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RESEARCH ARTICLE

PALYNOSTRATIGRAPHY AND PALEOENVIRONMENT OF BENIN FORMATION FROM UDUAK-1 WELL, GREATER UGHELLI DEPO BELT, NIGER DELTA BASIN, NIGERIA

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ABSTRACT

This study integrates Lithostratigraphic descriptions, palynological analyses and gamma-ray wireline data from Uduak-1well at (340–3,510 ft) interval to characterize the lithofacies, establish palynostratigraphy and reconstruct depositional setting and paleoclimate of the Benin Formation in the Greater Ughelli depo-belt. Forty-three ditch-cutting samples were collected at ~60 ft intervals and were examined and combined with GR-log motifs and sand/shale ratios. Two principal lithofacies packages were identified: a sand-dominated continental unit (340–2,600 ft; sand:shale ≈ 98:2) and a continental–transitional unit (2,600–3,510 ft; ≈85:15). GR logs are generally low with intermittent peaks reflecting thin shaly interbeds/paleosols, while cylindrical and bell-shaped motifs indicate stacked channel and point-bar architectures. Palynological assemblages are dominated by freshwater-swamp taxa (e.g., Retitricolporites irregularis, Pachydermites diederixi) and Botryococcus, with only sporadic dinoflagellate occurrences near the base. Three palynozones/subzones (P624, P580, P560) were recognized and dated to the Rupelian–Chattian (Early–Late Oligocene), supporting a tentative Benin/Agbada boundary near ~3,490 ft. The sequence records a shift from marginal-marine/deltaic to fully continental, high-energy fluvial deposition under a warm, humid tropical climate. Integration of these data refines local biostratigraphy, improves lithofacies correlation for reservoir prediction, and enhances understanding of late Oligocene depositional dynamics in the onshore Niger Delta Basin.

KEYWORDS

Benin Formation, Palynology, Gamma-Ray Log, Lithofacies, Niger Delta, Fluvial–Deltaic.

1. INTRODUCTION

One of the main basins in Africa that produces hydrocarbons is the Niger Delta (Doust and Omatsola, 1990; Kulke, 1995). The Tertiary Akata-Agbada Petroleum System is the name given to the basin's petroleum system (Doust and Omatsola, 1990; Ekweozor and Daukoru, 1994; Kulke, 1995). Palynology as a tool of biostratigraphy has to do with the study of pollen grains, spores and dinocysts as well as other palynomorphs that are found in geological deposits(Traverse, 2007; Jansonius and McGregor, 1996) The integration of lithofacies and palynology as a tool in evaluating sedimentary succession penetrated by a drill in any sedimentary basin has grown in significance in recent years, as evidenced by studies conducted by (Lucas, 2017; Helenes et al., 1998; Oloto, 1992; Geraldaad et al., 1968; Chiaghanam et al., 2013.

Most oil companies have their own zonation scheme and a standard scheme is needed to gain an understanding of the Ughelli Depobelt's intricate stratigraphic structure. the palynology has been proven to be an important tool for the exploration of oil and gas in the Niger Delta (Osokpor et al., 2015). Pollen, spores, dinocysts as well as ancillary microfossils have been used for palynological zonation and paleoclimatic reconstruction of the studied well section. This study aims to identify the age, paleoenvironment, paleoclimatic condition, and palynological zones of the sediments that the well penetrated. By combining sedimentological and palynological analyses, an insights can be gained into both the depositional environments and the paleoclimate, offering an understanding paleoenvironmental conditions and help to guide future exploration efforts in the Basin. Palynostratigraphy of particular Depobelt wells, like UDUAK-1 well, is less known because previous research has mostly concentrated on Onshore or regional stratigraphic interpretations. Comprehensive paleostratigraphic and paleoenvironmental analyses of the sediments from the UDUAK-1 well could improve the region's biostratigraphy and offer comprehensive of understanding depositional environments.

Within the Uduak-1 Well interval, the combined lithostratigraphic and palynological data points to environmental shifts from continental (fluvial/swamp) to transitional (deltaic or estuarine) depositional systems. A primarily continental depositional setting is indicated by the sandy, quartz-rich, and occasionally granule-sized sediments, as well as the sparse marine indices (such as dinoflagellate cysts and microforaminiferal linings) and abundant freshwater palynomorphs (such as Botryococcus and Pediastrum). A slight transitional influence is seen toward the interval's base (roughly 2,600–3,510 feet). While the slow increase in shale content and rare marine palynomorphs indicates a shift toward more transitional settings, this interpretation is consistent with well-established Lithological and palynological models that link continental environments with high sand content, low gamma ray response, and freshwater palynomorph dominance (Edwards, 1996; Nichols, 2009; Traverse, 2007; Jansonius and McGregor, 1996).

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The deduction of different depositional environments along the examined interval (340–3,510 feet) of the Uduak-1 Well has been improved by the integration of lithostratigraphy, wireline log (gamma ray) characters, and palynological features.

2. Study Area

The Uduak-1 Well is located geographically between latitude 5 30N and longitude 5 45E it is an exploratory Well drilled in the Greater Ughelli Depo-belt, Northwestern part of the Niger Delta Basin. This location provides a unique opportunity to study the Benin Formation and understand the depositional and paleoclimatic evolution of this important geological region.

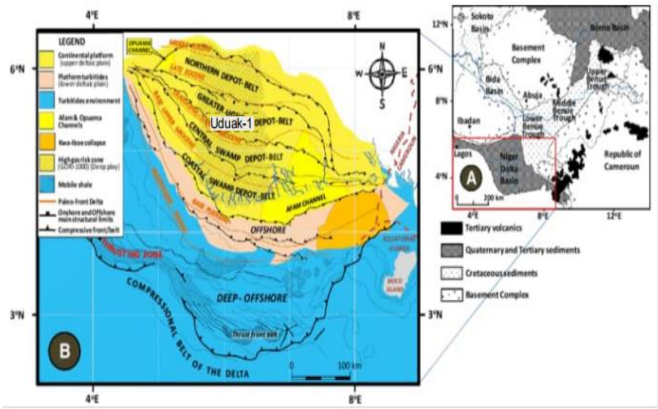

Figure 1: Geologic map of Nigeria showing the location of the Niger Delta Basin (a) (redrawn from Ebong et al. 2017) and sectional map of the Niger Delta depobelts and structural limits (b) (Redrawn from Doust and Omatsola, 1990)

3. Geology Setting Of Niger Delta Basin

The Niger Delta Basin's evolution and development were governed and affected by synsedimentary tectonics and Cretaceous tectonics in the Benue Valley (Evamy et al., 1978; Ejedawe, 1981; Knox and Omatsola 1987; Stacher 1995). The delta is located at the location of the Cretaceous triple junction on the Atlantic coast, on the African plate's trailing edge. The limits of the Niger Delta are defined by its geographic expanse, which is marked by latitudes 4° and 6° N and longitudes 3° and 9° E.

The current delta fill was formed by a north-south progradation that started as separate lobes but eventually merged due to regressive sedimentation influenced by climate and proximity to source (Reijers, 2011). Since the Eocene, the delta's regressive phase has expanded throughout the adjoining oceanic crust and the African continental margin, continuing into the Recent (Evamy et al., 1978). Rapid sedimentation has caused the delta to divide into five megastructural units: the Central Swamp, Coastal Swamp, Greater Ughelli, Northern Delta, and Offshore Depositional Belts. (Doust and Omatsola 1990; Tuttle et al., 1999; Saugy and Eyer, 2003; Reijers, 2011). These units show the locations of the delta's most active sedimentation across time.

The formation of the Niger Delta Basin is closely associated with the opening of the Gulf of Guinea during the Early Cretaceous, which is associated with the formation of the South Atlantic when the African and South American Plates separated. This tectonic event created a ridge ridge-ridge (R-R-R) triple junction (rifting) between the Early Albian (112 Ma) and the Late Albian (ca. 107 Ma) (Reyment, 1965; Short and Stauble, 1967; Burke et al., 1971; Murat, 1972; Lehner and De Ruiter, 1977; Wright, 1981; Saugy and Eyer, 2003). While the other two arms developed as active rifts into the Atlantic continental boundaries of Cameroon and Nigeria, the third arm of this junction—the Benue Trough—failed. Three depositional cycles have formed in the basins of southern Nigeria (Short and Stauble, 1967; Whiteman, 1982). The first cycle is pre-Albian and is defined by marine sequences deposited during an early maritime incursion that started during the Santonian orogenic disturbances and terminated during the northern characteristics of the Benue Trough. During the second cycle, which started with the Campanian, the proto-Niger Delta was formed north of Onitsha due to a transgression in the Paleocene (Whiteman, 1982).

According to a study, the Paleocene Transition ended in the Ypresian and started at the Cretaceous-Cenozoic transgression boundary in the Late Maastrichtian (Evamy et al., 1978; Evamy and others, 1978). The third cycle of sedimentation in southern Nigeria involves the continued southward progradation of the Cenozoic deltaic sediments during the Early Eocene. The progradation is characterized by sediment inflow from the extensive Niger-Benue River drainage systems, which originate in the Guinea Highlands and the Cameroon Mountains east of the Nigeria-Cameroon borders, via the Cretaceous Anambra Basin, and the insignificant Calabar drainage system, via the Afikpo Basin (Short and Stauble, 1967; Evamy et al., 1978; Whiteman, 1982).

The Tertiary Niger Delta's stratigraphy and geology have been described by (Short and Stauble, 1967). Three formations were identified. These are the Agbada, Benin, and Akata formations, in ascending sequence (Figure 4). Open marine and prodelta dark grey shale with siltstone and sandstone lenses make up the majority of the Akata Formation. There are turbidite and a few sand strata thought to be of continental slope channel fill (Weber and Daukoru, 1975).

A sudden shift in the depositional environment is indicated by a significant regional sequence boundary between the Akata and Agbada Formations (Morgan, 2003). The Agbada formation is the middle portion of the tripartite Niger delta stratigraphic sequence, as defined by (Short and Stauble, 1967). About 11 km to the northwest of Port Harcourt, the Agbada 2well was drilled, and it defines the Agbada formation (Short and Stauble, 1967). The Benin formation, which is thought to be the zone of maximum subsidence, is thickest where the Agbada Formation is heaviest, on the central swamp and coastal swamp depobelt. This sequence, which includes the majority of the hydrocarbon reservoirs, is linked to sedimentary growth faulting. The base of fresh water sand is frequently used to define the top of the Agbada Formation.

The Benin Formation, the Subject of the study , is made up of large, extremely porous sandstones that contain freshwater and a thin layer of shale that is thought to have originated from braided streams (Avbovbo, 1978; Short and Stauble, 1967). The structure can be recognized in the subsurface due to its high sand content (70–80%), the lack of brackish water and marine life, and the few shale cracks that become more frequent at the base. In general, the Benin Formation's sand and sandstone have coarse to fine particle sizes and are not well sorted. The basinward thinning of the formation ends close to the shelf edge.

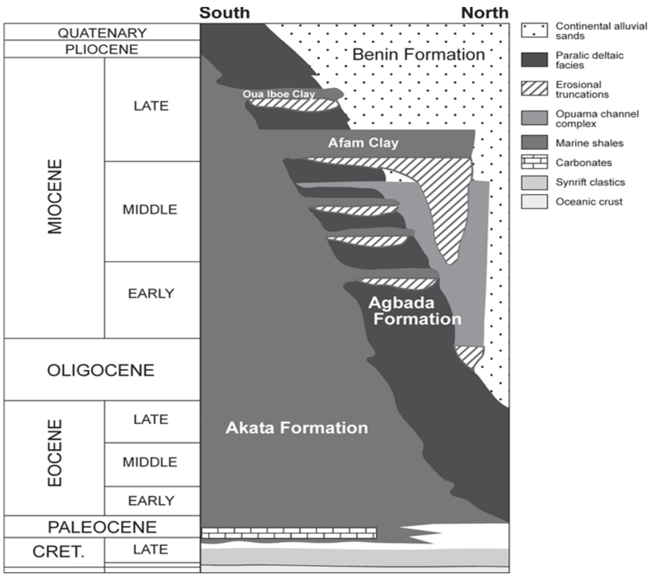

Figure 2: Stratigraphy of the formations of the Niger Delta Basin (Ige, 2010)

4. Materials And Methods

The study examined 43 ditch-cutting samples from Uduak-1 between 340 to 3,510 ft, collected at ~60-ft intervals for combined palynological and sedimentological analysis. Palynological processing followed standard laboratory protocols (maceration, carbonate removal, silicate dissolution, oxidation, humic removal and heavy-liquid separation) adapted from established methods (e.g., Faegri and Iversen, 1989). In brief, samples (~25 g aliquots) were decarbonated with HCl, silicates removed with HF (with repeated rinses to avoid gel formation), oxidized with HNO_3 as required, and humic material reduced with KOH. Organic residues were concentrated by heavy-liquid separation ($ZnBr_2$, SG ≈ 2.2), washed, sieved/sonified, and mounted on permanent slides using polyvinyl alcohol or equivalent mounting medium. Photomicrographs were taken for diagnostic taxa and, where possible, a minimum of ~200 palynomorphs were counted per sample. Taxonomic identification and zonation follow pantropical and regional schemes (e.g., Germeraad et al., 1968; Evamy et al., 1978).

Lithological work comprised standard lithologic descriptions (grain size, texture, sorting, sedimentary structures and accessory minerals) at the same sampling resolution; sand/shale ratios were computed from logs. Gamma-ray (GR) wireline data were correlated with lithologic descriptions and used to identify log motifs (blocky, bell/cylindrical) indicative of depositional architectures (channels, point bars, overbank) following established petrophysical interpretation practices (e.g., Asquith and Krygowski, 2004). Integrated interpretation combined palynological assemblages, lithology and GR signatures to produce biozonation, relative age assessments, and paleoenvironmental reconstructions. Standard laboratory safety and quality-control measures (PPE, fume-hood operations, control slides, duplicate counts, and photographic documentation) were applied throughout.

5. Result And Discussion

5.1 Presentation of Results

5.1.1 Lithostratigraphy

Within the Uduak-1 Well interval, the combined lithostratigraphic and palynological data points to environmental shifts from continental (fluvial/swamp) to transitional (deltaic or estuarine) depositional systems. A primarily continental depositional setting is indicated by the sandy, quartz-rich, and occasionally granule-sized sediments, as well as the sparse marine indices (such as dinoflagellate cysts and microforaminiferal linings) and abundant freshwater palynomorphs (such as Botryococcus and Pediastrum). A slight transitional influence is seen toward the interval's base (roughly 2,600–3,510 feet). While the slow increase in shale content and rare marine palynomorphs indicates a shift toward more transitional settings, this interpretation is consistent with well-established sedimentological and palynological models that link continental environments with high sand content, low gamma ray response, and freshwater palynomorph dominance (Edwards, 1996; Nichols, 2009; Traverse, 2007; Jansonius and McGregor, 1996).

Lithostratigraphy, wireline log (gamma ray) characters, and palynological features have been integrated to improve the deduction of different depositional environments over the Uduak-1 Well's examined interval (340–3,510 feet). Gamma-ray log responses, sand/shale ratios and paleobathymetric indicators show that the Uduak-1 interval (340–3,510 ft) is dominated by continental facies of the Benin Formation. Two principal lithofacies units are recognized:

340–2,600 ft — Continental unit

- Composed almost entirely of sands with sporadic thin shale beds.
- Sand:shale ≈ 98:2.
- Palynomorphs dominated by freshwater-swamp taxa.

2,600–3,510 ft — Continental / Transitional unit

- Predominantly sands with a minor shale component.
- Sand:shale ≈ 85:15.
- Freshwater-swamp palynomorphs predominate, with occasional marine indicators near the base.

Table 1: Show the lithofacies correlated with Benin formation (Based on this study)

Interval (feet)	Formation	Lithofacies Unit	Diagnostic Criteria
340 – 2,600	Benin	Continental	• Composed almost entirely of sands with sporadic thin beds of shale. • Sand/shale ratio of approximately 98:2. • Freshwater swamp pollens dominated the palynomorphs
2,600 – 3,510		Continental /Transitional	• Predominantly composed of sands with minor proportion of shales • Sand/shale ratio is approximately 85:15. • Freshwater swamp pollens dominated the palynomorphs.

5.1.1.1 Continental Unit (340-2,600 ft)

The uppermost stratigraphic unit of the Uduak-1 well (340–3,510 ft) is assigned to the Benin Formation and consists of ~98% sand and ~2% shale. Thick, milky-white, fine- to coarse-grained sand bodies with thin, widely spaced dark grey shales indicate a high-energy fluvial-dominated regime. Accessory ferruginous materials and carbonaceous detritus, more common in the lower part of the unit (1,420–2,600 ft), suggest strong fluvial input and periodic subaerial exposure. Palynological assemblages dominated by Retitricolporites irregularis, Pachydermites diederixi, and Botryococcus braunii indicate freshwater influence, while rare Zonocostites ramonae points to mangrove and wet climatic conditions. The presence of only spot occurrences of dinoflagellate cysts confirms minimal marine influence. Gamma-ray log motifs support interpretation of stacked distributary channel and point-bar sands interbedded with minor overbank or floodplain muds. Comparable integrated palynological–log analyses in Wells E001, NEP-1, and OSE-1, as well as OM-4 and OM-A wells, confirm a dominantly continental to transitional depositional setting for the Benin Formation in this part of the Niger Delta (Ayodeji, 2024; Ojo and Akande, 2013; Okezie and Akaegbobi, 2016; Taiwo et al., 2019).

5.1.1.2 Continental–Transitional Unit (2,600–3,510 ft).

The lower unit shows higher shale content (≈85:15 sand:shale) and similar sand textural ranges (fine to very coarse, commonly poorly sorted). Shales remain platy and moderately hard. Accessory ferruginous material and carbonaceous detritus are present but rare. Cylindrical and bell-shaped GR motifs, together with lithologic descriptions, support a depositional model dominated by distributary channels/point bars for sands and overbank/interdistributary bay or floodplain deposition for the interbedded shales. Palynological assemblages are still dominated by freshwater swamp taxa with only spot occurrences of marine dinoflagellate cysts near the base, indicating intermittent marine influence but overall terrestrial deposition. Similar work was conducted by (Ayodeji Fola-Dara, 2019). This well contains shales and friable sandstones that range in depth from around 3,010 to 6,030 feet. Zoocostites ramonae, Retitricolporites irregularis, Pachydermites diederixi, and Botryococcus are examples of plynomorph assemblages that closely resemble the organisms you mentioned.

5.1.2 Gamma-ray (GR) Log Data

GR logs are predominantly low throughout the interval, consistent with a sand-dominated sequence, with sporadic moderate peaks indicating thin clay/shale intercalations or paleosols (Avbovbo, 1978; Doust and Omatsola, 1990; Asquith and Krygowski, 2004). Correlating GR patterns with palynology yields three subzones with distinct signatures:

- Subzone P624 (~3,120–2,200 ft): Moderate to high GR variability with large sporadic peaks interpreted as shale or clay-rich intervals (see figure 3). Marine palynomorphs (e.g., Apectodinium crassum) occur here, indicating marginal-marine/lagoonal or delta-front conditions and possible correlation with upper Agbada-type facies at the base.
- Subzone P580 (~2,200–1,600 ft): Low to moderate GR with modest spikes (thin overbank/levee muds) and sharp decreases over thick sand intervals (see figure 3). This pattern signals progressive progradation from transitional deltaic to dominantly continental, channel-dominated deposition.
- Subzone P560 (~1,600–940 ft): Very low, blocky GR signatures indicative of massive sandstone bodies with minimal shale intercalations (see figure 3). Palynology here is strongly terrestrial, consistent with high-energy fluvial channels (braided/meandering) and delta-top/alluvial plain deposition.

5.1.3 Palynological Analysis

The assemblage is dominated by pollen and spores of terrestrial lowland taxa (e.g., Psilatricolporites crassus, Psilastephanocolporites spp., Cicatricosisporites dorogensis, Racemonocolpites hians, Peregrinipollis nigericus, Retitricolporites spp.).(see figure 3) Brackish-water taxa such as Acrostichum aureum and pteridophyte spores (e.g., Laevigatosporites spp., Verrucatosporites spp.) occur in appreciable amounts. Freshwater indicators (Botryococcus braunii) and sporadic dinoflagellate cysts and foraminiferal wall linings are present at low frequency.

Using established zonation schemes the section is divided into palynozones/subzones P624, P580 and P560 (Evamy et al., 1978; Germeraad et al., 1968). The identified marker taxa and their stratigraphic tops/bases indicate correlation with the Rupelian–Chattian (Early–Late Oligocene) interval. The palynostratigraphic framework provides reliable age control for the section and supports a tentative Benin/Agbada formational boundary near ~3,490 ft where marine influence diminishes upward.

Photomicrographs of diagnostic taxa are provided in figure 4 and 5; distribution is

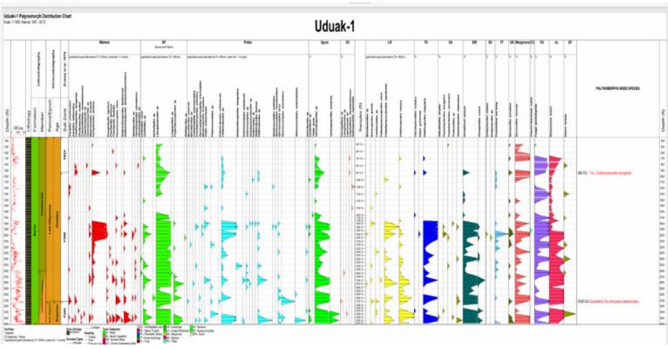

Figure 3: Palynomorph Distribution Chart of Uduak-1 Well Based on this Study

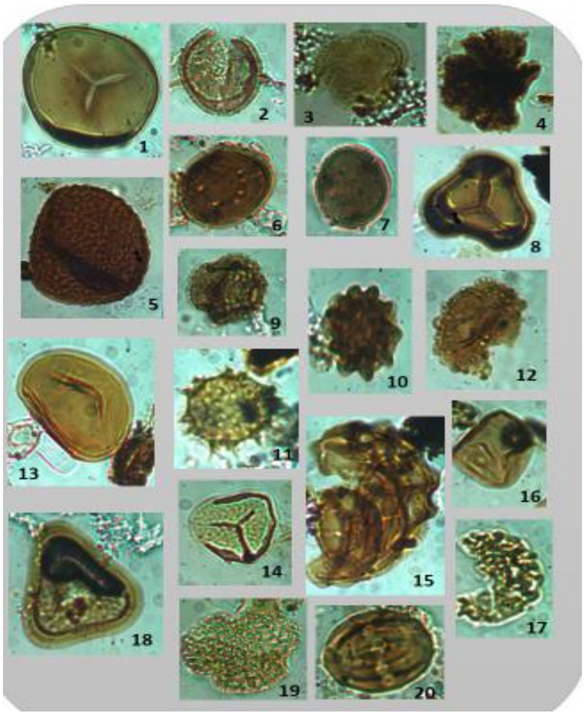

Figure 4: Photomicrograph of Some Of Makers Species Recovered From Uduak-1 Well Based on this study

(1) Acrostichum auresum (depth: 2760)
(2) Arecipites exilimuratus (depth: 3450)
(3) Bombacacidites sp (depth: 2820)
(4) Botryococcus braunii (depth: 940)
(5) Cicatricosisporites dorogensis (depth: 940)
(6) Cicatricosisporites mulleri (depth: 3330)
(7) Brevicolporites guinetii (depth: 1540)
(8) Cycadidites sp (depth: 2760)
(9) Canthium sp (depth: 1300
(10) Ctenolophonidites costatus (depth: 3270)
(11) Echitricolporites ecihinatus (depth: 3450
(12) Gemmastephanocolpites brevicolpites (depth: 3270)
(13) Lavigatosporites sp (depth: 2760)
(14) Lycopodium sp (depth: 1860)
(15) Magnastriatites howardii (depth: 2760)
(16) Monocolpites annulatus (depth: 3450)
(17) Peregrinipollis nigericus (depth: 940)
(18) Polypodiaceoisporites sp (depth: 2820)
(19) Magnocolpites faveolatus (depth: 1860)
(20) Psilatricolporites zapotecoae (depth: 1060

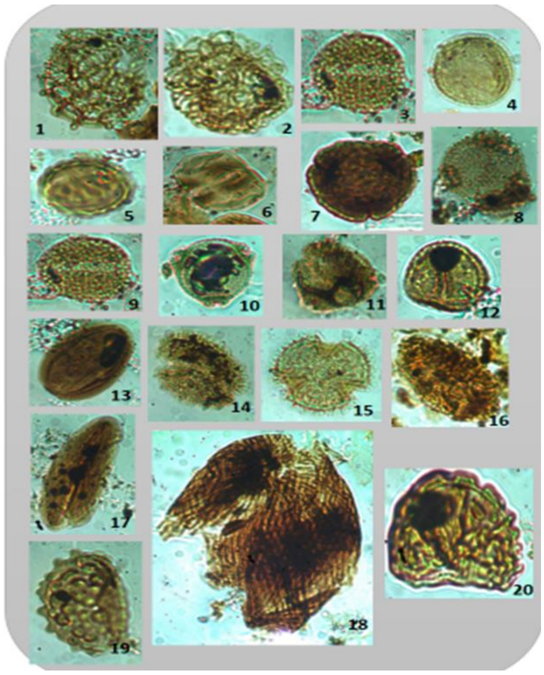

Figure 5: Photomicrograph of some of palynomorps recovered from Uduak-1 well Based on this study

(1) Praedopollis africanus (depth: 3450)
(2) Praedopollis flexibilis (depth:2760)
(3) Racemonocolpites hians (depth: 1720)
(4) Proxapertites cursus (depth: 2760)
(5) Psilastephanocolporites minor (depth: 2760)
(6) Psilatricolporites onitshaeanus (depth: 3060)
(7) Psilatricolporites crassus (depth: 2760)
(8) Retibrevitricolporites ibadanensis (depth: 1860)
(9) Racemonocolpites hians(depth:1720)
(10) Retitricolporites obodoensis (depth: 2760)
(11) Retibrevitricolporites triangulatus (depth:1800)
(12) Retitricolporites asabaensis (depth: 2760)
(13) Retistephanocolporites sp (depth: 2820)
(14) Retitricolporites turris (depth: 2000)
(15) Retitricolporites irregularis (depth: 1860)
(16) Retitricolporites tenuis (depth: 1800)
(17) Striamonocolpites neocostatus (depth: 3120)
(18) Triporopollenites gabonensis (depth: 1860)
(19) Verrucatosporites sp (depth: 2760)
(20) Verrucatosporites usmensis (depth: 3450

6. Discussion Of Results

6.1 Paleoenvironment

Integration of palynology, GR logs and lithology indicates a progressive shift from marginal-marine/deltaic settings at the base to fully continental fluvial systems upward:

- Lower part (P624): Mixed marine–continental signatures with higher silt/clay input and marine palynomorphs — interpreted as lagoonal/delta-front or upper Agbada-influenced facies.
- Middle part (P580): Transitional fluvio-deltaic regime with alternating channel and overbank deposits as marine influence wanes.
- Upper part (P560): Dominantly continental deposition , thick, stacked channel sands and minimal shales, characteristic of high-energy fluvial (braided/meandering) systems.

Lithological indicators (grain size distribution, sorting, channel-type GR motifs) and accessory minerals (carbonaceous detritus, ferruginous grains) point to fluvial dominance with episodes of subaerial exposure and local floodplain development. The high sand/shale ratios (>85%) and low GR values reinforce a largely non-marine, sand-rich succession.

Integration of palynological, gamma-ray log, and lithological data from the Uduak-1 borehole (340–3,510 ft) indicates a dominantly continental to transitional depositional setting within the Benin Formation. Comparable studies in the Niger Delta support this interpretation. Ayodeji (2024), for example, combined wireline log motifs with palynological assemblages in Well E001 to reconstruct a lower delta-plain to nearshore environment, using freshwater swamp pollen (Retitricolporites irregularis, Pachydermites diederixi) and sporadic Zonocostites ramonae as indicators of continental–paralic transitions. Similarly, a group researcher applied palynomorph data calibrated against gamma-ray facies in OM-4 and OM-A wells to identify stacked channel and point-bar sands interbedded with thin shales in a delta-plain context (Ehinola et al., 2012).

Parallel workflows in the NEP-1 and OSE-1 wells further demonstrate the value of integrating palynology with log-derived facies to differentiate between continental and transitional depositional environments (Ojo and Akande, 2013; Okezie and Akaegbobi, 2016). High sand/shale ratios, blocky to bell-shaped gamma-ray motifs, well-sorted coarse- to medium-grained sandstones, and abundant terrestrial palynomorphs (Zonocostites ramonae, Psilatricolporites crassus) with freshwater algae (Botryococcus) point to a humid tropical, non-marine fluvial system with dense riparian vegetation.

The absence of marine palynomorphs and foraminifera, along with ferruginized pollen grains, reinforces a fully terrestrial interpretation for most of the section. The recognized palynozones reflect a progradational shift:

- P624 – Braided to meandering fluvial channels, represented by clean, well-sorted sandstones from high-energy river systems.
- P580 – Meandering fluvial systems with periodic overbank and levee deposits, indicated by moderate gamma-ray peaks and interbedded shales.
- P560 – Distal fluvial to floodplain settings, marked by increased clay content and lower-energy depositional conditions.

6.2 Biostratigraphic zonation and Age determination

Palynological analysis of three palynozones (P560, P580, P624) that correlate with established regional schemes (Evamy et al., 1978; Germeraad et al., 1968). The succession (P560 at the base → P580 → P624 at the top) indicates an Early–Late Oligocene (Rupelian–Chattian) age for the studied interval, marking a transition from marginal-marine/delta-front conditions at depth to fully continental, high-energy fluvial deposition upward. Zone boundaries were defined using first/last occurrences and abundance tops of diagnostic taxa (e.g., quantitative top of Arecipites crassimuratus at ~3,120 ft) by recording first and last downhole occurrences (FDO/LDO) and abundance peaks of key palynomorph taxa. Preparations, counts (≥200 palynomorphs where possible) and taxonomic identifications follow standard workflows and nomenclature (Germeraad et al., 1968; Evamy et al., 1978). Biozones are correlated to the regional pantropical zonation using diagnostic and quantitatively significant taxa (Evamy et al., 1978).

Three palynological sub-zones were recognized in the Uduak-1 interval and correlated regionally Based on this study:

Table 2: Shows the Palynological Sub zone and Age Determination

Sub-zone	Depth interval (ft)	Correlated zone (Evamy et al., 1978	Age (this study)	Principal diagnostic / abundance taxa	Interpretation
P624	**340 – 940**	P600 / P624 (upper)	**(Late Oligocene)**	*Retitricolporites irregularis*, *Pachydermites diederixi*, *Zonocostites ramonae* (abundant); *Botryococcus* present	Continental, freshwater-swamp / mangrove influence; predominantly terrestrial deposition (uppermost section)
P580	**940 – 3,120**	P500 / P580 (middle)	**(Late Oligocene)**	*Striamonocolpites rectostriatus* (quantitative), *Peregrinipollis nigericus*, *Monoporites annulatus*, *Zonocostites ramonae*; minor foraminiferal traces	Transitional fluvio-deltaic — progressive progradation, alternating channel and overbank deposits
P560	**3,120 – 3,510**	P500 / P560 (lower)	**(Early Oligocene)**	*Arecipites crassimuratus* (quantitative top), *Proxapertites cursus*, terrestrial palynomorphs dominant; sporadic dinoflagellates/foraminifera	Marginal-marine to delta-front influence at base, grading into continental sediments upward

6.3 Paleoecology and Paleoclimate

6.3.1 Paleoecology

The Uduak-1 Well's paleontological records show a dynamic coastal plain ecology from the Miocene that was influenced by freshwater, rivers, and tides. Zonocostites ramonae's dominance is indicative of the large mangrove vegetation found in tidal-influenced river systems close to deltaic distributaries. Retitricolporites species indicate dense tropical lowland rainforest and riparian vegetation, whereas Psilatricolporites crassus and Monocolpites marginatus indicate freshwater marsh and floodplain environments.

Magnastriatites howardii denotes transitional open forest–savanna zones, while fern spores (Laevigatosporites, Deltoidospora) are associated with damp forest understories and disturbed floodplain settings. When taken as a whole, these assemblages show a humid tropical deltaic–fluvial ecosystem that includes vegetated floodplains, backswamps, and tidal swamps. The localized changes in depositional settings shown by subzonal variations between P560 and P624 are probably caused by variations in floodplain growth, channel migration, and fluvial energy. Across the Niger Delta, similar Miocene palynological patterns have been documented, consistently associating the decline of Z. ramonae with more continental swamp environments and its abundance with mangrove-dominated coastal settings (Oboh et al., 1992; Obiosio and Nwaejije, 2023; Alege and Joseph, 2024; Femi and Ojo, 2014).

6.3.2 Paleoecological Descriptions

Palynological data suggests a humid tropical deltaic-fluvial environment characterized by freshwater swamp and mangrove flora, notably Zonocostites ramonae (Oboh et al., 1992; Obiosio & Nwaejije, 2023; Alege and Joseph, 2024; Femi and Ojo, 2014). In a heavily vegetated floodplain, the assemblages depict backswamps, tidal swamps, and winding river channels. Localized changes in depositional settings caused by floodplain extension, channel migration, and changes in fluvial energy are suggested by variations between subzones P560 and P624 (Obiosio and Nwaejije, 2023; Alege and Joseph, 2024).

Table 3: Palynomorph Assemblages and Ecological Interpretation

Palynomorph	Ecological Indicator	Interpretation
Zonocostites ramonae	Mangrove vegetation	Suggests tidal-influenced fluvial systems near coastlines or deltaic distributaries.

Table 3 (Conts): Palynomorph Assemblages and Ecological Interpretation		
Palynomorph	**Ecological Indicator**	**Interpretation**
Retitricolporites spp.	Rainforest and riparian zones	Indicates dense tropical lowland rainforest vegetation.
Psilatricolporites crassus, *Monocolpites marginatu*	Freshwater swamp and riparian plants	Points to fluvial floodplains and freshwater influence.
Fern spores (*Laevigatosporites*, *Deltoidospora*)	Moist forest understory and disturbed areas	Common in floodplains and humid forest floors.
Magnastriatites howardii	Open forest to woodland vegetation	Reflects transitional zones between forest and savanna.

6.3.3 Paleoclimate

Palynological data from the Uduak-1 Well show a warm, humid tropical environment during the Miocene, with dense evergreen rainforests supported by high precipitation (diverse Retibrevitricolporites), mangrove-dominated systems (abundant Zonocostites ramonae), and persistently moist soils (abundant Laevigatosporites spores). The lack of arid or semi-arid stages during deposition is suggested by the deficiency of xerophytic pollen. These results are consistent with palynofacies from AP-4 and UK-2 wells and GBO-04 data, which together suggest that the Niger Delta was characterized by consistently wet, rainforest-dominated Miocene coastal plain conditions (Salard-Cheboldaeff, 1990; Akpunonu et al., 2014; Olayiwola and Bamford, 2020).

6.3.4 Paleoclimatic Description

In the Uduak-1 well, the Benin Formation was formed during a warm, humid tropical climate that was similar to the Miocene climatic optimum. Mangroves (Zonocostites ramonae) and evergreen rainforest pollen (Retibrevitricolporites) are abundant indicators of persistent tropical and wet conditions, but mangrove and inland forest species occasionally oscillate, most likely due to small climatic fluctuations or local sea-level changes. Floodplain and riverine sedimentary facies predominate, suggesting high rainfall regimes that may have supported vast swamp forests through seasonal flooding (Evamy et al., 1978; Germeraad et al., 1968).

Similar results from other Niger Delta cores closely match these paleoclimate inferences: some researcher recorded alternating dominance of swamp freshwater and mangroves in warm, humid conditions; interpretations of the GBO-04 well support the existence of humid tropical climates with mangrove ecosystems; and Emi-5 well data support coastal-deltaic humid tropical environment (Ojo and Femi, 2014; Ogbahon et al., 2019; Ekom et al., 2024).

Table 4: Palynomorph Assemblages and Ecological Interpretation		
Palynomorph	**Ecological Indicator**	**Interpretation**
Zonocostites ramonae	Mangrove vegetation	Suggests tidal-influenced fluvial systems near coastlines or deltaic distributaries.
Retitricolporites spp.	Rainforest and riparian zones	Indicates dense tropical lowland rainforest vegetation.
Psilatricolporites crassus, *Monocolpites marginatu*	Freshwater swamp and riparian plants	Points to fluvial floodplains and freshwater influence.
Fern spores (*Laevigatosporites*, *Deltoidospora*)	Moist forest understory and disturbed areas	Common in floodplains and humid forest floors.
Magnastriatites howardii	Open forest to woodland vegetation	Reflects transitional zones between forest and savanna.

7. Conclusion

Integration of lithological descriptions, gamma-ray log motifs, and palynological data from the Uduak-1 well (340–3,510 ft) provides a comprehensive interpretation of the studied interval. Lithostratigraphic evidence indicates two main lithofacies packages: a dominantly sand-rich continental unit and a continental–transitional unit with minor shale interbeds. Coarse- to medium-grained sandstones, very high sand/shale ratios, and blocky to bell-shaped gamma-ray responses confirm deposition in high-energy fluvial systems with sporadic overbank or floodplain deposits.

Palynological assemblages are dominated by terrestrial pollen and spores (Retitricolporites irregularis, Pachydermites diederixi, Zonocostites ramonae, Botryococcus), with only rare marine indicators at the base, supporting a progradational shift from marginal-marine/delta-front to fully continental conditions. Biostratigraphic correlation with established pantropical zonations constrains the section to the Early–Late Oligocene (Rupelian–Chattian) and places the tentative Benin/Agbada boundary near ~3,490 ft.

Overall, the results refine the local palynostratigraphic framework, improve lithofacies correlation, and enhance understanding of late Oligocene depositional systems in the Greater Ughelli depo-belt. These findings have direct implications for biostratigraphic and paleoenvironmental reconstruction within the Niger Delta Basin.

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Conflict Of Interest

The authors declare that there is no conflict of interest regarding the conduct of this research, the interpretation of its results, or the preparation and publication of this manuscript.

Authors Contribution

All three authors jointly conceived and designed the study. They collaboratively conducted data acquisition, processing, and analysis, as well as interpretation of the results. The authors also contributed equally to the drafting, critical revision, and final approval of the manuscript, ensuring that the work meets the highest academic and ethical standards.

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