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PALYNOSTRATIGRAPHY, PALEOCLIMATE AND SEQUENCE STRATIGRAPHIC ANALYSIS OF EMI-4 WELL, NIGER DELTA, NIGERIA

CHUKWUMA-ORJI, J. N., EKOM, J. C. AND ABE D. O.
Email: jacinta@futminna.edu.ng, abedaniel64@gmail.com, josephekom@gmail.com,

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ABSTRACT

Palynostratigraphic, Paleoclimatic and Sequence Stratigraphic analyses were conducted in a section of Emi-4 well, Offshore Niger Delta to establish palynozones, relative age, paleodepositional setting and reconstruct paleoclimatic changes overtime within the section of the well. The intercalation of the sandy and shaly intervals of the section evidenced from lithologic, textural, and wire line log data suggested that the entire studied interval belong to the Agbada Formation. Thirty-six (36) ditch cuttings within 6,158 ft - 10,452 ft were subjected to standard palynological analysis involving sample maceration with 10% HCl and 40% HF acids to remove carbonates and siliceous components, neutralization with distilled water and sieving through 5-micron sieve, followed by separation of palynomorphs from residue and mounting on glass slides for microscopic analysis. Recovered palynomorphs are marked by dominance of pollen and spores over dinoflagellate cysts. The occurrences of age diagnostic palynomorphs such as *Echiperiporites estelae, Belskipollis elegans, Verrutricolporites rotundiporus, Retribrevitricolpites protrudens, Pachydermites diederixi, Peregrinipollis nigericus, Cassoretitriletes vanraadshooveni, Magnastriatites howardii, Retistephanocolpites gracilis, Racemonocolpites hians, Praedapollis flexibilis, Elaeis guineensis, and Zonocostites ramonae* at some intervals of the studied wells suggest early Miocene to late Miocene age. Three distinct interval palynostratigraphic zones were delineated using the international stratigraphic guide for the establishments of biozones, they are *Racemonocolpites hians* - *Cyperaceaepollis* sp. Zone (early Miocene); *Gemmemonoporites* sp. - *Magnastriatites howardi* Zone (middle Miocene) and *Pachydemites diederixi* - *Retibrevitricolporites protrudens* Zone (late Miocene). The sequence stratigraphic study identified Maximum Flooding Surfaces (MFS) within the well intervals along with the identification of Highstand Systems Tract (HST) and Transgressive Systems Tract (TST). Paleoclimatic interpretations based on palynological evidence suggest the presence of wet climatic conditions throughout the studied intervals, characterized by abundant mangrove, freshwater, and rainforest taxa.

KEYWORDS: Niger Delta, Palynomorphs, Palynostratigraphic Zones, Paleoclimate, Miocene, Sequence Stratigraphy.

INTRODUCTION

The quest for hydrocarbon resources remains a fundamental driving force in the Nigeria energy sector. In the pursuit of these valuable fossil fuels, the exploration of sedimentary basins and the understanding of their geological characteristics are essential endeavors. One of such exploration procedures encompasses the study of palynofacies, palynostratigraphy, paleoclimate and sequence stratigraphy within sections of hydrocarbon exploratory wells, - a multidisciplinary approach rooted in the fields of palynology and petroleum geology.

Palynology refers to the organic materials extracted from rock or unconsolidated sediment using standard palynological processing methods, which involve treating samples with hydrochloric acid (HCl) or hydrofluoric acid (HF) (Batten and Stead, 2005). The term can also be defined as the complete acid-resistant particulate organic matter retrieved from sediments through palynological processing techniques (Allen, 1965). The study of microfossils (pollen and spores) preserved in sedimentary rocks, provides a valuable tool for dating and correlating

Chukwuma-Orji, J. N., Department of Geology, Federal University of Technology, Minna, Nigeria
Ekom, J. C., Department of Geology, Federal University of Technology, Minna, Nigeria
Abe D. O., Department of Geology, Federal University of Technology, Minna, Nigeria

stratigraphic sequences (Oyede, 1992). When integrated with sequence stratigraphy, it allows for a comprehensive analysis of basin evolution and depositional patterns. Palynostratigraphic data can also be used to establish biozones and reconstruct paleoclimatic conditions during the deposition of reservoir units (Akata and Harry, 2019).

The objective of this study is to carry out palynological analysis on the strata intersected by the Emi-4 well, located offshore in the Niger Delta. The goal is to establish palynostratigraphic zonation according to international stratigraphic standards, while also determining the paleoclimate of the strata for petroleum exploration purposes. Following standard stratigraphic guidelines ensures a consistent framework that facilitates the global correlation of geological events.

The most significant contribution to the understanding of Niger Delta palynology was made by Germeraad *et al.* (1968). Their research focused on palynomorph assemblages from Tertiary sediments across three tropical regions: parts of South America, Asia, and Africa (specifically Nigeria). They identified nine pantropical zones using a quantitative method based on the first and last appearances of key diagnostic species such as *Echitricolporites spinosus*, *Crassoretitriletes vanradshoveni, Magnastrites howardi, Verrucatosporites usmensis, Monoporites annulatus, and Proxapertites operculatus.*

Ajaegwu *et al*. (2012) explored the palynostratigraphy and paleoenvironment of the Late Miocene to Early Pliocene period from the Ane-1 well in the Eastern Niger Delta, Nigeria. Using the alphanumeric method developed by Evamy *et al*. (1978) and Morley (1997), they identified eight palynological zones, dating them to the Late Miocene to Early Pliocene. Ojo and Adebayo (2012) conducted a palynostratigraphic and paleoecological study of the Chev-1 well in the southwestern Niger Delta Basin. They identified nine palynozones and concluded that the sediments were deposited during the Miocene-Pliocene era, a time marked by high sea levels and wet-humid climate, as indicated by the dominance of mangrove swamp floras among the recovered palynomorphs.

Evamy *et al*. (1978) identified twenty-nine informal palynological zones in the Niger Delta using an alphanumeric coding system, which provided foundational data for Shell Petroleum Development Company's internal zonal scheme. Palynological analysis of sediments from the North Chioma-3 Well in the Niger Delta, along with paleoenvironmental interpretations, was conducted by Ige *et al*. (2011). Their study identified four pollen zones (I-IV) using the pollen diagram method. Additionally, they determined the presence of both wet and warm climates by analyzing the percentage occurrence of mangrove forest taxa.

GEOLOGICAL SETTINGS

The studied well (Emi-4) is within the Emi field which is located in the offshore depobelts, Niger Delta Basin, Southeastern Nigeria (Figure 1). The Niger Delta Basin is situated on the continental margin of the Gulf of Guinea in equatorial West Africa, positioned between latitudes 4° and 7° N and longitudes 3° and 9° E (Whiteman, 1982). It is bordered to the west by the Benin Flank, to the east by the Calabar flank, and to the south by the Gulf of Guinea (Figure 2). Its northern boundary intersects several older Cretaceous tectonic structures, including the Anambra Basin, Abakaliki Anticlinorium, and the Afikpo Syncline (Ejedavwe, 1981; Bustin, 1988). The stratigraphic succession of the delta consists of an overall coarsening-upward sequence that exceeds 12 km in thickness and covers an area of 75,000 km² in the Gulf of Guinea (Ejedavwe, 1981).

The basin is a clastic wedge that formed along a failed arm of a triple junction system during the separation of the South American and African plates in the late Jurassic period. The other two arms of the triple junction evolved into passive margins along the southwestern coast of Nigeria and the southeastern coast of Cameroon, respectively (Whiteman, 1982). The Delta began to form in the Paleocene epoch. Since the Eocene, it has progressed southwestward, creating depobelts, with each depobelt representing the most active area of the delta at each stage of its development (Doust and Omatsola, 1990; Ojo and Adebayo, 2012). The sedimentary sequence of the basin consists, in ascending order, of three diachronous formations: Akata, Agbada, and Benin formations (Figure 3).

The Akata Formation is characterized by dark grey shale and silty deposits, with occasional sand streaks likely resulting from turbidite flows (Doust and Omatsola, 1990). This formation is found offshore along the continental slope and is notable for its rich foraminiferal fauna, which indicates its potential as a source rock for hydrocarbons (Doust and Omatsola, 1990). Above the Akata Formation lies the Agbada Formation, which serves as the primary reservoir rock in the basin. It consists of alternating layers of sandstone and shale that originate from delta-front environments, distributary channels, and deltaic plains (Weber, 1971). The interbedded nature of the sandstones and shales in the Agbada Formation enhances its capacity to trap hydrocarbons, making it a critical component for petroleum exploration. At the top of the Agbada Formation is the Benin Formation, which is predominantly composed of massive, highly porous sandstones that are rich in freshwater. These sandstones are interspersed with thin layers of shale and are believed to have formed from braided stream systems (Short and Stauble, 1967). The Benin Formation's porosity and permeability make it an important reservoir for groundwater as well, and its geological characteristics play a significant role in the hydrology of the region.

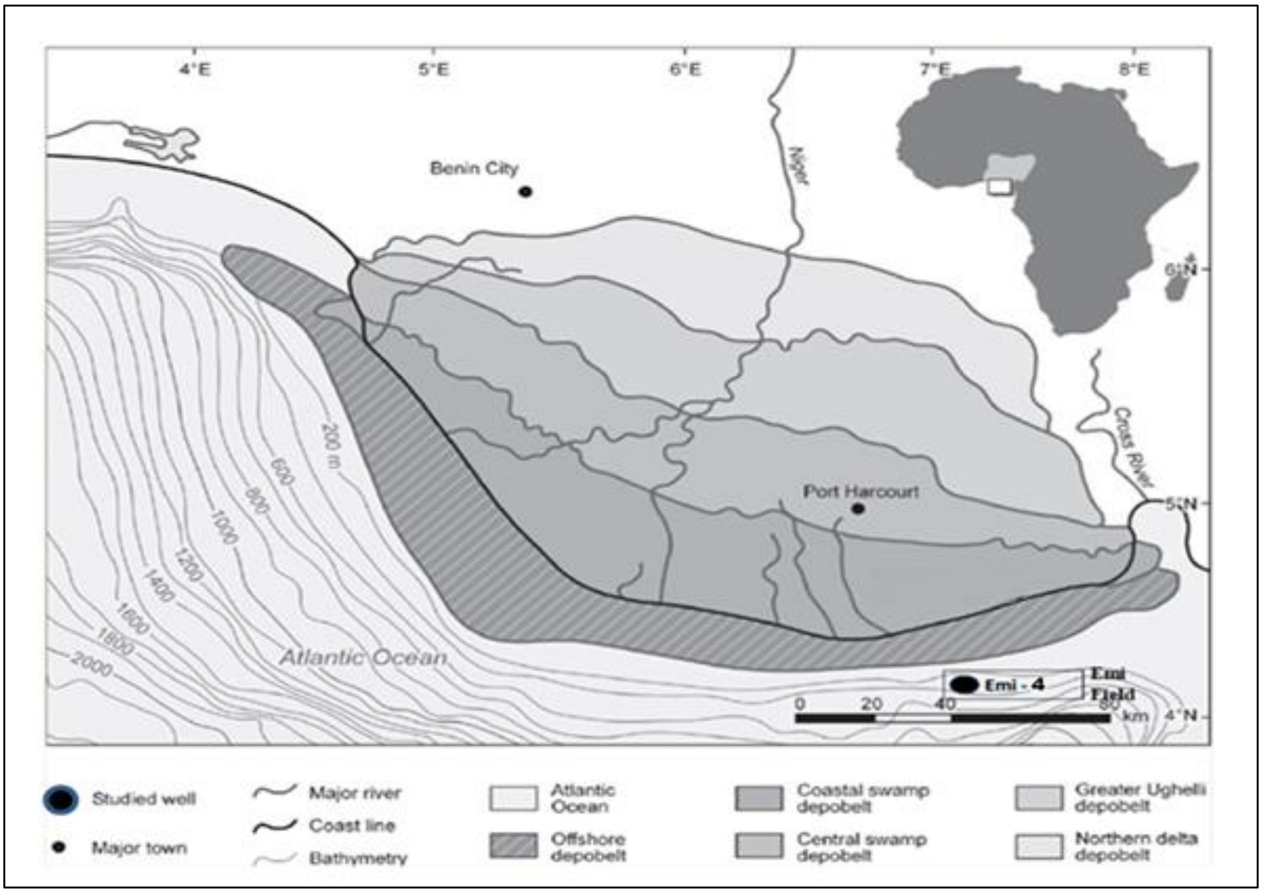

Figure 1: Depobelt map of the Niger Delta and location of the studied well "Emi-4" (modified after Okosun and Chukwuma-Orji, 2016).

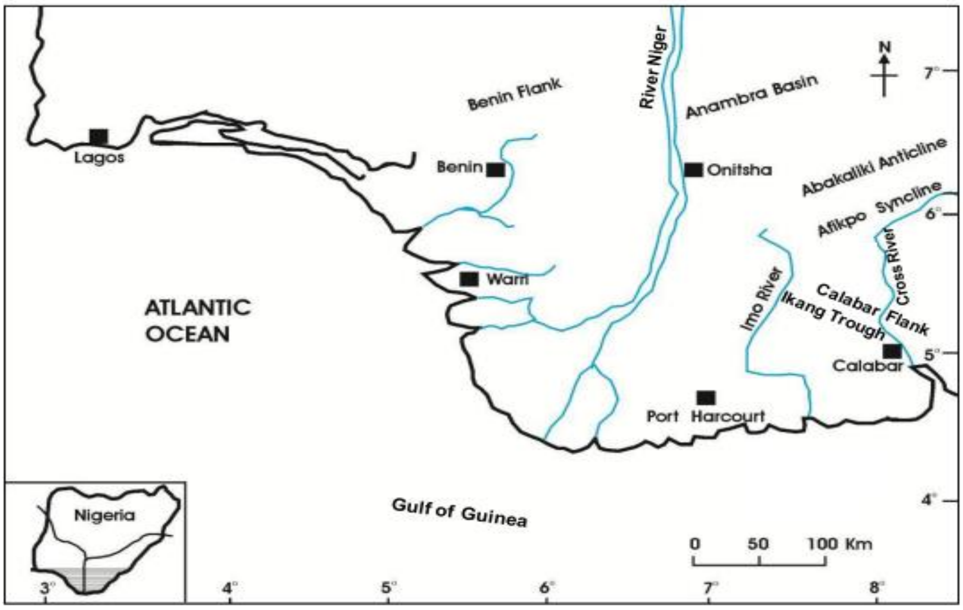

Figure 2: Tectonic elements and other basins bordering the Niger Delta Basin (Modified after Aturamu and Ojo, 2015)

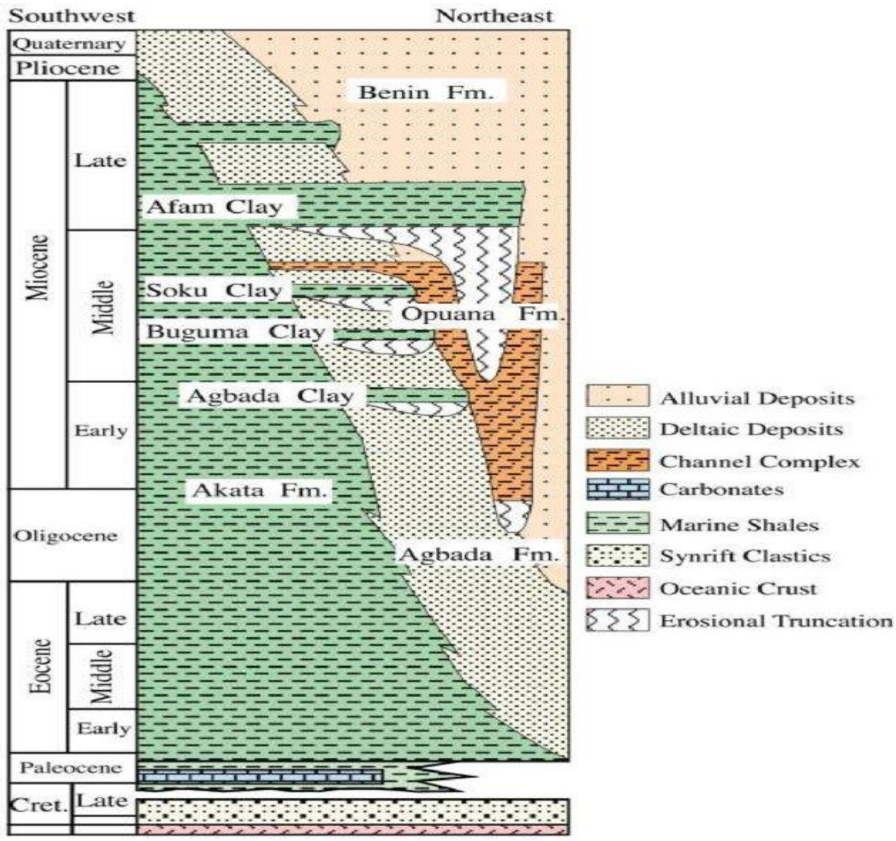

Figure 3: Stratigraphic column showing the three formations of the Niger Delta (Lawrence *et al.,* 2002).

MATERIALS AND METHODS

Ditch cuttings and wireline logs from the Emi-4 well were supplied by ExxonMobil Producing Nigeria Unlimited. The preparation and analysis of the samples were conducted at Mosunmolu Laboratory Nigeria Limited in Lagos, following the standard acid palynological preparation method.

A total of thirty-six (36) ditch cutting samples from the Emi-4 well were analyzed. Each sample, weighing ten grams, was treated with 10% HCl in a fume cupboard to ensure the complete removal of carbonates. Afterward, the samples were neutralized with distilled water before proceeding to the next step. Then, 40% HF was added to the samples, which were shaken until the silicates dissolved completely and the particles settled. The HF solution was then carefully decanted, followed by another round of neutralization with distilled water. Distilled water was added and decanted three times at intervals of 60 minutes to eliminate fluoro-silicate compounds that typically form during the reaction with HF.

Sieving and separation were conducted using a Branson Sonifier 250. The residues were then transferred into a centrifugal tube and centrifuged at a speed of 2,500 revolutions per minute for five minutes. The sieved residue underwent controlled oxidation using concentrated nitric acid (HNO_3), with the level of oxidation for each sample carefully monitored under a microscope. The same sample preparation procedure for recovering palynomorphs was applied to the palynomacerals; however, the oxidation step with HNO_3 was omitted to prevent bleaching the palynological debris. The recovered organic materials were evenly distributed on arranged cover slips measuring 22 x 32 mm and were allowed to dry before mounting. The mounting medium used for permanently affixing the cover slip to the glass slide was Loctite (Impruv), which minimizes the risk of loosening and leaks in the slide. The slides were dried under natural sunlight for five minutes.

Both palynology and palynofacies slides were examined using an Olympus binocular light transmitted microscope. The morphological descriptions of the palynomorphs focused on features observed at 600μm, with photographs taken using the CIX 41 Olympus binocular transmitted light microscope. The mounting medium used for permanently affixing the cover slip to the glass slide was Loctite (Impruv), which minimizes the risk of loosening and leaks in the slide. The slides were dried under natural sunlight for five minutes.

The identification of palynomorphs was carried out using palynological albums and the published studies of prior researchers (Germeraad *et al*., 1968; Ajaegwu *et al*., 2012; Bankole, 2010; Durugbo and Aroyewun, 2012; Ige, 2009; Ige *et al*., 2011).

Wireline log data from the target interval in Emi-4 well were also analyzed to ensure comprehensive coverage of the stratigraphic layers of interest.

RESULTS AND DISCUSSION

Palynostratigraphic Zonations and Biochronology of Emi-4 Well

Palynostratigraphic zonation allows for the subdivision of strata into biozones, which are small-scale stratigraphic units defined by the stratigraphic ranges of palynomorph species, independent of the lithology of the fossil-bearing beds. In this study, the recognized palynostratigraphic zones were established based on the International Stratigraphic Guide, an abridged version of Murphy and Salvador (1999), and the North American Stratigraphic Code (Boggs, 2006).

Age-diagnostic marker species were employed to ascertain the age of the intervals under investigation. The occurrences of age diagnostic palynomorphs such as *Echiperiporites estelae, Belskipollis elegans, Verrutricolporites rotundiporus, Retribrevitricolpites protrudens, Pachydermites diederixi, Peregrinipollis nigericus, Cassoretitriletes vanraadshooveni, Magnastriatites howardii, Retistephanocolpites gracilis, Racemonocolpites hians, Praedapollis flexibilis, Elaeis guineensis,* and *Zonocostites ramonae* at some intervals of the studied well suggest early Miocene to late Miocene age. (Figure 4)

The palynostratigraphic zones proposed in Emi-4 well are *Racemonocolpites hians - Cyperaceaepollis sp.* Zone; *Gemmemonoporites sp. - Magnastriatites howardi* Zone and *Pachydemites diederixi - Retibrevitricolporites protrudens* Zone.

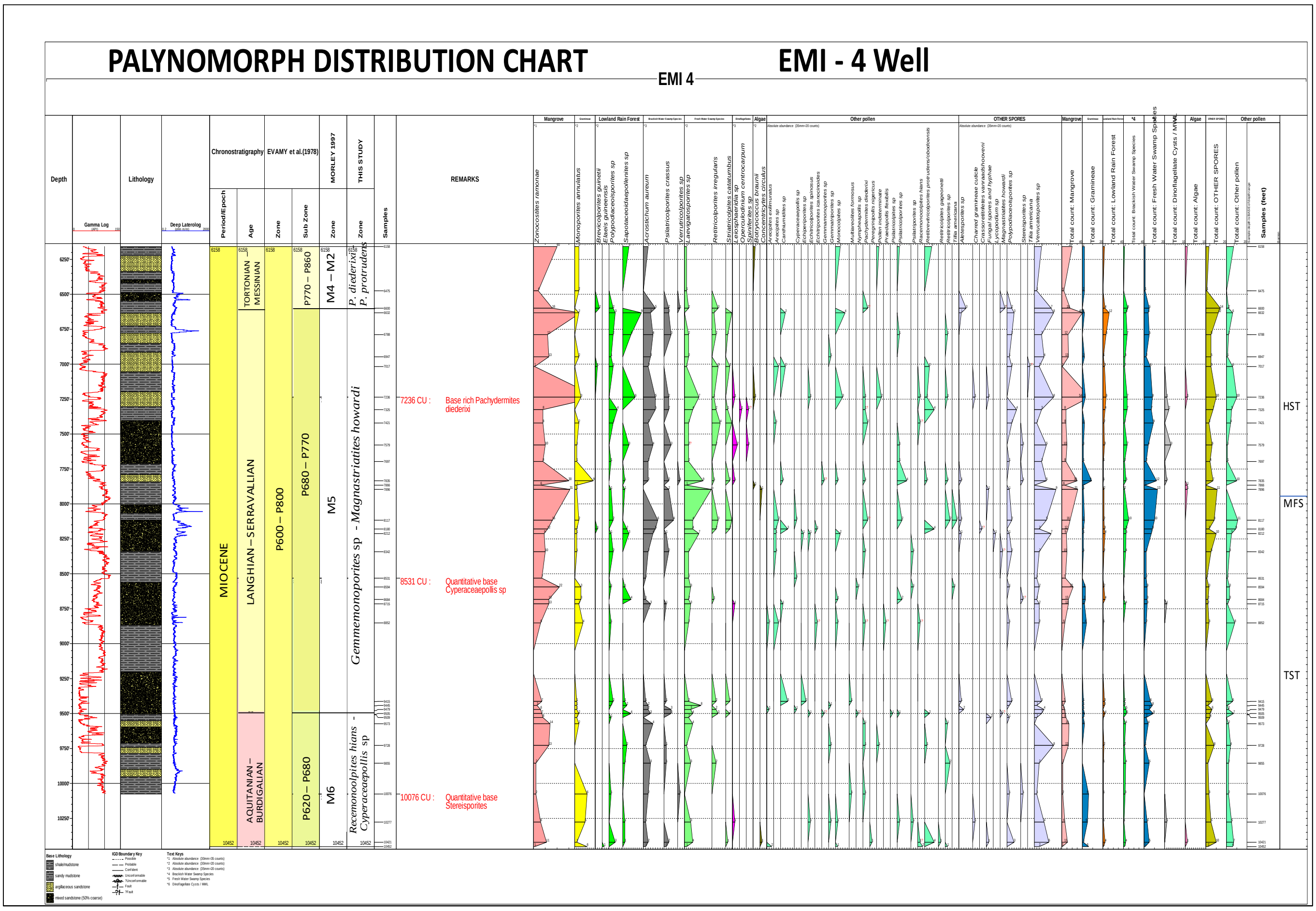

Figure 4: Palynomorph distribution chart of Emi-4 well.

***Racemonocolpites hians - Cyperaceaepollis* sp. Zone (Interval Zone)**

Stratigraphic Interval: 10452 ft – 9505 ft

Definition: The base of the zone is defined by the Last Downhole Occurrence (LDO) of *Racemonocolpites hians* at 10452 ft, while the top is marked by the Last Downhole Occurrence (LDO) of *Cyperaceaepollis* sp**.** at 9505 ft.

Characteristics: The assemblages of palynomorphs taxa that characterize this zone include *Polypodiaceoisporites* sp., *Elaeis guineensis*, *Sapotaceoidespollenites* sp., *Acrostichum aureum, Zonocostites ramonae, Laevigatosporites* sp., *Verrucatosprites* sp*., Retibrevitricolporites protrudens. Praedapollis flexibillis.* Other taxa occurring within the zone are *Leiosphaeridia* sp., *Sapotaceae, Psilatricoloporites crasssus, Peregrinipollis nigericus, Multiareolites formosus, Pteris* sp*.,* and *Psilatricoloporites* sp.

Age: The zone is dated early Miocene (Aquitanian – Burdigalian stage) because of the presence of *Cyperaceaepollis* sp. at the upper boundary of the zone which is a strong indication that the interval occurred within early Miocene.

Remark: The zone is equivalent to P620 – P680 subzone of Evamy *et al*. (1978).

***Gemmemonoporites sp - Magnastriatites howardi* Zone (Concurrent Range Zone)**

Stratigraphic Interval: 9505 ft – 6600 ft

Definition: The base of the zone is defined by the Last Downhole Occurrence (LDO) of *Gemmemonoporites sp* at 9505 ft, while the top is marked by the First Downhole Occurrence (FDO) of *Magnastriatites howardi* at 6600 ft.

Characteristics: The assemblages of palynomorphs taxa that characterize this zone include *Elaeis guineensis*, *Acrostichum aureum, Zonocostites ramonae, Laevigatosporites* sp., *Verrucatosprites* sp*., Retibrevitricolporites protrudens* and *Praedapollis flexibillis*. Other taxa occurring within the zone are *Sapotaceae, Psilatricoloporites crasssus, Peregrinipollis nigericus, Aletisporites* sp*., Pteris* sp*.,* and *Magnastriatites howardi*.

The zone has the most recovery of dinocyst: *Leiosphaeridia* sp., *Operculodinium centrocarpum* and *Spiniferites* sp. Algae taxa occurring also include *Botryococcus braunii* and *Concentricytes circulus.*

Age: The zone is dated middle Miocene (Langhian – Serravallian) because of the presence of middle Miocene markers such as *Crassoretitriletes vanraadshoveni, Magnastriatites howardi and Cyperaceaepollis* sp.

Remark: The zone is equivalent to P680 – P770 subzone of Evamy *et al*. (1978).

***Pachydemites diederixi - Retibrevitricolporites protrudens* Zone (Interval zone)**
Stratigraphic Interval: 6600 ft – 6158 ft
Definition: The base of the zone is defined by the First Downhole Occurrence (LDO) of Pachydemites diederixi at 6600 ft, while the top is marked by the First Downhole Occurrence (FDO) of Retibrevitricolporites protrudens at 6158 ft.
Characteristics: The assemblages of palynomorphs taxa that characterize this zone include *Elaeis guineensis, Acrostichum aureum, Zonocostites ramonae, Laevigatosporites* sp., *Verrucatosprites* sp*., Retibrevitricolporites protrudens* and *Praedapollis flexibillis.* Other taxa occurring within the zone are *Botryococcus braunii, Psilatricolporites* sp*.,* and *Monoporites* sp*.*
Age: The zone is dated late Miocene (Tortonian – Messinian) because of the presence of late Miocene markers: *Retibrevitricolporites protrudens, Echitricolporites spinosus, Verrucatosprites sp.* and *Peregrinipollis nigericus.*
Remark: The zone is equivalent to P770 – P860 subzone of Evamy *et al*. (1978).

Paleoclimate

The intervals 10452 ft – 6158 ft were delineated to have been deposited under wet climatic conditions (Figure 5). These intervals showed good representation of mangrove taxa (*Zonocostites ramonae*, *Psilatricolporites crassus* and *Acrostichum aureum)*, freshwater taxa (*Striatricolporites catatumbus*, *Levigatosporites* sp., *Botryococcus braunii*, *Verrucatosporites* sp. and *Gemmamonoporites* sp.) and rainforest taxa such as *Pachydermites diederixi* and *Sapotacea*. This is also supported by minimal occurrences of montane and savannah taxa within the intervals such as *Monoporites annulatus*, *Coryius* sp., *Pteris* sp. and *Cyperaceapollis* sp.

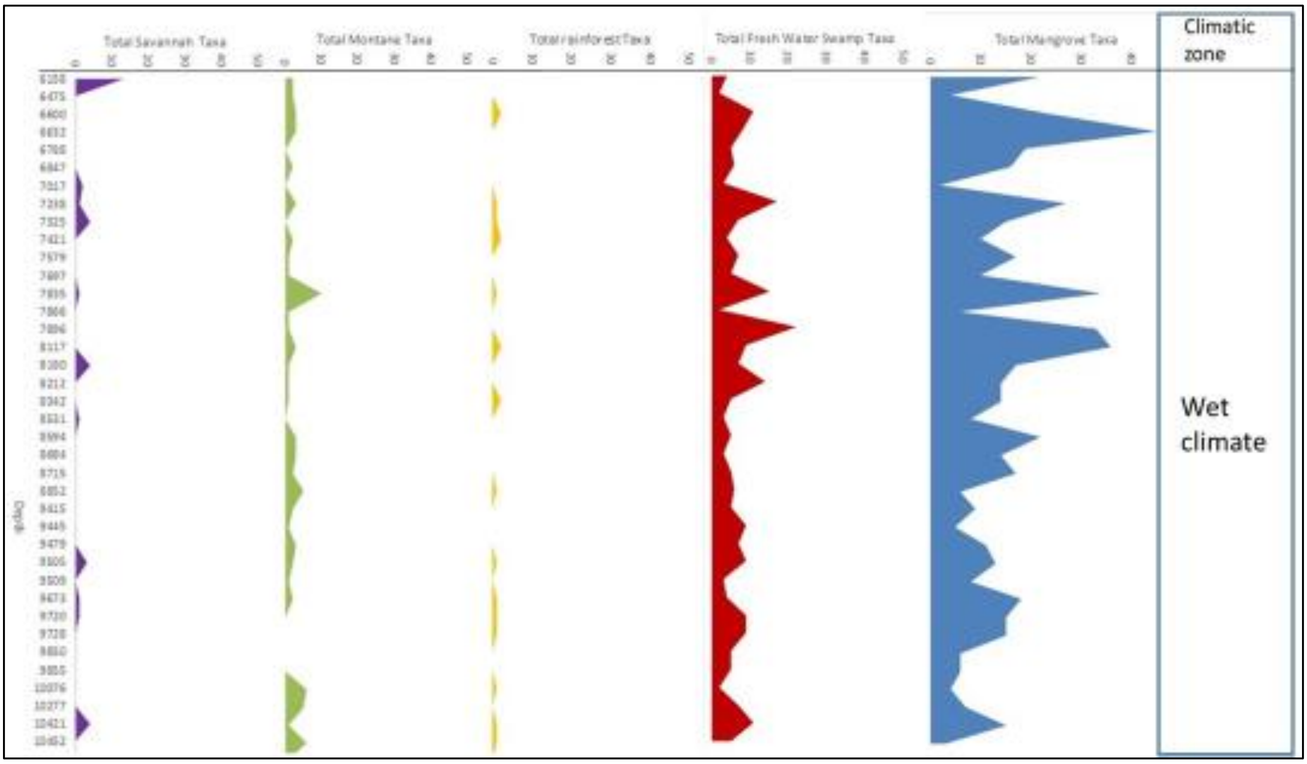

Figure 5: The abundance of the palyno-ecological groups and paleoclimatic zones of Emi-4 well.

Sequence Stratigraphy of Emi-4 Well

In this study, Highstand System Tracts, Maximum Flooding Surface and Transgressive Systems Tracts were identified within the studied intervals in Emi-4 well. The identified systems tracts followed the Genetic Sequence Model (Genetic Stratigraphic Sequences, consisting of strata bounded by Maximum Flooding Surfaces) of Galloway (1989).

Highstand System Tracts (HST)

The Highstand Systems Tract is the stratigraphic interval deposited during a relative decrease in sea level between the MFS and the overlying Sequence Boundary (Boggs, 2006). HST is characterized by a set of prograding coarsening upward and shallowing upward parasequence that terminates at SB (Reijers *et al*., 1996). HST is characterized with shift in palynomorph associations from dinoflagellate and marine organic matter dominant assemblages (TST) to spore-pollen and terrestrial organic matter dominated assemblages owing to increased freshwater influx and the progradation of the coastline (Sancay, 2005). Poumot (1989) stated that the development of upper delta plain (flood plain) that occurs during the highstand is controlled by freshwater and alluvial wetlands. Miospores from this source could be expected to exhibit the least abundance during the highstand. This could be attributed to a decreasing rate of sea-level rise and initial sea-level fall (Tyson, 1995).

The log pattern indicates interbedded sand and shale lithologic facies; and Highstand Systems Tract has characteristic depositional patterns that include aggradational to progradational parasequence sets of coastal plain sandstones and mudstones, shallow marine sandstones and shelf and slope mudstones with intercalated sandstones. Using the above criteria, In Emi-4, HST was identified from 7950 – 6158 ft. The reasons for these identifications are as follows:

i. From the logs, the lithology is composed of alternation of sand and shale/mudstones intervals (Figure 4);

ii. The logs show overall coarsening upwards and shallowing upward (progradational - aggradational) sequences;

iii. The intervals are bounded by MFS at the bottom. (Figure 4);

iv. There are few to zero occurrence of savannah and montane taxa with relative increase in marine taxa (dinocysts), rain forest, fresh water and mangrove taxa.

Maximum Flooding Surface (MFS)

Maximum Flooding Surface is a correlatable physical surface that commonly represents the maximum shale point between the fining upward (backstepping) Transgressive System Tract and the coarsening upward (forestepping) Highstand System Tract (Reijers *et al*., 1996).

The Maximum Flooding Surfaces (MFS) represent the apex of a major condensed section where marine influence has encroached the greatest distance beyond the shelf. Maximum Flooding Surface was recognized at 8000 ft – 7850 ft in Emi-4 well. The criteria for this recognition of Maximum Flooding Surface are:

i. Abundant and diverse recoveries of palynomorphs within the intervals. (Figure 4)

ii. The lithology is shale, deduced from the ditch cutting samples and Gamma Ray Log motifs (Figure 4).

The MFS in Emi-4 well occurred during Serravallian Stage (12.8 Ma). The dating is done by correlation to the Niger Delta Cenozoic Chronostratigraphic Chart which contains the eustatic curves of Vail (1987) and the global sea level cycles of Haq *et al*. (1988). The identification and dating are based on the shaliest (120 API) point within the condensed sections as deduced from the Gamma Ray Log.

Transgressive System Tracts (TST)

Transgressive System Tract is deposited during the relative rise of sea level and persists until the maximum relative rise of sea level is released at the MFS. Condensed section allowed easy recognition. TST has also the following criteria for its recognition:

i. Increase of mangrove pollen is typical during TST. High representation of coastal miospores (mangrove, freshwater and rainforest taxa) compared to few occurrences of savannah and montane taxa that characterize transgressive sediments deposited during sea level rise (Morley 1995; Olayiwola and Bamford, 2016);

ii. TST displays a fining upwards sequence and it is bounded below and above by Transgressive Surface (TS) and the downlap surface of the MFS respectively (Reijers *et al*., 1996); and

iii. TST in the Niger Delta is commonly made up of thick shales occasionally punctuated by relatively thin and poorly developed reservoirs sand bodies.

Transgressive Surface Tract was only encountered at 9200 ft in Emi-4 well. The reasons for these recognitions are as follows:

i. From the logs, the sequence within the intervals displayed overall fining upward sequence. The lithology is composed of fossiliferous pelagic shale (Figure 4);

ii. The TST are bounded at the top by MFS and the base was not seen in the well

iii. There is high representation of coastal miospores (mangrove, freshwater and rainforest taxa) compared to savanna and montane taxa (Olayiwola and Bamford, 2016).

CONCLUSION

Palynostratigraphic, Paleoclimatic and Sequence Stratigraphic analyses was conducted in a section of Emi-4 well, Offshore Niger Delta to establish palynozones, determine age, and reconstruct paleoclimatic conditions to permit stratigraphic correlation and provide insights into the depositional settings and changes overtime within the basin. Thirty-six (36) ditch cutting samples within 6,158ft - 10,452 ft were subjected to standard palynological method involving sample maceration with 10% HCl and 40% HF acids to remove carbonates and siliceous components, neutralization with distilled water and sieving through 5-micron sieve, followed by separation of palynomorphs from residue prior to mounting of the grains on glass slides for further analysis. The palynological composition is marked by dominance of pollen and spores over dinoflagellate cysts. The intercalation of the sandy and shaly intervals across the section evidenced from lithologic, textural, and wire line log data suggested that the entire studied interval belong to the Agbada Formation. The occurrences of age diagnostic palynomorphs such as *Echiperiporites estelae, Belskipollis elegans, Verrutricolporites rotundiporus, Retribrevitricolpites protrudens, Pachydermites diederixi, Peregrinipollis nigericus, Cassoretitriletes vanraadshooveni, Magnastriatites howardii, Retistephanocolpites gracilis, Racemonocolpites hians, Praedapollis flexibilis, Elaeis guineensis, and Zonocostites ramonae* at some intervals of the studied wells suggest early Miocene to late Miocene age.

Three distinct palynostratigraphic zones were delineated using the international stratigraphic guide for the establishments of biozones, they are *Racemonocolpites hians - Cyperaceaepollis sp.* Zone (early Miocene); *Gemmemonoporites sp. - Magnastriatites howardi* Zone (middle Miocene) and *Pachydemites diederixi - Retibrevitricolporites protrudens* Zone (late Miocene). The sequence stratigraphic study identified Maximum Flooding Surfaces (MFS) within the well intervals along with the identification of Highstand Systems Tract (HST) and Transgressive Systems Tract (TST). Paleoclimatic interpretations based on palynological evidence suggest the presence of wet climatic conditions throughout the well intervals, characterized by abundant mangrove, freshwater, and rainforest taxa. This study is significant for several reasons. It provides a stratigraphic framework that can be used to correlate sedimentary sequences which is vital for hydrocarbon exploration. Additionally, paleoclimatic reconstruction offers insights into the climatic conditions that influenced sediment deposition, which is crucial for interpreting past environments. The integration of sequence stratigraphic analysis helps in identifying potential reservoir zones and enhances the predictive modeling of hydrocarbon traps. Thus, the findings from this research will contribute to both academic knowledge and practical applications in the petroleum industry

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