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Palynology: A Useful Tool for Biostratigraphic and Palaeoenvironmental Reconstruction of the Late Miocene Subsurface Sediments from Offshore Western Niger Delta, Nigeria

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Abstract
This paper presents a biostratigraphic and palaeoenvironmental interpretation from the lithostratigraphic, gamma-ray log and palynological data of Uk-4 Well from the late Miocene interval of the offshore western Niger Delta Basin. Three lithologies that comprised sandstones, argillaceous sandstones and sandy-mudstones were recognised from both lithostratigraphic and well log analyses. Sandstones and argillaceous sandstones could be regarded as reservoir rocks, sandy-mudstones, on the other hand, could be considered as seal and source rocks. Five transgressive and three regressive depositional sequences, and three sequence stratigraphic surfaces comprising two sequence boundaries and one maximum flooding surface were recognized from the lithostratigraphical analysis. Sixty-nine palynomorph species belonging to 22 genera that is dominated by angiosperm assemblages were recovered from palynological analysis. The palynomorph assemblages were grouped into seven ecological groups, which comprised fresh water, savanna, brackish water swamp, mangrove, lowland rainforest, palmae and beach in order of their dominancy. Five informal palynological assemblage zones were delineated from the palynological assemblage analysis. Hence, the near shore/coastal deltaic and marginal marine paleoenvironments were inferred for the penetrated strata of Uk-4 Well. The recovered palynomorphs showed a relationship with the *Echitricolporites spinosus* Pan-tropical zone, which correlate with P800 palynological zone (P830, P840 and P850 sub-zones), J2-J3, and M4, M3 and M2 floral zones, and hence, Uk-4 Well was dated late Miocene. Deep water marine, prograding delta, basin floor fans, channel fill and tidal channels environments of deposition that are considered as mud and sand facies, are inferred from five delineated gamma-ray log shaped sequences. This investigation may be a functional means for forecasting facies associations and basin geometries in related Miocene hydrocarbon systems.

Keywords: *Palynology, palynostratigraphy, paleoenvironment, depositional environment, lithofacies.*

Introduction

The knowledge, which concerns with both modern and fossil palynomorphs is palynology. Palynomorphs are organic-walled microfossils 5–500 µm in diameter, established in the sediments of all geological periods, and comprise exclusively the pollen, spores, orbicules, dinocysts, acritarchs, chitinozoans and scolecodonts, together with particulate organic matter (POM) and kerogen (Traverse, 2007; Stephenson, 2018). Palynology is useful in solving geological problems in many ways. For example, the distribution of palynomorphs provides data for correlating and dating of rock strata, and for palaeoenvironmental interpretation. These are regular and commercial applications of palynology especially in the petroleum industry (Rawson *et al*. 2002).

Biostratigraphy is a cost-effective discipline in oil and gas exploration because it allows overpressure zone determination, quick and logistically simple way to determine sedimentation ages, and insights into sedimentary environments (Copestake, 1993; Giwa *et al*., 2002; Jaramillo and Rueda, 2004; Fajemila, 2012; Adekola *et al*., 2014; Fadiya, 2014). In addition, paleoenvironmental study helps us in the sequence stratigraphy interpretation (e.g., Oboh, 1992; Olayiwola *et al*., 2021). Unlike foraminifera and nannofossils that require marine conditions to produce their shells, palynomorphs are found in all environments including coastal deltaic and continental settings and therefore useful in characterizing these environments. They are very reliable in sediments of all environments and not limited by salinity or pH. The use of palynology for biostratigraphic and paleoenvironmental reconstruction purposes in basins of different ages worldwide has been demonstrated by prominent authors around the world. For example, Bercovici and Vellekoop (2017) used the pollen and spore record across the Cretaceous-Paleogene boundary of Hell Creek Formation, North America and this has proven to be one of the most precise and reliable means for pinpointing the major transition within terrestrial deposits. Radmachera *et al*. (2020) employed Cretaceous palynological assemblages from the southern margin of the Basque-Cantabrian Basin (northern Spain, Zumaia) to suggest depositional environment and to indicate the lower-upper Maastrichtian age of the section; and palynological assemblages from Cenozoic Niger Delta Basin, Nigeria, have been used for biostratigraphic and paleoenvironmental reconstruction (e.g., Nton and Famori, 2020; Olayiwola, 2021; Fajemila *et al.*, 2022). Palynological data combined with well-log data are most useful in recognising and interpreting depositional environments, lithology and sedimentary facies (Olayiwola and Bamford, 2016; Adebayo, 2014; Olayiwola and Bamford, 2019; Olayiwola, 2021). The analysis of well-log data plays an important role in the exploitation and exploration of petroleum fields (Timur, 1982; Etnyre, 1989; Gluyas and Swarbrick, 2004; Darlin, 2005; Fajemila, 2012; Mahdi *et al*., 2013; Nton and Rotimi, 2015; Taherdangkoo and Abdideh, 2016; Yao, *et al*., 2018; Yasser *et al*., 2021).

Previous studies on palynostratigraphy and palaeoenvironmental interpretations in the Niger Delta, Nigeria have used palynological data. For example, Adeonipekun and Olowokudejo (2013) and Bankole *et al*. (2016) used the distribution of palynomorphs for paleoenvironmental reconstruction. Adebayo (2014) employed palynologic and foraminiferal data to established sequence stratigraphic framework and paleoenvironments of the Neogene succession in the Niger Delta Basin. Obiosio and Nwaejije (2017) used palynologic data to reconstruct palynostratigraphic and paleoenvironment of Agbada Formation, Niger Delta Basin. Within the Niger Delta Basin, few studies have used combination of lithostratigraphic, well-log and palynological data to interpret palynostratigraphy and palaeoenvironment (Olayiwola and Bamford, 2016). Therefore, this study is aimed at integrating lithostratigraphic, well-log and palynological data in order to interpret the palynostratigraphy, depositional environment and to carry out paleoenvironmental reconstruction of the sediments encountered in the UK-4 well, Niger Delta, Nigeria.

The Uk-4 Well is situated in the offshore section, western Niger Delta basin. The Niger Delta basin covers an area of about 75,000 sq km and located between longitudes 3° and 9° E and latitudes 2° and 7° N (Fig. 1). The basin is bounded on the western side by the Benin hinge line, which trends east-northeast that is at the south of the West Africa basement massif. The basin was bounded on the southern, eastern and northern parts by the Gulf of Guinea, the Calabar flank hinge line bordering the adjacent Precambrian, and the outcrops of older Cretaceous on the Abakaliki High, respectively (Olayiwola, 2021). In an East-West bearing the basin started from Mt. Cameroon to the Okitipupa Ridge. Its peak located at the southeastern part of the Niger and Benue Rivers confluent.

Geologically, the study area is concealed within Tertiary section of the Niger Delta. Progradational depositional sequences were characterised in the basin based on the sand-shale ratio (Short and Stauble, 1967; Doust and Omatsola, 1990). Akata Formation, which was known as the source rock in this basin comprised marine shale sediments with sandstone components of deep-sea fan origin in the Paleocene period. Next to this in ascendant order is the paralic Agbada Formation, which is commonly referred to as reservoir rock, composed of sands with alternation of minor shales in the upper part and alternation of equal amounts in the lower part. Conversely, Benin Formation, which is made up of massive continental sediments, deposited from Eocene to Oligocene (Short and Stauble, 1967).

Materials and Methods

Ditch-cuttings samples and well-logs that were obtained from the UK-4 well, western offshore Niger Delta, Nigeria (Fig.1), were employed in this present study. The actual name and position of this well were top secret for proprietary reasons and, therefore, was code-named as Uk-4 well. The Department of Petroleum Resources (DPR) and National Petroleum Investment and Management Services (NAPIMS) gave the consent to Chevron Nigeria Limited (CNL) to supply the study materials and afterward gave the consent to publish the findings from the study. 104 ditch-cutting samples from Uk-4 well were investigated at 9.0-m intervals based on the standard laboratory and palynological process (Faegri and Iversen, 1989). Lithological, palynological and well-log data were used to support the understanding of biostratigraphy and paleoenvironments of the studied sediments.

Lithostratigraphic data

This investigation was to provide a detailed vertical lithologic description of the studied ditch cuttings samples. 80 g of each ditch-cutting sample was mashed, washed and dried for lithological investigation. The lithologic description, which followed a standard laboratory procedure, was improved by GR and resistivity log patterns, since high and low values of GR-log and RES-log indicated shale and sand lithologies, respectively (Adegoke, 2002). Essential parameters such as grain size, textures, roundness, color, sphericity, sorting and facies changes were documented. The occurrence and lack of accessory minerals such as carbonaceous detritus, ferruginous materials, pyrites, glauconite, and shell fragments as well as calcites were also examined and documented for each sampling

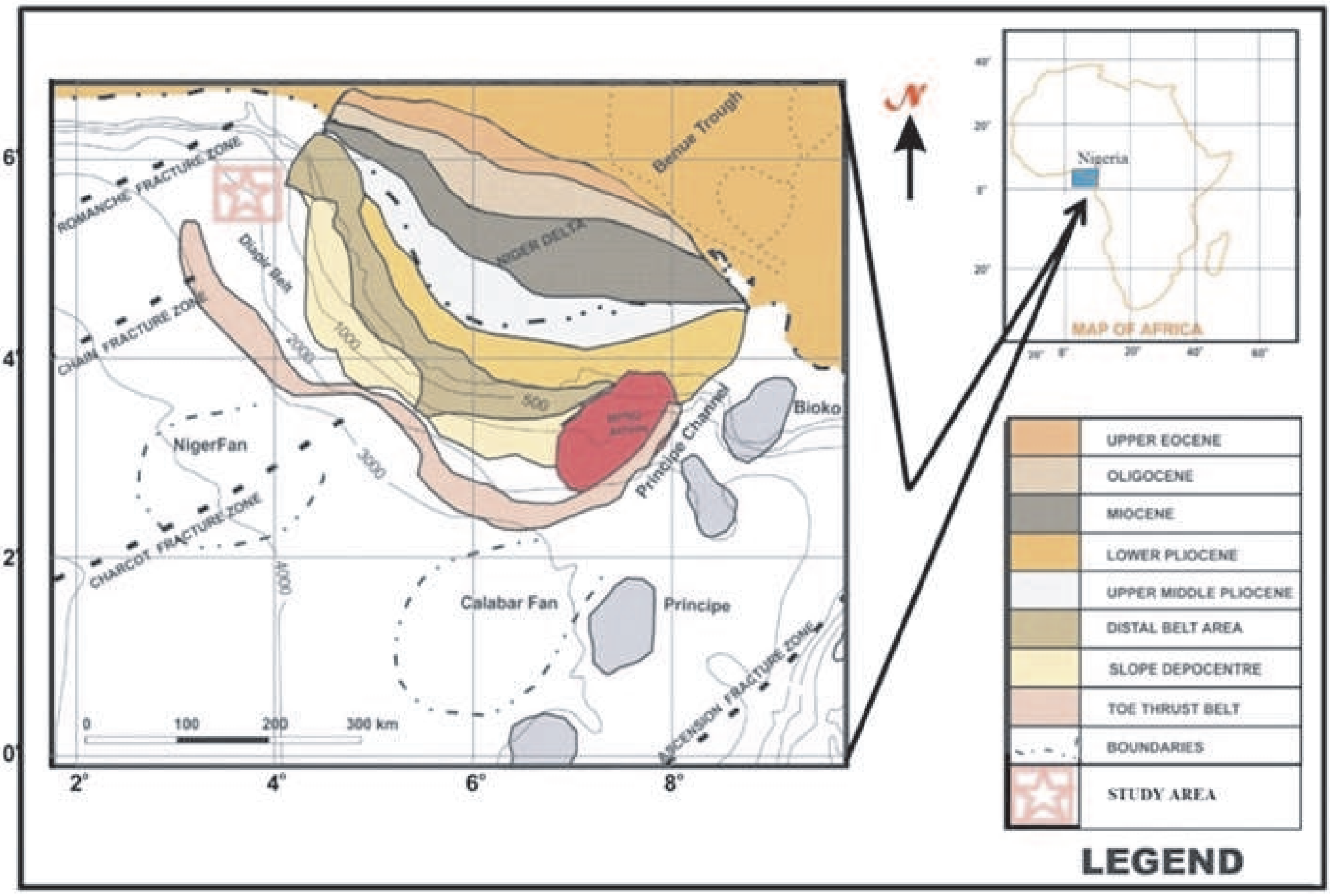

Fig. 1: Location map of the study area in the western offshore Niger Delta (modified after Wolak2011)

depth. SEDLOG™, Tilia and strataBug softwares were used to plot lithostratigraphic data to generate the lithostratigraphic diagram (Figs. 2, 3 and 4).

Palynological data

25g of each ditch-cutting sample was used for palynomorphs extraction based on standard palynological techniques (as shown by Faegri and Iversen,1989). The technique comprises the disintegration and elimination of carbonate and silicate components with hydrochloric (HCl) and hydrofluoric acids (HF), respectively. This was followed by separation with heavy liquid of a saturated $ZnCl_2$ solution and the preparation of slides. Observation of slides under the transmitted binocular light microscope, under x400 and x1000 magnifications, for identification, counting, and descriptions of all the palynomorphs present were carried out. Minimum and maximum of 200 and 250 palynomorphs were counted per sample, respectively. Distinguishable palynomorphs were recognised and illustrated based on their botanical affinity and specific ecological groups (e.g., Germeraad *et al*., 1968; Salard-Cheboldaeff, 1981; Sowunmi, 1981; Frederiksen, 1985; Rao, 2001; Rull, 2003; Eisawi and Schrank, 2008; Olayiwola *et al*., 2021). The palynomorph's relative abundance versus depth were plotted using Tilia™ and strataBug™ softwares. Photomicrographs of marker (age diagnosed) species are presented in plates 1 and 2. The slides were kept vertically in the wood microscope slide containers at the palynological laboratory of Natural History Museum, Obafemi Awolowo University, Ile-Ife, Nigeria. The studied slides were given curatorial museum numbers that ranged from NM Uk-4 Wsl 1 to NM Uk-4Wsl 104.

Well-log data

The obtained well-log suites comprised GR-log and RES- log. Well-log (GR) motifs of Uk-4 well were used to infer different lithologies, identify reservoir sand bodies, delineate depositional environment and determine shale content. Well log motifs/patterns are commonly depicted as funnel, bell, cylindrical, bowl and irregular shapes (Rider, 1990; 1999). Nonetheless, log pattern as established from a GR-log in clastic sediments is relayed more of clay content than of grain size (Elnaggar *et al*., 2018; Mohamed *et al*., 2018). Funnel GR-log patterns exhibit an upward decrease (i.e., deepening or upward fining sequence) in clay content while bell GR-log shape display the reverse trend (i.e., shallowing or upward coarsening sequence; Mohamed *et al*., 2018; Elnaggar *et al*., 2018). Cylindrical GR-log motifs showed comparatively no vertical change in clay content and are characteristic of clastic sediments that have little largely clay content (Montgomery *et al*., 1999). Recognition of depositional environment using GR- log motifs followed the works of Morris and Biggs (1990), Rider (1990, 1999) and Vail and Wornardt (1991).

Determination of the Gamma Ray Index (IGR) was carried out by using the equation of Schlumberger (1998).

IGR= GRlog - GR(minimum) / GR(maximum) - GR (minimum)..(1)
Where:
IGR= GR Index,
GRlog= GR reading from log
GR(minimum)= gamma ray minimum
GR(maximum)= gamma ray maximum (shale)
In this study, the Larionov (1969) equation for Tertiary sediments was employed to establish the Vsh:
$Vsh = 0.083 \times (2^{3.7} x^{IGR} - 1)$..(2)

Results and discussion

Lithostratigraphical Analysis

Lithostratigraphy analysis of Uk-4 well revealed several sea level fluctuations brought about changes in the depositional environment that led to the formation of three lithologies sandstones, siltstones and claystones (Figs. 2, 3 and 4). Two depositional sequences, transgressing (deepening or upward fining sequence) and regressing (shallowing or upward coarsening sequence), were also inferred at different dept intervals. Transgressive sequences occurred at depths intervals 1875-1800 m, 1800-1675 m, 1675-1605, 1605-1565 m and 1500-1380 m while regressive sequences were encountered at depths intervals 2150-1950 m, 1950-1875 m and 1565-1500 m. The abrupt changes from regressive depositional sequence to transgressive depositional sequence occurred at depths 1875 m and 1500 m which resulted into two sequence boundaries (SB1 and SB2; Fig. 2). Also, the abrupt change from transgressive depositional sequence to regressive depositional sequence was encountered at depth 1560 m and resulted in maximum flooding surface at this depth (Fig. 2).

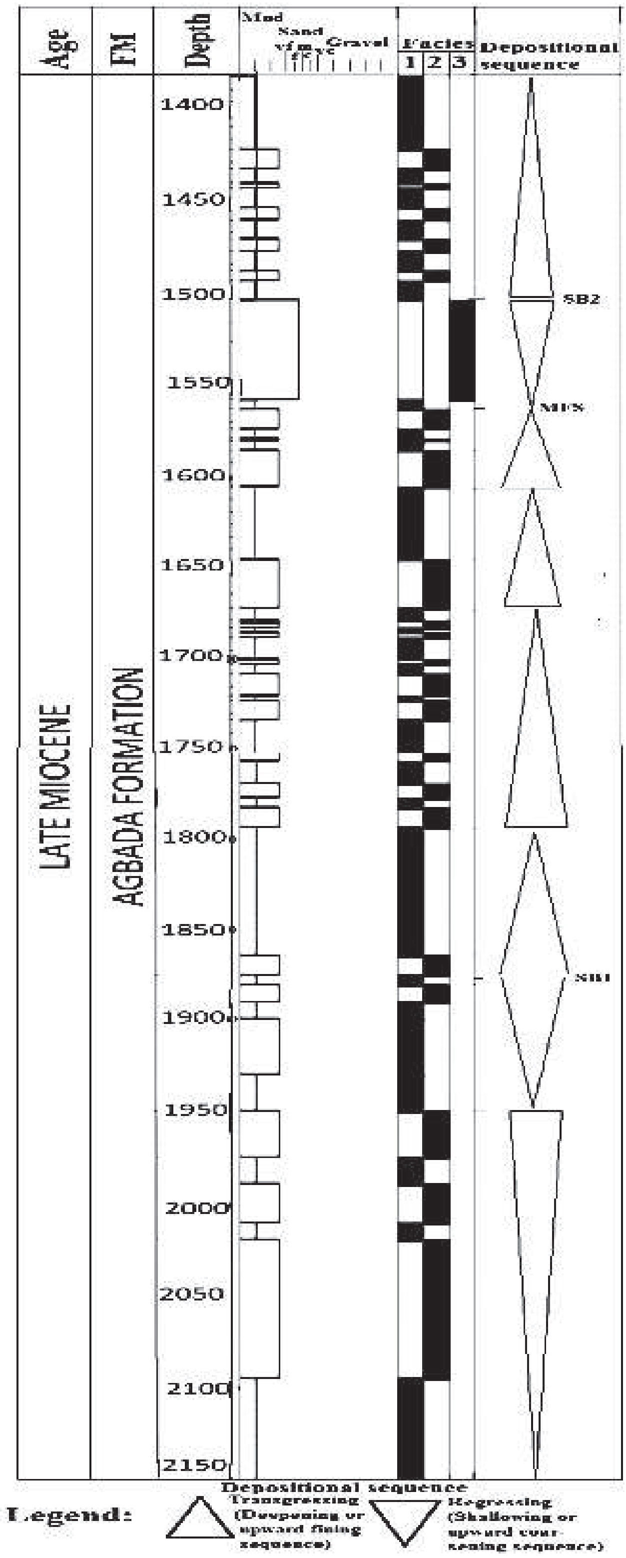

Fig. 2: Lithostratigraphic log of UK-4 Well showing depositonal sequences, lithology and lithofacies

The delineated lithologies and depositional sequences have been previously reported by many workers (e.g. Krapez, 1996, 1997; Gore, 2005). However, alteration in the seafloor-spreading rate, the polar ice caps size and local subsidence of the coastal area that were caused by the irregular rise and fall of the sea level (Gore, 2005). The deposition of sediments is relayed to local subsidence, while sediments spreading are managed by regional eustatic sea-level changes (as shown by Browning *et al*., 2006; Reijers, 2011; Rovere *et al*., 2016). The deepening or fining upward successions comprised finer-grained lithologies such as claystones that is on-lapping underneath younger coarser-grained lithologies such as shaly-sand that were fining-upward (Krapez, 1996, 1997). Hence, these depositional cycles were formed during transgressive period (i.e., sea-level rise). On the contrary, the shallowing-upward or upward coarsening successions, which happened during regressive periods deposited coarser-grained lithologies, such as sandstone, off-lapping underneath younger finer-grained lithologies that were coarsening-upward (Krapez, 1996, 1997). Moreover, the sequence boundaries (SB1 and SB2) and maximum flooding surface (MFS) recorded in this study are marked by abrupt changes from sandstone lithology to claystone lithology (at depths 1875 m and 1500 m) and abrupt changes from claystone lithology to sandstone lithology (at depth 1560 m), respectively, as previously reported by other workers in similar environments (e.g., Miller and West, 1998; Kieft, 2009; Khalifa *et al*., 2015).

The lithostratigraphic analysis showed that the Uk-4 well penetrated the Agbada Formation, which consists of paralic sequence of marine and fluvial deposits. The paralic sequence of marine and fluvial deposits of Agbada Formation has been previously documented by Weber (1971).

Palynological analysis

Sixty-nine (69) palynomorph taxa belonging to 22 genera with a total count of 1504 are recorded in Uk-4 section. The palynological assemblages are dominated by terrestrial palynomorphs species, which consists of angiosperm pollen (79.6%), spores (10.6 %), algae (3.7%) and fungal spores (2.7%). The Marine species (dinocysts, acritarchs and microferaminiferal wall-lining) represent 3.4%. The palynomorph assemblages are grouped into seven ecological groups. The ecological group is dominated by fresh water, which accounted for 34.59%; the remaining are savanna (26.77%), brackish water swamp (15.93%), mangrove (10.77%), lowland rainforest (8.48%), palmae (2.58%) and beach (0.88%).

Palynological zonation

The UK-4 well yielded moderate well-preserved palynomorphs within the analyzed depth intervals 2125-1359 meters which made palynological zonation possible. The recovered palynomorph assemblages (*Cyperaceaepollis* sp., *Echitricolporites spinosus*, *Laevigatosporites* sp., *Retibrevitricolporites protrudens/obodoensi*, *Verrucatosporites* sp., *Acrostichum aureum*, *Zonocostites ramonae*, *Monosporites annulatus*, *Striatricolpites catatumbus*, *Polypodiaeceoisporites* sp., *Botryococcus braunii*, *Acrostichum aureum* and *Retitricolporites irregularis* etc. Fig. 3) associated with the *Echitricolporites spinosus* Pan-tropical zone of Germeraad et al. (1968). It also correlated to P800 Zone of Evamy et al. (1978), and J2-J3 zones of Legoux (1978). Moreover, variation in the diversity and abundance of palynomorphs permitted the recognition of P830, P840 and P850 subzones of Evamy et al. (1978) and floral zones M4, M3 and M2 of Morley and Richards (1993). Therefore, Uk-4 well is dated late Miocene. Thus, the palynological subzones are differentiated briefly below.

(i) ***Depth interval: 2125–1760 m***

Characterized Palynological zone: P800 Zone; P830 Subzone (Evamy et al., 1978)
Age: Late Miocene
Characterization: Subzone P830 is the first and oldest palynological subzone in the Uk-4 Well. The Qualitative base occurrence of *Cyperaceaepollis* sp. at depth 1760 m characterized the upper boundary and the base of this subzone was marked at depth 2125 m that was the first, oldest and deepest sample analyzed. In addition, occurrences of other palynomorphs such as *Laevigatosporites* sp., *Verrucatosporites* sp., *Acrostichum aureum*, *Zonocostites ramonae*, *Monosporites annulatus*, *Striatricolpites catatumbus*, *Botryococcus braunii* and *Retitricolporites irregularis* characterized this subzone (Fig. 3). Nonetheless, subzone P830 has been previously described (e.g., Durugbo, 2010; Taiwo et al. 2017; Fadiya et al. 2020).

(ii) ***Depth interval: 1760-1560 m***

Characterized Palynological zone: P800 Zone; P840 Subzone (Evamy et al., 1978)
Age: Late Miocene
Characterization: The sub-zone top is defined at depth 1560 m and the base is marked at 1760 m. The top was defined by regular occurrence of *Cyperaceapollis* sp./downhole decrease of *Zonocostites ramonae*. This

interval was defined by the occurrence of other palynomorphs like *Zonocostites ramonae*, *Monosporites annulatus*, *Laevigatosporites* sp., *Botryococcus braunii*, *Striatricolpites catatumbus* and *Retitricolporites irregularis* (Fig. 3). However, subzone P840 has been previously defined by many authors (e.g., Durugbo, 2010; Taiwo *et al*., 2017; Fadiya *et al*., 2020).

(iii) ***Depth interval: 1560-1359 m***

Characterized Palynological zone: P800 Zone; P850 Subzone (Evamy *et al*., 1978)
Age: Late Miocene
Characterization: The top of the subzone is placed at depth 1359m, which is the shallowest sample analyzed, is characterized by regular occurrence of *Retibrevitricolporites protrudens/obodoensis* and the base is marked at depth 1560m with the base regular occurrence of *Cyperaceapollis* sp./downhole decrease of *Zonocostites ramonae* (Fig. 3). Furthermore, this interval is defined by the presence of other palynomorphs like *Monosporites annulatus, Zonocostites ramonae, Polypodiaceoisporites* sp., *Acrostichium aureum, Laevigatosporites* sp., *Leiosphaerida* sp. and *Retitricolporites* sp. (Fig. 3). Nevertheless, subzone P850 has been previously described by Durugbo (2010), Taiwo et al. (2017) and Fadiya et al. (2020).

Palynological assemblage zone (PAZ)

Two informal palynological assemblage zones (PAZ A and PAZ B) are recognized in Uk-4 Well. The PAZ A zone is subdivided into PAZ A1 and A2 subzones, while the PAZ B zone has B1, B2 and B3 subzones (using tilia statistics and CONISS analyses; Fig. 3).

i) ***PAZ A1 (2125-2000 m)***

The PAZ A1is the deepest palynological assemblage in Uk-4 well. It is correlated with subzone P830 of Evamy *et al*. (1978) and floral zone M4 of Morley and Richards (1993). The base of this informal palynological zone was defined at depth 2125 m, which is the base of the deepest analyzed sample of UK-4 Well (Fig. 3). The top of this zone was marked by the abundant mangrove pollen *Zonocostites ramonae* with the freshwater species *Verrucatosporites* sp. and *Laevigatosporites* sp. at depth 2000 m. The bottom is defined by high occurrence of *Zonocostites ramonae*, *Retitricolporites irregularis*, *Retibrevitricolporites protudens/obodoensis*, *Laevigatosporites* sp., *Monosporites annulatus* and *Botryococcus braunii*. The zone is further characterized by common microfloral assemblage freshwater swamp pollen such as *Retitricolporites irregularis* and *Striatricolpites catatumbus*, *Brevicolporites guinetii*; brackish-water elements *Acrostichum aureum*, *Pachydermites diederixi* and *Psilatricolporites crassus*. This is in association with spot records of the marine elements such as *Polysphaeridium zoharyi*, *Spiniferites ramosus*, *Impagidinium* sp., *Nematosphaeropsis labyrinthus*, *Lejeunecysta* sp., microforaminiferal wall linings and fungal elements. This palynological assemblage zone implies deposition in a marginal marine environment with frequent incursions of freshwater (Wall *et al*., 1977; Wrenn and Kokinos, 1986; Poumot, 1989; El Beialy and Ali, 2002).

ii) ***PAZ A2 (2000-1850 m)***

This palynological assemblage lies conformably on top of PAZ A1 in the UK-4 well. It occupied a position within subzone P830 of Evamy *et al*. (1978) and floral zone M4 of Morley and Richards (1993). The bottom of this informal palynological zone is recognized at 2000m. This assemblage zone is characterized by the presence of *Zonocostites ramonae*, *Laevigatosporites* sp., *Verrucatosporites* sp. and freshwater algae *Botryococcus braunii* (Fig. 3). The top of the zone at depth 1850 m was defined by high occurrence of the mangrove pollen *Zonocostites ramonae*. The zone is further characterized by common records of freshwater swamp species *Laevigatosporites* sp., *Retitricolporites irregularis*, *Striatricolpites catatumbus*, *Brevicolporites guinetii*; brackish water elements *Acrostichum aureum*, *Pachydermites diederixi*, *Psilatricolporites crassus*, *Monoporites annulatus*; moderate occurrences of algae *Botryococcus braunii*; spot records of the marine elements *Polysphaeridium zoharyi*, *Spiniferites ramosus, Nematosphaeropsis labyrinthus*, *Impagidinium* sp.. *Lejeunecysta* sp., and microforaminiferal wall linings; and fungal elements. This palynological assemblage indicates a marginal marine depositional environment with common freshwater incursions (Wrenn and Kokinos, 1986; Poumot, 1989).

iii) ***PAZ B1 (1850-1650 m)***

The PAZ B1 is the palynological assemblage zone in Uk-4 well that sits directly above the PAZ A2 and beneath the PAZ B2 (Fig. 3). This palynological assemblage zone is partly associated with upper part of subzone P830 and lower part of P840 of Evamy et al. (1978), and floral zone M4 of Morley and Richards

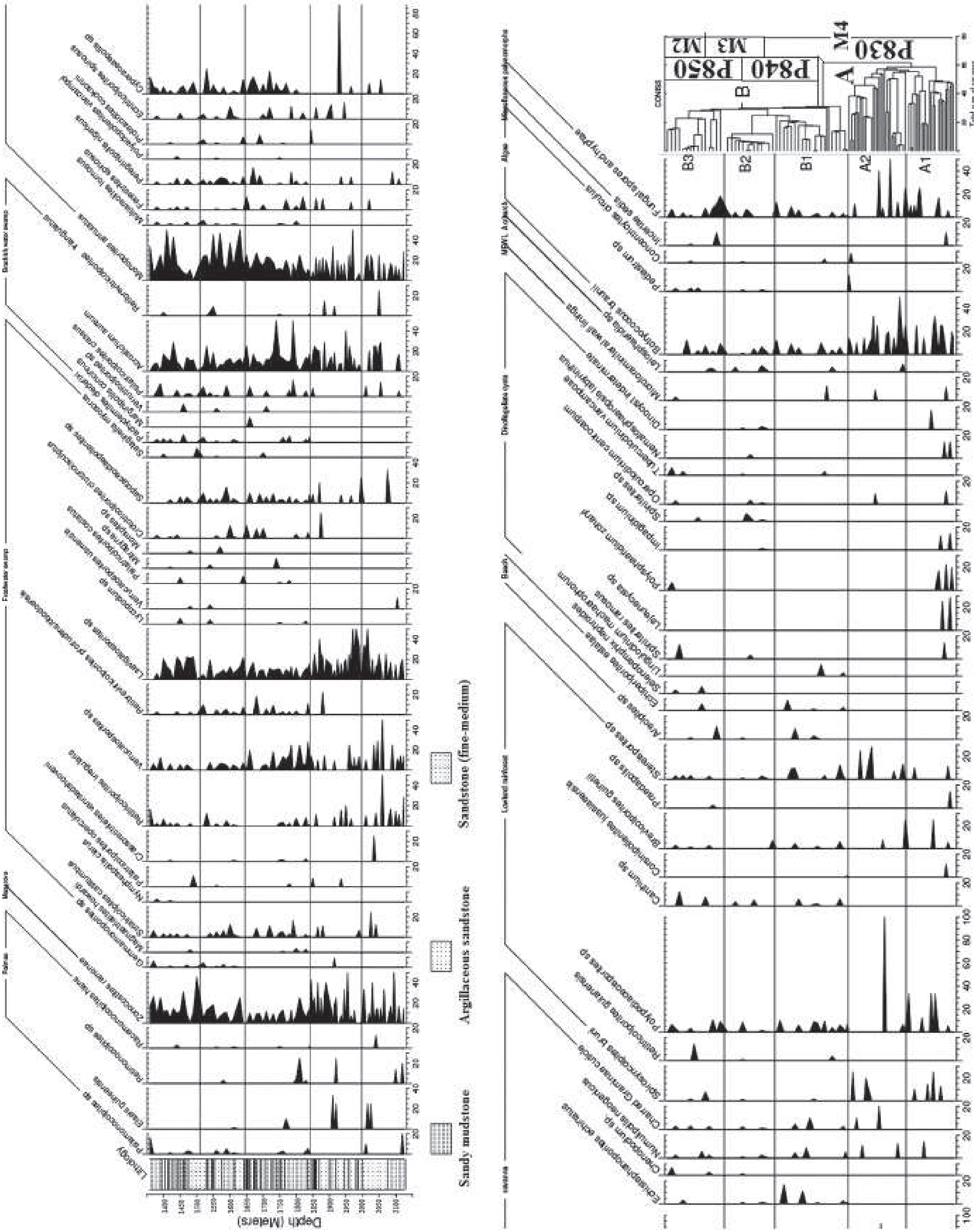

Fig. 3: Palynomorphs distribution chart for Uk-4 well

(1993). The bottom of this informal palynological zone was defined at depth 1845 m, which is defined by the high occurrence of *Zonocostites ramonae* in association with *Laevigatosporites* sp. and *Verrucatosporites* sp. The top of this informal zone is marked by the occurrences of *Monosporites annulatus*, *Acrostichum aureum* and *Laevigatosporites* sp. (Fig. 3). Moderate occurrences of *Zonocostites ramonae* and the freshwater swamp species *Laevigatosporites* sp., *Verrucatosporites* sp., *Retitricolporites irregularis*, *Striatricolpites catatumbus*, *Retibrevitricolporites protudens/obodoensis*, *Crassoretitriletes vanraadshooveni*, *Magnastiatites howardi*, *Sapotaceoidaepollenites* sp., *Psilatricolporites operculatus*, *Crototricolporites crotonoisculptus*, *Lycopodium* sp., *Selaginella myososrus* and *Psilamonocolpites* sp. were documented. Also recovered were the brackish water elements *Acrostichum aureum*, *Pachydermites diederixi*, *Psilatricolporites crassus*, *Marginipollis concinnus*, *Verrutricolporites* sp.; and lowland rainforest species *Brevicolporites guinetii*, *Polypodiaceoisporites* sp., *Stereoisporites* sp., *Canthium* sp., with common records of *Monoporites annulatus*, and regular occurrences of freshwater algae *Botryococcus braunii*. This is in association with spot records of the dinoflagellate cysts *Lingulodinium machaerophorum*. The occurrences of freshwater algae *Botryococcus braunii*, freshwater swamp species *Laevigatosporites* sp. and dinoflagellate cysts *Lingulodinium machaerophorum* indicate short times of marine transgressions during a predominantly wet climate (Wall *et al*., 1977; Wrenn and Kokinos, 1986; El Beialy and Ali, 2002). Conversely, the presence of savanna pollen at the top of this informal zone possibly suggests a short dry period after a predominant wet climate. Conclusively, the zone is defined by marine transgressions with frequent fresh water influx and alternation of wet and dry climatic conditions (Poumot, 1989).

iv) *PAZ B2 (1650-1500 m)*

The PAZ B2 is the palynological assemblage zone is located directly on top of PAZ B1 and beneath PAZ B3 in the Uk-4 well (Fig. 3). This palynological assemblage zone is partly related to the upper part of subzone P840 and lower part of P850 of Evamy et al. (1978), and floral zone M3 of Morley and Richards (1993). The bottom of this informal zone was characterized at depth 1650 m, which is defined by the occurrences of *Monosporites annulatus*, *Acrostichum aureum* and *Laevigatosporites* sp. (Fig. 3). The peak of the zone is defined by abundant records of the mangrove pollen, together with the freshwater swamp species *Laevigatosporites* sp. This zone is further characterized by common records of the freshwater swamp species *Retitricolporites irregularis*, *Striatricolpites catatumbus*, *Crototricolporites crotonoisculptus* and *Brevicolporites guinetii*. Also recovered were the brackish water elements *Pachydermites diederixi* and *Psilatricolporites crassus* with moderate records of freshwater algae. This is in association with spot records of the marine palynomorphs *Polysphaeridium zoharyi*, *Spiniferites ramosus*, *Nematosphaeropsis labyrinthus*, *Impagidinium* sp., *Lejeunecysta* sp., and microforaminiferal wall linings; and fungal elements. This palynological assemblage implies deposition in a marginal marine environment with frequent freshwater incursions (Wall *et al*., 1977; Wrenn and Kokinos, 1986; Poumot, 1989; El Beialy and Ali, 2002).

v) *PAZ B3 (1500-1350 m)*

The PAZ B3 is the shallowest palynological assemblage zone in the Uk-4 well that is located directly on top of PAZ B2 (Fig. 3). This palynological assemblage is partly related to upper part of subzone P840 and lowermost part of P850 of Evamy *et al*. (1978). It is also related to the uppermost part of M3 and lowermost part of M2 of floral zone of Morley and Richards (1993). The upper boundary of this informal zone was defined at 1359 m (Fig. 3) that is the shallowest, youngest and last of the analyzed sample of the UK-4 Well. The base had been defined by the *Retibrevitricolporites protudens/obodoensis*. Within this assemblage zone were abundant records of the grass pollen *Monoporites annulatus* and other savanna palynomorphs especially *Cyperaceapollis* sp., *Peregrinipollis nigericus*, *Multiareolites formosus*, *Fenestrites spinosus*, *Echitricolporites spinosus*, *Proteacidites cooksonni*, *Numulipollis neogericus*, *Polyadopollenites vancampoi* and charred graminae cuticle. Moderate records of *Zonocostites ramonae*, freshwater swamp species, palmae species and brackish water elements and low occurrence of lowland rainforest species were all documented within the zone. Common fungal elements with spot occurrences of the dinoflagellate cysts *Polysphaeridium zoharyi*, *Spiniferites ramosus*, *Nematosphaeropsis labyrinthus*, *Impagidinium* sp., *Spiniferites* sp., the acritarch *Leiosphaeridia* sp. and sparse records of freshwater algae occurred within the interval. This assemblage suggests deposition in a marginal marine environment with rare freshwater incursions during fall in seal level (Wall *et al*., 1977; Wrenn and Kokinos, 1986; Poumot, 1989; El Beialy and Ali, 2002). There was a marked interplay of wet and dry climate within this zone. The mangrove pollen, *Zonocostites ramonae*, which is a wet climate indicator was moderate in abundance within depth intervals 1510-1450m. However, from 1450-1410m depth intervals the savanna pollen (*Monoporites annulatus*) peaked, which suggests some dryness (Poumot, 1989; Morley and Richards, 1997).

Palaeoenvironmental deductions

The usage of the ratios of marine elements to land derived palynomorph taxa suggested that the studied sediment of the UK-4 Well fluctuated between near shore/coastal deltaic and marginal marine paleoenvironments. The moderate to abundant occurrences of the mangrove pollen in association with regular freshwater species and freshwater algae indicate deposition in a near-shore/coastal deltaic setting. Conversely, the incursion of marginal marine palaeoenvironment is defined by occurrence of dinoflagellate cysts especially *Nematosphaeropsis labyrinthus* and *Impagidinium* sp. The presence of *P. zoharyi* may suggest the frequency of tropical to subtropical climatic conditions during the deposition that make up the PAZ A2 and PAZ B3, as postulated for the Pliocene in the Kareem Formation of Gulf of Suez, Egypt (Pocknall *et al*., 1999).

Well log analysis

Well log patterns/shapes

Gamma ray log and results from sedimentological analysis of ditch-cutting samples were employed to delineate the facies and environments of deposition in this investigation. The GR-log patterns distinguish mostly into four classes i.e., funnel-shaped, cylindrical/box car-shaped, bell-shaped and Irregular trends sequences (Fig. 4).

i) *Funnel-shaped sequences*

The gamma ray log trends of Uk-4 that are encountered at depth intervals 2075-2000 m, 1990-1958 m, 1766-1740 m and 1740- 1680 m are indented funnel-shaped with thicknesses of about 75 m, 32 m, 25 m and 60 m, respectively (Fig. 4). The pattern is regularly understood to indicate deposition of coarsening upward sediment or shale content reduction of the turbidite bodies, as relayed to a deep marine setting. The environments of shallowing-upward during fall in sea-level were responsible for this sequence (Selley, 1998). However, this environment is further divided into three groups, which are regressive barrier bars, prograding marine shelf fans and prograding delta or crevasse splays (Selley, 1998). The first two of these depositional environments are usually formed with carbonaceous detritus and mica (Selley, 1998). It is not possible that these features are present in the well, since the description of the ditch-cutting samples from this study lack any of these accessories. The absence of these accessories in the Uk-4 well studied section eliminates the possibility of the environment being regressive barrier bar or prograding marine shelf. The environments of these sequences of Uk-4 well can then be interpreted to indicate a prograding delta. This is also supported by the relatively large thickness values of these sequences that range from 25 m to 75 m (Fig. 4).

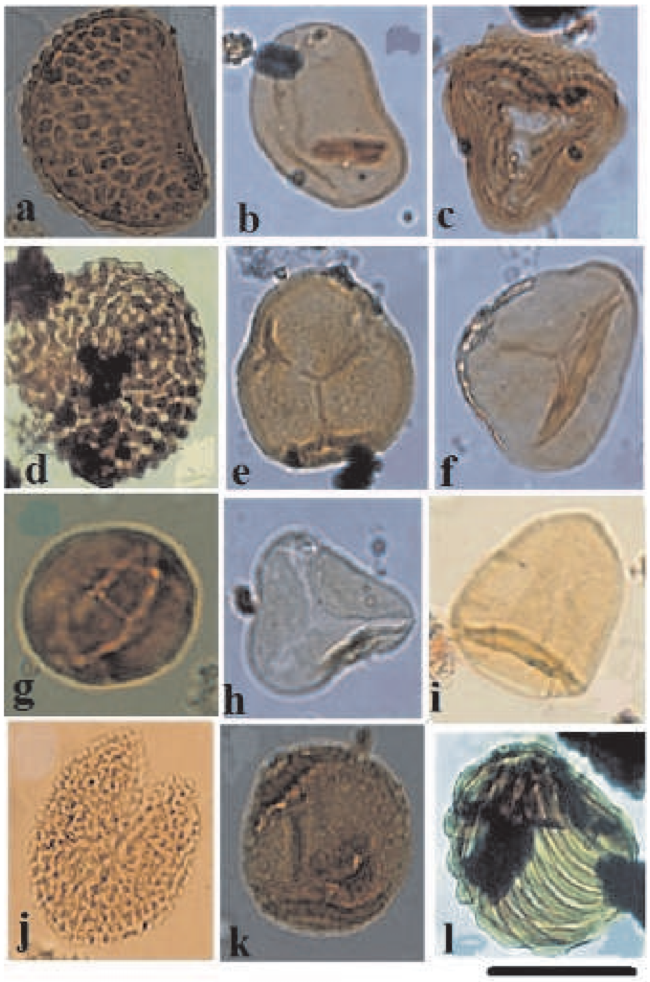

Plate 1: Photomicrographs of selected Palynomorphs (scale bar = 10μm). a) *Verrucatosporites* sp. (1420m)W28/4; b) *Laevigatosporites* sp. (1610m) H45/2; c) *Polypodiaceoisporites* sp.(1560m) J34/2. d. *Crassoretitriletes vanraadshooveni* (1420m) K37/3.e) *Stereisporites* sp. (1980-2040) O19/4. f) *Acrostichum aureum* (1420m) W38/4. g) *Zonocostites ramonae*, (1440m) V28/3. h) *Elaeis guineensis* (1610m) H29/2 i) *Cyperaceaepollis* sp. (1760m) F26/4; j) *Racemonocolpites hians* (1440m) N43/3; k) *Retibrevitricolporites protrudens/obodoensis* (1520m)U36/4; l) *Magnastriatites howardi* (1800m) N43/2.

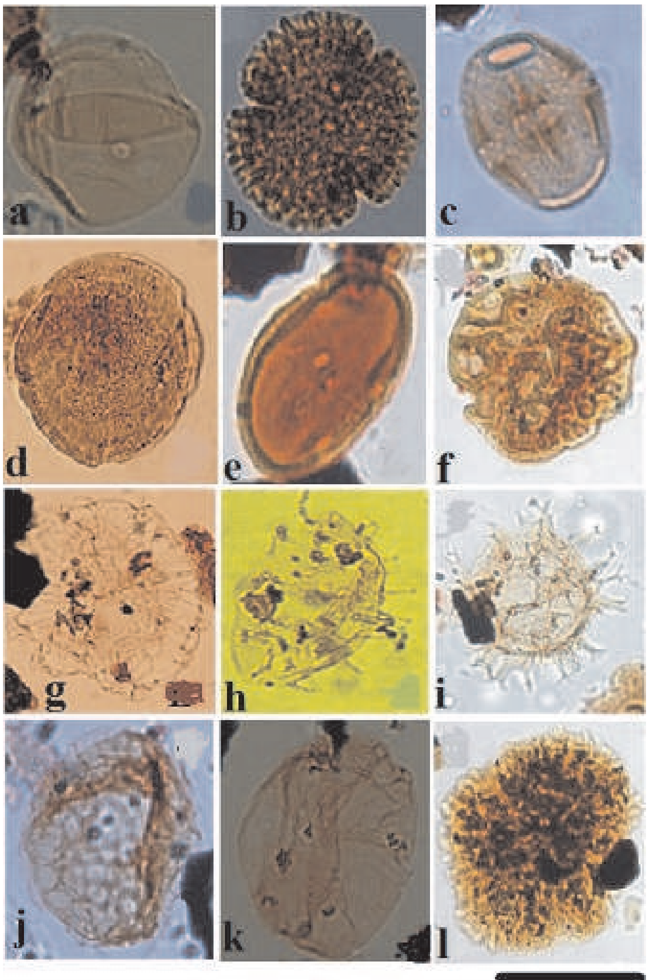

Plate 2: Photomicrographs of selected Palynomorphs (scale bar = 10µm). a) *Monoporites annulatus* (1760 m) S45/2; b) *Retitricolporites irregularis* (2110 m) D28/0; c) *Sapotaceoidaepollenites* sp. (*Psilastephanocolporites laevigatus* (1840 m) G48/2; d) *Psilatricolporites crassus* (1590 m) L48/2; e) *Multiareolites formosus* (1560 m) G25/1; f) *Peregrinipollis nigericus* (1470 m) J22/1); g) *Nematosphaeropsis labyrinthus* (2100 m) G42/1; h) *Polysphaeridium zoharyi* (2110 m) N38/3; i) *Spiniferites ramosus* (1580m) T43/4; j) *Impagidinium* sp. (1610m) O42/1; k) *Lejeunecysta* sp. (2115m) R36/3; l) *Botryococcus* (1610m) S28/2.

Chow *et al*. (2005) concluded that the prograding delta is comparatively having larger scale than the crevasse splay. Chan and Dott Jr. (1986) recognised prograding successions in Eocene Wave-Dominated Deltaic Complexes, Southwestern Oregon1 to be developed by variations in shoreline progradation, basin subsidence, sea level change, or an amalgamation of these processes. This succession is made up of fluvial, marsh-swamp, delta-distributary channel, delta-front, prodelta-shelf, and delta-margin facies.

ii) *Cylindrical-shaped sequences*

The cylinder-shaped GR-logs observed in this study are indented at depth intervals 1900-1866 m, 1648-1618 m and 1578-1556 m with thicknesses of 34 m, 30 m and 22 m, respectively (Fig. 4). The upper and lower boundaries of these sand sequences are sharp and bounded by mudstone. Cylindrical-shaped gamma ray logs in this study could be interpreted as a basin floor fans and channel fill environments as previously reported in North Sea and Niger Delta Basins (Shanmugam *et al*., 1995; Onayemi and Oladele, 2014; Olayiwola *et al*., 2021). Cylindrical trends with greater range of thickness are similar to those seen in Uk-4 well that interpreted as turbidite sands (Emery and Myers, 1996; Fig. 4). The turbidites are forms from turbulent current of sediment-laden turbidity current down a slope on the sea floor. The turbidite sands connected with the studied well belong to the upper Akata Formation of the Niger Delta that is comprised reservoir sands in the deep-water environment (Tuttle *et al*., 1999; Odundun and Nton, 2012).

iii) *Bell-shaped sequences*

The bell-shaped GR-logs in the Uk-4 well were found at depth intervals 1945-1900 m, 1866-1826 m and 1528-1468 m, with thicknesses 45 m, 40 m and 60 m respectively (Fig. 4). The bell-shaped sequences are regularly investigative of transgressive sand, tidal channel or deep tidal channel and fluvial or deltaic channel. Bell shaped successions with carbonaceous detritus are formed in environments of fluvial or deltaic channels (Selley, 1998). Absence of carbonaceous detritus in the samples remove the possibility of the environment being fluvial or tidal channel. Weber (1971) concluded that most cycles of sedimentation begin with the erosion of underlying sand unit and the deposition of a thin fossiliferous transgressive marine sand. Since the bell-shaped encountered in the Uk-4 well are of large scale, this gives the possibility that the tidal channels environment being transgressive marine environment. Nelson and James (2000) indicated that tidal channels commonly contain glauconite and shell debris. The occurrence of these accessory minerals in the Uk-4 well ditch-cuttings samples suggest the possibility of the environment being tidal channel environment. Previous findings have interpreted the bell-shaped gamma ray logs in the offshore Niger Delta and Douala Basins to be tidal channel environment (e.g., Odundun and Nton, 2012; Onayemi and Oladele, 2014; Chongwain *et al*., 2019).

iv) *Irregular log trends*

The irregular trend occurred below the funnel-shaped

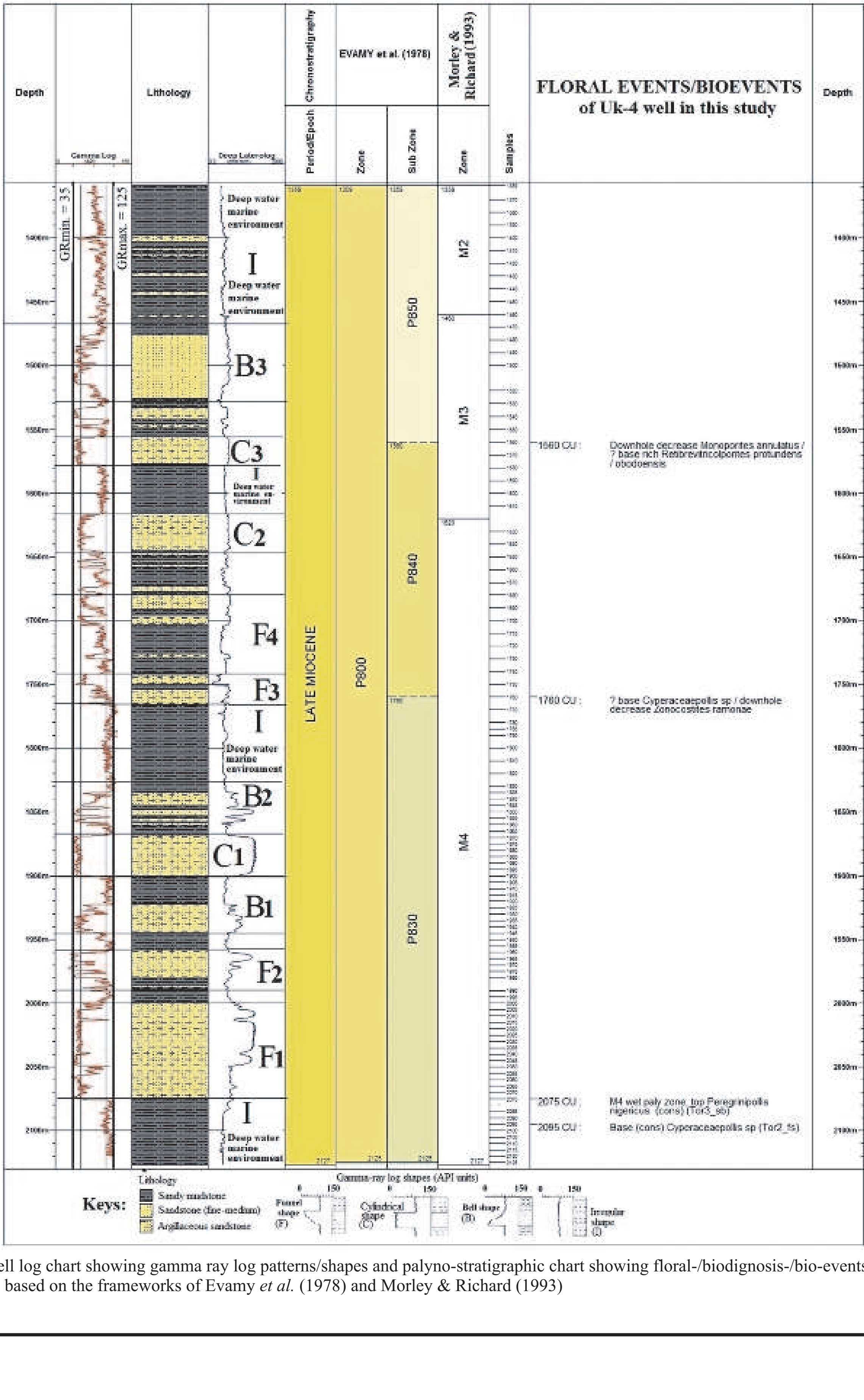

Fig. 4: Well log chart showing gamma ray log patterns/shapes and palyno-stratigraphic chart showing floral-/biodignosis-/bio-events of Uk-4 well based on the frameworks of Evamy *et al.* (1978) and Morley & Richard (1993)

successions at depth intervals 2125-2075 m and 1830-1770 m, and on top of bell-shaped and cylindrical/box car-shaped sequences at depth interval 1610-1580 m and 1470-1359 m, respectively of Uk-4 well (Fig. 4). These trends show no character and representing aggradation of shale or mudstone sediments. These trends have been previously observed by Emery and Myers (1996). The sedimentology analysis of ditch-cutting samples at these depth intervals indicates occurrence of mudstone (Fig. 4). The irregular log shape facies is categorized by deep water marine environment (Fig. 5). The environment of deposition is typically layers of fine silts and clays deposited from suspension at low energy, which is characterized by little lithologic changes, which occur during sea transgression (Coleman and Prior, 1980). Due to the basin-like shape of the ocean floor, the mud facies that is farthest away from continental margin is the only facies that make up the marine environment (Gary, 2009). However, the presence of shale or mudstone can economically serve as seals above and around the reservoir rocks as previously shown by many workers (Downey, 1984; Faerseth, 2006; Freeman, 2016). Moreover, when shale or mudstone is organically rich and matured it could serve as source rock (James, 2000; Gautier, 2005; Pollastro, 2021).

Shale content (shale volume) determination

The results of the shale content investigation demonstrate that shale volume is commonly low percent in all reservoir sands outlined in this investigation, which vary from 0.7% to 18.0% (Tables 1). However, many published works have revealed that reservoirs with low shale content are deduced to be clean zones and as well expected to be productive. Moreover, reservoir sands associated with low shale content are suggested to be very good to excellent hydrocarbon bearing sand-facies reservoirs in the Niger Delta Basin (Alao and Oludare, 2015; Olayiwola *et al*., 2019). However, having knowledge of Vsh is an essential factor to be considered in calculating the water saturation and formation evaluation (Adagunodo *et al*., 2017; Moradi *et al*., 2016; Mkinga *et al*., 2020). Nonetheless, corrections for shale content are very important to be relevant in a formation evaluation so that the porosity and water saturation will not over or underestimate the reserves (Iqbal and Rezaee, 2020).

Table 1: Volume shale (Vsh) of reservoirs of Uk-4 well

	Reservoirs	Depth intervals (m)	Thickness (m)	Gamma Ray Index (IGR)	Shale volume (Vsh)
1	F1	2075-2000	75	0.222	0.064
2	F2	1990-1958	32	0.111	0.027
3	B1	1945-1900	45	0.222	0.064
4	C1	1900-1866	34	0.033	0.007
5	B2	1866-1826	40	0.333	0.11
6	F3	1766-1740	25	0.444	0.18
7	F4	1740- 1680	60	0.222	0.064
8	C2	1648-1618	30	0.111	0.027
9	C3	1578-1556	22	0.033	0.007
10	B3	1528-1468	60	0.033	0.007

Conclusion

The integration of lithologic, palynogical and well log data from deep offshore western Niger Delta, Nigeria leads to the drawing of the following conclusions:

I. Lithostratigraphic and well log analyses of Uk-4 Well revealed three lithological types namely sandstones, argillaceous sandstones (siltstones) and sandy mudstones (claystones). The sandy mudstones lithologies are most likely the seal and source rocks, while sandstones and argillaceous sandstones lithologies could be the reservoir rocks in the Niger Delta Basin.

ii. Palynological analysis revealed sixty-nine palynomorph species belonging to 22 genera, which is dominated by angiosperm assemblages and common occurrences of monolete and trilete fern spores, algae, fungal spores and marine palynomorphs. In addition, seven ecological groups of palynomorphs, which comprise freshwater, savanna, brackish water swamp, mangrove, lowland rainforest, palmae and beach were delineated.

iii. Moreover, the recovered palynomorph assemblages associated with the *Echitricolporites spinosus* Pan-tropical zone of Germeraad *et al*. (1968), P800 zone of Evamy *et al*. (1978), J2-J3 zones of Legoux (1978) and M4, M3 and M2 of Morley and Richards (1993), and hence, the penetrated data of Uk-4 Well was dated late Miocene.

iv. Two major informal palynological assemblage zones A and B that are subdivided into A1, A2, B1, B2 and B3 subzones were identified. These palynological assemblages suggests the deposition in a nearshore/coastal deltaic paleoenvironments.

v. The gamma ray log qualitative analysis revealed five gamma-ray log shaped sequences, which are irregular trends, funnel-shaped, cylindrical-shaped and bell-shaped sequences. Deep and shallow marine depositional environments (Fig. 5), which comprise deep water marine, and prograding delta, channel fill and tidal channels environments of deposition are inferred from irregular trends, funnel, cylindrical and bell shapes, respectively, of Uk-4 Well gamma ray log. The mud facies served as seal rocks in the Niger Delta.

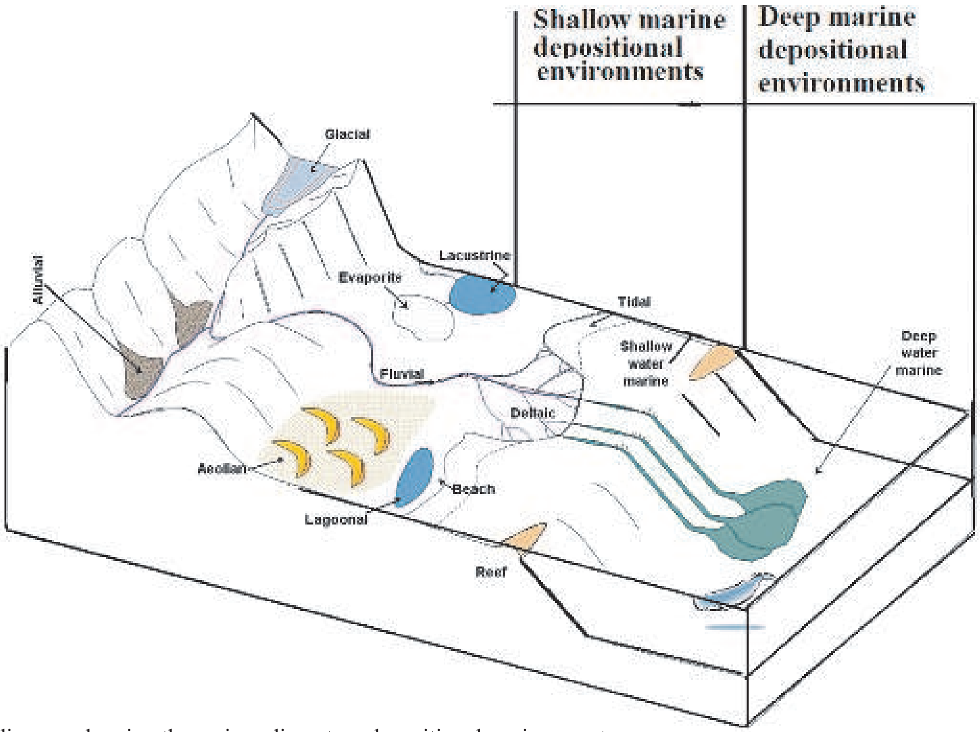

Fig. 5: Schematic diagram showing the main sedimentary depositional environments.

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