Facies Analysis and Kerogen Type Determination for Hydrocarbon Source Rock Potential: A Case Study of The Late Cretaceous Sediments in Asaga-Ohafia Axis, Afikpo Basin, Southeastern Nigeria

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ABSTRACT

Facies and kerogen type analyses were adopted for the evaluation of source rock potentials of the Late Cretaceous successions in the Asaga-Ohiafia Axis. Lithofacies typical of estuary bay and fill delta- shallow marine environment of deposition (EOD) were delineated. The 0.5 weight percent organic carbon content requirement for clastic source rocks was exceeded by the analyzed sediments. The Mamu Formation source rocks contained macerals with 30 - 50% amorphous organic matter (AOM); 5 – 10% Liptinite; 30 - 50% Vitrinite and 10 - 20% Inertinite, which are indicative Type II/III kerogens (oil and gas prone). The predominant Spore Color (SC) is lemon yellow, indicative of a Vitrinite Reflectance ratio of 0.80 - 1.50 % and a Thermal Alteration Index (TAI) of 3-3+. The presence of vascular spores and marine dinoflagellates are indicative of shallow marine EOD. The sediments of the Nkporo Formation revealed that the macerals are made up of 20 – 45% AOM; 0 – 20% Liptinite and Vitrinite of 40 – 65%. The sediments contain little coaly kerogen and Inertinite (0 – 5%) and are typically Type II/III kerogens, which are oil and gas prone. The color of the spores ranged from pale-lemon yellow to golden yellow, indicating theoretical Vitrinite reflectance values of 0.45 - 0.80% and TAI of 2 to 2+. Lacustrine and lagoonal EODs in the Nkporo Formation sediments were interpreted by a rather abundant collection of freshwater algae, fungal spores, and an almost absence of marine dinoflagellates.

Keywords: Lithofacies, Palynomorphs, Kerogen, Organic facies, Hydrocarbon source evaluation, Afikpo Basin

INTRODUCTION

The Afikpo basin is genetically related to the Anambra Basin (Nwajide, 2013; Onyekuru *et al.,* 2023), and contains the Campanian – Maastrichtian sedimentary units unconformably overlying the Santonian deposits of the southern Benue Trough (Fig. 1). It is one of the major sedimentary bodies that occupied the basins created after Africa and South American plates separated (Adegoke *et al.,* 2017; Anyanwu et al., 2022). The basin is geologically significant because of the occurrences of oil seepages which initially shaped the reason for broad surveillance for oil and gas by the Shell D'Arcy starting in 1937 and led to the first discoveries of gas fields in Cretaceous rocks in southeastern Nigeria (Reyment, 1965; Adegoke *et al.,* 2017).

Within the Afikpo and Anambra basins were deposited on thinly-draped post-Santonian sediments, the Nkporo Group as basal units on and older strata (Onyekuru and Iwuagwu, 2010). The Nkporo Group is superposed by off lap complexes of the coaliferous Mamu Formation, the flaggy Ajali Sandstone and the paralic Nsukka Formation that terminated the Cretaceous-proto Niger Delta successions in southern Nigeria (Reyment, 1965; Onyekuru *et al.,* 2017; Onyekuru *et al.,* 2023).

The sedimentology, stratigraphy and geochemistry of the Afikpo Basin have previously been investigated for hydrocarbon potential. In order to ascertain the degree and timing of sediments diagenesis in specific areas of the basins in the southeastern part of Nigeria, (Onyekuru *et al.,* 2015) evaluated the texture and petrophysical characteristics of sandstones. The study came to the conclusion that despite the observed diagenetic effect, the average porosity is reasonably high and contrasted favorably with some of the hydrocarbon producing basins across the world. Evaluations of petroleum sources within the Afikpo and Anambra basins identified matured organic matter (kerogen), with the total organic carbon (TOC) in the range of 0.49 to 56.05 wt. % (Olubayo, 2010). Akintola *et al.* (2021) indicated that the non-marine carbonaceous shales of the late Cretaceous Anambra Basin contain moderately to highly matured source rocks with the potential to generate and expel significant amount of natural gas. Okoro and Igwe (2018) conducted sequence stratigraphic analysis utilizing palynological biofacies and lithofacies data from outcrops. They identified four 3rd order depositional sequences that were unconformity-bounded.

The authors sincerely appreciate the Department of Geology, Federal University of Technology, Owerri for providing the enabling environment for this study.

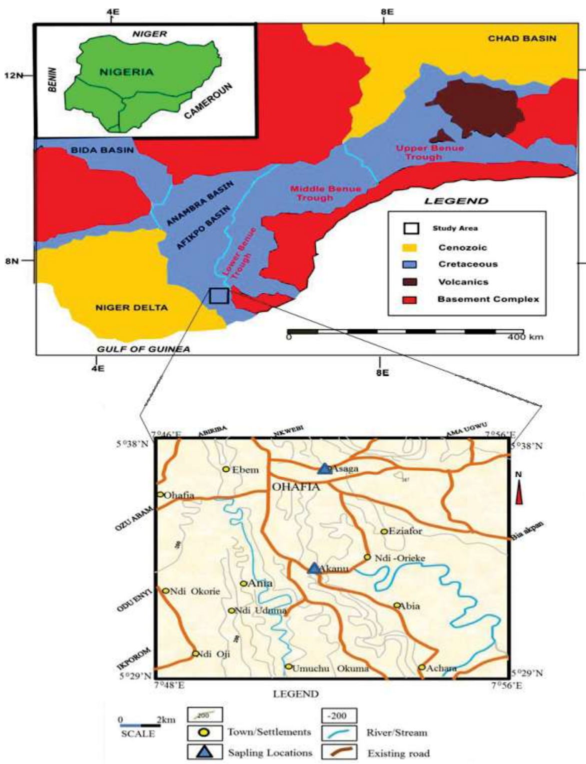

Figure 1: Location of the study area: a. Map of the Southeastern Nigeria (insert map of Nigeria); b. Location/Topographical Map of the study area showing sampling locations

The sequences were deposited in environments ranging in coastal and shallow marine shelf to tidally impacted bays, delta and estuarine settings. Similarly, Onyekuru et al., (2023) utilized lithofacies and biofacies information obtained from three outcropping sections of the Nkporo and Mamu Formations in the Afikpo basin for stratigraphy and paleoenvironmental studies. The study recognized two incomplete depositional sequences and play elements that were fundamental in basin wide correlations.

Recent exploration techniques use modern understanding of organic petrology of sediments to the identification of source rocks, estimated the quality, type and maturation levels of accompanying organic matters in the basins. They were also able to fingerprint the source rocks in a petroleum system (Margoon and Dow 1994; Anyanwu *et al.,* 2021), in order to improve the success rates of petroleum exploration. The hydrocarbon potential of the Anambra and Afikpo basins deserve consideration and in-depth evaluation for possible greater profitability and sustainability. Evaluation of source rocks is the process of determining how well sediments may produce hydrocarbons by examining their thermal maturity, organic matter content, and hydrocarbon-generating capability. Determining if a deposit has the potential to be an effective source rock is a significant component of source rock evaluation. In addition to having organic content that can produce hydrocarbons, an effective source rock also contains enough organic matter to produce enough hydrocarbons to be evacuated and contribute to an accumulation. While possible effective source rocks are only sediments depositions that have the potential to produce large volumes of hydrocarbons, true effective source rocks may be shown to have produced and ejected gas and/or oil. It is important to keep in mind that source rock evaluation only identifies possible, useful source rocks. It must be demonstrated that a sediment has contributed to a petroleum deposit before it can be referred to as a confirmed source rock. Most frequently, a multiple parameter method is used in source assessment studies.

At list twenty-one exploratory wells have been drilled in the Anambra and Afikpo Basins since 1952 (Onyekuru and Iwuagwu, 2010). Five of these wells (Akukwa -l, Alo-l, Amansiodo - l, Igbariam-l and Ihandiagu-l) encountered gas while only one well (Anambra River-1) encountered oil. Based on these reported occurrences of hydrocarbons, it is likely that this region contains gas-condensate (Ekweozor, 2006). Thus, there is need to assess the organic matter content of shale formations in the study area for source rock appraisal. The aim of this present study therefore is to assess the source rock potential of shale sediments from the Mamu and Nkporo Formations in Akanu and Asaga - Ohafia area, part of the Afikpo Basin. The study utilizes a multiple parameter approach for source rock evaluation involving facies description of outcrops, determination of the quantity and quality of the organic facies, palynofloral analysis, spore coloration and visual kerogen typing. The study area is located within latitudes 05029' and 05038' and longitudes 07048' and 07056' in the southern part of the Afikpo Basin (Fig. 1).

GEOLOGIC SETTING

It is generally accepted that the Santonian tectonic processes were responsible for the structural genesis of the Afikpo Basin (Burke, 1996). The Afikpo basin (Syncline) was known to have existed as a platform east of the Benue Trough before the Santonia deformation (Murat, 1972). According to Murat (1972) and others, the Santonian epeirogeny folding flexural depressed the Ikpe Platform (eastwards) to develop the Afikpo basin, and inverted the Abakaliki area into the Abakaliki Anticlinorium.

The primary sources of sediment deposition in the Afikpo Basin were the ancient Niger River moving westward and the erosion of the Abakaliki Fold Belt (Petters, 1978). The Nkporo shales which were layered on top of the Mamu Formation's coal measures, marked the beginning of sedimentation in the Afikpo Basin (Obaje, 2009) Figure. 2. In most areas, the Ajali Formation's side coequals are the fluvio-deltaic sandstones, which are situated on top of the Mamu Formation (Fig. 2). The Nkporo Shales are a representation of the fossiliferous, brackish, swampy prodelta depositional cycle (Reijers and Nwajide, 1998). This deposit shows a shallow marine channel habitat that graded into a low-energy setting. The Nkporo Formation's sediment cycle saw the accumulation of the coal-bearing Mamu Formation and the Ajali Sandstones. At a time when the coastline line was still shallow, the Ajali Sandstone records the maximum regression. The tidal sands that make up the Ajali Sandstone are proof that the clustered intertidal currents regulated the deposition (Obaje, 2009). Another transgression episode in the Afikpo Basin (Paleocene) began with the Nsukka Formation. The hydrocarbon bearing zones of the northern Niger Delta may have their implicit source in the shale units, which contain a considerable quantity biota (Reijers and Nwajide, 1998).

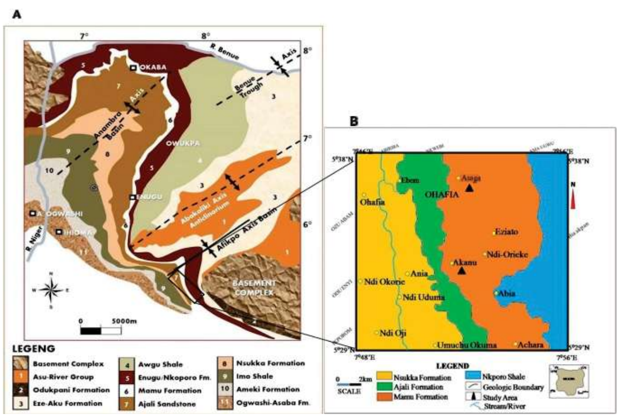

Figure 2: Geologic map of the research area: A. Regional geologic map; (Obaje, 2009) B. Study area geologic map with the sample site indicated.

MATERIALS AND METHOD

Field Investigation

In-depth geologic fieldwork in the study area included using a pogo stick to assess the thickness of individual beds. The compass-clinometer was used to determine the orientations of the bed and sedimentary structures, including their strike and dip directions and depths. Following georeferencing and elevation estimations using a global positioning system (GPS), lithostratigraphic sections and logs were created to graphically replicate the observations. For interpretations of the depositional environment and paleobathymetry, the beds were then categorized or divided into lithofacies based on similar/differing textural, structural, geometrical, and paleontological properties. At regular intervals of lithological changes, 14 representative outcrop samples were obtained and prepared for laboratory analyses.

Assessment of the Total Organic Carbon (TOC)

The samples were homogenized, grounded, and cleaned. To eliminate carbonates, concentrated hydrochloric acid (HCL) was applied to 0.10g of each ground-up sample. Hydrochloric acid was added to the samples and left for at least two hours. Using a filtering device with a glass microfiber filter, the acid was extracted from the sample. After the filter was put inside a LECO crucible, it was dried for at least one hour at 110 degrees Celsius. The samples were examined using a LECO 600 Carbon Analyzer to ascertain the TOC after drying.

Extraction of Soluble Organic Matter (SOM)

Prior to extraction, the samples were ground into a powder that was smaller than 120 mesh size using an agate mortar. Chloroform was used to do a 72-hour Soxhlet extraction on the powdered materials. In order to eliminate elemental sulfur from the extracts, activated copper powder was added. Using a hot water bath, excess solvent was distilled off to an aliquot volume of around 3 milliliters. After that, the aliquot was transported with a micropipette to a clean, weighed vial, and any leftover solvent was wiped off using nitrogen gas at a temperature lower than 500C. Next, a Mettler balance was used to weigh the soluble organic materials. To determine the samples' free hydrogen concentration, the soluble organic matter content was measured. The Soxhlet System HT2 Extraction Unit and a 9:1 methylene chloride/methanol combination were used as the solvent in this process. Glass wool and an adaptor were inserted into labeled cellulose thimbles containing 20g of each ground sample. Inside a tecator system were the thimble, extraction cups, and 100 milliliters of methyl chloride solution. After letting the solvent come to a boil, the thimbles were submerged in it and left for an hour. The stop cork was shut to facilitate quicker evaporation. Soluble materials were evaporated, then transferred into 20 ml glass vials that had been previously weighed, labeled, and nitrogen-dried at 40 °C. Weighing the dried extract at room temperature was done.

Next, the soluble organic matter (SOM) was computed as follows:

$$\text{SOM (ppm)} = \frac{\text{Weight of extract (g)}}{\text{Weight of sample}} \times 10^6$$

Palynological Analysis

To prepare the materials for the recovery of organic walled microfossils (palynomorphs), around 30 grams of the samples were employed. The specimens underwent processing in compliance with the conventional technique for palynological examinations of geological materials (Faegri and Iversen, 1989). To remove siliceous and calcareous materials, respectively, samples were treated with hydrochloric and hydrofluoric acids (HCl and HF); to do this, samples were placed in a 400 mL beaker, and 50 mL of HCl at a 36% concentration was added over the course of 24 hours to dissolve carbonates. Subsequently, the sample solution is washed periodically with distilled water to bring its pH down to neutral. After that, 50 mL of 40% HF was added to dissolve the silicates for 48 hours. Hot strong HCl acid was used to remove the fluoride gel, and a 10-µm sieve was used to wet sift the residue. After 30 minutes of oxidation in 70% HNO3, the leftovers were swirled and dyed with Safranin-O to improve contrast for identification and photography, making the fossils transparent for transmitted light microscopy.

Spore Coloration and kerogen type analysis

For optical examination, a subset of shale samples was coarsely ground. Excess hydrofluoric acid (HF) was used to eliminate any silicates from the samples after excess hydrochloric acid (HCH) had been used to eliminate the carbonates. After drying, washing, and mounting the kerogen particles on a glass slide, the relative abundances of vitrinite's, inertinites, Liptinite, and Amorphous Organic Matter (AOM) were estimated by spore coloration (SC) and kerogen type analysis under transmitted light. In the early to mature stages of oil production, this procedure is quite beneficial. Transmitted light microscope is employed in the procedure. Using a reference set of standard spores, the spore color was visually determined. By consulting the conversion chat (Fig. 3), the spore coloration index (SCI) was determined. The thermal alteration index (TAI) was calculated using (Staplin, 1969) standard scale, as seen in Figure 4.

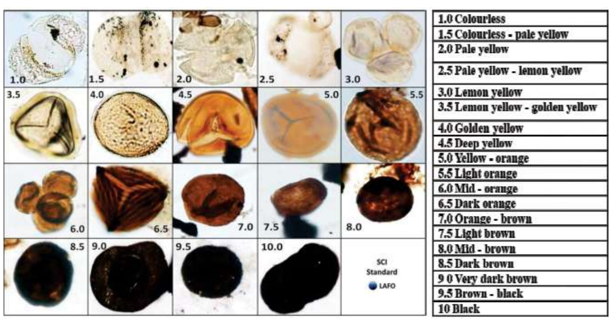

Figure 3: Spore coloration chart (After Fischer, 1980).

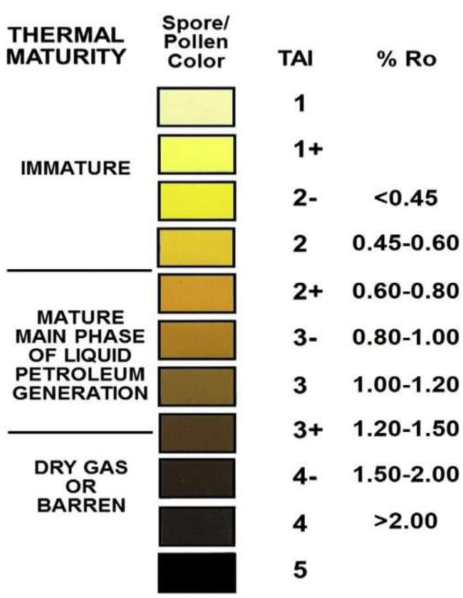

Figure 4: The thermal alteration index of (Staplin, 1969).

RESULT AND DISCUSSION

Description of Litho-sections

The Sediments of the Mamu Formation was exposed at Ndi-Orieke Junction and Akanu - Ohafia. The location is described by Latitudes and Longitudes N 050 33.3641 and 07052.0921E respectively. The elevation of this location is about 330 feet. The total logged section is about 50 meters with the shale beds averaging 9 meters in vertical thickness and 21 meters in lateral extent (Fig. 5). The Oolitic limestone beds, on the other hand, measured about 1.5 meters in vertical thickness and 4 meters in lateral extent (Fig 6). The basal shale portion of the section could not be determined with certainty as it was not completely exposed. The section is made up of an interbedding of ferruginous, highly-fissile dark-grey to black shales and bands of Oolitic limestones (Fig. 6) trending N-S in the general direction/strike of the study area.

The Nkporo Formation outcropped at Abia Road, Abia-Ohafia (Fig. 7). This section lies at N050 32.1821 and E 0070 52.7431 (Fig. 1). It is made up of two main units (L2U2) and the lower unit (L2U1) subdivided into heteroliths. The area is at an elevation of 303 feet above mean sea level. It is exposed by a road cutting, and is located 5km from Mamu Formation at Ndi-Orieke, Akanu (Fig 1). It is made up of an interbedding of sandstone and shales 2 meters thick, overlain conformably by bioturbated laminated sandstone of about 22 meters in thickness (Fig 8). Five lithofacies were altogether described and facie code assigned to them namely: dark grey shale facie (DSF), Oolitic limestone facie (OLF), heterolithic mudstone/sandstone facie (HMSF), laminated bioturbated sandstone facie (LBSF), and calcareous mudstone facie (CMF).

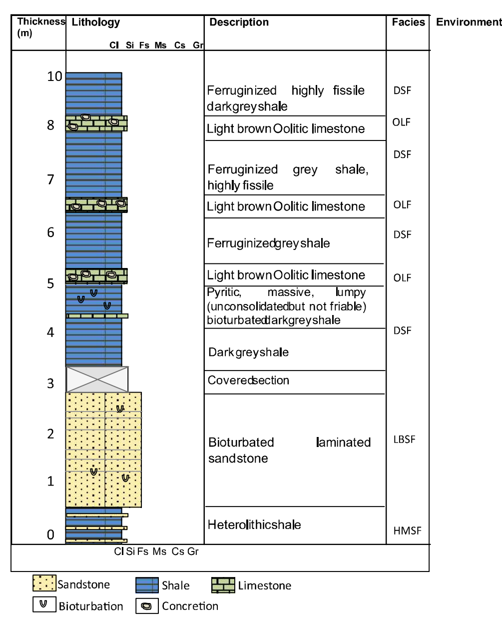

Figure 5: Litho-section of outcrop at Ndi-Orieke Junction.

Figure 6: Outcrop section at Ndiorieke Junction, Asaga Ohafia: a. Dark grey fissile shale with Oolitic limestone interbedded; b. Basal unit of section at Ndiorieke showing dark Grey-Black pyritic shale; c. Close-up of the Oolitic limestone unit; d. Concretionary nodules in the shale (red arrow).

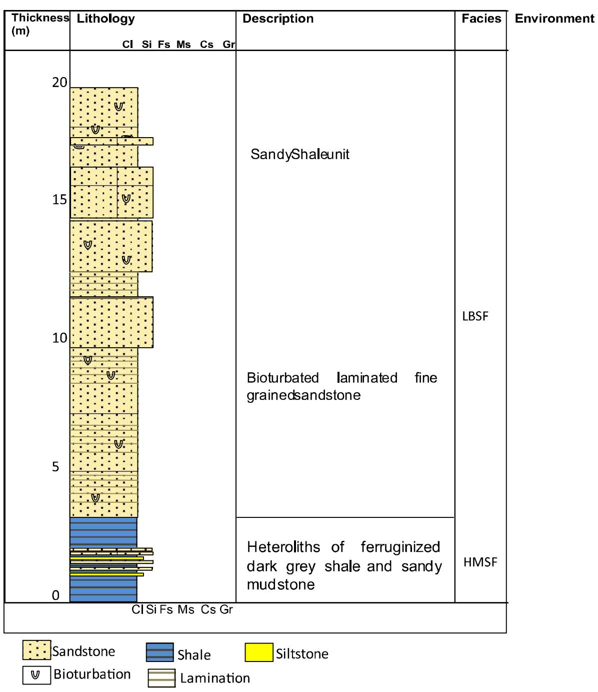

Figure 7: Litho-section of outcrop along Abia Road.

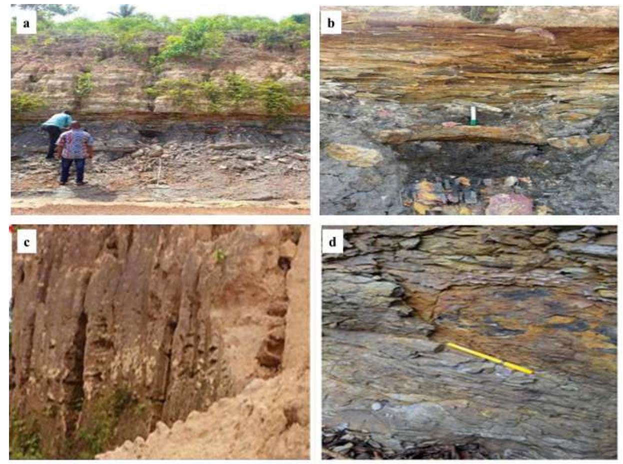

Figure 8: Outcrop section along Abia Road Asaga-Ohafia: a. Outcrop section along Abia Road; b. Heteroliths of fissile shale with bands of sandstone interbeds; c. Bioturbated sandstone; d. Outcrop section at km 2 off Ohafia Asaga road.

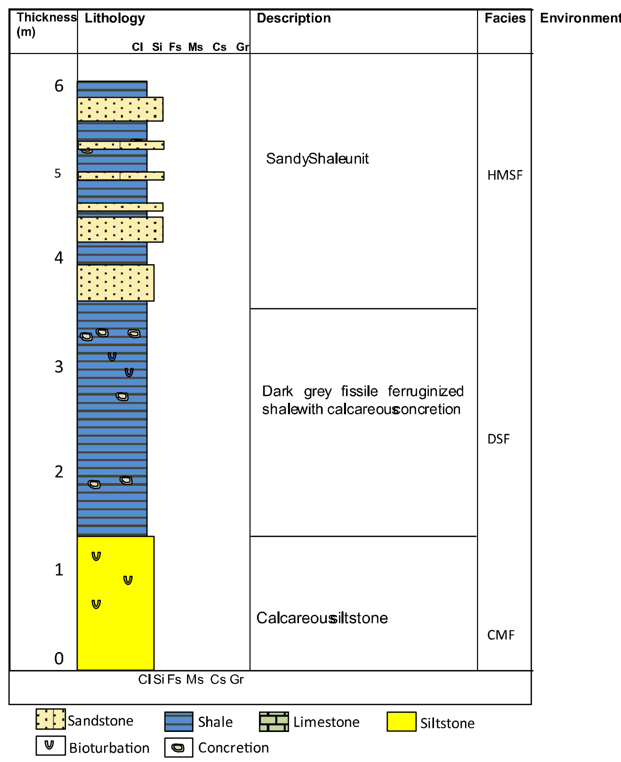

Figure 9: Litho-section of outcrop at km 2 off Ohafia-Asaga road.

Description of Facies and Facies Analysis

A. Dark Grey Laminated Shale Facies (DSF):

Shale that is unconsolidated, somewhat fissile, and varies in color from dark gray to black. The transition from the shales to the Oolitic beds in the study area were all sharp. These facies are characterized by pyritic concretions with ophiomorpha borings and plant organic materials (Fig 8). Ferruginous shale, highly-fissile and light-grey in color is the most consolidated shale unit of this facies. At Ndi Orieke junction, it is overlain by a band of Oolitic limestone brown in colour (Fig 6).

B. Oolitic Limestone Facies (OLF)

These facies are a carbonate rock composed mostly of Ooliths, also known as ooids, which are carbonate particles the size of sand with calcium carbonate rings around them. The color varied from reddish-brown to pale brown, with around 2 mm of grain size. The facies are described at the section at Ndi Orieke junction (Fig 6).

C. Heterolithic Mudstone/Sandstone Facies (HMSF)
This unit is comprised of heteroliths of laminated shale, mudstone and sandstone. Average thickness is about is about 2 meters. The section exposed along Ukwa road is characterized by ferruginous shale, slightly-fissile and dark-grey in colour overlain by sandy siltstone. It is fine-grained, consolidated, light-grey in colour and feels gritty. This in turn is overlain by fine-grained, whitish-grey in colour, slightly-consolidated and slightly-fissile sandy mudstone, and lastly by highly-consolidated grey shale (Fig. 7).

D. Laminated Bioturbated Sandstone Facies (LBSF)
This facie conformably overlies Facies HMSF in its entire occurrence. The facie is fine grain textured with drapes of intervening thin laminae. It is also bioturbated (Fig. 8).

C. Calcareous Mudstone Facies (CMF)
These facies have a gray coloration. Surface cut with faint, fine-scale laminations apparent. Not fissile (does not readily split along bedding planes) both fossils and fossil impressions are present. A few shimmering mica fragments, some of which are weathered and having a light brown-grey color. The Heterolithic and laminated bioturbated sandstone facies are typical of estuarine bay and fill delta facies composed of moderately sorted, bioturbated and ripple laminated sandstone and mudstone. The alteration reflects frequent energy fluctuation consistent with sub-tidal and intertidal setting (Onyekuru *et al.,* 2023). The presence of sandy lenticular clays in association with low diversity burrow types is indicative of a low energy setting such as in a tidally-influenced estuary (Oboh-Ikuonebo *et al.*, 2005). The laminated shale facies are interpreted as estuarine central basin facies. The facies comprise mainly finely laminated grey to dark shale with whitish probably calcareous materials. The preservation of primary lamination and pyritic concretions suggest anoxic environment devoid of mud-eating bottom dwellers (Maynard, 1983). Ooliths, also known as ooids, are sand-sized carbonate particles with concentric rings of $CaCO_3$ that make up the majority of the carbonate rock that makes up the Oolitic limestone facies. As sand grains or broken shells roll around on the shallow sea floor, layers upon layers of limestone are accumulated to produce these rings. The complex combination of physical, chemical, and biological factors that allow sediment to build up is known as the sedimentary environment. The characteristics of the sediments deposited in the habitats are mostly determined by this complex. Accordingly, depositional sedimentary settings are a geomorphic unit that represents the deposition site and is distinguished by a particular combination of physical, chemical, and biological processes that function at a certain pace and intensity. From the facies, facies association, facies sequences, and facies cycles, depositional habitats may be formed.

Paleo-depositional environment
From the facies, facies association, facies sequences, and facies cycles, depositional habitats may be determined. The Heterolithic and laminated bioturbated sandstone facies are typical of estuarine bay and fill delta facies composed of moderately sorted, bioturbated and ripple laminated sandstone and mudstone. The alteration reflects frequent energy fluctuation consistent with sub-tidal and intertidal setting (Onyekuru *et al.,* 2023). The presence of sandy lenticular clays in association with low diversity burrow types is indicative of a low energy setting such as in a tidally-influenced estuary (Oboh-Ikuonebo *et al.,* 2005). The laminated shale facies are interpreted as estuarine central basin facies. The facies comprise mainly finely laminated grey to dark shale with whitish probably calcareous materials. The preservation of primary lamination and pyritic concretions suggest anoxic environment devoid of mud-eating bottom dwellers (Maynard, 1983). The majority of the Ooliths were formed as sand grains or broken shells roll around on the shallow sea floor, layers upon layers of limestone are accumulated to produce these ooids (Maynard, 1983). Paleoenvironment interpretation of the analyzed samples were based on the presence of environmentally significant forms. Changes in the depositional environment can be inferred from the composition and relative abundance of the various groups of palynomorphs (Oloto, 1992). The presence of dinoflagellates species in Mamu Formation (Andalusiella polymorpha) may indicate shallow marine environment (Ojo and Akande, 2006).

Pteridophyte spores, which are sporomorphs of vascular tissue, are representative of nearshore shallow shelf habitats and proximal pro-delta (Ojo *et al.,* 2009). Additionally, it demonstrated the inflow of terrestrial organic materials into the shallow shelf as a result of delta expansion (Habib and Miller, 2003). Rich and varied tropical vegetation were nourished by the surrounding continent, as evidenced by the many and varied types of pollen and spores (Fig. 9). The presence of palmae pollens, which is indicative of warm, humid weather, supports this (Muller, 1959). According to Chang *et al.,* (2010), the depositional habitats of the sections under study underwent a full transition from marine to freshwater wetlands, as evidenced by the presence of aquatic species and freshwater algae. The great diversity and richness of palynomorphs may be caused by circulating currents having less of an impact and allowing the biotic materials to settle a little more quickly. According to Onuigbo *et al.*, (2012), the predominance of fresh water settings is shown by the scarcity of marine dinoflagellate in the downward portion of the Nkporo Formation (Fig. 9) and the presence of structured plant remnants, which are inputs sourced from the land. For the Nkporo Formation. According to

Edet and Nyong (1994), the distribution of recovered palynomorphs in the studied lithologic sections indicates that the assemblages are typical of those from the Campanian-Maastrichtian period in southeast Nigeria. The stratigraphic subdivision of the sampled portions of the Afikpo Basin has been aided by the presence and distribution of certain marker species, as well as the relative abundance of stratigraphically relevant palynomorphs. Miospore assemblages ranging from reasonably rich to rich and diversified were found in the outcrop samples (Fig. 9). The age of Mamu Shale samples is determined to be Late Maastrichtian. Based on the palynofloral assemblage that was seen, which consists of the occurrences of *Ubistephanocolpites cylindricus, Cingulatisporites ornatus, Foveotriletes margaritae, Constructipollenites ineffectus, Longapertites marginatus, Chlorophytum tuberosum, Zlivisporisblanenesis, Ephedripites ambonoides, Ctenolophonidite scostatus* and abundant occurrence of *Retidiporites magdalenensis* with the co-occurrences of some *dinoflagellate* sp *Andalusiella polymorpha* and *Palaeocystodinium* sp. (Late Campanian – Maastrichtian). The Nkporo Shale Samples are assigned Early to Middle Maastrichtian age based on the abundant occurrence of an index marker species *Retidiporites miniporatus/Macrotyloma brevicaule* which is restricted within Early – Middle Maastrichtian ages. Also supporting this age interpretation are the abundant occurrences of *Bacutriporites orluensis, Proteacidites longispinosus, Constructipollenite sineffectus, Azolla cretacea* and *Retidiporites magdalenensis* in association with the presence of *Hexaporotricolpites emelianova, Ariadnaesporites* sp, *Aquilapollenites minimus, Monocolpopollenites spheriodites, Smilacipites echinatus,* and *Tubistephanocolpites cylindricus* which made up the assemblage within this age. The Photomicrograph of the identified palynomorphs is presented in Fig 10.

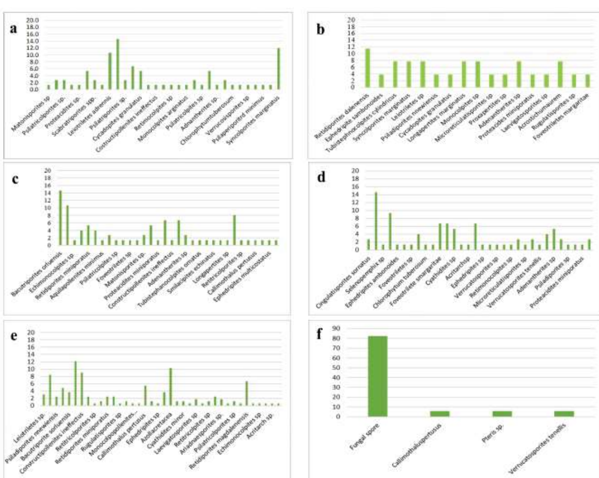

Figure 9: Results of Palynological analysis and relative abundance (%) of palynofloral for the analyzed samples:
a. Relative abundance (%) of Palynofloral for Shale sample of Mamu Formation (Unit 1); b. Relative abundance (%) of Palynofloral for shale in Mamu Formation (Unit 3);
c. Relative abundance (%) of Palynofloral in Mamu Shale (Pyritic Unit); d. Relative abundance (%) of Palynofloral for shale of Nkporo Formation (Unit 1a); e. Relative abundance (%) of Palynofloral for shale of Nkporo Formation (Unit 1 D) ; f. Relative abundance (%) of Palynofloral for shale of Nkporo Formation (Unit 2).

PLATE ONE

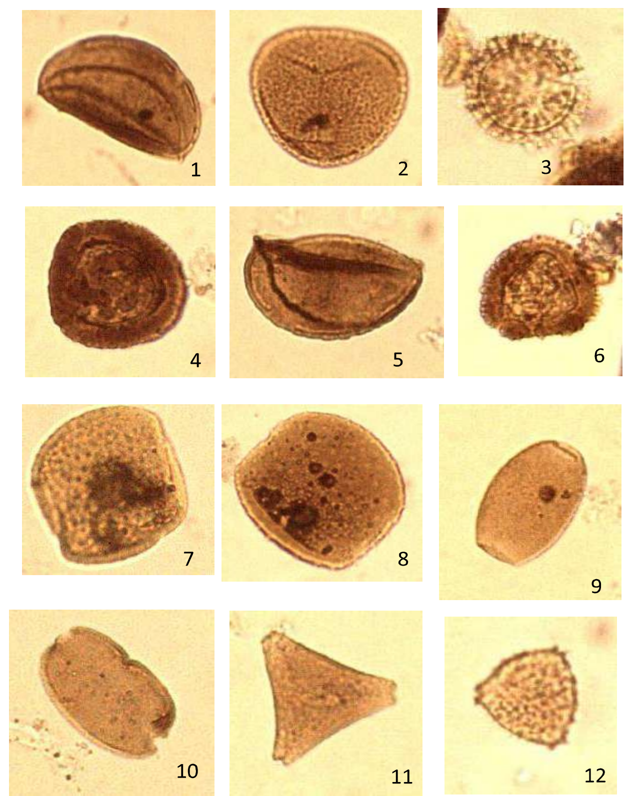

Figure 10a: Photomicrographs of palynomorphs:
1 &5. Ephedripites ambonoides
2. Foveotriletesmargaritae
3. Constructipollenitesineffectus
4&6 Cingulatisporites ornatus
7&8 Retidiporites miniporatus/Macrotyloma brevicaule
9 &10 Retidiporites magdalenensis
11. Proteaciditeslongispinosus
12. Echitriporites trianguliformis.

Organic Geochemistry

The geochemistry of the studied shale samples of Nkporo and Mamu Formations were ascertained using their Soluble Organic Matter (SOM) and Total Organic Carbon (TOC). According to Table 1, the samples' total organic carbon (TOC) values range from 1.47 to 2.40 weight percent. These results are above the minimum requirement of 0.5 weight percent for clastic source rock by a large

PLATE TWO

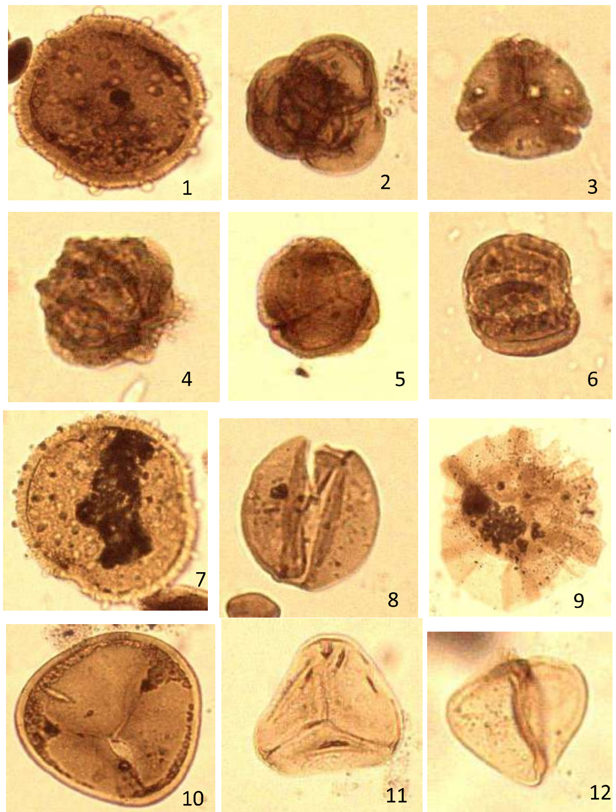

Figure 10b: Photomicrographs of palynomorphs
1&7Bacutriporites orluensis 2Adenantherites sp
3&5 Syncolporites marginatus
4 Ctenolophonidites costatus
6 Tubistephanocolpites cylindricus
8 Monocolpites marginatus 9 Acritarch sp.
10 Matonisporites sp. 11 Cyathidites minor
12 Leiotriletes sp.

PLATE THREE

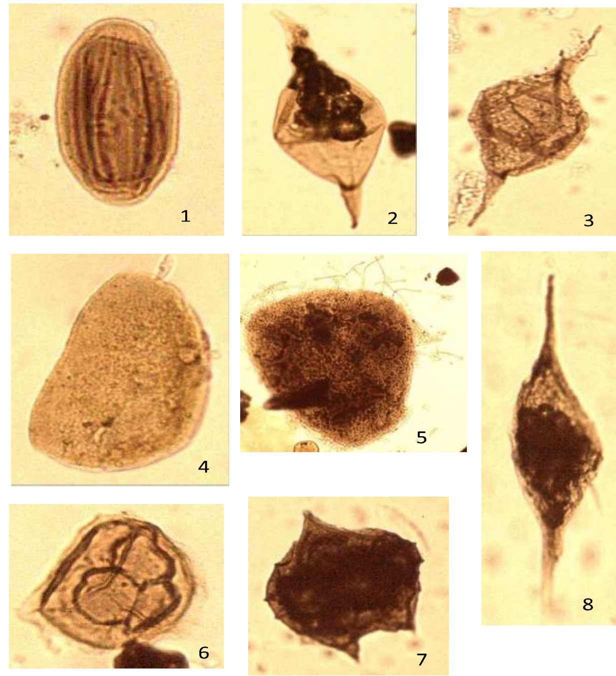

Figure 10c: Photomicrographs of palynomorphs
1 Ephedripites multicostatus 2&3Andalusiella polymorpha/ sp 4 Longapertite smarginatus
5 Azollacretacea 6 Zlivisporisblanensis
7Cerodinium sp. 8Palaeocystodinium sp.

margin (Hunt, 1996; Tissot and Welte, 1984). The levels of soluble organic matter (SOM) vary from 750.00 – 6000.00 ppm. This imply that the organic matter is adequate. These values are within the expected values for hydrocarbon generation (Tissot and Welte, 1984). The Plot of SOM (ppm) against TOC (wt %) (Jovancicevic *et al.,* 2002) is shown in Fig. 11.

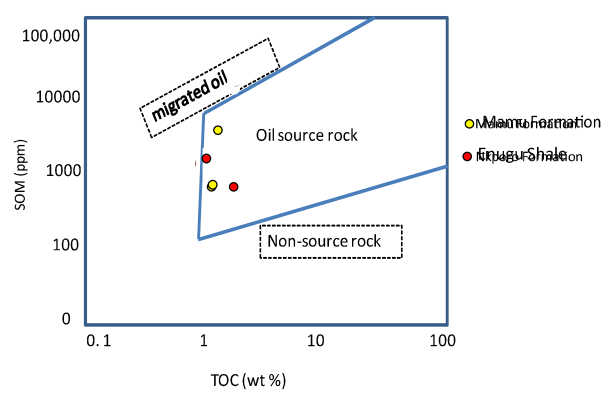

Figure 11: Plot of SOM (ppm) against TOC (wt. %) (Jovancicevic *et al.,* 2002).

Table 1: TOC and SOM values for shales from Mamu and Nkporo Formations.

S/N	SAMPLES	TOC (wt.%)	SOM (ppm)
1	Mamu Unit1 (base)	1.50	750.00
2	Mamu Shale Pyrite Unit 2	1.50	750.00
3	Mamu Shale Unit 3B	1.71	6000.00
4	Nkporo Unit 1A	2.40	750.00
5	Nkporo Shale Unit 2	1.47	1500.00

The TOC content of the Mamu and the Nkporo Shale samples ranges from 1.50- 2.40 wt.%. The lowest TOC values of 1.5 wt.% were observed in Mamu shales (Unit 1 base & Unit 2 Pyrite) while the highest value of 2.40 wt.% was observed in Nkporo shale Unit 2. These TOC values are considered to be good to very good. These shales have higher levels of organic carbon content than the required minimum of 0.5 weight percent for a possible source rock (Tissot &Welte, 1984; Killops and Killops, 1993), suggesting that they have the potential to produce gas and oil. Result of the SOM of the shale samples of the studied sections exceeds 500 ppm. Samples from the Mamu Formation range from 750-6000ppm with an average value of 2500 ppm while those of Nkporo Formation range from 750 to 1500 with an average value of 1125 ppm. The plot of TOC (%) against SOM (ppm) shows that most of the shale samples were clustered within the oil source rock field as shown in Fig.11.

Visual Kerogen Typing

The two main parts of organic materials in sediments are bitumen, which is part of the organic matter soluble in organic solvent, and kerogen, which is the insoluble fraction. A derivative of the diagenetic organic matter preserved in sediments by burial at a suitable pressure and temperature is called kerogen. The microscopic technique for examining kerogen is called visual kerogen analysis (kerogen typing), which is a kind of organic petrographic evaluation. It is predicated on the idea that the ability of a source rock to produce hydrocarbons may be linked to optically categorized kerogen particles (Staplin, 1969). The organic matter composition of the studied samples is listed in Table 2 and illustrated in Fig. 12. Based on the changes of the number of amorphous assemblages and vitrinite particles in the whole section, the interpretation is divided into two (2) assemblages viz: Assemblage 1: shale samples from Mamu Formation (Unit 1 and 2; Unit 3a and b) and Assemblage 2: shale samples from Nkporo Formation (Unit 1a and b). the main organic particles (adapted from Mahmoud *et al.,* 2004).

Table 2: Visual kerogen typing of samples from Mamu and Nkporo Formations.

Formations	Sample Sections	%AOM	% Liptinite	%Vitrinite	% Inertinite	TAI	SCI
Mamu	Unit 1 base	50	10	30	10	3+	8.5
	Unit 2 base	40	20	30	10	3	7
	Unit 2 Pyrite	30	10	40	20	3-	7
	Unit 3a	30	10	50	10	3-	4
	Unit 3b	35	5	50	10	3-	4
Nkporo	Unit 1 base	20	10	65	5	2+	3.5
	Unit 2 base	40	15	40	5	2+	3
	Unit 2 Pyrite	40	10	50	0	2	3

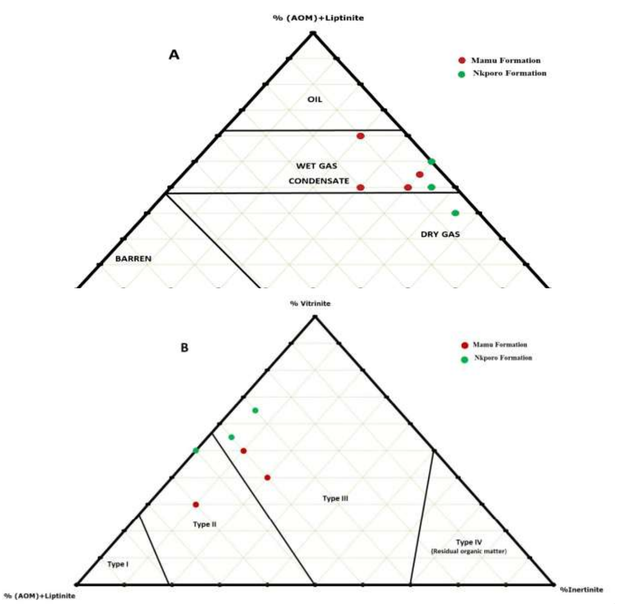

Figure 12: Organic Mater Composition of Mamu and Nkporo Formations using Visual Koregen Typing.

Assemblage 1: Mamu Formation

The visual kerogen analysis carried out on samples collected from this formation show that the organic materials are composed of particles of pollen/spores, leaf cuticles, thin cells which were placed in the class of liptinite and amorphous kerogen; these particles are believed to contain high amount of hydrogen and should produce oil (Staplin, 1969). Woody tissues, cell wall particles, and vitrinite's were known contain lignin with a propensity to generate gas (Staplin, 1969). The analysis indicates the presence of the various kerogen types (AOM 20- 50%, Liptinite 5 - 10%, vitrinite 30- 50%). There is also a presence of opaque particles (inertinite) ranging between 10 to 20% (Table 1). The amorphous kerogen is oil-prone because it was virtually solely produced from algae (Staplin, 1969; Tissot, 1984). It is believed that inertinite and coaly kerogen, which are opaque particles, are inert and do not really have the ability to produce hydrocarbons (Staplin, 1969). The color of the spores varies from pale to lemon yellow, yellow orange to dark brown, with lemon yellow being the most prevalent color (Figs. 13 and 14). This color range corresponds to the mature main phase of liquid petroleum generation, which is represented by theoretical vitrinite reflectance values of 0.80–1.50% and TAI value of 3- to 3+ (Staplin, 1969; Pearson, 1984). The hydrocarbon generation potential varies from type II to type III (Gas to oil-prone), and falls within the field of wet gas/condensate generation on the ternary plot (Fig. 12). Palynofacies analysis indicates the presence of marine dinoflagellates (Andalusiella polymorpha) suggesting shallow marine environment (Ukpong and Anyanwu, 2018; Onyekuru *et al.,* 2023). The presence of vascular spores also indicates habitats on nearshore shallow shelves and proximal prodelta (Ojo *et al.,* 2009).

Assemblage 2: Nkporo Formation

Visual kerogen examination of samples obtained from this formation reveals that the organic elements are made up of spore particles, pollen materials, leaf cuticles, and cell wall materials known as amorphous kerogen and liptinite. It was believed that woody tissues, cell wall structure, and vitrinite's contain lignin in sufficient amount and thus prone to gas, whereas these particles (e.g. leaf cuticles, spores and pollens) are assumed contain hydrogen in sufficient amount, and should be prone to oil (Staplin, 1969). The results indicate nearly equivalent amounts of these organic compounds (AOM 20- 45%, Liptinite 10%, and Vitrinite 40–65%). Coaly kerogen and inertinite had somewhat low incidences (0–5%), as shown in Table 1. The thermal alterations index (TAI) of 2 to 2+ and theoretical vitrinite reflectance values of 0.45-0.80%, which correspond to the immature to mature phase of liquid petroleum generation, are equivalent to the color range of the spores (Fig. 15): pale-lemon yellow to golden yellow (Staplin, 1969; Pearson, 1984). On the ternary plot (Fig. 13), the hydrocarbon generation potential ranges from type II to type III (Gas to oil-prones), and it falls into the categories of wet gas/condensate and dry gas production. Palynofacies is characterized by the near-absence of marine dinoflagellates and the presence of spore and rather abundant assemblages of fresh water algae, fungal spore (Fig 9). Fungal spores and freshwater algae are prevalent in lagoonal and lacustrine facies; they are only found in marine sediment by redepositions or transit (pro-deltaic facies, for example) (Tyson, 1995).

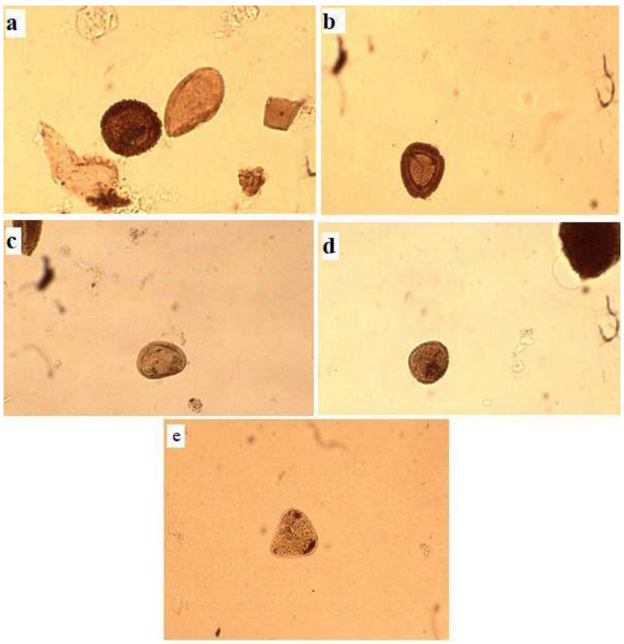

Figure 13: Photomicrographs of Kerogen particles identified using transmitted light microscopy in Mamu Formation (a, b Mamu Unit 1 base; c, d, e Mamu unit 2 base).

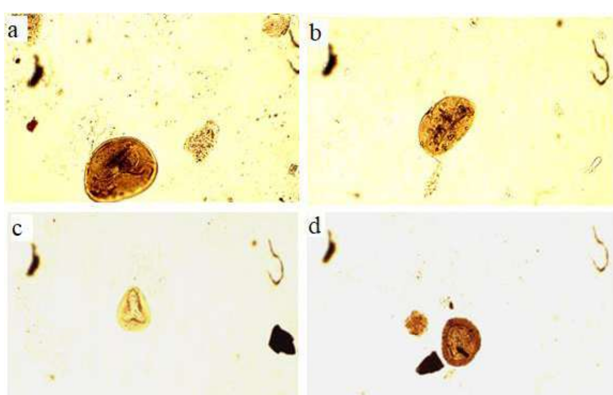

Figure 14: kerogen particles (spores) studied with the aid of transmitted light microscopy in the Mamu Formation (a, b, Unit 2 pyritic; c, d Unit 3b).

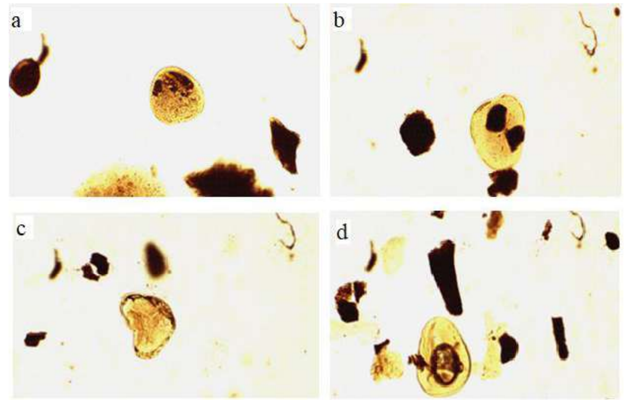

Figure 15: kerogen particles (spores) studied with the aid of transmitted light microscopy in the Nkporo Formation (a, b, Nkporo Unit 1a; c, d, Nkporo Unit 1d).

CONCLUSION

The presence of high-quality petroleum source rocks is essential for the development of any petroleum system or prospect. The stratigraphic placement of these rocks, the presence of high-quality reservoirs and seals lithologies, the time of the production of hydrocarbons, advantageous regional migratory paths, and trapping processes must also be taken into account. The Upper Cretaceous succession of the Mamu and Nkporo Formations in the Afikpo basin was studied in terms of outcrop facies, palynology, organic facies analysis, and Kerogen type analysis for source rock evaluation. A total of five lithofacies were described: heterolithic mudstone/sandstone facie, dark grey shale facie, laminated bioturbated sandstone facies, calcareous mudstone facies, and Oolitic limestone facies. The heterolithic and laminated bioturbated sandstone facies are typical of the estuary bay and fill delta facies, which are made up of moderately sorted, bioturbated, and ripple laminated sandstone and mudstone. The distribution of recovered palynomorphs in the studied lithologic sections reveals that the assemblage is typical of the Campanian-Maastrichtian age in southern Nigeria. The minimum 0.5 weight percent criteria for a possible source rock are exceeded by the levels of organic carbon content. Visual Kerogen Typing reveals that the Mamu Formation contains the several kerogen types (20–30% Amorphous Organic Matter (AOM), 20–50% Liptinite, and 5-10% vitrinite). Additionally, there are between 10% and 20% of opaque particles (inertinite) present. The predominant spore color (SC) is lemon yellow, which is equivalent to TAI of 3 to 3+ and theoretical vitrinite reflectance value of 0.80–1.50%, which are indicative of the mature main phase of liquid petroleum generation. The hydrocarbon generation potential ranges from type II to type III (gas to oil-prone), and it falls under the category of wet gas/condensate generation. The existence of vascular spores, which are indicative of prodeltaic, and nearshore to shallow shelf environment; and the presence of marine dinoflagellates *(Andalusiella polymorpha)* confirms shallow marine environment. The assemblage of Nkporo Formation reveals that the organic facies are made up of the several kerogen types (AOM 20-45%, Liptinite 10%, and vitrinite 40–65%), with very little coaly kerogen and inertinite (0–5%) occurrences. The spore color ranges from pale-lemon yellow to golden yellow, corresponding to TAI of 2 to 2+ and theoretical vitrinite reflectance values of 0.45-0.80%, which correlate to the immature to mature phase of liquid petroleum generation. Hydrocarbon generation potential ranges from type II to III (oil- to gas-prone), and it falls into the categories of dry gas generation and wet gas/condensate generation. Lacustrine and lagoonal facies are indicated by a rather abundant collection of freshwater algae, fungal spores, and almost entirely absence of marine dinoflagellates. Despite being used in paleothermal estimations for a considerable amount of time, spore colorations have not gained the same prominence as other techniques like vitrinite reflectance. This study offers an additional benefit by evaluating source maturation using spore color. Rather than perhaps unrelated particles from bulk samples, the observations were conducted on organic particles, which are an essential component of the hydrocarbon-sourcing kerogen. The importance of visual kerogen type and spore color analysis for hydrocarbon prospecting is highlighted by this work. Furthermore, spore color fluctuations can provide more accurate information than vitrinite reflectance values in the lower range of thermal maturation because they are more sensitive to these changes.

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