A. (1989). Paleogeographic setting for coal sequences in the Benue Trough Complex, Upper Cretaceous. 1 – 8.

Obaje, N. G. (2000). Biomarker Evaluation of the Oil-Generative Potential of Organic matter in Cretaceous strata from the Benue Trough (Nigeria). *Nigerian Association of Petroleum Explorationists Bulletin* 15, (1) 29 – 46

Obaje, N. G. & Abaa, S. I. (1996). Potential for Coal-derived Gaseous Hydrocarbons In the Middle Benue Trough of Nigeria. *Journal of Petroleum Geology* 19 (1), 77 – 94.

Obaje, N. G., Attah, D. O., Opeloye, S. A. & Moumouni, A. (2006). Geochemical evaluation of the hydrocarbon prospects of sedimentary basins in Northern Nigeria. *Geochemical Journal*, 40, 227 – 243.

Obaje, N. G., Abaa, S. I., Najime, T. & Suh, C. E. (1999): Economic Geology of Nigerian Coal Resources – a brief review. *Geosciences Review* 6, 1 – 12.

Obaje, N. G., Funtua, I. I., Ligouis, B. & Abaa, S. I. (1996). Maceral Associations, Organic Maturation and Coal-derived Hydrocarbon Potential in the Cretaceous Awgu Formation, Middle Benue Trough, Nigeria. *Journal of African Earth Sciences*. 23, (1) 89 – 94.

Obaje, N. G., Funtua, I. I., Ligouis, B. & Abaa, S. I. (1998). Organic Maturation and coal-derived hydrocarbon potentials of Cretaceous Coal Measures in the middle Benue Trough of Nigeria. *Journal of Mining and Geology*, 34, (1). 7 – 18.

Obaje, N. G. & Hamza, H. (2000). Liquid Hydrocarbon source-rock Potential of Mid-Cretaceous Coals and Coal Measures in the Middle Benue Trough of Nigeria. *International Journal of Earth Sciences*, 130 – 139.

Obaje, N. G., Ligouis, B. & Abaa, S. I. (1994). Petrographic Composition and Depositional Environments of Cretaceous Coals and Coal Measures in the middle Benue Trough of Nigeria. *International Journal of Coal Geology.* 26 (1994), 233 – 260.

Obaje, N. G. & Ligouis, B. (1996). Petrographic Evaluation of the Depositional Environment of the Cretaceous Oba/Lafia coal deposits in the Benue Trough of Nigeria. *Journal of Africa Earth Sciences.* 22, (2). 159 – 171.

Obianuju, P. U. (2005): Palynological study of the Okaba Coal Mine section in the Anambra Basin, Southeastern Nigeria. *Journal of Mining and Geology*, 41 (2) 193 – 203.

Obianuju, P. U. & James, J. E. (2008). Palynostratigraphy and Palaeoenvironments of the Type Area of Nsukka Formation of Anambra Basin, Southeastern Nigeria. *Nigerian Association of Petroleum Explorationist Bulletin*, 20, (2). 72 – 88.

Oboh, F. E. (1992). Multivariate Statistical Analysis of Palynodebris from the Middle Miocene of the Niger Delta and their Environmental Significance. *Palaios* (7), 559 – 573.

Odebode, M. O. (2010). A Handout on the Geology of the Benue and Anambra Basins, Nigeria.

Odedede, O. & Adaikpoh, E. O. (2011). Sequence Stratigraphic Analysis of the Gombe Sandstone and Lower Kerri-Kerri Formation exposed around Fika-Potiskum, Upper Benue Trough, Nigeria: A Consideration for Petroleum Reservoir Indicators. *Indian Journal of Science and Technology.* 4. (5). 492 – 498.

Ojo, O. J. (2009). Occurrence of some Maastrichtian Dinoflagellate Cysts from the Upper Cretaceous Sediments in Southeastern Bida Basin, Nigeria: Implications for Age and Paleoenvironments. *Ozean Journal of Applied Sciences* 2 (3), 291 – 305.

Ojo, O. J. & Akande, S. O. (2002). Petroleum Geochemical Evaluation of the Mid Cretaceous Sequence in the Dadiya Syncline, Yola Basin, Northeastern Nigeria. *Journal of Mining and Geology*, 38, (1) 35 – 42.

Ojo, O. J. & Akande, S. O. (2004). Palynology and Paleoenvironmental studies of the Gombe Formation, Gongola Basin, Nigeria. *Journal of Mining and Geology*, 40 (2); 143 – 149.

Ojo, O. J. & Akande, S. O. (2006). Sedimentological and Palynological studies of the Patti Formation, South Eastern Bida Basin, Nigeria: Implications for Paleoenvironments and Paleogeography. *Nigerian Association of Petroleum Explorationist Bulletin*, 19 (1). 61 – 77.

Okosun, E. A. (1995). Review of the Geology of Bornu Basin. *Journal of Mining and Geology,* 31 (2), 113 – 122.

Ola-buraimo, A. O. & Boboye, O. A. (2011). Palynological Investigation of the Albian to Lower Cenomanian Bima Formation, Bornu Basin, Nigeria. *World Applied Sciences Journal* 12 (7): 1026 – 1033.

Oloto, I. N. (1994). Nigerian Maastrichtian to Miocene Dinoflagellate and Miospore Biozonation. A Summary. *Journal of Mining and Geology,* 30. (1). 61 – 73.

Oyede, A. C. (1992). Training Manual on Palynomorps and Palynofacies for Shell Petroleum Development Company, Warri.

Pacltova, B. (1959) On some plant microfossils from fresh-water sediments of the Upper Cretaceous (Senonian) in the South Bohenian Basin. *Sbornik Ustred Geologie*, 26, 38 – 50.

Pacltova, B. (1970). New types of spores (genera and species) from the Bohemian Miocene: *Palaont; Abh. B-Palaobot*; III; (3 & 4) 599 – 617.

Pamela, J. W. G. (1988). Paleoecology and Sedimentology of a Late Triassic Lake, Culperer Basin, Virginia, U.S.A. Palaeogeography, Palaeoclimatology, Palaeoecology, 62. *Elsevier Science Publishers, B. V., Amsterdam*. 593 – 608.

Peters, K. E. (1986). Guidelines for Evaluating Petroleum Source Rock Using Programmed Pyrolysis. *The American Association of Petroleum Geologists Bulletin* 70, (3). 318 - 329.

Peters, K. E. & Cassa, M. R. (1994). Applield Source Rock Geochemistry. In: Magoon, L. and Dow, G. W. (Eds.). The Petroleum System – from Source to Trap. *American Association of Petroleum Geologist Bulletin.* 60, 93 – 120.

Petters, S. W. & Edet, J. J. (1996). Shallow Shelf and Auoxic Facies in Late Campanian – Early Maastrichtian of S.E. Nigeria. *Geologie de I'Afrique et de I'Atlantique Sud: Actes Colloques Angers* 1994. 219 – 233.

Pflug, H. & Thompson, P. W. (1953). Pollen und Sporen. *Mitteleuro Paischen Tertiars. Palaeontographica*. 94.

Pierce, R. C. (1961). Lower Upper Cretaceous plant microfossils from Minnesota. University of Minnesota, *Minnesota Geological Survey Bulletin*. 42.

Playford & Datemann (1996). Spores and Pollen. Retrieved January 21, 2012 from http://www.pollenandspores.

Popoff, M., Wiedmann, J. & Easz, I. (1986). The Upper Cretaceous Gongola and Pindiga Formation, Northern Nigeria. Subdivisions, Age, Stratigraphic Correlations and Paleogeographic Implications. *Eclogae Geologicae Helvetiae,* 79, 343 – 363.

Potonie, R. (1956). Synopsis der Gattungen der Sporae dispersae I. Teil Sporites, I. *Beiheffe zum Geologischen Jahrb* 23, 3 – 103.

Potonie, R. (1958). Synopsis der Gattungen dispersae II. Teil: Sporites Machuridge saccite Aletes praecolpates, tricolpates, monoclpates. *Beiheffe zum Geologischen Jahrb* 39, 3 – 139.

Potonie, R. (1960). Synopsis der Gattungen der Sporae dispersae III. Teil nachtrage Sporites, Fotsetziang pollenites. Micropaleon. General register zu Teil I – IV. *Beiheffe zum Geologischen Jahrb*, 39: 189

Raeburn & Brynmor Jones (1934); The Ogboyega Coal, Igala Division, Kabba Province. *Reconnaissance Survey of Nigeria.* (1955). 10 – 16.

Reyment, R. A. (1965). Aspects of the geology of Nigeria. The Stratigraphy of the Cretaceous and Cenozoic deposits. *Ibadan University Press.* 23 – 73.

Salami, M. B. (1983). Some Late Cretaceous and Early Tertiary Pteridophytic Spores From the Southern Nigeria Sedimentary Basin. *Revista Espanola de Micropaleontologia*. XV (2). 257 – 272.

Salami, M. B. (1990). Palynomorph taxa from the "Lower Coal Measures" deposits(? Campanian – Maastrichtian) of Anambra Trough, Southeastern Nigeria. *Journal of African Earth Sciences* 11: 135 – 150.

Salard-Cheboldaeff, M. (1990). Intertropical African Palynostratigraphy from Cretaceous to Late Quarternary Times: *Journal of African Earth Sciences,* 11, 1 – 24.

Salard-Cheboldaeff, M. & Dajax, J. (1991). Evidence of Cretaceous to Recent West Africa Intertropical Vegetation from Continental Sediment: Spore – pollen analysis. *Journal of African Earth Sciences*, 12 (1 & 2) 353 – 361.

Salvador, A. (ed) (1994). International stratigraphic guide. 2nd edition, *International Union of Geological Sciences and Geological Society of America, Inc*; 214.

Shemang, E. M., Ajayi, C. O. & Umego, M. N. (1998). The structure of the Gongola arm of the Upper Benue Trough as revealed by Gravity and Magnetic studies.

Simpson, A. (1954). The Nigerian Coal Field: The Geology of Parts of Onitsha, Owerri and Benue Provinces: *Nigeria Geological Survey Bulletin*. 24, 85.

Spicer, R. A. & Hill, C. R, (1979). Principal Components and Correspondence nalyses of Quantitative Data from a Jurassic Plant bed: *Review of Palaeobotany and Palynology*, 60, 255 – 282.

Spores and Pollen: Retrieved online on 15th January, 2012, at about 4.00 a.m www.ucl.ac.uk/geolsci/.../spores.html

Sykes, R. & Snowdon, L. R. (2002). Guidelines for assessing the Petroleum Potential of Coaly source rocks Using Rock-Eval pyrolysis. *Organic Geochemistry 33*, 1441 – 1455.

Thompson, J. H. (1958). The Geology and Hydrogeology of Gombe, Bauchi Province. *Records of the Geological Survey of Nigeria*, 1956. 46 – 65.

Tissot, B. P. & Welte, D. H. (1984). Petroleum Formation and Occurrence (2nd Ed.): *Heidelberg (Spring-verleg*).

Tukur, A., Samaila, N. K., Shettima, B. & Jauro, A. (2006); An Assessment of the Hydrocarbon potential of some Cretaceous Coals from the Benue Trough, Nigeria. *Jolorn* 7 (2) 57 – 64.

Van der Hammen, T. (1954). The development of Colombian flora throughout geological periods, I: Maastrichtian to Lower Tertiary. *Boletin Geologico* (Bogota), 2(1). 49 – 106

Van der Hammen, T. (1956a). A palynological systematic nomenclature. *Boletin Geologico* 4, 2 – 3, Bogota. 63 – 101.

Van der Hammen, T. (1956b). Description of some genera and species of fossils.

Van der Hammen, T. & Pierce, R. L. (1961). Lower Upper Cretaceous plant microfossils. *University of Minnesota – Mines Geological Survey Bulletin*. 42.

Van der Hammen, T. & Wymstra, T. A. (1964). A palynological study on the Tertiary and Upper Crateceous of British Guiana. *Leidse Geologische Mediedelingen*. ded 30.

Van Hoeken-Klinkenberg P. M. J. (1964). A Palynological Investigation of Some Upper-Cretaceous Sediments in Nigeria. Palynological Laboratory, *Geological Institute, Leiden*. Netherlands

Vidal, G. (1988). A Palynological Preparation Method. Micropaleontological Laboratory, Geology Department, University of Lund, Kemicentrum, Box 124. S – 22100 Lund Sweden.

Whiteman, A. J. (1982). Nigeria: Its petroleum geology, resources and potentials. (1) 176, (2) 238. *Graham and Trotman*, London, U.K.

Zaborski, P. M. (2003). Guide to the Cretaceous system in the Upper Part of the Upper Benue Trough, Northeastern Nigeria. *African Geosciences Research*. 10 (1 & 2). 13 – 32.

Zaborski, P. M., Nnabo, P. & Ibe, K. (1998). Stratigraphy and Structure of the Cretaceous Gongola basin, Northeastern Nigeria.

Zaborski, P. M., Ugoduluwa, F., Idornigie, A., Nnabo, P. & Ibe, K. (1997). Stratigraphy and Structure of the Cretaceous Gongola Basin, Northeastern Nigeria. *Bulletin des Centres de Recherches Exploration – Production Elf – Aquitaine*, 21. 153 – 185.

APPENDIX A

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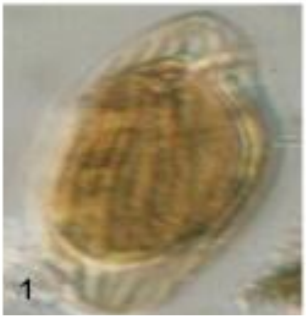
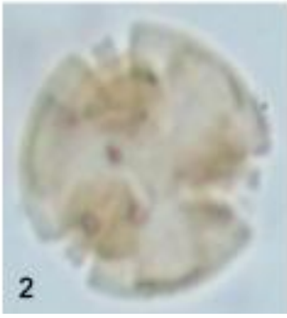
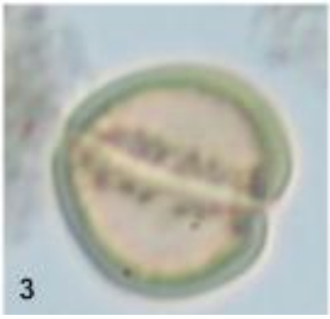


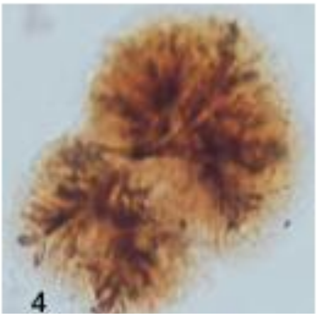
Ephedripites ambiguous



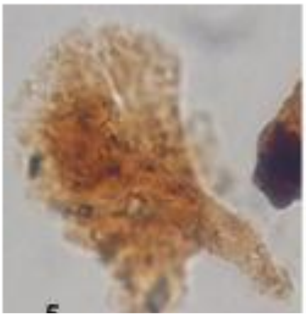
Psilatricolporites crassus



Monocolpopollenites sphaeroidites

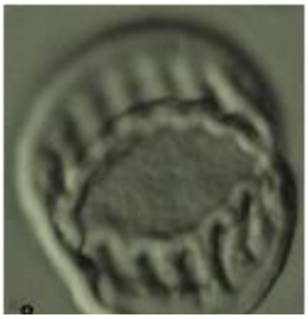


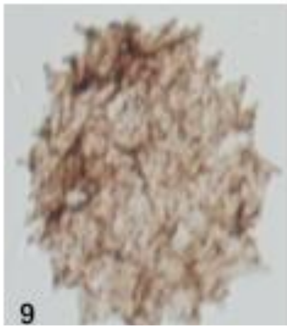
Botryococcus braunii (A)


Botrycoccus braunii (B)


Monocolpites marginatus


Retimonocolpites sp.

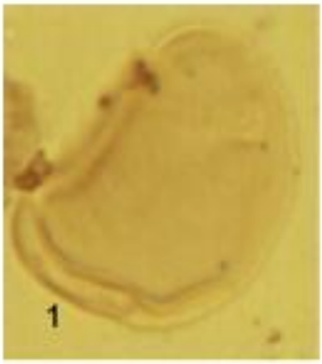

Tubistephanocolpites cylindricus



Pediastrum sp.

Appendix A.1: Microphotographs of some analysed palynomorphs

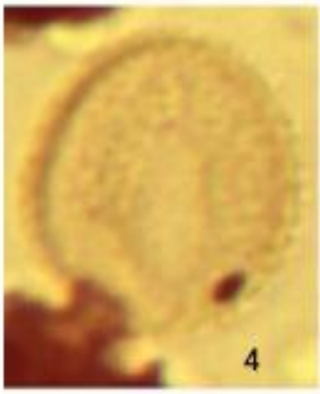
ALL MAGNIFICATION IS X 1000



Laevigatosporites haardtii

Fungal spore (A)

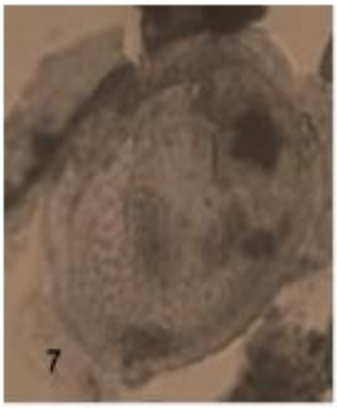
Fungal spore (B)



Arecipites crassimuratus

Ctenolophonidites costatus

Zlivisporites blanensis



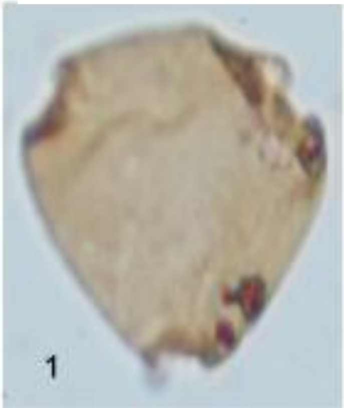
Proxapertites cursus

Sapotaceoidaepollenites sp.

Germmamonoporites sp.

Appendix A.2: Microphotographs of some analysed palynomorphs continued

ALL MAGNIFICATION IS X 1000



Cupanieidites sp.

Psilatricolporites crassus

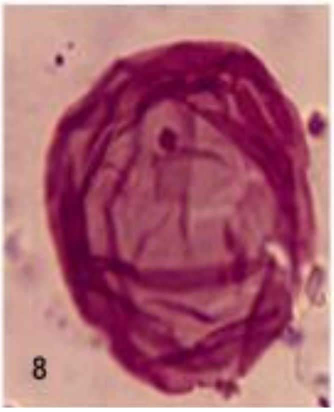
Tricolporopollenites sp.

Droseridites Senonicus

Foveotriletes margaritae

Cyathidites sp.

Osmundacidites sp.



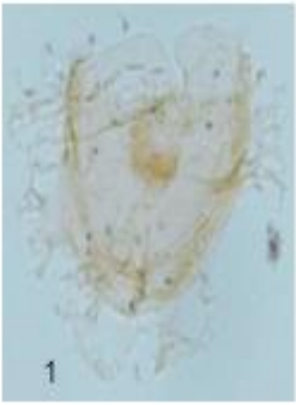
Leoisphaeridia sp.

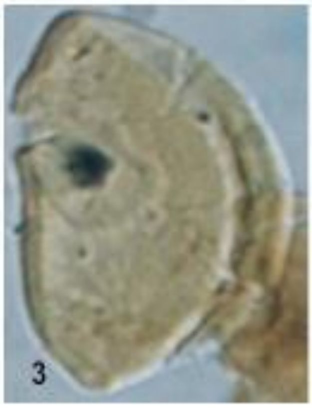
Proteacidites sigalii

Appendix A.3: Microphotographs of some analysed palynomorphs continued

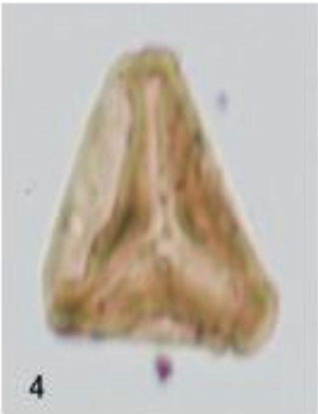
Appendix A continued

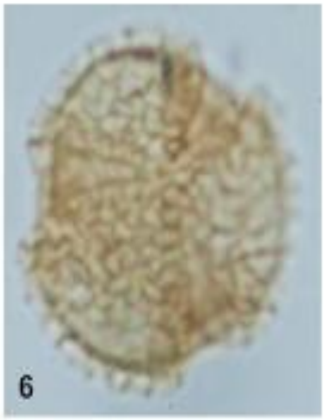
ALL MAGNIFICATION IS X 1000



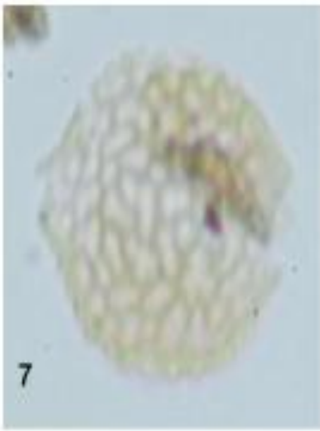


Nematosphaeropsis sp. *Cingulatisporites Ornatus* *Longapertites microfoveolatus*





Glechenidites Senonicus *Rugulatisporites caperatus* *Retitricolporites irregularis*



Auriculiidites sp. *Longapertites chlonovae* *Distaverrusporites* simplex

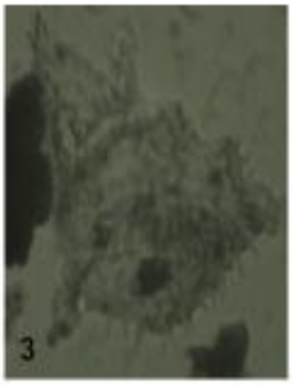
Appendix A.4: Microphotographs of some analysed palynomorphs continued

Appendix A continued

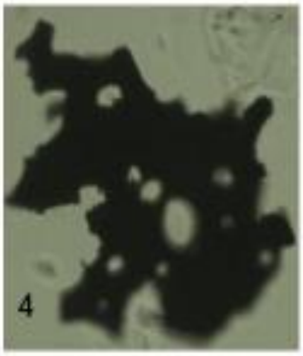
ALL MAGNIFICATION IS X 1000

Monoporites annulatus

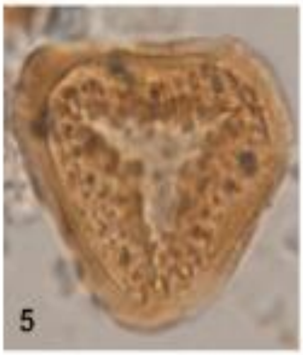
Echitriporites trianguliformis



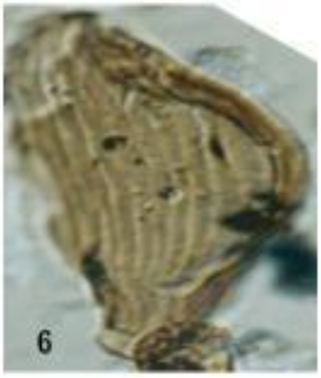
Auriculopollenites sp.



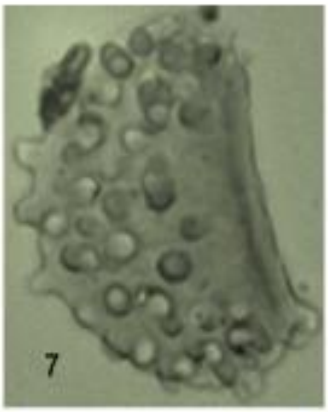
Charred Graminae Cuticle



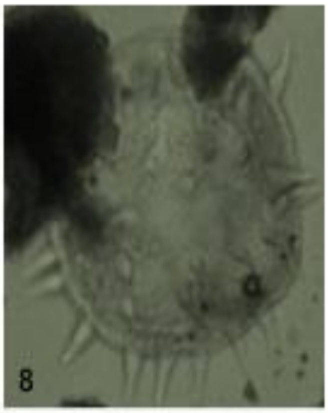
Polypodiaceoisporites sp.



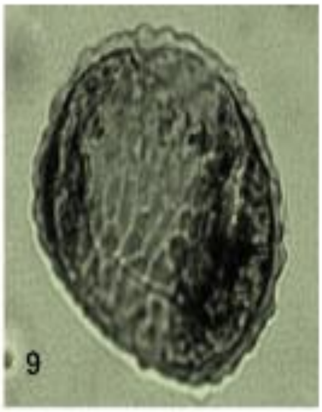
Gnetaceaepollenites sp.



Verrucatosporites usmensis



Spinizonocolpites echinatus

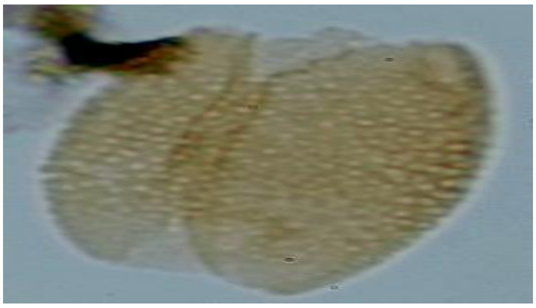


Verrucatosporites sp.

Appendix A.5: Microphotographs of some analysed palynomorphs continued

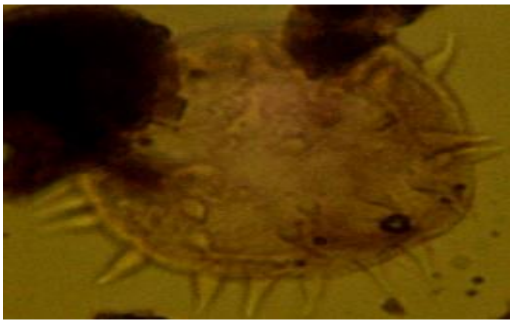
Appendix A continued

ALL MAGNIFICATION IS X 1000

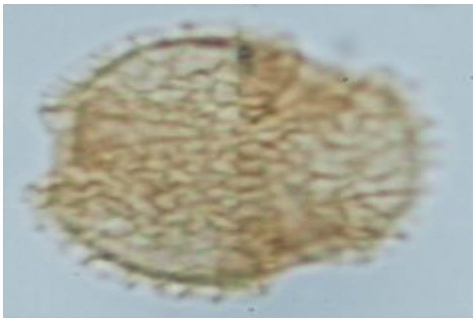


1: *Longapertites chlonovae*

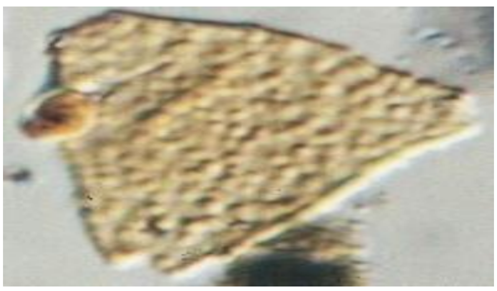
2: *Monoporites annulatus*



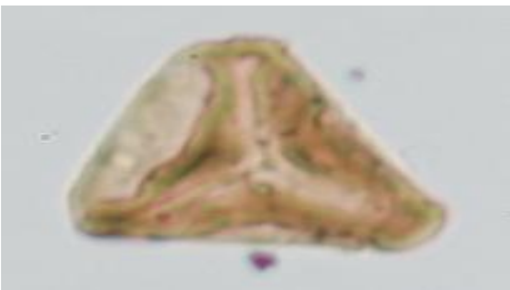
3: *Spinizonocolpites echinatus*



4: *Retitricolporites irregularis*



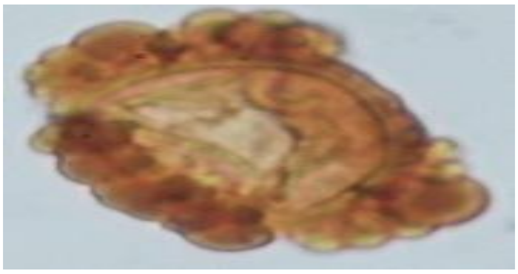
5: *Proteacidites Sigalii*



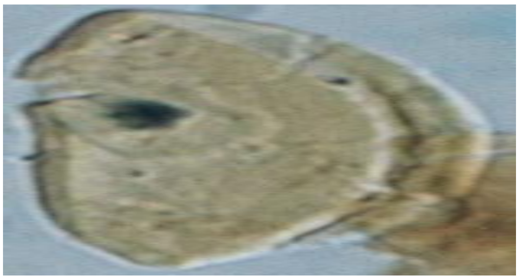
6: *Glecheniidites senonicus*

Appendix A.6: Microphotographs of some analysed palynomorphs continued

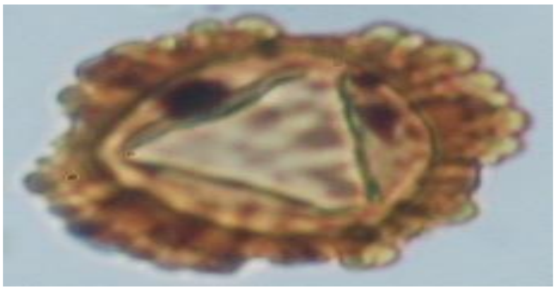
ALL MAGNIFICATION IS X 1000



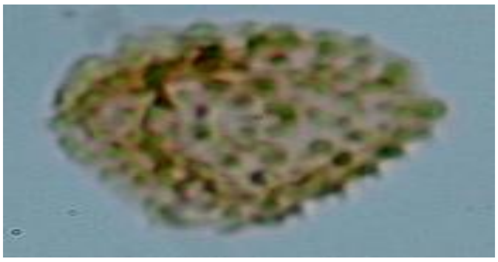
1: *Distaverrusporites simplex*



2: *Longapertites microfoveolatus*

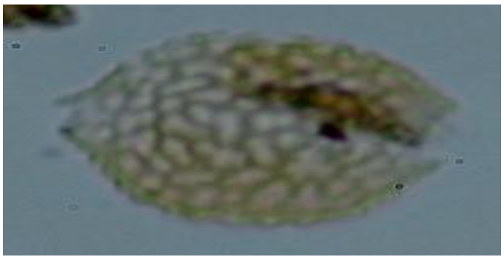


3: *Cingulatisporites ornatus*



4: *Echitriporites trianguliformis*

5: *Rugulatisporites caperatus*



6: *Auriculiidites* spp

Appendix A.7: Microphotographs of some analysed palynomorphs

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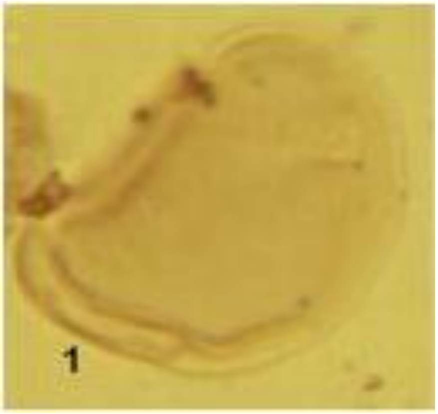
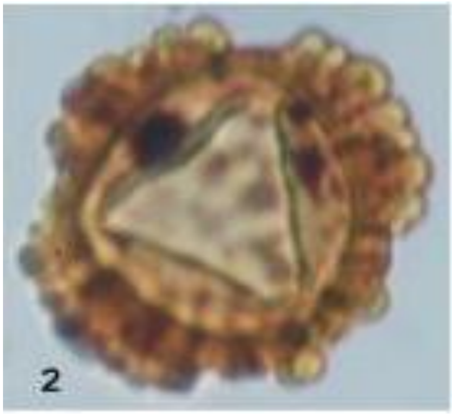
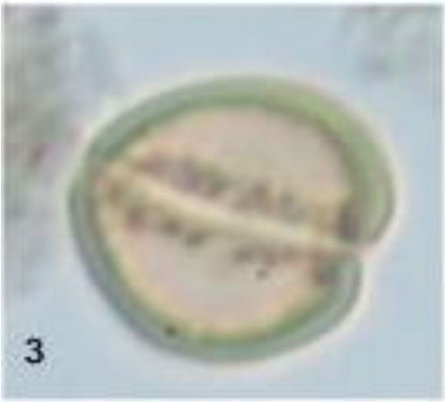


Laevigatosporites haardti sp



Cingulatisporites ornatus sp



Monocolpopollenites sphaeroidites sp

Droseridites senonicus sp

Appendix A.8: Microphotographs of some analysed palynomorphs

APPENDIX B

Frequency distribution tables of palynomorphs for BA – 7, BA – 16 and BA – 17

Appendix B.1: Frequency table for BA – 7 palynomorphs

Palynomorphs	Type	Count	Remarks
Proteacidites sigalii	Pollen	9	
Retidiporites magdalenensis	Pollen	6	
Monoporites annulatus	Pollen	1	
Brevicolporites guinetii	Pollen	1	
Cingulatisporites ornatus	Spore	11	
Proteacidites sp	Pollen	4	
Rugulatisporites caperatus	Spore	3	
Sapotaceoidaepollenites sp	Pollen	3	
Acrostichum aureum	Spore	37	
Gemmastephanocolporites brevicolpites	Pollen	1	
Longapertites marginatus	Pollen	28	
Proxapertites cursus	Pollen	4	
Psilatricolporites crassus	Pollen	1	
Psilatricolporites operculatus	Pollen	2	
Laevigatosporites sp	Spore	14	
Retitricolporites irregularis	Pollen	1	
Verrucatosporites sp	Spore	6	
Charred gramineae cuticle	Pollen	2	
Monoporites annulatus	Pollen	1	
Proteacidites cooksonni	Pollen	1	
Proteacidites longispinosus	Pollen	4	
Proteacidites sigalii	Pollen	9	
Arecipites sp	Pollen	1	
Botryococcus braunii	Algae	1	
Auriculiidites sp	Pollen	3	
Constructipollenites ineffectus	Pollen	3	
Corsinipollenites jussiaeensis	Pollen	1	
Droseridites senonicus	Pollen	1	
Echitricolporites trianguliformis	Pollen	44	
Ephedripites ambiguous	Pollen	1	
Galeacornea sp	Spore	1	
Gemmamonoporites sp	Pollen	2	
Gleicheniidites senonicus	Spore	5	
Inaperturopollenites sp	Pollen	18	
Incertae sedis	Pollen	1	
Longapertites chlonovae	Pollen	1	
Longapertites microfoveolatus	Pollen	4	
Longapertites sp	Pollen	31	
Longapertites vandeerburgii	Pollen	4	
Margocolporites sp	Pollen	1	
Margocolporites vanwijhei	Pollen	1	
Milfordia sp	Pollen	2	
Monocolpites marginatus	Pollen	15	

Appendix B.2: Frequency table for BA – 16 palynomorphs

Palynomorphs	Type	Count	Remarks
Cyathidites sp	Spore	23	
Proteacidites sigalii	Pollen	8	
Retidiporites magdalenensis	Pollen	4	
Brevicolporites guinetii	Pollen	2	
Cingulatisporites ornatus	Spore	6	
Crototricolporites crotonoisculptus	Pollen	1	
Cupanieidites reticularis	Pollen	1	
Perfotricolpites digitatus	Pollen	1	
Polypodiaceoisporites sp	Spore	1	
Proteacidites sp	Pollen	4	
Psilamonocolpites marginatus	Pollen	2	
Sapotaceoidaepollenites sp	Pollen	2	
Acrostichum aureum	Spore	19	
Longapertites marginatus	Pollen	11	
Proxapertites cursus	Pollen	5	
Proxapertites sp	Pollen	3	
Retibrevitricolporites triangulatus	Pollen	1	
Ctenolophonidites costatus	Pollen	1	
Laevigatosporites sp	Spore	24	
Retibrevitricolporites triangulatus	Pollen	1	
Verrucatosporites sp	Spore	3	
Proteacidites longispinosus	Pollen	2	
Proteacidites sigalii	Pollen	8	
Botryococcus braunii	Algae	1	
Adenantherites simplex	Pollen	1	
Auriculopollenites reticulatus	Pollen	4	
Clavainaperturites clavatus	Pollen	1	
Constructipollenites ineffectus	Pollen	2	
Corsinipollenites jussiaeensis	Pollen	1	
Cupanieidites reticularis	Pollen	1	
Echitricolporites trianguliformis	Pollen	70	
Gemmamonoporites sp	Pollen	1	
Gleicheniidites senonicus	Spore	10	
Gleicheniidites sp	Spore	3	
Inaperturopollinites sp	Pollen	11	
Incertae sedis	Pollen	1	
Longapertites chlonovae	Pollen	4	
Longapertites microfoveolatus	Pollen	7	
Longapertites sp	Pollen	22	
Longapertites vandeerburgii	Pollen	2	
Margocolporites sp	Pollen	2	
Margocolporites vanwijhei	Pollen	1	

Appendix B continued

Appendix B.3: frequency table for BA – 17 palynomorphs

Palynomorphs	Type	Count	Remarks
Proteacidites sigalii	Pollen	9	
Retidiporites magdalenensis	Pollen	2	
Monoporites annulatus	Pollen	3	
Brevicolporites guinetii	Pollen	1	
Proteacidites sp	Pollen	4	
Laevigatosporites sp	Spore	25	
Retitricolporites irregularis	Pollen	1	
Proteacidites cooksonni	Pollen	2	
Acrostichum aureum	Spore	47	
Echitriporites trianguliformis	Pollen	39	
Proxapertites cursus	Pollen	2	
Psilamonocolpites marginatus	Pollen	1	
Psilatricolporites crassus	Pollen	1	
Psilatricolporites operculatus	Pollen	2	
Retibrevitricolporites triangulates	Pollen	3	
Arecipites crassimuratus	Pollen	1	
Constructipollenites ineffectus	Pollen	6	
Crototricolporites crotonoisculptus	Pollen	2	
Cupaniedites sp	Pollen	1	
Gemmamonoporites sp	Pollen	4	
Gemmastephanocolporites brevicolpites	Pollen	3	
Gemmatricolpites scabratus	Pollen	1	
Gemmatriporites sp	Pollen	2	
Gemmazonocolpites sp	Pollen	7	
Gnetaceaepollenites sp	Pollen	1	
Inaperturopollenites sp	Pollen	23	
Longapertites chlonovae	Pollen	10	
Longapertites marginatus	Pollen	20	
Longapertites sp	Pollen	44	
Longapertites vandeerburgii	Pollen	2	
Milfordia sp	Pollen	2	
Monocolpites marginatus	Pollen	25	
Monocolpites sp	Pollen	23	
Monosulcites sp	Pollen	2	
Periretisyncolpites sp	Pollen	1	
Pollen indeterminate	Pollen	7	
Praedapollis protrudentiporatus	Pollen	1	
Proteacidites dehaani	Pollen	1	
Proteacidites otamiriensis	Pollen	1	
Proteacidites sigalii	Pollen	6	
Proxapertites operculatus	Pollen	2	
Proxapertites sp	Pollen	3	

APPENDIX C

Appendix C.1: Frequency Distribution of Palynomacerals

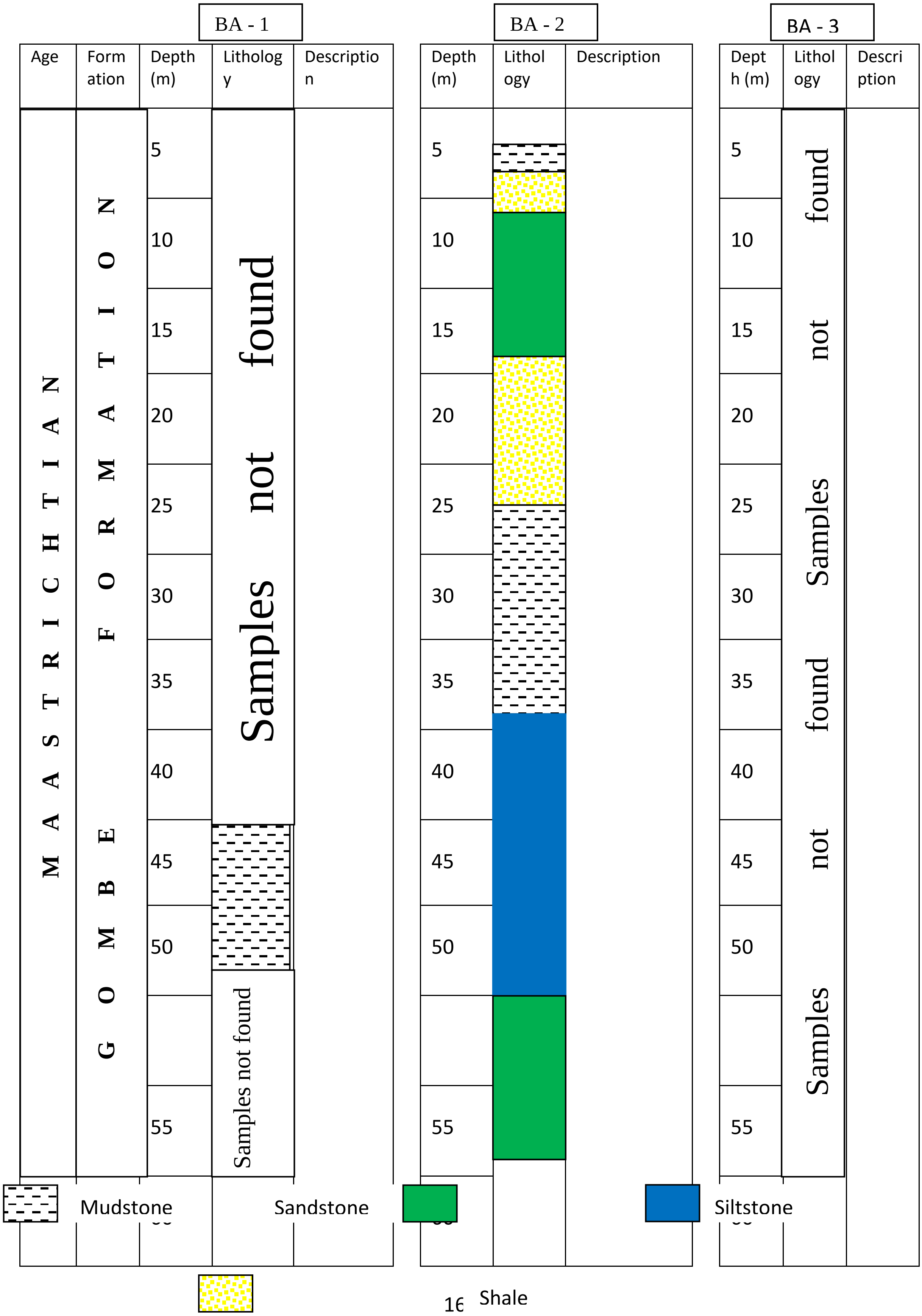
BA – 7	
PALYNOFACIES	**FREQUENCY**
Amorphous Plant Matter (PM 1)	900
Vinitric Brown / Blackwood (PM 2)	584
Cuticles and Membranus Debris (PM 3)	136
Platy Trucheidal Debris (PM 4)	278
Structureless Organic Matter (SOM)	34
BA – 16	
PALYNOFACIES	**FREQUENCY**
Amorphous Plant Matter (PM 1)	986
Vinitric Brown / Blackwood (PM 2)	605
Cuticles and Membranus Debris (PM 3)	135
Platy Trucheidal Debris (PM 4)	570
Structureless Organic Matter (SOM)	47
BA – 17	
PALYNOFACIES	**FREQUENCY**
Amorphous Plant Matter (PM 1)	1,197
Vinitric Brown / Blackwood (PM 2)	964
Cuticles and Membranus Debris (PM 3)	167
Platy Trucheidal Debris (PM 4)	534
Structureless Organic Matter (SOM)	44

Appendix C.2: Summative Frequencies of Palynofacies in the Three (3) Boreholes Sampled

PALYNOFACIES	FREQUENCY
PM 1	3,083
PM 2	2,153
PM 3	438
PM 4	1,382
SOM	125

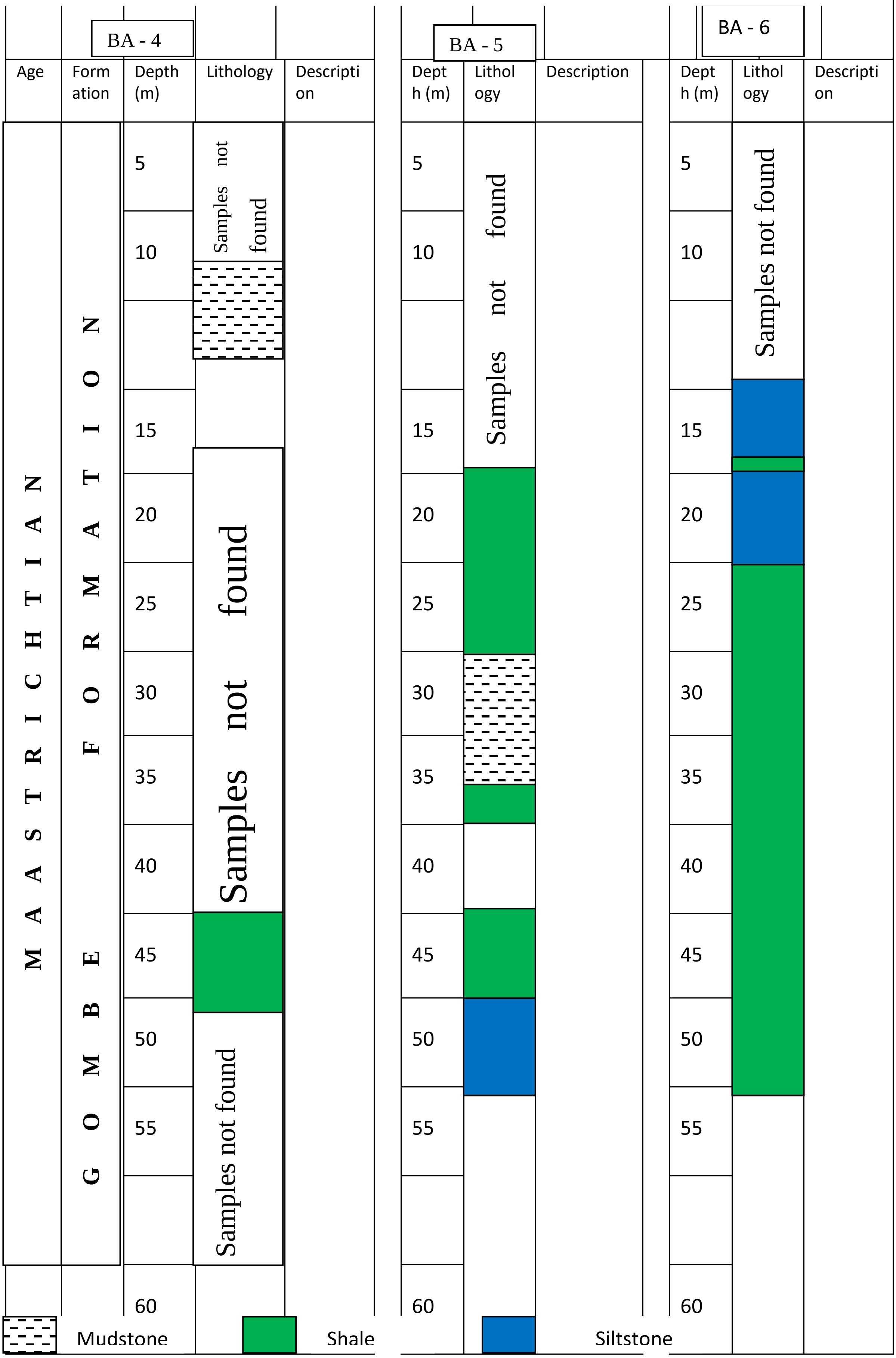
APPENDIX D

Appendix D.1: Lithology of boreholes BA – 1, B – A2 and BA – 3.



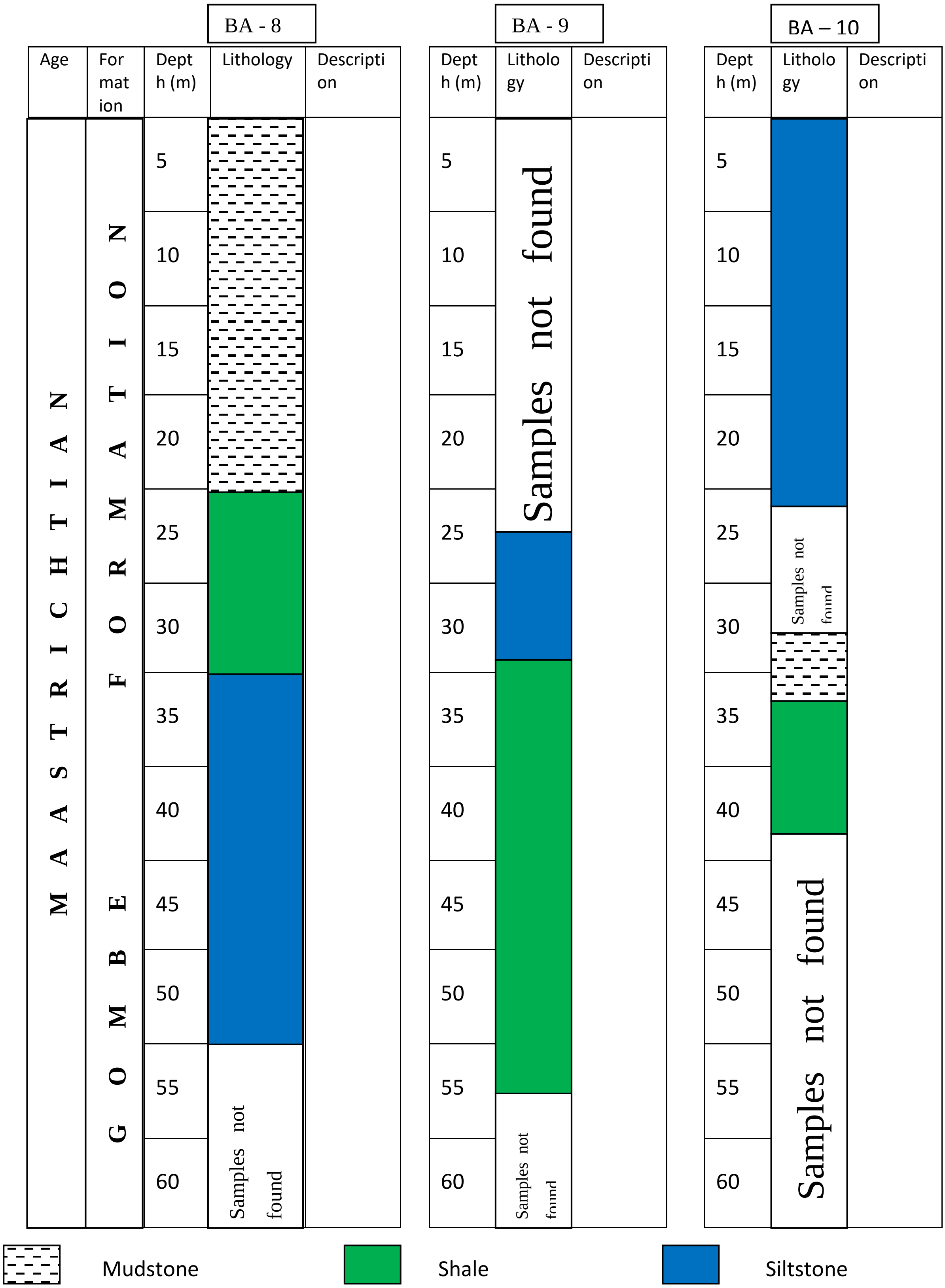
Appendix D continued

Appendix D.2: Lithology of boreholes BA – 4, BA – 5 and BA – 6.



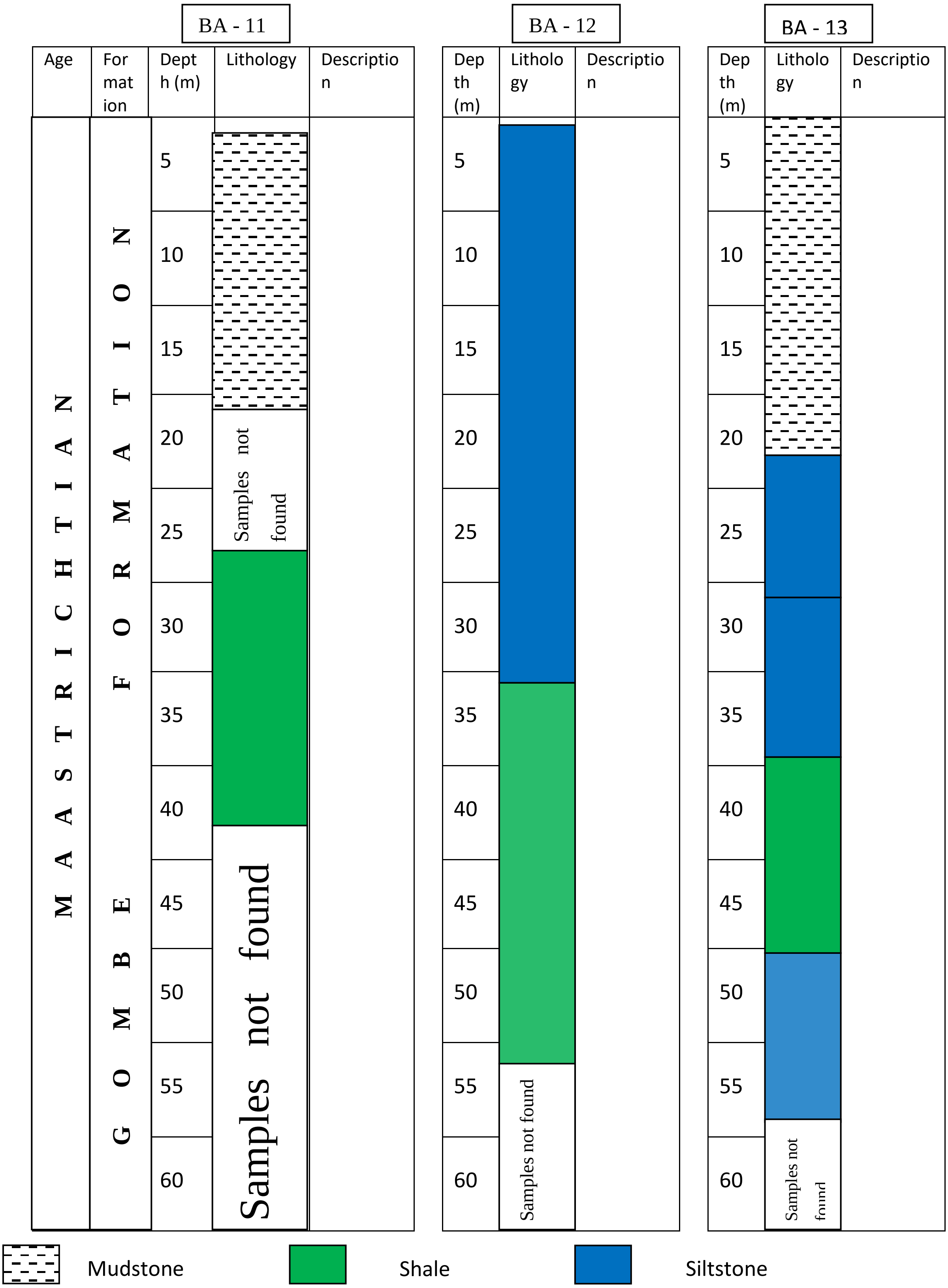
Appendix D continued

Appendix D.3: Lithology of boreholes BA – 8, BA – 9 and BA – 10.



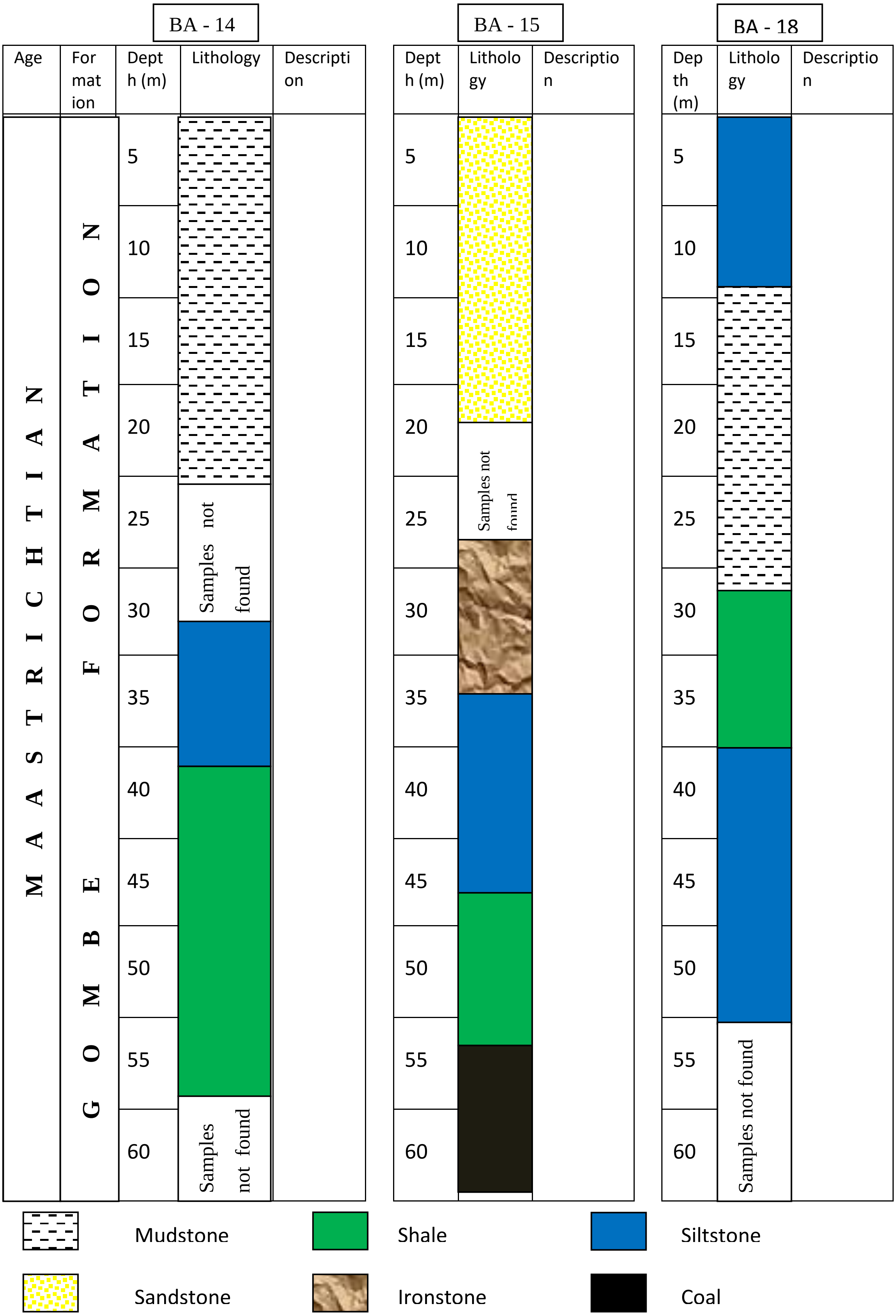
Appendix D continued

Appendix D.4: Lithology of boreholes BA – 11, BA – 12 and BA – 13.



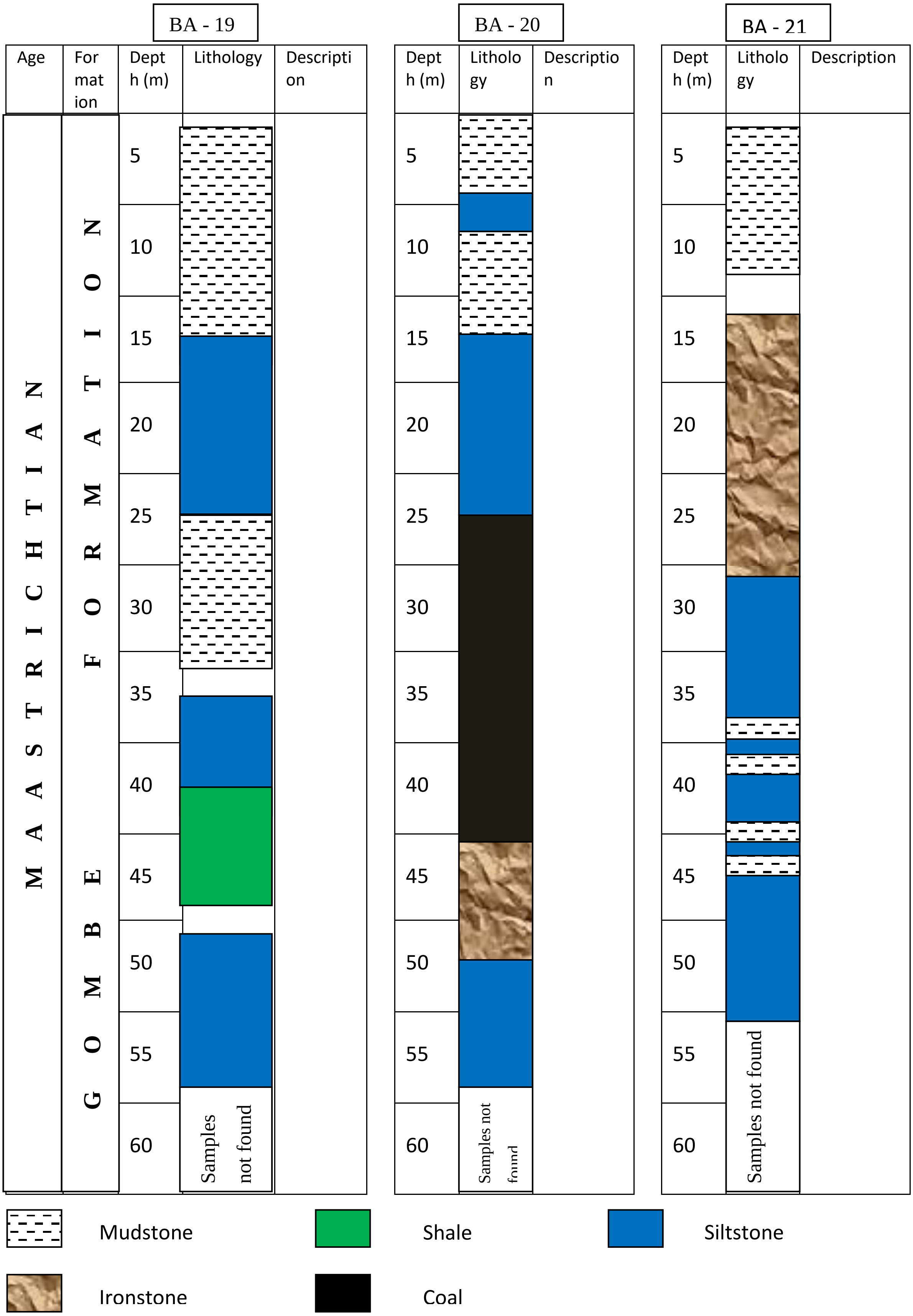
Appendix D continued

Appendix D.5: Lithology of boreholes BA – 14, BA – 15 and BA – 18.



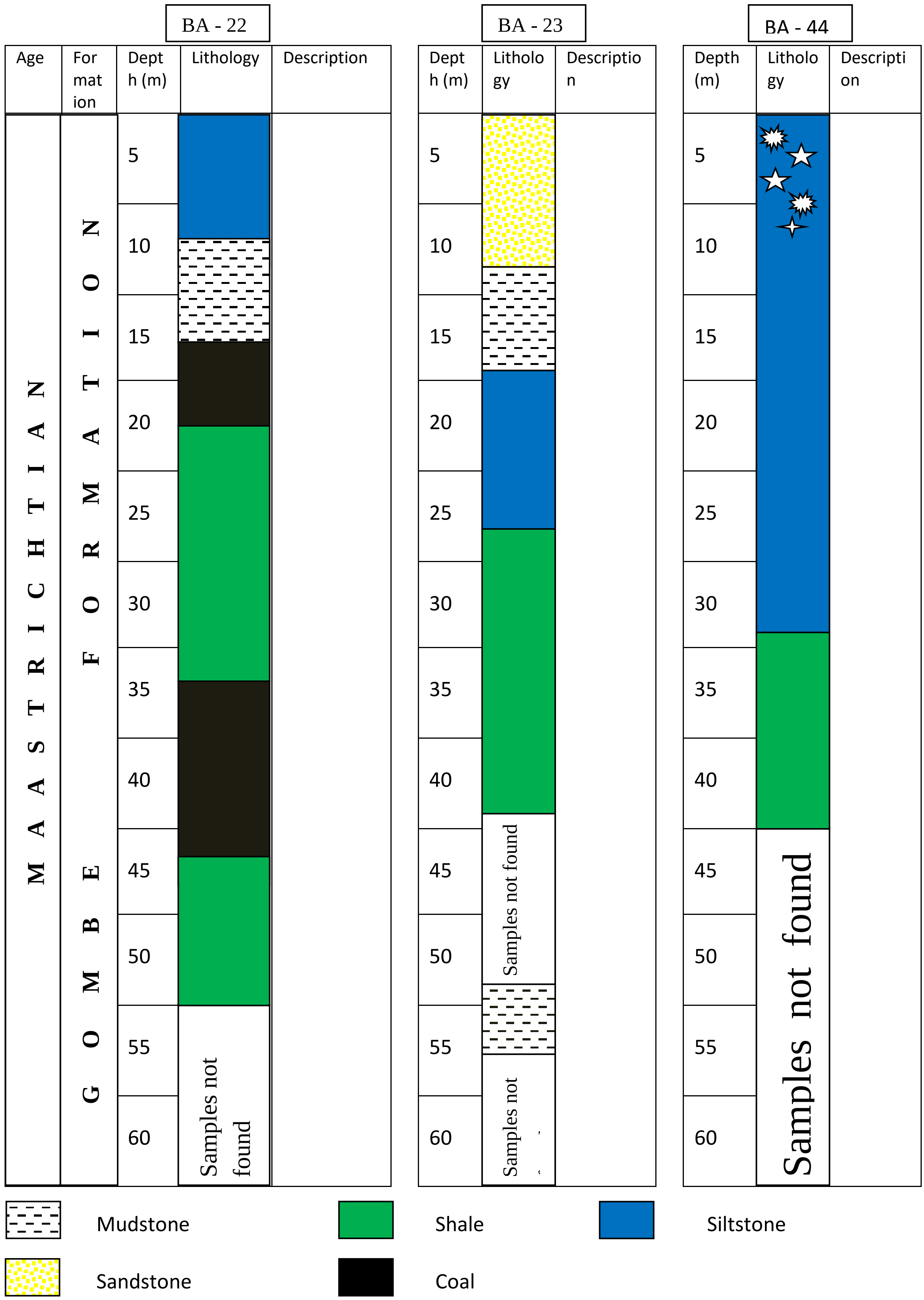
Appendix D continued

Appendix D.6: Lithology of boreholes BA – 19, BA – 20 and BA – 21.

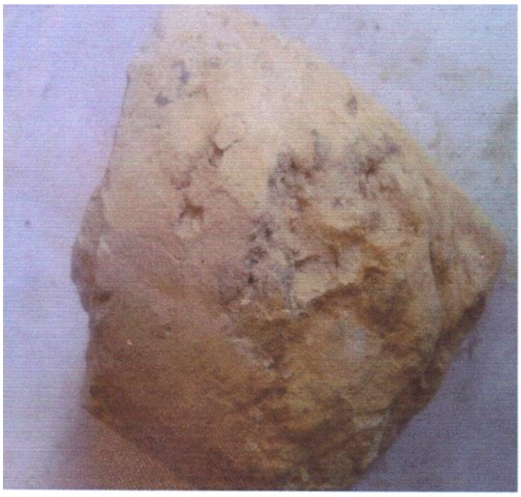


Appendix D continued

Appendix D.7: Lithology of boreholes BA – 22, BA – 23 and BA – 44.



APPENDIX E



BA2 No3 (Mudstone)

BA2 No2 (Oolitic sandstone)

BA2 No1b(Oolitic Sandstone)

BA2 No1 (Carbonaceous shale)

BA2 No6 (Coaly shale)

\5 No3 (Shale)

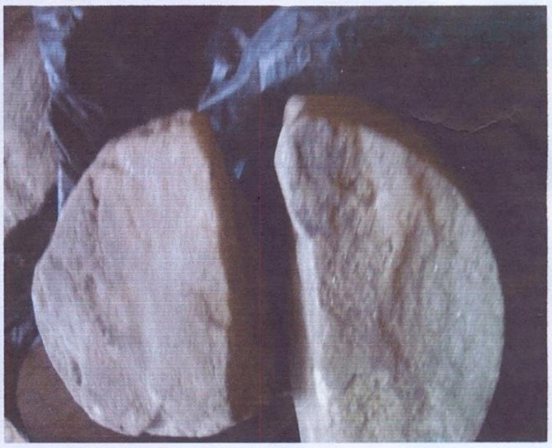
Appendix E.1: Photographs of boreholes cutting samples

Appendix E continued

BA5 No4 (Carbonaceous mudstone)

BA5 No5 (Siltstone)

BA6 No1 (Carbonaceous shale)



BA6 No4 (Carbonaceous shale)

BA6 No6 (Shale)

BA8 No3 (Shale)

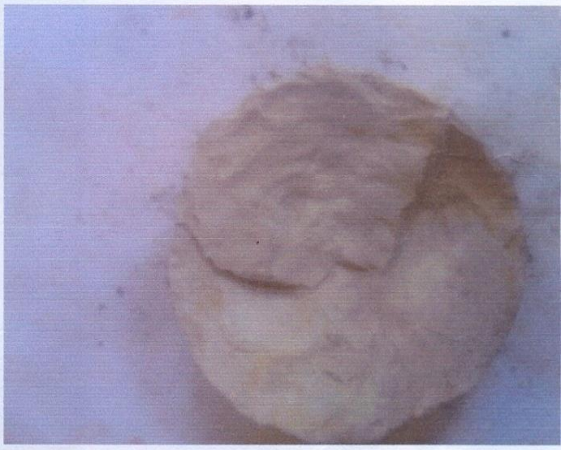
Appendix E.2: Photographs of boreholes cutting samples continued

Appendix E continued

BA8 No5 (Coaly siltstone)

BA9 No2 (Siltstone)

BA9 No3 (Shale)



BA10 No2 (Siltstone)

BA10 No4 (shale)

BA10 No5 (Mudstone)

Appendix E.3: Photographs of boreholes cutting samples continued

Appendix E continued

BA12 No1 (Siltstone)

BA12 No2 (Siltstone)

BA12 No2b (Mudstone)

BA12 No4 (Shale)

BA12 No3 (Coaly shale)

BA12 No4 (Siltstone)

Appendix E.4: Photographs of boreholes cutting samples continued

Appendix E continued

BA14 No1 (Mudstone)

BA15 No1 (Sand)

BA15 No3 (Siltstone)

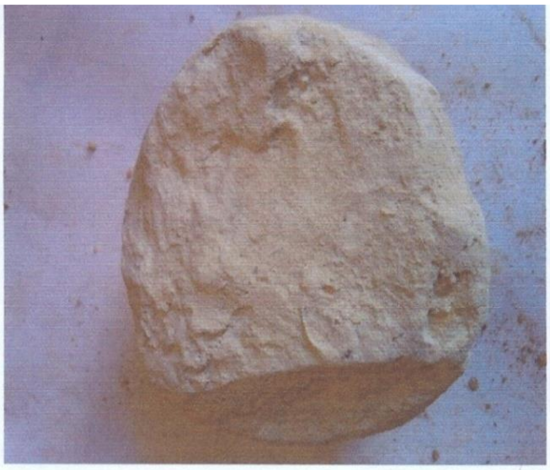
BA15 No7 (Coal)

BA16 No1 (Siltstone)

BA16 No1b (Coal)

Appendix E.5: Photographs of boreholes cutting samples continued

Appendix E continued

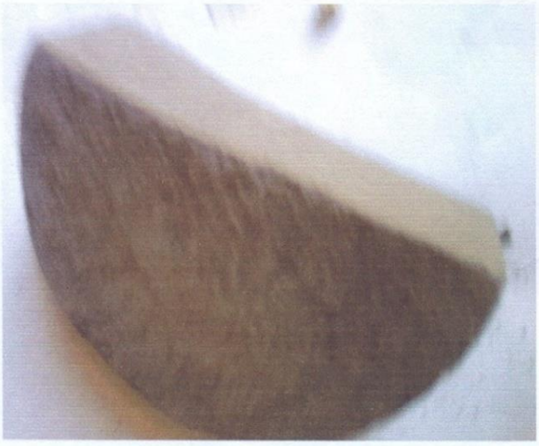


BA16 No2 (Siltstone)

BA16 No2b (Siltstone)

BA16 No4 (Carbonaceous shale)

BA16 No4b (Coal)



BA16 No5 (Carbonaceous shale)

16 No6 (Siltstone)

Appendix E.6: Photographs of boreholes cutting samples continued

Appendix E continued

BA16 No7 (Coaly siltstone)

BA17 No1 (Siltstone)

BA17 No1b (Ironstone)

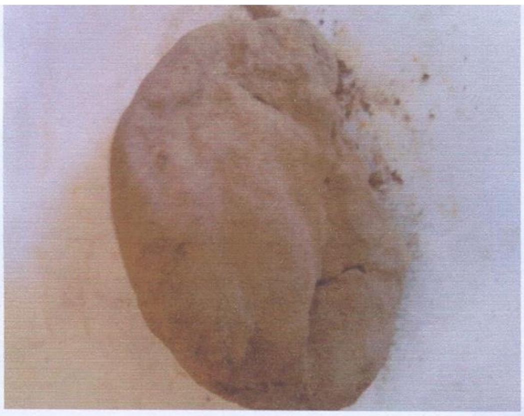
BA17 No2 (Siltstone)

BA17 No3 (Mudstone)

BA19 No1 (Mudstone)

Appendix E.7: Photographs of boreholes cutting samples continued

Appendix E continued



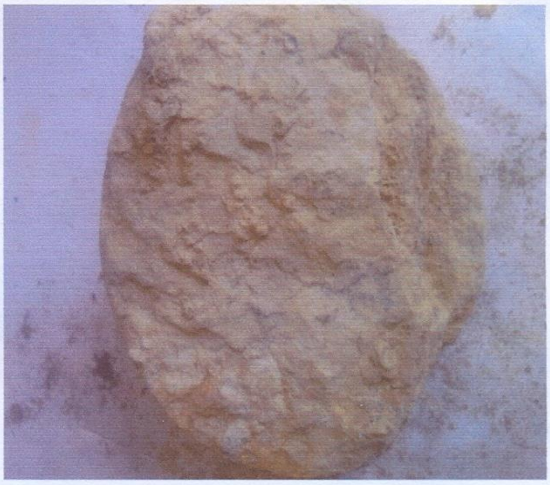
BA19 No3 (Mudstone)

BA19 No6 (Siltstone)

BA19 No10 (Carbonaceous siltstone)

BA20 No1 (Mudstone)

BA20 No1a (Coaly siltstone)

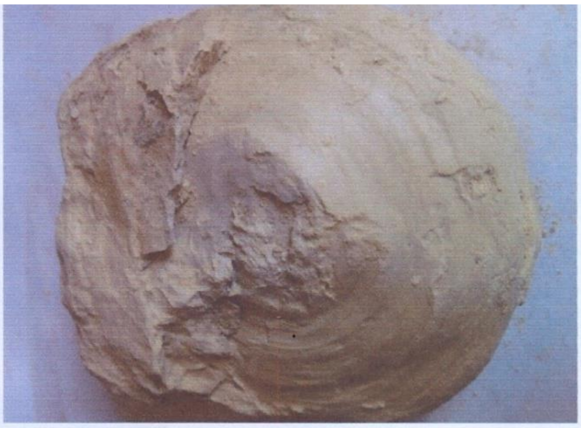


BA20 No2 (Siltstone)

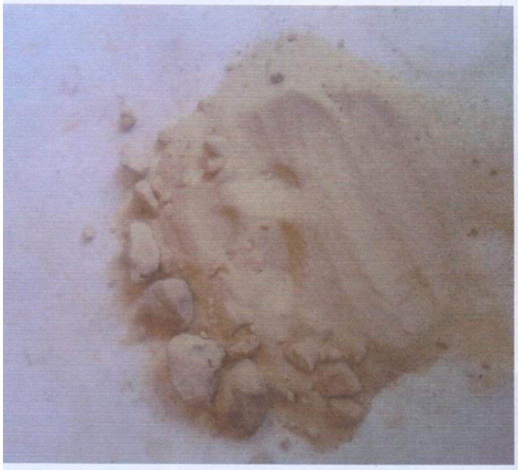
Appendix E.8: Photographs of boreholes cutting samples continued

Appendix E continued

BA23 No3 (Siltstone)

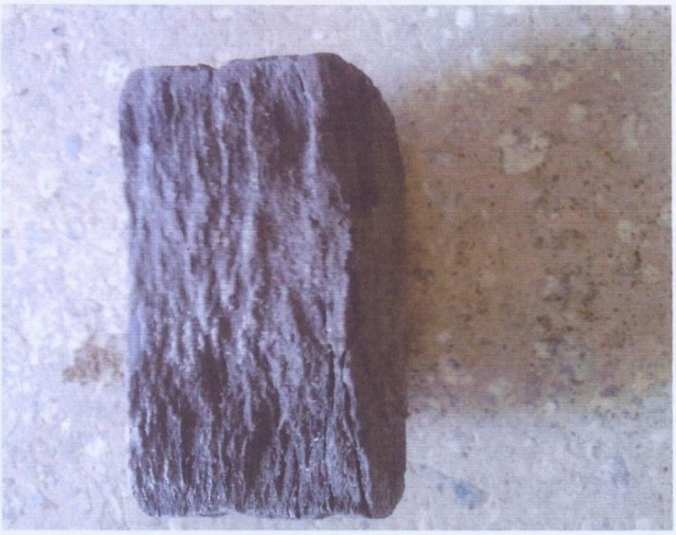


BA44 No1 (Siltstone)



BA44 No2 (Siltstone)

BA44 No3 (Siltstone)

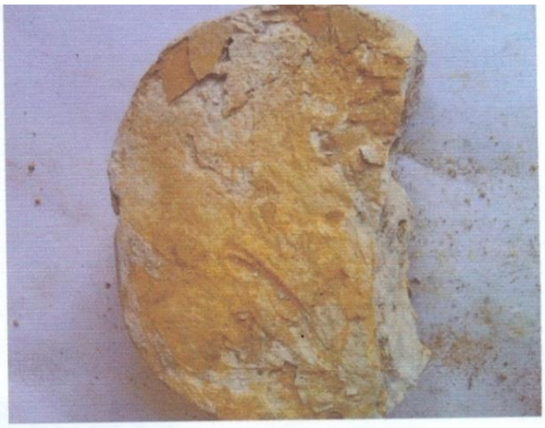


BA44 No4 (Carbonaceous shale)

Appendix E.9: Photographs of boreholes cutting samples continued

Appendix E continued

BA20 No5 (Ironstone)



BA22 No2 (Mudstone)

BA22 No3 (Graphitic shale)

BA22 No5 (Coal)

BA22 No6 (Carbonaceous shale)

BA23 No1 (Lateritic sandstone)

Appendix E.10: Photographs of boreholes cutting samples continued

Appendix F

Appendix F.1: Lithostratigraphy of BA - 7

DEPTH(M)	LITHOLOGY	DESCRIPTION
4.5	Sand (85%)	Fine grained, angular and very well sorted
	Mudstones (15%)	Brownish, soft and non-fissile
7.6	Sand (85%)	Fine grained, angular and very well sorted
	Mudstones (15%)	Whitish, soft and non-fissile
8.19	Mudstones (70%)	Whitish, soft and non-fissile
	Sand (30%)	Fine grained, angular and very well sorted
8.61	Mudstones (90%)	Whitish, soft and non-fissile
	Sand (10%)	Fine grained, angular and very well sorted
10	Mudstones (90%)	Whitish, soft and non-fissile
	Sand (10%)	Fine grained, angular and very well sorted
13.34	Sand (60%)	Fine to medium grained, angular and moderately hard well sorted
	Mudstones (40%)	Brownish, soft and non-fissile
13.6	Sand (80%)	Fine grained, angular and very well sorted
	Mudstones (20%)	Whitish, soft and non-fissile
16.51	Sand (90%)	Fine grained, angular and very well sorted
	Mudstones (10%)	Whitish, soft and non-fissile
16.89	Sand (90%)	Fine grained, angular and very well sorted
	Mudstones (10%)	Whitish, soft and non-fissile
19.03	Sand (50%)	Fine grained, angular and very well sorted
	Mudstones (50%)	Whitish, soft and non-fissile
19.36	Mudstones (90%)	Whitish, soft and non-fissile
	Sand (10%)	Fine grained, angular and very well sorted
22.35	Mudstones (90%)	Dark grey, soft to moderately hard and fissile
	Sand (10%)	Fine grained, angular and very well sorted
23.22	Mudstones (90%)	Dark grey, soft to moderately hard and fissile
	Sand (10%)	Fine grained, angular and very well sorted
24.64	Mudstones (90%)	Dark grey, soft to moderately hard and fissile
	Sand (10%)	Fine grained, angular and very well sorted
26.09	Mudstones (95%)	Dark grey, soft to moderately hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted
29.1	Mudstones (95%)	Dark grey, soft to moderately hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted
31.32	Mudstones (95%)	Dark grey, soft to moderately hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted
32.7	Mudstones (95%)	Dark grey, soft to moderately hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted
34.6	Mudstones (95%)	Dark grey, soft to moderately hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted
36.34	Coal (100%)	Dark, thick bands and hard
42.54	Mudstones (95%)	Grey, hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted
43.54	Mudstones (95%)	Brownish/grey, hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted
47.12	Mudstones (95%)	Grey, hard and fissile
	Sand (5%)	Fine grained, angular and very well sorted

Appendix F continued

Appendix F.2: Lithostratigraphy of BA – 16

DEPTH (M)	LITHOLOGY	DESCRIPTION
1.08	Mudstones (90%)	Whitish, soft to moderately hard and fissile
	Sand (10%)	Fine to medium grained, angular and moderately well sorted
3.2	Mudstones (95%)	Brownish, hard and non-fissile
	Sand (5%)	Fine to medium grained, angular and moderately well sorted
5.9	Sand (95%)	Fine grained, angular and very well sorted
	Mudstones (5%)	Whitish/brownish, soft and non-fissile
8.92	Sand (90%)	Fine grained, angular and very well sorted
	Mudstones (10%)	Whitish to brownish, soft and non-fissile
11.5	Sand (90%)	Fine grained, angular and very well sorted
	Mudstones (10%)	Whitish to brownish, soft and non-fissile
12.6	Sand (85%)	Fine grained, angular and very well sorted
	Mudstones (15%)	Whitish/brownish, soft and non-fissile
13.34	Sand (95%)	Very fine grained, angular and very well sorted
	Mudstones (5%)	Whitish to brownish, soft and non-fissile
14.04	Mudstones (70%)	Light/dark grey, soft and fissile/non-fissile
	Sand (30%)	Fine to medium grained, angular and moderately well sorted
14.55	Mudstones (90%)	Dark grey, hard and fissile/non-fissile
	Sand (10%)	Fine to medium grained, angular and moderately hard well sorted
14.75	Sand (95%)	Fine grained, angular and very well sorted sorted
	Mudstones (5%)	Whitish/dark grey, soft/moderately hard and non-fissile
17.6	Sand (85%)	Fine grained, angular and very well sorted well sorted
	Mudstones (15%)	Whitish/dark grey, soft/moderately hard and non-fissile
19.35	Mudstones (90%)	Whitish soft and non-fissile
	Sand (10%)	Fine grained, angular and very well sorted
20.6	Mudstones (90%)	Whitish soft and non-fissile
	Sand (10%)	Fine grained, angular and very well sorted
22.71	Mudstones (85%)	Whitish soft and non-fissile
	Sand (15%)	Fine grained, angular and very well sorted
26	Sand (95%)	Very fine grained, angular and very well sorted
	Mudstones (5%)	Whitish soft and non-fissile
27.4	Sand (90%)	Fine/medium grained angular and moderately well sorted
	Mudstones (10%)	Whitish soft and non-fissile
29.5	Mudstones (80%)	Grey, soft/moderately hard and fissile
	Sand (20%)	Fine/medium grained angular and moderately well sorted
31.2	Mudstones (80%)	Grey, soft/moderately hard and fissile
	Sand (20%)	Fine/medium grained angular and moderately well sorted
33.75	Coal (100%)	Dark, thick bands and hard
35.12	Coal (100%)	Dark, thick bands and hard
36.51	Mudstones (97%)	Light/dark grey, soft to moderately hard and fissile/non-fissile
	Sand (3%)	Fine to medium grained, angular and moderately well sorted
41.42	Mudstones (97%)	Light/dark grey, soft to moderately hard and fissile/non-fissile
	Sand (3%)	Fine to medium grained, angular and moderately well sorted
47.2	Mudstones (97%)	Light/dark grey, soft to moderately hard and fissile/non-fissile
	Sand (3%)	Fine to medium grained, angular and moderately well sorted
50.3	Mudstones (90%)	Light/dark grey, soft to moderately hard and fissile/non-fissile
	Sand (10%)	Fine to medium grained, angular and moderately well sorted
51.49	Mudstones (90%)	Brown/ grey, moderately hard and fissile/non-fissile
	Sand (10%)	Fine to medium grained, angular and moderately well sorted
52.76	Mudstones (95%)	Dark grey, moderately hard and fissile/non-fissile
	Sand (5%)	Fine to medium grained, angular and moderately well sorted
54.4	Mudstones (70%)	Dark grey, moderately hard and fissile/non-fissile
	Sand (30%)	Fine to medium grained, angular and moderately well sorted
56.65	Mudstones (80%)	Dark grey, moderately hard and fissile/non-fissile
	Sand (20%)	Fine to medium grained, angular and moderately well sorted

Appendix F continued

Appendix F.3: Lithostratigraphy of BA - 17

DEPTH (M)	LITHOLOGY	DESCRIPTION
0.65	Sand (95%)	Fine grained with very coarse, pebbly, sub-angular/sub-rounded and poorly sorted
	Mudstones (5%)	Brownish, soft and fissile
1.1	Sand (95%)	Medium grained with very coarse, pebbly, angular/sub-angular and moderate to poorly sorted
	Mudstones (5%)	Brownish, soft and fissile
2.15	Mudstones (75%)	Brownish, soft and fissile/non-fissile
	Sand (25%)	Very coarse grained, pebbly, angular/sub-angular and very well sorted
2.45	Mudstones (75%)	Dark grey, hard and fissile
	Sand (25%)	Fine grained with very coarse, pebbly, sub-angular/sub-rounded and poorly sorted
2.91	Mudstones (95%)	Brown/grey, hard and fissile
	Sand (5%)	Fine/medium grained, angular/sub-angular and poorly sorted
4.16	Mudstones (95%)	
	Sand (5%)	Fine/medium grained, angular/sub-angular and poorly sorted
5.27	Mudstones (95%)	
	Sand (5%)	Fine/medium grained, angular/sub-angular and poorly sorted
6.04	Mudstones (90%)	
	Sand (10%)	Fine/medium grained, angular/sub-angular and poorly sorted
8.03	Mudstones (90%)	Whitish, soft and fissile/non-fissile
	Sand (10%)	Fine/medium grained, angular/sub-angular and poorly sorted
9.4	Mudstones (95%)	Whitish, soft and fissile/non-fissile
	Sand (5%)	Fine/medium grained, angular/sub-angular and poorly sorted
10.3	Mudstones (95%)	Whitish, soft and fissile/non-fissile
	Sand (5%)	Fine/medium grained, angular/sub-angular and poorly sorted
11.97	Mudstones (95%)	Whitish, soft and fissile/non-fissile
	Sand (5%)	Fine/medium grained, angular/sub-angular and poorly sorted
12.7	Mudstones (95%)	Whitish, soft and fissile/non-fissile
	Sand (5%)	Fine/medium grained, angular/sub-angular and moderate to poorly sorted
14.65	Mudstones (90%)	Light/dark grey, soft and fissile
	Sand (10%)	Fine/medium grained, angular/sub-angular and moderate to poorly sorted
16.74	Mudstones (90%)	Light/dark grey, soft and fissile
	Sand (10%)	Fine/medium grained, angular/sub-angular and moderate to poorly sorted
19.25	Mudstones (90%)	Brown/grey, soft and fissile
	Sand (10%)	Fine/medium grained, angular/sub-angular and moderate to poorly sorted
21.1	Sand (95%)	Fine/medium grained, angular/sub-angular and poorly sorted
	Mudstones (5%)	Brownish, soft and fissile
21.56	Mudstones (90%)	Grey/soft, moderately hard and fissile
	Sand (10%)	Fine/medium grained, angular/sub-angular and moderate to poorly sorted
23.05	Sand (80%)	Fine/medium grained, angular/sub-angular and moderately sorted
	Mudstones (20%)	Dark grey, soft and fissile
27.3	Sand (95%)	Fine/medium grained, angular/sub-angular and moderately sorted
	Mudstones (5%)	Dark grey, soft and fissile
28.45	Mudstones (85%)	Dark grey, moderately hard and fissile
	Sand (15%)	Fine grained, angular/sub-angular and very well sorted
31.35	Mudstones (85%)	Dark grey, moderately hard and fissile
	Sand (15%)	Fine grained, angular/sub-angular and very well sorted
32.85	Mudstones (90%)	Whitish/grey, moderately hard and fissile
	Sand (10%)	Fine grained, angular/sub-angular and very well sorted
37.26	Sand (70%)	Fine/medium grained, angular/sub-angular and moderately sorted
	Mudstones (30%)	Grey, moderately hard and fissile
39.34	Mudstones (80%)	Dark grey, soft/ moderately hard and fissile
	Sand (20%)	Fine/medium grained, angular/sub-angular and moderately sorted
42.3	Mudstones (50%)	Whitish, soft/moderately hard and fissile
	Sand (50%)	Fine/medium grained, occasionally coarse angular/sub-angular and moderate/poorly sorted