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Source Rock Assessment and Palynological Studies of Lignite and Shale Deposits in Umuahia Area, Niger Delta Basin, Nigeria

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Abstract

Middle Eocene-Early Miocene lignite and shale units in the Umuahia area of the Niger Delta Basin were studied to assess their hydrocarbon potentials, determine their ages and environment of deposition. The lignite and shale samples obtained from the area were subjected to laboratory analyses, which include rock-eval pyrolysis and palynological studies. Results obtained from the rock-eval pyrolysis, indicate that Total Organic Carbon (TOC) values of the lignite samples range from 15.65 - 48.61wt.%, (averaged at 34.23wt.%) while that of shales ranged from 1.07-2.61wt.% (averaged at 2.11wt.%). S_1 yields of lignite and shale samples range from 0.11-3.28mgHC/g rock and 0.11-0.37mgHC/g respectively. S_2 yields ranged from 0.41-29.41mgHC/g rock in the lignite samples and 0.31-1.96mgHC/g rock in the shales. S_3 yields ranged from 7.11-38.80mgCO_2/g rock in the lignite samples to 0.79-2.28mgCO_2/g rock in the shales. Average values of Hydrogen Index (HI) is 23.4mgHC/g TOC in the lignite samples and 42.8mgHC/g TOC in the shales; Maximum temperature (Tmax) value ranges from 372-532°C in the lignites and 356-392°C in the shales; Production Index (PI) value is 0.04-0.25 in the lignite samples and 0.15-0.29 in the shale samples. Hydrogen Index (HI) versus Oxygen Index (OI) diagram classifies the organic matter in the samples as Type III and Type IV kerogen. Hydrogen Index (HI) versus Tmax plot also show that the lignite and shale samples are partly within the immature and postmature zone with source rock potential to generate little gas. Tmax and Production Index (PI) values of the analysed samples also fall within the thermally immature and post mature organic matter. Visual observation of the samples for dispersed organic matter and palynomorphs show that the most abundant groups were palynomorphs, structured and unstructured phytoclasts, and opaque organic matter while the least in occurrence is the amorphous organic matter. In addition, the major sporomorphs identified in the samples were the pollen grains and spores (about 99.9%). These are terrestrial palynomorphs, which support type III kerogen. An age range from Middle Eocene–Early Miocene was assigned using the age diagnostic pollen and spore marker species in the samples. Results derived from these analyses show that sediments within the study area, are aged Middle Eocene–Early Miocene, derived from mainly terrestrial organisms in fresh water swamp forest and possess immature organic matter having mainly type IV and minor type III kerogen. Furthermore, samples with high Tmax values indicating post mature are clearly recycled materials.

Keywords*: Source rock; Palynological studies; Rock-Eval pyrolysis; Lignite; Depositional environment.*

1. Introduction

Lignite and associated coal deposits occurs in substantial quantities in south-eastern Nigeria, with Nigeria having the largest known lignite deposit in Africa with proven reserves exceeding 300 Mmt [1]. The Lignite deposits are limited to a narrow belt about 16km wide, trending Northeast–Southeast direction and extending from The Niger in the northwest to the Cameroon border in the eastern part covering a total distance of about 240km (Fig. 1). Lignite seams of variable thicknesses occur at irregular intervals in streams, valleys and road-cuts within this belt. Shale deposits can be found in several parts of the county and have been studied more extensively than the lignite occurrences. Works have been done on source potential of some surface exposures of shales from the Chad Basin, north-eastern Nigeria to the

Dahomey Basin south-western Nigeria [2-8]. As an alternative source of hydrocarbon, the lignite deposits of southern Nigeria have become a focus of study. [9] stated that Lignite is one of the four fossil fuel resources found in substantial quantities in southeastern Nigeria with others being sub-bituminous, bituminous coal, oil and natural gas. Lignite was first reported in Umuahia–Okigwe area in 1919 and since then several studies have been carried out on the geochemistry, mineralogy, stratigraphic significance, depositional environment, source potential and thermal maturity within the southern parts of Nigeria [9-20]. However, very few documented studies have addressed the petroleum generation potential of the Lignite deposits in southern Nigeria and particularly within the Umuahia area.

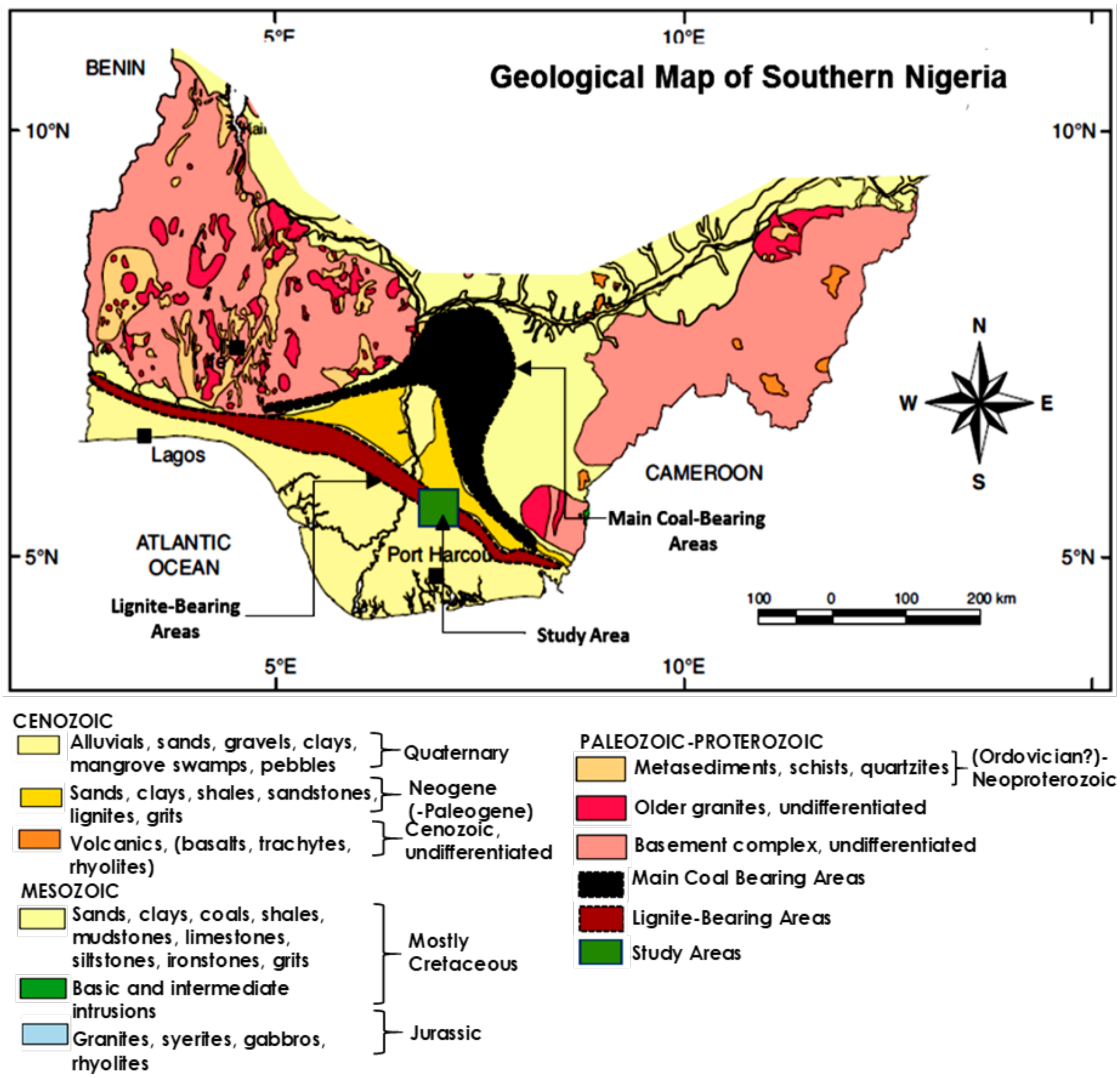


Fig. 1. Geologic map of Southern Nigeria showing the Coal and Lignite Zones (modified after [16])

The petroleum potential of lignite deposits continue to attract attention from researchers worldwide in order to ascertain the profitability of these resources [21-23]. It becomes imperative to adopt similar strategies to unravel the potential of hydrocarbon generation in the lignite seams of southern Nigeria.

The study area is located within the Ogwashi Formation of the Niger Delta Basin and is bounded by latitudes 5°27'N and 5°34'N, and longitudes 7°25'E and 7°35'E. Outcrop samples obtained from six localities (Ohiya, Amawom, Umuariaga, Umudike, Ibeku Okwuta and Isiador Ameke (Fig. 2) were used in this study.

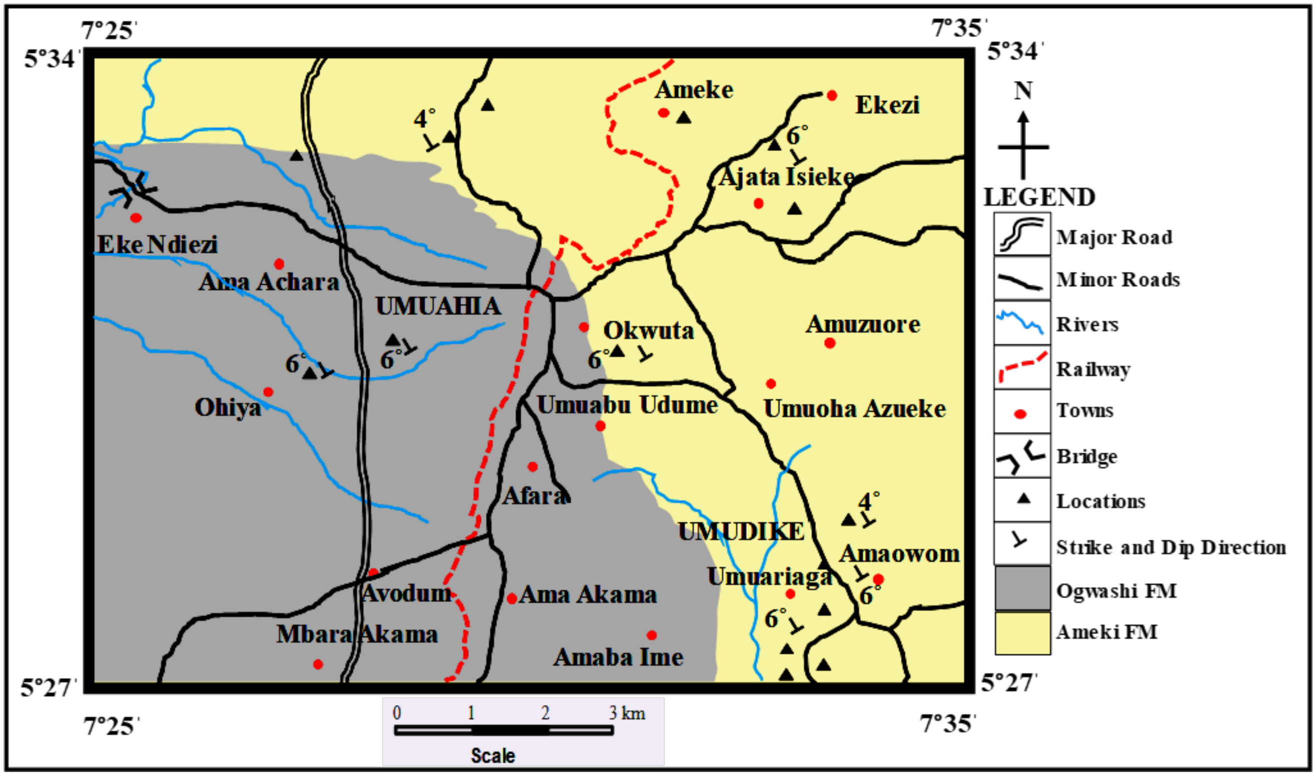


Fig. 2. Location map of the study area

Overall, this research was carried out to assess source rocks within the area and study their palynology to aid in the evaluation of their hydrocarbon potentials, determine the ages and reconstruct the environment of deposition of the sediments.

2. Geological setting and stratigraphy

The origin of the Niger Delta Basin is genetically related to that of the Benue Trough and many sedimentary basins in West Africa, which are associated with the splitting-up of the Gondwana supercontinent [24-29]. The Benue Trough is the failed third arm of a rift associated with this event and gave rise to the Benue Aulacogen, with the Niger Delta Basin at its southernmost extent [28,30]. The Niger Delta Basin extends out into the Gulf of Guinea, on the passive continental margin near the western coast of Nigeria covering a total distance of 300,000 km^2, with a depth between 9–12 km and a sediment fill of 500,000km^3 [31-32]. Sedimentation began during the Eocene and from the Eocene to the present; the delta has prograded southwestward forming several depobelts. The sedimentary sequence in the Niger Delta consists of the Akata and Agbada Formations, which are overlain by the Benin Formation, with the Imo Shale, Ogwashi/Ameki/Nanka Formations as their surface equivalents respectively [33]. The Imo Formation was deposited during the Palaeocene era and overlain by the regressive Ameki Formation (Eocene); the paralic Ogwashi Formation (Oligocene- Miocene) was capped by the continental Benin formation (Miocene-recent) constituting the surface exposures of the tertiary succession. The Formation of focus consists of a succession of coarse-grained sandstone, clay and carbonaceous shale, containing continental lignite seam intercalations [15,34]. [35] suggested an Oligocene-Miocene age for the Ogwashi Formation, but palynological study by [15] proposed a late Eocene age for the basal part. The lignite seams found within the Ogwashi Formation are usually brownish to black, varying in thickness from a few millimetres to a maximum of 6 meters. They are thinly laminated and fissile, having leaf and woody fragments on fresh cleats [36].

Table 1. Lithostratigraphic succession in Niger Delta and Anambra Basins [34,36,6]

AGE			SUBSURFACE UNITS	OUTCROPPING UNITS		LITHOLOGY	DEPOSITIONAL ENVIRONMENT	DELTA GROWTH PHASE	NET SEA MOVEMENT
Quaternary			Benin Fm, Agbada Fm, Akata Fm	Niger Delta Basin	Benin FM	Sandstones, Clay, Shales	Continental	Cenozoic Niger Delta	Regression
Tertiary		Pliocene, Miocene			Ogwashi FM	Clay, Shales, Ssandstones, Lignites	Continental		
Tertiary		Oligocene, Eocene			Ameki FM	Sandstones, Clay, Shales, Limestones	Estuarine, Shallow-Marine		
Tertiary	Paleocene	Thanatian, Danian			Imo FM	Sandstones, Clay, Shales, Limestones, Marl	Shallow-Marine, Deltaic	Transgression	Transgression
Upper Cretaceous		Maastrichtian	Pelagics and Fans	Anambra Basin	Nsukka FM	Sandstones, Clay, Shales, Limestones, Coals	Fluvio-Deltaic	Anambra Delta	Regression
Upper Cretaceous		Maastrichtian			Ajali FM	Sandstones, Claystones	Fluvio-Deltaic		
Upper Cretaceous		Maastrichtian			Mamu FM	Sandstones, Clays, Coals	Shallow-Marine, Deltaic		
Upper Cretaceous		Campanian			Nkporo GP	Sandstones, Clays, Coals, Shales, Siltstones	Shallow-Marine, Deltaic		
Upper Cretaceous			Major Unconformity						
Upper Cretaceous		Santonian, Coniacian	Pelagics and Fans	Benue Trough	Awgu FM	Sandstones, Clay, Shales, Coals, Siltstones, Limestones	Shallow-Marine, Deltaic	Prodelta	Transgression

3. Materials and methods

This study involved field studies, during which geological attributes were identified across the Ogwashi Formation and adjacent Ameki Formation (Fig. 2). Fresh samples were collected, and subjected to laboratory analyses. Fifteen (15) samples for Rock-Eval pyrolysis were pulverized and materials passing through 250-micron sieve was used for the analysis (Table 2). The samples were ground into powder and Soxhlet-extracted in cellulose thimbles for a total of 36hours in each case using 100% dichloromethane. The solvent from the resultant solution was removed by means of a rotary evaporator under vacuum (pressure not greater than 200mbar) and finally by a flow of nitrogen at not more than 30°C to yield the extractible organic matter (EOM).

The parameters obtained from the Rock-Eval pyrolysis (Table 2) include: Total Organic Carbon (TOC, wt.%) using a LECO 600 carbon analyser, S_1 (Free already generated hydrocarbons in the rock, mgHC/g rock), S_2 (Remaining hydrocarbon generated from the kerogen by thermal cracking, mgHC/g rock), S_3 (Organic carbon dioxide, mgCO_2/g rock), Tmax (Temperature at maximum evolution of S_2 hydrocarbons, °C), Hydrogen Index (HI = S_2 * 100/TOC, mgHC/gTOC), Generative Potential (GP = S_1+S_2), Oxygen Index (OI = S_3 * 100/TOC, mgCO_2/g TOC), Production Index (PI = S_1/S_1+S_2), S_2/S_3 and Normalized Oil Content (S_1/TOC * 100, mgHC/g TOC).

Standard laboratory techniques of digesting sediments in hydrochloric and hydrofluoric acids were used to process samples for dispersed organic and palynomorph group. Oxidation stage with nitric acid was omitted for kerogen residues used for palynological studies in order to preserve the colours of the organic debris, which were sometimes critical for identification. Palynological studies were carried out on six (6) samples (Table 5) from outcrops across the Ogwashi Formation and the adjacent Ameki Formation. Samples for palynological studies were prepared using the conventional maceration technique for recovering acid insoluble organic-walled microfossils from sediments. Each sample was, digested for 30minutes in 40% hydrochloric acid to remove traces of carbonate and 72hours in 40% hydrofluoric acid for removal of silicate. The extracts were sieve-washed through 10microns nylon mesh. The sieve-washed residues were, oxidized for 30minutes in 70% HNO_3 and 5minutes in Schulze solution to render the fossils translucent for transmitted light microscopy, rinsed in 2% KOH solution to neutralize the acid, swirled to sediment resistant coarse mineral particles and organic matter, and stained with Safranin–O to increase the contrast for study and photography.

For the coal samples, treatment started with 30minutes oxidation in Schulze solution and continued for the clastic sediments. Aliquots were dispersed with polyvinyl alcohol, dried on cover-slips and mounted in petro-poxy resin. Two slides were made from each sample, from which 200 grains were counted. The occurrence of each species was converted to percentage frequency in order to eliminate differences in counting. Light photomicrographs were taken with a Kyowa microscope.

4. Results and discussion

4.1. Rock-Eval data (REV)

Samples of lignites and shales were evaluated by Rock-Eval pyrolysis to determine the organic richness and quality of the organic matter in the rocks. The Rock-Eval pyrolysis data are presented in Table 2, showing parameters such as TOC, Tmax and their derivatives i.e. S_1, S_2, S_3, GP, HI, PI and OI.

Table 2. Rock-Eval pyrolysis results

SAMPLE NO	LITHOLOGY	LECO TOC	Tmax	S_1	S_2	S_3	GP S_1+S_2	S_2/S_3	S1/TOC *100	HI	PI	OI
KE/LN 02/01	Lignite	24.89	372	0.50	5.71	13.94	6.21	0.4	2	23	0.08	56
KE/LN 02/02	Shale	1.07	383	0.15	0.55	0.79	0.7	0.7	14	51	0.21	74
OH/LN 03/01	Lignite	39.15	406	1.67	29.41	18.77	31.08	1.6	4	75	0.05	48
OH/LN 03/02	Shale	2.61	361	0.11	0.31	2.28	0.42	0.1	4	12	0.26	88
OH/LN 03/03	Lignite	27.03	405	3.28	16.03	23.34	19.31	0.7	12	59	0.17	86
MG/LN 04/01	Lignite	33.12	496	0.13	0.41	12.55	0.54	0.0	0	1	0.25	38
EF/LN 05/02	Lignite	42.94	532	0.17	1.07	13.77	1.24	0.1	1	6	0.11	42
EF/LN 05/05	Lignite	32.27	531	0.11	0.94	10.53	1.05	0.1	0	3	0.11	33
EF/LN 05/07	Lignite	15.65	492	0.20	0.75	7.11	0.95	0.1	1	5	0.21	45
UM/LN 06/01	Shale	2.32	392	0.37	1.96	1.47	2.33	1.3	16	85	0.16	63
EB/LN 07/01	Shale	2.41	368	0.21	1.21	1.42	1.42	0.9	9	50	0.15	59
AG/LN 08/01	Lignite	45.74	523	0.36	2.87	19.20	3.23	0.1	2	6	0.10	42
AG/LN 08/05	Lignite	48.61	374	0.85	20.72	17.73	21.57	1.2	2	43	0.04	36
IA/LN 13A/01	Shale	2.18	356	0.14	0.34	2.07	0.48	0.2	6	16	0.29	95
IA/LN 13B/02	Lignite	32.98	395	0.63	5.47	38.80	6.1	0.1	2	17	0.10	85

4.2. Total organic carbon (TOC)

TOC values of 10 lignite samples within the study area ranged from 15.65 to 48.61wt.%, with an average value of 34.23wt.%, while that of shales range from 1.07 to 2.61wt.% with an average TOC value of 2.11wt.% (Table 2). In the lignites, the TOC values ranging from 15.65 to 48.61wt.% with an average of 34.23wt.% shows that the sediments have comparable average TOC contents, which are greater than the 0.5wt.% threshold value required for a potential source rock to generate hydrocarbons for clastic sediments. The TOC values averaging 34.23wt.% in the lignite and 2.11wt.% for the shale samples indicates a moderate to high organic matter concentration [37-38]. This shows that the samples are adequate for generation of hydrocarbon. Generally, there are variations in the TOC values among the lignite and shale samples, which could probably be attributed to localized changes in biological productivity, proximity to organic sources and preservation condition [39-40]. The highest concentrations of organic carbon are present in the AG/LN 08/01 and AG/LN 08/05 (Iyi Aga-Amawom) lignites with an average TOC of 47.18wt.% where there are inclusions of coal with woody plant debris in mudstone (Figs. 3 and 4). Apart from location KE/LN 02/02, other locations have TOC values greater than 2.0wt.% which is considered as good to excellent source rocks for hydrocarbon generation (Table 3C).

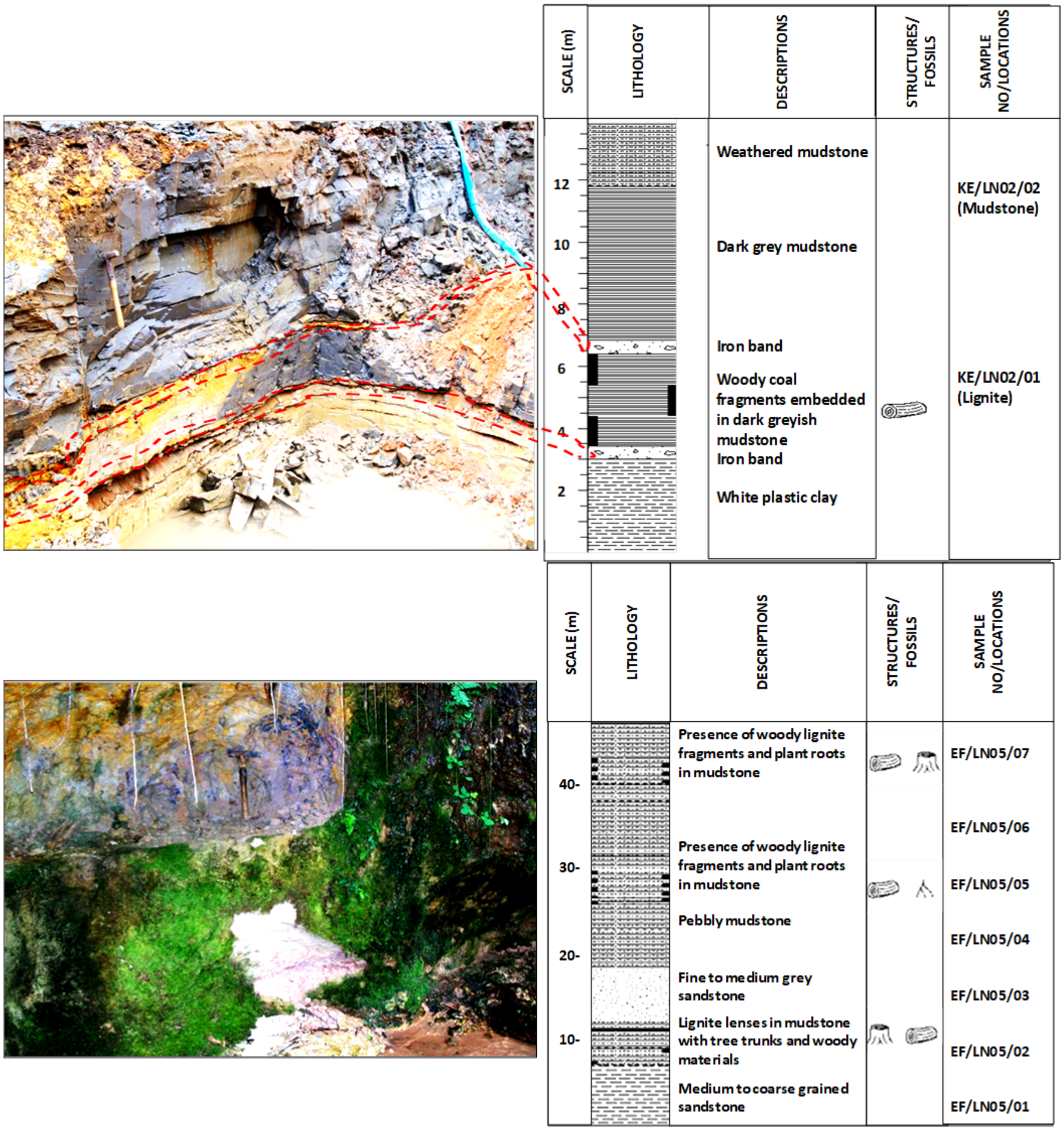


Fig. 3. (A) Mudstone with coal fragments underlain by whitish clay unit of the Ogwashi Formation at Kelly quarry alongside its litholog section showing the various lithofacies units. (B) Massive coarse to medium grained white sandstone of the Ameki Formation at Akpatala stream, Amawom alongside its litholog section

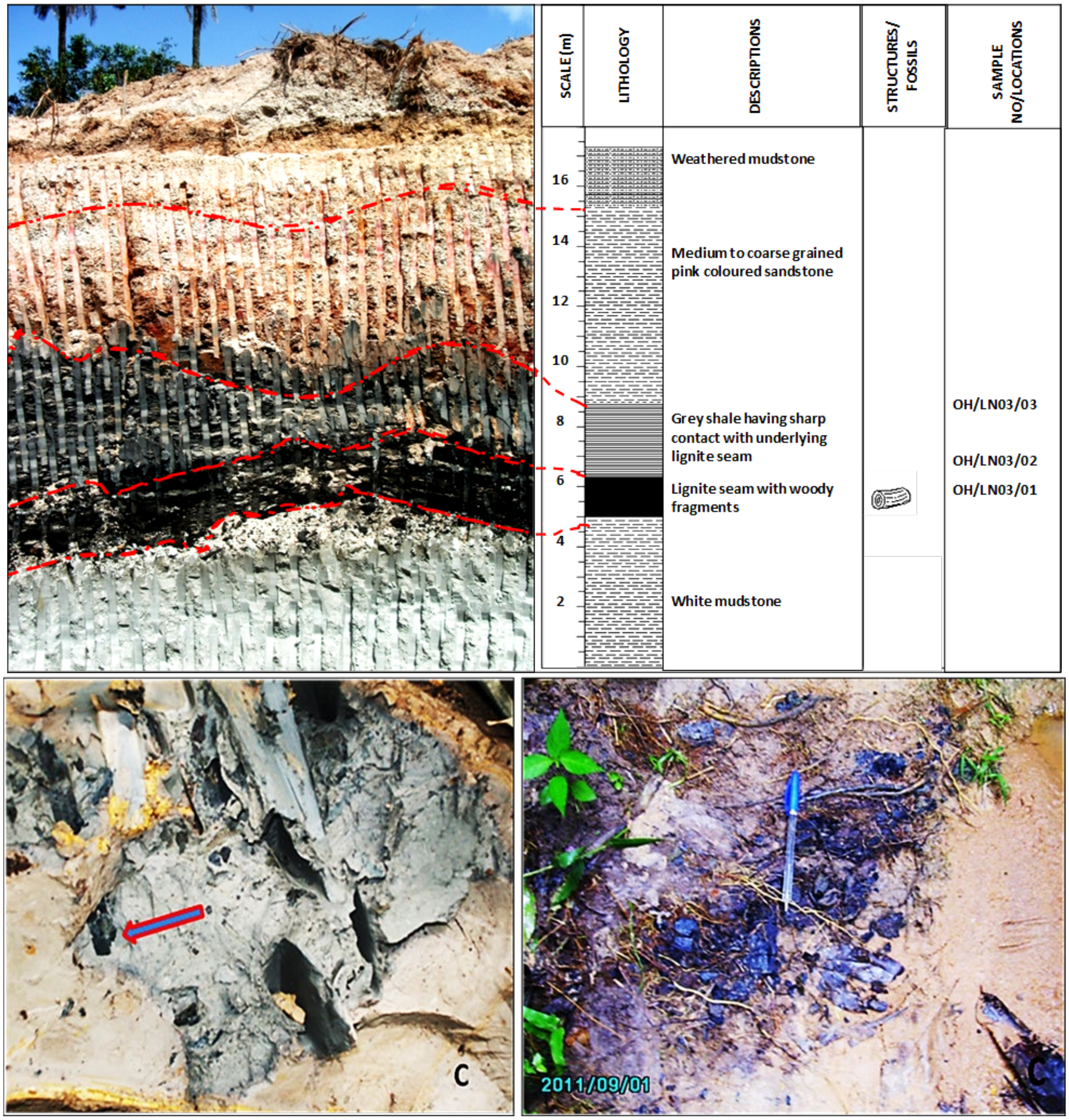


Fig. 4. (A) Coal seam of the Ogwashi Formation at Royal quarry Ohiya alongside its litholog section. (B) Grey mudstone with coal fragments at Iyi Aga, Amawom section of Ameki Formation. (C) Coal fragments in a siltstone unit at Iyi Efu, Ameki Formation

Table 3. (A) Parameters for describing the levels of thermal maturity of Source Rock *(modified after [43])* (B) Parameters for describing Kerogen Type (Quality) of an immature Source Rock *(modified after [43])* (C) Parameter for describing the petroleum potential of source rock. *(modified after [47])*

<table>
<tr><td colspan="2">STAGES OF THERMAL MATURITY FOR OIL</td><td colspan="2">MATURATION</td></tr>
<tr><td></td><td></td><td>VITRINITE REFLECTANCE Ro (%)</td><td>ROCK – EVAL Tmax (°C)</td></tr>
<tr><td>Immature</td><td></td><td>0.2 – 0.5</td><td><435</td></tr>
<tr><td rowspan="5">Mature</td><td rowspan="2">Early</td><td>0.5 – 0.65</td><td>435 – 445</td></tr>
<tr><td rowspan="2">0.65 – 0.9</td><td rowspan="2">445 – 450</td></tr>
<tr><td rowspan="2">Peak</td></tr>
<tr><td rowspan="2">0.9 – 1.35</td><td rowspan="2">450 – 470</td></tr>
<tr><td>Late</td></tr>
<tr><td colspan="2">Postmature</td><td>>1.35</td><td>>470</td></tr>
</table>

Table 3b

Kerogen type	HI (mgHC/g TOC)	S_2/S_3
I	>600	>15
II	300 - 600	10 - 15
II/III	200 - 300	5 - 10
III	50 - 200	1 - 5
IV	<50	<1

Table 3c

PETROLEUM POTENTIAL	ORGANIC MATTER ROCK – EVAL PYROLYSIS			TOC (wt.%)
	(S_1+S_2) (mgHC/g rock)	S_1 (mgHC/g rock)	S_2 (mgHC/g rock)	
Little or no oil but gas	<2	0 – 0.5	0 – 2.5	0 – 0.5
Moderate to fair oil and gas	2 – 6	0.5 – 1	2.5 – 5	0.5 – 1
		1 – 2	5 – 10	1 – 2
Good/excellent oil	>6	2 – 4	10 – 20	2 – 4
		> 4	> 20	> 4

4.3. Kerogen types

The different types of organic matter are of fundamental importance because; the relative abundance of hydrogen, carbon and oxygen determines what type of hydrocarbons that can be, generated from the organic matter upon diagenesis. The type and quality of organic matter was determined using the Hydrogen Index (HI) and Oxygen Index (OI) values obtained from whole-rock samples via Rock-Eval pyrolysis. This was plotted on a modified Van Krevelen diagram of Hydrogen Index against Oxygen Index (Fig. 5A), and showed minor type III and mostly type IV organic matter.

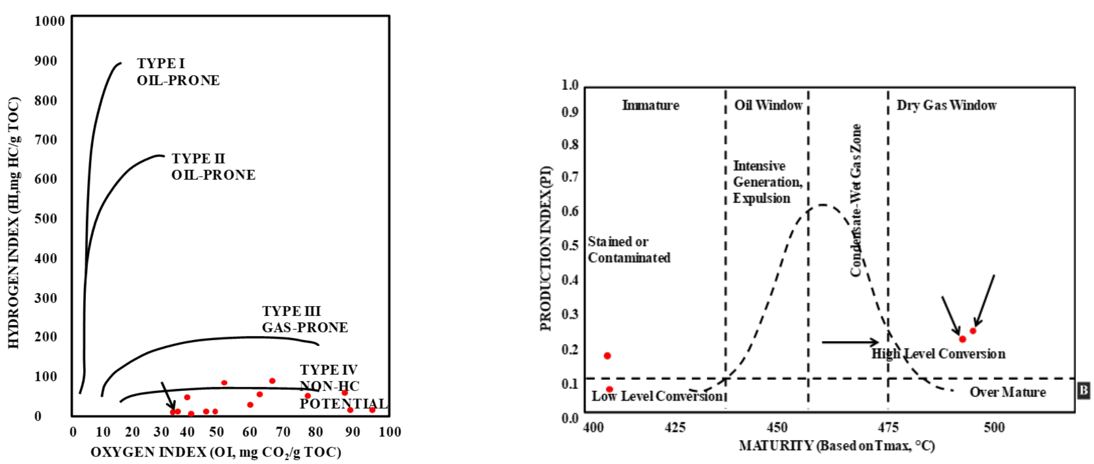


Fig. 5. (A) Modified Van Krevelen diagram (HI-OI diagram) showing minor type III and mostly type IV organic matter. (B) Plot of PI versus Tmax of the samples from the study area

The plot of remaining Hydrocarbon Potential (S_2) versus TOC (Fig. 6B) was also, used in determining the kerogen type [41]. The slopes of lines radiating from the origin are directly related to Hydrogen Index (HI= S_2 × 100/TOC, mgHC/g TOC). Hydrogen Index values of the samples fall below 100mgHC/g TOC. This classifies the organic matter into type III and IV kerogen. The relatively low Hydrogen Index (HI) values with respect to Oxygen Index (OI) values of the studied samples suggests that the source rocks have potential for very little gaseous hydrocarbon (Table 2). The most significant factor with respect to the capacity of source rock to generate petroleum is the amount of hydrogen in the kerogen [42]. Hydrogen-rich organic matter commonly generates more oil than hydrogen poor organic matter because oil is rich in hydrogen. Hydrogen Index (HI) from the analysed samples fall into two main groups according to [43], classification (Table 3B). This indicates a type III and IV kerogen.

This is an indication of significant contribution of organic materials from terrestrial sources in the rift basins during the Upper Cretaceous in Nigeria.

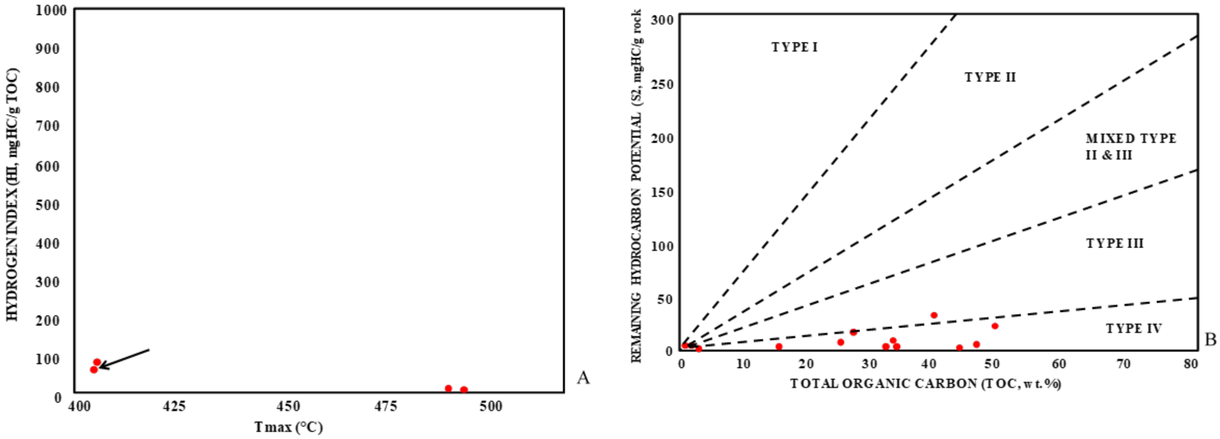


Fig. 6. (A) Plot of HI versus Rock-Eval Tmax for the samples from the study area. (B) Plot of remaining hydrocarbon potential (S_2) versus TOC [41]

4.4. Hydrogen index (HI)

[44-45] have shown that the higher the hydrogen contents of coal, the greater the ability to generate oil and gas. [44] observed that coals can form appreciable amount of oil when the hydrogen content relative to carbon is very high while it will form mainly gas when the hydrogen is low. The hydrogen type index (S_2/S_3) of the samples are less than 2 which is typical for gas generation. The hydrogen and oxygen indices (Table 2) from the samples plot between the type III and IV reference curves (Fig. 5A), with the majority showing affinity for the type IV reference curve in the modified van Krevelen diagram. Type III organic matter yields less hydrocarbon than types II or I during pyrolysis or burial maturation. This type of organic matter is dominated by vitrinite and lesser amounts of inertinite macerals and usually originates from terrigenous plants. Type IV (Inert) kerogens have very little hydrogen and plot near the bottom of the diagram. They are, depleted in hydrogen and oxygen relative to carbon and do not yield significant amounts of hydrocarbons because of the dominant presence of inertinite macerals. At high levels of catagenesis, all kerogens approach the composition of graphite (pure carbon) and plot near the lower left portion of the diagram. The type IV kerogen was, probably formed from higher plant matter, which was severely, oxidized on land before transportation to its deposition site (reworked). It has low atomic H/C and low O/C ratio and sometimes not considered as true kerogen because it has no hydrocarbon generative potential.

4.5.Generative potential (GP) (S_1 + S_2)

The Rock-Eval parameter S_1 + S_2 is a conventional measure of genetic potential or the total amount of petroleum that might be generated from a rock [46]. [47] (Table 3C), suggest that the threshold of S_1+S_2 greater than 2kg HC/t can be considered as prerequisite for classification as a possible oil source rock and provides the minimum oil content necessary for the main stage of hydrocarbon generation to saturate the pore network and permit expulsion. Rock-Eval Pyrolysis results shows that the total generative potential (S_1+S_2) of the samples ranges from 0.54 to 31.08mgHC/g rock averaging 9.13mgHC/g rock in the lignites and 0.42 to 2.33mgHC/g rock averaging 1.07mgHC/g rock in the shale samples. The shale samples in this study had GP values that are less than 2mgHC/g rock and as such, exhibit yields of little or no oil but gas. Additionally, majority of the lignite samples exhibit yields with moderate to fair source rock potential for gas generation. The cross plots of S_2 versus TOC (Fig. 6B) show about two values plotted within type III while a larger quantity plots within type IV curves. This indicates that the source rock will not yield significant amount of hydrocarbon.

4.6. Thermal maturity of organic matter

The organic maturation of the studied samples were evaluated based on Tmax and Production Index (PI) values of the shales and the lignites. Rock-Eval Tmax is the pyrolysis temperature (°C) at the maximum rate of kerogen conversion [48]. This is related to the amount of hydrogen the rock contains and level of maturation since the more mature the rock is, the lower the amount of hydrogen it contains and the highest amount of energy it needs to release hydrocarbons. The thermal maturity of organic matter is commonly derived from this Rock-Eval Tmax. The Tmax values for the samples ranges from 372 to 532°C, averaging 453°C in the lignite, then 356 to 392°C, averaging 372°C in the shale. According to [43]. interpretation (Table 3A), Tmax values of the analysed samples fall within the thermally immature and post mature organic matter with respect to petroleum generation. Production index values range from 0.04 to 0.26 in the lignite and 0.15 to 0.29 in the shale (Table 2). He also stated that PI for hydrocarbon generation range from 0.1 to 0.4, PI less than 0.1 indicate immature organic matter. The PI value for the studied samples fall within two groups: (PI<0.1), which indicate immature organic matter and (PI 0.1–0.4) postmature (gas generation) (Fig. 5B). Plot of PI versus Tmax (Fig. 5B), HI versus Tmax (Fig. 6A) data clearly shows that the organic matter is immature and samples with high Tmax values indicating post mature are clearly recycled materials.

4.7. Palynological studies

To delineate the environment of deposition and determine the age of the sediments within the study area, palynological studies was undertaken. Visual observation of the samples for dispersed organic matter and palynomorphs was carried out. The most abundant groups were palynomorphs, structured and unstructured phytoclasts, opaque organic matter while the least occurrence is the amorphous organic matter (Table 3C). The colour of the pollen grains and spores from the samples are characterised by light to yellowish through orange and brown which suggests low to high thermal conditions (Fig. 8A). The relationship between the colour of pollen and spores, and petroleum generation and expulsion from kerogens have been proposed by [47]. Fig. 8A shows a progressive colour change from light to brown (diagenesis) through brown to dark brown (catagenesis) and finally black (metagenesis). The kerogens are classified as woody (fibril materials with recognizable rectangular structures) and coaly (recycled materials plus plant materials that has undergone natural carbonization) (Fig. 7). This is obvious as seen in outcrop pictures shown in Fig. 4. Based on organic macerals, inertinite have high reflectance, no transmittance, and no fluorescence. It is highly oxidized and/or carbonized due to burning or exposure to the atmosphere or organic decomposition during and following deposition. Inertinite is considered "dead carbon" and will produce little to no hydrocarbons upon burial and thermal maturation. Table 4A shows a summary of [49] kerogen classification, which is used in this research for classification of kerogen.

Table 4. (A) Kerogen Classification (after [49]); (B) Description of palynofacies elements from the study

PALYNOLOGY	Algal	Amorphous	Herbaceous	Woody	Coaly
MACERALS	Liptinite (Exinite)			Vitrinite	Inertinite
EVOLUTIONARY PATHWAY	Type I or II	Type II		Type III	Type IV
H/C O/C	1.7 – 0.3 0.1 – 0.02	1.4 – 0.3 0.2 – 0.02		1.0 – 0.3 0.4 – 0.02	0.45 – 0.3 0.3 – 0.02
HYDROGEN INDEX	900 – 50	600 – 50		200 – 50	<50
SOURCE MATERIAL	Lacustrine and Marine	Terrestrial		Terrestrial	Terrestrial and Recycled
HYDROCARBONS GENERATED	Mostly Oil	Oil and Gas		Mostly Gas	Very Little Gas

PALYNOFACIES ELEMENTS	DESCRIPTION
Palynomorphs	These are embryophytic spores and pollen grains derived from land plants with colour ranging from yellow to dark brown and nearly black (Fig. 7 and 9)
Unstructured Phytoclasts	This class include highly degraded plant remains without much structure and colours ranging from yellow to dark brown and nearly black, comminuted brown debris and amber-coloured, globular to angular particles of resin (Fig. 7 and 9)
Amorphous Organic Matter (AOM)	Fluffy, clotted and granular masses with colours ranging from almost colourless to yellow and pale brown. This category is marine in origin, and formed as a result of degradation of algal matter (Fig. 7 and 9)
Opaque (Black debris)	Most particles are opaque and often have shapes similar to wood, although some are rounded and appear to be highly oxidized palynomorphs (Fig. 7 and 9)
Structured Phytoclasts	Structured remains of land plants, including lath-shaped or blocky wood particles, parenchyma, and thin cuticle fragments. With the exception of black debris, fragments with some form of cellular structure or definite shape are included in this category (Fig. 7 and 9)

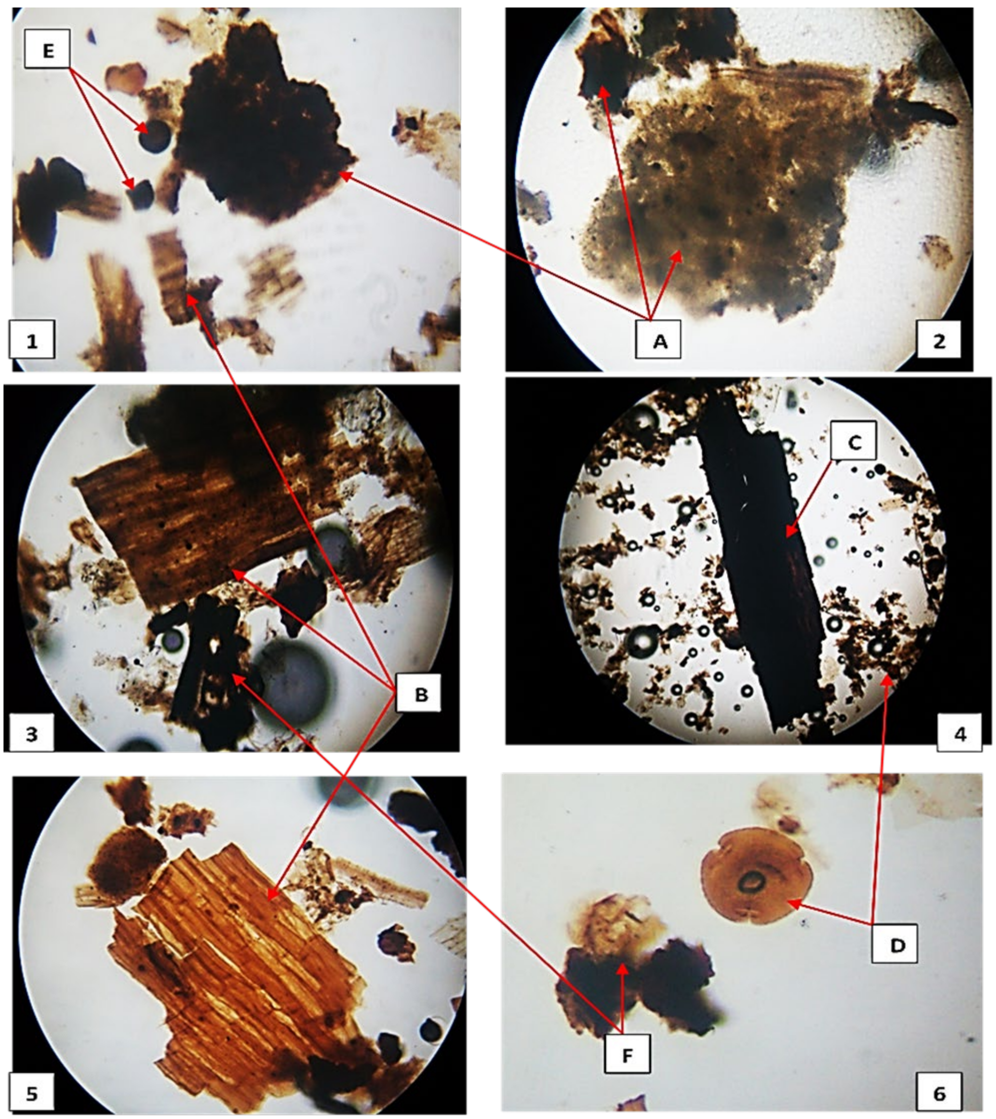
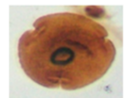
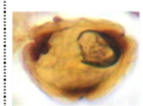
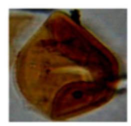


Fig. 7. Plate 1-6: Photomicrographs of Kerogens from the analyzed samples in the study area. Magnification X60. (A) Amorphous Organic Matter (AOM); (B) Well Preserved Structured Woods; (C) Carbonized Wood; (D) Light to Medium brown Palynomorphs; (E) Opaque debris

Values of total organic carbon (TOC), Hydrogen and Oxygen Index (HI and OI respectively) and maturity indices discussed above are consistent with the palynofacies characteristics of the studied samples. The palynomorph assemblages and results from kerogen slides are synonymous with geochemical results showing that the samples have potentials for very little gaseous hydrocarbon.

Sample No.	Palynofacies Association	Spore/Pollen Colouration	TAI	Vitrinite Reflectance R%	Thermal Maturity	Kerogen Type	Source Rock Potential
KE/LN 02/02	*Amorphous organic matter & Phytoclasts*	*Orange, Light brown - medium brown*	2-to 2	0.3 to 1.1	Immature 	Type III	Gas Prone
OH/LN 03/02	*Phytoclasts & Opaque Debris.*	*Yellow – Yellowish Orange*	2- to 2	0.3 to 0.5	Immature 	Type III	Gas Prone
UM/LN 06/01	*Phytoclasts & Opaque Debris.*	*Yellow – Yellowish Orange*	2- to 2	0.3 to 0.5	Immature 	Type III	Gas Prone
EB/LN 07/01	*Phytoclasts & Opaque Debris.*	*Yellow – Yellowish Orange*	2- to 2	0.3 to 0.5	Immature 	Type III	Gas Prone

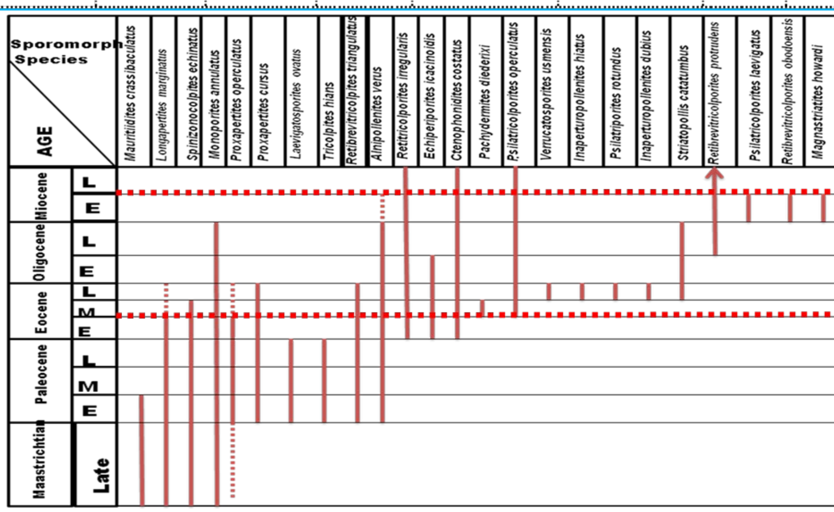


Fig. 8. (A) Summary of the palynofacies analysis and interpretation; (B) The stratigraphic range chart of selected key sporomorph species in the study area

4.8. Age determination and palaeoenvironment of deposition

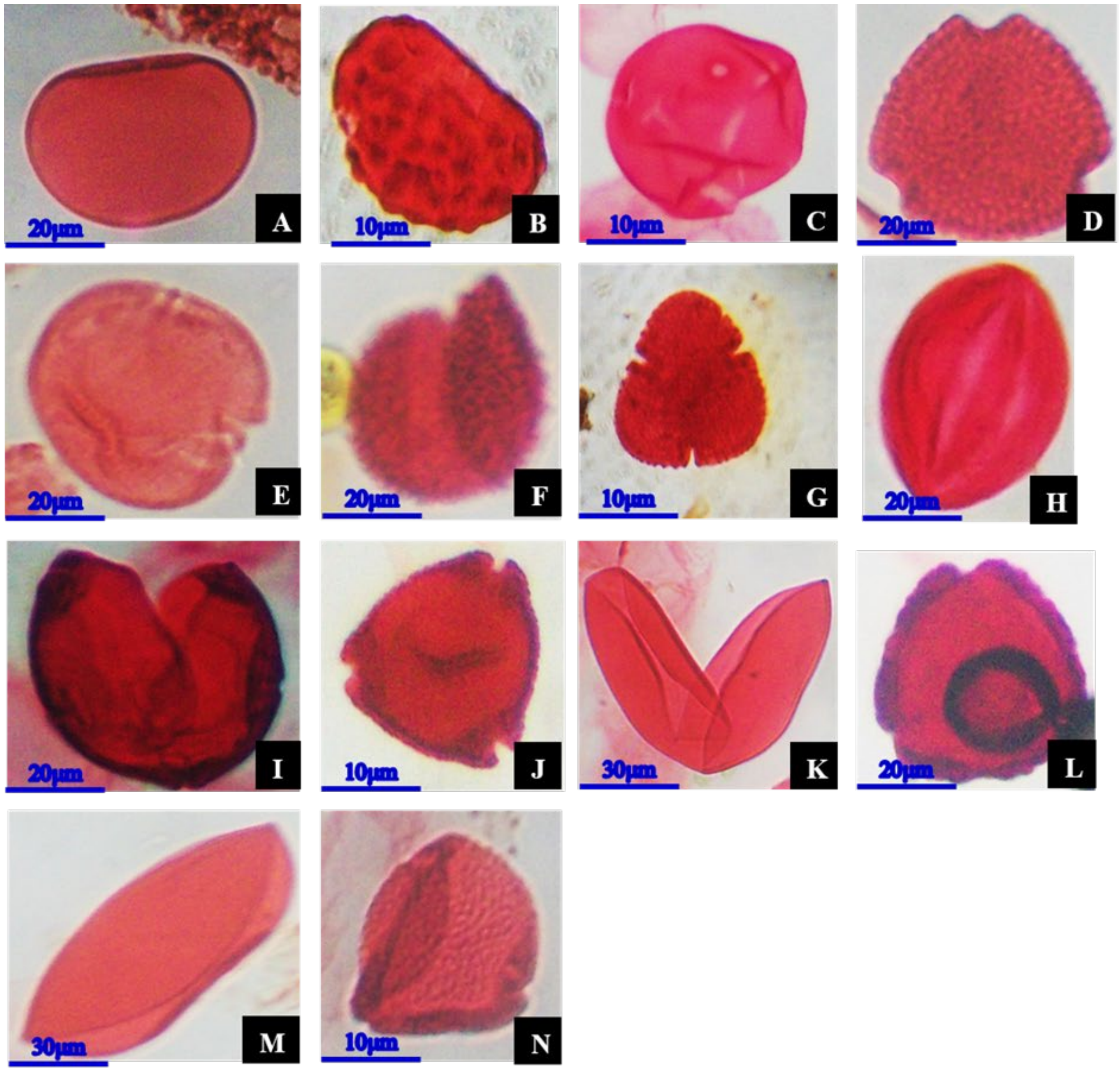
The pollen and spores, and other particulate organic matter, and the dinoflagellates occurring in a succession of rocks can be used effectively to define precisely the age and palaeoenvironment that prevailed during the deposition of the rocks. The palynofacies types and abundance provides information regarding the interpretation of these parameters. Pollen and spores play a major role due to their abundance and good preservation, while dinoflagellates are of minor importance due to their scarcity and poor preservation. They are used for age dating and palaeoenvironmental determination and as supporting evidence in this work. The definition of the proposed age and palaeoenvironment was, based on the distribution and range of the palynomorphs species and their abundance data (Table 3C and 4B). Fifty-two (52) palynomorph species were analysed from the slides (Table 6 and Fig. 9). Angiosperm pollens are the most abundant species in the analysed samples, followed by fern spores, and two microplanktons. The ages of the sediments were assigned based on identified age diagnostic pollen and spore markers species according to the zonation schemes of [50-51]. An age range from Middle Eocene–Early Miocene is assigned due to the presence of *Pachydermites diederixi, Verrrucatosporites usmensis, Inaperturopollenites hiatus, Psilatriporites rotundas, Magnastriatites howardi* in the samples (Fig. 8B). This corresponds with [9] classification of the lignite deposits in parts of Orlu using palynomorphs study. [52] also assigned Late Eocene-Miocene age to the Ogwasi Formation of the Niger Delta Basin based on the presence of *Margocolporites umuahiaensis, Verrrucatosporites usmensis and Proxapertites* marker species. The palynomorphs were all long ranging from Eocene to Miocene [53-54].

The percentage abundance of the different species at a particular time gives rise to the depositional environments (Table 5).

Table 5. Summary of the palynomorph distribution and palaeoenvironmental inference for the analyzed samples

Sample no.	Formation	Lithol-ogy	Palynomorphs frequency (%)			Palaeo-environment	Age
			Spore	Pollen	Dinocyst		
OH/LN 03/03	Ogwashi	Shale	56	43	1	Lower deltaic plain/lagoon	Early
OH/LN 03/02	Ogwashi	Lignite	64	36	0	Freshwater swamp/upper deltaic plain	Miocene
OH/LN 03/01	Ogwashi	Lignite	71	29	0	Freshwater swamp/upper deltaic plain	to
KE/LN 02/02	Ogwashi	Shale	44	55	1	Lower deltaic plain/lagoon	
EB/LN 07/01	Ameki	Shale	56	44	0	Lower deltaic plain/mangrove	Middle
UM/LN 06/01	Ameki	Shale	29	70	1	Brackish water/lagoon	Eocene

It is pertinent to note that the study area at that time was dominated by diverse forest plant (terrestrial) species. Some of these forest species include *Verrrucatosporites usmensis, Zonocostites ramonae, Retibrevitricolporites protrudens, Laevigatosporites ovatus, Psilatricolporites crassus, Retitricolporites irregularis,* etc. The presence of *Spiniferites sp.* and *Ceistospaeridium tribuliferum* associations indicates deposition under relatively reduced salinity, middle to outer neritic open marine environment. The abundance of *Proxapertites, Longerpertites marginatus* and *Echiperiporites sp.,* occur in brackish water (mangrove swamp) environment [55]. Also, [56-57] showed that the Palmae pollen, represented by *Proxapertites group, Echiperiporites estelae, Longerpertites marginatus, Psilatricolporites crassus Racemonocolpites hians* are products of mangrove swamp environment associated with warm and humid environment. The presence of fungal and algal spores alongside pteridophyte and bryophyte spores (*Verrrucatosporites usmensis, Laevigatosporites ovatus, Cyathidites minor and Cyathidites australis*) are indicative of fresh water swamps and marshes. The palynomorph assemblages from the study indicate predominance of phytoclasts and terrestrial derived pollen and spores with insignificant representation of marine dinoflagellates. The palynological studies indicate that sediments within the study area were deposited in a fluvio-deltaic setting alternating between upper deltaic plain (freshwater) and lower deltaic plain (brackish water).



A. *Laevigatosporites ovatus* Wilson and Webster, 1946 (x40)
B. *Verrucatosporites usmensis* (Van der Hammen) Gemeraad, Hopping and Muller, 1968 (x100)
C. *Monoporites annulatus* Van der Hammen, 1954 (x40)
D. *Retibrevitricolpites triangulates* Van Hoeken-Klinkenberg, 1966 (x60)
E. *Psilatricolporites operculatus* Van der Hammen et Wymstra, 1964 (x40)
F. *Racemonocolpites hains* Legoux 1971 (x40)
G. *Bombacidites sp.* Gemeraad, Hopping and Muller, 1968 (x100) oil immersion
H. *Striatopollis catatumbus* Takahashi and Jux, 1989 (x40)
I. *Pachydermites diederixi* Germeraad, Hopping and Muller, 1968 (x100) oil immersion
J. *Retibrevitricolporites obodoensis* Legoux, 1971 (x40)
K. *Inaperturopollenites dubius* (Ptonie and Venitz) Thomson and Pflug, 1953 (x60)
L. *Psilatricolporites crassus* Van der Hammen et Wymstra, 1964 (x60)
M. *Liliacidites nigeriensis* (Van Hoeken-klinenberg, 1966) Salami, 1985 (x60)
N. *Retibrevitricolporites protrudens* Legoux, 1971 (x40)

Fig. 9. Photomicrographs of Palynomorphs in the study area

Table 6. Occurrence and distribution of palynomorph species in the study area. X = Present; – = Absent

Palynomorphs/Samples	KE/LN02/02 Shale	OH/LN03/01 Lignite	OH/LN03/02 Shale	OH/LN03/03 Lignite	EB/LN07/01 Shale	UM/LN06/01 Shale
POLLEN *Retistephanocolporites minor*	-	X	-	-	-	-
Racemonocolpites hains	X	X	X	X	X	X
Retibrevitricolpites triangulatus	X	X	X	-	-	X
Psilatricolporites crassus	X	X	X	X	X	X
Monoporites annulatus	X	X	X	X	X	X
Echiperiporites icacinoides	X	X	X	-	-	X
Echiperiporites minor	-	x	-	-	X	-
Retibrevitricolporites obodoensis	-	-	-	-	-	-
Pachydermites diederixi	X	-	X	X	X	-
Cycadopites ovatus	-	-	-	X	-	-
Proxapertites cursus	-	-	-	-	-	-
Tricolpites hains	X	-	X	-	-	-
Liliacidites nigeriensis	x	X	X	X	X	X
Retibrevitricolporites ibadanensis	-	-	-	-	-	-
Calystegiapollis microechinatus	-	X	-	-	-	-
Chenopodipollis dispersus.	-	X	-	-	-	-
Inaperturopollenites hiatus	-	-	-	-	-	X
Psilatricolporites operculatus	X	X	X	X	X	-
Longapertites marginatus	X	X	X	X	-	X
Bombacidites sp.	-	-	-	-	-	-
Proteacidites sp.	-	-	-	-	X	-
Psilatricolpites minutus	X	-	X	X	-	-
Psilatriporites rotundus	X	X	X	-	-	-
Araucariacites austrialis	-	X	-	-	X	-
Graminidites minor	X	X	X	X	-	X
Inaperturopollenites hiatus	-	X	-	-	-	X
Retistephanocolporites laevigatus	-	X	-	-	-	X
Retitricolporites irregularis	X	X	X	X	X	-
Zonocostites ramonae	-	X	-	-	-	X
Retibrevitricolporites protrudens	X	X	X	-	-	-
Smilacipites echinatus	X	-	X	-	-	-
Ctelonophonidites costatus	-	-	-	-	X	-
Spinizonocolpites echinatus	X	-	X	-	X	-
Striatopollis catatumbus	X	-	X	-	-	-
Proxapertites operculatus	-	X	-	-	X	-
Mauritiidites crassibaculatus	X	-	X	-	-	-
Scabratriporites simpliformis	-	-	-	-	-	-
Quecoidites microhenrici	-	X	-	-	-	-
Retistephanocolpites williamsi	-	-	-	X	-	-
Alnipollenites verus	-	X	-	-	-	-
SPORE *Magnastriatites howardi*	-	-	-	-	-	-
Verrrucatosporites usmensis	X	X	X	X	X	X
Laevigatosporites ovatus	X	X	X	X	X	X
Cyathidites minor	-	-	-	-	-	X
Leiotriletes adriennis	-	X	-	-	-	X
Polypodiaceoisporites sp	X	X	X	-	-	X
Cyathidites australis	-	X	-	-	-	-
Leiotriletes maxoides	-	X	-	-	-	-
Schizosporis sp	-	X	-	X	-	X
Fungal spore	X	X	X	X	-	X
MICROPLANKTON *Spiniferites sp.*	X	-	x	-	-	-
Ceistospaeridium tribuliferum	-	-	-	-	X	X

5. Conclusion

Results from Rock-Eval pyrolysis shows an average Total Organic Carbon (TOC) of 34.23wt.% and 2.11wt.% for lignites and shales respectively. Hydrogen index (HI) and generative potential (GP) of samples were above the minimum values required for a potential source rock; [average values: 23.4mgHC/g TOC (lignites), 42.8mgHC/g TOC (shale) and 9.13mgHC/g rock (lignites), 1.07mgHC/g rock (shale)] respectively. Hydrogen Index (HI) versus Oxygen Index (OI) diagram classifies the organic matter in the samples as mainly Type

IV with minor Type III kerogen. Palynological classification indicates the kerogens are woody and coaly materials. Palynomorph assemblages from the study indicate predominance of phytoclasts and terrestrial derived pollen and spores with insignificant representation of marine dinoflagellates. Middle Eocene–Early Miocene is, assigned to the sediments due to the presence of *Pachydermites diederixi, Verrrucatosporites usmensis, Inaperturopollenites hiatus, Psilatriporites rotundas, Magnastriatites howardi* in the samples. The percentage abundance of forest plant species such as *Verrrucatosporites usmensis, Zonocostites ramonae, Retibrevitricolporites protrudens, Laevigatosporites ovatus, Psilatricolporites crassus, Retitricolporites irregularis, Proxapertites group, Echiperiporites estelae, Longerpertites marginatus, Racemonocolpites hians* e.t.c. Suggests the sediments were deposited in a fluvio-deltaic setting alternating between upper deltaic plain (freshwater) and lower deltaic plain (brackish water). From this study, it can be deduced that sediments within the study area were assigned an age range of Middle Eocene–Early Miocene, derived from mainly terrestrial organisms in fresh water swamp forest with immature organic matter having mainly type IV and minor type III kerogen, and samples with high Tmax values indicating post mature are clearly recycled materials.

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