Petroleum of the Deep: Palynological proxies for palaeoenvironment of deep offshore upper Miocene-Pliocene sediments from Niger Delta, Nigeria

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Better understanding of the palaeoenvironments under which the lithologies of the deepwater petroleum systems were deposited is necessary to unravel the problem surrounding the deep offshore petroleum exploration and production. Therefore, the integration of palynological, lithological and gamma ray log data of ditch-cutting samples from wells A and B from the Niger Delta region are utilized to delineate the upper Miocene-Pliocene depositional environments. The detailed palynological analysis revealed diverse and abundant palynomorph assemblages, which consisted of angiosperm pollen 85.7%, monolete spores 5%, fungal elements 4%, trilete fern spores 4%, freshwater algae 1% and marine elements 0.3%. Eight informal palynological assemblage zones (PAZ I–PAZ VIII) with corresponding eustatic sea level changes are delineated in Wells A and B. Four lithofacies, namely sandstones, siltstones, claystones and mudstones, are recognized in association with three depositional environments in the studied wells. Distributary channels are characterized by the erosive base and filled with moderate to fine, uniform and blocky sand-grain size sediments that are of good reservoir quality. Mud-rich sediments, which are of excellent sealing rock potential, capped this sand formation. Moreover, tidal channels are typified by the erosive base and filled with fining-upwards sand sequences with tops covered by muddy sediments. Finally, the regressive barrier sands are filled by coarsening-upwards sediments with basal organic-rich deposits that are likely to be good quality source rock. The oil potential of these sites is of interest to the oil company and the reconstructed palaeoenvironments will be useful for deepwater exploration and exploitation, and probably remove or minimize the risks that are commonly involved in this task.

Key words: palynological proxies, palaeoenvironments, lithofacies, deep offshore, ditch-cuttings, late Miocene-Pliocene, petroleum systems, Niger Delta

INTRODUCTION

The pursuit of petroleum resources has driven exploration and production from onshore terrains into offshore environments, which are geographically and geologically complex.

Deep-water exploration and production is a high-risk venture (Fadiya 2014). These include harsh offshore environments such as severe weather, ice and storms that pose engineering challenges to offshore drilling equipment, and risk due to incidents that may represent challenges for emergency preparedness. In addition, there are risks due to major hazards, occupational injury and illness (Vinnem 2010). The extremely high cost of maintenance of drillship/semisubmersibles, installation, and the decommissioning of the offshore structures also pose another problem to the deep-water exploration and production (Saifullah & Pudjihanto 1996; Byrd *et al*. 2014). Target missing and subsea blowout due to overpressured shale during drilling further complicates the risk and expenses for the oil and gas industry in the offshore terrain. The 2010 deepwater horizon drilling rig explosion and oil spills in the Gulf of Mexico are a typical example of this scenario, where many lives were lost and several billions of dollars were spent to stop and clean oil spillage.

Therefore adequate knowledge of the palaeoenvironment of the petroleum system, such as source, reservoir, and cap or seal rocks of the deep offshore area, is essential to guarantee the safety of the rig personnel and marine life in particular, and to reduce the overall cost of deep offshore exploration and production (Magoon & Dow 1994; Magoon & Schmoker 2000). In order to achieve this goal, it is imperative for us to have a better understanding of the environment under which the lithologies of this petroleum system were deposited.

The common deep offshore petroleum system was the shale-sandstone interaction where shale formed the source and seal rocks and sandstone formed the reservoir rock. The Gulf of Mexico (McDade *et al*. 1973; Hood *et al*. 2002), Niger Delta (Ekweozor & Daukoru 1994; Kulke 1995;Tuttle *et al*. 1999) and Bengal (Shamsuddin *et al*. 2001) basins are typical examples of this system. However, limestone occasionally can serve as both cap rock, when its matrix is tightly connected, and reservoir rock when it is fractured (Shamsuddin *et al*. 2001). Evaporite is, in addition, a potential deep-water reservoir rock (Hood *et al*. 2002). The shale-sandstone facies which generally make up the petroleum system elements occur either as transgressive-regressive sequences during the gradual rise and fall of the sea level relative to the land, or as turbidite deposits in deepwater offshore (Tuttle *et al*. 1999; Hood *et al*. 2002).

During the sea level rise the fining- or deepening-upward sediment sequences will be formed in the subaerial delta plain as channels, inter-distributary bay, crevasse splay and levee deposits (Horne *et al*. 1978; Coleman & Prior 1981). In contrast, coarsening- or shallowing-upward sediment sequences will be deposited during sea-level fall in the subaqueous delta plain that comprises distributary-mouth-bar, river-mouth tidal-ridge and subaqueous slump deposits (Coleman & Prior 1981). High representation of coastal miospores such as those from mangrove, beach, brackish and rainforest environments compared to minimal hinterland miospores, i.e. savanna and montane types , characterize subaerial sediments that were deposited during sea level rise; the opposite represents sea level fall (Morley 1995; Rugmaia *et al.* 2008).

Variations in the abundance of some spore and pollen taxa relate well to changes in eustatic sea-level and hence palynological analyses offer a proxy for the understanding of sea-level rise and fall (Poumot 1989; Morley *et al*. 2004). For instance, low eustatic sea level that is correlated with dry climatic conditions is characterized by an abundance of Poaceae pollen whereas mangrove pollen is predominant during transgressive-highstand that suggests humid climatic intervals (Morley & Richard 1993). For instance, low eustatic sea level that is correlated with dry climatic conditions is characterized by an abundance of Poaceae pollen, whereas mangrove pollen is predominant during transgressive-highstand that suggests humid climatic intervals (Morley & Richard 1993), or retreat of mangroves with rising sealevel and humid conditions (Ellison 1993, 2008).

Many other authors have also successfully employed the relative diversity and abundance of palynomorphs that make up the lithologies of different petroleum systems to reconstruct the palaeoenvironment of their deposition in different basins worldwide. Prominent among these are the Niger Delta Basin (Oboh 1992, 1995; Oboh *et al*. 1992; Durugbo *et al*. 2010), Sergipe Basin (Carvalho 2001, 2004), Barmer Basin (Tabaei & Singh 2002), McMurray Formation (Demchuk *et al*. 2008), Bornu Basin (Ola-Buraimo & Boboye 2011; Ayinla *et al*. 2013), Anambra Basin (Ola-Buraimo & Akaegbobi 2012), Dahomey Basin (Durugbo & Aroyewun 2012; Adeigbe *et al*. 2013), Larsen Basin (Carvalho *et al*. 2013) and the Gulf of Mexico (Barron & Oboh-Ikuenobe 2014). In particular, Oboh (1992) used palynomorphs from the middle Miocene onshore Kolo Creek Field to show that the depositional conditions were similar to today's but the climate was somewhat drier. Pollen and dinoflagellate cysts from cores from the western Niger Basin (Durugbo *et al*. 2010) showed that the Plio-Pleistocene (5.0–1.3 Ma) environment was mostly dry and there were two cooling events, possibly related to global glacial events, at –2.7 Ma and 2.0 Ma. In depth correlations by Evamy and colleagues (1978) and Morley & Richard (1993) are used as the framework for correlations in this project.

Data other than palynology have also been helpful for palaeoenvironmental reconstructions (Morley 1986). For example, gamma ray log and lithological data have been employed to delineate sub-environments of deposition such as distributary channel fill, lagoon and tidal delta, coastal barrier and delta fringe in the Niger Delta Basin, Nigeria (Oboh 1990, 1991, 1992, 1993, 1995). Seismic data is another useful tool for delineating the depositional environment (Owoyemi & Willis 2006).

The value of palaeoenvironmental interpretation in oil exploration is immense and is a major contributor to the characterization of facies, which may be of reservoir, source and seal rock potentials. Therefore palaeoecological studies will significantly increase the precision and resolution of the palaeoenvironmental interpretation that can provide templates for the distribution of lithologies and reservoir qualities to aid in the vertical and horizontal planning of wells' development (Bann *et al*. 2004; Powell & Riding 2005; Gregory *et al.* 2007).

Most previous research has been concentrated on the onshore deposits. The aim of this study, therefore, is to use the integration of palynological, lithological and gamma ray log data of ditch-cutting samples from Wells A and B from the deep offshore Niger Delta to delineate the past depositional environments or shoreline positions. This will provide a better understanding of the complex nature of the subsurface geology that is usually associated with the deep offshore settings. The findings of this study will enhance the exploration and exploitation of hydrocarbon in particular, and basin analysis in general, in the deepwater environments.

Geological setting of the study area

The study area is situated within the deep offshore (>200 m) part of the Niger Delta Basin that is located in the Gulf of Guinea, on the edge of the West African continental margin (Doust & Omatsola 1990). This basin lies between latitudes 2° and 7° N and longitudes 3° and 9° E and it is in contact with the older Cretaceous sedimentary rocks in the north, the 4000 m (13 100 ft) bathymetric contour line in the south, and the Benin and Calabar Flanks in the west and east, respectively (Tuttle *et al*. 1999; Fig. 1). This basin originated because of the tectonic activities that led to the opening of the South Atlantic in the Gulf of Guinea in the Late Jurassic-Cretaceous period. This is evidenced by the fractured zones along the oceanic crust, e.g. the Charcot fracture zone, expressed as trenches and ridges that are associated with the basin (Wolak 2011; Fig. 1).

Stratigraphically, the Niger Delta is made up of three diachronous formations, namely, in descending order: Benin Formation (continental sediments), Agbada Formation (transitional sand/marine sediments) and Akata Formation (marine sediments) (Short & Stauble 1967; Knox & Omatsola 1989; Doust & Omatsola 1990; Fig. 2). These formations are filled with time-transgressive regressive sequences of siliciclastic sediments that prograded basinward, forming depo belts, namely, Northern Delta,

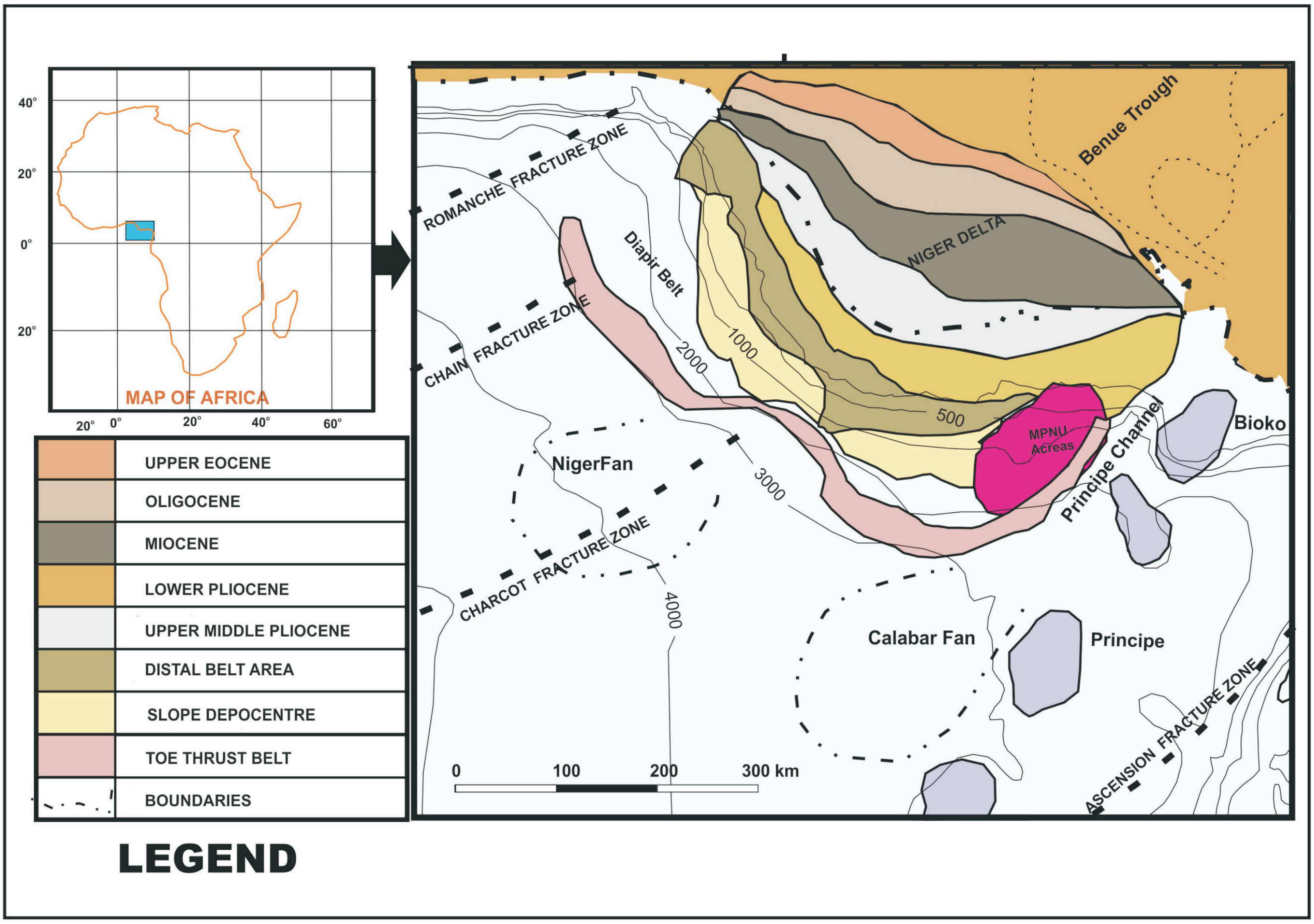

Figure 1. Location of the study area within the MPNU acreage in the southeastern offshore Niger Delta (modified after Wolak 2011).

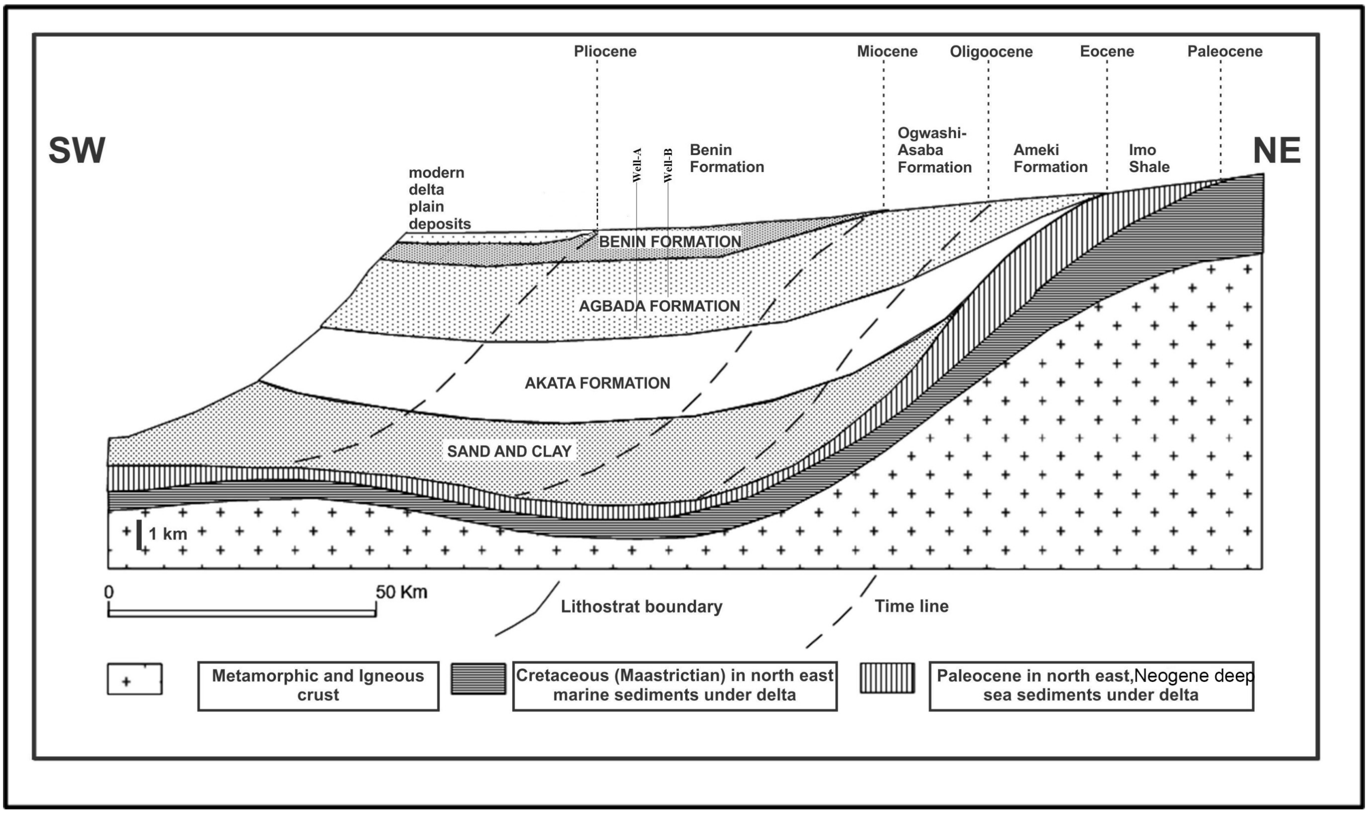

Figure 2. Stratigraphic equivalence of facies in the subsurface Niger Delta with the inferred locations of Wells A and B (modified after Wright *et al.* 1985).

Greater Ugheli, Central Swamp, Coastal Swamp, Shallow Offshore and Deepwater.

METHODS AND MATERIALS

Fifty and forty ditch-cuttings samples with Gamma ray logs of sedimentary rocks from Wells A and B, respectively, were acquired from the deep offshore Niger Delta, Nigeria. The names and locations of these wells are confidential for proprietary reasons. Therefore, these wells have been code-named Wells A and B and are located within the Mobil Producing Nigeria Unlimited (MPNU) acreage in the southeastern offshore Niger Delta (Fig. 1). MPNU acreage has been previously described (see Olayiwola & Bamford 2016). The Department of Petroleum Resources (DPR) and National Petroleum Investment and Management Services (NAPIMS) granted permission to MPNU to provide the material for the study. These acquired ditch-cuttings samples are mostly paralic Agbada Formation sediments while a few are likely to be continental Benin Formation sediments (Fig. 2).

Sample preparation for palynological data

Ninety samples from Wells A and B were used for this study. Ditch-cuttings samples are usually loose sediments and hence crushing was not needed. These samples were processed for palynomorphs following standard procedures (Faegri & Iversen 1989), which includes the addition of HCl, HF, KOH and heavy liquid separation within a saturated $ZnCl_2$ solution. Identification, counting and description were performed with a light microscope under ×400 and ×1000 magnification with the aid of reference photomicrographs published in the literature, namely: Clarke (1966); Hopping (1967); Germeraad *et al*. (1968); Legoux (1978); Salard Cheboldaeff (1979, 1990); Oboh & Salami (1989); Moore *et al*. (1991); Wood *et al*. (1996); Traverse (2007) and Durugbo *et al*. (2010). Approximately 250 pollen grains spores are counted per sample, excluding marine palynomorphs.

Species identification and pollen diagram

The identified palynomorphs are shown in Figs 3–5 with ranges and zones in Figs 6 & 7 which are based on previous work by Evamy *et al.* (1978) and Morley & Richards (1993).

The percentage abundance and the microfloral distribution trends of Wells A and B are illustrated in the Tilia (version 1.7.16) pollen diagrams (Grimm 1987; Locatelli 2011; Figs 8 & 9).

Pollen diagrams are divided into palynological assemblage zones (PAZ) for ease of interpretation. PAZ is a reflection of palynomorph compositions that can be interpreted by following an individualistic approach or CONISS (Olayiwola & Bamford 2016). Recovered pollen and spores were classified into ecological groups, namely, mangroves, brackish water swamp, freshwater swamp, lowland rainforest, savanna, freshwater algae, fungal elements and marine origin species (Table 1; Figs 6 & 7). The classification of palynomorphs into different ecological groups was based on the general assumption that nearly all the botanical families that existed during Paleogene times have an affinity with their present-day living relatives (Muller 1981).

The palaeoenvironment is herein reconstructed by reference to the models of Posamentier *et al.* (1988) as modified by Poumot (1989) and Morley (1995), which assumed landward shifting of coastlines during sea level rises and resultant deposition of marine sediments in the subaerial delta plain. There was also shifting of the mangrove and other coastal swamp plant belts during these periods due to their preference for saline water. Therefore, high representation of mangrove, other coastal swamp plants (from beach, brackish, freshwater swamp, rainforest and palm) miospores, fungal elements, freshwater algae and marine origin species characterized this depositional environment (Poumot 1989; Morley 1995; Morley *et al*. 2004; Rugmaia *et al.* 2008). In contrast, as sea level fell the coastline shifted basinward and the shelf area which was initially covered by marine water, was exposed and probably incised due to erosion caused by fluvial activities. Deposition of terrestrial sediments occurred in the subaqueous delta plain and was characterized by widespread savanna vegetation belts. Maxima spectra of savanna and montane pollen characterized this depositional environment (Poumot 1989; Morley 1995; Morley *et al*. 2004; Rugmaia *et al.* 2008).

Palynostratigraphy

The palynostratigraphical biozonation of Wells A and B are based on the recovered floral events and diagnostic bio-event species as defined by Evamy *et al*. (1978) and Morley & Richards (1993) (Figs 6 & 7). Evamy *et al*. (1978) used pollen abundance and diversity to subdivide the Palaeogene-Neogene periods of the Niger Delta Basin into eight super zones comprising P200–P900 Zones. Moreover, sixteen palynological zones were further erected for the Middle Eocene to Plio-Pleistocene segment of the Niger Delta Basin (G1–J3) by Legoux (1978); Morley & Richards' (1993) floral zonation scheme further subdivided the Miocene-Pleistocene epochs into 21 floral zones.

Sample preparation for lithological data

This analysis was carried out to provide the detailed lithological description of the strata penetrated by Wells A and B. An average of 80 g of each of the ditch-cutting samples were soaked in 250 ml aluminum containers with hot water and Sunlight™ liquid detergent for about 24 hours to disaggregate the material. The soaked samples were efficiently washed under a distilled water nozzle tap using a 63 μm mesh sieve. The retained samples on 63 μm sieve were dried over hot plates and enclosed in well-labelled drug dispensing cellophane bags.

The lithologic description followed a standard laboratory procedure whereby the washed samples, which were spread on a black anodized aluminum foraminiferal picking tray, were viewed using the binocular reflected light microscope. Gamma-ray and resistivity logs enhanced descriptions, since high and low values of GR-log and RES-log signified shale and sand lithologies, respectively (Adegoke 2002). The essential parameters studied were grain size, textures and facies changes. These lithological data were plotted, with the aid of SEDLOG™ software, to generate the vertical lithofacies profiles that were embedded in Figs 8 & 9.

Gamma ray logs (GR-logs) data

Acquired GR-logs from Wells A and B are utilized for the understanding of depositional environment changes. Natural radioactivity of rocks, which can be determined by GR-logs, shows generally a close relationship to grain size. The naturally radioactive elements are normally concentrated in shales (clay-size grains; Rider 1990). Clay is herein used in a textural sense, i.e. grain size less than 0.002 mm, which can also be used to describe lithologies, following the format of Rider (1990). Grain size and bedding of sedimentary rocks have an influence on the shape of the gamma ray log curve (https://www.spec2000.net/2-1-strat1.htm-01/12/2015). Therefore, GR-log allows the qualitative distinction of zones of shale lithology (high gamma values) from sand lithology (low gamma values). The values of these GR-logs ranged from 0–150 API units (American Petroleum Institute).

There is usually no fundamental relationship between gamma ray log data and the palynology. However, the palynological assemblages and gamma ray log exhibit cyclic changes, which have been used previously to correlate the sedimentary evolution (Sarah *et al*. 1995; Ziegler *et al*. 1997; Wagstaff *et al.* 2006; Adebayo 2014).

Hence, gamma ray curve shapes in association with vertical lithological profiles are used to subdivide the main subaerial and subaqueous delta plains, previously defined by palynomorph assemblages, into sub-environments (Selley 1985; Oboh 1995). The trend of changes of GR-log curve is herein used for the interpretation of the sedimentary depositional environments (Figs 8b & 9b).

RESULTS

The top of Well A is 716 m below sea level and the base is 3024 m below so the core represents 2308 m. Well B is presumably farther from shore and its top is 1472 m below sea level and extends down to 2542 m, so the core is 1070 m long. Nonetheless, the cores represent more or less the same time frame (based on the palynology) although core A is more than twice the length of core B. The core material from the two wells will be presented and discussed together.

Palynology

Thirty-one and 29 palynomorph species belonging to 33 genera are recorded in Wells A and B, respectively, and the palynomorph assemblages are dominated by angiosperm pollen that comprises 85.7% (Figs 8a & 9a). Monolete spores (5%), fungal spores (4%), trilete fern spores (4%), freshwater algae (1%) and marine palynomorphs (0.3%) followed this in abundance.

Palynostratigraphy

Since the palynomorphs recovered from Wells A and B were the same as those described by Evamy *et al.* (1978) and Morley & Richard (1993), their zonation schemes are used here to determine the age of the strata as well as the palaeoenvironment. The palynostratigraphic biozonation of the wells was defined using the recovered diagnostic markers and ecologically significant species. The first two informal subzones, which are established in these wells, are correlated with P860–P870 Subzones of Evamy *et al*. (1978) (Figs 6 & 7).

P800 Zone and subzone P860 (late Miocene)

The P860 Subzone is the older subzone of zone P800 in Wells A and B with the tops marked at 2548 m and 2185 m, respectively, by the quantitative base occurrence of *Retistephanocolpites gracilis*. The bases were tentatively marked at 3024 m and 2542 m which are the deepest samples analysed in Wells A and B, correspondingly. This subzone may continue below. The continuous co-occurrences of *Gemmamonoporites* sp., *Nymphaeapollis clarus, Peregrinipollis nigericus, Stereisporites* sp. and *Cyperaceaepollis* sp. characterized this subzone and, therefore, their presence indicates a late Miocene age according to the schemes of Evamy *et al*. (1978) and Morley & Richard (1993).

P800 Zone and subzone P870 (early to late Pliocene)

P870 was the youngest subzone documented in the analysed intervals of Wells A and B (Figs 6 & 7). The tops of the subzone were tentatively marked at 716 m and 1472 m which are the depths of the first samples analysed in these wells, respectively. The bases are marked by the quantitative base occurrence of *Retistephanocolpites gracilis* at 2548 m and 2185 m in Wells A and B, respectively. Co-occurrence of *Gemmamonoporites* sp. and *Retistephanocolpites gracilis* together with regular occurrences of *Nymphaeapollis clarus* and the absence of *Podocarpus milanjianus* confirmed early–late Pliocene age in this subzone.

Floral Zonation for Wells A and B

Secondly, the P860 and P870 Sub-zones of Evamy *et al*. (1978) in Wells A and B are further subdivided into seven floral zones of Morley & Richards (1993). P1 (914–716 m), Upper P3–Upper P2 (1487–914 m), Lower P3 (1679–1487 m), P4 (2045–1679 m), P6–P5 (2393–2045 m), P7 (2548–2393) and M1 (3024–2548 m) comprised floral zones in Well A (Fig. 6) while Well B comprised Upper P3 (1609–1472 m), Lower P3 (1692–1609 m), P4 (1774–1692 m), P6–P5 (1993–1774 m), P7 (2145–1993 m), M1 (2350–2145 m) and M2 (2542–2350 m) floral zones (Fig. 7).

Palynological, lithological and gamma ray data and the palaeoenvironmental reconstruction

Thirdly, eight informal palynological assemblage zones and eustatic sea level changes are recorded in Wells A and B which are designated as PAZ-1 to PAZ-VIII from the base to the top (Figs 8 & 9). Four lithofacies comprised of sandstones, siltstones, claystones and mudstones are well represented in Well A, whereas mudstones are predominant in Well B. Eight and five depositional sequences accompanied by nine and seven inferred depositional environments are recognized in Wells A and B, respec-

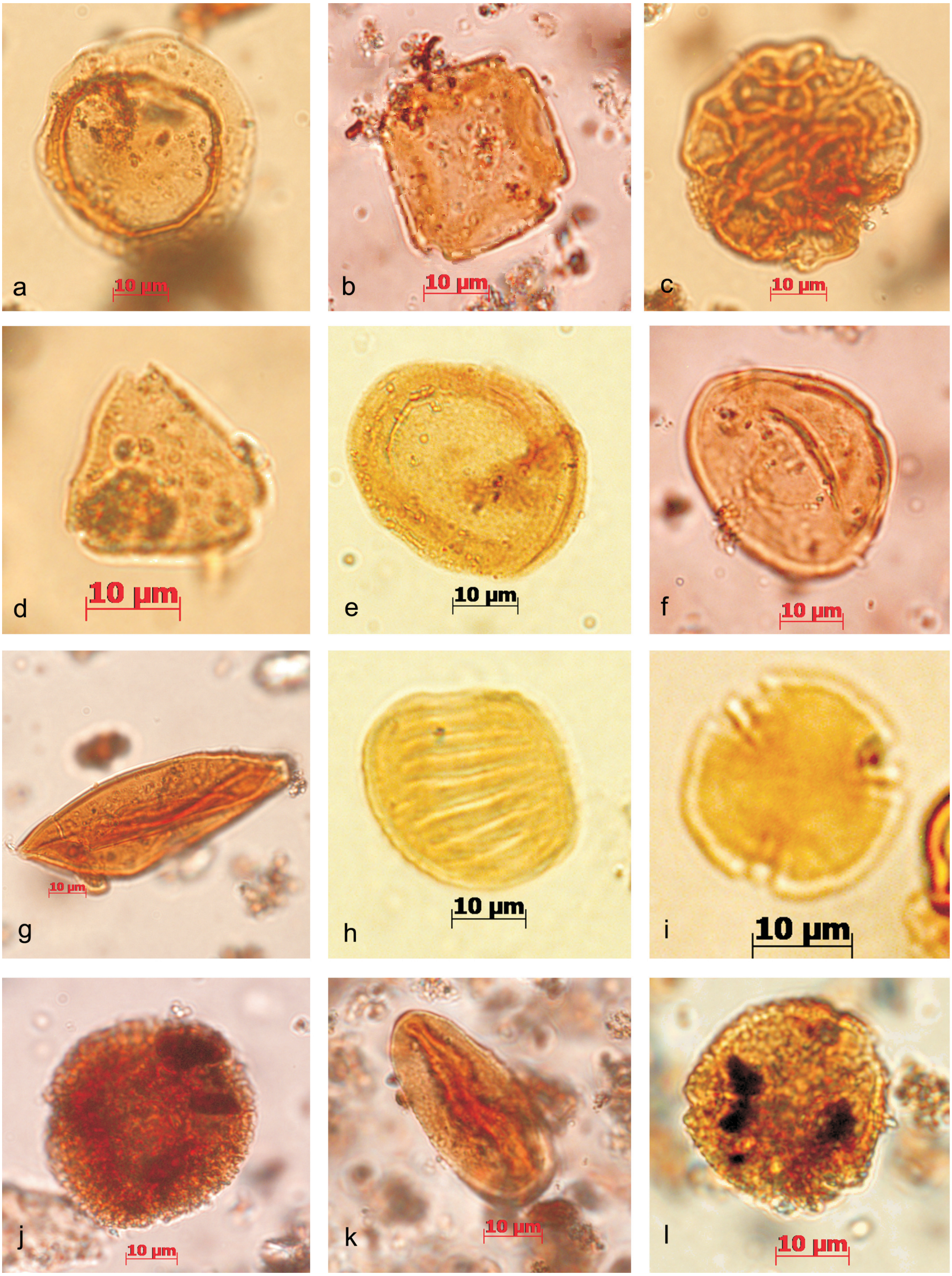

Figure 3. Common palynomorphs from Wells A and B from Niger Delta. (**a**) *Nympheaepollis clarus*; (**b**) *Pachydermites diederixi*; (**c**) *Peregrinipollis nigericus*; (**d**) *Proteacidites cooksonni*; (**e**) *Proxapertites cursus*; (**f**) *Psilatricolporites crassus*; (**g**) Psilamonocolpites sp.; (**h**) *Psilastephanocolpites* sp.; (**i**) *Psilatricolpites operculatus*; (**j**) *Retitricolporites irregularis*; (**k**) *Retimonocolpites* sp.; (**l**) *Retibrevitricolporites obodoensis*.

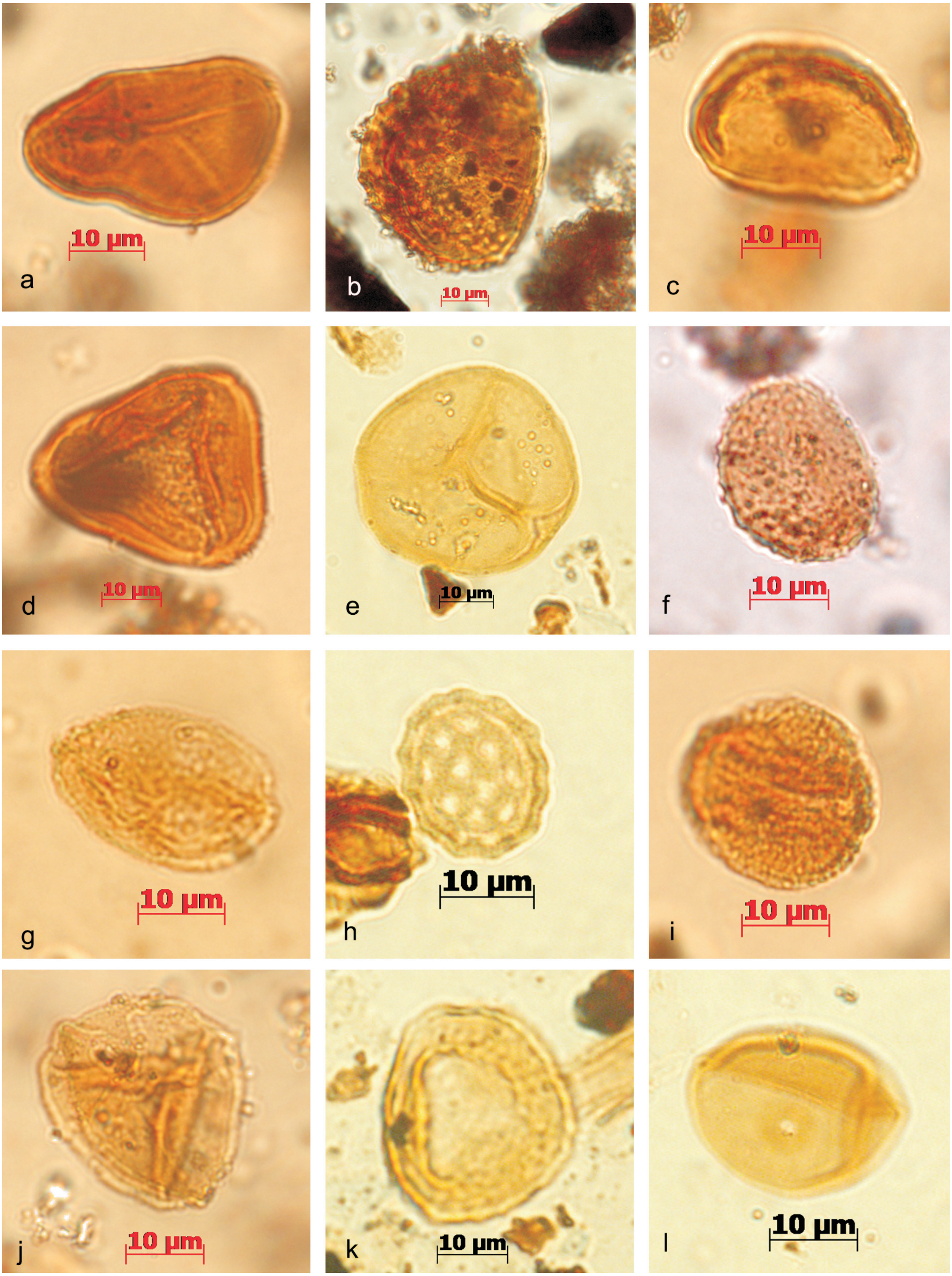

Figure 4. Common palynomorphs from Wells A and B from Niger Delta. (**a**) *Acrostichum aureum*; (**b**) *Crassoretitriletes vanraadshooveni*; (**c**) *Laevigatosporites* sp.; (**d**) *Polypodiaceoisporites* sp.; (**e**) *Stereisporites* sp.; (**f**) *Verrucatosporites* sp.; (**g**) *Arecipites exilimuratus*; (**h**) *Chenopodipollis* sp.; (**i**) *Crototricolpites densus*; (**j**) *Cyperaceaepollis* sp.; (**k**) *Gemmamonoporites* sp.; (**l**) *Monoporites annulatus*.

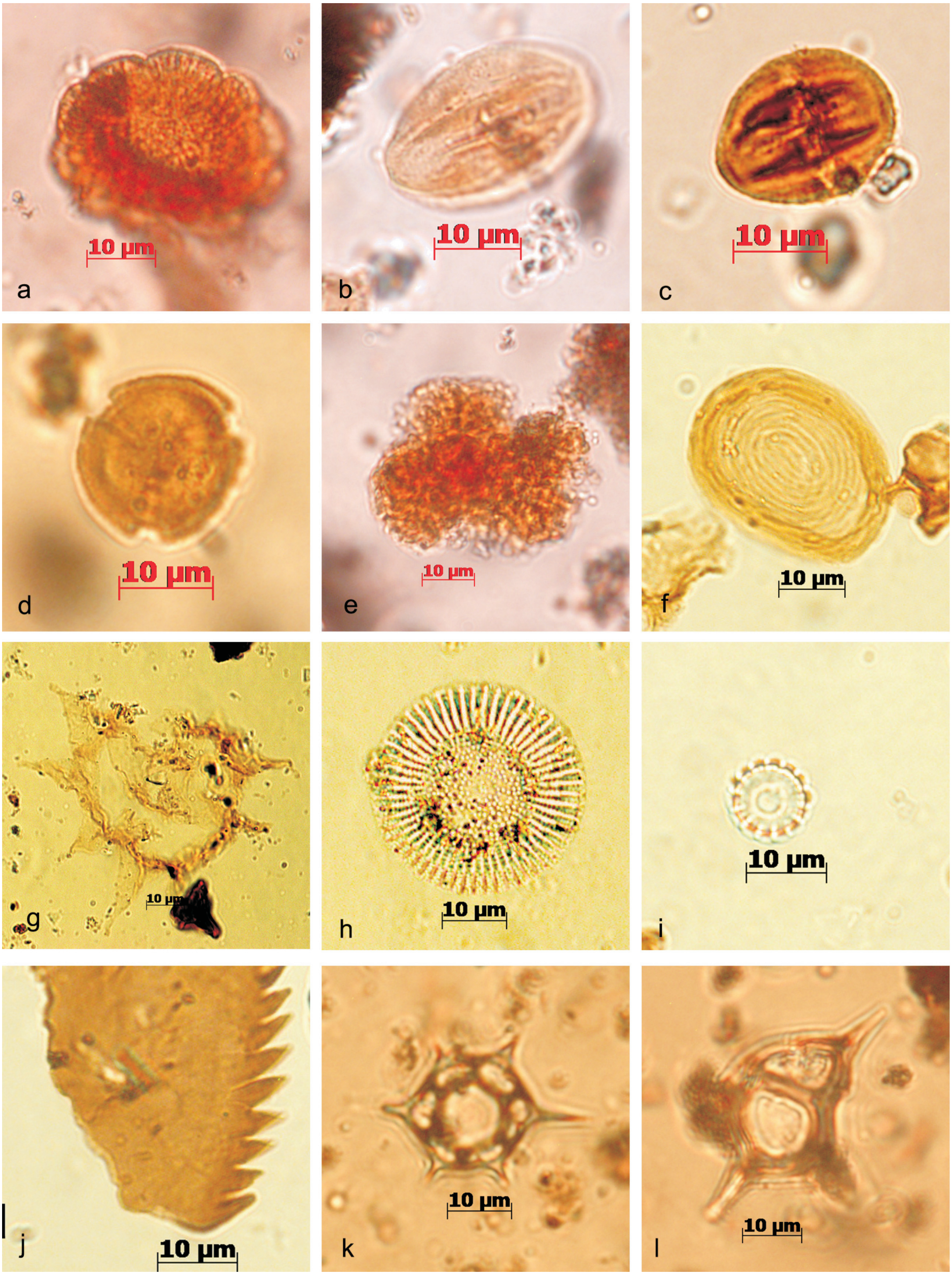

Figure 5. Common palynomorphs from Wells A and B from Niger Delta. (**a**) *Retistephanocolpites gracilis* (**b**) *Striatricolpites catatumbus*; (**c**) *Zonocostites duquei*; (**d**) *Zonocostites ramonae*; (**e**) *Botryococcus braunii*; (**f**) *Concentricytes circulus*; (**g**) *Pediastrum* sp.; (**h**) Diatom frustule 1; (**i**) Diatom frustule 2; (**j**) Scolecodont sp.; (**k**) *Distephanus boliviensis* (Silicoflagellate sp. 1); (**l**) *Naviculopsis robusta* (Silicoflagellate sp. 2).

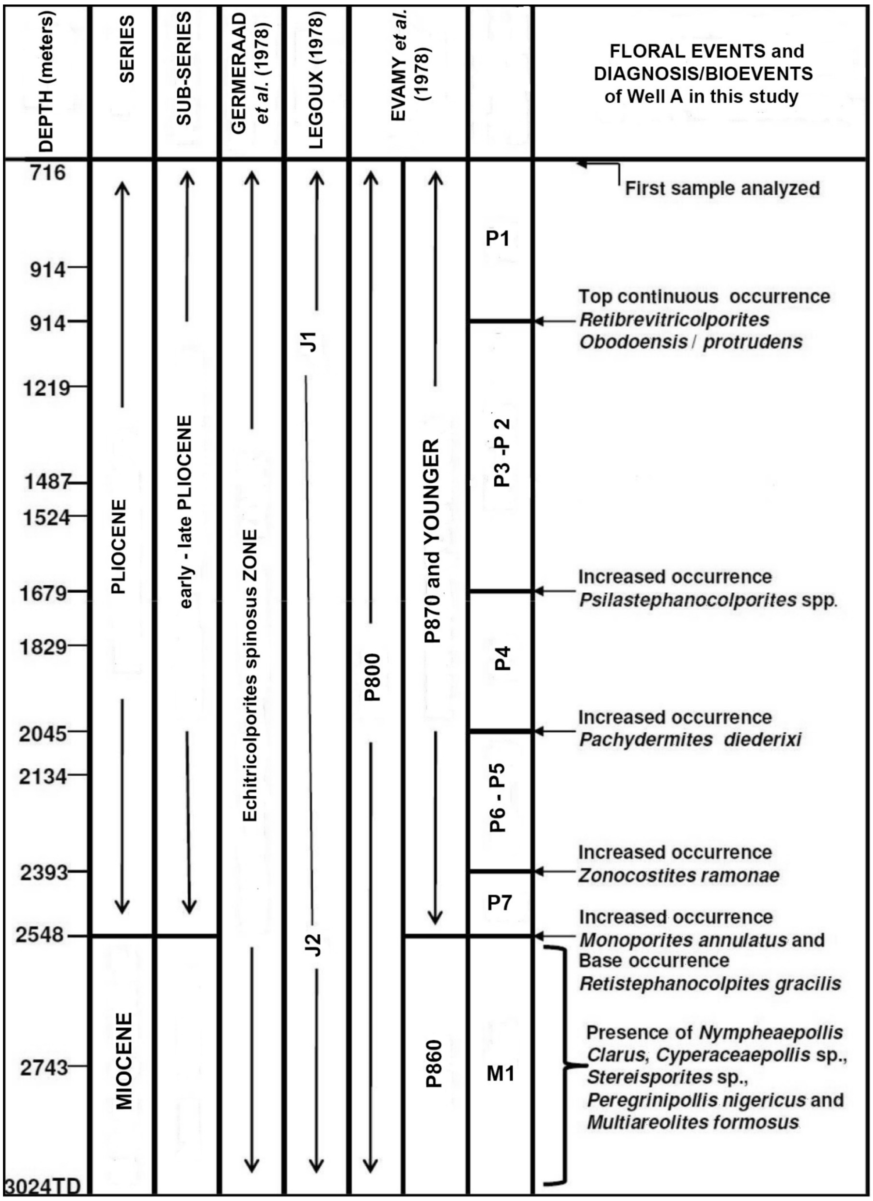

Figure 6. Chart showing palynomorph zones and subzones recognized in well A based on the frameworks of Evamy *et al.* (1978) and Morley & Richard (1993).

tively (Figs 8 & 9). These PAZs with their allied lithologies and likely inferred depositional environments are described below.

It should be noted that the ecological interpretations of the palynomorphs by Germeraad *et al*. (1968), Evamy *et al.* (1978) and Morley & Richards (1993), who have worked on the Niger Basin, have been followed here. There are other interpretations, however, for example, palms producing *Arecipites* pollen can grow along the beach (Povilaskas 2013) and inland along water courses. *Verrucatosporites* spp. represent several families of ferns (Stuchlik 2001). Cyperaceae grow in a range of poorly drained soils from permanent wetlands to dambos to patches in savanna and brackish wetlands. The Chenopodiaceae also grow in a variety of habitats but overall they indicate dry environments

PAZ-IA (2728–2289 m) and PAZ-IB (2542–2516 m); P860 Subzone (late Miocene)

PAZ-IA (from Well A) and -IB (from Well B; Figs 8 & 9) are the basal parts of the studied sections of Wells A and B. These palynofloral assemblages are correlated with P860 Subzone (of Evamy *et al*. 1978). Hence, the age of these palynozones are likely to be late Miocene. PAZs-IA and IB bases are defined by the first quantitative base increase of *Zonocostites ramonae*. The tops of this zone are marked by the first quantitative decrease of *Zonocostites ramonae* and increase of *Psilatricolporites crassus*, *Monoporites annulatus* and *Verrucatosporites* sp. PAZ-IA and 1B are dominated by mangrove, freshwater swamp, freshwater algae and marine palynomorphs (Figs 8a & 9a; Table 1). The rare occurrence of savanna pollen, fungal elements and lowland rainforest characterized this zone. Mudstone lithologies and bell-shaped gamma-ray curves are recorded for this zone.

PAZ-IIA (2899–2469 m) and PAZ-IIB (2515–2457 m); P860 Subzone (late Miocene)

These palynofloral zones are located within the uppermost parts of P860 Subzone of the analysed interval of

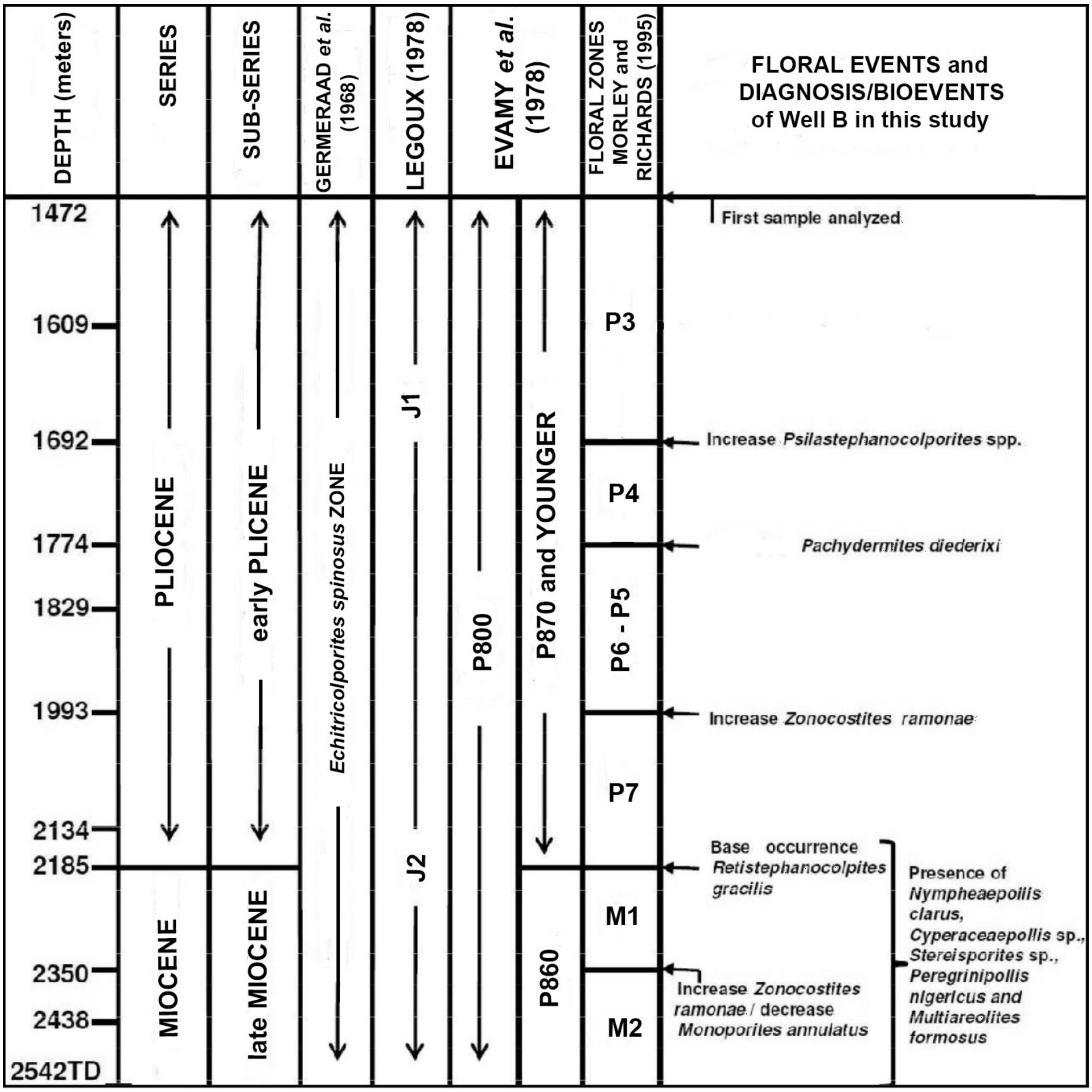

Figure 7. Chart showing palynomorph zones and subzones recognized in Well B based on the frameworks of Evamy *et al.* (1978) and Morley & Richard (1993).

Wells A and B and occurred within the uppermost late Miocene. PAZ-IIA and IIB (Figs 8 & 9) bases are marked by the first quantitative decrease of *Zonocostites ramonae* and increase of *Psilatricolporites crassus*, *Monoporites annulatus* and *Verrucatosporites* sp., while the quantitative increase of *Zonocostites ramonae* and the quantitative decrease of *Psilatricolporites crassus*, *Verrucatosporites* sp. and *Monoporites annulatus* defined the tops. These zones are characterized by the predominance of *Monoporites annulatus*, *Cyperaceaepollis* sp. *Verrucatosporites* sp. and *Acrostichum aureum* with reduced proportions of *Zonocostites ramonae*, beach and brackish miospores, algae and marine palynomorphs (Figs 3–5). Sandstone lithologies and boxcar gamma ray signatures are recognized in these zones.

PAZ-IIIA (2469–2335 m) and PAZ-IIIB (2463–2350 m); P870 Subzone (early Pliocene)

These zones that are located within P800 Zone and occurred within the early Pliocene (Zanclean) period of the analysed interval of Wells A and B. Base boundaries of these palynofloral zones are marked by the quantitative increase of *Zonocostites ramonae* and the quantitative decrease of *Psilatricolporites crassus*, *Verrucatosporites* sp. and *Monoporites annulatus*, while the quantitative decrease of *Verrucatosporites* sp. and quantitative decrease of fungal elements defined their tops. The overall prevalence of mangroves, *Laevigatosporites* sp., *Verrucatosporites* sp. and fungal elements, with reduced percentages of savanna palynomorphs, characterized these palynological zones. In these zones mudstone facies were recorded in Well A, while sandstones were upgraded to siltstone lithologies in Well B, with bell and funnel-shaped gamma ray curves, respectively, in these wells.

PAZ-IVA (2335–2155 m) and PAZ-IVB (2350–2179 m); P870 Subzone (early Pliocene)

These zones occurred in zone P800 within the early Pliocene (Zanclean). The base boundaries of these palynofloral zones are defined by the quantitative decrease of

Table 1. Distribution of recovered palynomorphs in Wells A and B.

S/No	Ecological	Genera	Species	Botanical affinities
1	Mangrove	*Zonocostites*	*ramonae*	Rhizophoraceae
			duquei	
		Psilatricolporites	*crassus*	Euphorbiaceae
2	Beach	*Arecipites*	*exilimuratus*	Arecaceae
3	Brackishwater swamp	*Pachydermites*	*diederixi*	Guttiferae - *Symphonia globulifera*
		Acrostichum	*aureum*	Pteridaceae
4	Freshwater swamp	*Nympheaepollis*	*clarus*	
		Retibrevitricolporites	*obodoensis*	Rubiaceae
		Retitricolporites	*irregularis*	Euphorbiaceae - *Amanoa*
		Gemmamonoporites	sp.	-
		Verrucatosporites	sp.	Polypodiaceae
		Laevigatosporites	sp.	-
		Striatricolpites	*catatumbus*	-
		Crototricolpites	*densus*	-
		Psilatricolpites	*operculatus*	-
		Crassoretitriletes	*vanraadshooveni*	-
5	Lowland rainforest	*Psilastephanocolpites*	sp.	-
		Stereisporites	sp.	?Sphagnaceae- *Sphagnum*
		Polypodiaceoisporites	sp.	Adiantiaceae - *Pteris*
6	Savanna	*Monoporites*	*annulatus*	Gramineae
		Cyperaceaepollis	sp.	*Cyperus*
		Proxapertites	*cursus*	Araceae- *Nypa*
		Chenopodipollis	sp.	Chenopodipodiaceae/Amaranthaceae
		Proteacidites	*cooksonni*	Proteaceae
		Peregrinipollis	*nigericus*	Caesalpinioides -Brachystegia cf. peltophorum
		Retistephanocolpites	*gracilis*	Rubiaceae-*Borreria*
		Retimonocolpites	sp.	-
7	Freshwater Algae	*Botryococcus*	*braunii*	Not applicable
		Concentricytes	*circulus*	Not applicable
		Pediastrum	sp.	Not applicable
8	Marine	*Distephanus* (*Silicoflagellate* sp.)	*boliviensis*	Not applicable
		Naviculopsis (*Silicoflagellate* sp.)	*robusta*	Not applicable
		Scolecodont	sp.	Not applicable
		Diatom	*frustule* 1	Not applicable
		Diatom	*frustule* 2	Not applicable

Verrucatosporites sp. and fungal elements, with the upper boundaries marked by the quantitative decrease of *Psilatricolporites crassus*, *Monoporites. annulatus*, peak of *Verrucatosporites* sp. and the peak of fungal elements. This palynofloral zone was characterized by the dominance of savanna, spores (*Verrucatosporites* sp. and *Acrostichum aureum*) and freshwater algae with corresponding low occurrences of mangrove, brackish water swamp, freshwater swamp, and fungal elements. Mudstones with intermittent claystones were deposited and accompanied with bell-shaped gamma ray signatures (Figs 8 & 9).

PAZ-VA (2155–1798 m) and PAZ-VB (2179–1996 m); P870 Subzone (early Pliocene)

These palynofloral assemblages are correlated with P870 Subzone within the early Pliocene (Zanclean stage). PAZ-VA and VB (Figs 8 & 9) bases are defined by the quantitative decrease of *Psilatricolporites crassus*, *Monoporites*

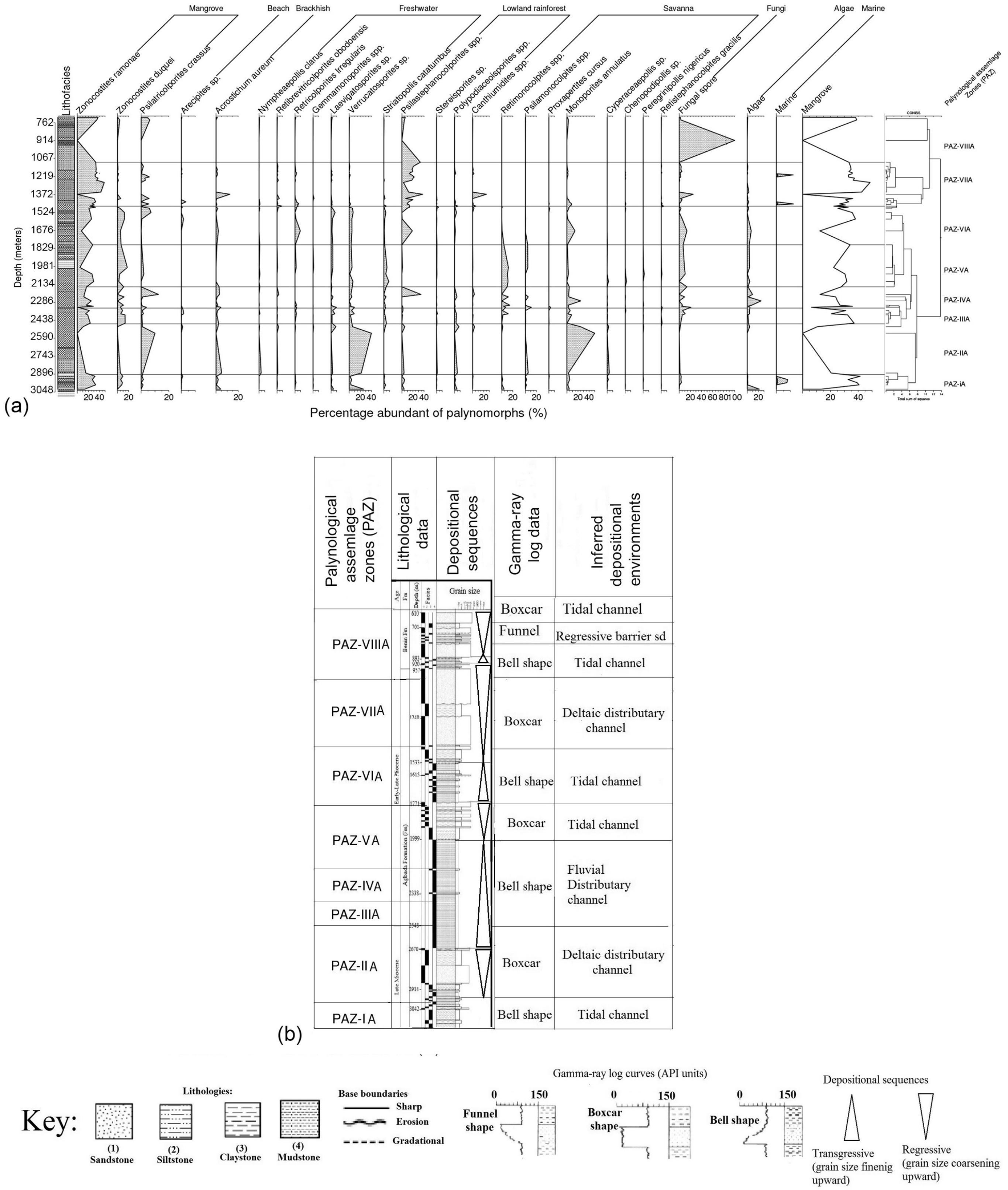

Figure 8. Chart showing integration of palynological, lithological and gamma ray log data with inferred depositional environments in Well A.

annulatus, peaks of *Verrucatosporites* sp. and fungal spores, while the quantitative peak of *Zonocostites ramonae*, quantitative increase of *Monoporites annulatus* and fungal spores marked their tops. PAZ-VA and VB are dominated by mangrove, brackish water swamp, freshwater swamp, freshwater algae, fungal elements and marine palynomorphs with the rare occurrence of savanna. Mudstones upgraded to sandstones are recognized in Well A, while mudstones facies are recorded in Well B. The accompanied gamma ray curves recorded in these zones are boxcar and bell-shaped in Wells A and B, respectively.

PAZ-VIA (1798–1469 m) and PAZ-VIB (1996–1710 m); P870 Subzone (mid-Pliocene)

These palynofloral zones are located in the middle parts of P870 Subzone of the analysed interval of Wells A and B

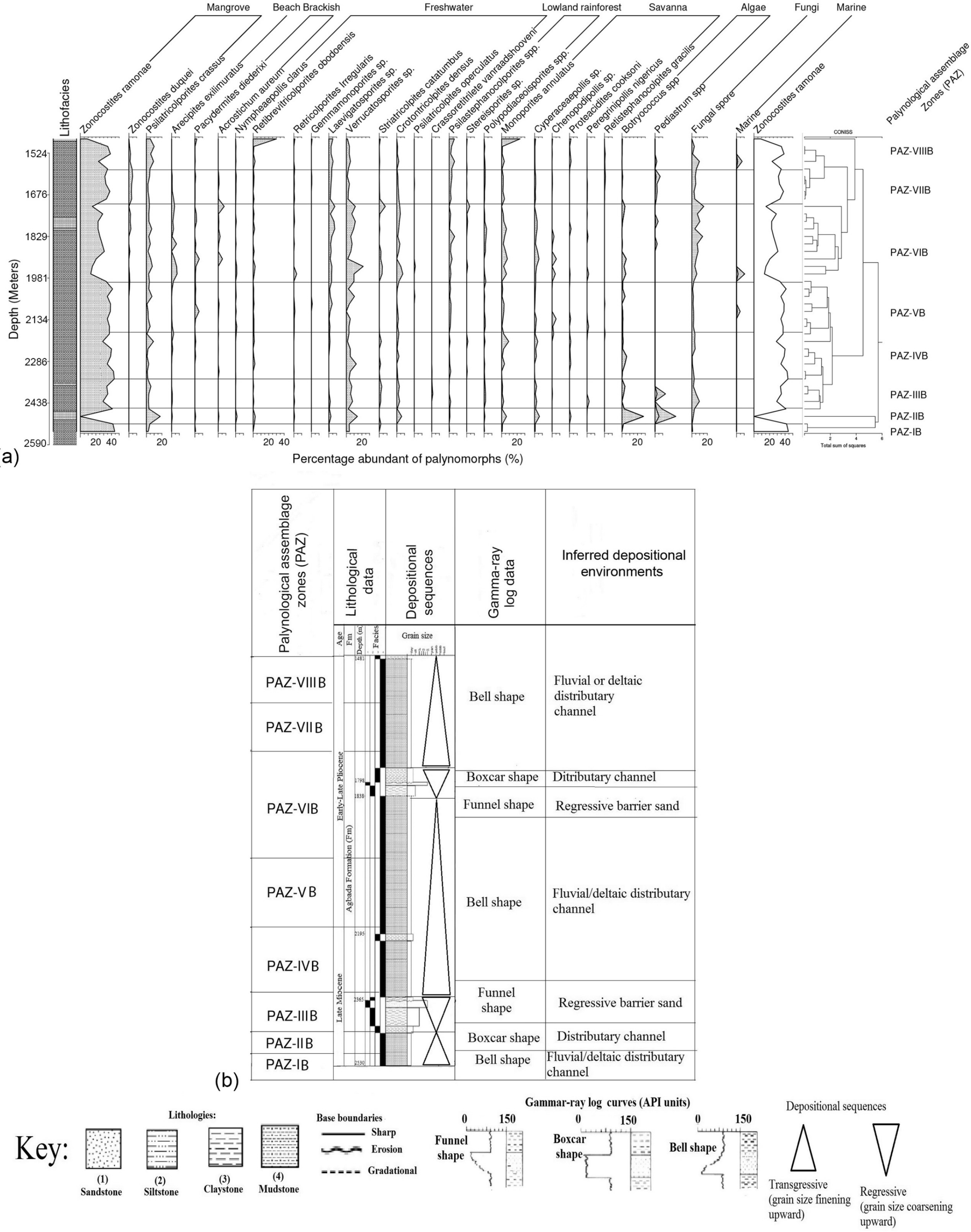

Figure 9. Chart showing integration of palynological, lithological and gamma ray log with inferred depositional environments in Well B.

(Figs 8 & 9), and occurred in the mid-Pliocene. The bases of these micro-floral zones are marked by the quantitative peak of *Zonocostites ramonae*, the quantitative increase of *Monoporites annulatus* and fungal elements, while the quantitative decrease of *Verrucatosporites* sp., the quantitative increase of *Monoporites annulatus* and the decrease of fungal elements defined their tops. PAZ-VIA and VIB are characterized by the predominance of *Monoporites annulatus*, *Cyperaceaepollis* sp. *Chenopodipollis* sp., fungal elements, *Verrucatosporites* sp., *Acrostichum aureum*, freshwater algae and marine palynomorphs with a reduced proportion of *Zonocostites ramonae*, beach and brackish miospores. The basal parts of these zones are dominated by deposition of mudstones while sandstones/siltstones lithologies were deposited in the upper parts. Bell-shaped gamma-ray signatures are recorded in these micro-floral zones (Figs 8 & 9).

PAZ-VIIA (1469–1097 m) and PAZ-VIIB (1710–1585 m); P870 Subzone (mid-Pliocene)

These palynological zones that are located within P870 Subzone and occurred within the mid-Pliocene period of the analysed intervals of Wells A and B. Base boundaries of these palynological zones are marked by the quantitative decrease of *Verrucatosporites* sp., the quantitative increase of *Monoporites annulatus* and the decrease of fungal spores. The quantitative decrease of *Zonocostites ramonae* and quantitative increase of fungal spores defined the tops of these floral zones. The overall prevalence of *Zonocostites ramonae*, *Psilastephanocolporites* sp., fungal spores and marine palynomorphs (silicoflagellates and diatoms), with rare to absent savanna, freshwater swamp, freshwater algae palynomorphs characterized these palynological zones. In these zones, sandstone facies were deposited in Well A, while mudstone lithologies were deposited in Well B. Boxcar and bell-shaped gamma-ray curves are recorded in Wells A and B, respectively, (Figs 8 & 9).

PAZ-VIIIA (1097–701m) and PAZ-VIIIB (1585–1463 m); P870 Subzone (late Pliocene)

These palynofloral zones are the uppermost part of Wells A and B and are the youngest stratigraphical zones recorded in these wells. The palynofloral assemblages occurred within P870 Subzone and dated to late Pliocene (Piacenzian statge). PAZ-VIIIA and VIIIB (Figs 8 & 9) bases are defined by the quantitative decrease of *Zonocostites ramonae* and quantitative increase of fungal elements, while the quantitative decrease of *Zonocostites ramonae*, fungal elements and quantitative increase of *Monoporites annulatus* tentatively marked their tops. PAZ-VIIIA and VIIIB are dominated by mangrove, freshwater swamp, lowland rainforest, fungal spores and marine palynomorphs (silicoflagellates and diatoms) with the rare occurrence of savanna. These zones are typified by the deposition of sandstones in Well A, while mudstone facies were deposited in Well B. The accompanied gamma ray curves in these zones are funnel and bell-shaped in Wells A and B, respectively.

DISCUSSION

The detailed palynological analysis revealed that palynomorphs form diverse and abundant assemblages in Wells A and B from the deep offshore Cenozoic Niger Delta and is supported by the previous reports from the Niger Delta (Oboh 1992; Ige 2011; Ige *et al*. 2011; Adebayo *et al*. 2012; Ojo & Gbadamosi 2013; Adebayo & Ojo 2014). The age of Wells A and B ranges from late Miocene (P860 Subzone) to Pliocene (P870 Subzone) (Evamy *et al*. 1978). The quantitative base occurrence of *Retistephanocolpites gracilis* at 2548 m and 2185 m in Wells A and B, respectively, defined the boundary between late Miocene and Pliocene that suggests the age is around 5.2 Ma (*Discoaster quinqueramus*, Morley & Richard 1993; Olayiwola 2014).

Palynofloral assemblages of Wells A and B are similar to those of West Africa and farther afield, for example, subzones P860 and P870 are correlated with the pantropical *Echitricolporites spinosus* Zone of Germeraad *et al*. (1968) and J2–J3 Zone of Legoux (1978). The base of micro-floral zone P3 of subzone P870, defined by increased occurrences of *Psilastephanocolporites* sp. at 1679 m and 1692 m in Wells A and B, respectively, suggest an age of about 4.1 Ma (*Gephyrocapsa demitre*, Morley & Richard 1993; Olayiwola 2014).

The palynological assemblages revealed that there is a landward shifting of the mangrove vegetation due to the sea level rise as shown in PAZ-IA, PAZ-IB, PAZ-IIIA, PAZ-VB, PAZ-VIIB and PAZ-VIIIB. Thick bodies of mudstone/claystone lithologies recorded at depths 2768 m, in Well A, 2469 m, and 1807 m, in Well B, on top of sandstones bodies, are likely to be overpressure zones in the studied wells. Conversely, the palynological assemblage zones PAZ-IIA, PAZ-IIB, PAZ-IIIB, PAZ-VA, and PAZ-VIIA revealed that there is a shifting of the savanna vegetation seaward during sea level fall. PAZ-VIIIA does not show any significant change in savanna pollen. It should be noted that Poaceae, e.g. *Monoporites annulatus*, can grow in diverse habitats, e.g. close to the coast (Rebata *et al.* 2006), and not only in savannas, although for Germeraad (1968) *M. annulatus* is a savanna element. There is no new evidence to contradict this.

Palynological assemblages in PAZs-1A, 1B, IIIA, IIIB, VA, VB, VIIA, VIIB, VIIIA and VIIB suggested deposition in a subaerial delta plain during sea level rise, while those of PAZs-IIA, IIB, IVA, IV, VIA and VIB suggested deposition in a subaqueous delta plain during sea level fall. The sedimentological analysis revealed two to three lithologies. The sandstones facies are recognized to have been deposited as the regressive sequences in the palynofloral zones PAZs-IIA, IIB, IIIB, IVA, IVB, VA, VIA and VIB (upper part), VIIA and VIIIA. In addition, mudstones or claystone are delineated to have been deposited as the transgressive sequences in palynozones PAZs-IA, IB, IIIA, VB, VIA and VIB (basal parts),VIIB, and VIIIB. In addition analysis of the gamma-ray signatures showed three patterns. These are bell, funnel, and boxcar-shaped, which indicated tidal channel (in PAZs-IA, IB, IIA, IVA, IVB, VB, VIA, VIB, VIIB and VIIIB), deltaic distributary channel (in PAZs-IIA, IIB, VA and VIIB), and regressive barrier (in PAZs-IIIB and VIIIB) depositional environments. The deltaic distributary channel that belongs to the deltaic system complex is recorded in Wells A and B and was previously interpreted to have been formed during the first stage of prograding sea level fall (Emery & Myers 1996). It usually has an erosive base that is interpreted as a sequence boundary and is commonly filled with moderate to well-sorted, uniform and blocky sand-grain size sediments with a good reservoir quality (Unukogbon *et al*. 2008). In addition, tidal channels, which are usually dominated by moderate to well-sorted sand deposits (Oboh *et al.* 1992; Emery & Myers 1996), are recognized in this study. They are characterized by an erosive base that is commonly filled with fining-upward sand sequences in association with the muddy sediments in the topmost part. The tidal channel sand usually forms a good quality reservoir rock with a sealing rock capacity on top (Unukogbon *et al*. 2008). Furthermore, the regressive barrier sand that formed when there is a drop in the base level of the sea, are recorded in Wells A and B. This sub-environment is characterized by deposition of coarsening-upwards sediments ranging from basal marine shale to continental coarse-grained sand at the top (Selley 1985). The basal organic mud-rich deposits underlying the regressive barrier sand are likely to be of a high-quality kerogen supply in the study area (Chow *et al*. 2005).

Many earlier authors have used a combination of palynologic, lithologic and well-log data to outline different sub-environments in the onshore portion of the Niger Delta. Amongst these are Oboh (1991, 1992a,b, 1993, 1995); Kulke (1995), Unukogbon *et al*. (2008) and Oyedele *et al*. (2012). They reported distributary and tidal channel fills that contained few palynomorphs (chiefly Poaceae) and were associated with erosive based, fining-upward and bell-shaped to blocky gamma-ray patterns. The regressive barrier has equally been described to be rich in palynomorphs (mainly grass, mangrove and ferns spores) in association with coarsening-upward and funnel-shaped patterns. However, three categories of interbedded shale, namely clay smears along faults, interbedded sealing units, and vertical seals, were previously recorded in the Agbada Formation that formed the chief seal rock in the Niger Delta (Doust & Omatsola 1990).

Overpressure zones have earlier been reported to be associated with young Tertiary basins such as the Niger Delta, Gulf of Mexico, Nile Delta and Baram basins (Nwozor *et al*. 2013). This is as a result of high rates of sediment accumulation, which rapidly generated sufficiently thick intervals of shales that commonly characterize these basins. However, the tops of the overpressure zones vary greatly from depo-belt to depo-belt in the Niger Delta (Krusi 1990). Consequently, some authors tried to detect and predict overpressure zones in this region by applying different methods. Amongst these are well logs (Owolabi *et al*. 1990; Osinowo *et al*. 2007) and seismic data (Alao *et al*. 2014; Omolaiye *et al*. 2011; Ayuku & Olorunniwo 2004).

CONCLUSION

The Late Miocene-Pliocene Niger Delta is characterized, in order of abundance and diversity, by angiosperm pollen, monolete spores, fungal elements, trilete fern spores, freshwater algae and marine palynomorphs. The alternation of sandstones and mud/claystone lithologies typified Wells A and B in this study. The sandstone lithologies likely served as reservoir rocks while mud/claystones are suggested to be the good source and seal rocks in the study area. Three different depositional sub-environments, namely, distributary channel, tidal channel, and regressive barrier sands, are delineated in this study. The findings of the multi-pronged approach used here will encourage further studies on offshore wells and help the exploration geologists in recognizing oil-prone deposits from sub-environments such as the distributary channel, tidal channel, and regressive barrier sands and in detecting/predicting the overpressure zones. Therefore, this will help to reduce the costs and risks that are usually associated with deepwater exploration and exploitation of petroleum sources.

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