Palaeoclimatology and biostratigraphic significance of late Neogene/Quaternary vegetational changes recorded in the offshore western Niger Delta

PETER ADEGBENGA ADEONIPEKUN[1*] and MARGARET ADEBISI SOWUNMI[2]

[1] Department of Botany, University of Lagos, Nigeria; e-mail: p1adeonipekun@yahoo.com
[2] Department of Archaeology and Anthropology, University of Ibadan, Nigeria; e-mail: bisisowunmi@gmail.com

ABSTRACT. Attempts at reconstructing palaeoclimatic changes over time using palynomorphs of three oil wells drilled in the shallow offshore Niger Delta led to cluster analysis-aided recognition of seven pollen zones. These pollen zones are equivalent to ten palaeoclimatic zones with alternating dry and wet conditions. The palynomorphs were classified into phytoecological groups and changes in their relative abundances were employed to interpret the palaeoclimatic conditions of their source areas. Contrasting fluctuations in the proportions of the Spore (Pteridophytes) phytoecological group and those of the Poaceae were the main basis for palaeoclimatic inferences. Trends of the occurrence of other phytoecological groups were used to substantiate our palaeoclimatic inferences. In the latest Miocene (5.8–5.5 Ma), climatic conditions were mainly wet until between 5.5 and 5.0 Ma, when extreme dry conditions prevailed. The early Pliocene part (5.0–>3.4 Ma) was generally wet, while the late Pliocene part (<3.0–2.7 Ma) was extremely dry, with wet conditions re-occurring at the latest Pliocene/earliest Pleistocene boundary at a lower magnitude than those of the early Pliocene. This is inferred from the bloom of open vegetation Acanthaceae undif., *Polygala* sp. and *Asystacia gangetica*, along with montane *Podocarpus milanjianus* from 2.4 Ma through 2.0 Ma and younger. The Acanthaceae bloom recorded the evolution of *A. gangetica* in the latest Pliocene/earliest Pleistocene at around 2.0 Ma in the Niger Delta. The upper Early Pliocene regional wet event is associated with distinct peaks of riverine forest, freshwater swamp and mangrove pollen. Our results further support earlier findings from other parts of West Africa with respect to palaeoclimatic changes in the late Neogene/earliest Quaternary. Equivalent qualitative palynostratigraphic events were recognized within the pollen zones which are useful for age determination, and the significance of biostratigraphic correlation of the zones is stressed.

KEYWORDS: biostratigraphy, palaeovegetational changes, phytoecological groups, palaeoclimate, Late Neogene/earliest Pleistocene, Niger Delta

INTRODUCTION

The palaeoclimatic history of the late Neogene–Pleistocene in Africa needs to be studied in more detail. This period has been linked to savanna establishment in Africa, commencement of glaciation in high-latitude areas (Northern Hemisphere Glaciation) and, more importantly, the evolution of the genus *Homo* (DeMenocal 1995, 2004, Sowunmi 1986, Leroy & Dupont 1997, Valle et al. 2014, Hoetzel et al.

2017, Herbert et al. 2016). Leroy and Dupont (1997) have given a good account of the stages involved in palaeoclimatic changes from 3.7 to 1.7 Ma from 658 ODP site sediments from offshore northwestern Africa. They established a link between climatic changes in temperate and tropical areas, and recognized the commencement of aridification of northwestern Africa at 3.2 Ma. This was coeval with the probable initiation of the Northern Hemisphere Glaciation, which intensified from around 2.4 Ma

---

* Corresponding author

onwards. In their study of ODP sites 659 and 658, Valle et al. (2014) also reported increasing long-term aridification and savanna expansion from about 3.0 Ma, which has been found to be contemporaneous with the Northern Hemisphere Glaciation. Their results linked the intensification of the northeast trade winds to the Northern Hemisphere Glaciation in the late Pliocene. They also found that the intensity of the NE trade winds was increased from around 2.7 Ma and has remained so since then.

The occurrence of montane bisaccate pollen – *Podocarpus milanjianus* – in the Niger Delta basin from around 2.7 Ma has been reported (Knapp 1971, Sowunmi 1987, Adeonipekun et al. 2015). This supports the invigoration of the NE trade winds at this time. In an aeropalynological study of a locality in southwestern Nigeria, Adeonipekun et al. (2016) reported peak recovery of bisaccate pollen similar to *Podocarpus milanjianus* in their aero-samples when wind speed peaked in the short dry season called the "August break". This gives credence to enhancement of the transport of these bissacates by higher wind speed. Joordens et al. (2019) most recently reviewed early hominid evolution and dispersal in the Coastal Forest of East Africa and related it to the impact of palaeoclimatic changes in the Pliocene/Pleistocene. According to Joordens et al. (2019), the Northern Hemisphere Glaciation led to fragmentation of the coastal vegetation in the middle Pliocene and shaped the development of isolated hominid populations on the African continent due to the unstable climate. These isolated populations were previously one prior to this time.

Durugbo et al. (2010) remains the only published work devoted to palaeoclimatic changes in the Niger Delta during the Pliocene–Pleistocene known to the authors, even though emphasis is laid more on stratigraphy. Durugbo et al. (2010) recognized domination of dry conditions, with some short, less conspicuous wet intervals. These "wet" phases were not clearly demarcated in their data (Tabs 1, 2), hence the low emphasis placed on the "wet" phases in their publication. What pollen and spores constituted their ecological groups, particularly the savanna and lowland rainforest, were not stated, and there was no graphical representation of the alternating dry/wet phases they recorded. It is curious, however, that the Niger Delta, situated within the Congo-Guinean lowland rain forest block since at least the early Tertiary (Germeraad et al. 1968, Evamy et al. 1978, Sowunmi 1986), would have its palaeovegetation strictly dominated by savanna pollen. In contrast, all published Tertiary, Quaternary and Holocene studies of the offshore Niger Delta have reported low content of typical savanna pollen (Sowunmi 1981a, Adeonipekun et al. 2015, 2017). The assumption that all Poaceae pollen is from inland savanna, which has informed the inference of domination by dry palaeoclimate, is therefore questionable, because coastal savanna contributed more than 50% of this Poaceae pollen (Adeonipekun & Olowokudejo 2013).

Stressing the potential of palaeoclimatic changes as a correlation tool in biostratigraphy,

Table 1. Phytoecological groups and taxonomic composition of recovered palynomorphs from the three wells

Spores	Pteridophyte spores (monolete and trilete)
Freshwater	*Pachydermites diederixi* (*Symphonia globulifera*), *Nymphaea lotus*, *Cyperus* spp., *Calamus deeratus*, Arecaceae, *Uapaca* spp., *Macaranga* sp., *Retimonocolpites* spp. *Psilamonocolpites* spp., *Ludwigia stenorapphe* (*Corsipollenites jussiaensis*), *Oncocalamus manni*, *Langucularia* sp., *Hygrophila* sp., *Retibrevitricolporites obodoensis*, *Proteacidites* spp. (*Protea* spp. F.O.P.O.)
Open coastal vegetation	Asteraceae (Compositae), *Echitricolporites spinosus* (cf. *Tridax procumbens*), *Echiperiporites estalae* (Malvaceae), Amaranthaceae, *Nummilipollis neogenicus*, Malvaceae unidentified, *Cintiperipollis mulleri*, Acanthaceae unidentified, *Perfotricolporites digitatus*, *Echiperiporites icacinoides*
Mangrove	*Rhizophora* spp. (*Zonocostites ramonae*), *Psilatricolporites crassus* (cf. *Amanoa*), *Acrostichum aureum* (*Leotriletes*)
Poaceae (Gramineae)	*Monoporites annulatus*
Rainforest	Sapotaceae, *Khaya* spp. (Meliaceae), *Canthium* spp., Bombacaceae, *Calpocalyx* sp., *Rauvolfia* spp., *Elaeis guineensis* (F.O.P.O.), *Acacia* spp., *Praedapolis flexibilis*, Annonaceae undifferentiated (F.O.P.O.), cf. *Cleistopholis patens* (*Gemmamonocolpites* sp.1), *Allophylus africanus*
Riverine	*Pandanus candelabrum*, *Raphia* spp., *Psilatricolporites operculatus* (*Alchornea cordifolia*), *Syzygium guineense*, *Eugenia* sp., *Ctenophonidites costatus* (*Petersianthus macrocarpus*), *Peregrinipollis nigericus* (*Brachystegia* spp.)
Savanna	*Grewia* sp., *Dalbergia* sp. *Parkia biglobosa*, *Spermacoce* (*Borreria*) spp. (*Retistephanocolporites gracilis*), *Acacia sieberiana*, *Gardenia sokotoensis*
Montane	*Podocarpus milanjianus*, *Justicia* spp., *Alnipollenites verus* (*Alnus* sp.) *Cyathidites* sp. (*Cyathea*), *Encephalatus* sp (*Cycadopollenites*), *Multiareolites formosus* (*Justicia* spp.)

Table 2. Average percentage of phytoecological groups in shallow offshore western Niger Delta

Phytoecological group	Average percentage
Poaceae (Gramineae)	44
Spores	22
Freshwater	7
Rainforest	3
Rhizophora (Mangrove)	16
Riverine	0.6
Savanna	0.03
Montane	0.4
Open coastal vegetation	0.8

Germeraad et al. (1968) stated that they provide the best means of correlation regionally. Salard-Cheboldaeff (1990) supported this view with the remark that repetitive floristic changes across intertropical Africa are connected to climate evolution. From their works, they recognized alternating wet and dry palaeoclimate conditions. Leroy and Dupont (1997) also stressed the importance of using cyclostratigraphy inferred from palaeoclimatic changes for palynostratigraphy and intersite correlation.

NIGER DELTA CLIMATE

The climate of the Niger Delta is controlled by the relative position of the Intertropical Front (ITF) (Short & Stauble 1967, Sowunmi 1981b, Adojoh et al. 2017), now known as the Intertropical Discontinuity (ITD). This front is the meeting point of two air masses, the southwesterly monsoon winds and the northeast trade winds that make up the West African Monsoon System (WAM). The southwesterly monsoon winds originate from the Atlantic Ocean and are moisture-laden; the northeast trade winds are continental in origin, becoming dry as they blow across the Sahara Desert, and are called the harmattan. From January to August, the moisture-laden monsoon winds bring rain from the Atlantic, while the northeast trade winds bring dry air between August and January. As the meeting point moves between the north and south of West Africa, the Niger Delta coast is entirely outside of that range, hence the dominant effect of the westerly winds. The coast experiences the harmattan only occasionally in January and February (Sowunmi 1981b). The temperature is uniform in the delta, ranging between 20°C at night and 30°C during the day (Short & Stauble 1967).

NIGER DELTA VEGETATION

The vegetation of the Niger Delta is as complex as the factors that led to the deposition of the sediments of its basin. The Niger–Benue drainage forms the major drainage system, while the drainage systems in both the east and west of the delta play secondary roles in sediment deposition (Allen 1965, Sowunmi 1981a, b). Except for the Sahel vegetation type, the major drainage system traverses all the vegetation types in Nigeria, which are important to understand in order to know the vegetation of the delta. Though complex, the vegetation of Nigeria can be divided into three major groups: savanna, rainforest and montane. The major vegetation groups are determined by relative humidity, rainfall and temperature, though edaphic or ecological factors override regional climatic influences. The impact of these ecological and edaphic factors shaped the establishment of a complex of subtypes such as lowland rainforest, freshwater, mangrove and other coastal types within the rainforest biome (Keay 1959). Similar factors led to the establishment of subtypes in the savanna group and even in the montane group. Rainforest and savanna as well as their subtypes are pseudo-parallel to the coast, while the montane group is found mainly in the Cameroun mountain range extension to Nigeria (Maley 1991) and in the Adamawa, Jos, Mambilla and Mandara plateau regions (Adeonipekun et al. 2015). The rainforest is made up of Beach vegetation, Mangrove, Freshwater and Lowland rainforest types, while the savanna has Guinea, Sudan and Sahel sub-types (Fig. 1). Details of these vegetation types and subtypes are given in Keay (1959), Sowunmi (1995) and Adeonipekun et al. (2015).

GEOLOGY AND STRATIGRAPHY OF THE NIGER DELTA

The Niger Delta is situated on the continental margin of the Gulf of Guinea in Equatorial West Africa (3–6° N, 5–8° E). This sedimentary basin extends beyond the limit of the modern delta into the Cross River Delta and the continental margins of Cameroun and Equatorial Guinea. Tectonically, the Niger Delta is the southern part of the larger and older Benue Trough which runs NE–SW across Nigeria
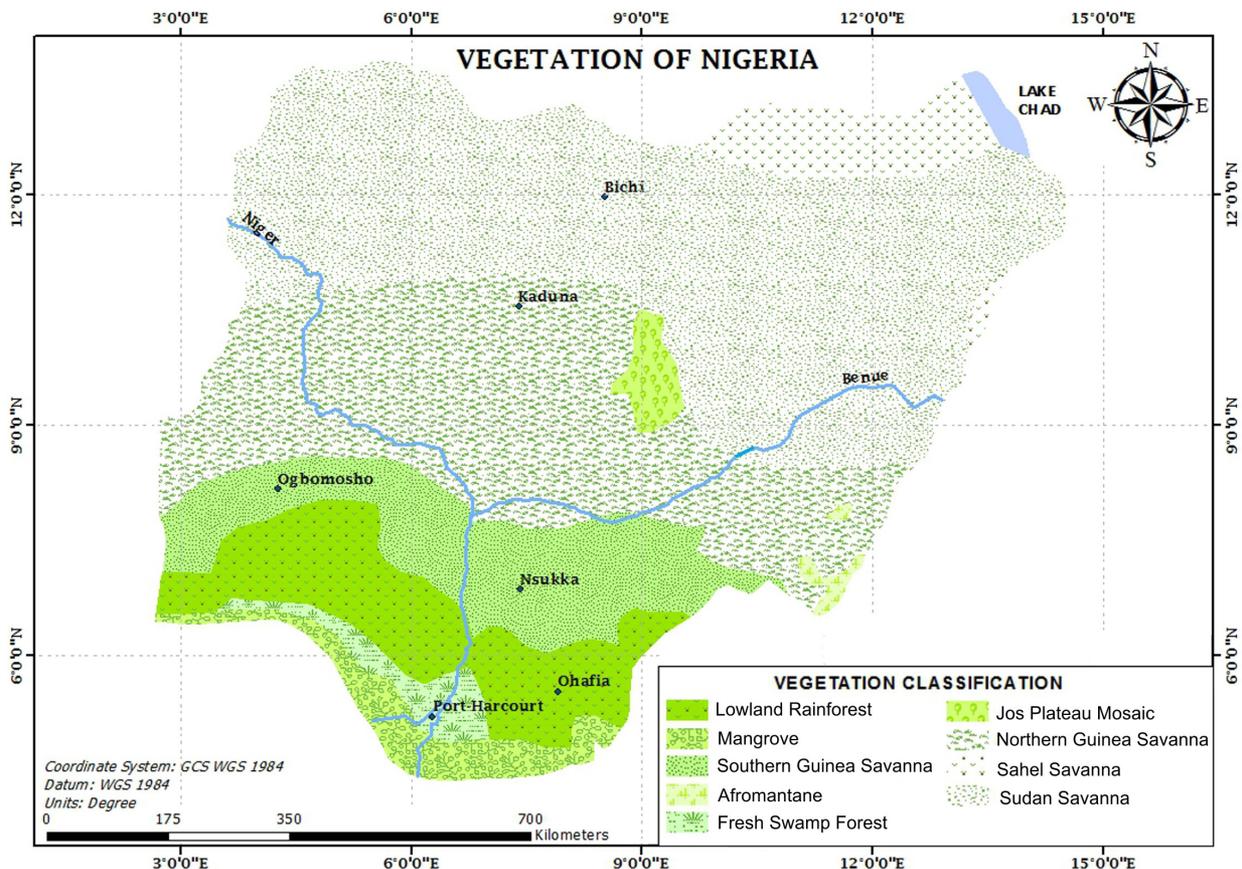
Fig. 1. Vegetation Map of Nigeria. Adapted from Adeonipekun et al. (2017)

(Reijers 1996, 2011). The southern basin of Nigeria began to form in the early Cretaceous, culminating in a proto-Niger Delta during the late Cretaceous. In the Palaeocene, a great transgression submerged the delta, and since then the present delta has been growing progressively seawards. Regression phases dominated that process, and local transgressions and regressions made the growth irregular (Short & Stauble 1967, Evamy et al. 1978).

The lithostratigraphy of the Niger Delta comprises three vertical units: the Benin, Agbada and Akata formations. The Benin Formation is topmost, consisting of thick bodies of highly porous sands, sandstones and gravels with freshwater materials. Local shale lenses are present but very few within the mainly continental delta top sediments (Short & Stauble 1967). The formation is massively thick (~1970 m; Avbovbo 1978) and dates from the Oligocene to Recent. The Agbada Formation is made up of alternating sandstones and shales of deltaic plain origin, which are transitional environment sediments. In the upper part it contains mainly shoreface and channel sands with minor shales, while the lower part contains an equal amount of alternating sand and shale (Reijers 1996). This formation contains hydrocarbons in commercial quantity and is the most important formation for petroleum exploration. It ranges from the Eocene to Recent (Delta front). The Akata Formation is the base of the Niger Delta's lithostratigraphy and is dominated by shaley components; the deposits are typically deep marine. The associated sandstones are lowstand turbidites and fans of deep marine setting. This formation is regarded as the source rock of the Niger Delta, while the Agbada is the reservoir rock. It ranges from the Palaeocene to Recent.

In oil exploration activities in the Niger Delta, problems such as clastic dilution that destroys diagnostic fauna, poor electronic log pattern and insufficient seismic resolution of bathyal sequences have impaired interpretation and inferences in basin evaluation. Morley (1986, 2000) and Morley and Richards (1993, 1997) used charred Gramineae (Poaceae) cuticles commonly encountered in Neogene sediments of the Niger Delta to erect a palynological zonation scheme based primarily on palaeoclimatic changes.

In the present work we made a palynological study of three oil wells in the offshore western

Niger Delta in order to shed more light on palaeovegetational changes in the Neogene–Pleistocene, to gain more insight into palaeoclimatic changes in the area and to assess their usefulness for biostratigraphic correlation.

MATERIALS AND METHODS

Palynological samples were prepared by standard methods from 330 ditch-cuttings taken at regular 18 m intervals from three oil wells in the offshore western Niger Delta, supplied by the Shell Petroleum Development Company, Warri, Nigeria (well A-1, 841–2405 m, 5°9′17″N, 5°3′29.319″E; well A-2, 469–2838 m, 4°57′18.267″N, 5°2′43.427″E; well A-3, 476–2582 m, 5°4′43.306″N, 5°5′34.988″E; Fig. 2). Electronic logs of the wells were also made available for sequence stratigraphy. Foraminifera, sedimentology and sequence stratigraphy were analyzed in order to augment inferences about age and the depositional environment, in addition to qualitative palynostratigraphy. The details of these other studies are outside the scope of this paper but are contained in Adeonipekun et al. (2015).

The standard palynological preparation techniques used involved the use of HCl, HF and acidified $ZnCl_2$ solution (details in Adeonipekun et al. 2015). Stored residues were observed by microscopy, studied, and 70% of the recovered palynomorphs were identified against the reference slide collection of the Palynology Laboratory of the Archaeology and Anthropology Department, University of Ibadan, Ibadan, Nigeria, and other published atlases and albums, as well as publications including Sowunmi (1973, 1987, 1995), Salard-Cheboldaeff (1980, 1981), Thanikaimoni et al. (1984), Thanikaimoni (1987) and Gosling et al. (2013). Those that could not be identified were categorized as indeterminate.

PHYTOECOLOGICAL GROUPING

Poumot (1989) applied a technique known as palynoecological grouping in solving biostratigraphic problems. It is a technique based on the finding that the quantity, quality and nature of recovered pollen and spores are functions of their proximity to shore, shore ecology and eustacy. Hence, the arrangement of phytoecological groups (Poumot's palynoecological groups) follows the order of the present-day positioning of vegetational zones from the shore. For the present work we considered nine phytoecological groups based on their proximity to the shore, in view of the pseudo-parallel arrangement of vegetation types from the coast. The ecological conditions of the present-day parent plants of the fossils were also considered. The works of Hutchinson and Dalziels (1954, 1958,
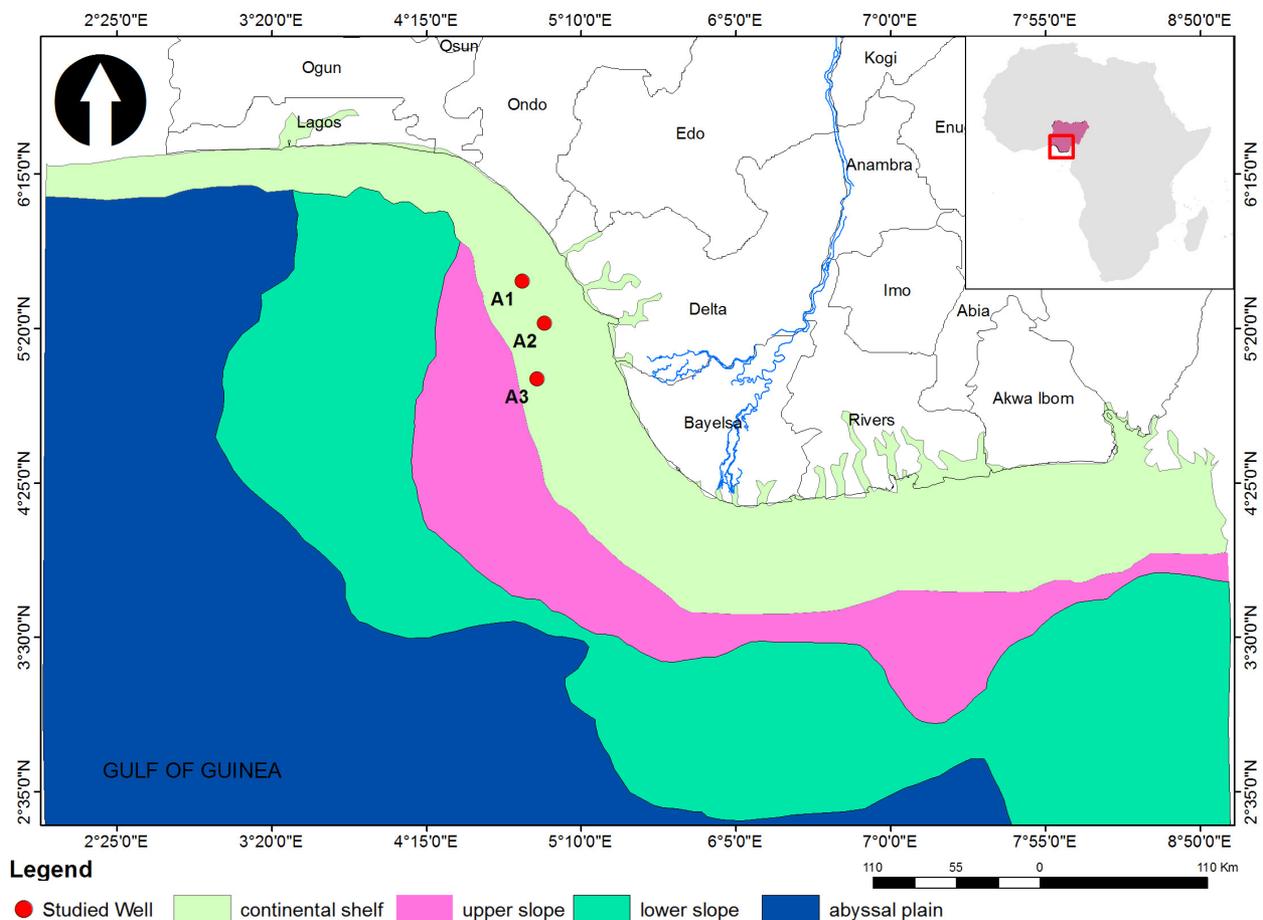

Fig. 2. Location map of studied wells (A-1, A-2, A-3) in the offshore western Niger Delta (Bakare et al. 2009, Adeonipekun et al. 2015)

1963, 1968, 1972), Keay (1959) and Sowunmi (1973, 1981a, b, 1995) primarily guided this grouping.

The trends of occurrence of many of the recovered palynomorphs with respect to the assigned groups also played a significant role in our consideration of the phytoecological grouping, based on our experience in the palynostratigraphy of oil wells across the Niger Delta basin. In this presentation, palynomorphs categorized according to our observations of their trends of occurrence bear the acronym F.O.P.O (= From Observed Pattern of Occurrence). The identified phytoecological groups are Spores, Freshwater, Open coastal vegetation, Poaceae (*Monoporites annulatus*), Mangrove, Rainforest, Riverine, Savanna and Montane. Their composition is outlined below in Table 1, and details of the form-generic and botanical names of some important recovered palynomorphs are listed in Table 5.

In the percentage composition of phytoecological groups, the Spores group was found to be as dominant as the Mangrove and Poaceae groups. These dominant groups were involved in calculating percentage compositions, along with other phytoecological groups (Freshwater, Rainforest, Open coastal vegetation, Montane, Savanna, Riverine), the members of which were selected strictly on the basis of their distinct ecological limits. As a result of this, and the fact that the studied wells are located in the shallow offshore part of the Niger Delta, 16% and above composition of the Mangrove group (Mangrove group's ≥16% share) is considered high. This was based on calculation of the mean percentage of mangrove along the stratigraphic column of each well. These mean values (A-1 13%, A-2 15%, A-3 20%) were then averaged to 16% for the average share of Mangrove in the three wells. Similarly, for the Poaceae group (mainly represented by *Monoporites annulatus*), 44% was regarded as high; lower values were taken as low in this study, based on the calculation of the shares of Poaceae in the three wells. Similar calculations were done for the remaining phytoecological groups, shown in Table 2.

AGE CONTROL

Age control was based on standard biostratigraphic demarcation of the intervals of the three wells, using marker palynomorphs and planktic and benthic foraminifera of the Niger Delta, integrated with sedimentology and sequence stratigraphy (Adeonipekun et al. 2015).

RESULTS

The studied interval was interpreted as belonging to the late Miocene–earliest Pleistocene based on the following features: (i) recovery of *Echitricolporites spinosus*, *Stereisporites* spp., *Nymphaea lotus*, *Cyperus* spp. and *Elaeis guineensis*, (ii) occurrence and recognition of base occurrence of *Borreria* spp. (*Retistephanocolporites gracilis*), (iii) recognition of top occurrences of aff. *Cleistopholis patens*

(*Gemmamonocolpites* sp.1) and (iv) occurrence and base occurrences of *Podocarpus milanjianus* and *Echitriletes pliocenicus*, all typical of the age bracket in published Niger Delta palynostratigraphy (Germeraad et al. 1968, Evamy et al. 1978, Durugbo et al. 2010, Adeonipekun et al. 2015). Supportive foraminiferal events of the recognized ages are first downhole occurrence (FDO) of *Amphistegina lessoni* at 506 m in A-3 (2.0 Ma), FDO of *Hoeglundina elegans* at 1009 m in A-3 (2.7 Ma), FDO of *Globorotalia margaritae* at 1363 m in A-1, the recovery of *Haplopragmoides narivaensis* at 2074 m in A-3 (3.4 Ma maximum flooding surface, mfs), FDO of *Haplophragmoides compressa* at 2074 m in A-3 (3.4 Ma), the occurrence of *Globigerina nepenthes* at 1393 m in A-3 (3.7 Ma), FDO of *Globorotalia merotumida* at 2307 m in A-3 (4.0 Ma mfs), last downhole occurrence (LDO) of *Neogloboquadrina dutertrei* at 2112 m in A-1 (5.0 Ma mfs), FDO of *Cyclammina* cf. *minima* at 1987 m in A-2 (close to 5.0 Ma mfs), FDO of *Ammobaculites stratearnesis* at 2737 m in A-2 (5.8 Ma mfs), and FDO of *Globoquadrina dehiscens* at 2646 m in A-2 (5.5 Ma), according to Blow (1969) and Bolli and Saunders (1985) as well as other Niger Delta foraminiferal biostratigraphic schemes such as Adegoke et al. (1976) and Ozumba (1999). Details of this qualitative biostratigraphy are contained in Adeonipekun et al. (2015).

The percentage calculations indicate that the Poaceae, *Rhizophora* and Spores groups were dominant, while Savanna gave the lowest mean value (0.03%). The Montane component, though low (0.4%), is relatively better represented than Savanna (Tab. 2), possibly due to *Podocarpus milanjianus* pollen being anemophilous and its adaptation to wind and water transport, coupled with its two "wings" for good aerodynamism.

In the reconstruction of palaeoclimatic changes over time, based on the recovered palynomorphs of all three studied wells we recognized seven pollen zones (A–G), which are equivalent to ten informal palaeoclimatic zones (1–10) with alternating dry (D) and wet (W) conditions (D2–D8; W1–W9, TW10; TW = transitional wet). The seven pollen zones were recognized by a cluster analysis-aided dendogram based on regional vegetation changes as indicated by diversity and abundance trends in each stratigraphic column. The palaeoclimatic zones,

Table 5. List of some recovered pollen and spores related to extant parent plants

Family	Pollen /Spores	Form-generic names
Lycopodiaceae	*Lycopodium* spp. L.	*Lycopodiumsporites*
Cyatheaceae	*Cyathea* sp.	*Cyathidites*
Polypodiaceae	–	*Laevigatosporites*
Polypodiaceae	*Verrucatospsorites* spp.	*Verrucatosporites*
Pteridaceae	*Acrostichum aureum* L.	*Acrostichumsporites* sp.
Pteridaceae	*Ceratopteris cornuta* (P. Beauv.) Le Prieur	*Magnastritites howardi*
–	–	*Praedapolis flexibilis*
Acanthaceae	*Hygrophila* R. Br.	–
Acanthaceae	*Justicia* L.	*Multiareolites formosus*
Acanthaceae	–	*Nummilipollis neogenicus*
Acanthaceae	–	*Cintiperipollis mulleri*
Amaranthaceae	–	*Polyporites* spp.
Annonaceae	*Cleistopholis patens* (Benth.) Engl.&Diels.	*Gemmamonocolpites* sp.1
Apocynaceae	*Rauvolfia vomitoria* Afzel	–
Arecaceae	*Elaeis guineensis* Jacq.	–
Arecaceae	*Calamus deeratus* Mann Et Wendl.	–
Arecaceae	*Oncocalamus manni* Wendl.	–
Arecaceae	*Raphia* spp. Pal.	*Retimonocolpites* spp.
cf Aracaceae	–	*Racemonocolpites hians*
Asteraceae	–	*Echitricolporites* spp.
Asteraceae	cf. *Tridax procumbens* Linn	*Echitricolporites spinosus*
Betulaceae	*Alnus* sp.	*Alnipollenites verus*
Bombacaceae	*Bombax*/*Ceiba*	*Bombacacidites*
Combretaceae	*Langucularia* Gaertner F.	–
Convovulaceae	cf. *Convolvulus* L.	*Perfotricolpites digitatus*
Cyperaceae	*Cyperus* L.	*Cyperaceapollenites*
Euphorbiaceae	*Alchornea cordifolia* SW.	*Psilatricolporites operculatus*
Euphorbiaceae	*Macaranga* sp. Muell. Ang	*Psilatricolporites* sp.
Euphorbiaceae	*Uapaca* sp. Muell. Ang	*Retitricolporites* sp.
Euphorbiaceae	cf. *Amanoa*	*Psilatricolporites crassus*
Fabaceae-Caesalpinioideae	*Crudia* / *Berlinia glandifolia*	*Striatricolpites catatumbus*
Guttifereae	*Symphonia globulifera* L.F.	*Pachydermites diederixi*
Icacinaceae	–	*Echiperiporites icacinoides*
Lecythidaceae	cf. *Petersianthus macrocarpus* (P.Beauv.) Liben	*Ctenophonidites costatus*
Leguminosae	*Acacia sieberiana* Miller	*Polyadopollenites* sp.
Leguminosae	*Brachystegia* sp. Benth.	*Peregrinipollis nigericus* Clarke 1966
Leguminosae	*Dalbergia* sp. L.F.	–
Leguminosae	*Parkia biglobosa* R. Br.	*Polyadopollenites* sp.
Malvaceae	*Echiperiporites estalae*	*Echiperiporites estalae*
Meliaceae	*Khaya* A. Juss	*Psilastephanocolporites* sp.
Mimosaceae	*Calpocalyx* sp.	–
Mimosceae	*Acacia* spp.	–
Myrtaceae	*Eugenia* sp. L.	*Myrtacidites* sp.
Myrtaceae	*Syzigium guineense* Gaertner	*Myrtacidites* sp.
Nymphaceae	*Nymphaea lotus* L.	*Nymphaeapollenites* sp.
Onagraceae	*Ludwigia stenorapphe* L.	*Corsinipollenites jussiaensis*
Pandanaceae	*Pandanus candelabrum* Parkinson	–
Poaceae	"Graminae"	*Monoporites annulatus*
Podocarpaceae	*Podocarpus milanjianus* L. Herit. Ex Pers	*Podocarpidites* sp.
Proteaceae	*Protea* spp.	*Proteacidites*
Rhizophoraceae	*Rhizophora* spp. L.	*Zonocostites ramonae*
Rubiaceae	*Gardenia sokotoensis* Ellis	–
Rubiaceae	*Spermacoce* spp. L. (*Borreria*)	*Retistephanocolpites gracillis*
Rubiaceae	–	*Retibrevitricoporites obodoensis*
Rubiaceae	*Canthium* sp.	*Retitriporites* "protundense"
Sapindaceae	*Allophylus africanus* P. Beauv.	–
Sapotaceae	–	*Psilastaphanocolporites laevigatus*
Tiliaceae	*Grewia* sp. L.	–
Zamiaceae (Cycadaceae)	*Encephalartos* sp. Lehm.	*Cycadopites* sp.

Table 3. Informal palaeoclimatic zonation scheme with diagnostic bioevents for the Neogene of Niger Delta

Period	Evamy et al. 1978	Palaeoclimatic zones (this work)	Pollen zone	Associated diagnostic palynostratigraphic events
Late Pliocene–Early Pleistocene	P900 Zone	TW10	G	* Abundant Acanthaceae * BO – *Asystacia gangetica*
		W9	F	
			E	* DD – *Laevigatosporites* spp. * QB – *Podocarpus milanjianus*
		D8	D	* QB – *Echitriletes pliocenicus* * BO – *Podocarpus milanjianus* * BO – *Echitriletes pliocenicus* * PO – *Cyperus* spp.
Late Pliocene	P880 Subzone of P800	W7		
		D6	C	* TR – *Retibrevitricolporites obodoensis* * PO – *Raphia* spp. * QT – *Cleistopholis patens* * TO – *Echiperiporites icacinoides*
		W5		
		D4		
Early Pliocene	P870 Subzone of P800	W3	B	* DD – *Raphia* spp. * DI – Sapotaceae * DD – *Pachydermites diederixi* * DI – *Zonocostites ramonae*
Late Miocene	P860 Subzone	D2	A	* BR – *Elaeis guineensis* * BO – *Borreria* spp. * QB – *Retibrevitricolporites obodoensis*
		W1		* TO – *Racemonocolpites hians*

however, were recognized based on the inverse relationship between the Spores and Poaceae phytoecological groups and were substantiated with support from other phytoecological groups. The nine phytoecological groups can be further categorized into dry condition and wet condition indicator groups. Savanna, Poaceae and Open vegetation make up the dry condition indicator group, while Lowland rainforest, Freshwater, Spores and Riverine form the wet condition indicator group. The Montane phytoecological group indicates coolness and wind strength irrespective of wet or dry condition (Adeonipekun et al. 2017).

For example, W1, the oldest and deepest palaeoclimatic zone, represents palaeo-wet conditions, with relatively low shares or the absence of Poaceae and Savanna, and with high or increasing proportions of Spores, Rainforest, Freshwater swamp and Riverine. Details of the taxonomic composition of each group are given in Table 1. This is followed by zone D2, representing palaeo-dry conditions, with characteristic high proportions of Poaceae and Savanna and with low or reduced proportions of Spores, Rainforest, Riverine, Freshwater swamp and Mangrove. These alternating phases are followed by zones W3, W5, W7 and W9, representing wet phases, while D4, D6 and D8 represent dry phases, commencing from the latest Miocene to earliest Pleistocene (Tab. 3). TW10 represents a transitional palaeoclimate zone. The boundaries of these palaeoclimatic zones were recognized by simultaneous inverse changes in the proportions of the Spores and Poaceae groups, guided by cluster analysis.

DISCUSSION

Since Poaceae flourishes only in open vegetation ecosystems while the Spore group thrives in moist and commonly closed vegetation, the alternating signatures of these two phytoecological groups, substantiated by fluctuations in the relative abundance of other phytoecological groups, are reliable tools for drawing palaeoclimatic inferences from analyses of

Neogene vegetational changes. High values for Freshwater, Mangrove, Rainforest and Riverine indicate wet conditions, while high values for Savanna and Open coastal vegetation indicate dry conditions. The regularity of the alternating occurrence of Spores and Poaceae (Gramineae), usually in appreciable proportions throughout the late Tertiary, makes the use of this inverse relationship more reliable and therefore preferable to other relationships such as coastal groups versus interland groups and wet condition indicator groups versus dry condition indicator groups. The traditional approach used for the temperate region, where alternating trends of arboreal and nonarboreal pollen (Naidina & Richards 2016) are used, cannot be applied directly to the tropics because of the high diversity and complex nature of the vegetation types, where each biome has several subgroups.

For instance, rainforest contains beach vegetation, mangrove swamp, freshwater swamp forest, lowland rainforest and even montane forest. In the savanna there are Guinea, Sudan, Sahel and montane savanna subgoups, and riverine groups are found in both forest and savanna biomes. Moreover, savanna has trees in addition to the traditional grasses and herbs, while rainforest has its trees, herbs and even coastal grasses. Therefore, the use of the occurrence and abundance of Rainforest, Freshwater and Riverine groups as indicators of wet conditions, and Savanna, Open Vegetation and Poaceae groups as indicators of dry conditions, sometimes suffers inconsistency. In our experience, several cores in the Niger Delta yielded strictly rainforest plant pollen from an interval interpreted as dry palaeoclimate, and strictly savanna pollen from wet palaeoclimate intervals. The reason for this is that most of the pollen was transported to the basin through the river system whenever it rained, hence savanna pollen deposited during the dry interval would only get to the Niger Delta basin when it rained during wet-climate periods at the sediment source, except for anemophilous pollen. Similarly, some rainforest pollen would also have been blown or reworked into the basin during dry palaeoclimate which was associated with lowstand systems tracts. Lowland systems tracts have been associated with high magnitude aerosional activities resulting from the created gradient difference. We assessed the relationships among these phytoecological groups and found the relationship between the Poaceae and Spores groups most consistent and reliable.

The consistency of the inverse relationship between these two groups can be seen from the percentage diagram of Core GIK 16776-1, Figure 2 of Jahns et al. (1998) based on a marine pollen record from offshore Liberia in the middle Pleistocene. Of all the ecological groups, the two contrasting ones are fern spores and Poaceae (Gramineae). It is easy to identify these groups, since the pollen grains of all Poaceae (Gramineae) group are psilate, with an annulated pore each, while each member of the spore group has a characteristic trilete or monolete scar on its sculptured or psilate thick walls (exine).

The proximity of the Poaceae and Spores groups to the depositional sites, due to their occurrence in coastal habitats, also enhances their usefulness, unlike others that have to traverse long distances before getting to the depositional sites. Moreover, the proximity of the habitats within the coastal belt suggests that they probably are subject to similar physical influences such as climate and geomorphology. This makes the observed inverse relationship a good contrast. Poaceae pollen and fern spores have always dominated the recovered palynological material from subsurface sediments of the Niger Delta (Sowunmi 1987, 1981a, b), because they are abundantly produced by the parent plants. The only assumptions are that there are negligible differences in pollen production, pollen preservation and dispersal mechanisms after deposition.

PALAEOCLIMATIC DEDUCTIONS

Sowunmi (1981a, b, 1986) reported the recovery of typical savanna pollen from Niger Delta offshore sediments in lower amounts than for other phytoecological groups. Similarly, the present authors have also not found them very reliable. This is because they are very scarce due to their low representation; furthermore, they may not be reliable for accurate palaeoclimatic and biostratigraphic deductions. The fact that they were sometimes recovered even in intervals interpreted as having wet palaeoclimate suggests that those were brought down to the depositional sites by river discharge from the continent during wet phases. Nevertheless, it is important to note the recovery of sparse pollen of two typical

savanna species – *Gardenia sokotoensis* and *Acacia sieberiana* – within the upper section of the studied wells. If they evolved prior to the late Pliocene, this scenario supports the suggestion of drier palaeoclimatic conditions in the late Pliocene/early Pleistocene than in previous times in the Late Miocene–Pliocene of the Niger Delta. It may also mean that typical inland savanna vegetation, as against coastal savanna vegetation, probably began in the late Pliocene in Nigeria.

In the materials from the studied three wells, from ~3.0 Ma there were increases in the proportions of *Acacia* spp., *Acacia sieberiana*, Amaranthaceae, *Syzygium guineense*, *Fenestritites spinosus* (*Vernonia* spp.), *Polyadopollenites* spp. (Mimosoideae), *Nummullinites neogenicus* (Acanthaceae) and *Borreria* spp., all components of modern-day woodland and grassland savanna. The openness of the vegetation is further supported by the increase in the proportion of Cyperaceae, a freshwater taxon but also thriving in open vegetation. On the other hand, there was a sharp drop in the proportions of lowland rainforest and freshwater trees such as Sapotaceae, aff. *Cleistopholis patens*, *Canthium* spp., *Pachydermites diederixi* and *Pandanus candelabrum*. These events continued until ~2.7–2.4 Ma, when there was a return to wetness (Most of these pollen trends are shown in Adeonipekun et al. 2015, Fig. 5). Cerling and Hay (1988) and Cerling (1992) reported similar openness and dryer vegetation after ~3.0 Ma, using paleosol carbonates in the Turkana and Olduvai basins of East Africa. In his review of African climates and faunal evolution in the Pliocene/Pleistocene of Africa, DeMenocal (2004) remarked that the palaeoclimates of Africa were dryer, cooler and more open, with increases in their variability and aridity at 2.8 Ma, 1.7 Ma and 1.0 Ma. The openness, aridity and variability were associated with landslide hominid evolutionary events, particularly at 2.9–2.4 Ma and 1.8 Ma. Supportive of this in the present study is the finding that the Riverine group occurred abundantly at ~5.8–3.0 Ma (Fig. 3, Appendices A–C).

On the whole, the palaeovegetational changes recorded here confirm that the Early Pliocene was dominated by wet climate, with relatively brief drier intervals (D2, D4). Leroy and Dupont (1997) made a similar observation in their work using ODP Site 658 sediments from offshore northwest Africa spanning 3.7–1.7 Ma. This also agrees with Tiedemann's (1991, in Leroy & Dupont 1997) conclusion that "persistent river discharge existed prior to 3.4 Ma". After this time bracket, in the three wells we studied the river activity indicator group disappeared or occurred in low and irregular proportions, suggesting poor discharge of the River Niger. This must have resulted from poor rainfall on the continent during dry palaeoclimate. Poumot (1989) observed a similar change in vegetation from wet to dry at ~3.0 Ma in the Niger Delta.

This scenario indicates that dry palaeoclimatic conditions commenced from 3.0 Ma upwards to 2.7 Ma; extremely dry climate prevailed, with abundant Poaceae (Gramineae) and reduction of the proportions of Spores (18%, the mean percentage being 22% for the whole studied period) and the Freshwater as well as the substantial reduction to near absence of the Rainforest group (Appendices A–C, Fig. 3). The reduction in rainfall on the continent is further reflected in the near disappearance of the Riverine group after 3.0 Ma; it had formed a substantial part of the wet climate vegetation in the 5.8–3.4 Ma interval, and only came back in the latest Pliocene–earliest Pleistocene period in the Niger Delta (2.7–2.4 Ma). This drier condition persisted until ~2.7 Ma, after which the Rainforest group became more established and Spores dominated the littoral, concomitantly with the contraction of the Poaceae (Gramineae). This does not mean that the Niger river dried up: material of the Freshwater group, another good indicator of rainfall at the sediment source area, was still recovered in substantial though lower amounts. At ~3.0 Ma the Freshwater group decreased appreciably across the three wells.
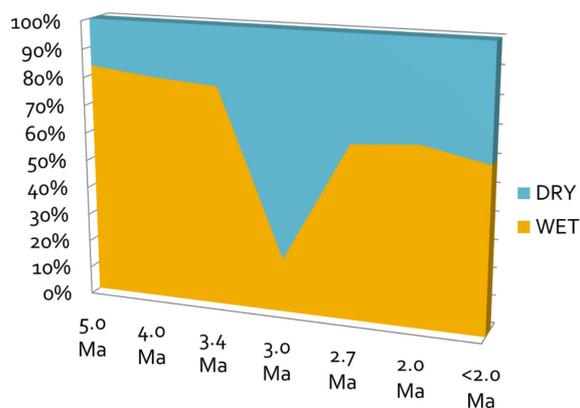

Fig. 3. Graphical representation of Niger Delta Neogene–Pleistocene palaeoclimate (from this work)

The late Pliocene wet conditions were significantly different from the early Pliocene humid phase in having the first strong occurrence of the Montane group (reaching 2% as against an average of 1.3% in this study), which heralded the beginning of the Pleistocene cooling phase (Appendices A–C). Therefore, between 2.7 and 2.4 Ma, *Podocarpus milanjianus*, an important montane plant in West Africa, along with Acanthaceae species, became more established as a result of the orogeny of the Cameroon volcanic range. Increased flow of the River Benue, a tributary of the Niger River, might have aided the transport of this pollen to the Niger Delta basin, but the lack of an expected increase in the proportions of Riverine and Savanna taxa traversed by this river weakens this suggestion. Furthermore, the similarity of increased occurrence between the Montane and Mangrove groups within this age bracket suggests that *Podocarpus milanjianus* pollen in the Niger Delta shallow offshore was deposited by sea transgression as a result of being blown into the ocean. This landward movement of the seawater during the transgression probably brought shoreward the air-borne *P. milanjianus* that was suspended in the seawater. This is supported by the abundant occurrence of the Montane group within the transgressive systems tracts of the studied wells, the details of which are outside the scope of this paper. Adeonipekun and Olowokudejo (2013) have also reported higher amounts of *Podocarpus milanjianus* pollen in recent bottom sediments from deeper and more distal locations of shallow offshore sediments of the Niger Delta as compared with proximal shallow locations. In the present study, finding the highest proportion of the Montane group in the most distal well (A-3, mean 0.6%), while the more proximal ones, A-2 and A-1, showed 0.3% and 0.4% respectively, also supports probable deposition during transgression (Appendices A–C).

That the time between 2.7 and 2.4 Ma was generally not as wet as the early Pliocene is further supported by the single-grain recovery of savanna pollen *Gardenia sokotoensis* from A-3 and two-grain recovery of savanna pollen *Acacia sieberiana* from A-2 within the dry palaeoclimatic zone – D6 in the late Pliocene (Tab. 3). None of this diagnostic savanna pollen was recovered from the late Miocene–early Pliocene in the studied three wells.

In summary, the late Miocene as analyzed in this study was found to be largely dry, with characteristic expansion of the savanna and openness of the vegetation, accompanied by great reduction of the rainforest. This represents the Messinian dry event. The early Pliocene was very wet, ending with a regional riverine episode. Dryer conditions returned from the late Pliocene, as indicated by abundant Poaceae and great reduction of Rainforest and other wet indicators. Wet conditions were restored towards the end of the late Pliocene to the earliest Pleistocene, though not as wet as in the early Pliocene. In this latest wet condition, the impact of the late Pliocene dryness, together with the reported orogeny of the late Pliocene (Knapp 1971), led to the blooming of montane taxon – Acanthaceae – in the latest Pliocene–earliest Pleistocene. By the early Pleistocene, the Acanthaceae diversified with the evolution of different types and particularly *Asystasia gangetica*. Knapp (1971) equated this period, late Pliocene–early Pleistocene, to that of the orogenic activity which also led to the evolution of montane *Podocarpus milanjianus* in Nigeria.

SIGNIFICANCE OF *RHIZOPHORA*

Rhizophora pollen (*Zonocostites ramonae*) has been used by several workers to infer palaeoclimate, to study sea level changes and to indicate proximity to the coast in West Africa (Sowunmi 1981 a, b, Poumot 1989, Jahns et al. 1998, Durugbo et al. 2010). Abundant occurrence of this fossil pollen has been commonly recorded in wet palaeoclimatic phases, and low occurrence in dry palaeoclimatic phases. Our results, however, show that *Rhizophora* cannot be consistently used for such palaeoclimatic inferences in a progradation-dominated sequence like the ones encountered here. This is because the Mangrove group shows abundance not only in some interpreted wet phases; it is also recorded as abundant in some dry palaeoclimatic phases. Durugbo et al. (2010) also reported this inconsistent occurrence. Abnormal occurrences like these are indicative of other factors apart from climate operating on mangroves. Factors such as transport mechanisms and the degree of freshwater influx as well as eustacy have significant effects on recovery of *Rhizophora* from Niger Delta sediments.

Jahns et al. (1998), quoting Muller (1959), remarked that *Rhizophora* trees are

Table 4. Correlation of palaeoclimatic zones with Evamy et al. (1978) across wells A1, A2 and A3 (exceptions in red)

Evamy et al. (1978)	Table 3	Well A1	Well A2	Well A3
P860 Late Miocene	W1, D2	D2	W1, lower D2	P860 not recognized
P870 Early Pliocene	W3, most of D4	W3, most of D4	**upper D2**, lower W3	D4, **lower W5**
P880 Late Pliocene	upper D4, W5, D6, most of W7	upper D4, W5, D6, most of W7	**upper W3**, D4, W5, D6, W7	upper W5, D6, lower W7
P900 Late Pliocene–Early Pleistocene	upper W7, D8, W9, TW10	upper W7	D8, W9	upper W7, D8, W9, TW10

wind-pollinated and that their pollen grains are wind- and water-transported. The implication of this is that transport of this pollen is equally enhanced even in dry climatic phases. Local subsidence or large-scale faulting may also cause this type of inconsistency in the signature of *Rhizophora*, since these can lead to local transgressions that are not linked to regional climate.

Sowunmi (2004: 209) reported that the 40% and higher proportion of *Rhizophora* in Sowunmi's (1981b) pollen spectra was indicative of "appreciable occurrence of mangrove, and hence tidal flooding, i.e., nearness to coast". Lower values were interpreted as "limited occurrence and a greatly reduced incursion of sea water, or increased distance from the coast". Sowunmi (2004) further supported this with the result of a study of modern-day surface samples in some coastal areas of West Africa, by Edorh through a personal communication. It revealed that in any area where *Rhizophora* was present, its share was not less than 40% of the spectra. This may be right for brackish water (lagoonal or estuary settings; Sowunmi 1981b) and other coastal onshore areas (Edorh). As revealed in our present work, the picture is different in the shallow marine offshore settings of the Niger Delta, where *Rhizophora* increases with distance from shore to shelf. The most distally located well, A-3, has an average 20% Mangrove; the next distally located, A-2, has 15%; and the most proximally located, A-1, has mean 13% for Mangrove. This result shows that the proportion of *Rhizophora* increases from shore to shelf, hence a higher share of the pollen of this plant in offshore locations does not indicate nearness to coast. Rather, it indicates the degree of marine influence.

That eustacy has a great influence on the recovery of *Rhizophora* has been shown by Sowunmi (1981b, 2004) and Jahns et al. (1998). In fact the amount of *Rhizophora* in a deposit depends on the location of the borehole or well drilled. Therefore the proportion of *Rhizophora*

is better used for proximity, as Muller (1959) suggested, and not so much as a palaeoclimatic indicator, because of the dual nature of the transport media: water and wind. It may, however, be used as an associated group to substantiate palaeoclimatic interpretations from locations with good paralic lithofacies as found in the eastern Niger Delta.

BIOSTRATIGRAPHIC CORRELATION POTENTIAL

The alternating wet and dry palaeoclimates inferred from the palynological data obtained from the stratigraphic columns of the studied three wells show the cyclical nature of the palynological components of sedimentary deposits in the offshore Niger Delta. This gives further support to the recommendation of Leroy and Dupont (1997) that cyclostratigraphy should become a tool in palynostratigraphy and intersite correlations, but for cyclostratigraphy to be correlation-useful more work needs to be done, particularly beyond the time span covered in the present work. This will enable each of the recognized palaeoclimatic zones to be accurately identified and tied to important palynological or micropalaeontological events – and eventually correlated with the Global Sequence Cycle Chart of Haq et al. (1987). With the recognition of the palaeoclimatic zones in the three wells, such correlation is possible, and can be extended across the delta and even beyond. The recognized pollen and palaeoclimatic zones from this study can be correlated because they have been tied with diagnostic palynological events (as shown in Tab. 3), and these can also be carried across the delta. It is important to note that cluster analysis-aided recognition of pollen zones A–G was based on regional vegetation assemblage changes in diversity and abundance, while the recognition of palaeoclimatic zones W1–TW10 was based on ecological considerations, and thus on different scales. Thus there seems to be less synchronicity in

their stratigraphy. Rather, the palaeoclimatic zones correlate more with the zones recognized by Evamy et al. (1978) across the three wells (Tab. 4). There are some exceptions, however, and they are the occurrence of the upper part of D2 in P870 in Well A-2 as against its restricted occurrence within P860 in the other two wells, the occurrence of the upper part of W3 in P880 as opposed to its restriction to P870 in other wells, and the straddling of P880 and P900 by W7. All these were most likely due to the use of quantitative and not qualitative events in marking the boundaries of the palaeoclimatic zones, which are of course subject to facies change to an extent. Even with the use of the traditional biostratigraphic schemes, the challenges of erosion, redeposition and faulting are characteristic of the growth-fault-dominated sediments of the Niger Delta. Instances of suppressed, eroded, raised and faulted tops and bottoms of palynomorph events are common. Despite these shortcomings, the outcomes of this attempt are good enough to justify using vegetational and palaeoclimatic changes as biostratigraphic tools in the progradation-dominated sequences of the Niger Delta.

CONCLUSIONS

The inverse relationship between pteridophyte spores and Poaceae pollen was found to be useful in interpreting palaeoclimatic changes in the Neogene–Pleistocene of the Niger Delta, supporting the call for integrated ecostratigraphy. We recognized seven pollen zones with ten palaeoclimatic zones, based on this inverse relationship and cluster analysis. Generally, the late Miocene section was dry and the early Pliocene (5.0–<3.4 Ma) was wet. The late Pliocene (>3.0–2.7 Ma) was extremely dry. Lower-magnitude wet conditions recurred at the latest Pliocene–earliest Pleistocene, compared to early Pliocene conditions. Our results support earlier findings from other parts of West Africa. This study recorded the evolution of *Asystacia gangetica* in the latest Pliocene–earliest Pleistocene at ~2.0 Ma in the Niger Delta.

ACKNOWLEDGEMENTS

REFERENCES

ADEGOKE O.S., OMATSOLS M.E. & SALAMI M.B. 1976. Benthonic Foraminiferal Biofacies off the Niger Delta. 1st International Symposium on Benthonic foraminifera. Maritime Sediments, Special Publication, 1: 279–292.

ADEONIPEKUN P.A. & OLOWOKUDEJO J.D. 2013. Palynology of Recent Bottom Sediments from Shallow Offshore Niger / Cross River Delta Nigeria: A Preliminary Study. Int. J. Bot., 9(3): 100–122. http://dx.doi.org/10.3923/ijb.2013.100.122

ADEONIPEKUN P.A., SOWUNMI M.A. & RICHARDS K. 2015. A new Late Miocene to Pleistocene palynomorph zonation for the western offshore Niger Delta. Palynology, 41(1): 2–16. http://dx.doi.org/10.1080/01916122.2015.1107652

ADEONIPEKUN P.A., AGBALAYA A.E. & ADENIYI T.A. 2016. Aeropalynology of Ayetoro-Itele, Ota Southwest Nigeria: A preliminary study: 130–153. In: Oyelaran P.A, Alabi R.A. & Adeonipekun P.A. (eds), Human Palaeoecology in Africa: Essays in Honour of M. Adebisi Sowunmi. University of Ibadan Press, Ibadan, U.I.

ADEONIPEKUN P.A., ADENIYI T.A., MATEAWO J. & AGBALAYA B. 2017. The Late Quaternary vegetational and environmental history of western tropical Africa: the eastern Benin Basin, Lagos, Nigeria. Geology, Geophysics & Environment, 43(4): 277–291. http://dx.doi.org/10.7494/geol.2017.43.4.277

ADOJOH O. MARRET F., DULLER R. & OSTERLOFF P. 2017. Tropical palaeovegetation dynamics, environmental and climate change impact from the low latitude coastal offshore margin, Niger Delta, Gulf of Guinea. Palaeoecology of Africa, 34: 107–144.

ALLEN J.R.L. 1965. Late Quatenary Niger Delta and adjacent areas: sedimentary environment and lithofacies. American Association of Petroleum Geologists, 49: 549–600.

AVBOVBO A.A. 1978. Tertiary lithostratigraphy of Niger delta. American Association of Petroleum Geologists Bulletin, 62(2): 295–306.

BAKARE O., KANU K.M. & NEIL H. 2009. Influence of mass transport deposits on Paleotopography, turbidite reservoir architecture and preservation, Niger Delta, West Africa. Nigerian Association of Petroleum Explorationists Bulletin, 21(1): 7–24.

BLOW W.H. 1969. Late middle Eocene to Recent planktic foraminiferal biostratigraphy: 199–422. In: Bronnimann P. & Renz H.H. (eds), Proceedings of the First International Conference on Planktonic Microfossils, Geneva 1967, 1.

BOLLI H.M. & SAUDERS S.B. 1985. Oligocene to Holocene low latitude planktic foraminifera: 155–262. In: Bolli H.M., Saunders J.B., Perch-Nielsen K. (eds), Plankton Stratigraphy. Cambridge University Press.

CERLING T.E. 1992. Development of grasslands, savannas in East Africa during the Neogene. Palaeogeogr., Palaeoclimat., Palaeoecol., 97: 241–247.

CERLING T.E. & HAY R.L. 1988. An isotopic study of paleosol carbonates from Olduvai Gorge. Quat. Res., 25: 63–78.

DeMENOCAL P.B. 1995. Plio-Pleistocene African climate. Science, 270: 53–59.

DeMENOCAL P.B. 2004. African climate change and faunal evolution during the Pliocene Pleistocene. Earth and Planetary Science Letters, 220(1–2): 3–24. https://doi.org/10.1016/S0012-821X(04)00003-2

DURUGBO E.U., OGUNDIPE O.T. & ULU O.K. 2010. Palynological Evidence of Pliocene-Pleistocene Climatic Variations from the Western Niger Delta, Nigeria. Int. J. Bot., 6: 351–370. https://doi.org/10.3923/ijb.2010.351.370

EVAMY B.D., HAREMBOURE J., KAMERLING P., KNAAP W.A., MOLLOY F.A. & ROWLANDS P.H. 1978. Hydrocarbon Habitat of Tertiary Niger Delta. American Association Petroleum Geologists Bulletin, 62(1): 1–39.

GERMERAAD J.H., HOPPING C.A. & MULLER J. 1968. Palynology of Tertiary sediments from tropical areas. Rev. Palaeobot. Palynol., 6: 189–343.

GOSLING D., MILLER S.M. & LIVINGSTONE D.A. 2013. Atlas of the tropical West African pollen flora. Rev. Palaeobot. Palynol., 199: 1–135. https://doi.org/10.1016/j.revpalbo.2013.01.003

HAQ B.U., HARDENBOL J. & VAIL P.R. 1987. Chronology of fluctuating sea levels since the Triassic. Science, 235: 1156–1167.

HERBERT T.D., LAWRENCE K.T., TZANOVA A., PETERSON L.C., CABALLERO-GILL R. & KELLY C.S. 2016. Late Miocene global cooling and the rise of modern ecosystems. Nature Geoscience, 9: 843–849. https://doi.org/10.1038/ngeo2813

HOETZEL S., DUPONT L.M., MARRET F., JUNG G. & WEFER G. 2017. Steps in the intensification of Benguela upwelling over the Walvis Ridge during Miocene and Pliocene. Int. J. Earth Sci., 106(1): 171–183. https://doi.org/10.1007/s00531-016-1309-0

HUTCHINSON J. & DALZIEL J.M. 1954. Flora of West Tropical Africa. vol 1 part 1 (2nd edition revised by Keay, R.W.J.). London: Crown Agents. 295 p.

HUTCHINSON J. & DALZIEL J.M. 1958. Flora of West Tropical Africa. vol 1 part 2 (2nd edition revised by Keay, R.W.J.). London: Crown Agents. 532 p.

HUTCHINSON J. & DALZIEL J.M. 1963. Flora of West Tropical Africa. vol 2 (2nd edition revised by Hepper FN.). London: Crown Agents. 544 p.

HUTCHINSON J. & DALZIEL J.M. 1968. Flora of West Tropical Africa. vol 3 part 1 (2nd edition revised by Hepper F.N.). London: Crown Agents. 276 p.

HUTCHINSON J. & DALZIEL J.M. 1972. Flora of West Tropical Africa, vol 3 part 2 (2nd edition revised by Hepper FN.). London: Crown Agents. 300 p.

JAHNS S., HULS M. & SAMTHEIN M. 1998. Vegetation and climate history of west equatorial Africa based on a marine pollen record off Liberia (site GIK 16776) covering the last 400,000 years. Rev. Palaeobot. Palynol., 102: 277–288.

JOORDENS J.C.A., FEIBEL C.S., VONHOF H.B., SCHULP A.S. & KROON D. 2019. Relevance of the eastern African coastal forest for early hominin biogeography. J. Hum. Evol., 131: 176–202. https://doi.org/10.1016/j.jhevol.2019.03.012

KEAY R.W.J. 1959. An outline of Nigerian vegetation. Federal Government of Nigeria, Nigeria, 46p.

KNAPP W.A. 1971. A montane pollen species from the upper tertiary of the Niger delta. Journal of Mining and Geology, 6: 23–29.

LEROY S.A.G. & DUPONT L.M. 1997. Marine palynology of the ODP site 658 (N-W Africa) and its contribution to the stratigraphy of late Pliocene. GEOBIOS, 30(3): 351–359.

MALEY J. 1991. The African rain forest: vegetation and paleoenvironments during late Quaternary. Climate Change, 19: 79–98.

MORLEY R.J. 1986. New approaches to stratigraphical and palaeoenvironmental modelling in Neogene deltaics with emphasis on the Niger Delta. Proceedings of the 3rd Annual Conference Nigerian Association of Petroleum Explorationists; November 1985; Lagos, p. 229–230.

MORLEY R.J. 2000. Origin and evolution of Tropical Rain Forests. UK: Wiley. 362 p.

MORLEY R.J. & RICHARDS K. 1993. Gramineae cuticle: a key indicator of late Cenozoic climatic change in the Niger Delta. Rev. Palaeobot. Palynol., 77: 119–127.

MORLEY R.J. & RICHARDS K. 1997. Offshore Niger Delta Palynological Zonation, prepared for the Niger Delta Stratigraphic Commission, Nigeria, p. 1–9.

MULLER J. 1959. Palynology of Recent Orinoco delta and shelf sediments. Micropaleontology, 5(1): 1–32.

NAIDINA O.D. & RICHARDS K. 2016. Pollen evidence for Late Pliocene – Early Pleistocene vegetation and climate change in the North Caucasus, North-Western Caspian Region. Quat. Int., 409(A): 50–60. https://doi.org/10.1016/j.quaint.2015.12.018

OZUMBA M.B. 1999. Middle to Late Miocene Sequence Stratigraphy of the western Niger Delta Nigerian Association of Petroleum Explorationists Bulletin, 14(2): 176–191.

POUMOT C. 1989. Palynological evidence for eustatic events in the tropical Neogene. Bulletin Centr. Reche. Expl.-Prod. d'Elf-Aquitaine, 13(2): 447–453.

REIJERS T.J.A. 1996. Selected chapters on Geology. Shell Petroleum Development Company, Nigeria, 197 p.

REIJERS T.J.A. 2011. Stratigraphy and sedimentology of the Niger Delta. Geologos, 17(3): 133–162. https://doi.org/10.2478/v10118-011-0008-3

SALARD-CHEBOLDAEFF M. 1980. Palynologie Camerounais I. Pollen de la mangrove et des fourres arbustifs ĉotiers. C.R. 105e Congres National des Societes Savantes. Caen; France, 1: 233–247.

SALARD-CHEBOLDAEFF M. 1981. Palynologie Camerounais II. Grains de pollen de la foret littorale

de basse altitude. C.R. 106e Congres National des Societes Savantes. Perpignan; France, 1: 125–136.

SALARD-CHEBOLDAEFF M. 1990. Intertropical African palynostratigraphy from Cretaceous to late Quaternary times. J. African Earth Sci., 11: 1–24.

SHORT K.C. & STAUBLE J.A. 1967. Outline of Geology of Niger Delta. American Association of Petroleum Geologists Bulletin, 6: 761–799.

SOWUNMI M.A. 1973. Pollen of Nigerian Plants I. Woody species. Grana, 13: 145–186.

SOWUNMI M.A. 1981a. Aspects of Late Quaternary vegetational changes in West Africa. J. Biogeogr., 8: 457–474.

SOWUNMI M.A. 1981b. Late Quaternary environmental changes in Nigeria. Pollen et Spore, 23(1): 125–148.

SOWUNMI M.A. 1986. Change of Vegetation with time: 273–306. In: Lawson John G.W. (ed.), Plant Ecology in West Africa. Wiley & Sons Ltd.

SOWUNMI M.A. 1987. Palynological Studies in the Niger Delta: 30–31. In: Alagoa E.J., Anozie F.N., Nzewunwa N. (eds), The Early History of the Niger Delta. Helmat Buske Verlag, Hamburg, UK.

SOWUNMI M.A. 1995. Pollen of Nigerian Plants II. Woody species. Grana, 43: 120–141.

SOWUNMI M.A. 2004. Aspects of Nigerian coastal vegetation in the Holocene: some recent insights: 199–218. In: Battarbee R.W., Grasse F. & Stickley C.E. (eds), Past Climate Variability through Europe and Africa. Springer, Dordrecht, The Netherlands.

THANIKAIMONI G. 1987. Mangrove palynology. Travaux de la section scienti. que et Technique, 24: 1–100.

THANIKAIMONI G., CARATINI C., VENKATACHALA B.S., RAMANUJAM C.G.K. & KAR R.K. 1984. Selected Tertiary angiosperm pollen from India and their relationship with African Tertiary pollen. Institut Français de Pondichéry, Travaux de la Section Scientifique et Technique, 19: 1–93.

VALLE F., DUPONT L.M., LEROY S.A.G., SCHEFUB E., WEFER G. 2014. Pliocene environmental change inWest Africa and the onset of strong NE trade winds (ODP Sites 659 and 658). Palaeogeogr., Palaeoclimat., Palaeoecol., 414: 403–414. https://doi.org/10.1016/j.palaeo.2014.09.023
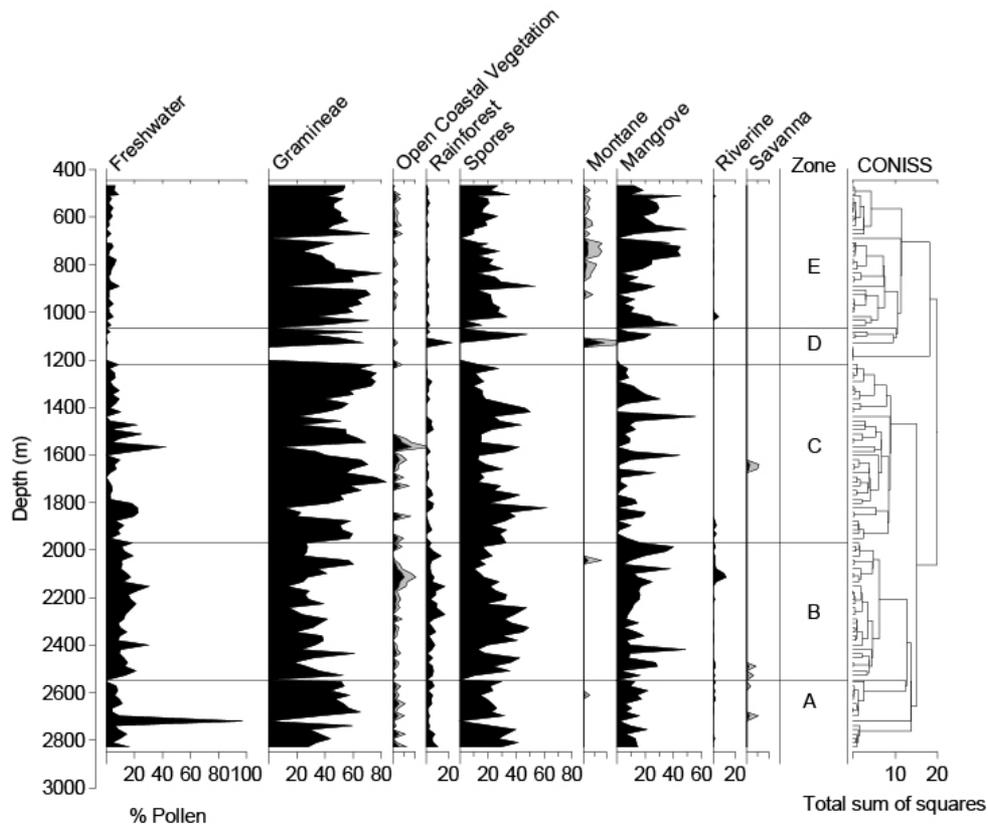
Appendix A (1): Well A-1 (a) phytoecological groups and cluster analysis-aided pollen zones of the Late Miocene–Earliest Pleistocene of the western Niger Delta
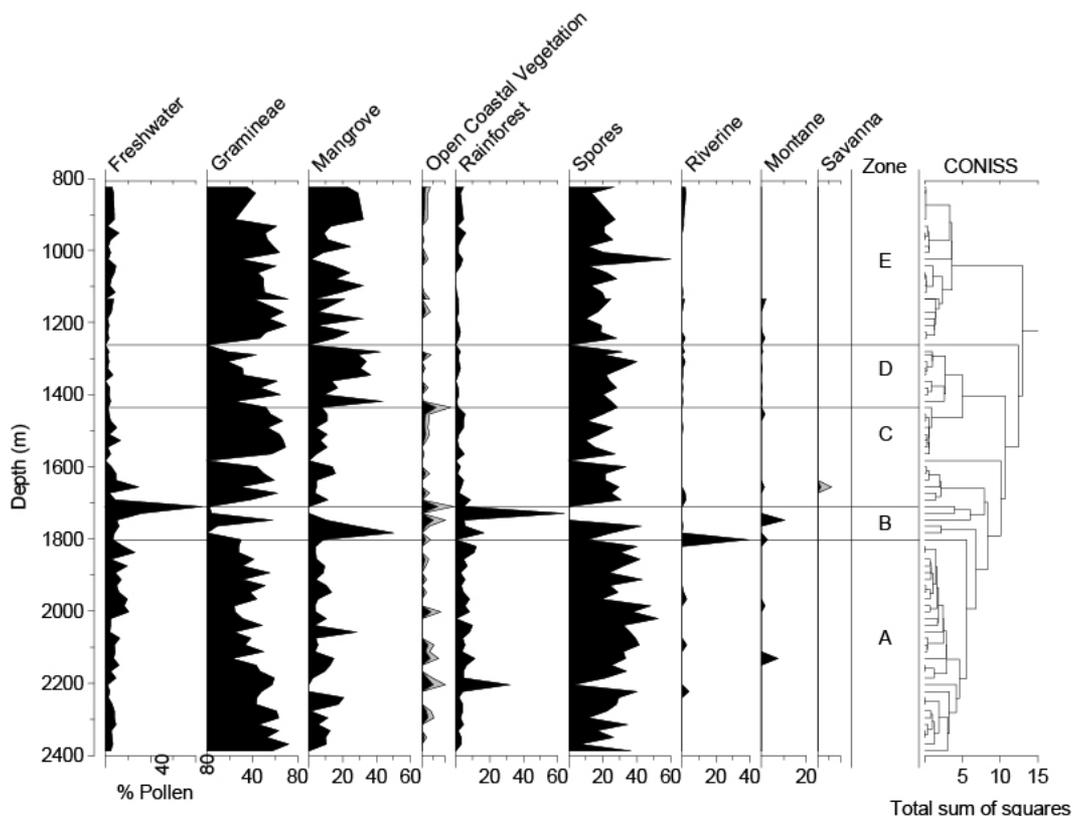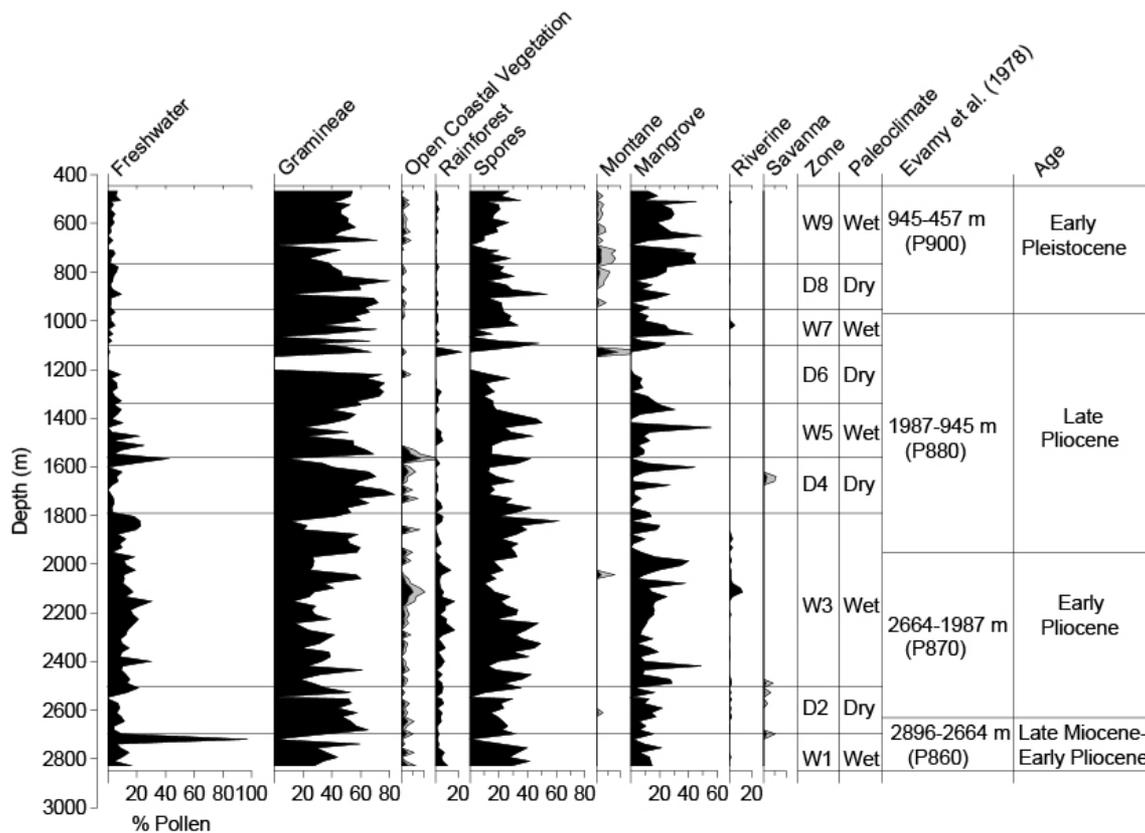

Appendix A (2): Well A-1 (b) phytoecological groups and recognized palaeoclimatic zones related to Evamy et al. (1978). Note the conversion of Evamy et al.'s (1978) zones from feet to meters.
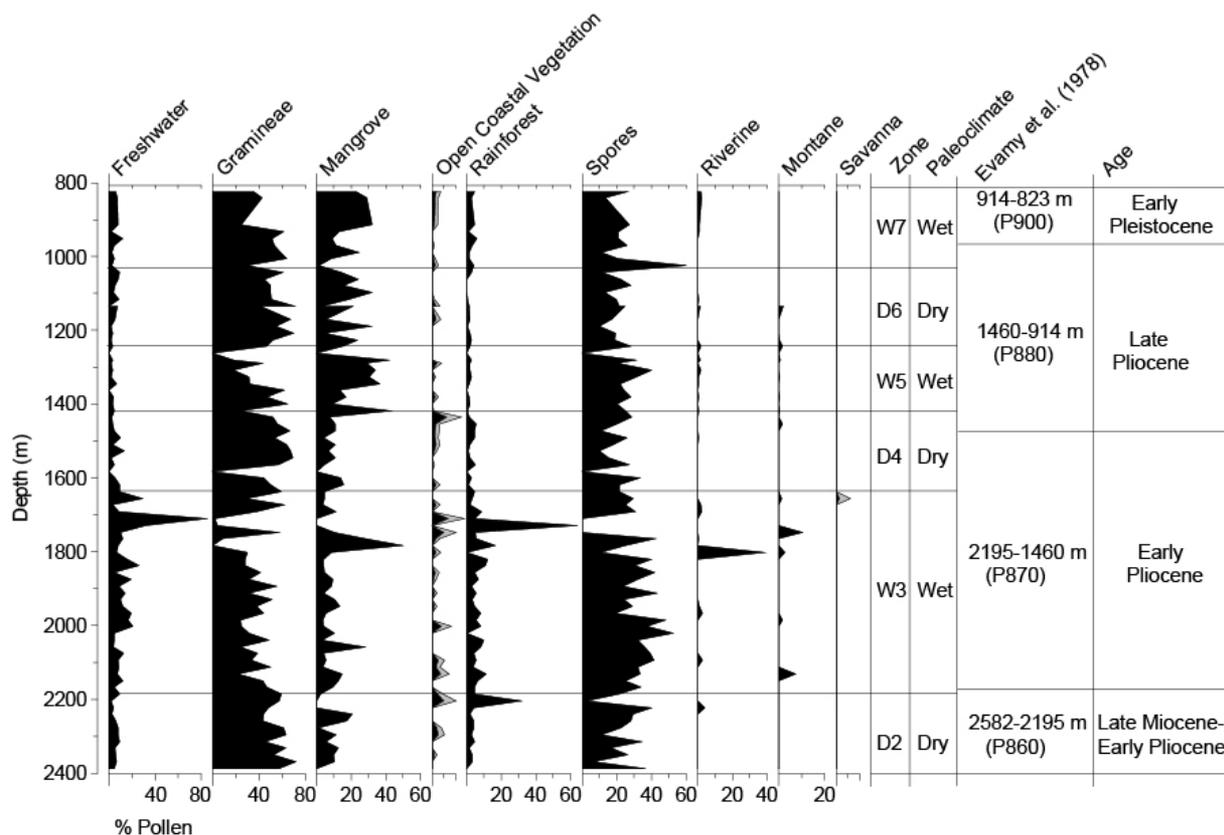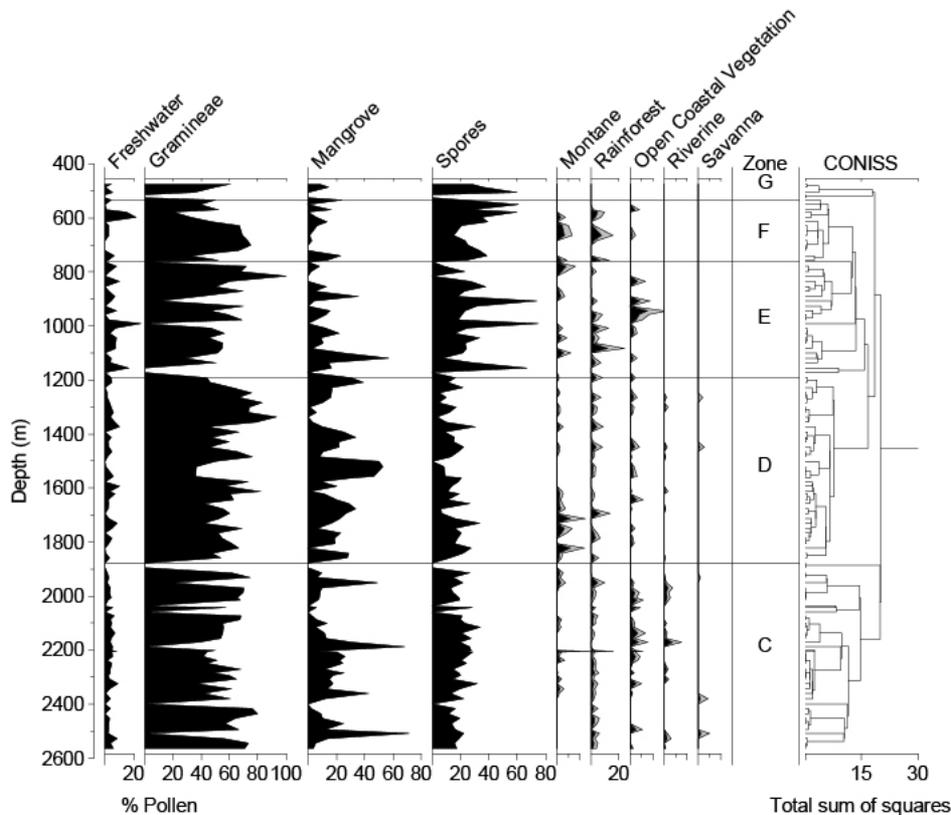
Appendix B (1): Well A-2 (a) phytoecological groups and cluster analysis-aided pollen zones of Late Miocene–Earliest Pleistocene of the western Niger Delta.

Appendix B (2): Well A-2 (b) phytoecological groups and recognized palaeoclimatic zones related to Evamy et al. (1978). Note the conversion of Evamy et al.'s (1978) zones from feet to meters.

Appendix C (1): Well A-3 (a) phytoecological groups and cluster analysis-aided pollen zones of Late Miocene–Earliest Pleistocene of the western Niger Delta.

Appendix C (2): Well A-3 (b) phytoecological groups and recognized palaeoclimatic zones related to Evamy et al. (1978). Note the conversion of Evamy et al.'s (1978) zones from feet to meters.