Palynological dating and palaeoenvironments of the M1 well, Middle Miocene, Niger Delta, Nigeria

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The need to increase our knowledge of palaeo-flora is important in palaeoclimatic and palaeoenvironmental reconstruction of the Tertiary Niger Delta as to highlight possible changes in the depositional environments over time. Hence, palynological data from the M1 well from the western Niger Delta region were employed in an attempt to reconstruct the Middle Miocene palaeoenvironment and palaeoclimate. The detailed palynological analysis revealed diverse and abundant palynomorph assemblages. This consisted of pollen species 60.14%, spores 25.86%, algae (*Botyococcus braunii*, *Pediastrum* sp., and *Concentricytes circulus*) 10.53%, miscellaneous palynomorphs (fungal elements, diatom frustules and charred Gramineae cuticle) 2.62%, dinoflagellate cysts 0.79% and acritarchs 0.06%. The well is dated Middle Miocene based on the common occurrences of diagnostic middle Miocene Niger Delta palynomorphs. Four informal palynofloral assemblage zones (MPAZ) I–IV were defined and correlated with major cycles of alternating dry and wet climatic conditions. Sediments within MPAZ I and MPAZ II were assumed to have been deposited during dominantly wet periods while MPAZ IV and III showed brief dry pulses coupled with periods of marine transgressions. The palaeoenvironment fluctuated between nearshore and marginal marine inferred from abundant records of land-derived palynomorphs and the spotty records of the dinoflagellate cysts *Nematosphaeropsis labyrinthus*, *Nematosphaeropsis lemniscata* and *Impagidinium* sp.

Keywords: palynomorphs, Niger Delta, Miocene, palaeoenvironment, palaeoclimate.

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INTRODUCTION

Ige (2009; Durugbo 2010b; Ige *et al*. 2011) had all lamented the dearth of published palynological studies on the Niger Delta compared to other parts of the world. They had agreed with Oboh (1992) who asserted that most palynological reports are available as confidential reports of the different oil-prospecting companies in Nigeria. For a thorough understanding of the Nigerian vegetation in the geological past, a more holistic approach needs to be adopted to address this problem. In the last three decades, more palynological investigations on the Niger Delta have been undertaken by different individuals, especially Knapp 1971; Evamy *et al*. 1978; Legoux 1978; Sowunmi 1981a,b; Biffi & Grignani 1983; Oboh & Salami 1989; Oloto 1990; Oboh 1992; Oboh *et al*. 1992. Others are Morley & Richards 1993; Morley 1995; Morley & Richards 1997; Demchuk & Morley 2004; Adekanmbi & Sowunmi 2006, 2007; Ige 2009, 2011; Ige *et al*. 2011; Durugbo 2010a,b; Durugbo *et al*. 2010. However, in the last few years new breeds of palynologists have arisen in Nigeria and they have carried out different research projects all aimed at bettering our knowledge of the Nigeria palaeo-vegetation. Among them, Ajaegwu *et al*. (2008) worked with late Miocene–early Pliocene strata of the Ane-1 well. Using lithological characters of the strata, percentage of the mangrove pollen *Zonocostites ramonae* in the total sum of palynomorphs, and the nature of organic matter in the sediment, they were able to infer a coastal to marginal marine environment of depositions. Furthermore, using foraminiferal test linings as the main marine indicator, they subdivided the macro-environments into coastal deltaic, coastal deltaic-inner neritic and inner neritic.

Again, Ige (2009) studied the Atala-1 well, which penetrated the Benin and Agbada Formations (two of the three lithological units in the Niger Delta). He defined nine informal lithological units based on textural characteristics and four pollen assemblage zones (PZ I–IV) based on the recovered palynomorphs, which he used to reconstruct the vegetation. Using differences in the occurrences of the mangrove pollen (*Rhizophora* sp.) and Poaceae, he deduced unstable wet and dry climatic conditions together with sea-level rise. Again, from the assessment of the pH of the samples, he reported the possible effects of the high pH of the samples on pollen preservation, which led to low recoveries of palynomorphs. Furthermore, he produced a Tilia™ graph highlighting the different phyto-ecological groups and pollen zones and later described the distribution of palynomorphs in each zone.

Durugbo (2010b) had studied 389 ditch cuttings from four wells donated by Chevron Nigeria Limited and

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drilled in parts of the western Niger Delta whose ages spanned middle Miocene to early Pleistocene. He documented a dominantly wet middle Miocene typified by abundant records of the mangrove pollen *Zonocostites ramonae* in association with common freshwater swamp, brackish-water swamp, lowland rainforest species, Palmae and freshwater algae. These occurred with brief periods of dryness sandwiched in-between. However, the early Pliocene to early Pleistocene was predominantly dry with *Monoporites annulatus* and other savanna elements dominating the microflora. Furthermore, the dinoflagellate cysts collaborated the dry periods characterized by low sea levels inferred from the preponderance of *Operculodonium centocarpum* and *Polysphaeridium zoharyi*, especially around the 2.4Ma and 2.7Ma (Durugbo *et al*. 2010).

Using 20 ditch cutting samples between 1271 and 2131 m, Ige *et al.* (2011) had carried out palynological and lithological (textural) assessment of the North Chioma-3 well donated by Chevron Nigeria Limited. They recognized seven lithological units comprised of sandy shales, shaly sands, and shales typical of the Benin and Agbada Formations in the Niger Delta. They recovered 46 diverse, fairly well preserved pollen, spores, and fungi species. The microflora was dominated by the mangrove pollen *Zonocostites ramonae* along with Poaceae, *Ceraptoteris* spp., *Laevigatosporites* spp., *Verrucatosporites* spp., *Verrucatosporites usmensis*, monolete and trilete spores, *Multicellaesporites* sp., *Fusiformisporites* sp. and other fungal elements. They used these for the palaecological and palaeoenvironmental interpretations of the well. They inferred a mangrove swamp environment due to the preponderance of mangrove vegetation. Furthermore, they recognized four pollen zones (I–IV) and suggested vegetational and climatic fluctuations during the late Tertiary of the Niger Delta. Again, they posited that the immediate vegetation of late Tertiary Niger Delta was composed of mangrove swamps, freshwater swamp forests and lowland rainforests.

Working on a section of the Bog-1 well from southeastern Niger Delta, Adebayo *et al.* (2012) were able to date the well late Oligocene to Miocene based on the co-occurrence of *Cicatricosisporites dorogensis*, *Retibrevitricolporites protrudens*, *Retimonocolpites pluribaculatus*, *Zonocostsites ramonae*, *Psilatricolporites crassus*, *Retitricolporites irregularis*, *Racemonocolpites hians*, *Pachydermites diederixi*, *Brevicolporites guinetii*, and *Proxapertites cursus*. Again, they inferred a marginal marine depositional environment under terrestrial influence due to the paucity of dinocysts and moderate cuticular matter. On the other hand, high records of the mangrove pollen *Zonocostsites ramonae* (*Rhizophora*) and *Foveotricolporites crassiexinus* (*Avicennia*) suggested a tidal swamp shoreline along which mangroves thrived.

Finally, Ojo & Gbadamosi (2013) had carried out a sequence stratigraphic study of Del-2 well from the southwest Niger Delta between 609.60 m and 975.36 m. They recovered 88 palyno-species composed of 60 pollen grains, 14 spores species and 14 other species comprising dinocysts, acritarchs and algal cysts, charred Graminae cuticle and microforaminiferal wall linings. Using such diagnostic palynomorphs as *Racemonocolpites hians*, *Retistephanocolpites gracilis*, *Peregrinipollis nigericus*, *Multiareolites formosus*, *Verrutricolporites rotundiporus*, *Gemmamonocolpites* sp., and *Retibrevitricolporites obodoensis*/*Retibrevitricolporites protrudens*, they dated the well to be of early–late Pliocene age. They used the first down-hole occurrence of *Gemmamonocolpites* sp. and regular occurrence of *Retibrevitricolporites obodoensis*/*Retibrevitricolporites protrudens* to delineate the early/late Pliocene boundary at 710.18 m. Furthermore, they inferred shallow, deep and open marine depositional environments using the relative abundance and diversity of miospores and marine microfossils, and proposed four pollen biozones due mostly to the distribution and abundance of *Monoporites annulatus* and *Zonocostites ramonae* together with other miospores. Again, they identified one candidate sequence boundary and three systems tracts: *viz.* a highstand, a transgressive and lowstand systems tracts within the studied interval of the Del-2 well.

The present study was undertaken to further broaden our knowledge of the Niger Delta palaeo-flora, highlight possible changes in the depositional environment and make palaeoclimatic inferences of the different areas of the Niger Delta when compared to the results of other workers.

Geology and palaeogeography of the Niger Delta

The Niger Delta (Fig. 1) belongs to the southern Nigeria sedimentary basins in which the depositional history commenced in the Early Cretaceous. It is located in the eastern corner of the Gulf of Guinea between longitude 4°–9°E and latitude 4°–9° N (Fig. 1). It occupies an area of about 75 000 km^2 and is composed of an overall regressive clastic sequence, which reached a maximum thickness of 9000–12 000 m (30–40 000 ft) (Doust & Omatsola 1990). This basin formed in a failed rift, the product of the separation of the South American and African plates, during the Early Cretaceous (Burke *et al*. 1972). The sedimentary infill of the southern Nigeria sedimentary basin was controlled by three major tectonic stages together with epirogenic movements, which led to major transgressive–regressive cycles (Burke *et al*. 1972; Murat 1972). These tectonic events led to the displacement of the main basin axis and subsequently the emergence of three successive basins, *viz.* Abakaliki-Benue Trough, Anambra Basin and the Niger Delta with ages ranging from Albian–Lower Santonian, Upper Santonian–Lower Eocene, and Lower Eocene–Recent, respectively (Short & Stauble 1967; Reijers 2011) (Table 1).

The Niger Delta Basin contains Cenozoic to Recent deposits that were formed in high-energy constructive deltaic environments. The Tertiary Niger Delta is a large arcuate delta of the destructive, wave dominated type and its development is based on the balance between the rate of sedimentation and the rate of subsidence. The Cenozoic basin infill is represented by three formations; a) the basal formation is the pro-delta Akata Formation composed predominantly of over-pressured marine shales. Its thickness is up to 6500 m, with age ranging from Eocene to

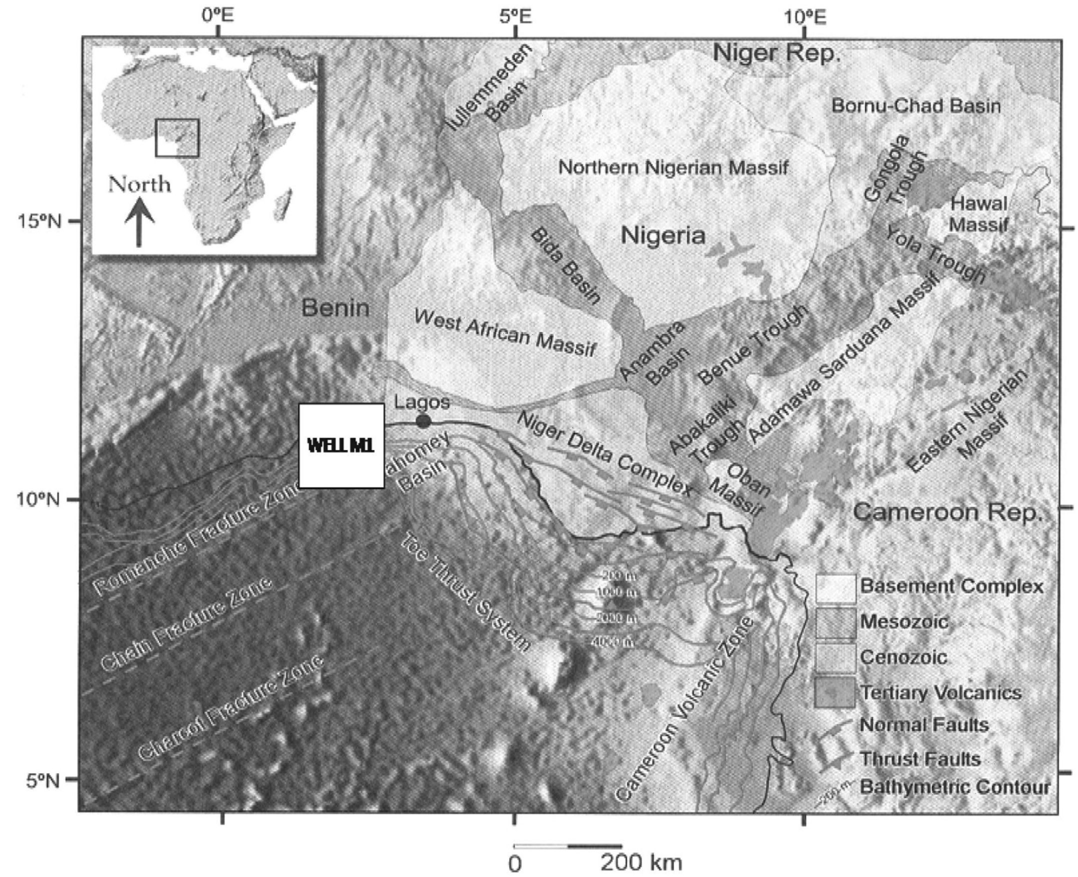

Figure 1. Map of the Niger Delta showing the studied wells (after Corredor *et al*. 2005).

Recent (Short & Stauble 1967; Knox & Omatsola 1989; Doust & Omatsola 1990; Oboh 1992). The Akata Formation is overlain by b) the paralic Agbada Formation, which is a coarsening-upward sequence of alternating sandstones and shales of delta front and lower delta plain origin. This is the most petroliferous formation with a maximum thickness of 4000 m, ranging from Eocene to Recent in age. The topmost and youngest formation, c) is the Benin Formation, which is a predominantly sandstone sequence of continental delta origin up to 2000 m in thickness and ranging in age from Oligocene to Recent (Wright *et al*. 1985).

MATERIALS AND METHODS

Thirty-one ditch cuttings between 6060 and 8760 ft donated by Chevron Nigeria Limited were prepared for this study. 30 g of each sample was prepared using the standard palynological techniques of disaggregation and

Table 1. Table of formations, Niger Delta area (after Short & Stauble 1967).

SUBSURFACE			SURFACE OUTCROPS		
Youngest known age		Oldest known age	Youngest known age		Oldest known age
Recent	Benin Formation (Afam Clay Member)	Oligocene	Plio/Pleistocene	Benin Formation	Miocene
Recent	Agbada Formation	Eocene	Miocene	Ogwashi-Asaba Formation	Oligocene
			Eocene	Ameki Formation	Eocene
Recent	Akata Formation	Eocene	Lower Eocene	Imo Shale Formation	Paleocene
			Paleocene	Nsukka Formation	Maestrichtian
			Maestrichtian	Ajali Formation	Maestrichtian
			Campanian	Mamu Formation	Campanian
	EQUIVALENTS		Campanian/Maestrichtian	Nkporo Shale	Santonian
	NOT KNOWN		Coniacian/ Santonian	Awgu Shale	Turonian
			Turonian	Eze Aku Shale	Turonian
			Albian	Asu River Group	Albian

removal of carbonates and silicates with hydrochloric acid and hydrofluoric acid under a fume cupboard (Faegri & Iversen 1989). Later, the samples were treated with hot Hydrochloric acid (HCL) and wet-sieved over a 5 -micron mesh polypropylene sieve. Complete removal of silt and clay particles was achieved using the Branson Sonifier 250. Each residue was oxidized using concentrated nitric acid (HNO_3) and prepared for study as strewn mounts using Loctite. The slides were stained with Safranin O to enhance the study of dinoflagellate cysts. The slides were analysed for palynomorphs at the palynology laboratory of the Evolutionary Studies Institute at the University of the Witwatersrand, Johannesburg, South Africa, using an Zeiss Axioskop 2 microscope with an attached Axiocam 1 Cc 1 camera. All the palynomorphs present (pollen, spores, dinoflagellate cysts, acritarchs, algae, fungal remains, and some miscellaneous palynomorphs like diatom frustules, charred Graminae cuticle) present on each slide were counted. The presence of diatom frustules was probably due to the incomplete digestion process of the sediment as earlier reported in Durugbo & Aroyewun (2011), Adeonipekun & Olowokudejo (2013), Sciscio *et al*. (2013), Olayiwola, (2014) and Olayiwola & Bamford, (2016). The distribution of each palynomorph present on each slide was plotted against depth using Tilia™ and the distribution chart (Fig. 2) produced. Photomicrographs at 3 μm of some diagnostic species with their respective depths and England Finder™ graticule coordinates are presented in Figs 4 and 5.

RESULTS

Palynology

A total of 107 palynomorphs with a total count of 6952 composed of 63 pollen species with a total count of 4181 accounting for 60.14%; 17 spores with a count of 1798 making up 25.86%; 20 dinoflagellate cysts with a total count of 55 contributing 0.79% (Table 2). One acritarch that occurred four times making up 0.06%; 3 algae (*Botyococcus braunii*, *Pediastrum* sp. and *Concentricytes circulus*) with a total count of 732 (10.53%); and 7 miscellaneous palynomorphs (fungal elements, diatom frustules and charred Graminae cuticle) accounting for 182 (2.62%) of the total sum were recovered in the M1 well. The depth-by-depth occurrences of these palynomorphs according to their ecological groups are displayed on a Tilia™ Graph (Fig. 2), while the percentage plot of the palynomorphs based on ecological groupings per sample are displayed in Fig. 3.

Table 2. Total and percentage occurrence of different palynomorph groups recovered.

Palynomorphs group	Total counts	Percentage occurrence
Pollen	4181	60.14
Spores	1798	25.86
Algae	732	10.53
Dinoflagellate cysts	55	0.79
Acritarchs	4	0.06
Miscellaneous	182	2.62
Grand total	6952	100

Age determination

The well is dated Middle Miocene based on the common occurrences of the diagnostic Niger Delta middle Miocene marker species *Verrutricolporites rotundiporus*, *Verrutricolporites microporus*, *Belskipollis elegans* and *Crassoretitriletes vanraadshooveni*. According to Evamy *et al*. (1978), the top regular occurrence of *Racemonocolpites hians* delineates the late Miocene/middle Miocene (P820/P780) boundary, this marker species occurred moderately from the first sample analysed indicating that the top of the P780 subzone was higher up-section. Furthermore, the top rich occurrence at 6240 ft (1965.82 m) of the P770 marker species *Verrutricolporites rotundiporus*, which occurred moderately from the first sample (6060 ft (1847.09 m) denotes the penetration of the P770 subzone. However, the top regular occurrence of *Belskipollis elegans* at 8220 ft (2505.46 m) marked the penetration of the P740 subzone of Evamy *et al.* (1978). Based on the aforementioned, four palynological assemblage zones MPAZI–MPAZIV based on phytoecological groupings were recognized in the studied section of the M1 well (Fig. 2).

Phytoecological zones

MPAZ I (8760–7770 ft)(2670.05–2368.30 m) P700 Subzone P740 Middle Miocene

The base of this informal zone was marked at 8760 ft (2670.05 m), the base of the analysed portion of the M1 well. The top of the zone was defined by the abundant records of the mangrove pollen *Zonocostites ramonae*, together with the freshwater elements *Verrucatosporites* sp., at 7770 ft (2368.30 m). The zone is further character ized by common records of *Belskipollis elegans*, *Verrutricolporites rotundiporus*, *Racemoncolpites hians* and *Crassoretitriletes vanraadshooveni*. Within this section the mangrove pollen *Zonocostites ramonae* dominated the microfloral assemblage in association with common freshwater algae, freshwater swamp species (*Verrucatosporites* sp.and *Gemmamonoporites* sp.), mangrove/coastal swamp species (*Acrostichum aureum*, *Psilatricolporites crassus*, *Verrutricolporites rotundiporus*, *Verrutricolporites microporus*), lowland rainforest species (*Sapotaceoidaepollenites* sp., polypodiaceoisporites sp.), Palmae (*Racemonocolpites hians*), savanna pollen, especially *Monoporites annulatus* occurred in low numbers. The sediments within this section must have been deposited during a predominantly wet period, possibly an upwelling period in which mangroves and palms thrived. The presence of *Impagidinium* sp., *Nematosphaeropsis labyrinthea*, *Lingulodinium polyedrum* and *Brigantedinium* spp. in this section further surported this upwelling episode.

MPAZ II (7770–6960 ft)(2368.30–2121.41 m) P700 Subzone P740 Middle Miocene

The base of this zone was defined by the abundant records of *Zonocostites ramonae*, and freshwater elements such as *Verrucatosporites* sp. at 7770 ft (2368.30 m). The top was recognized by the marked reduction in miospores abundance at 6960 ft. This section of the well revealed a marked reduction in the occurrences of palynomorphs, especially *Zonocostites ramonae* and algae. Other recovered

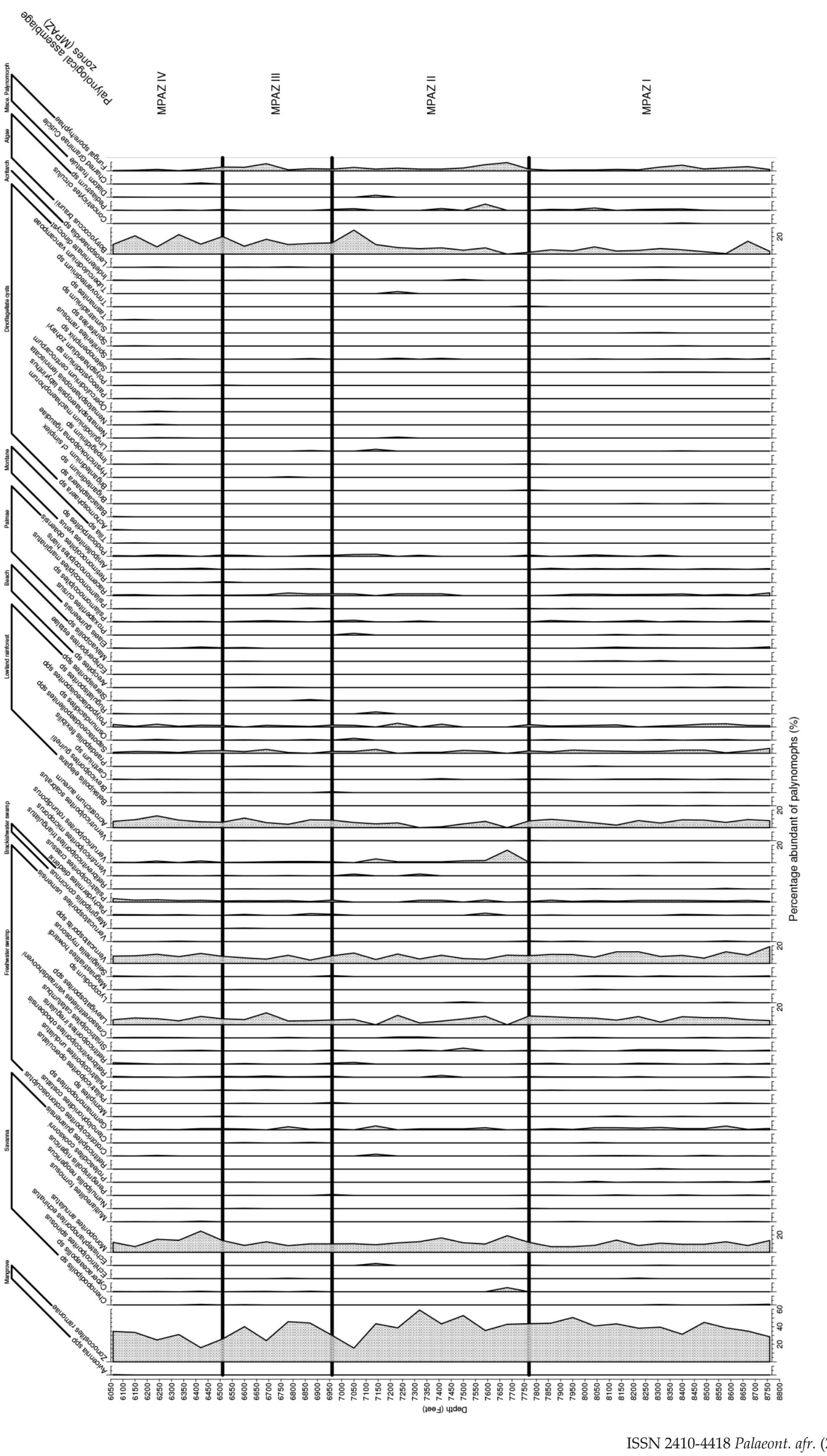

Figure 2. Phytoecological grouping zonation chart

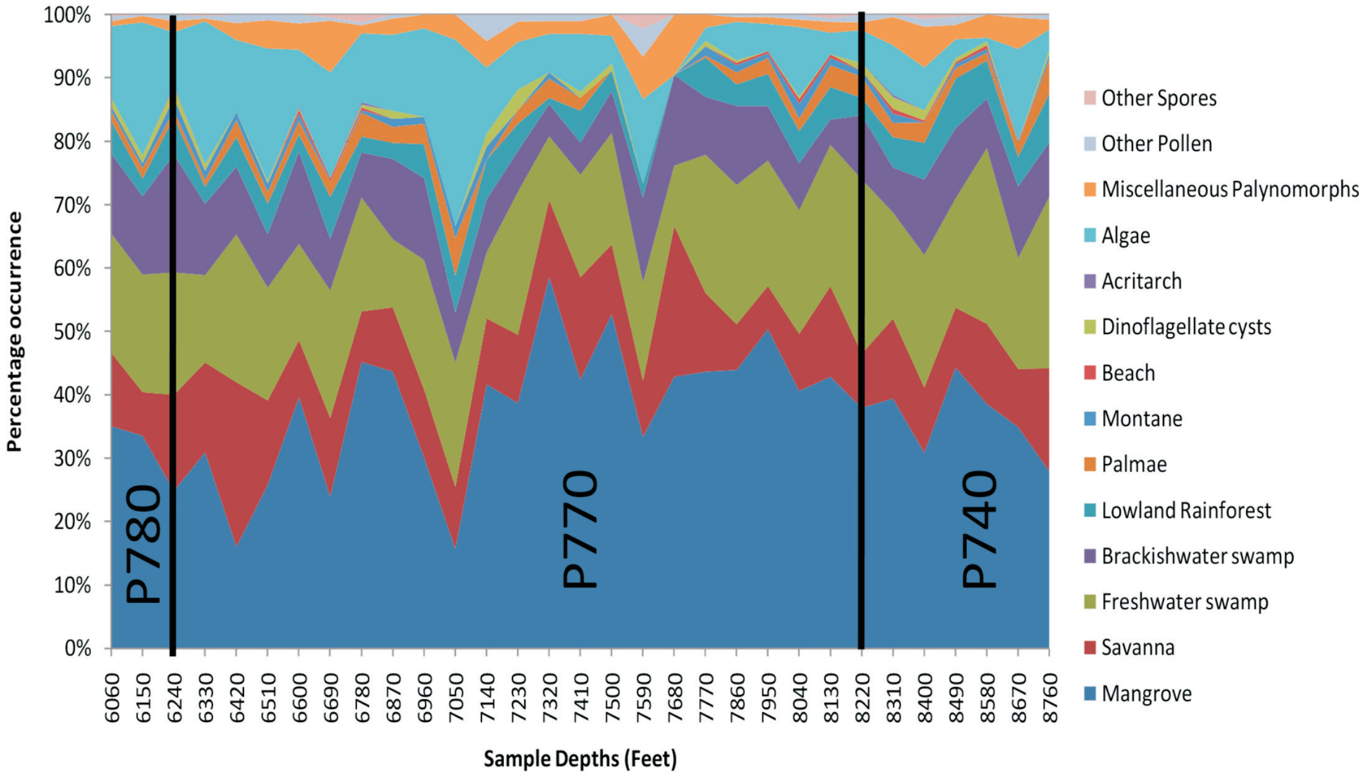

Figure 3. Percentage plot of ecological groups per depth

palynomorphs were common freshwater swamp species (*Verrucatosporites* sp., *Laevigatosporites* sp. (Hoorn, C. (1994), *Gemmamonoporites* sp., *Striatricolpites catatumbus*), lowland rainforest species (*Sapotaceoidaepollenites* sp., *Polypodiaceoisporites* sp.), mangrove/coastal swamp species (*Acrostichum aureum*, *Psilatricolporites crassus*, *Verrutricolporites rotundiporus*, *Verrutricolporites microporus*), Palmae (*Racemonocolpites hians*, *Psilamonocolpites* sp.) in association with low counts of savanna elements (*Monoporites annulatus*, *Pergrinipollis nigericus*, *Numulipollis neogenicus* and *Cyperaceaepollis* sp.). The sediments within this section must have been deposited during a predominantly wet period with brief dry periods.

MPAZ III (6960–6510 ft) (2121.41–1984.25 m) P700 Subzone P770 Middle Miocene

The increased occurrence of the freshwater algae *Botryococcus braunii* defined the top of this informal zone at 6510 ft (1984.25 m), while the base was marked by the abundant records of *Zonocostites ramonae*, and the freshwater elements *Verrucatosporites* sp. at 6960 ft (2121.41 m). The microflora assemblage within this section is characterized by common records of mangrove, freshwater swamp, brackish-water swamp, Palmae and lowland rainforest species co-occurring with savanna species and spot occurrences of the dinoflagellate cysts *Lingulodinium machaerophorum*, *Spiniferites ramosus*, *Polysphaeridium zoharyi* and *Hystrichokolpoma rigaudiae* suggesting brief periods of marine transgressions during a predominantly wet climate.

MPAZ IV (6510–6060 ft) (1984.25–1847.09 m) P700 Subzone P770-P780 Middle Miocene

This section is the uppermost section of the M1 well, the top of this informal zone is marked at 6060 ft (1847.09 m), the depth of the first analysed sample. The increased occurrence of the freshwater algae defined the base of this informal zone at 6510 ft (1984.25 m). Within this zone were common occurrences of mangrove pollen *Zonocostites ramonae* in association with common freshwater swamp species, brackish-water species palms, especially *Elaeis guineensis* and *Racemonocolpites hians*, with fungal elements (*Mediaverrusporites* sp., *Fusiformisporites* sp., *Dyadosporites* sp., *Diporisporites* sp., *Involutisporites* sp., *Multicellites* sp.). There were also abundant records of freshwater algae *Botryococcus braunii*, and spot records of dinoflagaellate cycts, especially the oceanic species *Nematosphseropsis labyrinthus*, *Impagidinium* sp., co-occurring with *Spiniferites ramosus*, *Lingulodinium machaerophorum*, *Polysphaeridium zoharyi*, *Spiniferites* sp., *Paleocystodinium* sp., and the acritarch *Leiosphaeridia* sp. The peak occurrence of savanna pollen *Monoporites annulatus* at 6420 ft (1956.82 m) possibly denotes a brief dry period sandwiched in-between a predominantly wet climate characterized by brief marine transgressions with frequent freshwater influx.

Palaeoenvironments

Using the proportions of marine elements to land-derived palynomorphs, the studied section of the M 1 well was subdivided into six sections (palaeoenvironments) which fluctuated between nearshore/coastal deltaic characterized by moderate to abundant records of the mangrove pollen *Zonocostites ramonae* co-occurring with common freshwater swamp species and large to medium-sized phytoclasts indicating deposition in a nearshore setting. Records of dinoflagellate cysts, especially *Nematosphaeropsis labyrinthus*, *Nematosphaeropsis leminiscata* and *Impagidinium* sp. characterize the marine sections.

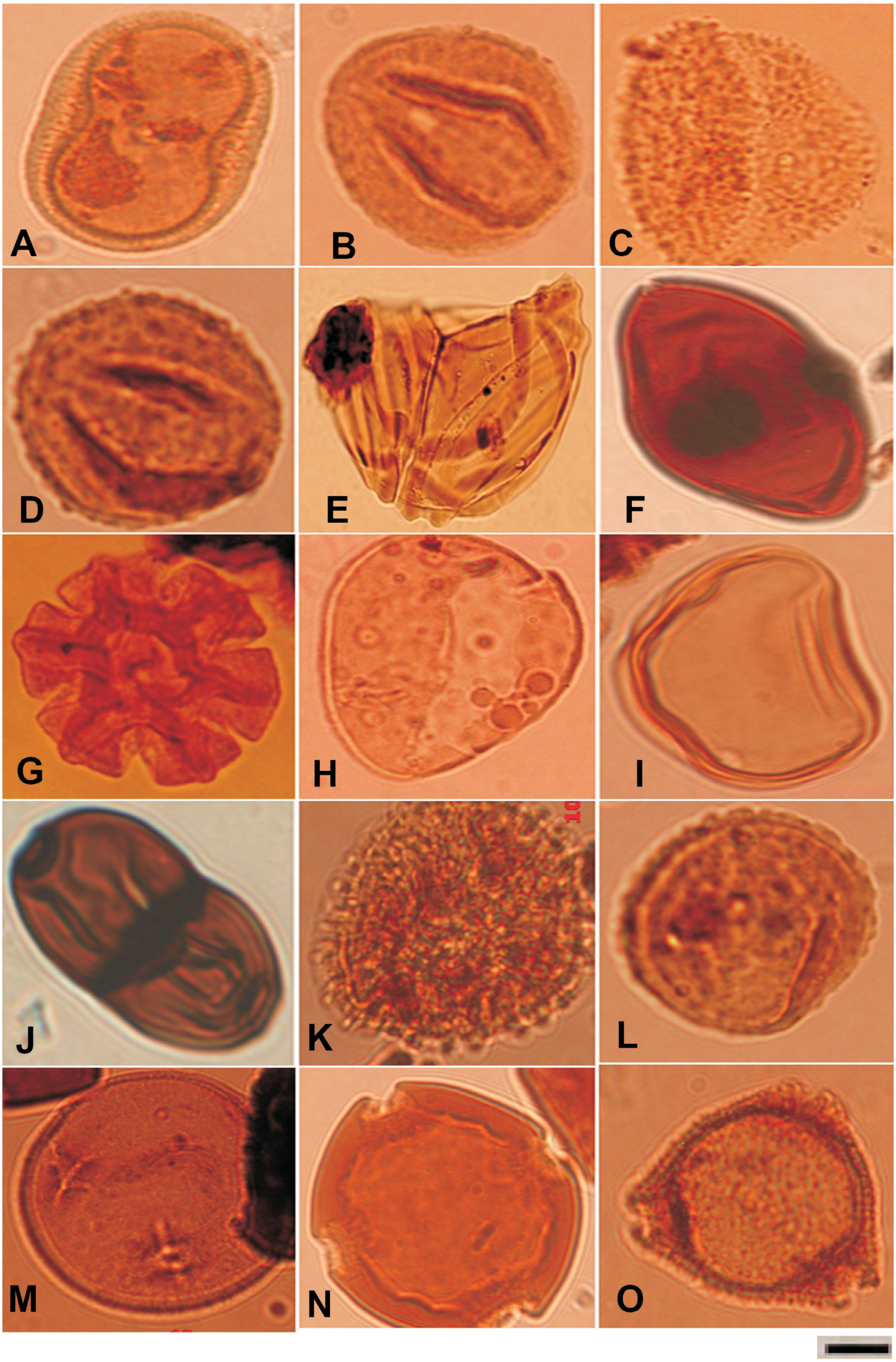

Figure 4. **A**, *Multiareolites formosus* Van der Hammen, 1954, G.H.M. 1968 8670 ft (K39/1); **B**, *Verrutricolporites rotundiporus* Legoux, 1978; Van der Hammen & Wymstra, 1964 6240 ft (S27/3); **C**, *Racemonocolpites hians* Legoux, 1978 6420 ft (Q51/4); **D**, *Verrutricolporites microporus* Legoux, 1978 6330 ft (S23/2); **E**, *Magnastriatites howardi* G.H.M. 1968 6600 ft (T31/4); **F**, *Mediaverrusporites* sp. 6600 ft (T38/2); **G**, *Ctenolophonidites costatus* (Van Hoeken-Klinkenberg, 1966) van Hoeken-Klinkenberg. Rao 1990 6870 ft (S42/2); **H**, *Gemmamonoporites* spp. 7860 ft (N28/3); **I**, *Laevigatosporites* sp. (Ibrahim, 1933) 6690 ft (W35/3); **J**, *Dyadosporites* sp. 7770 ft (M28/1); **K**, *Retitricolporites irregularis* Van Der Hammen & Wymstra, 1964 8580 ft (J45/4). **L**, *Verrutricolporites rotundiporus* Legoux, 1978; Van der Hammen & Wymstra, 1964 7140 ft (R42/1); **M**, *Psilatricolporites crassus* Van Der Hammen & Wymstra, 1964 7860 ft (R34/3); **N**, *Pachydermites diederixi* G.H.M., 1968, 6600 ft (S36/4); **O**, *Retibrevitricolporites obodoensis/protrudens* Legoux, 1978 6600 ft (O28/2), Scale bar = 3 μm.

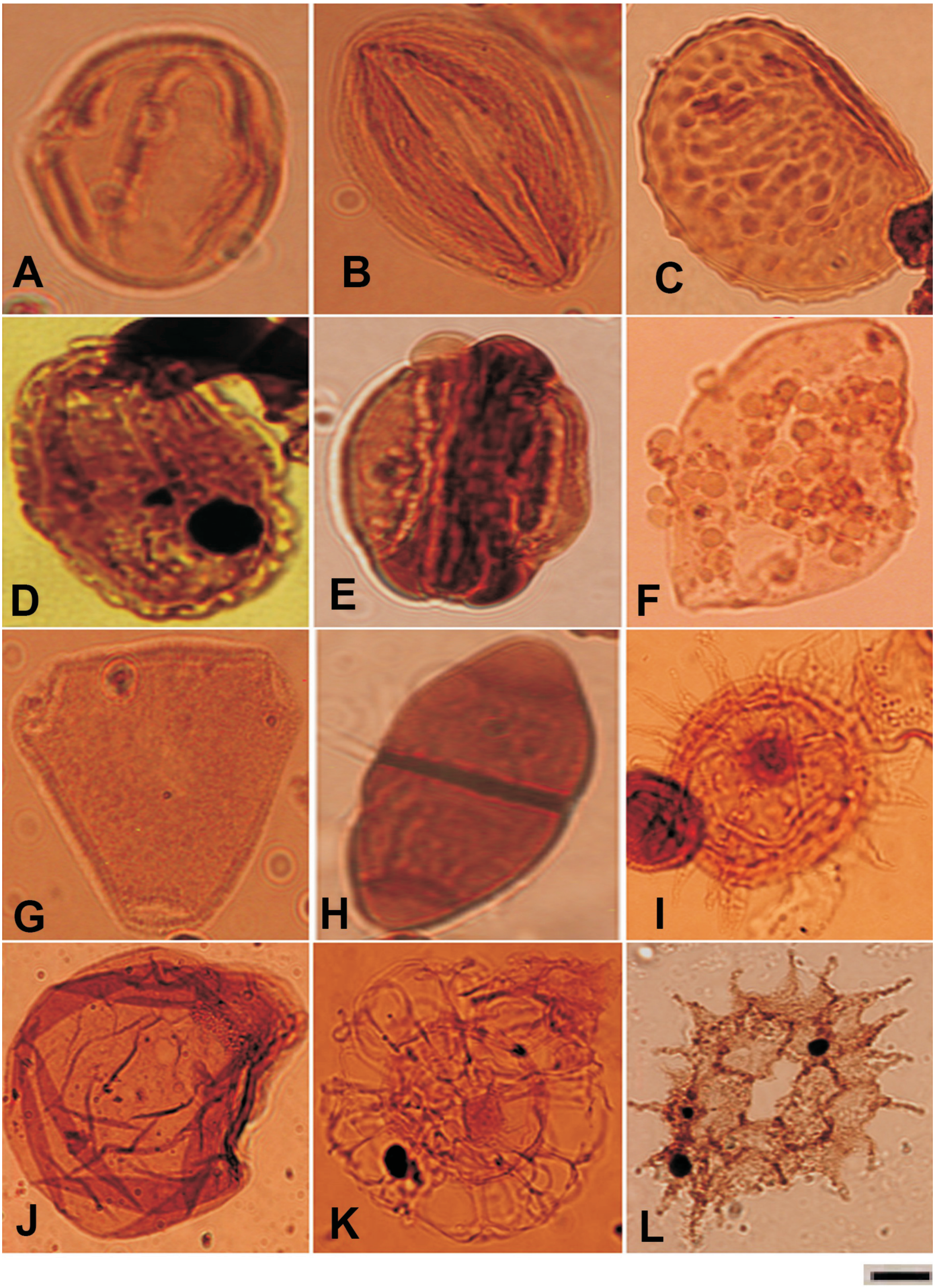

Figure 5. **A**, *Sapotaceoidaepollenites* sp. (*Psilastephanocolporites laevigatus*) Salard-Cheboldaeff, 1978 8130 ft (H46/3); **B**, *Striatricolpites catatumbus* Gonzales, 1967, 6780 ft (O49/2); **C**, *Verrucatosporites* sp. (Pflug &Thomson, 1953, Potonié, 1956) 6600 ft (M31/2); **D**, *Belskipollis elegans* Legoux, 1978 8490 ft (N31/4); **E**, *Marginipollis concinnus* Clarke & Frederiksen, 1968 6600 ft (P35/3); **F**, *Gemmamonoporites* spp.8220 ft (J41/4); **G**, *Proteacidites cooksonni* 7860 ft (M42/3); **H**, *Multicellaesporites* sp. 6600 ft (F34/3); **I**, *Lingulodinium machaerophorum* (Deflandre & Cookson, 1955) 6150 ft (S42/1); **J**, *Batiacasphaera* sp. 8310 ft (P25/2); **K**, *Nematosphaeropsis labyrinthus* (Ostenfeld, 1903, Reid, 1974) 7230 ft (P38/4); **L**, *Pediastrum* sp. 8040 ft (C30/4). Scale bar = 3 μm.

8760–8400 ft (2670.05–2560.32 m) (Nearshore/Coastal Deltaic)

The microflora is dominated by the mangrove pollen *Zonocostites ramonae* with common pteridophyte spores *Verrucatosporites* sp., *Laevigatosporites* sp., *Gemmamonoporites* sp., *Acrostichum aureum*, *Polypodiaceoisporites* sp., *Psialtricolporites crassus* and *Sapotaceoidaepollenites* spp. In addition, there is common occurrence of *Psilastephanocolporites* spp. with spot records of the dinoflagellate cysts *Spiniferites ramosus*, *Briganthedinium* sp. and *Batiacasphaera* sp., co-occurring with common freshwater algae *Botryococcus braunii* and fungal elements (*Mediaverrusporites* sp., *Fusiformisporites* sp., *Dyadosporites* sp., *Diporisporites* sp., *Involutisporites* sp., *Multicellites* sp.). This assemblage suggests sediment deposition in a shallow marine environment with frequent incursion of freshwater.

8400–8220 ft (2560.32–2505.46 m) (Marginal marine)

Common records of the dinoflagellate cysts *Lingulodinium machaerophorum*, *Spiniferites ramosus*, *Spiniferites* sp., *Sumatradinium hispidum*, *Briganthedinium* sp., *Selenopemphix* sp. together with land-derived palynomorphs, algae and rare fungal elements characterized this thin section of the M1 well. This assemblage suggests a marginal marine environment of deposition with frequent freshwater incursion.

8220–7860 ft (2505.46–2395.73 m) (Nearshore/Coastal Deltaic)

The mangrove pollen *Zonocostites ramonae* together with common freshwater swamp, brackish-water swamp and lowland rainforest species characterized this interval. These co-occurred with common freshwater algae *Botryococcus braunii*, *Pediastrum* sp., rare dinoflagellate cysts and fungal elements (*Dyadosporites*, *Mediaverrusporites* sp., *Fusiformisporites* sp., *Multicellites* sp. and *Fusiformisporites crabbii*) all indicating a mangrove-fringed environment of deposition.

7860–7770 ft (2395.73–2368.30 m) (Marginal marine)

Within this thin section was base spot occurrence of the deep-water dinoflagellate cyst *Impagidinium* sp. co-occurring with moderate records of land-derived palynomorphs indicating a brief period of marginal marine deposition.

7770–6330 ft (2368.30–1929.38 m) (Nearshore/Coastal Deltaic)

Moderate records of *Zonocostites ramonae*, *Monoporites annulatus*, *Verrucatosporites* sp., *Laevigatosporites* sp., *Psialtricolporites crassus*, *Gemmamonoporites* sp., *Sapotaceoidaepollenites* (*Psilastephanocolporites* spp.), *Acrostichum aureum*, *Retibrevitricolporites obodoensis*/*Retibrevitricolporites protrudens*, *Psilamonocolpites* sp., *Pachydermites diederixi*, together with abundant freshwater algae, spot records of dinoflagellate cysts and fungal elements (*Mediaverrusporites* sp., *Fusiformisporites* sp., *Dyadosporites* sp., *Diporisporites* sp., *Involutisporites* sp., *Multicellites* sp.) characterized this interval. This assemblage suggests deposition in a nearshore environment with frequent freshwater incursions.

6330–6060 ft (1929.38–1847.09 m) (Marginal marine)

This uppermost section of the M1 well is characterized by records of the oceanic dinoflagellate cysts *Nematosphaeropsis labyrinthus*, *Nematosphaeropsis lemniscata*, *Impagidinium* sp., in association with *Lingulodinium machaerophorum*, *Spiniferites ramosus*, *Operculodinium centrocarpum*, *Spiniferites* sp., *Achomosphaera* sp. and *Batiacasphaera* sp. (Wrenn & Kokinos 1986).

DISCUSSION

A total of 107 palynomorphs were recovered from the studied section of the M1 well as mentioned earlier. The microfloral assemblage is dominated by pollen species (angiosperms). This trend could have arisen from the marked proliferation of angiosperms since the early Miocene (Muller 1981). Poumot (1989) had reported that Muller (1981) demonstrated that 75% of the present botanical families existed in Oligocene times, 95% in the late Miocene and nearly 100% in the Pliocene. Adebayo (2013) had also reported the preponderance of angiosperm pollen species in the late Miocene to Pliocene of the Niger Delta, which accounted for 92% of the total palynomorphs he recovered. In the present study, increases in mangrove occurred with correspondingly high counts of other wet climate ecological groups indicators such as freshwater swamp species, brackish-water swamp species, Palmae (*Arecaceae*) and algae. This concurs with the suggestions of Morley (1995) that a close link exists between high relative sea levels and humid climates (i.e. high rainfall) in the low latitude tropics. The proliferation of palms and wet climate indicators in the M1 well fossil record further gives credence to a humid climate.

The preponderance of typical middle Miocene Niger Delta diagnostic marker species *Racemonocolpites hians*, *Verrutricolporites rotundiporus*, *Belskipollis elegans* and *Crassoretitriletes vanraadshooveni* resulted in the delineation of the studied section of the M1 well into three palynological subzones (P740, P770 and P780) subzones of Evamy *et al.* (1978). However, due to the broad nature of these subzones which Durugbo (2010) had pointed out, four informal palaeoecological zones (MPAZI–MPAZIV) were erected to present in detail a high-resolution report of the floral constituents and ecological associations of the well. A general assessment of the studied section of the well revealed a predominantly wet Middle Miocene in which the mangrove pollen *Zonocostites ramonae* dominated the microfloral assemblage, the percentage occurrence ranged between 58.59% at 7320 ft (2231.14 m) and 15.7% at 7050 ft (2148.84 m). These occurred in association with freshwater swamp, brackish-water swamp species and Palmae (*Arecaceae*). Only a single peak of the savanna element *Monoporites annulatus* at 6420 ft was recorded. This corroborates the report of Durugbo (2010) who analysed four wells from part of the western Niger Delta donated by Chevron Nigeria Limited, two of which were dated middle Miocene to earliest Pliocene. He documented the dominance of the mangrove pollen *Zonocostites ramonae* in most of the studied samples together with common freshwater swamp, brackish-water swamp species and Palmae (Arecaceae) and posited that those samples where the counts of the grass pollen, *Monoporites annulatus* dominated represented dry periods sandwiched in-between well-pronounced wet periods. Increases in mangrove occurred with correspondingly high counts of other wet climate ecological groups indicators such as freshwater swamp, brackish-water swamp, and algae.

The present results further concur with the report of the Igbomotoru-1 well from the Central Niger Delta by Oboh and Salami (1992) which was dated middle Miocene to upper Miocene. They had highlighted the dominance of *Zonocostites ramonae* in most of the horizons. This they concluded to have represented mangrove swamp influence which, together with the common occurrence of laevigate trilete spores indicated deposition in coastal plain environments.

Commenting further on the Igbomotoru-1 well Oboh *et al.* (1992) noted the paucity of marine organisms in the sections they studied. They attributed this to slight marine influences, which were further supported by the high percentages of *Zonocostites ramonae* indicating coastal deposition close to source. Again, they suggested that the common records of *Crassoretitriletes vanraadshooveni*, *Verrucatosporites usmensis* both climbing ferns pointed to swamp forests, while *Magnastriatites howardi* indicated some freshwater influence. The percentage occurrence of *Zonocostites ramonae* in the present study coupled with those of the Igbomotoru-1 well (Oboh *et al*. 1992) could not reach the high levels quoted for the modern vegetation of the Orinoco delta by Muller (1959). These results from the ?late–middle Miocene (P740) western Niger Delta contradict those of Oboh (1992) for the earliest-middle Miocene section of the E2.0 Reservoir in the Kolo-Creek field Central Niger Delta where she inferred a drier environment due to the abundance of grass pollen. Though two mangrove pollen species *Zonocostites ramonae*, *Verrutricolporites rotundiporus* and the grass pollen *Graminidites* sp. (*Monoporites annulatus*), dominated the palynological assemblage. These were in association with the fern spores *Leoitriletes cf. L. adriennis*, *Polypodiaceoisporites* sp., *Verrucatosporites usmensis*, and *Magnastriatites howardi* and the angiosperm pollen *Racemonocolpites hians* and *Striatopollis catatumbus*. She opined that the abundance of grass pollen when compared with Recent sediments suggested that the lower delta plain had more open vegetation. This she attributed to the drier conditions associated with the early part of the middle Miocene of which Frakes (1979) had reported to be characterized by fluctuations of wetter and drier conditions. Notwithstanding, the climate was wet and humid enough for the development of mangroves. She had used the presence of *Spirosyncolpites bruni*, *Multiareolites fromosus*, the relative abundance of *Verrutricolporites rotundiporus* and the absence of *Crassoretitriletes vanraadshooveni* with foraminiferal data to date the reservoir as the earliest part of the middle Miocene. In the present study, the common records of *Racemonocolpites hians*, *Verrutricolporites rotundiporus*, *Belskipollis elegans* and *Crassoretitriletes vanraadshooveni* had restricted the age to ?Late Middle Miocene (P740) to Late Miocene (P780) (Evamy *et al*. 1978; Legoux 1978). The mangrove pollen *Zonocostites ramonae* had dominated the microfloral assemblage in association with common *Acrostichum aureum*, *Verrucatosporites* sp., *Laevigatosporites* sp., *Polypodiaceoisporites* sp., *Pachydermites diederixi*, *Psilatricolporites crassus*, *Retitricolporites irregularis*, spot occurrences of *Magnastriatites howardi*, and *Marginipollis concinnus*. This results contrasts the report of Ige *et al.* (2011) for the North Chioma-3 well from Late Tertiary Niger Delta in which Poaceae (grass) pollen (60.9–71%) dominated the microfloral assemblage with common savanna elements in their zone I, coupled with paucity of freshwater swamp species, lowland rainforest species and varied occurrences of fern spores. However, mangrove forest prospered during zones II, III and IV. The highest records were in zone III where *Rhizophora* pollen together with other mangrove pollen *Avicennia* sp., and *Acrostichum aureum* dominated over low records of *Poaceae* pollen. These co-occurred with common lowland rainforest, freshwater swamp forests species and fern spores. They had inferred cool and dry climate for the former, while the latter period indicated wet and warm climates. They had attributed the proliferation of mangrove swamp vegetation to rise in sea levels which agrees with the models of Morley (1995). In zone IV, there was a slight reduction in mangrove pollen and low occurrences of Poaceae, which they suggested resulted from stable sea levels and presence of open vegetation without closed forest canopy due to the presence of secondary forest species, freshwater swamp forest, lowland rainforest and riverine forest species. Conclusively, they asserted that the vegetation of the Late Tertiary Niger delta fluctuated between wet and dry and arid climates.

The reports of the Atala-1 well (Ige 2009) revealed wet and warm climate to part of the Niger delta due to the high percentage of *Rhizophora* pollen associated with risen sea levels which promoted the proliferation of mangrove vegetation over the coast thereby encouraging the existence of freshwater swamp forests and lowland rainforests. This report agrees with the present study thereby confirming the presence of well-established mangrove vegetation in parts of the Niger Delta during the Late Tertiary.

Slightly more marine events were recorded in the M1 well compared to the Igbomotoru-1 and the Kolo Creek wells. The common records of *Nematosphaeropsis labyrinthus*, *N. lemniscata*, and *Impagidinium* sp., in the M1 well indicated deeper water conditions (Oboh 2001; Head 1998; Udeze & Oboh-Ikuenobe 2005; Morley & Richards (1997) had opined that a single occurrence of these species indicated deep marine conditions. Harland (1993) had listed *Nematosphaeropsis labyrinthus*, *N. lemniscata* and *Impagidinium* spp., among the oceanic species. The low number of *Impagidinium* species in the M1 well agrees with its poor representation on the distribution maps for recent dinoflagellate cysts sketched by Harland (1983), and the report of Morzadec-Kerfourn, (1992) for the Gulf of Guinea. According to Reyssac (1970), this rarity may have been caused by low salinity ≤35% in the warm season in the Gulf of Guinea because *Impagidinium* genus is generally associated with salinities ≥35% (Wall *et al.*

1977). The common records of mangrove pollen as highlighted above corroborates this low salinity and the presence of brackish water conditions supported by common records of the brackish-water elements *Acrostichum aureum*, *Verrutricolporites rotundiporus*, *Pachydermites diederixi*, *Psilatricolporites crassus*, and records of inner neritic dinocysts *Selenopemphix* sp., and *Brigantedinium* sp. (Adeonipekun & Olowokudejo 2013). Furthermore, the presence of *Lingulodinium polyedrum* and *Brigantedinium* spp. in M1 well indicated upwelling activities. Holzwarth et *al*. (2007) reported the presence of *Lingulodinium polyedrum* and *Brigantedinium* spp. to characterize active upwelling condition.

Palaeoclimatic inferences

The palaeoclimatic deduction revealed a more predominantly humid environment in the Middle Miocene of the studied area as the pollen records revealed the dominance of mangrove pollen in association with freshwater swamp, brackish-water swamp species and common algae in association with dinoflagellate cysts.

CONCLUSIONS

M1 well microfloral assemblage revealed a typical Niger Delta Middle Miocene palynological signature, which was characterized (in order of abundance and diversity) by angiosperm pollen, monolete spores, fungal elements, trilete fern spores, freshwater algae and marine palynomorphs. The recovered palynomorphs helped in delineating four informal palynofloral assemblage zones (MPAZ) I–IV, which were correlated with major cycles of alternating dry and wet climatic conditions in the studied area. The climatic condition that was predominantly wet agreed with the reports of earlier investigators. The palaeoenvironments fluctuated between nearshore/coastal Deltaic mangrove fringed environments and a marginal marine depositional environment.

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