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Depositional Systems and Sequence Stratigraphy of Late Oligocene to Late Miocene Sediments in the Western Niger Delta Basin, Nigeria: Insights from Well-Log Patterns and Palynomorphs

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ABSTRACT

The Late Oligocene–Late Miocene succession of the Niger Delta Basin contains valuable records of sedimentary evolution, depositional environments, and sequence stratigraphic development. This study integrates lithostratigraphic, palynological, and well-log analyses to reconstruct depositional systems and establish a sequence stratigraphic framework for selected wells within the basin. Lithostratigraphic characterisation, palynological analysis, and gamma-ray well-log interpretation were conducted on sediments from three wells (MTX#1, MTX#2, and MTX#3). We determined age from diagnostic palynomorph assemblages and used variations in palynomorph abundance and diversity, along with log motifs, to identify key stratigraphic surfaces and systems tracts. We identified four principal lithologies: sandy mudstone, argillaceous sandstone, sandstone, and shale/mudstone. Palynological data indicate a Late Oligocene–Late Miocene age (P580–P8650) for the studied succession. Integrating palynological and well-log data enabled recognition of lowstand (LST), transgressive (TST), and highstand (HST) systems tracts. Seven maximum flooding surfaces (26.2 Ma, 24.3 Ma, 22.0 Ma, 19.4 Ma, 15.9 Ma, 7.4 Ma, and 6.0 Ma) and six sequence boundaries (27.3 Ma, 24.9 Ma, 21.8 Ma, 17.7 Ma, 16.7 Ma, and 6.7 Ma) were delineated. Gamma-ray log patterns revealed channel, slope fan, backstepping shoreline, prograding shoreline/delta, and basin-floor fan depositional systems. Palynofloral assemblages were characterised by moderate abundances of mangrove, lowland rainforest, brackish-water, and freshwater swamp taxa. This palynomorph assemblage indicates predominantly delta front depositional environments, whereas sparse occurrences of gonyaulacoid dinoflagellate cysts at selected intervals suggest marine incursions.

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Introduction

Sequence stratigraphy is a branch of sedimentary geology concerned with the organisation, distribution, and temporal succession of sedimentary deposits within basin fills. Its fundamental unit, the depositional sequence, develops in response to variations in sediment supply and accommodation space. Factors such as relative sea-level fluctuations (eustasy and tectonism), sedimentation rates, and compaction processes control accommodation [1–3], whereas climatic conditions strongly influence sediment supply [4]. According to Hashmie et al. [5], sequence stratigraphy provides a framework for understanding depositional systems, systems tracts, and stratigraphic surfaces in relation to changes in relative sea level.

Sequence stratigraphic principles have been successfully applied in numerous sedimentary basins

worldwide. Studies in the Malay Basin [6], Upper Magdalena Basin, Colombia [7], Gulf of Cambay, India [8], Persian Gulf and Koppeh-Dagh Basin, Iran [9,10], Taranaki Basin, New Zealand [11], Gulf of Suez, Egypt [12], and the Mississippi–Alabama region of the United States [13] have significantly advanced the understanding of depositional architecture, basin evolution, and hydrocarbon prospectivity. These studies demonstrate that integrating multiple datasets provides more reliable sequence stratigraphic interpretations than relying on a single line of evidence.

Palynology has proven to be an effective tool for paleoenvironmental reconstruction and sequence stratigraphic analysis [14–16]. For example, Garzon et al. [7] identified cyclic palynomorph distribution patterns corresponding to different stages of

sequence development in the Upper Magdalena Valley Basin. Likewise, Maleki-Porazmiani et al. [10] employed several palynofacies indices, including the Palynological Marine Index (PMI), Chorate/Proximate-Proximate-Chorate-Cavate ratio (C/PPC), Outer Neritic/Inner Neritic Index (ON/IN), and Continental/Marine ratio (CONT/MAR), to reconstruct paleoenvironmental conditions and sequence architecture in the Koppeh-Dagh Basin. In addition, Sporomorph Ecological Groups (SEG) have increasingly been recognised as reliable indicators for differentiating systems tracts and depositional sequences [17,18]. Modern sequence stratigraphic studies routinely integrate palynological, seismic, core, and well-log datasets to improve the identification of sequence boundaries, maximum flooding surfaces, and systems tracts. Where seismic and core data are unavailable or limited, gamma-ray logs have proven valuable alternatives because of their sensitivity to lithological variations. For example, Moradi et al. [19] identified sequence boundaries and maximum flooding surfaces in the Sarvak Formation of southwest Iran using well-log attributes, while Tavakoli [9] and Al-Masgari et al. [11] successfully integrated well-log data into regional sequence stratigraphic interpretations. Similar applications of gamma-ray and electric logs have also been reported in the Gulf of Mexico [20].

Despite these advances, equivalent integrated sequence stratigraphic studies remain limited in the Niger Delta Basin. Previous investigations by Magbagbeola [21], Owoyemi [22], and Ozumba and Dim [23] established important sequence stratigraphic frameworks using combinations of seismic, biostratigraphic, and well-log data. However, these studies were largely regional and relied predominantly on seismic interpretation. Consequently, integrating detailed palynological data with wireline log signatures for high-resolution sequence stratigraphic analysis has received relatively little attention. This limitation is particularly significant in mature fields and data-limited areas where seismic quality is poor or core data are unavailable, making alternative datasets essential for accurate stratigraphic interpretation. Furthermore, although palynological techniques such as Sporomorph Ecological Groups (SEG) and palynofacies indices have been widely adopted in other sedimentary basins to delineate systems tracts, sequence boundaries, and depositional environments, their application within the Niger Delta remains limited.

As a result, the full potential of integrating palynomorph assemblages with wireline log responses to refine sequence stratigraphic frameworks and improve depositional interpretations has not been adequately explored.

This study addresses this gap by integrating detailed palynological analyses with gamma-ray and other wireline log data to establish a robust sequence stratigraphic framework for the studied succession in the Niger Delta Basin. This integrated approach improves recognition of sequence boundaries, maximum flooding surfaces, systems tracts, and depositional environments, particularly where seismic and core data are absent or inadequate. The findings provide a higher-resolution stratigraphic framework that can improve regional stratigraphic correlations and support more effective hydrocarbon exploration and reservoir characterisation within the Niger Delta Basin.

Geological setting of the study area

The Niger Delta Basin is an extensional rift basin positioned in the Gulf of Guinea on the passive continental margin close to the western coast of Nigeria [24,25; Fig. 1]. It formed at a rift triple junction linked to the opening of the southern Atlantic in the Late Jurassic and continued into the Cretaceous [26].

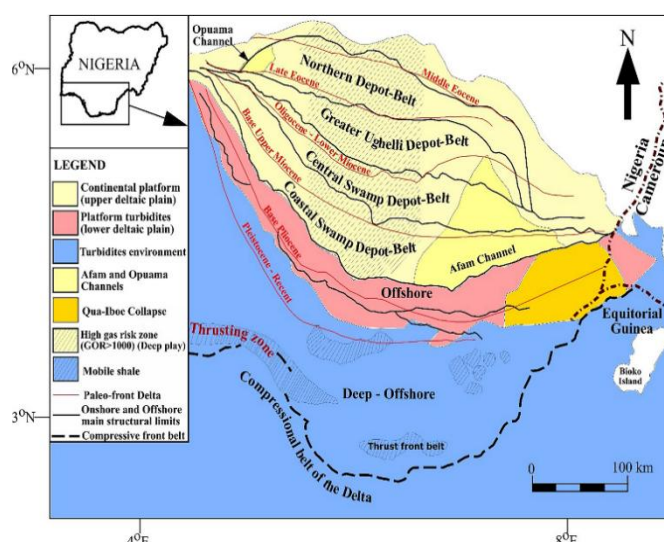


Fig. 1. Generalised map of the Niger Delta showing the six depobelts

Geographically, the Niger Delta Basin lies between longitudes 4°00' and 8°00' E and latitudes 3°00' and 6°00' N (Fig. 1). The basin is bounded by the Calabar Flank to the east and the Benin Flank to the west. Older Cretaceous sedimentary rocks bound it to the north, and the 4000 m (13,100 ft) bathymetric

contour bounds it to the south [26]. The basin has a subaerial area of about 75,000 km², a total area of 300,000 km² and a sediment fill of 500,000 km, which made it one of the largest subaerial basins in Africa [26,27].

The Niger Delta Basin was divided into two lithostratigraphic units: outcropping and subsurface units. The subsurface units are the marine Akata, the petroliferous paralic Agbada, and the continental Benin Formations, while the outcropping units include the Imo Formation and the Ameki Group (Ameki, Nanka, Nsugbe, and Ogwashi-Asaba Formations) [28]. Thick shales and turbidite sands, along with patches of silt and clay, make up the Palaeocene and Recent Akata Formation. The formation formed during lowstands with anoxic conditions and relative sea-level fall. This formation is estimated to be 7,000 meters thick. The Akata Formation contains the hydrocarbon source rocks of the Niger Delta [29, 25, 26].

The Agbada Formation, formed in the Eocene and persisting into the Recent, consists of paralic sediments with continental and marine facies. This formation, which is about 3,700 meters thick, is the main facies in the Niger Delta Basin that contains natural gas and oil [29, 25, 26]. The continental floodplain sands and alluvial deposits that make up the Benin Formation are Oligocene to Recent in age. The thickness of this formation is estimated to be 2,000 meters [29, 25, 26].

Materials and methods

The research materials used in this study comprised ditch-cutting samples and wireline log data obtained from three wells located in the western Niger Delta. A total of 104, 107, and 134 ditch-cutting samples were collected from wells designated MTX#1, MTX#2, and MTX#3, respectively. In addition, complete wireline log suites were acquired for each of the three wells. The datasets were obtained from Mobil Producing Nigeria Unlimited (MPNU), which granted permission for their use and publication in this study. However, for confidentiality and proprietary reasons, the actual names and locations of the wells were not given. Consequently, the wells were assigned the code names MTX#1, MTX#2, and MTX#3 throughout this study.

The ditch-cutting samples were collected at 10.00 m intervals in MTX#1 and at 18.00 m intervals in both MTX#2 and MTX#3. The 10.00 m interval adopted for MTX#1, an exploration (wildcat) well, provided higher sampling resolution to maximise geological and

paleontological information in an area of relatively uncertain subsurface geology. In contrast, the 18.00 m interval taken for MTX#2 and MTX#3, which are development wells within established fields, was considered adequate because the subsurface geological framework had already been well defined. These sampling intervals also ensured that fossil assemblage zones and significant stratigraphic boundaries were adequately recognised.

The acquired ditch-cutting samples and wireline log datasets formed the basis for the lithostratigraphic, palynological, and well-log analyses conducted in this study.

Lithostratigraphic data

The ditch-cuttings samples were slightly crushed, washed with water, and dried for the analysis. Roundness, colour, sphericity, and sorting of the sand particles were observed under a SWIFT™ reflected light microscope and recorded. The presence and absence of accessory minerals such as ferruginous materials, glauconite, carbonaceous detritus, pyrites, and calcites, as well as shell fragments, were also examined and documented for each sample. The lithological variations across the vertical profiles of the wells were observed for the identification of different depositional cycles and systems [30]. The lithological data were plotted with the aid of Stratabug™ (version 1.8) software to generate a chart.

Palynological preparation

25 g of each ditch-cutting sample from the three wells was processed for palynomorphs. The processing followed standard procedures [31] that comprised the addition of HCl, HF, KOH, and heavy liquid separation within a saturated ZnCl₂ solution. Identification, counting and description of palynomorphs were performed with a SWIFT™ transmitted light microscope under ×400 and ×1000 magnifications, under oil immersion with the aid of reference photomicrographs in published literature [e.g., 32,33,34,35,36,37]. Approximately 250 pollen grains and spores are counted per sample. The relative abundances, diversities and palynomorph distribution trends in the wells were illustrated using the STRATABUG™ (version 1.8) software. The distribution of the palynomorph markers was used for the zonation and age dating of the sediments [28]. The recognition of sequence stratigraphy and system tracts using palynological data was based on published materials [7,10,38]. The recovered

palynomorphs were grouped into Sporomorph Ecological Groups (SEGs), as shown in Table 1, following the work of Shivanna and Singh [17], Li et al. [18], Adojoh et al. [39], and Luke et al. [36]. The slides were stored vertically in wooden microscope slide boxes at the Biological Sciences laboratory of Redeemer's University, Ede, Nigeria.

Well log data

The well log dataset used in this study comprised Gamma Ray (GR) and Deep Laterolog (LLD) logs acquired from three wells. The logs were qualitatively interpreted by examining their vertical trends and characteristic curve motifs. Gamma-ray log attributes were identified and correlated across the wells to delineate lithological variations, infer depositional environments, and establish sequence stratigraphic frameworks, including systems tracts, following the interpretation approaches of Vail [20] and Vail and Wornardt [41].

Vail [20] and Vail and Wornardt [41] recognised four main gamma-ray log patterns: crescentic-, funnel-, bell- and cylindrical-shaped log patterns (Fig. 2). The crescentic log pattern is characterised by repeated vertically stacked cycles of coarsening-upward and fining-upward successions. On the gamma-ray log, these appear as alternating decreases and increases in gamma-ray values, reflecting cyclic fluctuations in shale content. Such repetitive stacking patterns are commonly associated with environments influenced by repeated changes in sediment supply and accommodation, including tidal flats, estuarine settings, deltaic successions, and shallow marine environments, where alternating transgressive and regressive depositional cycles occur.

The funnel-shaped gamma-ray motif represents a coarsening-upward (cleaning-upward) succession in which gamma-ray values progressively decrease upward, indicating reduced shale content and a corresponding increase in sand content. This pattern reflects progradational deposition resulting from increasing depositional energy and sediment influx. Funnel-shaped motifs are typically interpreted as deposits of prograding delta fronts, shorefaces, mouth bars, strandplains, and other regressive shallow-marine environments.

The bell-shaped gamma-ray motif displays a fining-upward succession, characterised by low

gamma-ray values at the base that gradually increase upward as shale content increases. This trend records a progressive reduction in depositional energy and a transition from coarse- to fine-grained sediments. Bell-shaped patterns are commonly interpreted as channel-fill deposits formed in fluvial, distributary-channel, estuarine, or tidal-channel environments, where waning flow conditions promote upward fining.

The cylindrical (blocky or boxcar) gamma-ray motif is characterised by relatively uniform low gamma-ray readings throughout the interval, indicating a thick, homogeneous, clean sandstone unit with little vertical variation in grain size or shale content. This pattern generally reflects deposition under relatively stable hydrodynamic conditions and is commonly associated with fluvial channel sands, barrier bars, distributary channels, tidal channels, and amalgamated shoreface sand bodies.

The characterised gamma-ray log motifs were integrated with lithological correlations and sequence stratigraphic concepts to distinguish depositional environments, define depositional systems, identify key stratigraphic surfaces, and delineate systems tracts across the study area. Correlating these log signatures across wells enabled reconstruction of the spatial and temporal evolution of sedimentary facies and depositional architecture.

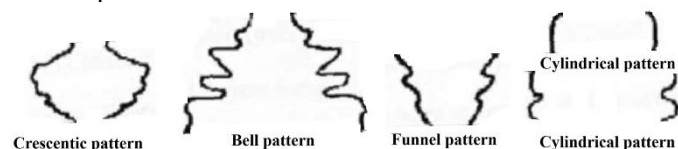


Fig. 2. Typical Log patterns associated with depositional sequences and systems tracts (Modified after Vail, [20])

Results

Lithostratigraphic results

Lithostratigraphic analysis revealed three lithologies in MTX#1 (sandy mudstone, sandstone, and argillaceous sandstone), two lithologies in MTX#2 (sandy mudstone and argillaceous sandstone), and three lithologies in MTX#3 (shale/mudstone, sandy mudstone, and argillaceous sandstone) (Figs. 3a–3c).

The sandy mudstones are moderately hard, whitish in colour, sub-fissile to non-fissile, and contain accessory minerals like mica flakes, glauconite and carbonaceous detritus. Argillaceous

Table 1: Distribution of palynomorphs recovered from MTX-#1, MTX-#2 and MTX-#3 Wells into Sporomorph Ecological Groups (SEGs)

No	Sporomorph ecological group (SEG)	Pollen/spore species	Family [Stuchlik (38), Adojoh [39], Luke et al. [35], Sciumbata et al [40]]	Botanical affinities (NLR) [Rull [41], Adojoh [39], [Stuchlik [38], Sciumbata et al [40] Botanical affinities (NLR) [Rull [41], Adojoh [39], [Stuchlik [38], Sciumbata et al [40]
1	Mangrove	<i>Zonocostites ramonae</i> (Germeraad, Hopping & Muller, 1968) <i>Psilatricolporites crassus</i> (Van der Hammen) (1956) <i>Bombacacidites</i> sp <i>Brevicolporites guinetii</i> (Salard-Cheboldaef, 1978)	Rhizophoraceae Euphorbiaceae Malvaceae -	<i>Rhizophora mangle</i> <i>Alchornea</i> Bombacoideae -
2	Lowland Rain Forest	<i>Elaeis guineensis</i> (Sowumi, 1973) <i>Polypodiaceoisporites</i> sp. (Nagy, 1963) <i>Proteacidites</i> sp <i>Sapotaceoidaepollenites</i> sp (Muller, 1968) <i>Psilatricolporites operculatus</i> (Van der Hammen and Wymstra, 1964)	Arecaceae Polypodiaceae Proteaceae Sapotaceae Euphorbiaceae	Palm tree Pteridophyta/ fern spores Macadamieae <i>Chrysophyllum africanum</i> <i>Amanoa</i>
3	Brackish Water Swamp Species	<i>Acrostichum aureum</i> <i>Marginipollis concinnus</i> <i>Proxapertites cursus</i> (Van der Hammen) <i>Retibrevitricolporites ibadanensis</i> (Legoux, 1978) <i>Verrutricolporites microporus</i> <i>Verrutricolporites</i> sp (Legoux (1978) <i>Ctenolophonidites costatus</i> (Van Hoeken-Klinkenberg, 1966)	Pteridaceae Malvaceae - - - Polypodiaceae	<i>Acrostichum</i> - Araceae Euphorbiaceae Rubiaceae Polypodium
4	Fresh Water Swamp Species	<i>Laevigatosporites</i> sp <i>Magnastriatites howardi</i> (Germraad et al, 1968) <i>Retitricolporites irregularis</i> (Van der Hammen and Wijmstra (1964) <i>Striatricolpites catatumbus</i> (Gonzales, 1967) <i>Racemonocolpites hians</i> (Legoux, 1978)	Trachyleberididae Pteridophyta Parkeriaceae Euphorbiaceae Striatricolpites	Ctenolophonaceae Marattiaceae Parkeriaceae Amanoa Fabaceae
5	Savanna	<i>Proteacidites cooksonni</i> (Cookson, 1950) ex-Couper, 1953 <i>Cyperaceaepollis</i> sp (Cheeseman, 1925; Moore and Edger, 1970) <i>Echistephanoporites echinatus</i> (Muller, 1968) <i>Echitricolporites spinosus</i> (Van der Hammen, 1956) <i>Retistephanocolpites gracilis</i> (Regali et al., 1974) <i>Monporites annulatus</i> ((Van der Hammen, 1954)	- Proteaceae Arecaceae - Asteraceae - - -	Palmae Macadamieae <i>Borassus</i> - - Ctenolophonaceae

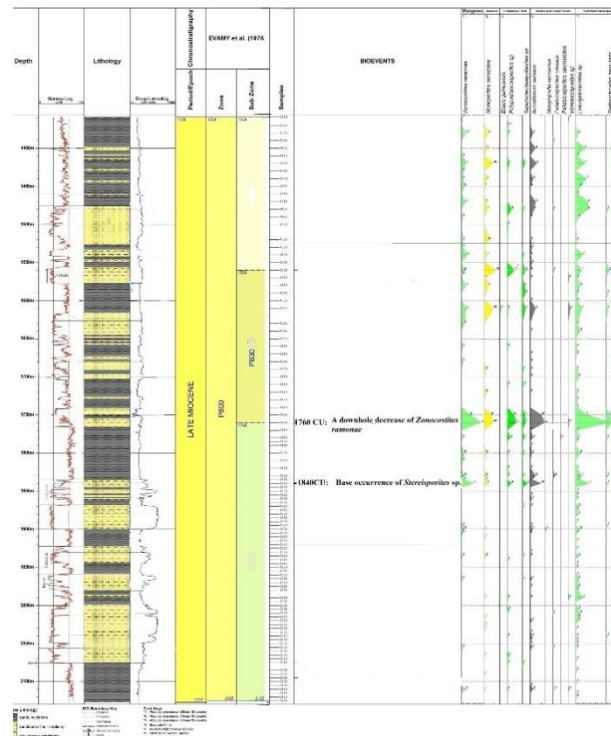


Fig. 3a. Stratigraphic distribution of palynomorphs in MTX#1 well

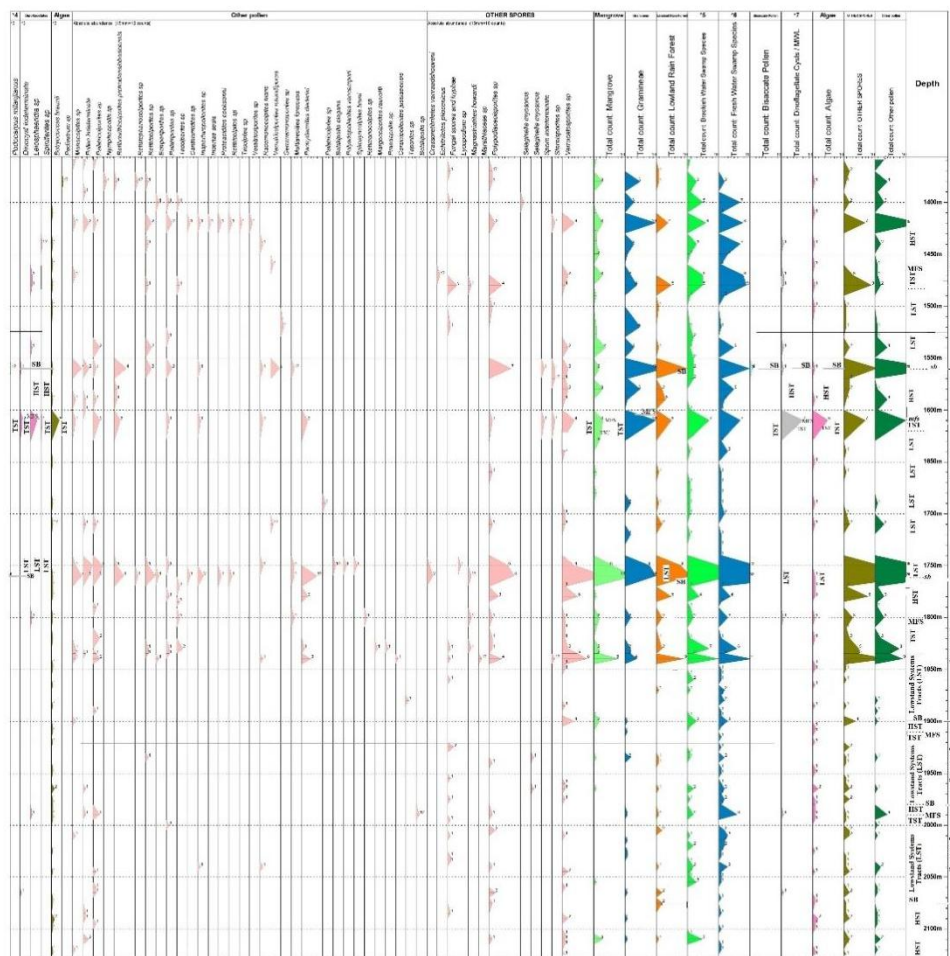


Fig. 3a cont'd.

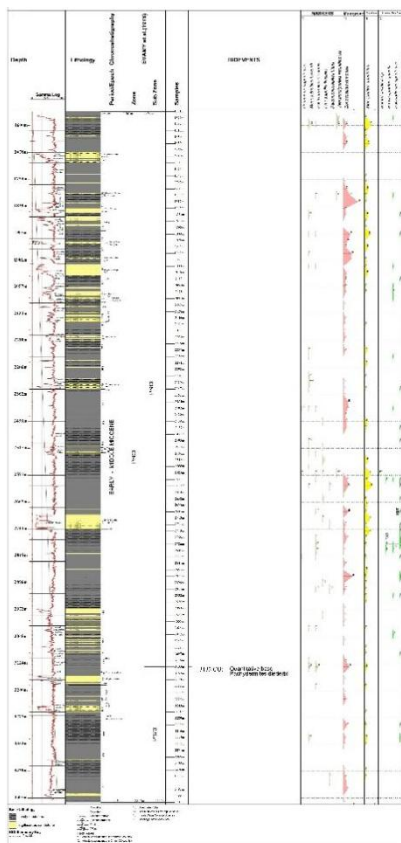


Fig. 3b. Stratigraphic distribution of palynomorphs in MTX#2 well

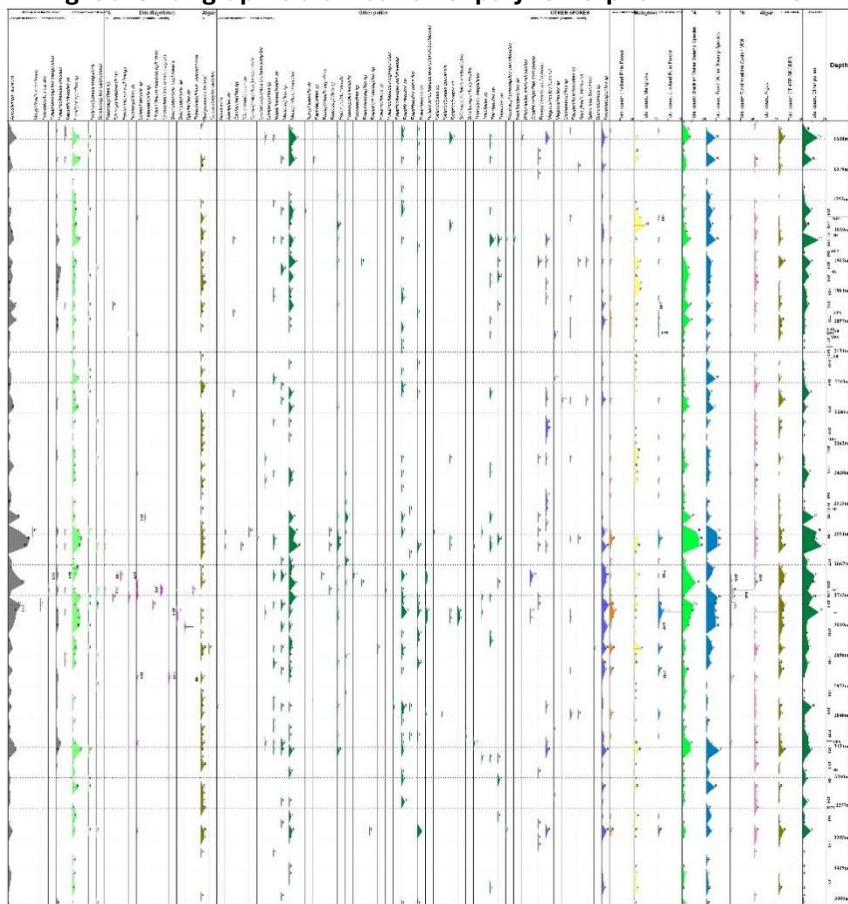


Fig. 3b cont'd

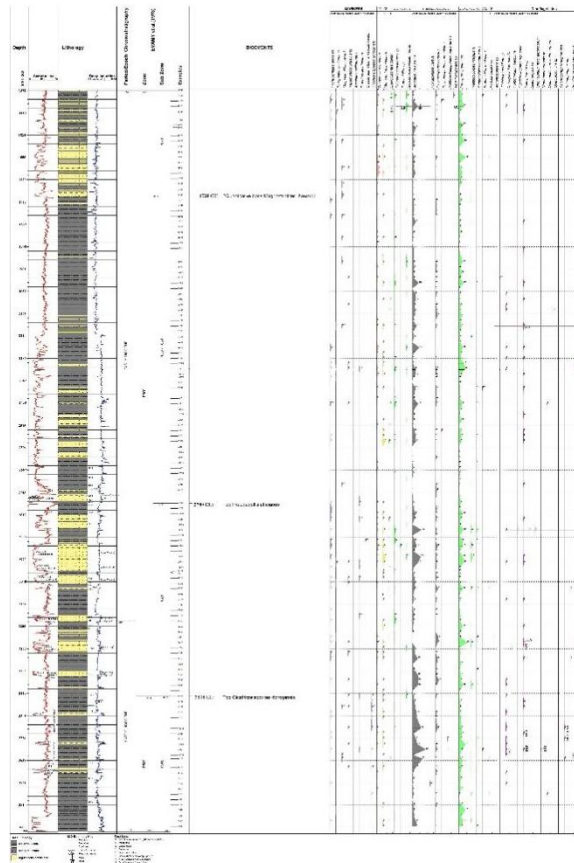


Fig. 3c. Stratigraphic distribution of palynomorphs in MTX#3 well

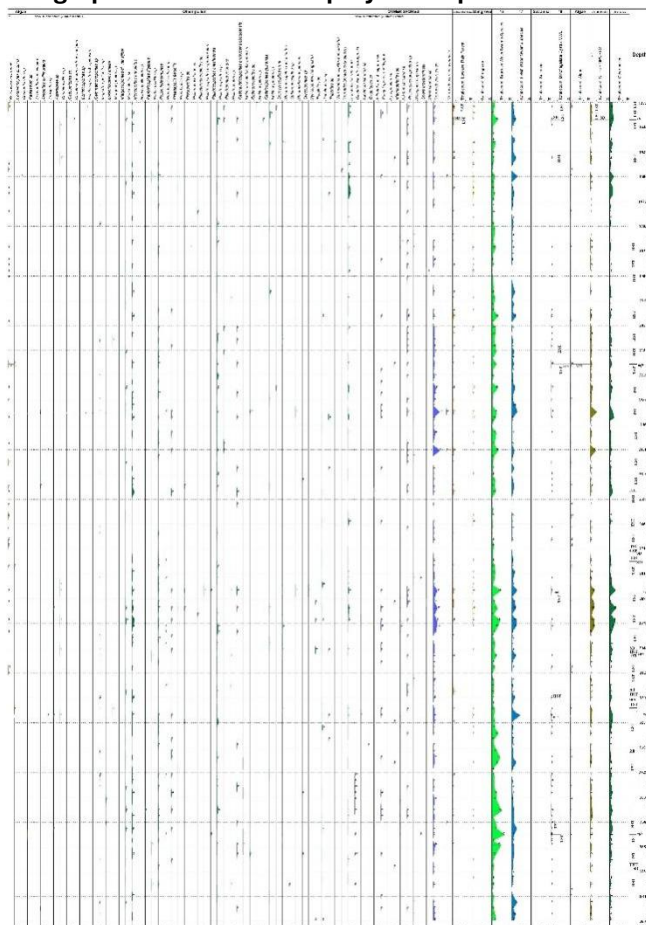


Fig. 3c. Cont'd

Sandstones are fine- to medium-grained, rounded to sub-rounded grains, poorly to moderately sorted with ferruginous materials, a small number of mica flakes, and shells. Sandstones are yellow/whitish, characteristically medium- to coarse-grained, ferruginized, poorly sorted, and friable, with common accessory minerals such as zircon, tourmaline, and glauconite. The shaly/mudstone are dark/gray in colour, moderately hard, sub-fissile to fissile, and moderately massive in nature, with the presence of mica flakes, glauconite and carbonaceous detritus.

Palynological results

A thorough palynological analysis of ditch-cutting samples from the three wells revealed stratigraphically significant occurrences of pollen, spores, and algae, associated with rare dinoflagellates and acritarchs (Plate 1; Figs. 3a-3c). Marker species recovered from the studied wells were used for zonation. However, the zonation followed Evamy et al. [28]'s palynological zones P500 (subzone P580), P600 (subzones P620, P630-P650, P670 and P680) and P800 (subzones P840 and P850).

Palynostratigraphical Zonation of the MTX#1 well

(i) Depth interval: 2127-1760 m.

Recognised palynological zone: P800 zone and P830 subzone [28].

Deduced age: late Miocene.

Description: Subzone P830 is stratigraphically the oldest palynological subzone recognized, based on the depth the last sample analyzed in MTX#1 (Fig. 3a). This Subzone was found to be the only identifiable palynological subzone within the studied interval of the well (2127–1359 m; Fig. 3a). It is defined by the base occurrence of *Stereisporites* sp. at 1840 m, together with the presence of the diagnostic pollen *Nymphaeapollis* sp. and a downhole decrease in *Zonocostites ramonae* at 1760 m. It is further characterized by diverse and abundant palynoflora assemblage dominated by terrestrial angiosperm pollen and spores including *Retitricolporites irregularis*, *Striatricolpites catatumbus*, *Monocolpites* sp., *Psilamonocolpites* sp., *Pachydermites diederixi*, *Laevigatosporites* sp., *Monoporites annulatus*, *Sapotaceoidaepollenites* sp., *Acrostichum aureum*, *Polypodiaceoisporites* sp., *Leiosphaeridia* sp., and *Botryococcus braunii*, with rare marine palynomorphs such as *Spiniferites* sp.

Palynostratigraphical Zonation of the MTX#2 well

(i) Depth interval: 3517-3133 m.

Recognised palynological zone: P600 zone and P670 subzone [28].

Deduced age: early-middle Miocene.

Description: Subzone P670 is stratigraphically the oldest palynological subzone recognised, based on the depth of the last sample analysed in the well (Fig. 3b). The top of this subzone was marked by the quantitative occurrence of *Pachydermites diederixi* at a depth of 3133 m. Other

microfloral assemblages that characterised this subzone comprised common *Zonocostites ramonae*, *Peregrinipollis nigericus*, *Laevigatosporites* sp., *Verrucatosporites* sp. and *Botryococcus braunii*, with rare *Leiosphaeridia* sp.

(ii) Depth interval: 3133-1561 m.

Recognised palynological zone: P600 zone and P680 subzone [28].

Deduced age: early-middle Miocene.

Description: The base of this subzone is characterised by the quantitative occurrence of the *Pachydermites diederixi* at a depth of 3133 m in MTX#2 (Fig. 3b). The top boundary of this subzone is not determined because the topmost sample of this subzone is not likely to have been analysed. Other microfloral assemblages that characterised this subzone are *Zonocostites ramonae*, *Acrostichum aureum*, *Magnastriatites howardi*, *Sapotaceoidaepollenites* sp., *Polypodiaceoisporites* sp., *Acrostichum aureum*, *Psilatricolporites crassus*, *Verrutricolporites* sp., *Verrucatosporites* sp., and *Botryococcus braunii*, with rare occurrences of foraminiferal wall-lining dinoflagellates and *Leiosphaeridia* sp.

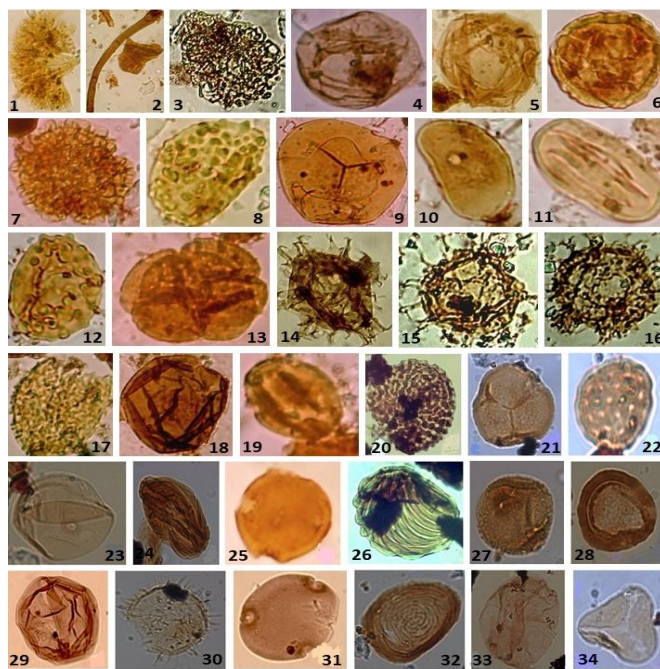


Plate 1. Photomicrographs of some palynomorph species from MTX# 1-MTX#3 wells-

1. *Botryococcus braunii* 2. Fungal hypha 3. *Praedapollis flexibilis* 4. *Leiosphaeridia* sp. 5. *Leiosphaeridia* sp. 6. *Psilatricolporites crassus* 7. *Retitricolporites irregularis* 8. *Verrucatosporites* sp. 9. *Acrostichum aureum* 10. *Laevigatosporites* sp. 11. *Sapotaceoidaepollenites* sp. 12. *Spiniferites ramosus* 13. *Verrucatosporites usmensis* 14. *Polypodiaceoisporites* sp. 15. *Spiniferites pseudofurcatus* 16. *Spiniferites* sp. 17. *Racemonocolpites hians* 18. Fungal spore 19. *Zonocostites ramonae* 20. *Crassoretitricolporites vanraadshooveni* 21. *Stereisporites* sp. 22. *Cyperaceapollis* sp. 23. *Peregrinipollis nigericus* 24. *Striatricolpites catatumbus* 25. *Pachydermites diederixi* 26. *Magnastriatites howardi* 27. *Retibrevitricolporites protrudens/obodoensis* 28. *Operculodinium centrocarpum* 29. *Selenopemphix nephroides* 30. *Selaginella myosorus* 31. *Brevicolporites guinetii* 32. *Concentric circulus* 33. *Lejeunecysta* sp. 34. *Elaeis guineensis* (X400 magnification)

Palynostratigraphical zonation of the MTX#3 well**(i) Depth interval: 3901-3438 m.**

Recognised palynological zone: P500 zone and P580 subzone [28].

Deduced age: late Oligocene.

Description: Subzone P580 is the oldest palynological subzone identified, based on the depth of the last sample analysed in MTX#3 (Fig. 3c). The top of this subzone was defined by the first occurrence of *Cicatricosisporites dorogensis* at 3438 m. Other microfloral assemblages that characterised this subzone are common occurrences of *Pachydermites diderixi*, *Magnastriatites howardi*, *Racemonocolpites hians*, *Praedapollis africanus*, *Sapotaceoidaepollenites* sp., *Acrostichum aureum*, *Psilatricolporites crassus*, *Retitricolporites irregularis*, *Peregrinipollis nigericus* and *Botryococcus braunii*, with rare *Spiniferites* sp., *Selenopemphix* sp., and *Leiosphaeridia* sp.

(ii) Depth interval: 3438-2780 m.

Recognised palynological zone: P600 zone and P620 subzone [28].

Deduced age: early Miocene.

Description: The top of the P620 subzone is defined by the first occurrence of *Praedapollis africanus* at 2780 m in MTX#3 (Fig. 3c). The base of this subzone is defined by the first occurrence of *Cicatricosisporites dorogensis* at 3438 m. This subzone is further characterized by other palynofloral assemblage including common *Pachydermites diderixi*, *Crassoretitrites vanraadshooveni*, *Zonocostites ramonae*, *Brevicolporites guinetii*, *Polypodiaceoisporites* sp., *Magnastriatites howardi*, *Racemonocolpites hians*, and *Praedapollis africanus*. Other rare species in this subzone include *Homotryblium plectilum*, *Spiniferites ramosus*, *Selenopemphix* sp., *Leiosphaeridia* sp. and *Botryococcus braunii*.

(iii) Depth interval: 2780-1728 m.

Recognised palynological zone: P600 zone and P630-P650 subzone [28].

Deduced age: early Miocene.

Description: The top of the P630-P650 subzone was characterised by the (?)quantitative base occurrence of *Magnastriatites howardi* at 1728 m in the MTX#3 well (Fig. 3). The base was defined by the first occurrence of *Praedapollis africanus* at 2780 m. The palynofloral assemblage that characterised this subzone includes common occurrences of *Zonocostites ramonae*, *Polypodiaceoisporites* sp., *Sapotaceoidaepollenites* sp., *Verrucatosporites usmensis*, *Stereisporites* sp., *Selaginella myosorus*, *Cyathidites* sp., *Syncolporites triangulatus*, *Magnastriatites* sp., *Acrostichum aureum*, and *Psilatricolporites crassus*. Others are rare occurrences of *Leiosphaeridia* sp. and *Botryococcus braunii*.

(iv) Depth interval: 1728-1372 m.

Recognised palynological zone: P600 zone and P670 subzone [28].

Deduced age: early Miocene.

Description: The top boundary of the P670 subzone was tentatively put at the depth of the first sample analysed in the well (Fig. 3). The base was characterised by the (?)quantitative base occurrence of *Magnastriatites howardi* at a depth of 1728 m. The palynofloral assemblage that further characterised this subzone is characterised by the common occurrence of *Pachydermites diderixi*, *Zonocostites ramonae*, *Polypodiaceoisporites* sp., *Proteacidites* sp., *Sapotaceoidaepollenites* sp., *Verrucatosporites* sp., *Tricolporites* sp., *Retitricolporites* sp., *Monocolpites* sp., *Acrostichum aureum*, and *Psilatricolporites crassus*. Others are rare *Leiosphaeridia* sp. and *Botryococcus braunii*.

Sequence stratigraphy**Biostratigraphic results**

Lowstand system tracts (LSTs) were recognised based on spikes in the abundance of spores accompanied by abundance of pollen and low abundance and diversity of dinoflagellate cysts at depth intervals 1770-1740 m and 1570-1550 m in MTX#1, 2786-2749 m in MTX#2 and 1426-1390 m in MTX#3 (Figs. 3a-3c; Table 2). Also, based on low populations of dinoflagellates cysts and dominant occurrence of lowland Sporomorph Ecological Groups (SEGs) *Polypodiaceoisporites* sp. and *Sapotaceoidaepollenites* sp., and spores, sequence boundaries (SBs) are recognized at depths 1560 m and 1760 m in MTX#1 (Fig. 3a). In addition, the abundant of lowland SEGs *Brevicolporites guinetii*, *Polypodiaceoisporites* sp. and *Sapotaceoidaepollenites* sp. at depths 2786 m in MTX#2 (Fig. 3b), and *Sapotaceoidaepollenites* sp. at depths 1426 m and *Brevicolporites guinetii* and *Sapotaceoidaepollenites* sp. at 2569 m in MTX#3 (Fig. 3c; Table 2)

Table 2: Table that shows the criteria for distinguishing LST/TST/HST using palynology and well logs

Criteria	LST	TST	HST
Palynological	Spikes in spore abundance, with high pollen abundance and low dinocyst abundance and diversity.	The relative abundance and diversity of dinoflagellate cysts.	Gradual decrease in <i>Spiniferites</i> sp. and <i>Homotryblium</i> sp., with the occurrence of euryhaline acritarchs <i>Leiosphaeridia</i> sp. and terrestrial representatives.
Well-log	Crescentic well-log patterns and Cylindrical well-log patterns	Bell well log patterns	Funnel well-log pattern

Conversely, based on the relative abundance and greater diversity of dinoflagellate cyst at depth intervals 1630-1600 m in MTX#1 and 2749-2728 m in MTX#2 marked recognition of transgressive system tract (TST) and the peaks at depths 1610 m and 2731 m marked the maximum flooding surfaces (MFSs) in MTX#1 and MTX#2, respectively (Figs. 3a and 3b). Additionally, the increase in abundance of dinoflagellate cyst at depth intervals 3652-3603 m, 3277-3237 m and 2890-2850 m revealed TSTs, and the peaks at depths 3621 m, 3255 m, and 2871 m marked MFSs in MTX#3 (Fig. 3c). This is corroborated by the occurrences of high abundant of algae *Botryococcus braunii* and increase in assemblage of mangrove species *Zonocostites ramonae* at these depths in MTX#1, MTX#2 and MTX#3 (Figs. 3a-3c). As sea level starts to fall, the gradual decrease in open marine dinoflagellates such as *Spiniferites* sp. and *Homotryblium* sp. along with the occurrence of euryhaline acritarchs such as *Leiosphaeridia* sp. and terrestrial representatives correspond to highstand systems tracts (HST) at depth intervals 1600-1570 m and 2731-2694 m in MTX#1 and MTX#2, and at depth intervals 3621-3566 m and 2176-2125 m in MTX#3 (Figs. 3a-3c; Table 2).

Well-log pattern results

Depositional sequence

Based on well-log patterns (Crescentic, Funnel, Bell, and Cylindrical), we delineated depositional sequences, depositional systems, sequence stratigraphy, and systems tracts for MTX#1, MTX#2, and MTX#3 (Figs. 3a-3c).

Crescentic well-log pattern with associated depositional system, systems tracts, and sequence stratigraphy

Crescentic well-log patterns with the associated lowstand systems tracts encountered at depth intervals 2076-2000 m, 1980- 1950 m, 1900- 1835 m, 1780-1750 m and 1580-1480 m in MTX#1. They were also recorded at depth intervals 3188-3152 m, 2530-2512 m and 1848-1835 m in MTX#2 and 3292 – 3223 m in MTX#3 (Figs. 3a-3c).

Bell well-log pattern with associated depositional system, systems tracts, and sequence stratigraphy

Bell well log patterns with the associated transgressive systems tracts were encountered at depth intervals 2004-1990 m, 1925-1910 m, 1835-1800 m, 1625-1600 m, and 1475-1460 m in MTX#1 (Fig. 3a), at intervals 3499-3289 m, 3152-3104 m, 2512-2347 m, and 2121-2100 m in MTX#2 (Fig. 3b), and at intervals 3688-3452 m, 3223-3200 m, 3071-3063 m, 2864-2781 m, and 2743-2728 m in MTX#3 (Fig. 3c).

Funnel well-log pattern with associated depositional system, systems tracts, and sequence stratigraphy

Funnel well-log pattern and the associated highstand system tracts (HSTs) were encountered at depth intervals 1990-1960 m, 1670-1625 m, and 1506-1495 m MTX#1 (Fig. 3a), at intervals 3271-3188 m, 3114-2969 m, 2347-2329 m, 2237-2201 m, 2095-2068 m, 2032-1940 m, 1871-1848 m,

1796-1780 m, 1698-1674 m in MTX#2 (Fig. 3b), and at intervals 3726-3719 m, 3368-3353 m, and 3185-3170 m in MTX#3 (Fig. 3c).

Cylindrical well-log pattern with associated depositional system, systems tracts, and sequence stratigraphy

Cylindrical well-log patterns and associated lowstand system tracts were encountered at depth intervals 1900-1870 m and 1578-1506 m in MTX#1 (Fig. 3a), at interval 2747- 2694 m in MTX#2 (Fig. 3b), and at interval 2773-2750 m in MTX#3 (Fig. 3c).

Discussions

Lithostratigraphy

The results of lithostratigraphic analysis revealed the presence of sandy mudstone, sandstone, argillaceous sandstone, and shale/mudstone lithologies which were previously reported from the Niger Delta Basin and other relevant basins by Krapez [50,51], Adegoke [52], Gore [29], Adegoke et al. [27] and Nwaezeapu et al. [53]. The deposition of these lithologies is related to local subsidence or land uplift, while the sediment spreading is restricted to regional eustatic sea-level changes as reported by Reijers [54] and Revere et al. [55].

Biostratigraphic interpretation of sequence stratigraphy

Sequence stratigraphic analysis, integrated with biostratigraphic interpretations, identified lowstand systems tracts (LSTs), transgressive systems tracts (TSTs), highstand systems tracts (HSTs), sequence boundaries (SBs), and maximum flooding surfaces (MFSs). Shivanna and Singh [17], Li et al. [18] and Maleki-Porazmiani et al. [10] have previously recognised LSTs and SBs based on the abundance of pollen, lowland SEGs, and low abundance and diversity of dinoflagellate cysts. Garzon et al. [7] and Okeke and Umeji [56] have previously documented TSTs and MFSs based on the relative abundances and diversity of dinoflagellate cysts.

Depositional systems and sequence stratigraphy

The crescentic well-log motif is interpreted to represent channelized depositional systems, while the corresponding sequence stratigraphic element is identified as a slope fan ([20,57]; Fig. 3c). Sequence boundaries (SBs) were recognized at depths of 2076 m, 1980 m, 1900 m, 1760 m, and 1580 m in the MTX#1 well (Fig. 3a). In MTX#, SBs occur at depths of 3188 m, 2530 m, and 1848 m, whereas a sequence boundary was identified at 3056 m in MTX#3 (Figs. 3b and 3c).

Bell-shaped log motifs are interpreted to be associated with maximum flooding surfaces (MFSs). These surfaces were identified at depths of 1990 m, 1910 m, 1800 m, and 1460 m in the MTX#1 well (Fig. 3a); at 3289 m, 3104 m, 2347 m, 2100 m, 2033 m, 1871 m, and 1798 m in the MTX#2 well (Fig. 3b); and at 3452 m, 3200 m, 3063 m, and 3781 m in the MTX#3 well (Fig. 3c). The depositional systems associated

with these patterns are interpreted as backstepping shorelines ([20]).

Funnel-shaped log motifs are interpreted to represent prograding shoreline and deltaic depositional systems. Their corresponding sequence stratigraphic element is identified as a prograding wedge ([20,42]) (Figs. 3a–3c).

Cylindrical log motifs are interpreted to indicate fluvial sand depositional systems. The associated sequence stratigraphic elements include incised valley fills (IVFs) in the MTX#1 and MTX#2 wells, and basin floor fans (BFFs) in both MTX#2 and MTX#3 wells ([17,43–45]).

The identified depositional systems have been widely documented in the Niger Delta and analogous sedimentary basins [20,42–57]. Channel and slope fan deposits are typically associated with high-energy depositional environments, resulting in clean, porous, and low-shale-content sand bodies that constitute excellent hydrocarbon reservoirs [54,57]. Backstepping shoreline deposits are commonly linked to the development of source and seal rocks [55,56]. Prograding shoreline/delta and prograding wedge systems favour the accumulation of fine- to medium-grained sandstones that serve as important hydrocarbon reservoirs [57,58]. Basin floor fan deposits also form high-quality submarine reservoir sands [59,60], while fluvial sands and incised valley fills are characterised by sandstone-rich, highly porous, and permeable sediments that provide effective pathways and storage sites for hydrocarbon migration and accumulation [61–63].

Key stratigraphic surfaces

Key stratigraphic surfaces constitute fundamental boundaries within stratigraphic sequences and provide important information on variations in relative sea level, sediment supply, and depositional environments. In this study, the principal stratigraphic surfaces identified include sequence boundaries (SBs) and maximum flooding surfaces (MFSs). These surfaces are essential for delineating and correlating sedimentary sequences and systems tracts, thereby improving understanding of basin evolution and hydrocarbon prospectivity.

The identified MFSs were recognised using biostratigraphic data and commonly correspond to the boundary between a retrogradational unit and an overlying progradational unit on gamma-ray logs. In contrast, sequence boundaries were identified where clean sandstone units abruptly overlie shale intervals, indicating significant changes in depositional conditions. The interpreted stratigraphic surfaces were subsequently correlated with the Niger Delta chronostratigraphic framework of Haq et al. [68] (Fig. 4).

The recognised MFSs correspond to ages of 26.2 Ma, 24.3 Ma, 22.0 Ma, 19.4 Ma, 15.9 Ma, 7.4 Ma, and 6.0 Ma, whereas the identified SBs occur at 27.3 Ma, 24.9 Ma, 21.8 Ma, 17.7 Ma, 16.7 Ma, and 6.7 Ma. These stratigraphic markers have been previously documented within the Niger

Delta and have proven valuable for regional sequence stratigraphic analysis and correlation [69–74].

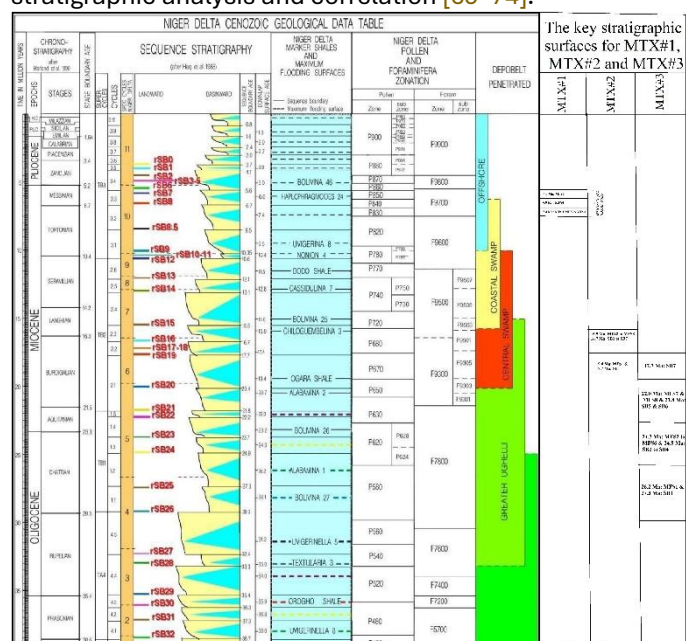


Fig. 4. Niger Delta cenozoic chronostratigraphic chart (Modified after Haq et al. [64])

Paleoenvironments

The paleoenvironmental synthesis of the three wells was based on the distribution and abundance of terrestrial, freshwater, brackish-water, and marine palynomorphs. In the MTX#1 well, the uppermost interval (1440–1359 m) (Fig. 3a) is characterized by moderate occurrences of mangrove pollens (*Zonocostites ramonae* and *Monoporites annulatus*), lowland rainforest taxa (*Sapotaceoidapollenites* sp. and *Polypodiaceoisporites* sp.), brackish-water swamp indicators (*Acrostichum aureum* and *Psilatricolporites crassus*), freshwater swamp taxa (*Laevigatosporites* sp. and *Striatricolpites catatumbus*), freshwater algae (*Botryococcus braunii* and *Pediastrum* sp.), and rare acritarchs (*Leiosphaeridia* sp.). These palynofloral assemblages suggest deposition within a delta-front environment [71,72]. The interval between 1800 and 1440 m (Fig. 3a) contains abundant gonyaulacoid dinoflagellate cysts, particularly *Spiniferites* spp., which suggest deposition under marginal-marine conditions [79]. The lowermost interval (2127–1800 m) (Fig. 3a) shows a similar terrestrial and marginal-marine palynofloral assemblage, including mangrove, freshwater, and brackish-water taxa, indicating a return to delta-front depositional conditions [71,72].

In the MTX#2 well, the upper interval (2713–1561 m) (Fig. 3b) is dominated by mangrove pollen (*Zonocostites ramonae*), lowland rainforest taxa, brackish-water swamp species, freshwater swamp indicators, and rare acritarchs, with an absence of dinoflagellate cysts. This assemblage is interpreted as representing a nearshore/deltaic environment [73,74]. The interval between 2822 and 2713 m (Fig. 3b) contains marine palynomorphs, including

Spiniferites sp., *Homotryblum plectilum*, *Operculodinium centrocarpum*, and foraminiferal wall linings, indicating deposition in a marginal-marine setting [74]. The lowermost interval (3517–2822 m) (Fig. 3b) is characterised by moderate occurrences of mangrove, rainforest, brackish-water, freshwater, and algal taxa, along with rare acritarchs, suggesting deposition within a delta-front environment [71,72].

Similarly, the uppermost section of the MTX#3 well (2323–1372 m) (Fig. 3c) contains abundant mangrove, lowland rainforest, brackish-water swamp, freshwater swamp, and acritarch taxa but lacks dinoflagellate cysts, indicating deposition in a delta-front environment [74,75]. In contrast, the interval between 3773 and 2323 m (Fig. 3c) contains diverse marine dinoflagellate cyst assemblages, including *Spiniferites pseudofurcatus*, *Spiniferites ramosus*, *Spiniferites* spp., *Operculodinium centrocarpum*, and *Homotryblum plectilum*, which indicate a well-oxygenated open marine environment [75]. The lowermost interval (3901–3773 m) (Fig. 3c) is dominated by mangrove, brackish-water swamp, freshwater swamp, and lowland rainforest taxa, with no recorded dinoflagellate cysts, suggesting deposition in a delta-front setting [71,72].

Overall, the palynological assemblages from the three wells indicate repeated alternations between delta front and marginal-marine depositional environments, reflecting fluctuations in relative sea level and shoreline migration during sediment accumulation.

Conclusion

Palynostratigraphic analysis indicated that MTX#1, MTX#2 and MTX#3 wells fall within the P500 (P580 subzone), P600 (P620, P630-P650, P670 and P680 subzones) and P800 (P830, P840 and P850 subzones) palynological zones. This confirmed that the sediments in these three wells were deposited during the late Oligocene to late Miocene periods. Based on lithological and palynological evidences, the lower to upper alternations of sandy mudstone and argillaceous sandstone sandwiched with fine-medium grained sandstone at the middle confirmed late Miocene age in MTX#1, while alternations of sandy mudstone and argillaceous sandstone established early-mid Miocene in MTX#2; and the lower to upper alternation of sandy mudstone and argillaceous sandstone sandwiched with shale or mudstone at the middle confirmed the late Oligocene to early Miocene age in MTX#3. The relative abundances of the various palynomorph assemblages, together with well-log patterns, facilitated recognition of lowstand, transgressive, and highstand systems tracts in association with key stratigraphic surfaces such as sequence boundaries and maximum flooding surfaces. Well-log patterns enabled interpretation of depositional systems such as channels, slope fans, incised valley fill, basin floor fans, backstepping shorelines, prograding shorelines/deltas, and prograding wedges in the three wells. The frequent occurrence of mangrove, lowland rain forest, brackish-water swamp species, and freshwater swamp

species, in association with algae and rare acritarchs, revealed a delta-front environment. Conversely, few records of gonyaulacoid dinoflagellate cysts such as *Spiniferites pseudofurcatus*, *Spiniferites ramosus*, *Spiniferites* sp., *Operculodinium centrocarpum*, *Homotryblum plectilum* and foraminiferal wall linings at few horizons suggested marine incursions.

This study is limited by its analysis of only three wells and its reliance mainly on palynological, well-log and lithological datasets. Future research should incorporate additional wells, high-resolution biostratigraphic data, seismic interpretation, calibration of core well-log patterns, and geochemical proxies to improve regional correlation and better understand sedimentary evolution and basin architecture. Integrating multidisciplinary datasets across a wider geographical area would also refine the chronostratigraphic framework, constrain depositional models more robustly, and strengthen predictive models for hydrocarbon exploration and reservoir evaluation within the Niger Delta Basin.

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Author contributions

All authors contributed to the study and its design. Material preparation, data collection and analysis (i.e., Methodology, formal analysis, and investigation) were performed by Olayiwola Moshood Adegboyega and Olugbenga Temitope Fajemila; while Festus Ojenabor served as the data curator. Olayiwola Moshood Adegboyega wrote the first draft of the manuscript. All authors commented on previous versions of the manuscript. All authors read and approved the final manuscript.

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