Vegetation Dynamics vs. Sediment Supply During the Late Quaternary: Paradigm of Sea Level Change and Two Distinct Time-Bound Stages of the Niger Delta Coastal Evolution

Onema Adojoh[1,1]

[1]Case Western Reserve University

January 20, 2023

Abstract

This study examines the impact of climate-sea level controls on the vegetation and evolution of the Niger Delta during the Late Quaternary. The extraneous controls on the environment outlined in this context confirm a direct link between vegetation dynamics (pollen data), sediment supply, and the landscape evolution of the Niger Delta between 20 ka and 6.5 ka. Two phases of sedimentation are recognized based on multiple proxies analyzed in three gravity cores obtained from the shallow offshore at ˜40 m water depth. Phase I records abundant occurrences of Poaceae, Cyperaceae, and Podocarpus pollen from a dry hinterland, charred grass cuticles, nonmarine alga Pediastrum, high Ti/Zr ratio, and lower sedimentation from 20-11.7 ka. Phase II records an expansion of mangrove vegetation, high Fe/S ratio, and increase in planktonic foraminifera between 11.7 ka and 6.5 ka. This second phase is attributed to sea-level rise and higher sedimentation during the development of delta plain and mangrove vegetation on the gently sloping shelf. These sequential records provide a new clue about the link between the evolutionary stages of the Niger Delta landscape and vegetation dynamics during two distinct time-bound intervals, which potentially delineate the boundary between two Marine Isotope Stages: MIS2 (late glacial period) and MIS1 (interglacial period). Keyword: Sea level- climate change, Late Quaternary, mangrove pollen, biogeochemistry, Niger Delta, landscape evolution.

Geochemical vs. palynological records during the Late Quaternary: Paradigm of sea level change and two distinct time-bound stages of the Niger Delta evolution

Onema C. Adojoh[abc], Fabienne Marret[c], Robert Duller[c], Peter L. Osterloff[d] and Francisca E. Oboh-Ikuenobe[b]

[a]Department of Environmental and Agricultural Sciences, Lincoln University, Jefferson City, MO65101, USA

[b]Department of Geosciences and Geological and Petroleum Engineering, Missouri University of Science and Technology, Rolla, MO 65409, USA

[c]School of Environmental Sciences, University of Liverpool, Liverpool, L69 7ZT, UK

[d] Exploration and Production, Shell International, London, E14 5NR, UK

Corresponding author: adojoh@ Lincolnu.edu; adojoho@mst.edu

Abstract

This paper examines the impact of climate-sea level controls on the vegetation and evolution of the Niger Delta during the Late Quaternary. The extraneous controls on the environment outlined in this context confirm a direct link between vegetation dynamics (pollen data), sediment supply, and the landscape evolution of the Niger Delta between 20 ka and 6.5 ka. Two phases of sedimentation are recognised based on multiple proxies analysed in three gravity cores obtained from the shallow offshore at ~40 m water depth. Phase I records abundant occurrences of Poaceae, Cyperaceae, and *Podocarpus* pollen from a dry hinterland, charred grass cuticles, nonmarine alga *Pediastrum* , high Ti/Zr ratio, and lower sedimentation from 20-11.7 ka. Phase II records an expansion of mangrove vegetation, high Fe/S ratio, and increase in planktonic foraminifera between 11.7 ka and 6.5 ka. This second phase is attributed to sea level rise and higher sedimentation during the development of delta plain and mangrove vegetation on the gently sloping shelf. These sequential records provide a new clue about the link between the evolutionary stages of the Niger Delta landscape and vegetation dynamics during two distinct time bound intervals, which potentially delineate the boundary between two Marine Isotope Stages: MIS2 (late glacial period) and MIS1 (interglacial period).

Keyword : Mangrove pollen, biogeochemistry, Niger Delta, landscape evolution, sea level- climate change, Late Quaternary

Introduction

The reconstruction of the vegetation dynamics and deltaic shift of the Niger Delta during the late to post-glacial period (Marine Isotope Stages MIS1 and MIS2) over the last 20 ka has been the subject of debate (2009; Adojoh et al., 2017; Adeonipekun and Sowunmi, 2019). This study presents a model that explains the interplay between the driving mechanisms and palaeoenvironmental settings in the basin based on biotic and abiotic evidence (Zong et al., 2009; Adojoh et al., 2017; Boyden et al., 2021). Previous studies of the Late Quaternary sea level in the shallow offshore of the Niger Delta and other West African regions indicate post-glacial sea level rise (SLR) and a middle Holocene SLR, followed by a subsequent fall to the present time (e.g., Lézine, 1997; Lézine et al., 2005; Scourse et al., 2005; Miller and Gosling, 2013; Bouimetarhan et al., 2015; Joo-Chang et al., 2015; Chadwick et al., 2020). Climate-driven sea level change and local fluvial sediment discharge are among the factors controlling evolution of the Niger Delta during the Quaternary (Lézine, 1997; Adojoh et al., 2017; Adeonipekun and Sowunmi, 2019). Several shallow offshore palaeoenvironments exist in this setting, such as the littoral realm (mangrove swamps, barrier islands, lagoons, deltas), and inner neritic realm. These palaeoenvironments may be composed of an integrated depositional system, and thus cannot be examined in sequestration (Woodroffe, 2002, Cohen et al. 2014). The major depositional systems under rising sea level on a gently sloping sandy coast are barrier islands or littoral system, while strand-plains (sand belt) with beach-ridges are essentially absent (Cohen et al., 2014, Chadwick et al., 2020).

The response of the shallow offshore paleoenvironments of the Niger Delta to sea level changes is influenced by tidal impact, and climate driven-nearshore wave and fluvial discharge relative to the nature of the sedimentary budget (Lézine et al., 2005; Adojoh et al., 2017). All littoral settings assumed their present structure during the sea level transgression that occurred during the Last Glacial Maximum (LGM), about 20-25 ka (Poumot 1989; Lézine, 1997; Riboulot et al., 2012; Cohen et al., 2014 Adojoh et al., 2017; Chadwick et al., 2020). Nevertheless, a sea level fall promotes extremely adverse conditions for the origination and preservation of the littoral and neritic realms, especially in wave-controlled settings of the delta. Thus, if rapid fluvial/sediment supply occurs during shoreline progradation, it may generate a delta (Cohen et al., 2014, Chadwick et al., 2020). Under this circumstance and depositional complexities, lagoons, shoreface and the neritic realm evolve, and wave-dominated deposits may rapidly prograde, causing regressive sand strands (Martin and Suguio, 1992; Chadwick et al., 2020).

Some major questions associated with this complexity remain unanswered in relation to the link between the nature of the vegetation dynamics and timing of sediment supply to the onshore and shallow offshore Niger Delta areas, as well as the impact of the Niger and Benue Rivers and their tributaries (Adojoh et al., 2017) (Figure 1). The significance of the key vegetation distribution over the post glacial evolution of the Niger Delta is still not well known, in particular how the mangrove ecosystem has responded to sea level changes and the impact of Holocene warm and wet conditions on the coastal vegetation. This study attempts to answer some of these questions through the evaluation of palaeovegetation dynamics and sediment supply using three gravity cores (GCs) (Figure 1). When present, mangrove vegetation and marine sediments along the littoral realm can be used as markers of coastal and delta dynamics, since their locations within the intertidal zone are strongly influenced by SLR (Woodroffe,1989, 1995, 2002; Lézine, 1997; Scourse et al., 2005; Adojoh et al., 2017; Adeonipekun and and Sowunmi, 2019). The mangroves and littoral fringe of most tropical settings have kept up with sedimentation and can accommodate eustatic SLR rates of ˜ 3.8 mm/year. However, when eustatic rates surpass 5.2 mm/year, then the mangroves would not be preserved (Mckee et al., 2007; Cohen et al., 2014; Chadwick et al., 2020).

The main aim of this study is to establish the relationship between the evolution of the Niger Delta landscape and vegetation dynamics during the Late Quaternary. In addition, it explores the significance of detailed and integrated multiproxy data (key pollen indicators, biogeochemistry, planktonic foraminifera and sedimentology) to identify the main controls on the distinct stages of the Niger Delta evolution and its reorganisation during the Late Quaternary (MIS1 and MIS2). The methodological approaches will contribute to the body of knowledge on the factors affecting the depositional succession (stages of evolution) of the West African region through the impact of climate-driven sea level fluctuations on the coastal/littoral vegetation and delta dynamics.

2. Niger Delta setting

The Niger Delta is situated in the Gulf of Guinea on the passive Atlantic margin of West Africa and consists of a tripartite sedimentary sequence (Figure 2). During the Palaeogene and Neogene, it built out onto the Atlantic Ocean at the mouth of the Niger-Benue River system, a catchment area that encompasses more than one million square kilometres of predominantly savannah-covered lowlands (Morley, 1995; Adeonikpekun and Sowunmi, 2019). A recent comprehensive analysis by George et al. (2019) indicates that the extent of the Niger Delta is 70,000 km^2, contrary to earlier publications that documented 75,000 km^2 (Figure 2). The delta has also been remapped and classified into mega- sedimentary environments as follows: upper deltaic plain, lower deltaic plain, and delta front comprising 69%, 25%, and 6% of the total extent, respectively (Doust and Omatsola, 1990; Omuije et al., 2015; George et al., 2019). The regressive wedge of clastic sediments which comprises the delta is estimated to reach a maximum thickness of about 12 km (Okpoli and Arogunyo, 2020).

The palaeoenvironmental and sedimentological evolution of the Niger Delta has experienced dramatic changes over the Quaternary period (Doust and Omatsola, 1990; Reijers, 2011). The accumulation of marine sediments in the rifted basin undoubtedly commenced during the Early Cretaceous period (Albian time), following the opening of the South Atlantic Ocean as a result of rifting between the African and South American plates (Bonne, 2014; George et al., 2019). However, the current delta development only began in the late Palaeocene-Eocene when sediments began to bulge outside the syncline between the basement horst blocks at the northern flank of the recent delta setting (Figure 2). Since then, the delta plain has advanced southward onto the oceanic crust, possibly assuming a lobate morphology across the shallow offshore shoreline (Reijers, 2011). The proprietary concern of the petroleum companies prospecting in the basin and lack of published data have complicated the interpretations about the evolution of the delta for a long time.

The Niger Delta is normally categorised as tidally and wave-influenced in the classic terminology of Galloway (1975). The Cenozoic stratigraphic sequence comprises clastic sediments (Agbada and Benin formations) advancing over ductile marine shales (Akata Formation) (George et al., 2019; Figure 2). Previous studies indicate that the sedimentation pattern is composed of five depobelts (Figure 1) controlled by gravity-driven tectonism due to the presence of a mobile ductile shale at the base of the sediment fill (e.g., Corredor et al., 2005; George et al., 2019). The deltaic configuration has experienced broad progradation (circa 300 km) since the Palaeocene, with a maximum sediment thickness of approximately 12 km, and a surface area of 140,000 km^2 (Doust and Omatsola, 1990; Stacher, 1995; Reijers, 2011; George et al., 2019; Figure 2). In addition, past investigations of marine core sediments obtained from the Niger Delta suggest that changes in the riverine input during the Late Quaternary were linked to global glacial-interglacial cycles (e.g., Riboulot et al., 2012; Adojoh et al., 2017, 2019; Adeonikpekun and Sowunmi, 2019). Periods of warm temperature over Greenland were found to be associated with enhanced river discharges in West Equatorial Africa and conversely, cold conditions were related to weak river input (Shannahan et al., 2007; Weldeab et al., 2007; Miller and Gosling, 2013; Adojoh et al., 2017, Adeonikpekun and Sowunmi, 2019).

3. Materials and methods

The three gravity cores (GCs) utilized for this study were collected from the Niger Delta by Fugro Geotechnical Company for Shell Petroleum Development Company of Nigeria in 2002 (Adojoh et al., 2020; Figure 1). The cores were acquired from the seabed within the near shore (shallow marine) realm at approximately 40 m water depth (Adojoh et al., 2017, 2020). They were well positioned in the eastern (GC1 = Latitude - 4deg49"43 N, Longitude - 5deg20'20" E), central (GC2 = Latitude - 4deg05'08" N, Longitude - 6deg33'30" E) and western (GC3 = Latitude - 4deg11'59" N, Longitude - 7deg21'29" E) parts of the delta (Figure 1; Adojoh et al., 2017, 2020). A detailed lithological description on the scale of 1:10 cm was undertaken to select the intervals for detailed microfossil and biogeochemical analyses. Each gravity core was sampled at every 2 cm for detailed stratigraphic, chronostratigraphic and palaeoenvironmental study, and to further infer the imprints of sea level/climate cycles and vegetation dynamics over time.

Preparations for palynomorphs, nannoplankton and foraminifera data followed the standard procedures described in Adojoh et al. (2017, 2020). In addition, the geochemical components of the three GC samples were analysed at 2 cm intervals for physical and chemical properties using a Bruker S2 Ranger XRF Spectrophotometer Autosampler. In this study, 28 samples were selected as required for the maximum batch of 28 clean and dry pots. Nylon film was used to separate the individual pots while the bases of the pots were kept flat and level with no protrusions. The samples were compacted gently by using the brass plunger. All recorded measurements were obtained from the saved drive of the XRF analyser database and used for graphical plots.

The samples for Ti/Zr and Fe/S ratios were selected in their ranges of elemental analyses for the XRF Spectrophotometer. High Ti/Zr ratios of hinterland pollen provide information on the extent of fluvial materials supplied from terrestrial environments, whereas high Fe/S ratios provide the extent of inherent marine shale deposited on the continental shelf (Marius and Lucas, 1991; Zabel et al., 2001; Adegbie et al., 2003; Doktorgrades, 2004; Mendoza, 2007).

Adojoh et al. (2017, 2020) based the age model for each gravity core only on biostratigraphy defined by the first occurrences (FO) of calcareous nannoplankton (NN19 to NN21) and planktonic foraminifera (*Glorobotalia tumida* and *Glorobotalia truncatulinoides*). Those studies could not utilize radiometric dating because the impact of freshwater dilution on the near-shelf margin affected the preservation and quantitative counts of fossil materials, such as foraminiferal tests, macrofossil shells (gastropod, bivalves), and wood particles, that could have been used for dating. However, this present study has compared the dated multiple proxy records from the GCs with published data on relative sea level change for the Niger Delta region over the last 20 ka. In Figures 3-5, we have extrapolated the relative sea level curve for the Gulf of Guinea region plotted against the radiocarbon date from a global isostatic model database (Peltier, 1994) and a representative location (5830V S, 11830V E, T89-16 core) on the Congo shelf margin (Scourse et al., 2005).

4. Results

The photomicrographs and microfossil taxonomical records of the three GCs published by Adojoh et al. (2017, 2019), other non-pollen proxies, and some selected key pollen/vegetation proxies are used to establish the link between vegetation dynamics and landscape evolution of the Niger Delta. The three GCs record remarkably similar changes in the different proxies and two main phases of sedimentation were distinguished (Figures 3-5).

4.1 Phase I: Lower Depths (GC1: 272-202 cm, GC2: 266-202 cm, GC3: 260-202 cm)

The lower depths record lower sedimentation of intercalated fine to medium sand (GC1 = 9.8cm/kyr; GC2 = 13.9cm/kyr; GC3 = 13.1 cm/kyr), high abundances of hinterland components (e.g., ~40-41% Savannah grass pollen – Poaceae, 30% Cyperaceae (Fluvial and Freshwater indicator), 19-21% charred grass cuticles, ~43% afromontane taxon – *Podocarpus*), ~18-19% freshwater algae – *Pediastrum* , high Ti/Zr ratio (Table 1). In addition, low abundances of planktonic foraminifera *Globorotalia*spp. (~18-20%) and mangrove pollen

(*Rhizophora*21%, Avicenniaceae ~13%), and low Fe/S ratio (~10-15 mg^{-1}/ppm) are also recorded at these depths (Figures 3-5). Thus, hinterland indicators increased relative to mangrove/littoral proxies.

4.2 Phase II: Mid-Upper Depths (GC1: 0-202 cm, GC2: 0-202 cm and GC3: 0-202 cm)

These depths cover the middle to the upper parts of the three GCs and are characterised by a slower sedimentation rate of mudstone, expansion of mangrove vegetation (~60-80% *Rhizophora* sp. and 25-30% Avicenniaceae), high Fe/S ratio (Table 1), and increase in planktonic foraminifera (~60-79 % *Globorotalia*spp.). These depths also record fewer hinterland pollen (e.g., ~10-20% Poaceae, 0-5% *Podocarpus* , ~7% Cyperaceae, 0-4% charred grass cuticles), 2-5%*Pediastrum* , low Ti/Zr ratio, and higher sedimentation rate of very fine-silty sand (GC1 = 78.2 cm/kyr; GC2 = 57.3 cm/kyr; GC3 = 57.3 cm/kyr) (Table 1). During this interval of rapid expansion of mangrove-dominated pollen, hinterland pollen and other components (e.g., Ti/Zr, cuticles) dramatically decline when compared to the lower depths (Figures 3-5).

5. Discussion

The three GCs record a coherent signal of significant changes in geochemical ratios and abundances of palynomorphs and planktonic foraminifera that correlate with the effects of the transition from low sea level (phase I) to sea level rise (phase II) on the coastal margin of the Niger Delta. This change in sea level has been reported elsewhere especially along the West equatorial African margin (Lezine, 1997; Scourse et al., 2005; Adeonikpekun and Sowunmi, 2019). In addition, these phases record transitions between seasonal variations in vegetation dynamics, sediment supply, catchment preferences, and climate change in the Niger Delta.

5.1 Phase I: NN19/MIS2

This phase correlates to the later part of the last glacial period (MIS2) which is characterised by fluvial runoff from open landscape vegetation (Dupont and Agwu, 1991; Morley, 1995; Morley et al., 2011, 2017; Miller and Gosling, 2013; Cohen et al., 2014; Adojoh *et al.* , 2017; Adeonikpekun and Sowunmi, 2019) (Figure 7). It provides evidence of fluvial sediment supply to the Niger Delta based on abundant records of the hinterland indicators interpreted from the lower part of the GCs Zabel et al., 2001; Adegbie et al., 2003; (Pastouret et al., 1978; Morley and Richards, 1993; Skonieczny et al., 2015; Adojoh et al., 2017; Adeonipekun and Sowunmi, 2019; Boyden et al., 2021) (Figures 3-5). Significant records of hinterland pollen taxa in several other sediment cores in west equatorial Africa, such as T89-16, MD03-2708, and GeoB-4905 (Kim et al. , 2010; Marret et al. , 2001; Skonieczny et al., 2015) indicate dry conditions. In addition, the observed fluvial sediment supply could be linked to the seasonal latitudinal migration of the Intertropical Convergent Zone (ITCZ) with a mean annual position assumed to be around 13°N positioned further south (10°S) (Leroux, 1993; Marret et al. , 2001; Shannahan et al., 2015; Adojoh et al., 2017; Hopker et al., 2019; Dai et al, 2021; Boyden et al., 2021).

Assuming the sedimentation pattern remained uneroded, this phase could be the main conduit through which terrestrial and riverine materials were transported to the Niger Delta during the sea level fall and dry climate (Figure 1). It was possible that sediment transport was local (period of intense tectonism), regional (climate sea and level change), or experienced both conditions, which contributed to the volume of sediment discharge through the Niger and Benue Rivers to the Niger Delta (Adegbie et al., 2003; Skonieczny et al., 2015; George et al., 2019) (Figure 1).

5.2 Phase II: NN20-NN21/MIS1

Mangrove assemblages (e.g., *Rhizophora* sp.) can be linked to stages of sea-level and climate change over the last 20 ka (Lezine, 1997; Scourse et al., 2005; Punwong et al., 2013; Adojoh et al., 2017; Morley, 2017), as also inferred in this study (Figures 6-7). During the Early to mid-Holocene (11-6.5 ka), this phase experienced sea level transgression and warm climate based on the higher sedimentation rate, expansion of mangrove vegetation, and marine indicators in the GC depths of ~202-0 cm (Figures 3-5). This was a setting of both rapid spread of the coastal/littoral vegetation zone associated with sea level rise and linked to the gently sloping shelf where transgressive sedimentation took place, leading to delta plain retreat (Morley, 1995; Rull, 2002; Torricelli et al., 2006; Amorosi et al., 2014; Adojoh et al. , 2015, 2017; Adeonikpekun and Sowunmi, 2019; Hopker et al., 2019: Dai et al, 2021). This phase also experienced increased marine (tidal) influence when compared to phase I (GC depths of ˜272-202) (Figures 3-5), implying that mangrove pollen abundance in intertidal and tidal settings would be much higher (Oomkens, 1974; Poumot, 1989; Morley, 1995; Rull 2002; Punwong et al. , 2013; Joo-Chang et al., 2015; Hopker et al., 2019) (Figures 6-7). Consequently, abundance of mangrove pollen type (*Rhizophora*) is acknowledged as an indicator of sea level transgression when correlated with the regional sea level curve (e.g., Peltier, 1994; Scourse et al. , 2005; Joo-Chang et al., 2015; Adojoh et al., 2017; Chadwick et al., 2020; Boyden et al., 2021) (Figures 3-5).

5.3 Palaeoenvironmental evolution, climate and sea level change implications

The integrated multi-proxies obtained in this study provides a link to two evolutionary time-bound stages of vegetation dynamics and sediment supply in the Niger Delta during the last 20 ka. These two succinct time-bound stages provide a resonating clue on the prevailing past environment, climate and sea level change as follows: stage 1 (advancing or prograding delta) and stage 2 (retreating or retrograding delta) (Figures 6-7)

During stage 1, the GC data confirm the emergence of the continental shelf in response to a lower than present day sea level (Figures 6-7). The littoral environment (mangrove and coastal swamp) is subaerially exposed, and sedimentation and fluvial transport are effected by mass movement triggered by the weak West African Monsoon (WAM) (Morley, 1995; Reijers, 2011; Zong et al. , 2009; Shannahan et al., 2015; Skonieczny et al., 2015; Adojoh et al., 2017; Hopker et al., 2019; Chadwick et al., 2020; Dai et al, 2021). The GC records indicate the predominance of hinterland pollen during stage 1 evolution of the Late Quaternary Niger Delta. The pollen types identified were transported beyond the littoral realm/coastal zone, representing a strong signal of the prevalent arid conditions and low sedimentation rates (Figures 3-5; 6-7). In addition, the dominance of hinterland pollen taxa and low abundance of planktonic foraminifera suggest that stage 1 was a distal offshore/lower shoreface prodelta environment (Adegoke, 1975; Murray, 1991; Morley, 1995) (Figure 7). On a regional scale, this stage was a period of an enhanced sediment transport, as observed in the settings of the Amazon, Senegal (Ogolian regression), and Congo Rivers (Figures 3-5; 7) (Barusseau, 1988; Barusseau et al. , 1995; Marret et al., 2001; Giosan et al., 2005; Bonne, 2014; Adeonipkekun and Sowunmi, 2019: Boyden et al., 2021).

Following stage 1 was a period of rapid sediment retreat in the Niger Delta attributed to sea level rise (Figures 6-7). This period of an onset of Early to mid-Holocene sea level rise coincides with an episode of shoreline transgression and fine-grained sediment suspension reflecting the proximity of turbidity currents (Peltier, 1994; Goodbred , 2003; Scourse et al., 2005; Joo-Chang et al ; 2015; Hopker et al., 2019; Dai et al, 2021). Increases in the values of mangrove pollen (e.g., *Rhizophora*) and the Fe/S elemental data suggest a reducing environment with the potential of rapid post-dissolution of pyrite (FeS) minerals and organic-rich sulphur content during the warm climate (Fletcher, 2005; Mendoza, 2007) (Figures 3-5; 6-7). In addition, this stage suggests a proximal-upper shoreface (delta plain/delta front) palaeoenvironment based on the dominance of the planktonic foraminiferal (*Globorotalia* spp.) (Figure 7). Sediment supply and pollen deposition during stage 2 was principally driven by the interaction between the creation of accommodation space and density of mangrove vegetation spread across the near shore (Bonne, 2014) (Figures 6-7). On a regional extent, stage 2 correlates to the period of sea level rise (Nouakchottian transgression) as observed from the coastal margins of Congo, Senegal, and Mauritania (Barusseau, 1988; Barusseau et al. , 1995; Lezine 1997; Lezine and Denefle, 1997; Dalibard et al., 2014; Scourse et al., 2005; Hopker et al., 2019; Dai et al, 2021).

6. Conclusions

Integration of the multiple datasets in the three GCs permitted the identification of the direct link between delta landscape and vegetation dynamics in the eastern (GC1), central (GC2), and western (GC3) parts of the Late Quaternary Niger Delta. The study clearly identified two time-bound stages (1 and 2) of delta evolution as inputs for interpreting seasonal variations in climate and sea level change. The major findings are as follow:

1. Stage 1 linked the period from 20-11.7 ka to higher influx of hinterland pollen, slow sedimentation on the prodelta, sea level fall. and drier climate in the Niger Delta.
2. Stage 2 (11.7-6.5 ka) indicated a phase of expansion of the littoral realm/mangrove vegetation, higher sedimentation rate on the delta front, sea level rise, and warm climate.
3. The changes in the geochemical ratios during the two phases of sedimentation provided the first clarification on the timing between seasonal variation in vegetation, sediment supply, and palaeoenvironmental settings (lower / upper shoreface) in the Niger Delta.
4. Sea level change was apparently the major driver in the evolution of the Niger Delta based on the dominance of *Rhizophora* pollen recorded from the GCs during stage 2.
5. The integrated datasets (e.g., mangrove and hinterland pollen, planktonic foraminifera, trace elemental ratios) provided a robust and coherent information for delineating the MIS2 (late glacial) and MIS1 (interglacial) boundary.

Acknowledgements

We sincerely appreciate the Petroleum Technology Development Fund of Nigeria (PTDF Grant ID: PTDF/E/OSS/PHDAOC/385/11), and the University of Liverpool, UK, and Missouri University of Science and Technology, USA for funding the first author's doctoral studies and post-doctoral research fellowship, respectively. Professor Malcolm Hart (Plymouth University, UK) and Shell Petroleum Development Company are thanked for their help in terms of logical suggestions and the provision of the Gravity Cores samples, respectively.

References

Abbink, O.A., 1998. Palynological investigations in the Jurassic of the North Sea region. LPP Contribution Series 8: 192.

Abbink, O.A., Van Konijnenburg-Van Cittert, J. H. A., and Visscher, H., 2004. A Sporomorph Ecogroup Model for the Northwest European Jurassic - Lower Cretaeous I - Concepts and framework. Netherlands Journal of Geociences / Geologie en Mijnbouw 83, 1: 389–404

Adegbie, A.T., Schneider, R., Rohl, U. and Wefer, G., 2003. Glacial millennial-scale fluctuation in central African precipitation recorded in terrigenous sediment supply and freshwater signals offshore Cameroon. Palaeogeography, Palaeoclimatology, Palaeoecology, 197, 323-333.

Adegoke, O.S., 1975. Foraminifera fauna of the polyhaline lagoons of the Gulf of Guinea. Journal Mining and Geology, 12, 1-8.

Adeonipekun, P.A., and Sowunmi, M.A., 2019. Palaeoclimatology and biostratigraphic significance of late Neogene/Quaternary vegetational changes recorded in the offshore western Niger Delta. Acta Palaeobotanica, 59, 373-390.

Adojoh, O., Dada, S., 2015. Geomorphic resources and tourism potentials of the Niger-Benue confluence area, Central Nigeria. Journal of Geosciences and Geomatics, 3, 44-49.

Adojoh, O., Adebayo, L.F. and Dada, S., 2015. Palynocycles, palaeoecology and systems tracts concepts: A Case Study from the Miocene Okan-1 Well, Niger Delta Basin, Nigeria. Applied Ecology and Environmental Sciences, 3, 66-74.

Adojoh O., Marret, F., Duller, R. and 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.

Adojoh, O., Fabienne, M., Duller, R., Osterloff. P., 2019. Taxonomy and phytoecology of palynomorphs and non-pollen palynomorphs: a refined compendium from the West Africa Margin. International Journal of Biodiversity, 3,188-200.

Adojoh O., Marret, F., Duller, R., Osterloff, P., Ikuenobe, F., Hart, M. Smart, C., 2020. The biostratigraphy of the offshore Niger delta during the Late Quaternary: Complexities and progress of dating techniques. Quaternary Science Advances, 1, 100003.

Amorosi, A., Rossi, V., Scarponi, D., Vaiani, S.C. and Ghosh, A., 2014. Biosedimentary record of postglacial coastal dynamics: high-resolution sequence stratigraphy from the northern Tuscan coast, Italy. Boreas, 43, 939-954.

Armentrout, J.M., Fearn, L.B., Rodgers, K., Root, S., Lyle, W.D., Herrick, D.C., Bloch, R.B., Snedden, J.W. and Nwankwo, B., 1999. High-resolution sequence biostratigraphy of a lowstand prograding deltaic wedge: Oso field (Late Miocene), Nigeria. In: Jones, R.W. and Simmons, M.D. (eds.) Biostratigraphy in production and development geology. Geological Society, London, Special Publications, 152, 259-290.

Bankole, I., Schrank, E. and Osterloff, P., 2014. Palynostratigraphy, palaeoclimates and palaeodepositional environments of the Miocene aged Agbada Formation in the Niger Delta, Nigeria. Journal of African Earth Sciences, 95, 41-62.

Barusseau, J.P., Ba-diar, A.M., deScamps, C., Diop, H. S., Giresse, P. and Saos J.l., 1995. Coastal evolution in Senegal and Mauritania at 103, 102 and 101-year scales: natural and human records. Quaternary International, 29, 61-73.

Barusseau, J.P., Giresse, P., Faure, H., Lezine, A.M. and Masse, J.P., 1988. Marine sedimentary environments on some parts of the tropical and equatorial margins of Africa during the Late Quaternary. Continental Shelf Research, 8, 1-21.

Bonne, P.M., 2014. Cenozoic Atlantic margin of Africa during the Cretaceous and the implications for sediment supply to the Equatorial Reconstruction of the evolution of the Niger River. Geological Society, London, Special Publications, 386.

Bouimetarhan, I., Dupont, L., Kuhlmann, H., Patzold, J., Prange, M., Schefuss, E. and Zonneveld, K., 2015. Northern Hemisphere control of deglacial vegetation changes in the Rufiji uplands, Tanzania. Climate of the Past, 11, 751-764.

Boyden, P., Weil-Accardo, J., Deschamps, P., Oppo, D., and Rovere, A., 2021. Last interglacial sea-level proxies in East Africa and the Western Indian Ocean, Earth Syst. Sci. Data, 13, 1633-1651.

Chadwick, J.A., Lamb, P.M., Ganti V., 2020. Accelerated river avulsion frequency on lowland deltas due to sea-level rise. Proceedings of National Academy of Sciences in the USA, 3017584-17590.

Cohen, L.C.M., Franca, M.C., Rossetti, F.D., Pessenda, R.C.L., Giannini, F.C.P., Lorente, F.L., Buso-Junior, A.A., Castro, D., and Macario, K., 2014. Landscape evolution during the Late Quaternary at the Doce River mouth, Espirito Santo State, Southeastern Brazil. Palaeogeography, Palaeoclimatology, Palaeoecology, 415, 48-58.

Corredor, F., Shaw, J.H., Bilotti, F., 2005. Structural styles in the deep-water fold and

thrust belts of the Niger Delta. AAPG Bulletin 89, 753-780.

Dai, L., Li, S., Yu, J., Wang, J., Peng, B., Wu, B., Lao, J., Zhang, Q., Hao, Q., 2021. Palynological evidence indicates the paleoclimate evolution in southeast China since late marine isotope stage 5. Quaternary Science Reviews, 266, 106964.

Dalibard, M., Popescua, S., Maley, J., Francois Baudin, F., Melinte-Dobrinescue, M., Pittetf, B., Marsset, T., Dennieloug, B., Droz, L. and Succ, J., 2014. High-resolution vegetation history of West Africa during the last 145 ka Geobios, 46, 183-198.

Doktorgrades, E., 2004. Reconstruction of the sedimentary environment and climate conditions by multi-geochemical investigations of Late Palaeozoic glacial to postglacial sedimentary sequences from SW-Gondwana. Dissertation submitted to Universitat Bonn, Germany, 96 - 117.

Doust, H.E. and Omatsola, E.M., 1990. Niger Delta. In: Edwards J.D., and Santagrossi, P.A (eds.). Divergent/Passive Basins. American Association of Petroleum Geologists Memoir, 48, 201-238.

Dupont, L.M. and Agwu, C.O., 1991. Environmental control of pollen grain distribution patterns in the Gulf of Guinea and offshore NW-Africa. International Journal of Earth Sciences, 80, 567-589.

Fletcher, W.J., 2005. Holocene Landscape History of Southern Portugal. Doctoral thesis, University of Cambridge; https://doi.org/10.17863/CAM.20470.

Fredoux, A. and Tastet, J.P., 1976. Analyse pollinique d'une carotte marine au large de la Cote d'Ivoire. Variations de la vegetation et du climat depuis 225 000 ans BP. Palynosciences, 2, 173-188.

Galloway, W.E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems. In: Broussard, M.L. (Ed.), Houston Geological Society, Deltas, 87-98.

George, D.C., Franklin, I.M., and Spagnolo, M.M., 2019. Deltaic sedimentary environments in the Niger Delta, Nigeria. Journal of African Earth Sciences 160, 103592.

Giosan, L., Donnelly, J.P., Vespremeanu, E. and Buonaiuto, F.S., 2005. River delta morphodynamics: Examples from the Danube delta, In: Giosan, L., and Bhattacharya, J. (eds.), River Deltas: Concepts, Models, Examples, SEPM Special Publication 83, 393-411.

Goodbred, S.L., 2003. The response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstade. Sedimentary Geology, 162, 83-104.

Hopker, S.N., Wu, H.C., Muller, P., Barusseau, J.P., Vernet, R., Lucassen, F., Kasemann. S.A., and Westphal, H., 2019. Pronounced Northwest African monsoon discharge during the Mid-to Late Holocene. Frontiers in Earth Science, 7, 314.

Joo-Chang, J.C., Islebe, G.A., and Torrescano-Valle, N., 2015. Mangrove history during middle- and late-Holocene in Pacific south-eastern Mexico. Holocene 25, 651-662.

Kim, S.Y., Scourse, J.D., Marret, F. and Lim, D.I., 2010. A 26,000-year integrated record of marine and terrestrial environmental change off Gabon, west equatorial Africa. Palaeogeography, Palaeoclimatology, Palaeoecology, 297, 428-438.

Knox, G.J. and Omatsola, E.M., 1990. Development of the Cenozoic Niger Delta in terms of the escalator regression model and impact on hydrocarbon distribution. In: van der Linden, W.J.M., Cloetingh, S.A.P.L., Kaasschieter, J.P.K., van der Graff, W.J.E., Vandenberghe, J., and van der Gun, J.A.M. (eds.), KNGMG Symposium on coastal lowland geology and geotechnology, proceedings. The Netherlands, Kluwer Academic Publishers, 181-202.

Knox, G.J. and Omatsola, M.E., 1987. Development of the Cenozoic Niger Delta in terms of the escalator regression model. Kluwer Academic Publishers, 181-202.

Leroux, M., 1993. The mobile polar high: A new concept explaining present mechanisms of meridional airmass and energy exchanges and global propagation of palaeoclimatic changes. Global and Planetary Change, 7, 69-93.

Lezine, A.M., Cazet, J.P. and Duplessy, J.C., 2005. West African monsoon variability during the last deglaciation and the Holocene: Evidence from freshwater algae, pollen and isotope data from core KW31, Gulf of Guinea. Palaeogeography Palaeoclimatology, Palaeoecology, 219, 225-237.

Lezine, A.M, 1997. Evolution of the West African mangrove during the Late Quaternary. Geographie Physique et and Quaternaire, 51, 405-414.

Lezine, A.M. and Denefle, M., 1997. Enhanced anticyclonic circulation in the eastern North Atlantic during cold intervals of the last deglaciation inferred from deep-sea pollen records. Geology, 25, 119-122.

Martin, L., Suguio, K., 1992. Variation of coastal dynamics during the last 7000 years recorded in beach-ridge plains associated with river mouths: example from the central

Brazilian coast. Palaeogeography, Palaeoclimatology, Palaeoecology, 99, 119-140.

Marius, C. and Lucas, J., 1991. Holocene mangrove swamps of West Africa sedimentology and soils. Journal of African Earth Sciences, 12, 41-54.

Marret, F., Scourse, J., Versteegh, G., Jansen, J., Fred, S., and Ralph, R., 2001. Integrated marine and terrestrial evidence for abrupt Congo River palaeodischarge fluctuations during the last deglaciation. Journal of Quaternary Science, 16, 761-766.

Mendoza, U.M., 2007. Dynamics of phosphorus and sulphur in a mangrove forest in Braganca, North Brazil. PhD thesis, University of Bremen 1-16.

Miller, C.S., and Gosling, W.D., 2013. Quaternary forest associations in lowland tropical West Africa. Quaternary Science Reviews, 84, 7-25.

McKee, K.L., Cahoon, D.R., and Feller, I.C., 2007. Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation. Global Ecological Biogeography, 16, 545–556.

Morley, R.J., 1995. Biostratigraphic characterisation of systems tracts in Tertiary sedimentary basins. Proceedings of International Symposium on Sequence Stratigraphic in SE Asia, 50-71.

Morley, R.J., 2014. Rifting and mountain building across Sundaland, a palynological and sequence biostratigraphy perspective. Proceedings, Indonesian Petroleum Association Thirty-Eighth Annual Convention and Exhibition, IPA 14-G-011M.

Morley, R.J., 2017. The complex history of mountain building and the establishment of mountain floras in Southeast Asia and Eastern Indonesia. In: Hoorn, C., and Antonelli, A. (eds.), Mountain, climate and diversity. Wiley, 475-494.

Morley, R.J. and Richards, K., 1993. Gramineae cuticles: A key indicator of Late Cenozoic climatic change in the Niger Delta. Review of Palaeobotany and Palynology, 77, 119-127.

Morley, R.J., Swiecicki, T. and Thi-Pham, D., 2011. A sequence stratigraphic framework for the Sunda region, based on integration of biostratigraphic, lithological and seismic data from Nam Con Son Basin, Vietnam. Proceedings, Indonesian Petroleum Association 35th Annual Convention and Exhibition, IPA11-G-002.

Murray J.W., 1991. Ecology and palaeoecology of benthic foraminifera. Amsterdam, Elsevier. 397.

Omuije, J. Ozumba, B. Adojoh, O. 2015. Depositional Controls on Niger Delta Onshore Reservoirs. Conference Proceedings on the Sedimentology of Paralic Reservoirs: Recent Advances and their Applications. Geological Society, London.

Oomkens, E., 1974. Lithofacies relations in Late Quaternary Niger delta complex. Sedimentology, 21,195-222.

Okpoli, C.C., and Arogunyo, D.I., 2020. Integration of Well logs and seismic attribute analysis in reservoir identification on PGS field onshore Niger Delta, Nigeria. Pakistan Journal of Geology, 4, 12-22.

Pastouret, L., Chamley, H., Delibrias, G., Duplessy, J.C., Thiede, J., 1978. Late Quaternary climatic changes in Western Tropical Africa deduced from deep-sea sedimentation off the Niger delta. Oceanologica Acta 1, 217-232.

Poumot, C., 1989. Palynological evidence for eustatic events in the tropical Neogene. Centres for Research Exploration Production Elf Aquitaine, 13, 437-453.

Punwong, P., Marchant, R., and Selby, K.A., 2013. Holocene mangrove dynamics from Unguja Ukuu, Zanzibar. Quaternary International, 298, 4-19.

Reijers, T.J.A., 2011. Stratigraphy and sedimentology of the Niger Delta. Geologos, 17, 133-162.

Riboulot, V., Cattaneo, A., Berne, S., Schneider, R., Voisset, M., Imbert, P., and Grimaud, P., 2012. Geometry and chronology of Late Quaternary depositional sequences in the Eastern Niger Submarine Delta. Marine Geology, 319-322, 1-20.

Rull, V., 2002. High impact palynology in petroleum geology. Applications from Venezuela (northern South America). American Association of Petroleum Geologists Bulletin, 86, 279-300.

Scourse, J., Marret, F., Versteegh, G.J.M., Jansen, J.H.F., Schefuss, E., and van der Plicht, J., 2005. High resolution last deglaciation record from the Congo fan reveals significance of mangrove pollen and biomarkers as indicators of shelf transgression. Quaternary Research, 64, 57-69.

Shannahan, T.M., Overpeck, J.T., Sharp, W.E., Scholz, C.A. and Arko, J.A., 2007. Simulating the response of a closed-basin lake to recent climate changes in tropical West Africa (Lake Bosumtwi, Ghana). Hydrological Processes, 21, 1678-1691.

Street-Perrott, F.A. and Roberts N., 1983. Fluctuations in closed-basin lakes as an indicator of past atmospheric circulation patterns. In: Perrott F.A. et al. (eds), Variations in the Global Water Budget. Street-Reidel, Dordrecht, 331-345.

Skonieczny, C., Paillou, P., Bory, A., Bayon, G., Biscara, L., Crosta, X., Eynaud, F., Malaize, B., Revel, M., Aleman, N., Barusseau, J., Vernet, R., Lopez, S. and Grousset, F., 2015. African humid periods triggered the reactivation of a large river system in Western Sahara. Nature Communications, 6, 8751.

Stacher, P., 1995. Present understanding of the Niger Delta hydrocarbon habitat. In: Oti, M.N., and Postma, G. (eds.), Geology of Deltas. Rotterdam, A.A. Balkema, 257-267.

Torricelli, S., Knezaurek, G. and Biffi, U., 2006. Sequence biostratigraphy and paleoenvironmental reconstruction in the Early Eocene Figols Group of the Tremp–Graus Basin (south-central Pyrenees, Spain). Palaeogeography, Palaeoclimatology, Palaeoecology, 232, 1-35.

Weldeab, S., Lea, D.W., Schneider, R.R. and Andersen, N., 2007. 155,000 years of West African Monsoon and ocean thermal evolution. Science, 316, 1303-1307.

Woodroffe, C.D., 1995. Response of tide-dominated mangrove shorelines in northern Australia to anticipated sea-level rise. Earth Surface Processes and Landforms, 20, 65–85.

Woodroffe, C.D., 2002. Coasts: Form, Process and Evolution. Cambridge University Press, Cambridge, 623.

Woodroffe, C.D., Chappell, J.M.A., Thomas, B.G., Wallensky, E., 1989. Depositional model of a macrotidal estuary and flood plain, South Alligator River, Northern Australia. Sedimentology, 36, 737-756.

Zabel, M., Schneider, R.R., Wagner, T., Adegbie, A.T., de Vries, U. and Kolonic, S., 2001. Late Quaternary climate changes in Central Africa as inferred from terrigenous input to the Niger Fan. Quaternary Research, 56, 207-217.

Zong, Y., Huang, G., Switzer, A., Yu, F. and Yim, W., 2009. An evolutionary model for the Holocene formation of the Pearl River delta, China. The Holocene, 19, 129-142.

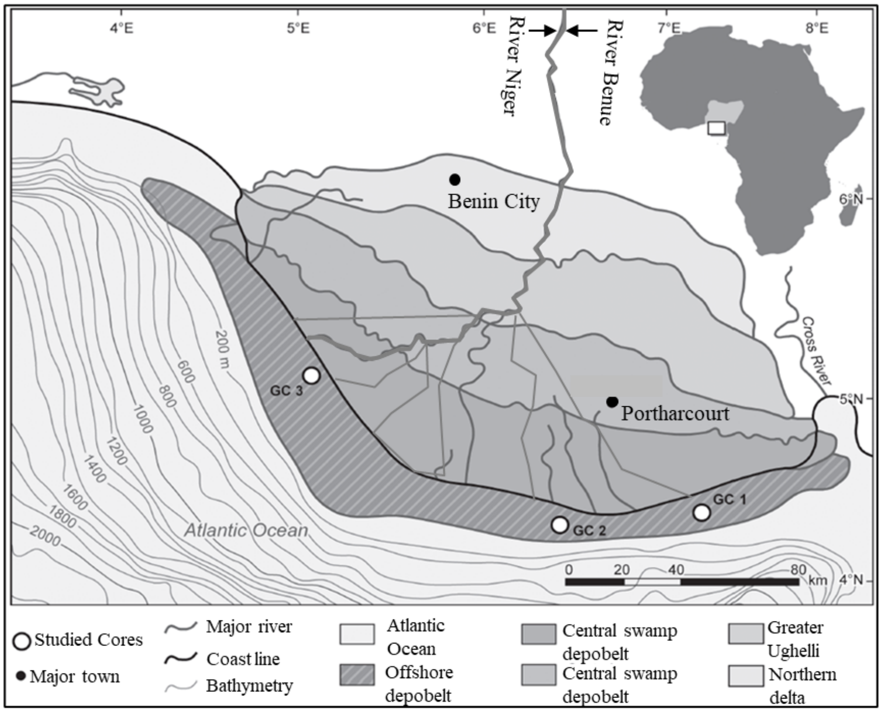


Figure 1. Map of the Niger Delta showing its location in southern Nigeria (inset) and the locations of the gravity cores (GCs). Note - The major river was formed from the confluence of Niger (North-West Nigeria) and Benue (South-West Nigeria) Rivers (modified after Adojoh et al., 2017).

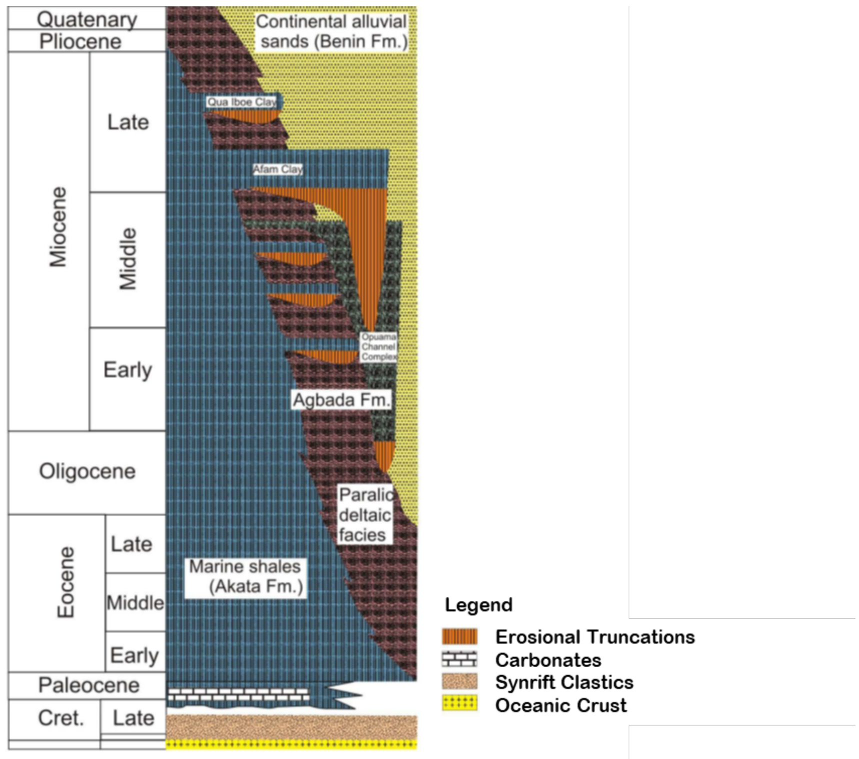
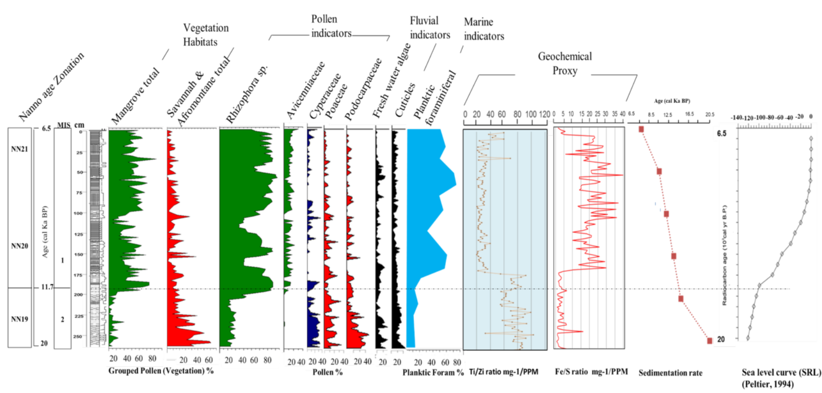


Figure 2. The stratigraphy of the Niger Delta; FM = Formation (after Doust and Omatsola, 1990).



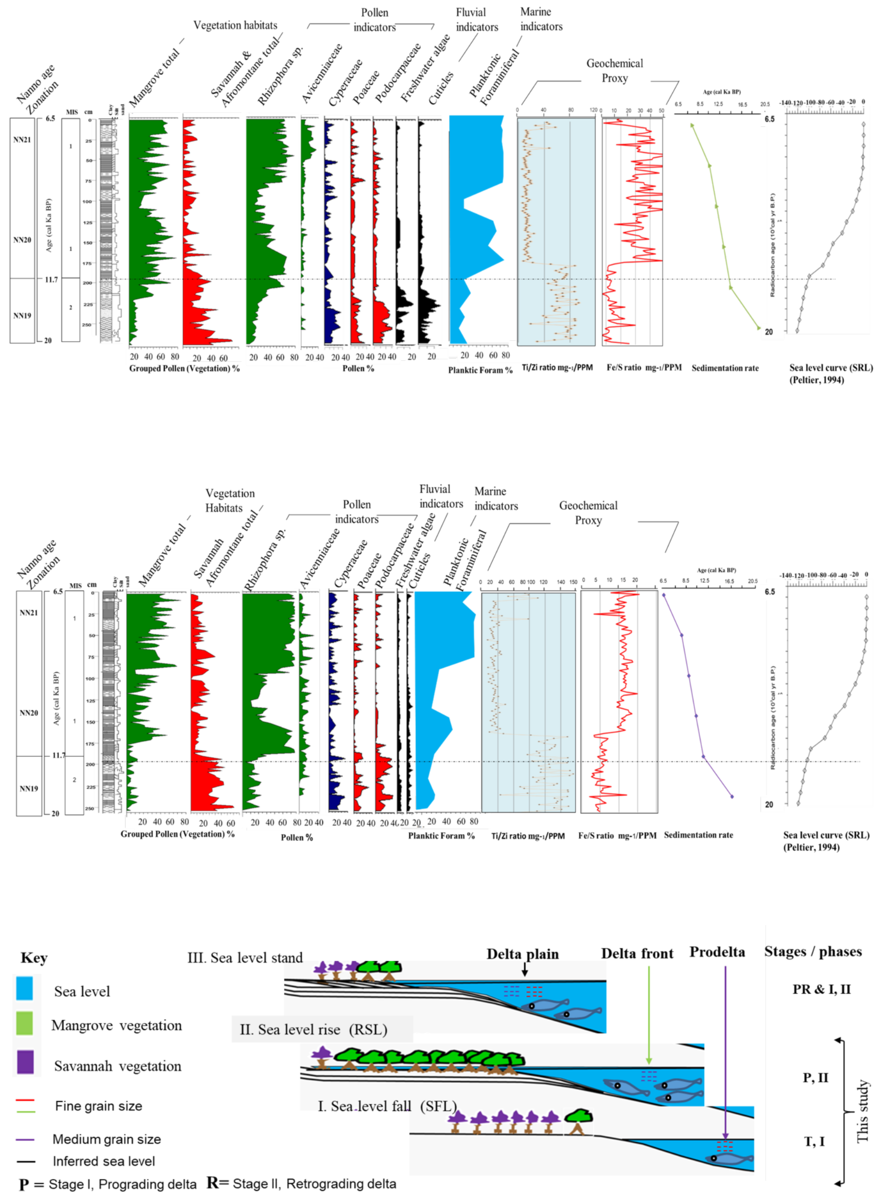


Figure 6. A model of sea level change in relation to vegetation dynamics, deltaic evolution, and sediment supply (grain size variation) (modified after Morley, 2011 and Adojoh et al., 2015).

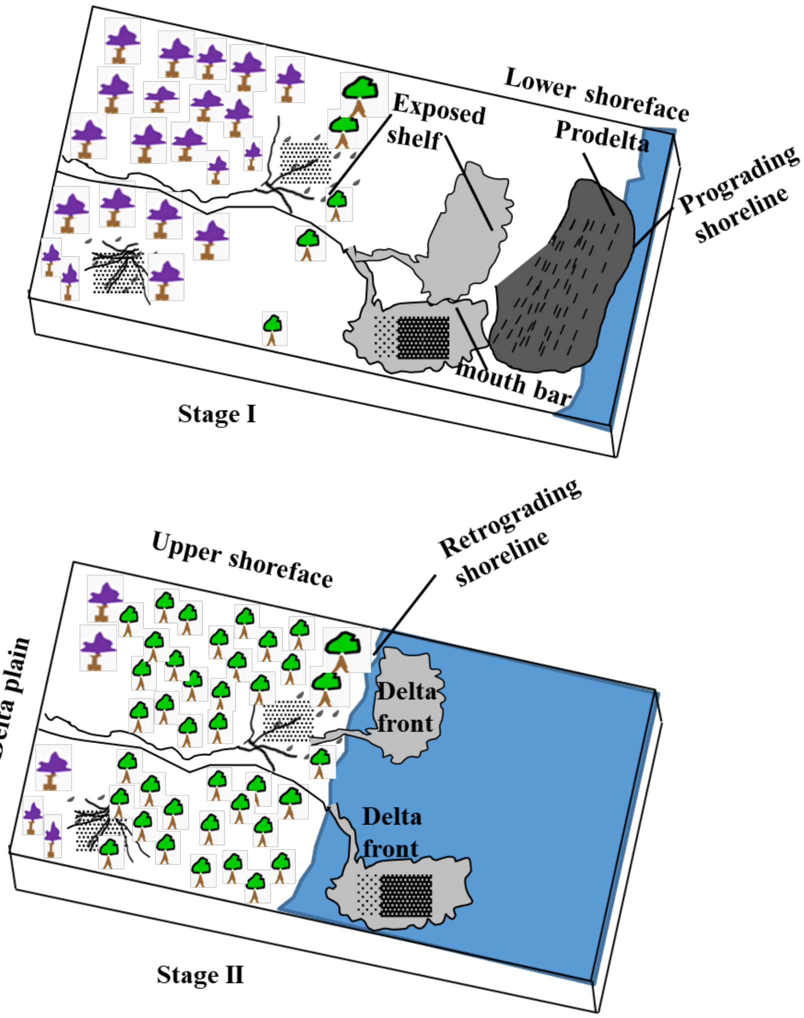


Figure 7. Two stages of vegetation dynamics, sea level change, and depositional settings observed in Figures 3-5 modified into the landscape evolution of the Niger Delta during the Late Quaternary (last 20 ka).

Table 1: Sedimentation rate records of the GCs. Sedimentation rate (SR, cm/kyr) is the thickness of sediment (Z, cm) that accumulates over a specified time interval (age difference) (T, kyr). Therefore, SR = Z/T where = Intervals between samples (cm); T= Age difference between samples (kyr). The first two intervals (i.e, from 11.7-8.5 + 6.5) ka were added to compute the SR result for the phase II.

Gravity Core (GC)	**Age (ka)**	**GC1**	**SR (cm/ kyr)**	**GC 2**	**SR SR (cm/kyr)**	**GC3**	**SR (cm/ kyr)**
Depth (cm)	6.5	0-40	6.2	0-40	6.2	0-40	6.2
Depth (cm)	11.7	40-184	72.0	40-142	52.6	40-142	52.6
Depth (cm)	20	184-272	9.8	142-266	13.8	142-260	13.1

Case Western Reserve University; The Nigerian Government Petroleum Technology Development Fund Scholarship; University of Liverpool; AGU Fall Meeting, New Orleans, LA & Online Everywhere, 13-17 December 2021

Vegetation Dynamics vs. Sediment Supply During the Late Quaternary: Paradigm of Sea Level Change and Two Distinct Time-Bound Stages of the Niger Delta Coastal Evolution

Onema Adojoh[a], Fabienne Marret[b], Robert Duller[b], Peter Osterloff[c], & Beverly Saylor[a], [a]Department of Earth, Environmental & Planetary Sciences, Case Western Reserve University, Cleveland, OH44160, [b]School of Environmental Sciences, University of Liverpool, Liverpool, L69 7ZT, UK. [b]Shell UK Ltd, Aberdeen, AB12 3FY, UK. Email: onema.adojoh@case.edu

1. Introduction

- This study provides the implications of the factors driving (controls) the environment changes of the coastal offshore of the Niger Delta, West Africa (Fig. 1) through detailed analyses of Nannofossils, Sedimentology, Grain Size Palynology & Geochemistry with respect to the timing of West African Monsoon (WAM) & Intertropical Convergence Zone (ITCZ) migration during the last 20 ka.
- The consequence of this interaction in the North Atlantic causes an increase in the average sea surface water temperature (SSTs) of the North or South Atlantic Ocean. This effect may coincide with a south/northward shift of the ITCZ (EPICA members, 2006; Dupont *et al*., 2008; Collins *et al*., 2010).
- The results permit a re-evaluation of the controls of climate, sea level and sediment supply contributing to the understanding of the two stages evolution of the Niger Delta & West African regions for the future exploration, exploitation and sustainability of the settings (Fig. 4).

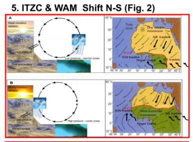
2. Objectives

- To probe further and reconstruct the evolution of the Niger Delta environments and to present a model that explains the interplay between the driving mechanisms, palaeoenvironments, sea-level and climate change based upon biotic and abiotic evidence (Fig. 4).

3. Methodology

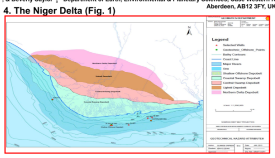
- This research involves a multi-proxy study based upon three gravity cores of just under 3 metres length each (Fig. 3).
- **Nannofossils**, **Sedimentology and Grain Size Analysis Palynology, and Geochemistry** techniques were applied (Fig. 3).

5. ITZC & WAM Shift N-S (Fig. 2)



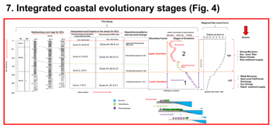
Positions of the Intertropical Convergence Zone (ITCZ) and West African Monsoon System (WAM) during the boreal winter (A), and summer (B). ITCZ is indicated by red dotted lines. Figure modified from Griffiths (1972) and after Leroux (1993).

4. The Niger Delta (Fig. 1)

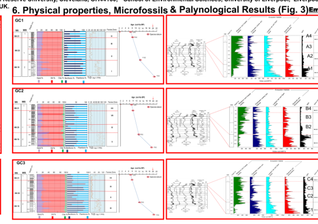


- The Niger Delta is located in southern Nigeria building out roughly southwards into the Gulf of Guinea (Kulke et al., 1995). Divided into 5 structural / depositional units (Depobelts - in colours).
- Consists of 3 Formations namely the Akata, Agbada and Benin Formations that are roughly dated diachronously between the Eocene and Recent.
- GC1= East, GC2=Central, GC3=West geotechnical positions along the Shallow offshore (Fig. 1).

7. Integrated coastal evolutionary stages (Fig. 4)



6. Physical properties, Microfossils & Palynological Results (Fig. 3)

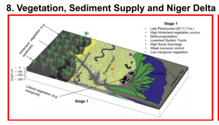


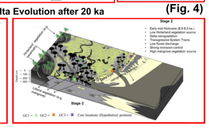
Note:

Zones: I, V, IX, A1, B1 &C1 consists of high abundant of medium sand, Ti/Zr elements, Benthic foraminifera, hinterland pollen and spores source influenced by dry climate and low sea level in relation to weak monsoon / southern migration of the ITCZ (Figs. 3).

Zones: II-IV, VI-VIII, X-XII, A2-A4, B2-B4 & C2-C4 comprises of high abundance of silty-fine sand, Planktonic foraminifera, Mangrove pollen and spores source influenced by warm climate and sea level rise in relation to strong monsoon / northern migration of the ITCZ (Figs. 3).

8. Vegetation, Sediment Supply and Niger Delta Evolution after 20 ka (Fig. 4)





9. Discussions

- **A multi-proxy investigation** in relation to the stratigraphic evolution has resulted in the reconstructions of two regional coastal delta shoreface Stages namely: Delta advancing (Stage 1) and retreat (Stage 2) (Figs. 3 &4,).
- During the Late Pleistocene regression, the bottom of the GCs sequences shows a contrasting facies variations indicating a dry climate and low sea level in the glacial period (MIS2) supporting the assumption of a weak WAM, linked to the episode of "palaeodischarge and delta progradation" (Fig. 4)
- Conversely, in the mid to Early-Holocene transgression the dominant facies change could have been triggered during the warm climate and sea level rise in the interglacial period (MIS1), supporting the assumption of a strong WAM, "subsequent delta retrogradation and sea level retreat" (Fig. 4).
- This study indicates that the records link well in time to the known hypotheses of the land-ocean interactions providing the main drivers for study of the climate and sea level change in relation to the sedimentary and vegetation evolution of the Niger Delta compared with previous studies from West Equatorial Africa (Fig. 4).

10. Conclusions and Implications of the coastal evolutionary stages of Late Quaternary Niger Delta, West African margin

In addition to the past studies, the current study proposes two regional Stages driving the evolution of the Niger Delta in the Gulf Guinea, West Africa. These are:

A) Regional climate-driven fluvial variations for the initial progradation (e.g., the cooling of the North Atlantic and the weak WAM), and sedimentary supply to the Niger Delta which lasted until 11.7ka (Fig. 4). (Stage 1) (Figs. 2 & 4).

B) Global sea level rise (e.g., the warming of the South Atlantic and the intensification of WAM) preceding retrogradation period until 6.5ka. (Punctuated by a pulse of the sedimentary supply starvation across the Niger Delta reaffirming the ongoing sea level rise) (Stage 2) (Figs. 2 &4).

- The main contribution is related to the improved understanding of transgressive shoreface and vegetation interactions observed between the evoked climate-sea levels driving or controlling the littoral-coastal sediments and vegetation of the Niger Delta, with variable facies (GCs) changes in relation to the strength of West African Monsoon system.
- Inputs (Stage 1) and outputs (Stage 2) of sediments often reflect the amounts of erosion or accretion affecting the coastal morphology.
- These relationships could be a prerequisite for the reconstructions of sedimentary budgets, coastal management, and for the understanding of the potential variability of ancient deltaic sequences and vegetation where there is no potential control prominent on the Quaternary sediment could help in decoding the past signals more thoroughly for the sustainable initiatives of the region.

11. References

Collins, J. A., Schefusz, E., Heslop, D., Mulitza, S., Prange, M., Zabel, M., Tjallingii, R., Dokken, T. M., Huang, E., Mackensen, A., Schulz, M., Tian, J., Zarriess, M., and Wefer, G., 2010. Interhemispheric symmetry of the tropical African rainbelt over the past 23,000 years. Nature Geosciences, **4**, 42-45.
Dupont, L. M., Behling, H. and Kim, J. H., 2008. Thirty thousand years of vegetation development and climate change in Angola (Ocean Drilling Program Site 1078). Climate of the Past, **4**, 107–124.
EPICA Community Members, 2006. Eight glacial cycles from an Antarctic ice core.Nature, **429**, 623-628.
Griffiths, J. F., 1972. Climate of Africa: Seasonal changes cause a moist inflow of monsoonal air towards the low-pressure centre over North Africa in summer: (In) Earth's climate - past and future. Amsterdam – Elsevier, **9**, 195.
Jermannauda, P., Roubya, D., Robina, C., Nalpasa, T., Guillocheaua, F. and Raillard, S., 2010. Plio-Pleistocene sequence stratigraphic architecture of the eastern Niger Delta: A record of eustasy and aridification of Africa. Marine and Petroleum Geology, **27**, 810-821.
Kulke, H., 1995. Nigeria: (In) Kulke, H., ed. Regional petroleum geology of the World part 11: African, America, Australia and Antarctica: Berlin, Gebruder Bornbraeger, 143-172.
Leroux, M., 1993. The mobile polar high: A new concept explaining present mechanisms of meridional airmass and energy exchanges and global propagation of palaeoclimatic changes. Global and Planetary Change, **7**, 69–93.