



**Controls on Palaeovegetation and Delta Evolution: Implications
from the Coastal Margin, Niger Delta, Gulf of Guinea**

Onema Christopher Adojoh

BTech (Hons), Applied Geology, ATB University, Bauchi

MSc Petroleum Geology, University of Benin

Submitted in accordance with the requirements

for the degree of Doctor of Philosophy

School of Environmental Sciences (Geography and Geology)

University of Liverpool, UK

September, 2016

Dedication and approval content

“Umu otakida ki de du tefu owo ojo, okpejima mi (Gabriella, Rachael, and Antonia), oyami (Paula) kpayu aboduu kuma do wo tu mi kun-eke chekpa lafia, manyu eneduu ki tene chukocheewn palynology, micropalaeontology manyu geology”!

“I dedicate this thesis to God, my triplets (Gabriella, Rachael, and Antonia), wife (Paula), and all those who ensured that I had a complete successful end to this write up, and finally to aspiring micropalaeontologists, palynologists and geologists”.

I certify that this thesis, and the research to which it refers, are product of my initiatives and that any ideas from other people were referenced according the standard practice.

Approved as to style and content by:

Dr. Lydie Dupont, Bremen University, Germany (External examiner)

Prof. Andy Plater, University of Liverpool, UK (Internal examiner)

Dr. Fabienne Marret, University of Liverpool, UK (Primary supervisor)

Dr. Robert Duller, University of Liverpool, UK (Secondary supervisor)

Dr. Peter Osterloff, Shell, Aberdeen, UK (External supervisor, Biostratigrapher)

Mr. Onema Adojoh (Author - PhD Environmental Science: Quaternary Geology, Micropalaeontology and Palaeoenvironmental Change)

Controls on Palaeovegetation and Delta Evolution: Implications from the Coastal Margin, Niger Delta, Gulf of Guinea

Abstract

Delta systems are not only the interface between the land and the ocean, but also sites of long-term sediment accumulation, pollen and organic matter storage that can be used for environmental investigations. Deltas are particularly sensitive to climate and sea level change, which can be expressed with change in the shelf morphology and the associated vegetation.

The Niger Delta, ideally located in a region of great sensitivity to climate change and sea level fluctuations, offers the possibility to provide an insight on the “late” Quaternary history of environmental change in West Equatorial Africa. Up to now, this deltaic system has been sparsely studied, compared with other major tropical deltas and therefore, its response to past climate change and sea level fluctuation is poorly understood.

This study aims to fill this scientific gap through a detailed analysis of a multi-proxy dataset collected from three gravity cores obtained from the shallow margin of the Niger Delta. The dataset included sedimentology, grain size, geochemistry, calcareous nanoplankton, foraminifera and palynomorphs. Using these data, a robust biostratigraphic framework was established for the littoral shallow offshore deltaic sequence. In addition, a refined biostratigraphic technique was developed based on foraminiferal and nannofossil (NN) indicators linked to the Marine Isotopes Stages, which helped to define the age model of the sequences (NN19= MIS2, NN20 & NN21=MIS1). Within this new biostratigraphic framework the spatial and temporal evolution of the coastal environment of the Niger Delta were evaluated. This study hypothesised that the dynamics of the Intertropical Convergence Zone (ITCZ), the West African Monsoon (WAM) and sea level fluctuation played a major role in shaping the landscape in the Niger Basin and adjacent coastal regions.

The palynological sequences defined in the three gravity cores show very similar fluctuations, with a dominance of the Afromontane Forest (Podocarpaceae), Freshwater Swamp (Cyperaceae), Savannah (Poaceae) and Lowland Rainforest (Polypodiaceae) during the late glacial and deglaciation period, followed by the

development of the Mangrove (Rhizophoraceae) during the Early to mid-Holocene. In addition, high values of charred grass cuticles and Ti/Zr are observed during the late glacial, whereas high values of Fe/S ratio and planktonic foraminiferal are concomitant to the expansion of mangrove vegetation during the interglacial period.

These records suggest dry conditions, with lower sea level during the late glacial and deglaciation periods, and warm conditions leading to the rise of the sea level during the interglacial in the Early to mid-Holocene periods respectively.

To summarise, the outcome of 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. The results permit a re-evaluation of the controls of climate, sea level and sediment supply contributing to the understanding of the two stages in palaeovegetation and the littoral/coastal evolution of the Niger Delta (progradation and retrogradation) for the future exploration, exploitation and sustainability of the region.

Acknowledgements

I remain grateful to God and my sponsors, Petroleum Technology Development Fund (PTDF) of Nigeria for, sponsoring my PhD studentship. Without their funding (PTDF), this research would have been difficult for me to undertake. It is really a rare privilege to come over to the multi-racial environment of the United Kingdom to undertake this study experience and unforgettable experience.

I am indebted to my academic supervisors, Dr. Fabienne Marret and Dr. Robert Duller, for their unending enthusiasm, knowledge, support and guidance throughout my PhD. Dr. Fabienne Marret, you pushed me to attend the social forum, conferences and to make presentations. These have exposed me to many professional colleagues, and the learning worldwide. Without you, I am not sure I would have had this opportunity to be trained and supervised with high tech equipment. To Dr. Peter Osterloff (Principal Biostratigrapher, Shell Upstream, Europe), I will forever remain grateful and committed to the dreams he has inspired in me right from 2009, when we first met. His influence through Shell made it possible for me to get those materials looking at the difficulties in obtaining samples and materials from an area in which data acquisition is restricted due to prospecting companies. I thank him also for agreeing to be my external supervisor during my PhD studentship. I sincerely thank you all, for all the pains and co-operations to see that I am able to reach an end point.

I am grateful to the University of Liverpool, to members of staff (Geography and Geology), all of whose names I cannot. Also, I was fortunate to have wonderful laboratory support from the department of geography. Thank you all for providing the favourable environment for this study.

My stay at Liverpool has been a glorious one, in no small measure due to my fellow research colleagues. The cooperation and entertainment value of previous and current research students and post docs in the school of environmental sciences (Geology and Geography) throughout my PhD studentship cannot be exaggerated – Dan, Rafa, Bev, Jen, Tim, Fiona, Lee, Matt B, Madeleine, Kush, Josh, Amy, Chris, Ai, Cai, Raymond, Cyril, Yola, Veronica, Thea, Elvis, William, Celestine, Chris, Rachael Lem, Sally Hoare, Jennifer Clear and Karen Halsall. They have really assisted me in so many ways during my time at the University of Liverpool that I cannot pay them back for their benevolence. Many thanks to them for days out in the fresh air and for

sharing much during the monthly literature review organised under the generosity of my supervisor Dr. Fabienne Marret.

I must thank the following for their training and support in so many ways: Stephen Packer, Stephen Starkie, Lydie Dupont (Bremen University, Germany), Tim (University of Utrecht, the Netherlands), Jen O’Keefe (Morehead State University, Kentucky, USA) and Hanjie Sun (Institute of Oceanology, China), Robert Morley (Padova), Richard Tyson (Statoil), Oboh Francisca (Missouri State University, USA), Carlos Jaramillo (Smithsonian research group, USA) for their guide in the identification of some nannofossil forms and palynology training. My thanks also go to Claudia, Andrea and Paul for their assistance on the nannofossil biostratigraphic dating and micropalaeontology guidance during my research internship visit at the CCG Roberson Research Company, North Wales, UK.

I will also like to extend my appreciation to the following people from St. Anne & Bernard’s Parish: Fr Peter Morgan, Mr. Denis and Sister Magrette, as well as the following from the University of Plymouth: Stephen Grimes, Matthew Watkinson, Meriel Fitzpatrick, Christopher Smart, Malcolm Hart, Luke Mander, Catherine Johnson, Ann Treeby, Mike Fuller, Anna, Sharon Healy and Sarah Kearns for their support in different ways that I cannot mention. I am highly indebted to Mr. John Phillips of Hope University and Dr. Bamber David for their time and suggestions as well.

To my lovely wife, Dr (Mrs) Pauline Onema, and the triplets (Gabiella, Rachael and Antonia) I say thank you for your patience, endurance and cooperation for allowing me to stay away for such a long time to complete this study. You are my pride and asset, and I will forever love you all for the covenant that bonds us together.

For my parents, Mr and Mrs Gabriel Amodu, I do not know where to start from looking at the background you gave me in all aspects. For the on-going support and overall loveliness, you are always there. I remain thankful to you for your prayers and guidance. An adage which says “a tree cannot make a forest” was manifested by the overwhelming support of my brothers and sisters: Abaode, Ojoma, P.S, Uma, Mercy and Ele. You are all very wonderful people; your weekly calls, also were a boost to my emotional support. Many thanks for all your support when I had no helping hand.

Finally, I am grateful to Dr. Lydie Dupont (External Examiner) and Prof. Andy Plater (Internal Examiner) for their thorough evaluation, pleasing discussion and numerous constructive criticisms rendered during the *viva voce* of this thesis examination.

Content	pages
Title page	i
Dedication	ii
Abstract	iii
Acknowledgement	v
Contents	viii
List of Figures	ix
List of Tables	xv
Appendices	xvi
Chapter 1: Introduction	1
1.1 Background Rationale	1
1.2 Aims and Objectives	5
1.3 Background Study Conclusions and Focus	8
1.4 Thesis structure	10
Chapter 2: Literature Review	11
2.1 Introduction	11
2.2 The impact of ITCZ and WAM on West African climate	12
2.3 Climate forcing and Feedback	14
2.4 Quaternary palaeovegetation of West Africa	18
2.5 Hydrography of the Gulf of Guinea	22
2.6 The Quaternary Delta and the Niger Delta	25
2.6.1 Controls on Delta Morphology	27
2.6.1.1 Climate Control	28
2.6.1.2 Wave and Tide Control	29
2.6.1.3 Morphology and Facies Supply of the Basin	30
2.7 The Background Geology of the Niger Delta (Study location)	32
2.7.1 Sedimentation and Depobelt Successions	32
2.7.2 Climate, Hydrography and Vegetation of the Niger Delta	37
2.7.2.1 Climate	37
2.7.2.2 Hydrography	37
2.7.2.3 Vegetation	38

2.8 Why this Study in the Niger Delta?	40
2.8.1 Access to Data	41
2.8.2 Confidentiality and Research Interests	41
2.8.3 Nature of the Environmental Settings	42
2.8.4 Right Approach to Data Application	43
2.8.5 Funding and Research Support	43
2.9 Conclusion	44
Chapter	3: Data Collection Techniques 45
3.1 Site selection	45
3.2 Sampling the GCs	46
3.3 Sample preparation	47
3.3.1 Sedimentology Methods – Grain Size Analysis and XRF Techniques	47
3.3.2 Micropalaeontological (Foraminifera) Techniques	48
3.3.3 Calcareous Nannofossil Techniques	50
3.3.4 Palynological Techniques	50
3.4 Palaeovegetation Diagrams and Statistical Analysis	52
3.5 Palynological Grouping/Analysis	53
3.6 Conclusions	54
Chapter 4: Dating techniques:	Biostratigraphic Records 55
4.1 Introduction	56
4.2 Biostratigraphic Dating Methods	57
4.2.1 Foraminifera	58
4.2.2 Nannofossils	61
4.3. Global chronostratigraphic scheme correlation with the Combination of the two biostratigraphic dating methods of this study (GCs)	65
4.4 Plots of FOC on each GC vs. regional / global sea level curves	70
4.5 Sedimentation Rates	73
4.4.1 Sedimentation Rates in GC1	76
4.4.2 Sedimentation Rates in GC2	77
4.4.3 Sedimentation Rates in GC3	78

4.5 Conclusions	79
Chapter 5: Results	82
5.1 Introduction	82
5.2 Lithological description of the GCs	83
5.2.1 GC1 Lithological Descriptions	83
5.2.2 GC2 Lithological Descriptions	86
5.2.3 GC3 Lithological Descriptions	88
5.3 Grain Size Analysis	90
5.3.1 GC1 Grain Size Distributions	90
5.3.2 GC2 Grain Size Distributions	91
5.3.3 GC3 Grain Size Distributions	91
5.4 Geochemical Composition of the GCs	92
5.5 Foraminiferal Data from the GCs	93
5.5.1 GC1 Foraminiferal Distributions	93
5.5.2 GC2 Foraminiferal Distributions	95
5.5.3 GC3 Foraminiferal Distributions	96
5.6 Palynomorphs Recovered from the Gravity Cores	98
5.6.1 Assemblage Zonations	101
5.6.1.1 Description of the Palynomorph Assemblages from GC1	101
5.6.1.2 Description of the Palynomorph Assemblages from GC2	106
5.6.1.3 Description of the Palynomorph Assemblages from GC3	111
5.6.2 Conclusions	114

Chapter 6: Interpretation of Physical Properties and Calcareous	
Microfossil records	117
6.1 Interpretation of Results	117
6.1.1 GC1 Lithological Interpretation	119
6.1.2 GC2 Lithological Interpretation	120
6.1.3 GC3 Lithological Interpretation	122
6.2 Discussion	123
6.2.1 Controls on the Chronostratigraphic Evolution of the Niger Delta	124
6.2.1.1 Late Pleistocene record (20 – 11 ka)	124
6.2.1.2 Early Holocene record (11 - 8.5 ka)	125
6.2.1.3 Mid-Holocene record (8.5 – 6.5 ka)	126
6.2.2 Comparison of GC Data with other Deltas during Post-Glacial Periods	130
6.2.3 Controls and Impact of Sediment Supply on the Coastal Evolution on the Niger Delta	131
6.3 Conclusions	135
Chapter 7: Interpretation of the Palynomorph records	136
7.1 Interpretation of Palynomorph Records from the GCs	136
7.2 GCs Palynomorph records	137
7.2.1 GC1 Palynomorph Record	138
7.2.2 GC2 Palynomorph Record	139
7.2.3 GC3 Palynomorph Record	144
7.3 General discussions on the GCs Palynomorph Records	147
7.3.1 Preservation and Dispersal of Palynomorphs	147
7.3.2 Controls of Climate Drivers on Palynomorph Records	148
7.3.2.1 Migration of the ITCZ and WAM, and their Impacts on the Evolution of Vegetation in the Niger Delta	149
7.3.2.2 Controls on <i>Rhizophora</i> and Coastal Littoral Vegetation of the Niger Delta	150

7.3.2.3 Controls and Evidence of Fluvial Palaeodischarge/Terrestrial Influx on the Niger Delta Sedimentary Succession	155
7.4 Conclusions	156
Chapter 8: Implications and Contributions of the Integrated Multi-proxy Dataset on the Niger Delta environment	159
8.1 Implications of the Study	159
8.2 Impact of Climate Change on the Littoral Mangrove Ecosystems of the Niger Delta	160
8.3 Implications of Shelf Transgression in relation to the Sequence Stratigraphic Studies	162
8.4 Palaeoenvironmental Evolution of the Niger Delta	165
8.5 Conclusions	170
Chapter 9: General Conclusions, Broader Implications, Future Research and Recommendations	171
9.1 General Conclusions	171
9.2 Key Findings	173
9.3 Broader Implications and Summary of all the Conclusions	175
9.4 Limitations	176
9.5 Future Research and Recommendations	177
References	178
Appendices	211
Curriculum Vitae	248

Figures

- Figure 1.1. Interactions between climate, ecosystem, geosystem and socio-economic systems (modified after Harff *et al.*, 2007) 3
- Figure 2.1. 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 (modified from Griffiths (1972) and after Leroux (1993)) 14
- Figure 2.2. Climate systems and the interaction of their components on the Earth (modified after Ruddiman, 2001) 16
- Figure 2.3. Complex interaction path of climate system, positive (amplified) and negative feedback (mute) caused by external factors (modified after Carpenter, 1990) 17
- Figure 2.4. Map of the modern vegetation biomes of West Africa (White, 1983; Olson *et al.*, 2001) with oceanographic and climatological data. GC= Guinea Current; SEC= South Equatorial Current; EUC= Equatorial Undercurrent; SECC= South Equatorial Counter Current; AC = Angola Current; BOC= Benguela Ocean Current; BCC= Benguela Counter Current; ABF = Angola–Benguela Front (adapted from Dupont *et al.*, 2000). Marine cores cited in the text are included here 19
- Figure 2.5. Schematic representation map of the hydrographic currents for the Gulf of Guinea (modified after Peterson and Stramma, 1991). Guinea Current (GC); Equatorial Undercurrent (EUC), North Brazil Current (NBC); North Brazil Undercurrent (NBUC); North Equatorial Current (NEC); North Equatorial Countercurrent (NECC); North Equatorial Undercurrent (NEUC); South Equatorial Current (SEC) 24

Figure 2.6. Major ocean currents of the world (red arrows indicate warm currents, while blue represents cold currents (after Pidwirny, 2006)	25
Figure 2.7. The classification of deltas (Galloway, 1975) as a result of wave, tide and river controls (modified from Syvitski <i>et al.</i> , 2009)	26
Figure 2.8. Niger Delta distributary river systems (modified after Okonkwo <i>et al.</i> , 2015)	27
Figure 2.9. The concept of climate influencing fluvial transportation (modified from Posamentier and Kolla, 2003), illustrating the importance of climate on sediment delivery to the continental shelf margin (modified after Posamentier and Kolla, 2003; Castellort and Van DenDriessche, 2003)	29
Figure 2.10. Deltaic sedimentation and clinoform configuration (modified after Gosian <i>et al.</i> , 2005)	31
Figure 2.11. Location of the Niger Delta and Gravity Core (GC) positions (after Shell, 2011)	33
Figure 2.12. The stratigraphy and evolution of Niger Delta Formations (modified after Reijers, 2011). Rd = rate of deposition; Rs = rate of subsidence; E = Fluvial backswamp deposits; D = Upper shoreface heteroliths; C = Lower shoreface heteroliths; B2 = Open marine shale; B1 = Transgressive marine shale; HST = highstand systems tracts; TST= transgressive systems tracts; MFS = maximum flooding surface; FS = flooding surface; SB = surface boundary	34
Figure 2.13. The Niger Delta depobelts and structural framework: (A) Location of Niger Delta in Africa; (B) Location of Delta field	

along the northwest corner of Niger Delta (after Short and Stauble, 1967); (C) Chronostratigraphic chart showing the regressive nature of formations in the Niger Delta clastic wedge (after Knox and Omatsola, 1989); (D) Schematic diagram showing the development of successive growth-fault-bounded depobelts during progradation of the unstable Niger Delta clastic wedge (modified from Weber, 1987; after Knox and Omatsola, 1989); (E) Geometry of strata and major faults interpreted from a regional dip-oriented seismic reflection profile (modified from Cohen and McClay, 1996) 36

Figure 2.14. Vegetation map of Nigeria (modified from Nigerian geographical (map: https://en.wikipedia.org/wiki/Geography_of_Nigeria) 39

Figure 3.1 Photographs of GCs 47

Figure 4.1. Distribution of the calcareous nannofossil and planktonic foraminiferal markers species in the GC1 and its estimated biostratigraphy. 65

Figure 4.2. Distribution of the calcareous nannofossil and planktonic foraminiferal markers species in the GC2 and its estimated biostratigraphy 66

Figure 4.3. Distribution of the calcareous nannofossil and planktonic foraminiferal markers species in the GC3 and its estimated biostratigraphy 67

Figure 4.4. Correlation of the global nannoplankton age zonation with the GCs age constrained and the marine isotope stages (MIS). MNN = Mediterranean Neogene Nannoplankton, FOC = first occurrence, LOC = last occurrence, FAD = first appearance datum and continuous occurrence, LAD = last appearance datum

and continuous occurrence 68

Figure 4.5. Age model constrained for the three GC based on planktonic foraminiferal and nannoplankton marker species.

This is placed in context with globally-defined zonations 69

Figure 4.6a. Plot of Relative sea-level curve for location (5830VS, 11830VE) on the Congo margin extracted and modified from Peltier (1994) in calibrated years B.P and the biostratigraphic First

Occurrences (FOC) at 20ka (blue) and 11ka (red) of GCs respectively 71

Figure 4.6b. The combined plots of the estimated global sea-level results of different locations from the Last Glacial Maximum to the present day, and for the Holocene calibrated years ka and the biostratigraphic First Occurrences (FOC) at 20ka/~21ka (blue) and 11ka (red) of GCs respectively (Modified after Fleming *et al.*, 1998) 72

Figure 4.7. Sedimentation Rate (SR) and age-depth model for GC1 75

Figure 4.8. Sedimentation Rate (SR) and age-depth model for GC2 76

Figure 4.9. Sedimentation Rate (SR) and age-depth model for GC3 77

Figure 5.1. Description of the GC1 84

Figure 5.2. Description of the GC2 86

Figure 5.3. Description of the GC3 88

Figure 5.4. Summary diagram for Grain Size, Benthonic and Planktonic Foraminiferal assemblages, and geochemical data for GC1 96

Figure 5.5 Summary diagram for Grain Size, Benthonic and Planktonic Foraminiferal assemblages, and geochemical

data for GC2	96
Figure 5.6. Summary diagram for Grain Size, Benthonic and Planktonic Foraminiferal assemblages, and geochemical data for GC3	97
Figure 5.7. Relative Palynomorph Distribution diagram and proposed zonation for GC1. Note that Rhizophoraceae percentages were calculated on a total pollen sum basis, whereas other pollen taxa percentages were calculated on the pollen sum excluding Rhizophoraceae	104
Figure 5.8. Relative Palynomorph Distribution diagram and proposed zonation for GC2. Note that Rhizophoraceae percentages were calculated on a total pollen sum basis, whereas other pollen taxa percentages were calculated on the pollen sum excluding Rhizophoraceae	109
Figure 5.9. Relative Palynomorph Distribution diagram and proposed zonation for GC3. Note that Rhizophoraceae percentages were calculated on a total pollen sum basis, whereas other pollen taxa percentages were calculated on the pollen sum excluding Rhizophoraceae	115
Figure 6.1. Schematic expression of gross sedimentary environments and foraminiferal distributions: (1-3 <i>Ammonia beccarii</i> , 4 <i>Elphidium</i> sp., 5 <i>Cassidulina</i> sp., 6 <i>Bolivina</i> sp., 11 <i>Uvigerina</i> spp., 12 <i>Cibicidoides</i> sp., 8 <i>Globorotalia inflata</i> , 18 <i>Globigerinoides ruber</i>) (modified after Allen, 1964 and Cattaneo <i>et al.</i> , 2004)	122
Figure 6.2. Stratigraphic evolution of the lithofacies, biogeochemical and sedimentation rate records for GC1	126
Figure 6.3. Stratigraphic evolution of the lithofacies, biogeochemical	

and sedimentation rate records for GC2	127
Figure 6.4. Stratigraphic evolution of the lithofacies, biogeochemical and sedimentation rate records for GC3	127
Figure 6.5. Source-to-sink concept in sediment supply, showing tectonic hinterland source where the sediment is produced, the fluvial transportation process that convey the sediment to the continental shelf continental shelf, and the shelf, which serves as a platform for sediment delivery to the slope (shoreface) and basin floor fan (modified after Castellort and Van Den Driessche, 2003)	128
Figure 6.6. Schematic expression of the lithostratigraphic evolution of the Niger Delta in relation to the sea level changes and sediment supply based on GC data	132
Figure 7.1. Vegetation dynamic diagram of GC1 correlated to MIS 1 & 2 summer LIG 60°–30° (Davis and Brewer, 2009); summer insolation curve at 15°N (Berger and Loutre, 1991); WAM system curve of Ba/Ca ratio (Weldeab <i>et al.</i> , 2007); Gulf of Guinea SSTs (Schneider <i>et al.</i> , 1997), Congo Mean Annual Temperature; Vostok CO ₂ level curve (Petit <i>et al.</i> , 1992)	139
Figure 7.2. Vegetation dynamic diagram of GC2 correlated to MIS 1 & 2 summer LIG 60°–30° (Davis and Brewer, 2009); summer insolation curve at 15°N (Berger and Loutre, 1991); WAM system curve of Ba/Ca ratio (Weldeab <i>et al.</i> , 2007); Gulf of Guinea SSTs (Schneider <i>et al.</i> , 1997), Congo Mean Annual Temperature; Vostok CO ₂ level curve (Petit <i>et al.</i> , 1992)	142
Figure 7.3 Vegetation dynamic diagram of GC3 correlated to MIS 1 & 2 summer LIG 60°–30° (Davis and Brewer, 2009); summer insolation curve at 15°N (Berger and Loutre, 1991); WAM system curve of Ba/Ca	

ratio (Weldeab <i>et al.</i> , 2007); Gulf of Guinea SSTs (Schneider <i>et al.</i> , 1997), Congo Mean Annual Temperature; Vostok CO ₂ level curve (Petit <i>et al.</i> , 1992)	145
Figure 7.4. Diagram demonstrating similar phase of Mangrove fluctuations (% calculated on a total sum excluding Rhizophoraceae) and with Rhizophoraceae percentages for the GCs.	151
Figure 7.5. Diagram comparing the Fe/S ratio curves with % of Mangrove (calculated on total sum excluding Rhizophoraceae) and % of Rhizophoraceae for the three GCs.	153
Figure 7.6. Integrated diagram showing evidence of terrestrial influx (Highlighted) based on higher occurrence of Pollen Data, Non Pollen Palynomorph, Geochemical Ratio (Ti/Zr ratio) and Rapid Sedimentation Rate of medium sand at the base of the GCs ~ 272-202 cm depth during the Late Pleistocene (NN19 = 20-11.7 ka)	157
Figure 8.1. Integrated and correlated multi-proxy component and their systems tracts appraisal for the GC1 linked to the regional sea-level curve (Peltier, 1994)	163
Figure 8.2. An end-point of the broad palaeoenvironmental evolution and the controlling mechanisms of the Niger Delta from the GCs data (integrating all proxies)	167
Figure 8.3. Two evolutionary stages of vegetation dynamic and depositional settings as observed from Figure 8.2 modified into the landscape of the Niger Delta (modified after, Cohen <i>et al.</i> , 2014) (GC1 = East of Niger Delta, GC2 = Central Niger Delta, GC3 = West of Niger Delta).	168

Tables (note that the table numbering does not follow the chapters' numbers)

Table 1. Selected palaeovegetation and phytoecological groupings of Nigeria/Niger Delta (after Adojoh and Osterloff, 2010; modified from Sowunmi, 1981; Morley, 1995)	40
Table 2. GC coordinates and details	46
Table 3.1. Biostratigraphic Quantitative counts of Nannofossils and Planktonic foraminifera for GC1	65
Table 3.2. Biostratigraphic Quantitative counts of Nannofossils and Planktonic foraminifera for GC2	66
Table 3.3. Biostratigraphic Quantitative counts of Nannofossils and Planktonic foraminifera for GC3	67
Table 3.4. Summary Table of the Sedimentation Rates (SR)	74
Table 4.1. GCs Lithological Units Subdivision	82
Table 4.2. Summary of Characteristics relative to lithofacies types	82
Table 4.3. GC1 Geochemical Results	92
Table 4.4. GC2 Geochemical Results	92
Table 4.5. GC3 Geochemical Results	92
Table 4.6. Family & Botanical Nomenclature relating to Morphogenic/Species Nomenclature – example (in colour) within the same family and vegetation habitat applicable in the GCs study	100

Appendices	211
Appendix 1 Data Collection Techniques: Taxonomical and palaeoecological records	211
Appendix 2 Key words and terminology applied in the thesis	238
Appendix 3 Basis for biosequence stratigraphy from the impact of “Wetter” vs. “drier” sea level cycles from the studied GCs	242
Appendix 4 Published abstracts from GC cores data presented at different conferences	245
Appendix 5 Photographs of the three Gravity Cores	246

Chapter 1: Introduction

Highlights

- The African continent is generally highly sensitive to climate forcing
- Sea level fluctuations have greatly affected coastal regions in West Africa
- There is a gap in our knowledge of past environmental coastal conditions in West equatorial Africa due to scarcity of suitable proxy records
- The Niger Delta is of particularly great interest as it offers suitable archives for past environmental studies, notably to investigate land-ocean interactions and the role of the Intertropical Convergence Zone
- Three gravity cores (GCs) from the shallow marine region of the Niger Delta are investigated for their palynomorph and microfossil content as well as the sedimentological and geochemical context

1.1 Background Rationale

The African continent is one of the most vulnerable regions in the world to climate change. The Intergovernmental Panel on Climate Change report documents that the African continent is strongly influenced by prevailing socio-economic challenges including poverty, corrupt governance, lack of infrastructure and technical knowledge, ecosystem degradation and political/religious unrest (IPCC, 2013), many issues that can relate to prevailing climate change. Consequently, investigating past climate change on this continent becomes interesting in order to assess how ecosystems respond to those invoked climate changes and may give an insight to future impacts through analysis and prediction. Apart from the impact of climate change affecting the coastline of the African continent, the characteristics of coastal deltaic landforms may also change as a result of alteration in the hydrological regime, which poses threats to the host communities and various habitats (Zong *et al.*, 2009).

These threats can be divided into those causing damage to the natural environment and those posing problems for the coastal population. An increasing

sensitivity of socio-economic systems to environmental stressors (e.g. climate, coastal sea level rise, sedimentary budget) has stirred numerous proposals to encourage a sustainable management of the deltaic environments and the natural habitat. This implies that deltaic coastlines adjacent to large river systems (e.g. Niger and Benue rivers) and their distributaries influencing monsoonal regions can be recorded as important and virgin ground for future climate-based studies.

In this regard, this section introduces the study of coastal littoral features of the Niger Delta in relation to its local sedimentary setting and hydrological conditions to understand how the shoreline position and coastal settings evolved in the past and potentially evaluate the consequences of further changes in the future. It is also expected from the background review that this study will highlight the interaction between sediment supply and ecosystems, considering both short and long term evolution of the Niger Delta deltaic environments, and the possible extraneous drivers controlling the entire system (Figure 1.1). This interplay in the region is expected to characterise the diversity of the deltaic evolution in the role of sediment supply, vegetation, interregional climate variability and coastal response to sea level fluctuations.

Across the Niger Delta, the understanding of this interplay and its influence on vegetation dynamics are limited by the relatively small numbers of well-dated palynomorph records from the Gulf of Guinea, particularly on the fringes of the Niger Delta coastal margin. This is because the Niger Delta has not been the focus of extensive research in the fields of climate and vegetation evolution over the years due to prevailing oil company “closed doors” policy and limited academic research elsewhere. Similarly with other regions of West Africa, the understanding of palaeoenvironmental change is also poorly developed due to a great extent by the scarcity of stratified lakes or reducing environments to provide favourable conditions for the preservation of palynomorph material (Massuanganhe, 2016).

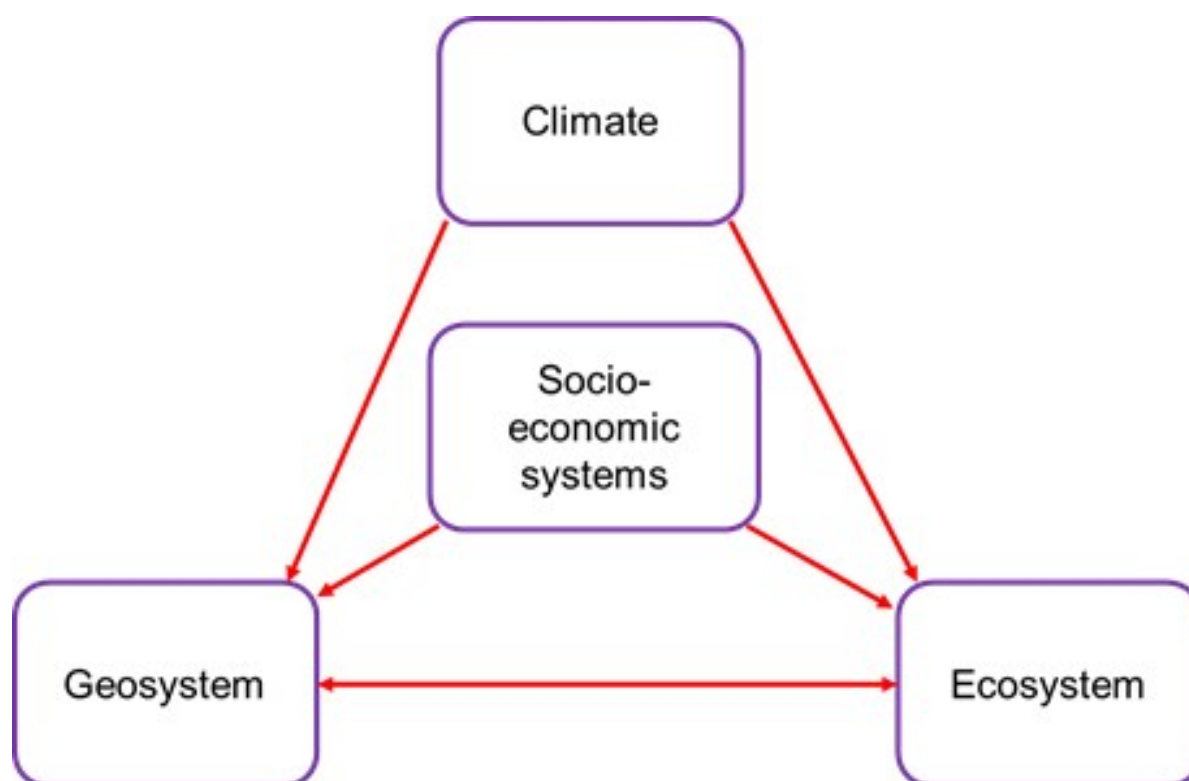


Figure 1.1. Interactions between climate, ecosystem, geosystem and socio-economic systems (modified after Harff *et al.*, 2007).

Thus, to improve our knowledge of the evolution of vegetation and delta development linked to its connection with predominant climate, sea level impact and coastal offshore conditions of the Niger Delta during the Late Pleistocene to the Holocene, a detailed multi-proxy series of data records is herein studied. To assess how palynomorph and sediment supply records respond to climate and sea-level change, three (3) Gravity Cores (GCs) from the eastern (GC1), central (GC2) and western parts (GC3) of the Niger Delta (Nigeria) were selected and investigated. The palynomorph evidence obtained from the deltaic and coastal boundary of the terrestrial and marine domains of the Niger Delta means that the region can provide a sound record relating to both global and local climates, further linked to wet and dry catchment settings.

Past records of other West African regions focused on climate drivers have shown that climate and vegetation along the deltaic systems of today in the tropics are influenced by several atmospheric-oceanic interactions (e.g., Dupont *et al.*, 1998 Kim *et al.*, 2010; Dupont, 2011; Marret *et al.*, 2013). These interactions show consistent

insight in the ongoing research in the region even though the Niger Delta has not yielded much information as yet. Therefore, in order to assess how the theory of the regional scale climate and vegetation components is intensely affected by atmospheric and oceanic interactions, our study evaluates the hypotheses surrounding the relative position of the Intertropical Convergence Zone (ITCZ) and the intensity of the West African Monsoon (WAM) in relation to dynamic vegetation and sediment supply (Shanahan *et al.*, 2007).

Moreover, it has been suggested that during glacial times, the African monsoon was weaker due to the presence of numerous large polar ice sheets (e.g. Weldeab *et al.*, 2007; Shanahan *et al.*, 2007). In other words, the cooling of the North Atlantic sea-surface waters during the last glacial period (Late Pleistocene) is presumed to have triggered the movement of the ITCZ towards a more southerly position (Braconnot *et al.*, 2000; Shanahan *et al.*, 2007; Mulitza *et al.*, 2008; Collins *et al.*, 2010). But, during interglacial periods, the strength of the African monsoon intensified due to a northward migration of the ITCZ during the summer insolation. As a result, this has influenced the development of vegetation habitat through the prevailing climate over the period of time. In other words, this statement indicates that global or regional vegetation patterns are mainly influenced by the prevailing climate.

Under this premise, this Niger Delta study tests the hypotheses of the ITCZ and WAM migration during the Late Quaternary to determine the response of the vegetation and sediment supply with climate and sea level oscillation in relation with other studies from West Africa. Thus, this section highlights two different vegetation settings considered paramount to evaluate seasonality of the West African climate and sea level oscillation through interpretation of the stages in vegetation and sedimentary changes. These are hinterland (terrestrial) and littoral vegetation (coastal marine) settings.

In context, hinterland (terrestrial) vegetation components indicate or represent all vegetation in arid regions where their existence is influenced by prevailing dry climates (e.g. some Open Forest; Savannah/Afromontane vegetation) (Adojoh and Osterloff, 2010; Marret *et al.*, 2013; Bouimetarhan *et al.*, 2015). Whereas, the littoral vegetation (coastal marine) components represent all the vegetation influenced by sea level or wet climates in close proximity to an overall lower delta plain setting (e.g.

Mangrove/Coastal Swamp; some Fresh Water Swamp vegetation) (Poumot, 1989; Morley, 1995; Rull, 2002). Therefore, this study explores three Gravity Cores in various settings across the Niger Delta referencing marginal marine and terrestrial sedimentary records of Quaternary age to provide evidence to explain relatively well understood environmental change patterns.

Given this evidence, this study will explore the impact of the dynamics of the ITCZ and the West African Monsoon circulation through vegetation reconstructions within the Niger Delta. It is expected that these two regional events would have influenced the evolution of the coastal margin and host communities within the setting of the Gulf of Guinea, and thus the Niger Delta. Consequently, palaeovegetation and deltaic sediment data studied from the Gravity Cores (Niger Delta) may be used as an analogue for discerning the post-glacial records (MIS1 and MIS2) which would serve as a unique period where environments have been affected by physical and natural factors, and where possible sustainable measures may be outlined for future preservation of the region, should climate change adversely in the near future.

1.2 Aims and Objectives

The **aim** of this study is to understand the impact of the factors driving (control) changes in environment through detailed reconstruction of vegetation and sediment supply with respect to the timing of WAM and ITCZ migration during the Late Pleistocene – mid-Holocene in the area of the coastal offshore region of the Niger Delta, Gulf of Guinea. Within this thesis, the following objectives are designed to structure the framework for this study:

- To constrain an age model for the complex deltaic setting of the Niger Delta (shallow offshore) based on samples taken from three strategically positioned Gravity Cores (GCs).
- To reconstruct the vegetation patterns and delta shift (stages of evolution) of the Niger Delta during the post-glacial period through investigation of the palynomorph records.

- To determine the control and compare the timing of mangrove vegetation (mainly *Rhizophora*) expansion in relation to sea level rise (transgression) and apply the signal to a biosequence stratigraphic studies.
- To evaluate the Holocene warm and wet climate impact on littoral vegetation for the future sustainability and management of littoral/coastal zone of the Niger Delta.
- 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.

To achieve the specific objectives and the aim above, multiple proxies were selected for this study. Among the proxies specified below, palynomorph distribution is selected to be the main tool for this study. This is because palynology is becoming increasingly important since correlation of strata by pollen and spores analysis has advantages over other biostratigraphic disciplines or inorganic methods.

Good climate and sea-level indicators must require one or more of the following attributes of terrestrially derived sporomorphs (pollen and spores):

- The main attribute is that spores and pollen are extremely resistant to physical destruction over time, and being light, they may be carried for some considerable distance out to sea; thus they can be present in different environments (i.e. fluvial, lacustrine, lagoonal, littoral, neritic) due to their dispersal by air and water.
- Pollen and spores do not have environmental restrictions like foraminifera and ostracods, hence providing the basis for correlating sediments and vegetation deposited in different environments (non-marine and marine) that are of the same age.

Review of palynological data offers the opportunity to establish various palaeoecological habitats consisting of: Mangrove - Fresh Water Swamp, Lowland Rainforest-Open Forest, Savannah-Afromontane and Non-Pollen Palymorphs (NPPs)

to then be related to palaeogeographic studies and other palaeoenvironmental change (climate and sea level) interpretations.

Given this, their study provides the basis for stratigraphical correlation and provides the background for palaeoenvironmental and palaeoclimatological studies. In light of the above, palynomorphs have been considered as the main tool for this study. In addition, several other proxies have been investigated and considered for obvious objectives and roles during:

Nannofossil and Foraminiferal data have been recorded to be relevant for dating Quaternary sediments. This potentially may allow the development of a high resolution biostratigraphic age definition for the Gravity Core intervals. Successive biochronology may be recognised from the informal zonal sequence developed by correlating all potential biostratigraphic datum levels – First Occurrence and Last Occurrence (FOC and LOC) or the equivalent First Appearance Datum and Last Appearance Datum (FAD and LAD) in the cored sequences in this study.

Elemental geochemistry and grain size data allow the interpretation of the relationships between marine and terrestrial palaeodischarge from the surrounding catchment areas in which the pollen is deposited and concentrated.

Foraminiferal data in combination with geochemistry and pollen data will enable us to establish the stages of delta evolution and depositional environments during the time frame.

1.3 Background Study Conclusions and Focus

This section summarises the specific application of each comparative multiple proxy components derived from the studied Gravity Cores (GCs) to identify a number of phenomena which merit further investigation and conclusions in this study. The focus of the study on the deltaic sedimentary record, climate and sea level change is based on the foraminiferal abundance, sedimentology and geochemistry datasets related to the impact of post-glacial palaeoenvironmental change across the Niger Delta. The extent to which these changes and phenomena are identifiable in the GCs, and by extension, the characteristics of the locations across the Niger Delta will be explored mainly through the application of new palynomorph botanical family groupings. Other data associated with this study discussed above are also expected to provide similar interpretation of the changes associated with the variance in recordable palynomorphs.

The principal challenge in the Niger Delta for palaeoecological research in general, and palynomorphs in particular, is the lack of access to a location offering good organic preservation and the available state of art (modern techniques). These issues have often prejudiced the possibility of palynological studies in the past within the delta region, when compared with other locations where lacustrine deposition with favourable preservation of pollen species has led to successful pollen analysis interpretation (e.g. East Africa).

Overall, this study is expected to link well to the known hypothesis associated with the ITCZ and the WAM, as well as, to detect the climate variability and the evolution of the Niger Delta in relation to those drivers (i.e. ITCZ and WAM). These implications from the interactions should provide a clear transitional series of depositional sequences at different depths within the GCs. Consequently, the outcome is expected to explain the mechanisms driving the sedimentation stages and vegetation patterns of the Niger Delta in a more coherent way compared to previous studies for West Equatorial Africa.

Furthermore, it is expected that the result of GCs records placed in the wider regional context of the Niger Delta framework could provide an understanding of the

stratigraphic evolution and sediment dynamics associated with the timing, and nature of changes impacting the coastal (littoral) environment. Given the above focus, in anticipation this study could confirm and complement the strength of those factors (climate, sea-level and sediment supply) in line with the applied multiple proxies to attempt to reconstruct past vegetation patterns and deltaic history.

1.4 Thesis Structure

This thesis comprises of nine chapters with chapter 2 focusing on the literature review, chapter 3 on the data acquisition and methodological approach, chapters 4 to 7 dedicated on data analysis, results, interpretation and discussion, with some of the content used as a basis for submission to peer reviewed journals. The last two chapters (8 and 9) provide the exclusive implications summary and broad conclusions of this study respectively.

Chapter 2: Literature Review

Highlights

- Tropical environmental settings are generally rich and diverse in flora and fauna but highly sensitive to environmental changes
- The ITCZ and WAM are the major climatic drivers controlling vegetation and sediment supply in the Gulf of Guinea
- Marine pollen records provide excellent archives to investigate the Quaternary history of the West African vegetation
- The Niger Delta, despite access restriction, is a site of strong interest to reconstruct the late Quaternary environmental history of the Niger Basin

2.1 Introduction

Low latitude tropical environments such as South America, Africa, South-East Asia and Indonesia are amongst the richest and most diverse ecological systems in the world with respect to their respective biome vegetation. However, the mechanisms that control their evolution and spatial distribution are not fully understood (Morley, 2000; Dalibard *et al.*, 2014). This knowledge is essential if we are to forecast the future development of tropical vegetation through time. In particular, additional research is required to tie successive vegetation variations with key parameters associated with climate (e.g. Tjallingii *et al.*, 2008; Clemens *et al.*, 2010). To advance in this area, a high resolution temporal framework linked to vegetation and ecological systems development is required, which provides the framework to undertake reconstructions of past evolution of vegetation patterns. Information from such vegetation will form part of an important contribution to such models which take vegetation/climate forcing into consideration. In most cases the vegetation/climate forcing is directly linked to the seasonal changes in the prevailing atmospheric pressure circulation (Dalibard *et al.*, 2014).

The resultant effect of the position of the ITCZ and WAM, influenced by the interaction of atmospheric air and oceanic conditions, determines the prevailing

climate and vegetation types through time and therefore, seasons. The overall atmospheric movement of the southern hemisphere is usually linked to the intensity and location of the easterly wind belt at tropical latitudes, the westerly wind belt at middle latitudes and the polar easterlies at polar latitudes (Hessler *et al.*, 2009). Given this premise, this chapter is designed to understand how the strength of this atmospheric movement varies from season to season throughout the year and its implications on the vegetation dynamics within West African settings. The following sections will present the environmental settings with regards to general climate variables over West Africa (Section 2.2), Climate forcing, feedback and phenomena (Section 2.3), Quaternary palaeovegetation in West Africa (Section 2.4), hydrography of the Gulf of Guinea (Section 2.5) and a detailed description of the Quaternary Delta, Niger Delta environments and focus on overriding forcing (Section 2.6).

2.2 The impact of ITCZ and WAM on West African climate

Intertropical Convergence Zone (ITCZ)

The prevailing climate of West Africa is controlled by the periodic or annual movement of the Intertropical Convergence Zone (ITCZ) during atmospheric circulation pattern variance in the low latitude Hadley cells (Colins *et al.*, 2010). ITCZ movement consistently follows changes in solar insolation, North and South of the equatorial axis during seasonal variations (Shanahan *et al.*, 2007). Seasonal patterns can be very sharply defined by latitude orientation mainly due to the differences in humidity, for instance, the amount of precipitation and distribution along the ITCZ path (Weldeab *et al.*, 2007). In the tropical Atlantic, the climate is controlled by annual insolation changes leading to complex oceanic-atmospheric interaction. The convergence of the South East and the North East trade winds related humid air circulation near the equator, causing significant rainfall is connected to the ITCZ (Nelson and Hutchings, 1983; Hastenrath, 1988b; Tyson and Preston, 2000). It has been observed that during the boreal summer, the ITCZ is positioned at about 21°N over the western Africa landmass due to the invading South East trade wind in the Northern Hemisphere. In other words, this tends to demarcate the boundary between northwestern trades and southwestern monsoon systems. During the boreal winter, the ITCZ moves to a southeasterly position about 40°N (Barry and Chorley, 2003; Shanahan *et al.*, 2015) (Figures 2.1 & 2.2).

West African Monsoon System (WAM)

Solar radiation causes rapid warming of the land during the day, but less abrupt warming of the ocean, which triggers substantial land-sea cold air circulation at night. The resultant seasonal circulation of heat between the land and ocean generates or triggers the monsoon (Weldeab *et al.*, 2007). The seasonal climate variation within West Africa is affected by the position of the monsoon which is being controlled by the south-westerly and north-easterly periodic monsoon wind migration (Leroux, 1993). The West African Monsoon (WAM) delivers moisture from the equatorial and southern tropical Atlantic Ocean towards tropical Africa (Gasse *et al.*, 2008). Despite the “monsoon playing a limited” role in the formational dynamics of Niger Delta (Nigeria), it has been identified as a key climate driver across tropical Africa (Hessler *et al.*, 2009). The WAM winds are initiated from the South Atlantic circulation of winds, and drift into northwest Africa during the boreal winter (Gasse *et al.*, 2008) (Figure 2.1).

The mechanism surrounding the WAM indicates that during the boreal summer, the abrupt heating over North East Africa causes the upward movement of warm air creating a region of low pressure at the surface, and causes warm, moist air transfer from the tropical Atlantic towards a low pressure area (Figure 2.1). The laden moisture associated with the monsoonal rainfall migrates northwards to about 19°N during the intervening summer triggering heavy precipitation to the Sudan–Sahel regions, whereas the West African setting in the southern hemisphere experiences dry conditions (Ruddiman, 2001) (Figure 2.1). During boreal winter the solar radiation is weak, abruptly cooling off air over North Africa and propelling a downward circulation of cool air, thus creating an area of high pressure over northeast African Sub-Sahara Desert, moving dry/cold air from North Africa and across the southwest tropical Atlantic. The resultant monsoon circulates dry air over North East Africa and drifts the dry air across the Gulf of Guinea in West Africa (Leroux, 1993) (Figure 2.1).

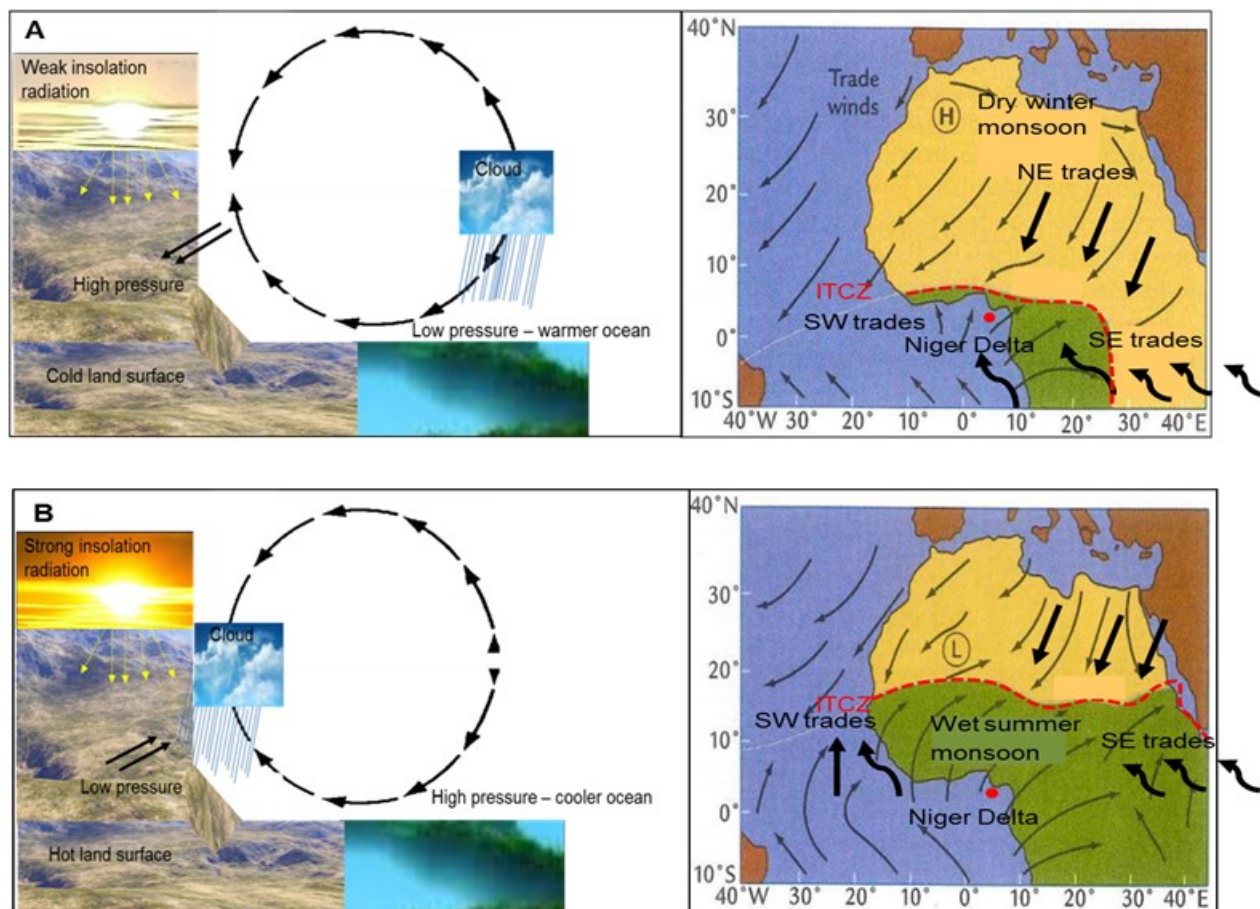


Figure 2.1. Positions of the Intertropical Convergence Zone (ITCZ) and West African Monsoon System (WAM) during the boreal winter (A) and summer (B). ITCZ is indicated by red dotted lines (modified from Griffiths (1972) and Leroux (1993)).

2.3 Climate forcing and Feedback

The aim of this section is to present a synthesis concerning feedback and phenomena of the climatic condition variation to help understanding certain principal drivers controlling terrestrial deposits, littoral coastal biome distribution, and their response with time within the Niger Delta region.

Climate forcing is any upset within the Earth's energy balance. It refers to the quantity of energy transferred from the sun, and the amount of energy radiated back into space (Carpenter, 1990). The changes in climate forcing are normally evaluated by physical factors in the atmosphere such as axial and orbital changes, and also the

quantity of greenhouse gas in the atmosphere (Figure 2.2). In this study, four fundamental types of climate forcing are considered to occur within nature (after Ruddiman, 2001). They are as follows:

- Change in the Sun's strength (strength of the Sun's solar radiation effect on the Earth);
- Changes in plate tectonics (generated by Earth's internal heat affecting its surface by means of processes that alter the Earth biogeosphere of the physical Earth);
- Changes in the Earth's orbit (variation in Earth's orbit around the Sun);
- Anthropogenic forcing (impact of agricultural, industrial and human activities such as releasing or flaring of gases).

Climate forcing is the main cause of climate change. In another way it can be termed as any influence on climate that emanates from external climate system itself. These systems include ocean, biosphere, atmosphere, cryosphere and land surface (Ruddiman, 2001). Records from different authors on the Earth's climate indicate an amalgam of broad processes. These complex processes are shown below (Figure 2.2). A specific number of factors drive or enforce climate change. These processes cause interactions among the internal components of the climate system, (e.g. water, air, vegetation, land surface). The outcome of the interaction leads to a quantifiable variation called "feedback".

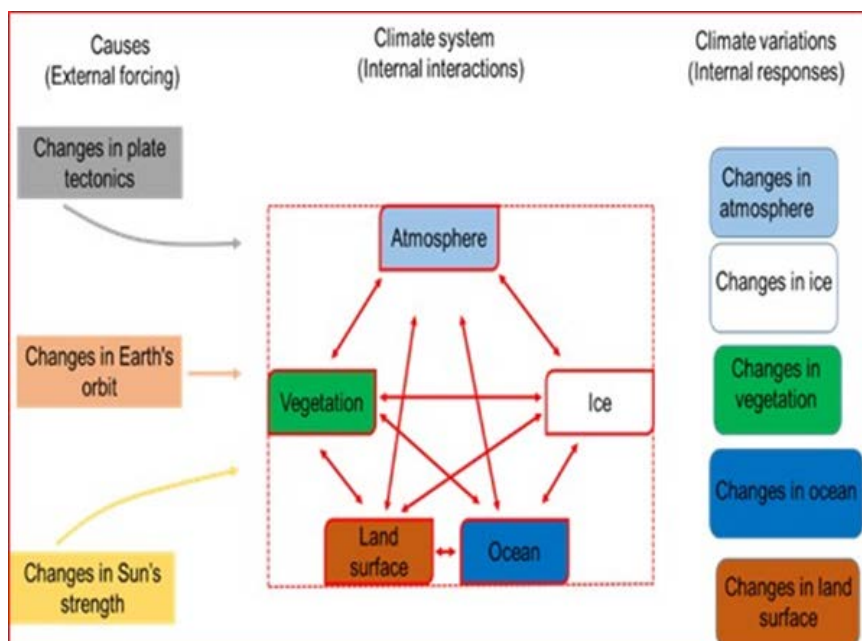


Figure 2.2. Climate systems and the interaction of their components on the Earth (modified after Ruddiman, 2001).

Feedback can be termed as a response to the initial forcing and resultant forcing. Within the climate system, feedback could also be suggested as the processes that alter climate change through amplification or suppression (Ruddiman, 2001). It supposes that some external factors (e.g. change in the strength of radiation from the sun) causes Earth's climate change. The alteration will result in many different feedback scenarios among the types of internal components of the climate systems suggested (Carpenter, 1990) (Figure 2.2). Therefore, the resultant response of these components will perhaps trigger climate change through the process of feedback.

Feedback could be positive or negative. Any change in the environment which results in additional and enhanced changes in that system is the outcome of a positive feedback. Positive feedback creates additional climate change different from what the original factor or driver is (Carpenter, 1990). For example, ocean warming, is an important sink for the CO₂ accumulation through the gas absorption within the water surface (Figure 2.3). The increase in CO₂ increases the warming capacity of the atmosphere. The ability of the ocean to evacuate CO₂ from the atmosphere reduces with rising temperatures. Thus, expansion of CO₂ in the atmosphere could result or intensify the physical upward movements of CO₂ in the atmosphere. Another example is the reduction in the quantity of heat energy transferred to the Earth by the sun. This could enable snow and ice to melt across regions at high latitudes which has not occurred before (Ruddiman, 2001) (Figure 2.3). Due to the fact that the snow and ice

reflect more sunlight energy than normal ground, the expansion of the area should further reduce the quantity of heat absorbed by the Earth's surface through cooling of the climate. In other words, due to the fact that the positive feedback intensifies changes in both directions, the original warming initiated by increasing energy from the sun would intensify by the climate system into a more substantial warming (Figure 2.3).

In the case of a negative feedback climate system, as soon as the original climate change is initiated, some of the Earth's climate system components (water, air, land surface) respond by following a path in order to reduce the original change (Figure 2.3). For instance, if the expansion in temperature increases, the quantity of the cloud shield increases in parallel (Figure 2.3). The increase in the cloud thickness in a way could decrease the incoming solar radiation and reduce the warming (Carpenter, 1990).

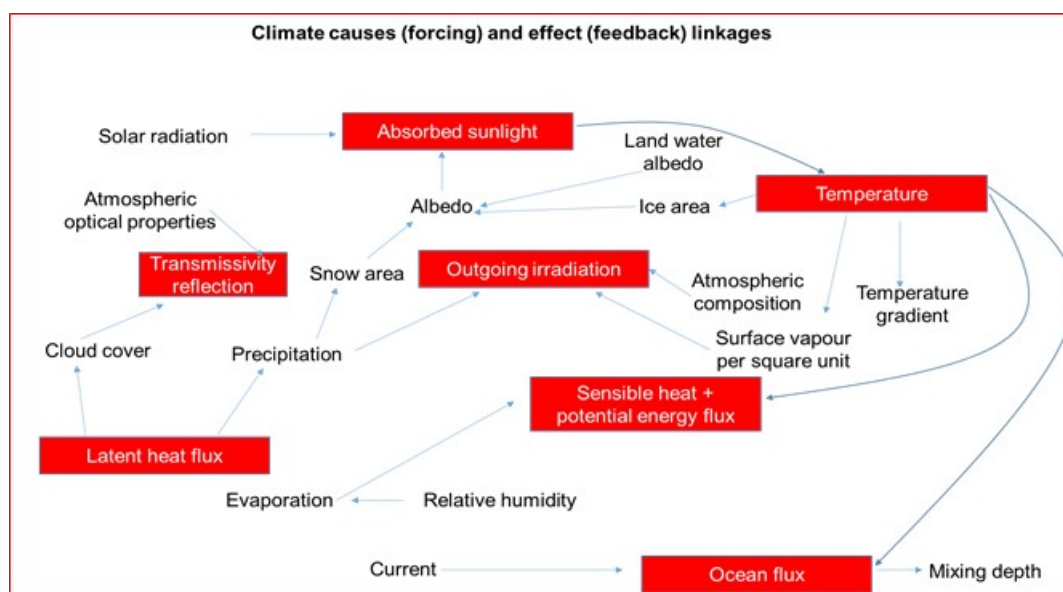


Figure 2.3. Complex interaction path of climate system, positive (amplified) and negative feedback (mute) caused by external factors (modified after Carpenter, 1990).

2.4 Quaternary Palaeovegetation of West Africa

Given that the feedback process of the past climate records depend strongly on palaeovegetation changes, this section discuss connection between the past climate drivers, palaeovegetation and feedback phenomenon.

African phytoecology (vegetation) is closely connected to the ITCZ and its associated rainfall (e.g. White, 1983). Among the different regions of Africa, Equatorial West Africa is an ideal region to reconstruct phytoecology, and therefore local climate over time, because the region shows a general succession of vegetational change (Figure 2.4). Some of the West African palaeovegetation that has developed due to both variances in latitude and altitude (orography) is also affected directly by climate changes (e.g. Dupont, 2011; Marret *et al.*, 2013; Dalibard *et al.*, 2014). In the north central location of the West African Basin, forested environments along the littoral coast (e.g. Rhizophoraceae) are demarcated during the interglacials, while the expansion of marshy vegetation characterises glacial periods (Figure 2.4). In the north of the West African Basin, savannah is the dominant environment (Dupont *et al.*, 2000; Olago, 2001; Dalibard *et al.*, 2014).

Given this, this study adopted one of the most complex and extensively used description of Africa's vegetation classification and map, namely of White (1983). On the basis of physiognomic parameters White (1983) grouped vegetation according to floristic regions (phytochoria) and established 17 key phytogeographical regions for the African continent (Figure 2.4). Also, White (1983) and Olson *et al.*, (2001) established seven vegetation biomes in tropical West Africa, which consist of deserts and xeric shrublands; savannas and shrublands; tropical and subtropical dry broadleaf forest; tropical and subtropical grassland; tropical and subtropical moist broader forests; flooded grassland and savannah; montane, grasslands; shrublands; and mangroves (Figure 2.4).

The savannah and forest biomes constitute the majority of the biome in the hinterland with mangroves restricted to littoral/coastal areas. These seven biomes are sub-divided into ecological regions which have modern-day vegetation associations that are related to the prevalent climate situations (Olson *et al.*, 2001; Miller and

Gosling, 2014). This study has accessed case histories from the different authors based on detailed literature reviews in order to improve the understanding of vegetation dynamics and climate change in the Niger Delta.

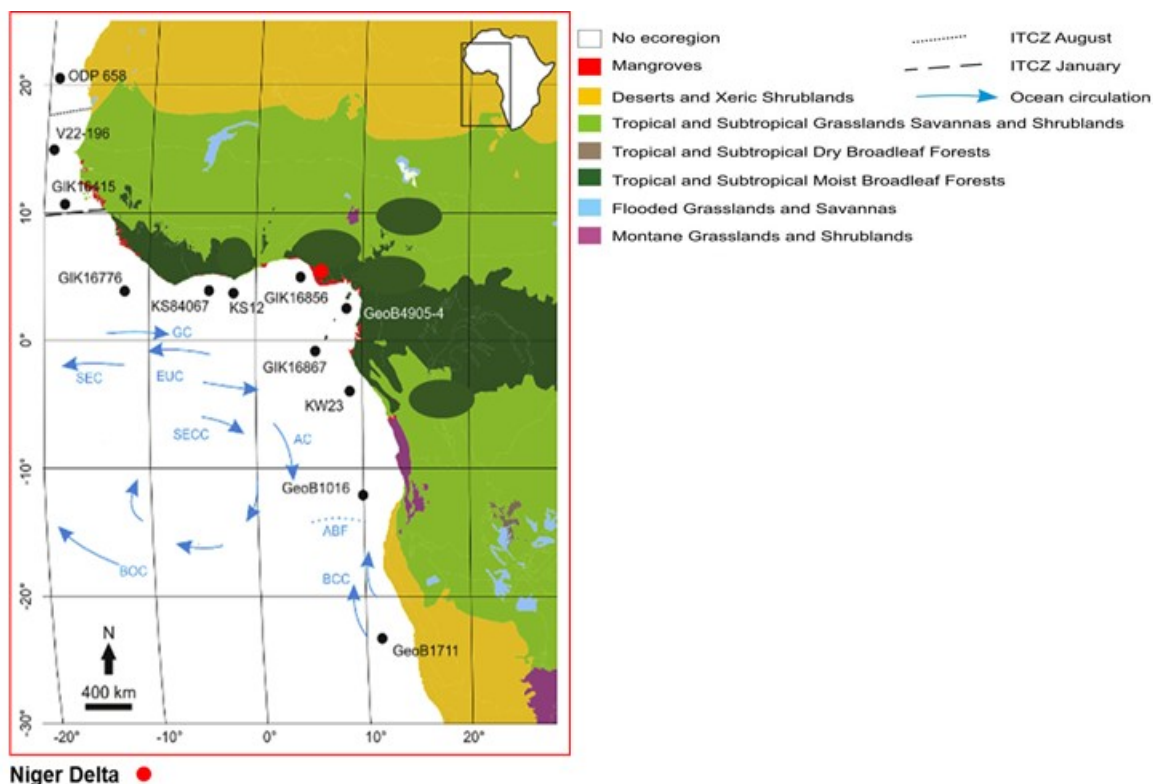


Figure 2.4. Map of the modern vegetation biomes of West Africa (White, 1983; Olson *et al.*, 2001) with oceanographic and climatological data. GC= Guinea Current; SEC= South Equatorial Current; EUC= Equatorial Undercurrent; SECC= South Equatorial Counter Current; AC = Angola Current; BOC= Benguela Ocean Current; BCC= Benguela Counter Current; ABF = Angola–Benguela Front (adapted from Dupont *et al.*, 2000). Marine cores cited in the text are included here.

Given the above information related to present day distribution of floristic composition on the African continent, there is a need to review the floristic composition associated with forest development during interglacial stages along the West African coast using marine core materials. These offer numerous records of vegetation dynamics associated with what is termed during the warm period of the Marine Isotope Stage (MIS). Different forest zones documented by various authors are used to discuss the successive vegetation patterns within West Africa during the interglacial period, as discussed below.

Marine Isotope Stage (MIS) 13:

Pollen records of Marine Isotope Stage during MIS13, an interglacial period occurring about 500 ka (Figure 2.4) at ODP 658 location offshore Mauritania, constitute high abundances of grass pollen group Poaceae. In addition to the high abundances of Poaceae, Chenopodiaceae-Amaranthaceae are also dominant, which are both typical of the tropical and subtropical grassland biome (White, 1983; Hooghiemstra *et al.*, 1986; Dupont *et al.*, 1989). Core GIK16415 (located southwest of Dakar, Senegal) shows numerous ferns and *Uapaca* surrounding the development of a tropical and subtropical moist broadleaf forest biome (Dupont and Agwu, 1992; Miller and Gosling, 2014). Abundances of taxa from the montane grasslands and shrubland biomes are apparent in Core GIK16867 located offshore Gabon (Dupont *et al.*, 1998; Dupont, 2011) (Figure 2.4).

Marine Isotope Stage (MIS) 11:

West African vegetation throughout the interglacial period between 424 ka and 374,000Ka is deduced from four marine core locations (ODP 658, GIK16415, GIK16867 and GIK16776) and provide a vegetation record of MIS11 (Figure 2.4). Occurrences of Poaceae and Chenopodiaceae-Amaranthaceae are distinctive of the tropical and subtropical grassland biomes (Dupont *et al.*, 1989; Dupont, 2011). Furthermore, ODP 658 sequence shows abundances increase of *Rhizophora*, suggesting a rise of the sea level. The GIK16415 core comprises of an increased association of fern spores and *Rhizophora* richness during the late MIS11 (Dupont and Agwu, 1992; Versteegh *et al.*, 2004; Kim *et al.*, 2005). A large development of the montane taxa *Podocarpus* is observed in marine cores GIK16867 and GIK16776 (Dupont *et al.*, 1998).

Marine Isotope Stage (MIS) 9:

West African vegetation developed around 330 ka, years age was recorded in the same four marine cores (Figure 2.4). High abundances of taxa characteristic of the tropical and subtropical grassland biomes (Dupont *et al.*, 1989) were observed at ODP 658 similar to the MIS11. Cores GIK16415, GIK16867 and GIK16776 show the development of the tropical and subtropical moist broadleaf and mangrove biomes (Dupont and Agwu, 1992; Dupont *et al.*, 1998; Jahns *et al.*, 1998; Dupont, 2011; Gosling *et al.*, 2013).

Marine Isotope Stage (MIS) 7:

During MIS7, the vegetation record across West Africa shows a slight cold climate inference due to fluctuations associated with climate forcing (Figure 2.4). Within the ODP 658 core climate changes are categorised through having taxa characteristic of the tropical and subtropical grassland biome associated with temporal ages of around during 184 Ka (Dupont *et al.*, 1989; Dupont, 2011). The dominant vegetation of MIS7 at the locations GIK16776 and GIK16415 are ferns and *Rhizophora* (Dupont and Agwu, 1992; Jahns *et al.*, 1998; Dupont, 2011). Evidence of an expansion of the tropical and subtropical moist broadleaf forest and mangrove biomes in West Africa during MIS7 was also recorded in cores GIK16415, GIK16867, GIK16776 and KS84067 (towards the Ivory Coast; Figure 2.4) (Dupont and Agwu, 1992; Jahns *et al.*, 1998; Dupont, 2011).

Marine Isotope Stage (MIS) 5e:

During the MIS5e, the West African vegetation was recorded at the core locations (ODP 658, V22-196, GIK16415, KS84067, GIK16856, KW23, GeoB1016 and GeoB1711; (Dupont, 2011) Figure 2.4). The tropical and subtropical grassland biomes record Chenopodiaceae-Amaranthaceae and Poaceae as dominant at both the ODP 658 and V22-196 locations. Core GIK16415 contains a low pollen concentration of these categories, but a higher occurrence of fern spores (Dupont and Agwu, 1992). The KS84067, GIK16856 and KW23 cores recorded an abundance of elements typical of the tropical and subtropical moist broadleaf forest and mangrove biomes with a withdrawal in the montane grasslands and shrubland biome throughout MIS5e (Figure 2.4) (Frédoux, 1994; Dupont and Weinelt, 1996; Dupont, 2011).

Marine Isotope Stage (MIS) 1:

The currently developed interglacial vegetation of West Africa is well documented in both terrestrial and marine cores (Figure 2.4). High grassland concentrations through the Holocene were recorded at the core GIK16415 location with an increase in fern spore percentages and taxa encompassing the recent tropical and subtropical moist broadleaf forest biome at 11,7 ka (Figure 2.4) (Dupont and Agwu, 1992). These records of an increase in taxa from modern-day tropical and subtropical moist broadleaf forest biomes during the Holocene were recorded at GIK16856, KS84067, GIK16867 locations, as well as terrestrial records from Lake Bosumtwi and Lake

Barombi-Mbo in Ghana (Figure 2.4) (Maley, 1991; Frédoux, 1994; Dupont and Weinelt, 1996; Dupont *et al.*, 1998). Mangrove vegetation expanded after the Last Glacial Maximum along the West African coast during this time. This successive expansion during the Early-mid-Holocene was very predominant, but gradually reduced towards the present day (Sowunmi, 1981; Lezine and Vergnaud-Grazzini, 1993; Miller and Gosling, 2014).

2.5 Hydrography of the Gulf of Guinea

This section discusses the hydrography of the Gulf of Guinea in relation to the coastal littoral and seasonal variations observed within the Niger Delta region. The aim of this section is to present a synthesis concerning the seasonal variation of the salinity and temperature in the Gulf of Guinea, to help understand certain principal drivers controlling marine and terrestrial deposits, littoral coastal biome distribution, and their evolution with time within the region.

The hydrography of the Gulf of Guinea is characterised by a shallow thermocline, stable oceanographic conditions and high temperature gradient throughout the seasons (Njock, 1985) (Figure 2.5). The surface water temperature varies between 25°C to 30°C with a surface salinity of 35.24‰ depending on palaeodischarge associated with effluent rivers and average annual discharge from surface run-off (William, 1968). On an annual basis, river run-off from nearby large African river systems combined with Global (oceanic) Currents (GoCs) which are driven by the SE trade winds, relocates the water mass and suspended loads towards the Northwest tangentially along the west coast of southern Africa, moving cold and saline waters into the Gulf of Guinea (Figures 2.6; 2.7).

The major surface current systems that directly affect the hydrography of the Gulf of Guinea are the Benguela Current, the South Equatorial Current and the Guinea Current. The Guinea Current flows eastward from Senegal to the Bight of Biafra (Figures 2.6; 2.7). The South Equatorial Current transports cold waters of the central Atlantic to the Gulf of Guinea, which replaces the warm layers of surface water due to the periodic upwelling (Dovlo, 2016). The Benguela Current (BC) is positioned at the

eastern boundary of the South Atlantic subtropical gyre (Wedepohl *et al.*, 2000). The axis of the BC migrates as a northward flow off the Cape of Good Hope (South Africa) to a point where it shares borders around the equatorial western African coast until it changes direction around 24°S to 30°S (Figure 2.6). At this point most of BC diverges from the coast as it eventually moves towards the northwest of the Gulf Guinea. On a regional basis, the two branches of the Benguela Current eventually continue to drift along the coast, but one of the branches later joins the Angola Current at the Angola-Benguela front near 16°S (Wedepohl *et al.*, 2000) (Figures 2.6; 2.7). Other sources of the Benguela Current include Indian and South Atlantic subtropical thermocline water and fresh water subantarctic water (Garzoli *et al.*, 1996). Those sources are also affected by the global ocean current and have been recorded by many authors to be the sole distributor of the Benguela Current (Figure 2.6).

From a regional perspective, the hydrography of the Gulf of Guinea is mostly connected to the BC which separates into two surface water outlets, namely the Benguela Oceanic Current (BOC) and the Benguela Coastal Current (BCC) (Figure 2.5). The BOC moves northwest offshore compared to the BCC, which drifts along the coastal realm of the Atlantic Ocean. In some cases due to seasonal variation, the BOC transports cold nutrient rich waters from the South Atlantic thereby increasing the amount of cold nutrient rich water fetching into the Gulf Guinea (Stramma and England, 1999).

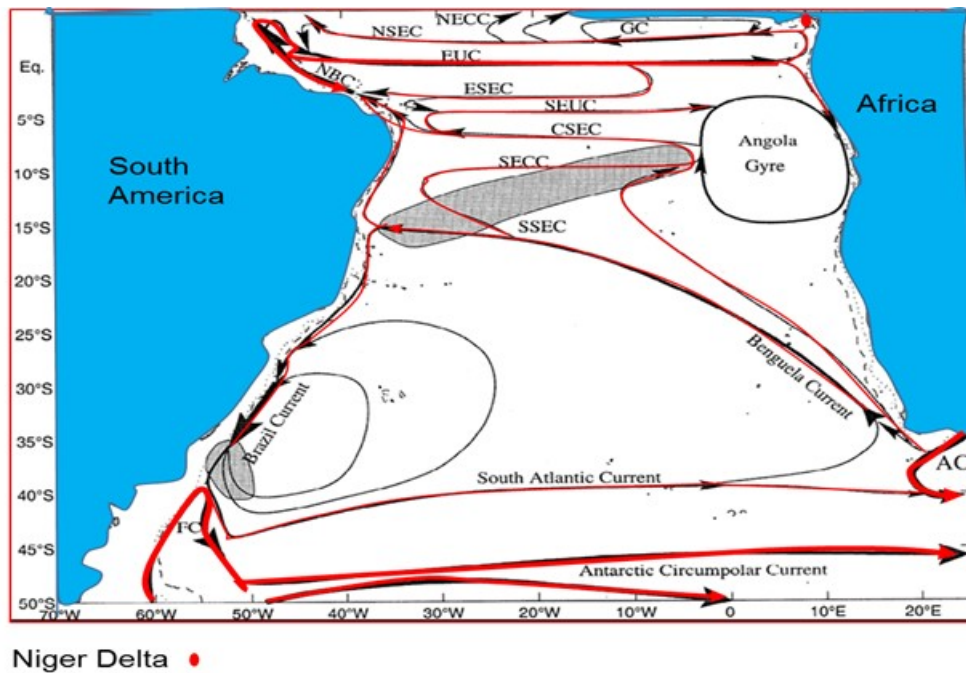


Figure 2.5. Schematic representation map of the hydrographic currents for the Gulf of Guinea (modified after Peterson and Stramma, 1991). Guinea Current (GC); Equatorial Undercurrent (EUC), North Brazil Current (NBC); North Brazil Undercurrent (NBUC); North Equatorial Current (NEC); North Equatorial Countercurrent (NECC); North Equatorial Undercurrent (NEUC); South Equatorial Current (SEC).

The warm waters of this North Equatorial region are strongly controlled by the warm waters relocated through by the Global Current (Stramma and England, 1999). The Global Current continues to exert an influence on the hydrography along the Western coast of Africa, from 3°N to the Gulf of Guinea (latitude between 8°W and 9°E (Dovlo, 2016). These are known as the North Equatorial Counter Current and Canary Current, whereby periodic fluctuations also affect the general hydrologic regime and coastal upwelling leading to an increased level of productivity in the Gulf of Guinea (Wedepohl *et al.*, 2000).

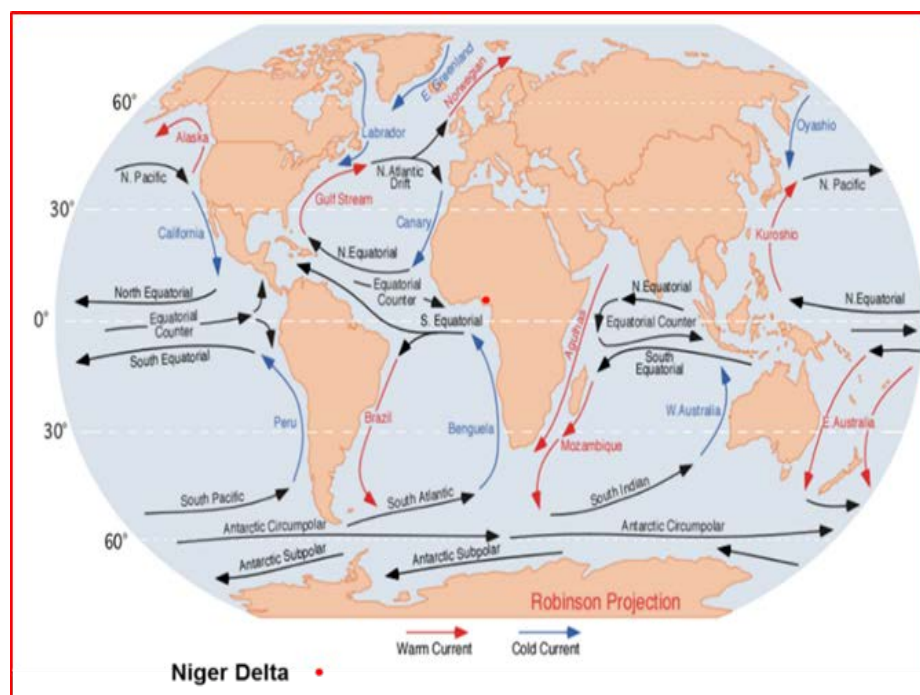


Figure 2.6. Major ocean currents of the world (red arrows indicate warm currents, while blue represents cold currents) (Pidwirny, 2006).

2.6 The Quaternary Delta and Niger Delta

Following the aforementioned controls on palaeovegetation, this section discuss the relevant roles played by different factors on the Quaternary delta and Niger Delta evolution in relation to the hydrographic background of the world deltas.

Deltas are dynamic and progressively developing landforms that evolve at the mouths of river distributary systems, where sediments are transported and deposited into the sea or basin through fluvial, wave and tidal processes (Zong *et al.*, 2009) (Figure 2.7). Many authors have discussed different kinds of deltas worldwide (e.g. Allen, 1964; Nichole, 2011). The type of deltas categorised by these authors are based on what controls the delta formation. Most literature document the influence of waves or tides to be solely responsible for the formation of many marine deltas. The marine delta could be wave dominated or tide dominated, whereas inland deltas and gilbert deltas are fluvially controlled (Giosan *et al.*, 2005). From the categories of deltas listed above, a wave-dominated delta is one where wave erosion determines how much sediment is deposited in the deltaic setting after the river flow decreases (e.g. Mississippi Delta). A tide-dominated delta is one that develops due to tidal and sea-level rise influence (e.g. Ganges Delta) (Giosan *et al.*, 2005). Amongst these

categories of deltas, the Niger Delta is classified differently as a “mixed delta” because it is the product of both fluvial and marine influence (Allen, 1964).

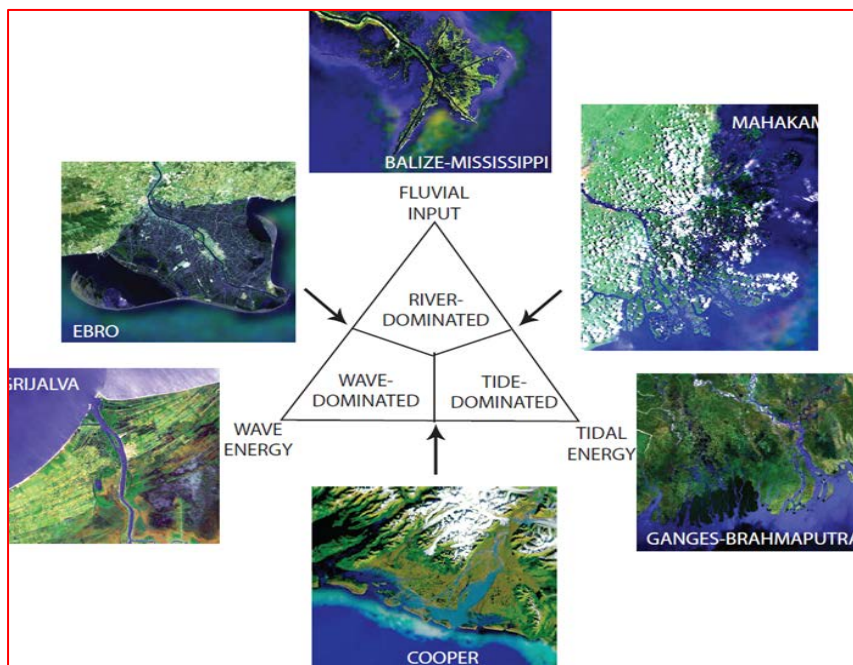


Figure 2.7. The classification of deltas (Galloway, 1975) as a result of wave, tide and river controls (modified from Syvitski *et al.*, 2009).

Reviewing regional and basin configurations and associated facies architecture, the resultant products of delta formation have resulted in its classification into three main geographic areas. These consist of the upper delta plain, the lower delta (delta front) and pro-delta settings. The delta plain is associated with the land, the pro-delta is linked to deposition within the marine realm, while the delta front is the transition between the delta plain and the pro-delta settings (Figure 2.8) (Galloway, 1975; Bhattacharya and Walker, 1992).

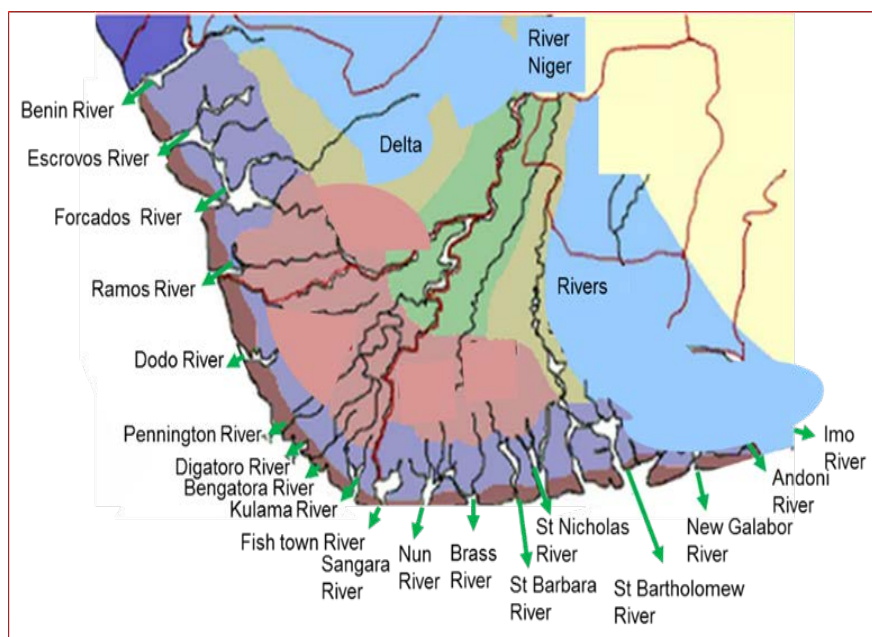


Figure 2.8. Niger Delta distributary river systems (modified after Okonkwo *et al.*, 2015).

2.6.1 Controls on Delta Morphology

Deltaic deposits show characteristic arrangement of internal architecture, as long as the major factors controlling sedimentation are comparable (Weber, 1987). Such factors consist of the location of the delta in relation to local tectonic features, climate, sea level, topography, subsidence, hinterland structure and plate boundaries. These factors control the evolutionary patterns that develop during wider delta formation. Though numerous factors as stated above have been considered by past authors (e.g. Giosan *et al.*, 2005) on the control of the morphology of the delta, in this study only three main factors are considered to be responsible for controlling the development of the delta. These are as follows: climate, wave and tidal controls, morphology and facies supply of the basin.

2.6.1.1 Climate Control

Worldwide regional climate and sediment transport variance is linked with summer insolation and on the basis of the strength of monsoon which controls levels of precipitation (Figure 2.9). Studies have shown that sediment supply does not alter because of present climate change relating to Milankovitch time scales thereby creating a false imprint on the stratigraphic succession. Nevertheless, under icehouse conditions the variation in warm climate-controlled sedimentary sources is significantly dominated by the glacio-eustatic periodic sea level change. These presumptions include most studies of detailed theoretical concepts which document climate modelling as very essential. However, it can be assumed that the impact of wetter climate control due to the orbital shift is secondary on the control of the deltaic sequences formation.

Most controls on deltaic sequences under this category are linked to the subtropical monsoon system. These systems are inclined to be highly seasonal, receiving almost all their precipitation during the wet seasonal monsoon when the ITCZ is at its greatest proximity (Shanahan *et al.*, 2007). In some cases at the level of orbital time intervals, both the position and location, as well as, the migration of the ITCZ fluctuate in response to global boundary conditions and maximum summer insolation (Giosan *et al.*, 2005). Therefore, such systems have been shown to be responding to Quaternary climate change and variations in precipitation. On a general note, most of these differences are likely to arise due to the limited suitable examples of pre-modern climate and coastal-riverine locations.

Therefore, the impact of climate on deltaic successions is largely considered to be a function of changes in the sea level, estuarine-riverine water and sediment supply to the continental shelf, and the influence of these influxes on the coastal and marine sedimentation (Giosan *et al.*, 2005; Goodbred, 2003) (Figure 2.9). Hence, under these processes, climate through orbital rotation could be seen to play a substantial role in fluvial transport processes, sea level and coastal weathering in the adjacent basins during precipitation. In this way, a robust climate overprint on deltaic systems becomes inevitable, but specific indicators are difficult to access due to the complex responses and secondary implications. In addition, in the continental realm of a deltaic distributary

system, the most substantial role played by climate revolves around precipitation. Under these conditions of sediment yield, precipitation is a primary factor controlling glacial and fluvial, weathering, slope failure and fluvial incision of existing delta formations (Giosan *et al.*, 2005) (Figure 2.9).

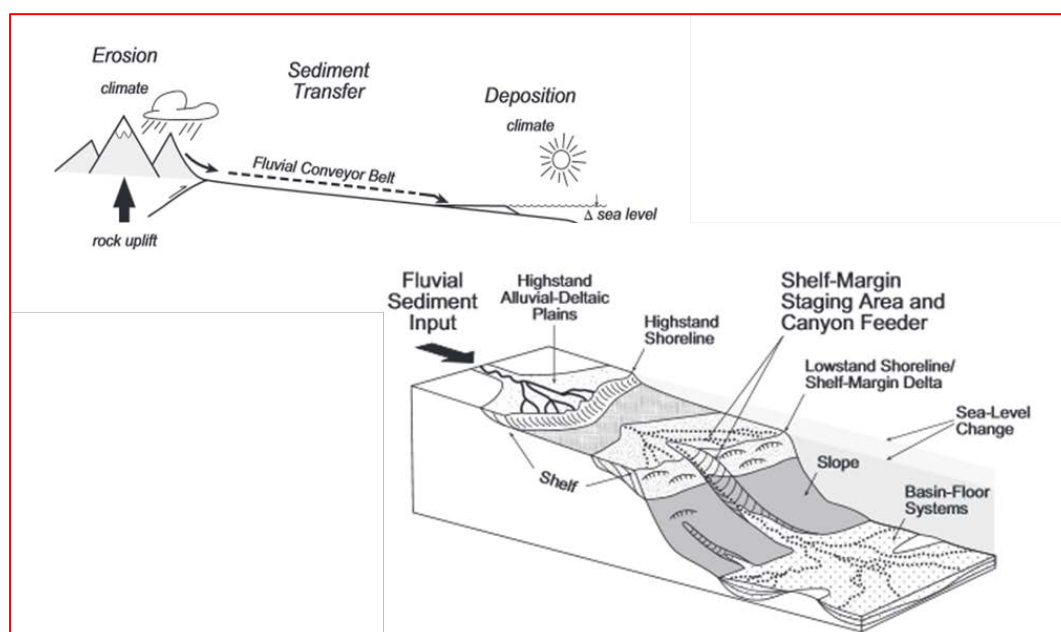


Figure 2.9. The concept of climate influencing fluvial transportation, illustrating the importance of climate on sediment delivery to the continental shelf margin (modified after Posamentier and Kolla, 2003; Castellort and Van DenDriessche, 2003).

2.6.1.2 Wave and Tidal Control

The impact of waves and tides are essential controls for the evolution of deltaic systems over 10s to 100s of year periods, but on the general note delta evolution over longer time scales is influenced by tectonics, sea level and climate change (Oomkens, 1974; Giosan and Bhattacharya, 2005).

Waves driven by strong winds have the capacity to rework and redistribute sediment in shallow water settings, especially under storm conditions. The river mouth and mouth-bar areas of a delta are susceptible to the action of waves, resulting in a modification of the patterns seen in river dominated deltas (Bhattacharya and Giosan, 2003). Wave action is effective at sorting the bedload into different grain sizes and the

mouth bar deposits of a wave-influenced delta may be better sorted than those of the river or fluvial-dominated (Nichole, 2011).

In the case of a tidal controlled delta, coastlines with high tidal ranges experience onshore and offshore tidal currents that move both bedload and suspended load. A delta building out into a region with strong tides will be modified into a pattern that is different to both river and wave dominated deltas. For example, the delta top channel is subject to tidal influence with reverses of flow and periods of stagnation as a flood tide balances the fluvial discharge (Goodbred, 2003). Overbank areas on the delta top may be partially tidal flats, and all of the delta top will be susceptible to flooding during periods of high fluvial discharge coupled with high tides. The tidal currents rework sediments at the river mouth into elongated bars that are perpendicular to the shoreline. These are modified mouth bars, which may show bidirectional cross bed forests due to the reversing nature of the flood tidal currents (Willis *et al.*, 1999a, b). Tidally influenced deltas can be distinguished from other deltas by presence of sedimentary structures and facies associations which indicate that tidal processes were active (e.g. reversals of palaeoflow and mud drapes), and subaqueous mouth bars will be elongated parallel to the river channels (Nichole, 2011). Given the above controls, an understanding of a wave dominated and tidal processes can possibly provide substantial evidence on the formation of deltaic sequences.

2.6.1.3 Morphology and Facies Supply of the Basin

The morphology of the delta is significantly influenced by the shape of the basin (Wright and Coleman, 1973; Oomkens, 1974). This is dependent on the shelf configuration (e.g. width vs. gradient), which varies with the associated type of continental margin (e.g. passive vs. active) and also with the changes in sea level which may influence the vertical accommodation space and the measure of coastal incision. For instance, if the deltas move nearer to the middle of the basin (i.e. between the delta front and outer shelf) their morphology could be controlled by cumulative wave effect associated with deeper nearshore sea level inundation (Allen, 1965; Stanley, 2001; Giosan *et al.*, 2005). With regards to the muddy prodelta, this part subsequently develops a clinoform geometry connected with the shoreface and deep offshore muddy clinoforms (Figure 2.10) (Kuehl *et al.*, 2005; Giosan *et al.*, 2005;

Reijers, 2011). Though this seems to be the end product, the resulting or developing prodeltaic clinoforms are not globally reproduced, even though the result of fluvial input and sink hydrodynamic influences during seasonal variations is constant (Doust and Omatsola, 1990); Swenson *et al.*, 2005; Giosan *et al.*, 2005).

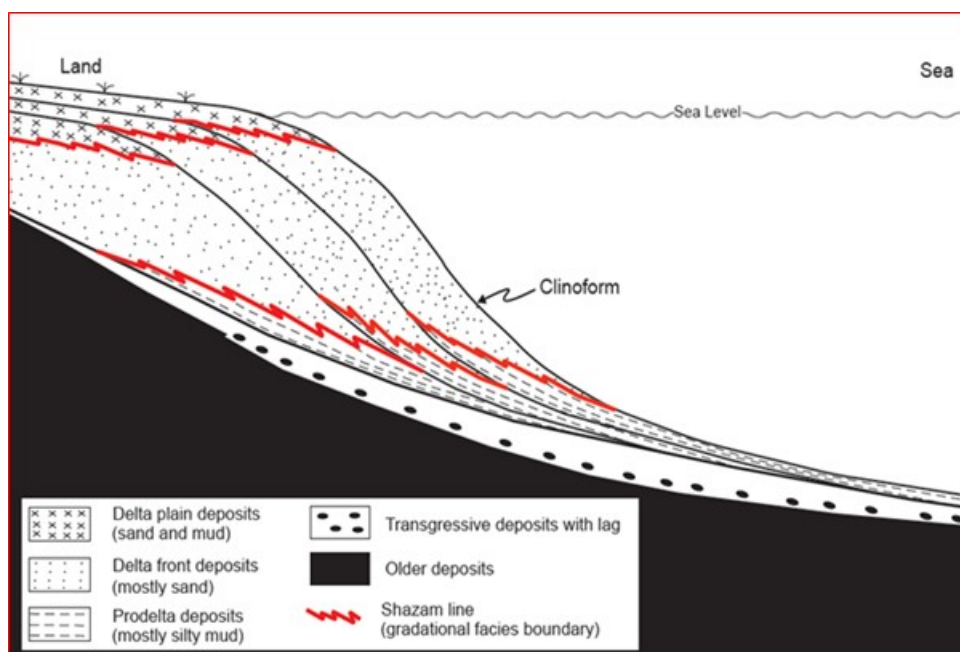


Figure 2.10. Deltaic sedimentation and clinoform configuration (modified after Giosan *et al.*, 2005).

The combinations of factors that control delta morphologies give rise to wider spectrum of possible delta characteristics. For instance, the modern deltas that provide examples of a number of possibilities in this regards are: Mississippi Delta (USA), which is fine grained and river dominated; the Rhone Delta (France) is a mixed sand-mud system and is wave dominated; and the Skeidarasandur delta (Iceland) is mainly gravelly with river and wave influence (Nichole, 2011). Every modern delta will have individual characteristics due to the different factors controlling its form, and it may be expected that the deposits of ancient deltas will be similarly variable. Therefore, it is more instructive to consider the effects of different controls on the delta morphology and consequently on the delta facies during the formation of the delta.

2.7 The Background Geology of the Niger Delta (Study location)

The Cenozoic Niger Delta has been noted as one of the largest delta systems in the world with an areal surface extent of about 300,000 km² (Kulke, 1995) with a sediment thickness of over 12,000m in the basin depocentre (Doust and Omatsola,

1990; Reijers, 2011). The delta system is axially positioned across southern Nigeria building out roughly southwards into the Gulf of Guinea (Figure 2.11). It is commonly referred to as a wave-controlled delta in the conventional technical terms of Galloway (1975); however, some interpretations suggest that the deltaic front indicates evidence of robust tidal influence (Sexton and Murday, 1998).

The geological subdivisions applied to most deep wells drilled across the Niger Delta basin document a tripartite lithostratigraphic succession of regressive sequences, namely the Akata, Agbada and Benin formations (Avbovbo, 1978; Reijers, 2011). These units are roughly dated diachronously between the Paleocene and Recent (Figure 2.12).

2.7.1 Sedimentation and Depobelt Successions

The depobelts concept applied to the Niger Delta, are thick sedimentary cycles of deposition within a basin which have been compartmentalised by bounding faults as a result of overburden pressure on the older sediments deposited (Doust and Omatsola, 1990) (Figure 2.11). A pronounced succession is observed in the Niger Delta and to date has been targeted for hydrocarbon exploration by many oil companies and researchers worldwide (Figure 2.12). In Paleocene and Eocene times, marine shales were deposited over most of the Niger Delta; paralic and marine/paralic sediments appear to have been restricted to the area where the present Niger River flows between the Abakaliki Fold-Belt and Oban Massif (Evamy *et al.*, 1978).

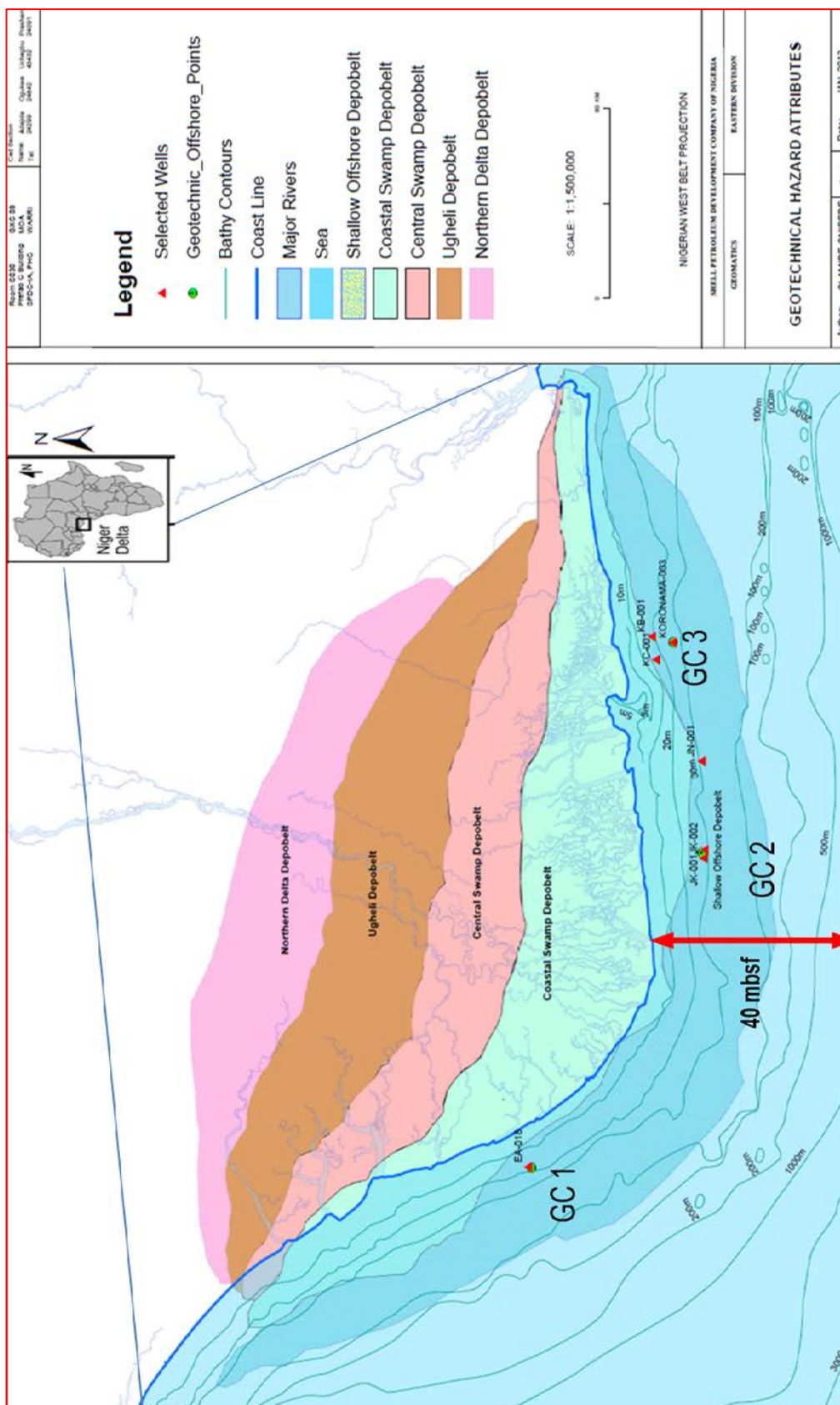


Figure 2.11. Location of the Niger Delta and Gravity Cores positions (GCs) (after Shell, 2011).

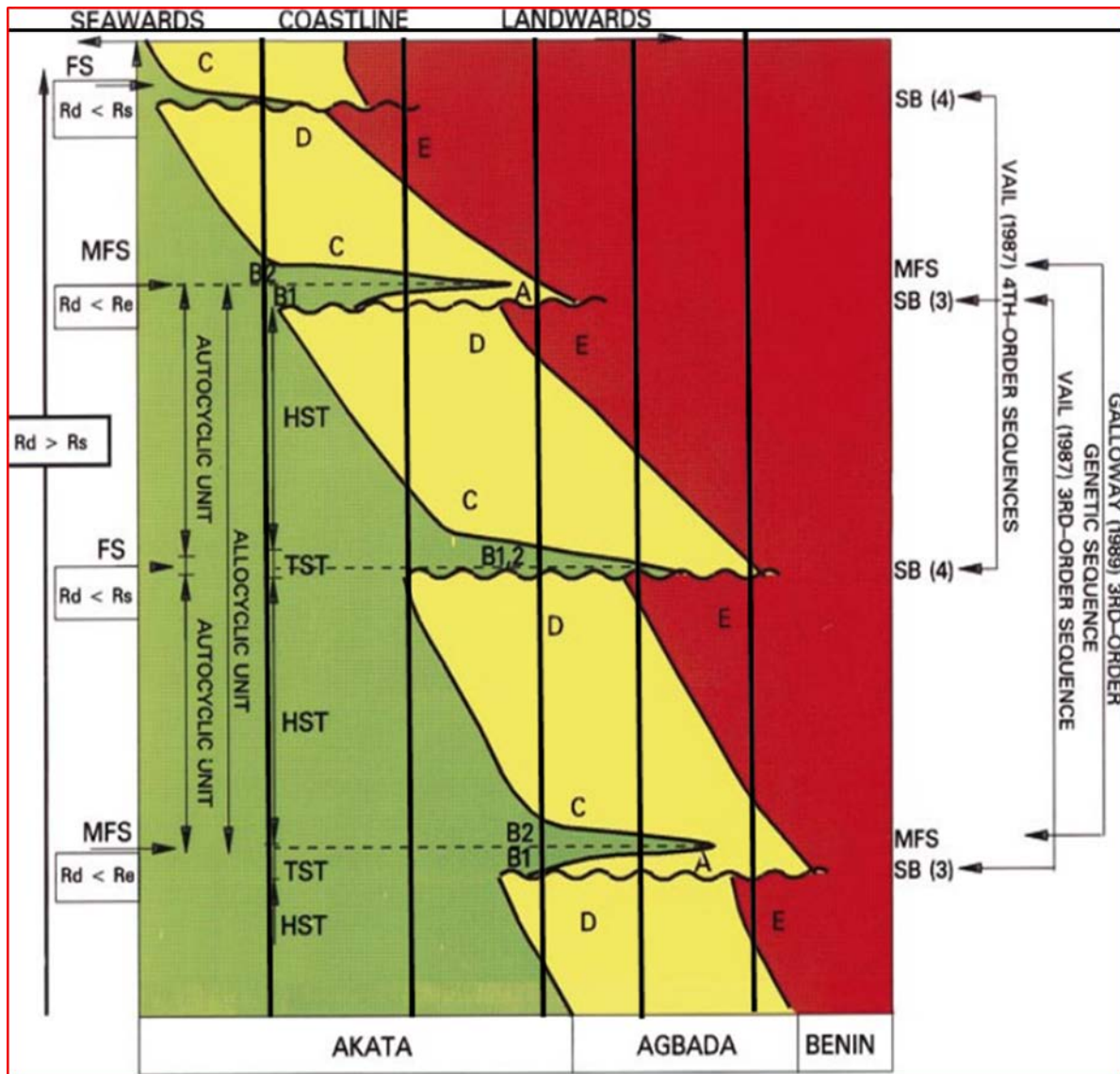


Figure 2.12. The stratigraphy and evolution of Niger Delta Formations (modified after Reijers, 2011). Rd = rate of deposition; Rs = rate of subsidence; E = Fluvial backswamp deposits; D = Upper shoreface heteroliths; C = Lower shoreface heteroliths; B2 = Open marine shale; B1 = Transgressive marine shale; HST = highstand systems tracts; TST= transgressive systems tracts; MFS = maximum flooding surface; FS = flooding surface; SB = surface boundary.

As the drainage expanded into the African craton, this passive margin subsided. The upward-coarsening strata, offlapping this continental margin, has been divided into three dichronous lithological sections. They consist of the Akata, Agbada and Benin formations as stated above (modified after Reijers, 2011) (Figure 2.12). The development of those formations is due to the continental-margin collapse leading to the development of the structural framework within the region. Those structures

exerted an important control on depositional and stratigraphic patterns within the Niger Delta clastic wedge. At the largest scale, these structures extend laterally along depositional strike across nearly the entire Niger Delta, i.e. hundreds of kilometres (Evamy *et al.*, 1978) forming associated depobelts that are tens of kilometres wide perpendicular to the shoreline (Knox and Omatsola, 1989; Doust and Omatsola, 1990). Five regional depobelts were deposited from the Paleocene to Recent, named: Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp and Offshore depobelts (Figures 2.12, 2.13). Depobelts tend to become finer-grained laterally away from areas of most rapid growth-fault development (Doust and Omatsola, 1990). This pattern of deposition continues today, with an extensional growth of prodeltaic growth faults on the continental shelf and slope break (Figure 2.12).

Given that the marine shales were buried and loaded by the prograding delta, they became overpressured and shifted basinward (Figure 2.12). This deposition of shale caused structural collapse under the prograding delta (defining an overriding megastructure). In the proximal areas of a collapse structure, sandy deposits migrate rapidly as the growth faults develop in a succession basinward-inclined to the normal faults (Reijers, 2011). In the distal parts of a collapse structure, finer-grained pro-delta deposits were deformed by the rising underlying shale and landward-dipping antecedent normal faults (Figure 2.12). As underlying mobile shales become depleted, continued delta progradation filled accommodation within the collapsed structure, eventually overriding areas of rising mobile shale. This shifted the locus of deposition basinward, rapidly loading a more distal area of the basin floor, which led to a new area of shale mobilisation and associated structural collapse (Figure 2.13).

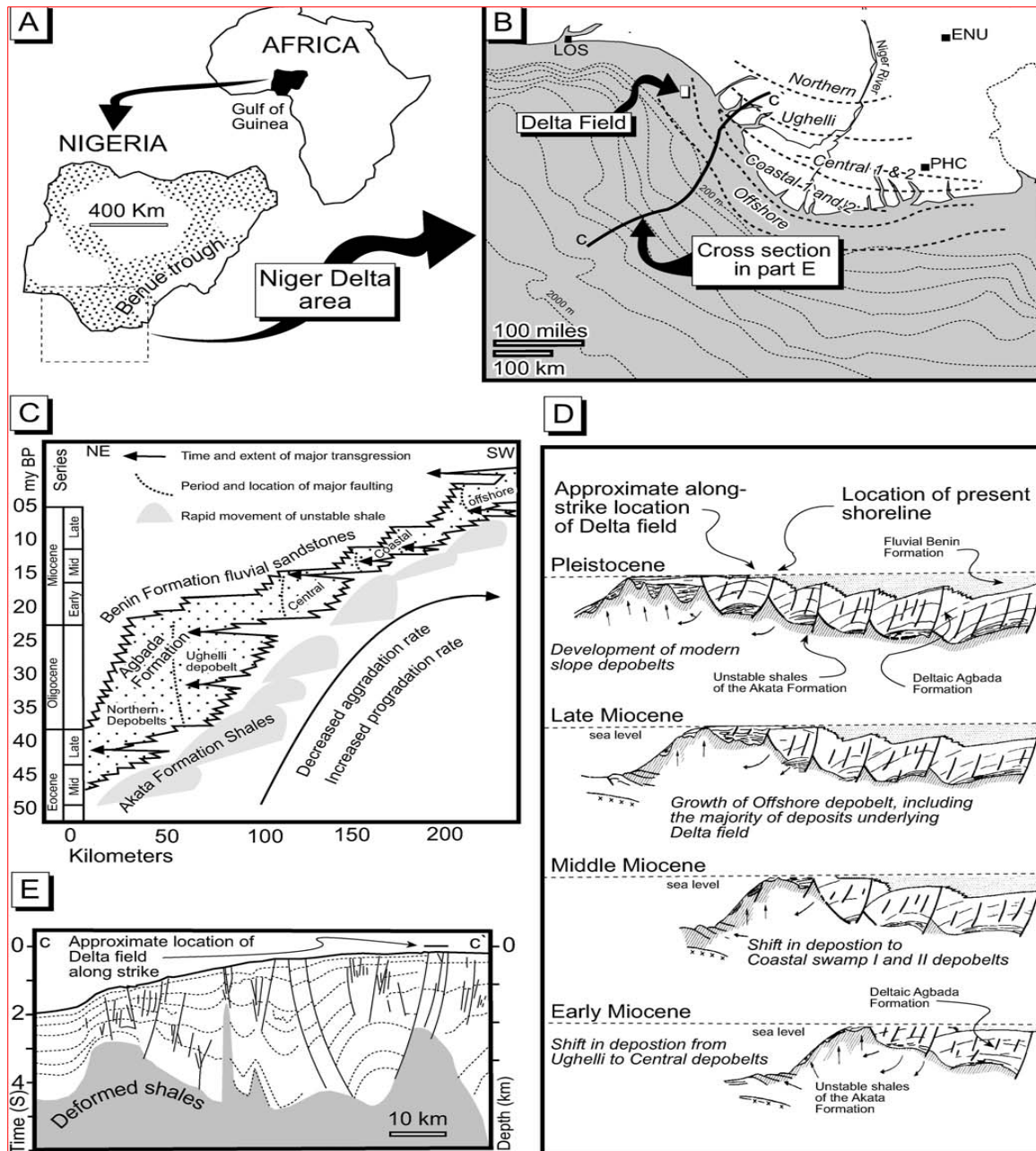


Figure 2.13. The Niger Delta depobelts and structural framework: (A) Location of Niger Delta in Africa; (B) Location of Delta field along the northwest corner of Niger Delta (after Short and Stauble, 1967); (C) Chronostratigraphic chart showing the regressive nature of formations in the Niger Delta clastic wedge (after Knox and Omatsola, 1989); (D) Schematic diagram showing the development of successive growth-fault-bounded depobelts during progradation of the unstable Niger Delta clastic wedge (modified from Weber, 1987; after Knox and Omatsola, 1989); (E) Geometry of strata and major faults interpreted from a regional dip-oriented seismic reflection profile (modified from Cohen and McClay, 1996).

2.7.2 Climate, Hydrography and Vegetation of the Niger Delta

This section summarises the “palaeogeography of the Niger Delta” from the broad literature review of West Africa outlined in the previous sections. This is summarised under climate, hydrography and vegetation belts below.

2.7.2.1 Climate

The Niger Delta climate is conditional on the movements of the ITCZ which mark the transition between the humid air masses from south to north, depending on the prevailing season (Short and Stauble, 1967) (Figure 2.1). In general, humid air masses and the associated rain-bearing South-Westerly monsoon winds dominated the Delta and the dry northerly “Harmattan” winds reached the coast only sporadically, in the months of January and February. Temperatures over the Delta are very uniform and range from 20°C at night to more than 30°C during the daytime. Under the impact of South-Westerly winds, the area receives a significant amount of rainfall, ranging 40mm per year in the east to 150-170 mm over the Delta, decreasing towards the North and West to 75mm as is recorded in both Onitsha and Lagos, in the South West of Nigeria (Figure 2.11).

2.7.2.2 Hydrography

Highly energetic currents shape the Niger Delta coastline (Figure 2.6) (Pidwirny, 2006). This effect is caused by the consistent strong swell of the South Atlantic coming in from a general 30°C tangential (South West) direction (Figure 2.6). Subsequently, this swell reaches the coast at an oblique angle, creating strong longshore currents which move eastward along the western flank of the Delta and westward along the western flank (Figure 2.5). The outcome of this control diverts the watermass and sediment plume arriving in the marine realm by the major tributaries of the Niger River system, which then laterally transport and relocate sediments along the delta coastline away from the sediment entry points (Figures 2.6, 2.12). Aside from the washing effect of the tidal currents along the coast and into estuaries and up-river, a physical chemical anomaly is caused by a dense salt water wedge which, at high tides, pushes far inland (Short and Stauble, 1967).

The discharge of Niger River ranges from 5,420 m³/sec (171 X 10⁹ m³/) to 9,400 m³/sec (298 X 10⁹ m³/year) (Okonkwo *et al.*, 2015) (Figures 2.6, 2.12). These figures show the discharge of the river as about two-fifths that of the Mississippi River, outpouring into the Gulf of Mexico. However, the Mississippi River carries only an estimated 2.62 X 10⁶ m³ of sediment which, represents only about 35% compared with the Niger Delta system, where most is noted to be of fine fraction and is transported out to the sea, with the lesser coarser-fraction being deposited in the delta since the Oligocene (Short and Stauble, 1967).

2.7.2.3 Vegetation

The vegetation of the Nigeria differs from some of the broader vegetation types and patterns from other West African countries discussed previously. It varies from the tropical rainforest in the south to dry savannah in the northern boundary of Nigeria, but of course the main river systems running from the interior down to the Benue-Niger confluence have passed through other orographic and geographic settings. A proposed seven-fold classification of vegetation groups found in Nigeria are given as Figure 2.14. They consist of the marginal savannah, short grass savannah, woodland and tall grass savannah, rainforest, fresh water swamp, mangrove and montane.

Along the coastal section of the Niger Delta, the dominant vegetation is made up of swampy ground terrain demarcated by fresh or brackish water lagoons and a network of creeks. A typical mangrove swamp forest has developed on the muddy banks of these creeks where the water is brackish (Figure 2.14). This mangrove swamp forest is characterised by the species of *Rhizophora* (Red Mangle or Red Mangrove), as well as fern types. Unlike other West African vegetation ecosystems where extensive research has been recorded on the factors or controls responsible for their dynamics, there are very few ecosystems records for the Niger Delta. The summary of vegetation types in Nigeria/Niger Delta is tabulated below (Table 2).



Figure 2.14. Vegetation map of Nigeria (modified from Nigerian vegetation map, 1979).

Botanical Affinity		Morphological Affinity		Family	Natural Habitat
Heteropteris	leona	Calystegiapollis	microechinatus	Chenopod/Amaranth	Coastal
cf. Ipomoea	pes-casprae	Echiperiporites	sp.	Convolvulaceae	Coastal
aff. Thespesia	sp.	Echiperiporites	estalae	Malvaceae	Coastal
Crenea	maritima	Verrutricolporites	rotundiporis	Lythraceae	Coastal
Acrostichum	aureum	Vadaszsporites	sacali	Adiantaceae	Mangrove Swamp
Avicennia	germinans	Foveotricolporites	crassiexinus	Avicenniaceae	Mangrove Swamp
cf. Excoecaria	africana	Psilatricolporites	kigwiensis	Euphorbiaceae	Mangrove Swamp
Rhizophora	sp.	Zonocostites	ramonae	Rhizophoraceae	Mangrove Swamp
cf. Bauhinia	pauletia	Psilatricolporites	crassus	Caesalpinioidae	Mangrove Swamp
aff. Nypa	sp.	Spinizonocolpites	adamanteus	Arecaceae (Palmae)	Mangrove Swamp
Ceratopteris	cornuta	Magnastriatites	howardi	Adiantaceae	Fresh Water Swamp
Alchornea	aff. cordifolia	Psilatricolporites	operculatus	Euphorbiaceae	Fresh Water Swamp
Anthonotha	gilletii	Striatricolpites	catatumbus	Caesalpinioidae	Fresh Water Swamp
cf. Nymphaea	micrantha	Zonosulcites	sp.	Nymphaeaceae	Fresh Water Swamp
Nymphaea	lotus type	Cingulapollenites	aegyptiaca	Nymphaeaceae	Fresh Water Swamp
Cyperus	aff. rotundus	Cyperus	type	Cyperaceae	Fresh Water Swamp
Symphonia	globulifera	Pachydermites	diederixi	Hyperiacaceae	Fresh Water Swamp
Stenochlaena	palustris	Verrucatosporites	usmensis	Polypodiaceae	Lowland Rainforest
Polypodium	vulgare	Verrucatosporites	sp.	Polypodiaceae	Lowland Rainforest
Hypolepis	sparsisora	Verrucatosporites	prosecundus	Polypodiaceae	Lowland Rainforest
Lycopodium	cernuum	cf. Lycopodiumsporites	fastigioides	Lycopodiaceae	Lowland Rainforest
Lycopodium	sp.	Rotaspora	ergonulii	Lycopodiaceae	Lowland Rainforest
Lycopodium	cernuum	cf. Lycopodiumsporites	fastigioides	Lycopodiaceae	Lowland Rainforest
aff. Malacantha	alnifolia	Psilastephanocolporites	cf. malacanthoides	Sapotaceae	Lowland Rainforest
Leea	guineensis	Nyssoidites	edmontonensis	Ampellidaceae	Lowland Rainforest
Syzygium	guineense / owariensis	Syncolporites	poricostatus	Myrtaceae	Lowland Rainforest
Dipterocarpus	sp.			Dipterocarpaceae	Lowland Rainforest
Dipterocarpus	arbocarpifolius			Dipterocarpaceae	Lowland Rainforest
Dipterocarpus	sp.			Dipterocarpaceae	Lowland Rainforest
Areca	sp.	aff. Retimonocolpites	irregularis	Arecaceae (Palmae)	Lowland Rainforest
Anonidium	friesianum	Proxapertites	cursor	Annonaceae	Lowland Rainforest
Pancratium	aff. trianthum	Liliacidites	aff. nigeriensis	Amaryllidaceae	Lowland Rainforest
Knema	attenuata	Arecipites	sp.	Myristicaceae	Lowland Rainforest
Areca	sp.	Retimonocolpites	pluribaculatus	Arecaceae (Palmae)	Lowland Rainforest
Anonidium	mannii	aff. Monosulcites	magnosagenatus	Annonaceae	Lowland Rainforest
Afrosersalisia	cerasifera	Psilastephanocolporites	laevigatus	Sapotaceae	Lowland Rainforest
cf. Mezoneuron	angolense	cf. Gemmatricolpites	pergammatus	Caesalpinioidae	Lowland Rainforest
Nypa	fruticans	Spinizonocolpites	echinatus	Arecaceae (Palmae)	Tidal Estuaries / Creeks
aff. Nypa	fruticans	Spinizonocolpites	baculatus	Arecaceae (Palmae)	Tidal Estuaries / Creeks
Uapaca	acuminata			Typhaceae	Tidal Estuaries / Creeks
Amanoa	oblongifolia	Retitricolporites	irregularis	Euphorbiaceae	Riverine
Mohria	sp.	Cicatricosisporites	sp.	Schizaeaceae	Savanna
Mohria	sp.	Cicatricosisporites	sp.	Schizaeaceae	Savanna
Anemia / Mohria	sp.	Cicatricosisporites	dorogensis	Schizaeaceae	Montane Forest
aff. Isoglossa	lactea	cf. Nummulipolis	neogenicus	Acanthaceae	Montane Forest
Melia	sp.	Psilastephanocolporites	cf. laevigatus	Meliaceae	Montane Forest
Mimulopsis	solmisi	Belskipollis	elegans	Acanthaceae	Montane Forest
Nothofagus	type	Nothofagidites	sp. brassi-type	Fagaceae	Montane Forest
Podocarpus	milanjianus			Podocarpaceae	Montane Forest

Table 1. Selected palaeovegetation and phytoecological groupings of Nigeria/Niger Delta (after Adojoh and Osterloff, 2010 (proprietary); modified from Sowunmi, 1981; Morley, 1995).

2.8 Why this Study in the Niger Delta?

Given the literature review and outcomes suggested, this section highlights the important research gaps and feedback that have occurred in the past from the Niger Delta on palaeovegetation and sediment reconstructions. Despite the inevitable complexity of any review of this type, the overview provided in this thesis serves to

clearly indicate the type of research on vegetation and palaeoenvironmental change that has been in vogue in most other parts of the World.

“The major research gap observed from the literature reviewed suggests that there is no clear evidence from the Niger Delta where the hypotheses or climate drivers (ITCZ and WAM) have been applied or tested in the reconstruction of the palaeovegetation and sediment supply in relation to climate control and sea level regimes on the coastal evolution of the region during the Late Quaternary”.

The literature review has identified the above hypothesis or climate drivers and controls as an important research gap in the region: the following issues are some of the background reasons which may have previously contributed to this major research gap on the Niger Delta.

2.8.1 Access to Data

Among many reasons outlined below, it might be worth considering that one of the main hindrances for the low number of recent research projects on the Niger Delta is the discovery of hydrocarbons in 1950, which makes it a prolific region for the exploration of oil and gas by many companies. Acquiring data from this region is thus under strict confidentiality and adverse compliance is required with the oil companies, as they own the concessions in the Niger Delta region. This suggests that data accessibility for public research is restricted and proprietary to only the oil companies (Ige, 2009).

2.8.2 Confidentiality and Research Interests

In addition, some previous studies undertaken by companies whereby documented palaeoenvironmental and stratigraphic age reconstructions on the Niger Delta have been made, unfortunately have remained confidential for business purposes. For instance, the palynological age range data of the Niger Delta is of interest to most companies and some researchers have reviewed sequences extending from the Pliocene to Eocene (e.g. Morley and Richards, 1993). Most companies, and a limited number of academic researchers linked with the oil and gas

industry, focus precisely on those older ages without having interest in the Quaternary sediments (as yet not a hydrocarbon prospective interval), while it contains significant information about sedimentary processes and the factors controlling sediment depocenters (Riboulot *et al.*, 2012). Therefore, proper dating within late Quaternary sediments is still an issue.

Also, Oboh *et al.* (1992) reported that palaeoenvironmental reconstructions have so far made modest progress in Nigeria in the Late Holocene, but, apart from the published works of Allen, 1964; Oomkens, 1974; Sowunmi 1981 on the Late Holocene Eastern Niger Delta, and Ige and Sowunmi, 1997, there has been a paucity of published information on the palaeoenvironmental changes in the Niger Delta under this time frame (late Pleistocene to Holocene).

Moreover, even those few palynological studies carried out detailing Cenozoic palaeoenvironmental changes especially in the Niger Delta area, do not really tie vegetation dynamics to any controlling mechanisms owing to the confidentiality and research interest on data associated with the oil industry. Thus, for some researchers, there is still a difficulty studying the issues on the controlling mechanisms overriding the Quaternary palynological records from the Niger Delta.

2.8.3 Nature of the Environmental Settings

Unlike Eastern Africa, where numerous Rift Valley lakes, and associated anoxic environments have generated interest and attention linked with the Quaternary sedimentary infill, the Niger Delta setting (West Africa) has very few lakes or other conducive environment settings for the preservation of palynomorphs (pollen and spores). The lack of palynomorph preservation in lacustrine settings, enhances the concerns that a fully quantifiable data set may not be available for the onshore realm. This realisation leads to the examination of sediments within the end point position in the basin, through wind and riverine transport process, and then preservation within the marine realm. This may well have prejudiced research interest from some academics.

2.8.4 Right Approach to Data Application

It is suggested that conventional use of palynofloral distributions/assemblages offers key insights into palaeovegetation and palaeogeographical reconstructions from different authors (e.g. Morley, 1995, Rull, 2002, Dupont *et al.*, 2007). But, historically, a number of worldwide research programs have tested this hypothesis through different authors from academia and industry alike. They have placed pollen taxa to their correct botanical family affinities or habitat before relating the proxy to the Quaternary events. Under this evidence, in tropical settings, especially the Late Quaternary Niger Delta basin, this concept is still a fledging science and in some cases, offering conflicting evidence. Therefore, it is very significant to point out that allocating specific pollen taxa to a wrong family or habitat could affect the quantitative information and interpretation (e.g. Ige, 2009). Of course, this inevitably has consequences on researchers who are keen to undertake a rigorous research on vegetation and palaeoenvironmental change within region, thus they are somewhat sceptical to undertake such a research topic for this reason.

2.8.5 Funding and Research Support

Finally, in addition to the aforementioned factors, it is very important also to highlight that research funding is an economic issue in Nigeria. Unlike the western world where governments through Research Council funding (in the UK for example), have substantially supported individuals and different institutions in contributions to fund research, it is very much a slow process in Nigeria. In addition, some of the support provided in the past by companies and governments was not judiciously utilised for the purpose for which it was intended.

Given these insights, I am motivated to foster a research or investigate further into the coastal offshore of the Niger Delta under the proposed objectives, having obtained research funding and materials from the Nigerian Government and Shell (SPDC) respectively.

To this effect, given the above research gap and hinderances, an enumerated summary of the research questions to test the impact or the hypothesis of the climatic

drivers (ITCZ and WAM) on the vegetation and sedimentary successions of the littoral coastal margin of the Niger Delta is outlined below. Such resultant controls from climate and sea-level drivers, and vegetational ecosystem feedbacks are expected to have a direct consequence on the evolution of the Niger Delta, which seems to be the subject of an “on-going debate” among researchers for sometime now.

In line with the concise objectives and literature reviewed, multi-proxy datasets have been generated to address the following scientific questions:

- How have interactions between the position of the ITCZ and the strength of WAM migrated over the Quaternary period, aided in the understanding of both global and local control on the palynomorph records and delta evolution during the late Quaternary?
- What is the impact of climate and sea-level variations on both palynomorphs and sediment supply on the littoral coastal margin of the Niger Delta?
- How quickly did the Niger Delta evolution and biota changes response to palaeoenvironmental shifts during the time frame?

2.9 Conclusion

In conclusion, having completed the literature review and examined some of the background data available, it is clear that there is an apparent scientific research gap, for further study in this region. Given this, the study presents the first set of possible hindrances affecting or mitigating modern research in the Niger Delta region. At the same time, this also provides the relevant hypotheses to be tested over the time frame (Late Pleistocene to mid-Holocene).

In this section an attempt is being made to present relevant research questions with a view to answering those by using terrestrial and marine proxies records through examination of selected gravity cores (GC), located on the Eastern side (GC1), Central side (GC2) and Western side (GC3) of the Niger Delta respectively. This is expected to bridge the research gap and to further contribute to knowledge on the the impact of climate on the depositional coastal succession of the offshore and the surrounding environments in the future.

Chapter 3: Data Collection Techniques

Highlights

- Three gravity cores were collected in the shallow waters of the Niger Delta
- Grain size, geochemistry, and micropaleontological (foraminifera, nannofossils and palynomorphs) investigations were carried out on these three cores

3.1 Site Selection

The selection of the gravity cores (GC) was made on the basis of their transect positions (East to West) to reflect the parallel shoreline palaeoenvironmental characteristics of the littoral coastal setting of the Niger Delta. The selected GCs would be expected to reflect deltaic processes with imprints of fluvial processes, combatting tidal and longshore activities. In addition to the imprints of the marine versus fluvial dynamics, the GCs will encapsulate the changes of climate through time. The geographic limits anticipated within the cores are expected to be between the Limit Of Tidal Influence (LOTI) and Limit of Freshwater Influence (LOFI), however, other extraneous processes that contribute imprints on the sediments and microfossils arrays contained are also considered (Figure 2.11). Therefore, at the onset of this research, a set of criteria was outlined to assist in identifying potential sites. Initial selection determined that sites would be chosen within the coastal deltaic sequences of the Niger Delta which would involve tidal/wave controlled deltaic sediments that had previously been under marine control, but were now fully terrestrial or partially reclaimed as shallow coastal wetlands or near the shoreline depositional systems.

Thus, this research is directed towards presenting new methodologies that would support local and regional-scale correlation along the West African coast. In this way the appropriate application of the right research methodology becomes important to deliver against the over-riding key research objectives 1, 2, 3 and 4. These are further reiterated below:

- To develop a biostratigraphic age model for the GCs;
- To reconstruct the vegetation and deltaic shift patterns in Niger Delta during post-glacial time periods through investigation of palynomorph arrays;

- To determine and compare the timing of mangrove vegetation (*Rhizophora* sp.) expansion in relation to sea level transgression and apply the signals to a biosequence stratigraphy studies;
- To evaluate the Holocene warm climate impact on littoral vegetation for the future sustainability and management of the littoral/coastal zone of the Niger Delta.

3.2. Sampling the GCs

Three Gravity Cores (GCs) were collected by Shell Petroleum Development Company of Nigeria, having been drilled by Fugro in 2002 from the sea-bed within the shallow marine realm, at approximately 40m water depth in the Niger Delta (Figure 2.11). Each of the Gravity Cores was collected in order to gain information regarding sea-bed site suitability for future Exploration and Appraisal wells to be drilled by the same company. The spread of selected sites was to enable recognition of local changes in analytical proxies, and link more regionally across the delta from West to East.

Table 2. GCs coordinates and details

Cores	GC1	GC2	GC3
Latitude	20° 00' N	40° 00' E	30° 00' N
Longitude	20° 10" E	10° 10" E	70° 10" W
Water depth	120m	120m	120m
Length	272cm	266cm	260cm

For each GC, approximately 3m of core was collected and sampled at 2cm intervals for detailed stratigraphic, chronostratigraphic and palaeoenvironmental investigation. Each core had been pristinely preserved and was to a certain extent “water wet” on being accessed for sampling demonstrating the integrity of the core housing that kept the sediments in place/“right way up”. The applied research techniques were focused on standard preparatory and descriptive methods. These methods involved: core description, nannofossil analysis, palynological analysis, foraminiferal analysis, elemental geochemistry and grain size analysis. The palynological components for this study were analysed taking into consideration the

laboratory routines suggested for the preparation of African samples (e.g. Dupont *et al.*, 2000; Marret *et al.*, 2001; Scourse *et al.*, 2005).



Figure 3.1. Photographs of the GCs during detailed sampling, with on the left, unsliced cores, in the middle, sliced cores and on the right, the detailed sampling resolution at 2cm.

Each of the multiproxy components analysed is meant for a specific purpose under this study as stated briefly in Chapter 1 (Introduction). The palynological analysis has been the major driver of this research and this was used to derive palynological signals to interpret climate and sea level influences on the delta and palaeovegetation patterns that fed into the study location. Foraminifera and nannofossils are used to confirm the palaeoenvironments and confirm age dating of the sediment respectively; while the grain size and elemental geochemistry were to determine the energy regime and catchment of the sediment respectively.

3.3. Sample Preparation

3.3.1 Sedimentology Methods – Grain Size Analysis and XRF Techniques

Grain Size Analysis

- Each core was logged at cm-scale resolution to record grain size, subsidiary components and identification of key stratal boundaries.
- Samples were analysed at 2cm intervals for physical properties using a Malvern Mastersizer 2000 Laser Particle Size Analyser (LPSA).

- About 0.1g Sodium Hexametaphosphate was added to deionised water (10ml) and applied to both 2 sub-samples per depth measured. All vial sub-samples were then added to 1000ml within the sample unit (i.e. 0.001%).
- Sub-samples were allowed to flow in a computerized system for 90 seconds of pre-measured ultrasonic dispersion using Red laser measurements: 30000 (30 seconds) analysing replicate of 2 measurements.
- Grain Size Analysis (GSA) results consisting of clay, sand, silt, sorting, skewness, and percentiles were recorded. This thesis presents only the percentage of clay, sand and silt in order to determine energy regimes and palaeoenvironmental changes recognised across the three Gravity Cores.
- The grain size was measured at 2cm interval depending on the uniformity of the sediments.

XRF Analysis

- Samples were analysed at 2cm for chemical properties using a Bruker S2 Ranger XRF Spectrophotometer Autosampler.
- XRF analysis required the preparation of a maximum batch of 28 clean and dry pots. Nylon film is used to separate the individual pots while the base of the pots must be flat and level with no protrusions.
- 0-2cm of level sample were added to individually labelled beakers.
- The samples were compacted gently by using the brass plunger to make it firm and care was taken not to spread the dust.
- All XRF analyses were calibrated at first with a standard, and the first samples were placed in Bruker S2 Ranger XRF Spectrophotometer Autosampler. While initial samples were left running, the rest was packed waiting for the next available slots to place the pots. All recorded measurements were obtained from the saved drive of the XRF link on the desktop for graphical plots and subsequent interpretations.

3.3.2 Micropalaeontological (Foraminifera) Techniques

The preparation procedure is as follows:

- About 2.5g of material was collected for each core sample.

- Sample was soaked in a clean, dry aluminium bowl containing warm water.
- Normal procedures would be to add Sodium Hexametaphosphate to help disaggregate the sample but in most cases the sample material was quite soft and friable and so no chemicals were added.
- The samples were left for 24 hours to enable the sample to disaggregate as completely as possible.
- The disaggregated sample material was washed through a 63µm sieve to wash away the coagulated particles. The fine residues were placed on the filter paper to let the water soak away.
- The finer residue of each sample in the filter paper was placed in an aluminium bowl and kept in the oven to dry at 40°C for 24 hours. Once the sample was fully dried, it was weighed and then sieved through 250, 125 and 63 µm fraction sieves respectively.
- The remaining residues were placed in separate plastic vials and marked with the size fraction.

Analysis

- Micropalaeontological analysis was undertaken for each size fraction. For most samples, fewer than the required minimum 250 specimens were picked using an eyelash sable brush under a binocular microscope. It is acknowledged that this specification (250 species count) is below the standard suggested by Smart (2002). All the picked foraminifera were mounted on gummed micropalaeontological grid slides (Chapman Slides).
- Detailed identification of foraminiferal species was undertaken using a Scanning Electron Microscope (SEM) by mounting each specimen stub with a double sided sticker and coated twice with gold.

3.3.3 Calcareous Nannofossil Techniques

- Thirty samples (10 each) were selected from each of the GCs for the nannofossil preparation adopting the pipette and smear methods.
- During these preparations, precautions were taken during all stages to avoid contamination, be it mud or cross-sample contamination. A standard preparation required 30g of sample, but this study used 5g because other analysis undertaken in this study required more grams of samples for their preparation.

Analysis

- Following the routine procedure of Harland *et al.* (1989), the samples were disaggregated using distilled water.
- To ensure an even distribution of particles in the final mount, a small quantity of Sodium Hexametaphosphate was added to disperse the clay content.
- A glass pipette was used subsequently to draw suspended liquid from beakers which were then carefully pipetted onto glass cover slips (22mm x 22mm).
- After a while, little drops of distilled water were added to the dilute suspension and then dried on a hot plate.
- Due to the presence of the dispersed clay content on the slide, a clean mount of two drops of Norland Optical Adhesive (index~1.56) were placed on the glass coverslips, followed by inverting over the glass slides to enable the adhesive to spread uniformly.
- Once adhered, and dry, the glass slides were then analysed under the microscope.
- The numerical count obtained from each identifiable species were recorded to establish the stratigraphic datum (First and Last Appearance Datum).

3.3.4 Palynological Techniques

A first batch of samples (15 in total, five from each core) were prepared at the British Geological Survey (BGS) as there was no palynological laboratory set-up at the University of Plymouth where this PhD study commenced. However, the processing method at the BGS included fractionated sieving at both 10µm and 20µm mesh sizes,

which is not suitable for Low Latitude Tropical Pollen (Africa) analysis. Therefore, all remaining samples were prepared at the University of Liverpool, using routine processing techniques adopted from Scourse *et al.* (2005).

Prepared samples were analysed to establish the variety and abundance of palynological components (sporomorphs, palynodebris, non-palynomorphs, etc.). Initial preparation procedures of the samples were as follows:

- An unknown volume of wet sediment was oven-dried at 40°C overnight and was weighed.
- Dry sediments were placed in the test tube vials with distilled water and one tablet of exotic marker (*Lycopodium clavatum*) added to estimate palynomorph concentrations.
- The samples were sieved at 100µm to remove broken shells, coarser particles, contaminants such as plastic housing, and later centrifuged and decanted.
- Small amount (~10 to 15ml) of cold 10% hydrochloric acid (HCl) was added to the sieved material to dissolve the carbonate component. This was left for 20 minutes.
- The residue was decanted and neutralised ready for the HF. Cold 40% hydrofluoric acid (HF) was added to the test tube vial and left for 24 hours to dissolve the silicate component.
- The residue was rinsed in distilled water, separated through centrifuging, decanted and treated with a small amount (~10 to 15 ml) cold 40% hydrofluoric acid (HF) was added to the test tube vial and left overnight (12 hours) to dissolve the silicate material.
- This process was repeated every 20 minutes with HCl-HF repeated cycles, whilst Sodium Pyrophosphate was added to remove the sand and liberate the clays respectively.
- The final residue was treated with heavy liquid (Sodium Polytungstate; density of 2.4g/cm³) to separate palynomorphs and non-palynomorphs from the residue.
- Two drops of phenol in the remaining fractions were added to avoid bacterial degradation.
- Sieving using a 5µm mesh was adopted to ensure capture and retain of small tropical pollen, as well as the key mangrove indicator *Rhizophora*.

- The final residues were placed in small vials, with a small amount of glycerin jelly added, and then centrifuged to homogenise the residue.
- Each sub-sample of the residue was placed on a microscope slide and covered with a cover-slip and sealed with Cotex wax (Hair wax) to prevent drying out of the mounted residue.
- Finally, the slides were mounted on the microscope stage and where possible, a minimum of 300 palynomorphs and 120-200 mangrove taxa were counted on 400X magnification for the quantitative interpretation.

3.4 Palaeovegetation Diagrams and Statistical Analysis

Two statistical palynological models were adopted for the interpretation of pollen data, namely: Palaeovegetational and Tidal Limit Index. The former is the ratio between the scores of two major principal groups representing different vegetation types (Rull, 2002). These were re-modified in the present studies to reflect littoral and hinterland vegetation changes influenced by the climate and sea-level change. To establish these indices, Tilia Version 1.7 and CONISS (*sensu* Grimm, 1987) were used to plot possible vegetation groups that supported the validity of their theoretical foundation applied in the Gravity Cores.

Statistical analysis involves the quantitative counting of the pollen to attain 300 counts for a complete coverage. This was undertaken by adopting Constrained Cluster Analysis (through CONISS) and percentages to confirm a palynomorph zonation. In addition, concentration and fluxes of each basic sum from the total sporomorphs (after Alexandre *et al.*, 1997) were counted and calculated. The total sum includes all pollen taxa (e.g. Mangrove and Lowland Rainforest pollen). In this study concentration is expressed using the formula below:

$$\left(\frac{N \text{ species counted} \times N \text{ Lycopodium spores added}}{N \text{ Lycopodium spores counted}} \right) \times \text{sediment weight}$$

Where N = number or count of the species

3.5 Palynological Grouping / Analysis

This study adopts species grouping into their family/botanical affinities after the promulgation and deliberation sequel to the last International Palynological Conference, Tokyo (IPC, 2012). Due to the high diversification and complex nature of low latitude tropical pollen research in palynology and palaeobotany most researchers adopt grouping of species into their family affinity in order to reflect its vegetational and ecological dynamics rather than assuming a species entity based on their morphology alone.

Therefore, this study adopted this method to avoid any potential wrong assignment of any identified pollen to an incorrect ecology or vegetational group due to their extensive diversity and complexity as stated in Chapter 2. In essence the pollen were first grouped in line with correct morphological parameters to allow assignment with correct family or botanical affinity (e.g. Rull, 1998; Fletcher, 2005; Gosling *et al.*, 2013) before linking their interpretation to develop models concerning prevailing palaeoenvironmental change.

As an aside, industrial applications, in most cases, adopt the morphological identification because of the demand for quick results to meet client and company business protocols during and after drilling activities. This quick demand without adopting both morphological and botanical classification of pollen has in some cases created a negative impact on many servicing companies for the interpretation of some basins.

From the academic perspective, in alignment with IPC (2012) and others (e.g. Rull, 1998; Fletcher, 2005; and references cited in Appendix 1), adopting both the morphological and botanical (family) classification suggests that different taxa in the same family may occur in more than one vegetation group/sub-group. For example (see tables 1 and 4.6).

Given the above, this study identified each species based on the morphological description before linking the same species to its family/botanical affinity to reduce the potential ambiguity arising from the industrial and academic understanding of different

species concepts and origins. For more clarification on this grouping/species naming convention and application refer to Appendix 1.

3.6. Conclusions

- In conclusion, the adopted techniques in this section provide a general focus on how the multiple proxies were analysed and mapped into the objectives of this study.
- Nannofossil techniques will provide data to let us define a biostratigraphic age definition for the Gravity Cores.
- Palynological techniques will provide data that will help us to establish palynomorph habitat records for the reconstruction of vegetational change and to determine different control (s) driving the ecological succession of the Niger Delta.
- Elemental geochemistry and grain size analysis techniques will provide data that allow us to interpret the relationship from the surrounding catchment in which the pollen is concentrated.
- Finally, foraminiferal studies will provide data in combination with geochemistry and pollen data to aid in the establishment and understanding of the shift in the depositional environment during the last post-glacial period (Late Quaternary). For further information on the data obtained or collected from the Gravity Cores using the analytical techniques and family/botanical affinity (See Appendix 1).

Chapter 4: Dating Techniques: Biostratigraphic Records

Highlights

- Foraminifera (*Globorotalia truncatulinoides* and *Globorotalia tumida* and nannofossil (*Emiliana huxleyi* and *Gephyrocapsa oceanica*) occurrences in the three GCs enabled to establish a stratigraphical framework
- The three cores recovered the late Pleistocene (~20/ ~20 ka) to mid-Holocene (~6.5ka) time span
- These results enabled the development of an age model (depth/age related) and sedimentation rates at different depths

4.1 Introduction

The importance of an age/depth model in any stratigraphic study, especially when working in the Quaternary, cannot be over-emphasised. Once the age coverage has been calculated from the individual depth/interval, the next stage is to produce age appraisals for all the depth/intervals in the depositional sequence (Blaauw, 2010). This is usually achieved through the modelling of the accumulation rates within the stratigraphic sequences. Most methods for age modelling are dependent on the depositional environment and the dating method used. For instance, sediments deposited in a stable or quiet environment will possibly have accumulated with low number of sedimentary breaks or accumulation rate changes, compared to one from an unstable environment which is more likely be modelled by applying a smoothing age/depth model (Bennett, 1994). Most authors apply radiometric dates to stable environments (because of better stratification), whereas some other authors adopt biostratigraphic methods to environments which are thought unstable (faunally demonstrating depositional hiatus) (Bennett, 1994).

Therefore, palaeoenvironmental reconstructions from the Late Pleistocene to mid-Holocene of the coastal offshore Niger Delta rely on an appropriate method of dating because of the nature and complexity of this region. Given the above conditions, this study found it suitable and important to develop a biostratigraphic age model for the Gravity Cores as one of the main objectives of this study. In addition, to build a conceptual understanding of the remaining four aforementioned objectives in Chapter 1, a chronostratigraphic framework is first required. It becomes necessary to develop

a chronostratigraphic framework by assigning a biostratigraphic age for each sample within the three cores.

There are several different methods which can be applied to assign a chronology. The method chosen depends upon the time-frame which is to be studied, the depositional setting, and depth of coring, sedimentation, bioturbation, tectonic, material availability and structural deformation of the setting. This requires the interpolation of disparate discipline age data to produce a distinctive age-depth relationship for each sample interval depending on the prevailing condition affecting the dating technique (Miller, 2011).

Given this, the following dating methods are used in this study: Foraminifera and nanofossils. Difficulties are associated with each method and each has inherently different margins of error associated with them (Sowunmi, 1981; Gehrels, 1999). This study has considered biostratigraphic method for many reasons stated above. Among the reasons stated above, the key issue of inavailability of monospecific planktonic foraminifera / broken shells in the samples hindered radiometric or isotope dating. Under the broad context of age dating, the aim or application of the biostratigraphic approach is to recognise and apply fossil occurrences present in the samples to establish relationships between time-equivalent rock strata and apply a stratigraphic surface correlation.

Moreover, widespread taxa or distributions enable subdivision and correlation of lithostratigraphic successions over wider regions (Bralower *et al.*, 1995; Sandberg and Ziegler, 1996). The concept is generally straightforward, i.e. the occurrence of a particular fossil species in two geographic areas shows that the rocks comprising the fossil specimens were deposited at about the same time. Furthermore, the shorter the time-range existence of a particular species, the greater the resolution of stratigraphic correlation (i.e. potential diachroneity is reduced).

In the present study, the main traditional biostratigraphic microfossils forms were considered (foraminifera, nanofossils, and palynology) for age correlation. Clearly, benthic and nektonic planktonic fossil forms can be used to establish relative biostratigraphic age zonation in the marine setting, but pollen and spores are more effective at establishing age zonations in the terrestrial environment.

Given this condition, this study adopts usage of the foraminifera and nannofossils biostratigraphic methods for the age evaluation of the Gravity Cores. After careful consideration, the palynological dating method was not considered because most of the pollen species identified were thought to be non-time bound marker species analysed from thirty samples (ten from each core). They are stratigraphically ubiquitous (found everywhere) and not viable for succinct age dating. For example, *Verrucatosporites usmensis* (Polypodiaceae), *Stereisporites* sp., (Sphagnaceae), Poaceae, and *Zonocostites ramonae* (Rhizophoraceae) amongst others, are considered not useful for accurate age dating (Morley and Richards, 1993).

Furthermore, apart from the reason stated above, palynology (pollen and spores) among the dating methods is generally unsuccessful and difficult in dating sediments older than mid Pleistocene, considering the regional and global chronostratigraphic chart evaluated (Adeonipekun *et al.*, 2015). No cogent explanation was stated in this regard. Although, palynology is the major proxy designed for this study, because it is not quite suitable for succinct age dating of Late Quaternary sediments, foraminifera and nannofossil methods were further analysed. Thus, the procedures and methods adopted for accurate biostratigraphic dating from these microfossils are discussed below.

4.2 Biostratigraphic Dating Methods

First Appearance Datum (FAD) and Last Appearance Datum (LAD) of fossils are conventionally used for establishing a stratigraphic framework for any given sedimentological record that contains suitable biostratigraphic markers. With regards to the studied cores here, FOC (First Occurrence) is defined as the precise depth interval in which the marker species first appeared in the Gravity Core (from the bottom up-ward, i.e. its recorded inception in the cored-sequence), whereas LOC (Last Occurrence) is the last depth/interval appearance of the same marker species, working from bottom to top, highlighting its apparent extinction within the cored interval. FOC and LOC will be then correlated with the known FAD and LAD of a number of foraminifera and nannofossils in order to establish an age model for each core when applicable.

4.2.1 Foraminifera

Unlike benthic foraminiferal forms, planktonic foraminifera have been applied globally for dating Quaternary sediments. The marker species were considered more relevant for dating of marine sequences due to their wide palaeogeographical distributions. Planktonic marker species (that float and live in the surface water of the oceans) are preferred for age dating because they are widely distributed independent of the type of seafloor sediment, unlike the benthic (seafloor) species which are restricted to particular bottom sediments (Murray, 1991). In this study, though the planktonic foraminifera were considered relevant for dating because the quantity is sufficiently of standard for biostratigraphic dating, however, the required quantity for radiometric dating was below the standard because monospecific species were in low numbers. This situation is not only peculiar to this study, but previous studies in the Niger core (GeoB 4905-4), also had difficulties in obtaining enough quantity of planktonic foraminifera for monospecific AMS and radiometric dating as well (Kim *et al.*, 2010). This is because the study locations are positioned in the shallow marine realm not deemed to have enough recovery of planktonic foraminifera for isotope studies because the environmental conditions resulting from fresh water dilution of River Niger and its tributaries are prejudicial (Bankole *et al.*, 2014; Adeonipekun *et al.*, 2015).

In detail, foraminiferal marker species were analysed from 60 samples (twenty from each of the cores). Careful analysis of the species observed from both the benthic and planktonic foraminiferal of GCs shows favourable preservation from four to ten (10) samples from each core (Tables 3.1-3.3). The benthic forms are few in number, with with morphology prejudiced by preservation.

Among the planktonic foraminifera marker species present in the lower parts (bottom) of each of the gravity core is *Globorotalia* spp. which was noted as a genus has been used to date the Late Quaternary sedimentary succession locally and globally (Murray, 1991). *Globorotalia truncatulinoides* and *Globorotalia tumida* evolved in the latter part of the Late Pleistocene and mid-Holocene respectively in the Gulf of Guinea and other representatives extend to mid-Pleistocene in the Mediterranean region (Cita, 1975) (Appendix 1; Plate C). The following bullet points outline the steps

that have been taken to define a planktonic biostratigraphic age model for the three Gravity Cores:

- An attempt was made to utilise *Globorotalia* forms analysed from the planktonic foraminifera spectrum, i.e. those forms related to *Globorotalia truncatulinoides* and *Globorotalia tumida* were considered to offer the highest value for age dating amongst the species identified (Figures 4.1-4.3). Concurrent occurrence of *Globorotalia tumida* in tropical regions in relation to *Globorotalia truncatulinoides* for dating Middle Holocene sediments has made it possible to combine the two marker species for dating (Kennett and Srinivasan, 1983).
- The figures below obtained from the data tabular representation show how the key biostratigraphic datum was established for this study on the basis of the FOC and LOC of the marker species that have been identified from the three Gravity Cores (Figures 4.1-4.3).
- A standard reference count was adopted, whereby quantities of >30, but <50 individual marker species were recovered to define the datum and age range for the sections analysed (Figures 4.1-4.3) (Tables 3.1-3.3).
- An age range stratigraphic chart distribution of each marker species was erected based on the quantitative counts and tabulated depth from the Gravity Cores to determine the age zonation below (Figures 4.1-4.3).
- The fairly rich and diverse planktonic marker species observed at the different intervals across the three cores allows them to be easy cross-referenced to worldwide applicable schemes (Saito, 1962; Banner and Blow, 1965; Cita, 1975; D'Orbigny, 1983; Berggren *et al.*, 1995a; Mikkelsen *et al.*, 1997; Niger Delta Consortium, 2000 (Figures 4.4-4.5).

Dating from the lowermost parts of the GCs using Planktonic Foraminifera (Bottom)

Stratigraphic Intervals and Remarks: Similar and different depths at bottom of GCs (1, 2 & 3) were sampled and analysed for foraminiferal dating respectively (Tables 3.1-3.3). The figures 4.1-4.3 summarise the intervals and the corresponding bioevents abundant distributions of each marker species. These intervals are marked by the LOC and FOC of the marker species *Globorotalia truncatulinoides* (Figures 4.1-4.3). The

intervals (bottom) (200-202cm, 224-226cm, 258-260cm, 264-266cm, 270-272cm) were dominated by *Globorotalia truncatulinoides* as defined by Cita (1975); Mikkelsen *et al.*, 1997; Niger Delta Consortium, 2000 in presumed relationship of the event relative to the publications of the global standard zonation (Figures 4.4, 4.5). Therefore, the absence of the *Globorotalia tumida* at these intervals/depths in Figures 4.1-4.3 indicates that the base of the three GCs does not exceed the Late Pleistocene in age (20-11 ka) (Stefano, 1998).

Dating from the middle parts of the GCs using Planktonic Foraminifera

Stratigraphic Intervals and Remarks: A range of sample interval depths were studied from the middle of the three gravity cores (Tables 3.1-3.3). The depths relate to roughly the intervals ranging (38-40cm, 68-70cm, 140-142cm, 182-184cm). Within these intervals the FOC and LOC of species *Globorotalia tumida* is recorded. The absence of *Globorotalia truncatulinoides* in Figures 4.1-4.3 indicates that within the middle of the three cores the age does not exceed Early Holocene (11-8.5 ka) based on reference to Saito, 1962; Banner and Blow, 1965; Cita, 1975; Berggren *et al.*, 1995a) Mikkelsen *et al.*, 1997 (Figures 4.4, 4.5).

Dating from the topmost parts of the GCs using Planktonic Foraminifera

(Uppermost)

Stratigraphic Intervals and Remarks: The following intervals within the uppermost sections of the cores have been analysed (0-2 cm, 28-30 cm, 30-40 cm) (Tables 3.1-3.3). Within these intervals the LOC of the marker species *Globorotalia tumida* is recorded. The absence of *Globorotalia truncatulinoides* within the uppermost part of the three cores in Figures 4.1-4.3 indicates that a mid-Holocene age is not exceeded, but constrained to 8.5-6.5 ka when in reference to previous authors, (e.g. Cita, 1975; Niger Delta Consortium, 2000; Berggren *et al.*, 1995a); Mikkelsen *et al.*, 1997 (Figures 4.4a-b).

4.2.2. Nannofossils

To cross-verify and provide a robust biostratigraphic age-model for the three cores, calcareous nannofossils were used in conjunction with planktonic foraminifera. The present study found that calcareous nannoplankton are well preserved within the three Gravity Cores. Analyses of nannofossils from 10 samples were selected at 2cm from the top to the bottom of the GCs (Tables 3.1-3.3). The results of the calcareous nannoplankton recovery in terms of abundance and diversity strongly mirrors that as determined through the planktonic foraminifera. In light of the above, a robust age model is established based on four globally recognised nannofossil marker species. These are: *Gephyrocapsa oceanica* <3µm in size = (NN19); *Helicosphaera sellii* and *Reticulofenestra asanoi* = (NN20); and *Emiliania huxleyi* = (NN20 & NN21) particular age-reference sub-species (Appendix 1, Plate B). However, because the occurrence of *Gephyrocapsa oceanica* <3µm in size and *Emiliania huxleyi* are very dominant in most sediments during the latest Quaternary, this study considered specifically their application for dating the cores in light of global application (Rio *et al.*, 1990) (Figure 4.4). Thus, based on the standard zonation format of the common occurrence of each marker species, this study defined a Late Pleistocene to mid-Holocene age model for the cores on the basis of the FOC and LOC of the abundance of *Gephyrocapsa oceanica* <3µm and *Emiliania huxleyi* (increasing in abundance up-hole) (Figures 4.1-4.3).

To enable direct comparison between the age model derived from this study and the globally applied zonation scheme (Figure 4.4) this study adopted the biostratigraphic classification scheme applicable in the “tethyan” Mediterranean record using calcareous nannofossils. This is because most widely published nannofossil biostratigraphy has been more successive and comprehensively recorded within the region compared to other settings across the World (e.g. Raffi and Rio, 1979; Rio *et al.*, 1990) for Late Pleistocene and mid-Holocene aged sediments in the Gravity Cores (Figure 4.4). The following are the steps taken to define the biostratigraphic age model for the three cores based on a nannofossil approach:

- A total of 30 samples, i.e. 10 for each GCs were analysed for age dating based on a semi-quantitative method to confirm their reliability for further detailed age determinations.
- Quantitative format for assigning the markers species to the three GCs were considered similar to those applied for planktonic foraminifera dating. This format is as follows: Few/Rare (5 - 7 species); Common (15 - 16 species); Abundant (30 - 50 species) (Tables 3.1-3.3).
- Some authors use the relative size changes of specimens encountered and abundance of marker species to delineate the Pleistocene–Holocene boundary (e.g. Stefano, 1998 studies in the Mediterranean region). In the mid-Holocene, abundant increase in “*Emiliana huxleyi* Zone” is noticed to increase up-hole which may correspond to that of the (I assume here) *E. huxleyi* Zone of Gartner, 1977.
- This study adopted the approach of dating by using the size of *Gephyrocapsa oceanica* <3µm in size and *Emiliana huxleyi* (increase in abundance up-hole) to establish the Late Pleistocene and mid-Holocene respectively.
- Absence of large *Gephyrocapsa oceanica* >3/4µm in size and increase abundance of *Emiliana huxleyi* up-hole was used to delineate the bottom and topmost part of the GCs respectively (Tables 3.1-3.3). This suggests that there is a potential temporal relationship that allows this study to make a statement about the ages of the three cores, both at the base and the top of the sections studied.
- The interpretation and implications of nannofossil dating of the GCs are described below on the basis of the First and Last Occurrences by defining the stratigraphic occurrence distribution of each potential “marker” species (Figures 4.1-4.3).

Dating from the lowermost parts of the GCs using Calcareous Nannoplankton (Bottom)

Stratigraphic Intervals and Remarks: Similar and different depths ranges of the cores were sampled and analysed for nannofossil dating (Tables 3.1-3.3). The LO and FO of *Gephyrocapsa oceanica* <3µm in size is defined in each of the cores, whilst the

lowest occurrences of *Helicosphaera sellii* and *Reticulofenestra asanoi* was fairly represented within the lowermost intervals of each of the cores studied (Figures 4.1-4.3). These intervals (182-184 cm, 200-202 cm, 224-226 cm, 258-260 cm, 264-266 cm, 270-272 cm) are dominated by *Gephyrocapsa oceanica* <3µm in size as defined by Martini, 1971, relating to the NN19 Zone (Figures 4.1-4.3). Therefore, the absence of large *Gephyrocapsa oceanica* >3/4µm and *Emiliana huxleyi* at these levels suggests that the base of each of the three cores is not older than Late Pleistocene (Figures 4.4, 4.5).

Age : Late Pleistocene (20-11 Ka)

Nannofossil Zone : NN19

References : Raffia *et al.*, 2006; Martini, 1971

Dating from the middle parts of the GCs using Calcareous Nannoplankton

Stratigraphic Intervals and Remarks: In similar fashion, the following intervals/depths were analysed from the middle of the three cores (38-40 cm, 68-70 cm, 140-142 cm) (Tables 3.1-3.3). These intervals are highlighted by the notable range appearance of *Emiliana huxleyi*, whereby within the interval a gradual quantitative increase and slight decrease are recorded and replicated. Occurrences of *Helicosphaera sellii* and *Reticulofenestra asanoi* were also fairly well represented within these depth ranges as well (Figures 4.1-4.3). The absence of *Gephyrocapsa oceanica* <3µm in size indicates that the middle part of the three cores are not likely to be older than Early Holocene (Figures 4.4, 4.5).

Age : Early Holocene (11.-8.5 Ka)

Nannofossil Zones: NN 20 (NN 21 - other authors such as Stefano, 1998)

References : Emiliani and Shackleton, 1974; Castrodiri, 1993

Dating from the topmost parts of the GCs using Calcareous Nannoplankton (Uppermost)

Stratigraphic Intervals and Remarks: The following intervals from the uppermost parts of the cores (0-2 cm, 28-30 cm, 38-40 cm) were analysed (Tables 3.1-3.3). Within these intervals, the first down-hole common occurrence of marker species *Emiliana*

huxleyi is significant and increase up-hole when compared to the middle part of the cores (Tables 3.1-3.3). In addition, occurrences of *Helicosphaera sellii* and *Reticulofenestra asanoi* were fairly well represented as well (Figures 4.1-4.3). The absence of the *Gephyrocapsa oceanica* <3µm in size within the uppermost part of the three cores indicates that a mid-Holocene age is not exceeded (Stefano, 1998) (Figures 4.4, 4.5). The age range of *Gephyrocapsa oceanica* in European and Mediterranean regions may extend to the Early Holocene, but study from the Gulf of Guinea suggests this to be Middle Holocene (Niger Delta Consortium, 2000).

Age : mid-Holocene (8.5-6.5 Ka)

Nannofossil Zone : NN 21

References : Raffia *et al.*, 2006; Martini, 1971

In combination with the planktonic foraminifera, the fairly rich and diverse calcareous nannofossils observed at the different intervals across the three GCs were constrained based on the world-wide applicable generic zonal schemes of Martini (1971), Okada and Bukry, 1980; Rio *et al.*, 1990; Castradori, 1993; Yildiz *et al.*, 2003, Backman *et al.*, 2009 (Figure 4.1).

4.3. Global chronostratigraphic scheme correlation with the combination of the two biostratigraphic dating methods of this study (GCs)

The combination of an integrated biostratigraphic age framework (using both planktonic foraminifera and calcareous nannoplankton) has demonstrated a sufficient degree of precision to apply reliable age dates in this study (Figure 4.5). The similarity of the correlated markers species and stages in the chronological framework below suggests a strong age relationship between the GCs and other referenced locations, locally within the Niger Delta setting, and more globally to the Mediterranean region. The link between the local age model presented here for the Niger Delta, and the global models, offers a level of confirmation for dating the mid-Holocene to Late Pleistocene sedimentary succession of the Niger Delta through analyses of the Gravity Cores. (Figures 4.4, 4.5). The outcome of this combination confirms that similar age connotations derived from both applied disciplines (foraminifera and nannofossils) using main marker species could be established (Figures 4.1-4.3, 4.5).

Table 3.1. Biostratigraphic Quantitative counts of Nannofossils and Planktonic foraminifera for GC1. **Note:** Between 0-40 cm is increasing up-hole (*Emiliana huxleyi*) for the three GCs, column with “G” (*Globorotalia*) represents the foraminiferal count for the GCs.

Depth (cm)	<i>E. huxleyi</i>	<i>G. oceanica</i>	<i>H. sellii</i>	<i>R. asanoi</i>	<i>G. tumida</i>	<i>G.truncatulinoides</i>
0-2	50	0	0	0	35	0
28-30	45	1	4	0	0	0
38-40	42	0	2	3	40	0
48-50	32	0	0	0	0	0
68-70	0	0	3	4	0	0
140-142	36	2	0	14	41	4
182-184	0	35	0	10	0	35
202-204	0	34	0	0	0	0
224-226	0	40	5	0	0	40
270-272	0	38	0	3	0	47

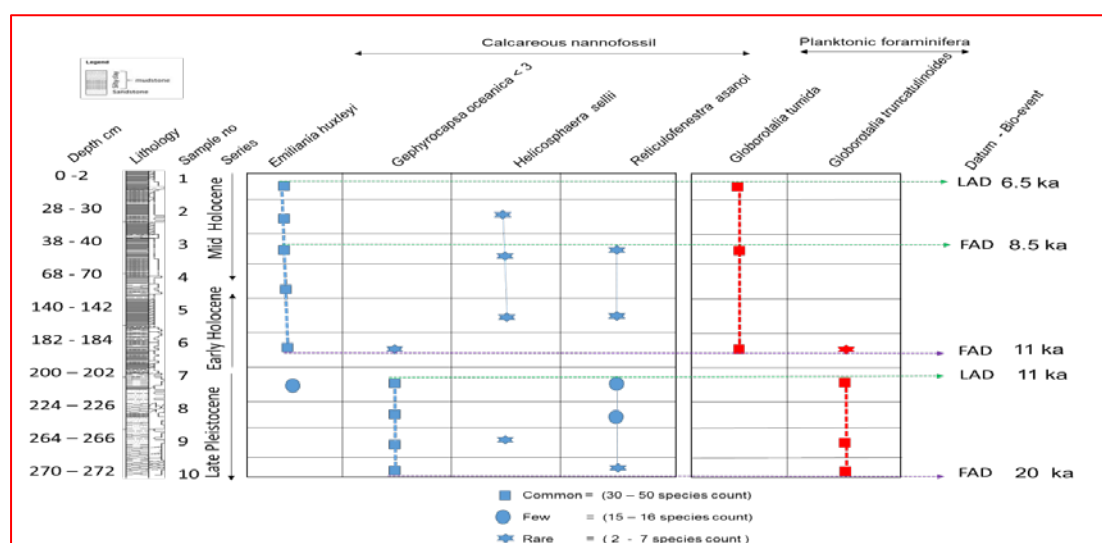


Figure 4.1. Distribution of the calcareous nannofossil and planktonic foraminiferal markers species in the GC1 and its estimated biostratigraphy. **Note:** Between 0-40 cm is increasing upwards (*Emiliana huxleyi*) for the three GCs.

Table 3.2. Biostratigraphic Quantitative counts of Nannofossils and Planktonic foraminifera for GC2.

Depth (cm)	<i>E. huxleyi</i>	<i>G. oceanica</i>	<i>H. sellii</i>	<i>R. asanoi</i>	<i>G. tumida</i>	<i>G. truncatulinoides</i>
0-2	48	0	0	0	35	0
28-30	46	0	0	0	40	0
38-40	40	0	2	3	44	0
48-50	31	0	0	0	0	0
68-70	0	0	2	4	0	0
140-142	33	4	4	0	0	0
182-184	0	35	0	10	35	0
200-202	0	32	3	11	0	42
224-226	0	40	0	2	0	45
264-266	0	38	0	0	0	40

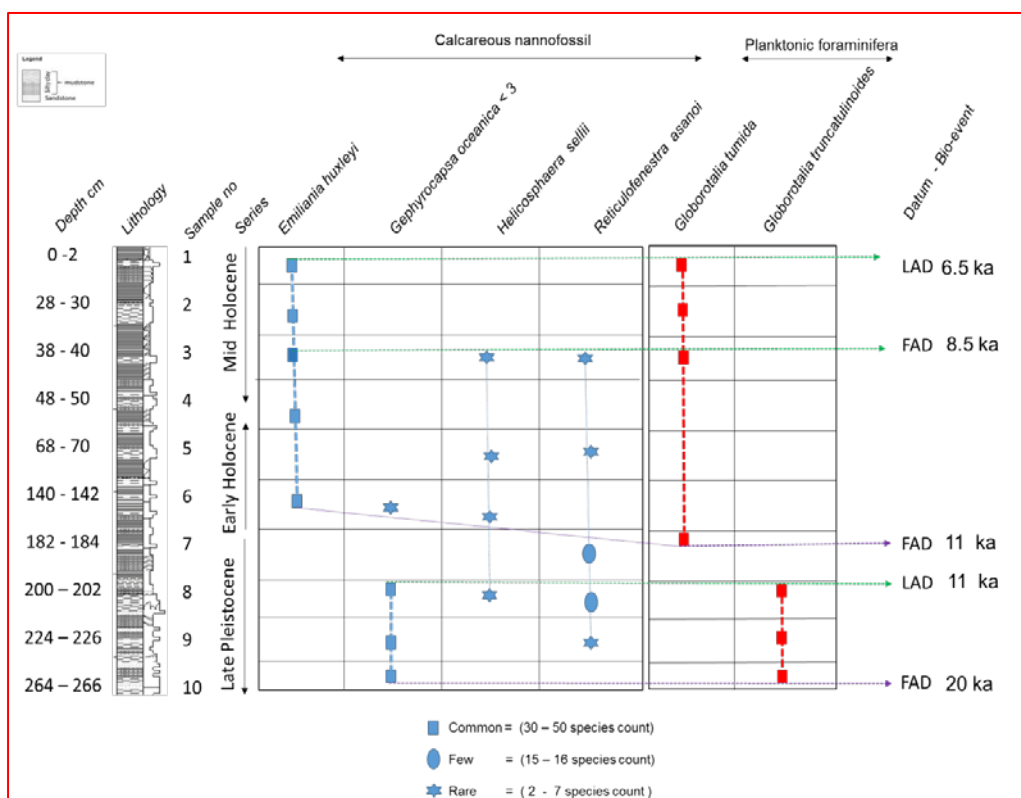


Figure 4.2. Distribution of the calcareous nannofossil and planktonic foraminiferal markers species in the GC2 and its estimated biostratigraphy. Legend same as in figure 4.1.

Table 3.3. Biostratigraphic Quantitative counts of Nannofossils and Planktonic foraminifera for GC3.

Depth (cm)	<i>E. huxleyi</i>	<i>G. oceanica</i>	<i>H. sellii</i>	<i>R. asanoi</i>	<i>G. tumida</i>	<i>G. truncatulinoides</i>
0-2	47	0	0	0	32	0
28-30	46	0	0	0	32	0
38-40	43	0	2	0	34	0
48-50	3	11	11	13	0	0
68-70	34	0	3	3	0	0
140-142	37	3	4	0	0	0
182-1847	4	36	0	14	36	0
200-202	0	46	0	10	0	32
224-226	0	40	13	3	0	34
258-260	0	35	0	0	0	35

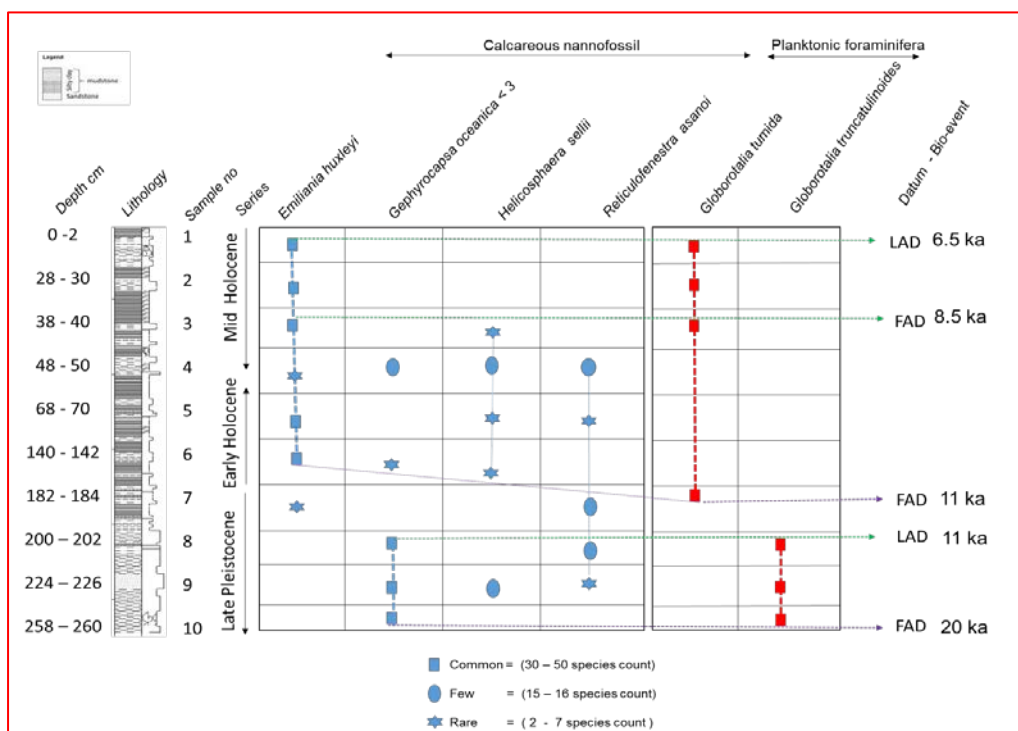


Figure 4.3. Distribution of the calcareous nannofossil and planktonic foraminifera markers species in the GC3 and its estimated biostratigraphy. Legend same as in figure 4.1.

Chrono-stratigraphy	Martini (1977), Emiliani & Shackleton, 1974		Bukry and Okada, 1980; Rio et al., 1990		Stefano, 1998; Raffia et al., 2006		Backman et al., 2009, Niger Delta, 2000		This study (Niger Delta)		Age (ka)		Bioevent		MIS			
Holocene	Late	MN21 E. huxleyi LO	MNN 21b									(0)ka						
	Middle	MN21 E. huxleyi FO	E. huxleyi LO	NN21	E. huxleyi LO	NN21	E. huxleyi LO	NN21	E. huxleyi LO	E. huxleyi LO		(6.5)ka	LAD				1	
		Early	MN20 E. huxleyi FO	MNN 20a	E. huxleyi FO	NN20	E. huxleyi FO	NN20	E. huxleyi FO	E. huxleyi LO		(8.5)ka						
Pleistocene	Late	MN19f R. asanai G. Oceanica <3 FO	MNN 19f	G. Oceanica <3 FO	NN19	H. Sellii LO G. Oceanica <3 FO	NN19	R. asanai G. Oceanica <3 FO	NN19 G. Oceanica <3 FO		(11.7)ka		FAD					2
	Middle	MN18-16 H. Sellii LO	MNN 18-16a	H. Sellii LO	NN 18-17	G. Oceanica >4 FO (large)	NN 18-17	G. Oceanica >4 FO (large)	NN 18-17	G. Oceanica >4 FO (large)		(24)ka						

Figure 4.4. Correlation of the global nannoplankton age zonation with the GCs age constrained and the marine isotope stages (MIS). MNN = Mediterranean Nannoplankton, FOC = first occurrence, LOC = last occurrence, FAD = first appearance datum and continuous occurrence, LAD = last appearance datum and continuous occurrence.

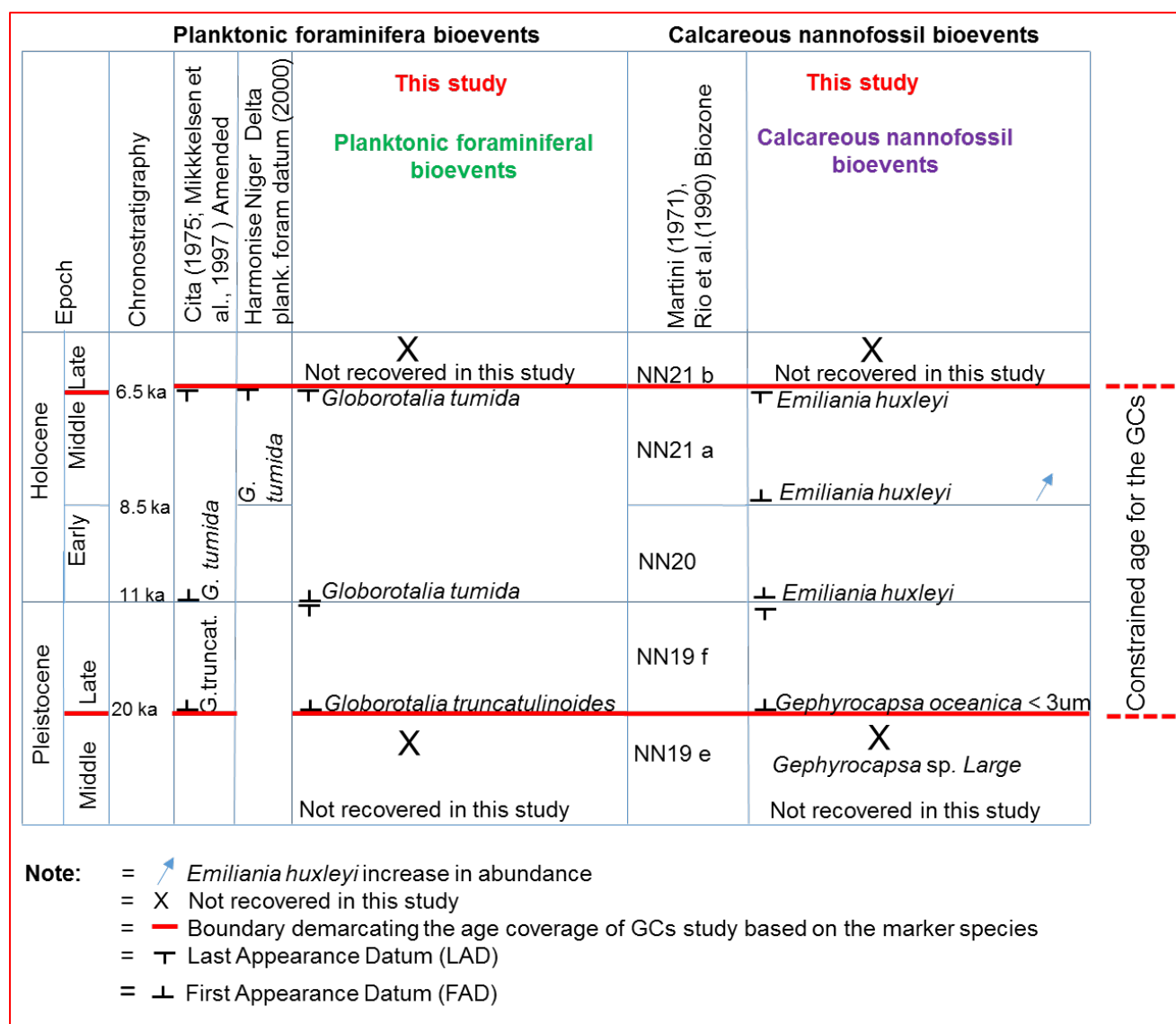


Figure 4.5. Age model constrained for the three GCs based on planktonic foraminiferal and nannoplankton marker species. This is placed in context with globally-defined zonations.

4.4 Plots of FADs / FOC on each GC vs. regional / global sea level curves

The Niger Delta stratigraphic and depositional complex is less structured than the Amazon and Mississippi fans as its terrestrial sedimentation has been continuous, unlike the “on/off” glacial-interglacial sedimentation on the Amazon Fan and sedimentary sequences. In contrast, the Niger Delta seems to be constructed entirely by turbidite facies thereby making it difficult to define exact biostratigraphic datums (FOC) at bottom of most wells or cores drilled (Allen, 1965).`

However, given that such definition can be accomplished through successive reconstructions using sea-level curve, this section adopts this principle in order to estimate the age of the bottom of the GCs which coincides approximately with 20ka / and 11ka using the available data.

In order to instil more confidence in the First Occurrence (FOC) Datum of each marker species in the GC, an additional constraint is applied through using both aspects of regional and global sea level curves of Peltier (1994) and Fleming *et al.* (1998). Given that the apparent depth of the gravity cores was 120m below the sea level surface when the sea level was low, and at 40m when the sea level started to rise, it becomes reliable to history match the given dates at 20Ka and after (11Ka) using the FOC of the following marker species:

- *Gephyrocapsa oceanica* / *Globorotalia truncatulinoides* at the bottom of each GC at approximately 20Ka or 21Ka (Blue line arrow) and;
- *Emiliana huxleyi* / *Globorotalia tumida* at 11ka (Red line arrow) respectively based on their correspondence with the altitude of the two standard regional and global sea level curves plotted in relation to the timing of each FOC of the marker species below (Figures 4.6a, b).

There are two distinct phases of Niger Delta sediment supply during the late Quaternary period (Oomken *et al.*, 1975). During interglacial (~ 12 /11 -8.5 ka) high sea levels, most of the sediment transported by the Niger and Benue Rivers were deposited near the river mouth, and only mudstone prone open-ocean sedimentation took place on the delta slope (Reijers, 2011). This phase correlates with the regional / global sea level rise established below at 11ka (Figures 4.6a, b). During glacial (~ 20/22 -11 ka) periods with greatly reduced sea level, most of the sediments emanating from the Niger Rivers sandstone sediments were channelled directly to the deep sea floor fan forming extensive glacial-stage deposits in the fan area which corresponds to both regional/global sea level altitude at 20ka (Figures 4.6a, b).

This “on/off” sedimentation on the Niger Delta is one of the reasons for it being so unstructured, thus allowing successful biostratigraphic investigations and timing of the FOC marker species in each GC to be history matched in relation to both altitudes of regional and global sea level curves at and after 20ka to be determined below (Figures 4.6a, b). This ecostratigraphic zonation (FOC) was defined in the tropical

Atlantic Ocean by the presence or absence of marker species using the Ericson Z/Y Zone boundary which is approximately equivalent to the Holocene/Pleistocene boundary (e.g., Ericson and Wollin, 1968; Damuth, 1977; Prell and Damuth, 1978).

Thus, this section, presents biostratigraphic information from the Niger Delta gravity core drilling and attempted organising the information into a coherent stratigraphic model at ~ 20/22ka and 11ka using the FOC of each GC at the bottom and after 20ka with timing of the two sea level curves in view of the Delta's complicated stratigraphy (Figures 4.6a, b).

In summary, this section demonstrates both regional and global sea level links of Peltier, 1994 and Fleming *et al.*, 1998 with the GCs FOC of each marker species biostratigraphy date to instil more confidence, that Niger Delta deposits can provide comprehensive and valuable biostratigraphic information when samples and data are carefully selected and interpreted using sea level records as shown below (Figures 4.6a, b).

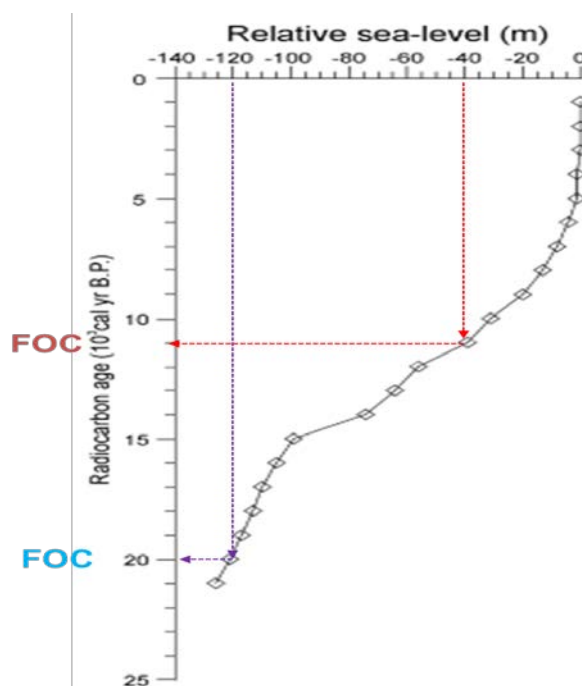


Figure 4.6a. Plot of Relative sea-level curve for locations (5830VS, 11830VE of Congo) on the Congo margin extracted and modified from Peltier (1994) in calibrated years B.P and the biostratigraphic First Occurrences (FOC) at 20ka (blue) and 11ka (red) of GCs respectively.

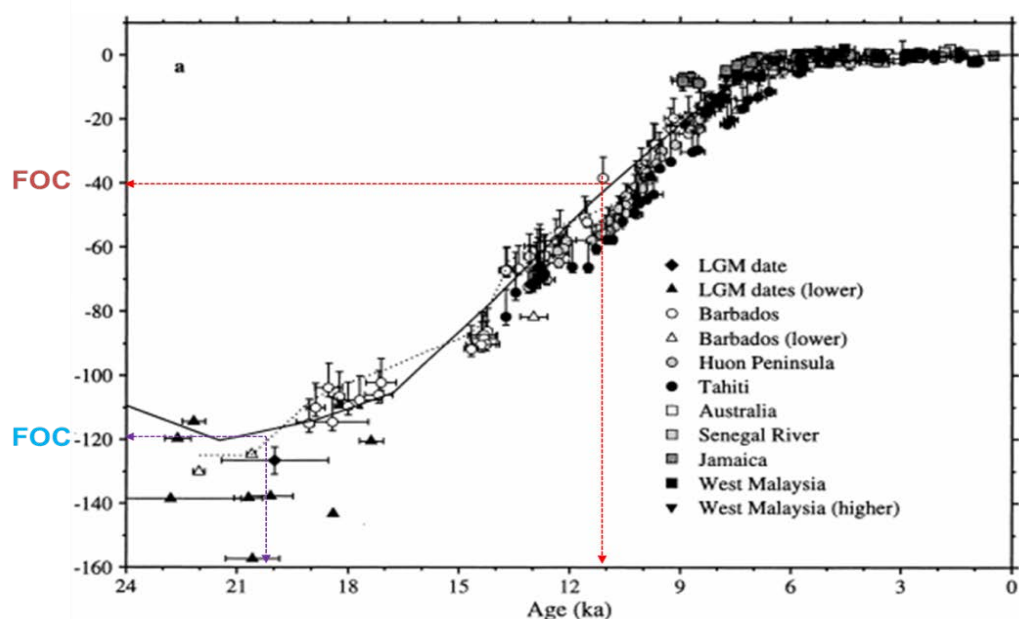


Figure 4.6b. The combined plots of the estimated global sea-level results of different locations from the Last Glacial Maximum to the present day, and for the late Quaternary calibrated years Ka and the biostratigraphic First Occurrences (FOC) at 20ka/~21ka (blue) and 11ka (red) of GCs respectively (modified after Fleming *et al.*, 1998).

4.5 Sedimentation Rates

This section calculates Sedimentation Rates (SR) from the confirmed age model to generate data linking the calculation of sediments and carried pollen. Also, to confirm the similarity of the age between the GCs on the assurance that any age/depth related problem during interpretation could be mitigated. Calculation of the sedimentation rates and application to the gravity cores may suggest another proxy in lieu of marker species being absent, or for another reason, mechanically or geologically not in alignment with anticipated positions in a particular cored section.

Given this, sedimentation rates over time of each of the three GC (Figures 4.6-4.8) were calculated using the age model described in sections 4.2 and 4.3. 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 Z = Intervals between samples (cm); T = Age difference between samples (kyr)

There are different ways to interpolate SR between intervals (depth cm) on a graph, which are important to consider. The following are some published methods used depending on the purpose:

- 1) Cubic, smoothed or locally weighted splines;
- 2) Linear interpolation between dated points;
- 3) Linear or higher order polynomial regression.

This study adopted the linear interpolation between dated points option for two reasons, being the biostratigraphic dating method, and environmental setting (regressive deltaic sequences). A careful step was taken for the construction of stratigraphic range chart diagrams. This is indicated or constructed by a scattered horizontal line bars representing sequence of events recorded which is assumed to be a standard datum reference. This study adopted variables in thickness or depth and the notional geological time scale to cross-relate to the ages (e.g. at 20 ka, 11 ka, 8.5 ka, and 6.5 ka time reference datums) (Figures 4.1-4.3). Both depth and time scales were compared in order to determine the SR. As a consequence, the direct plot between the depth and age reference enables the construction of a “line of correlation” between each datum relating to the marker species (FAD and LAD), which effectively represents the accumulation rates (SR) calculated for the individual cores (Figures 4.1-4.3).

The standard approach taken to construct a SR is as follows:

Step 1: Define a well-spaced datum, using both FOC and LOC of the calcareous nannofossil and planktonic markers species whose age calibration was considered accurate and reliable (Figures 4.1-4.3). These points are marked with a red circle and blue asterisk (Figures 4.6-4.8; also reported in figure 4.5).

Step 2: Subsequently, using the age model with recourse to Figure 4.5 a standard reference was established by comparing and linking the scattered dots of the ages plotted in Figures 4.1-4.3 to establish on the vertical axis four nannofossil events

(datum). This was presented as stratigraphic bars to construct the line of correlation from each datum points (Figures 4.6-4.8).

Step 3: From each datum point (FOC and LOC), an observable trace of a line of correlation matching all age/depth plots was evaluated from the specific upper most bottom datum for each GC. These are represented by red circles on both axis (Figures 4.6-4.8).

Step 4: To be aware of perceived calibration issues (uncertainties) (Gradstein *et al.*, 2012), and the possibility for substantial diachroneity (hiatus) (e.g. Sanfilippo and Blome, 2001), this study constructs SR curves based on a selection of specific datum tie points rather than joining all the biostratigraphic points from the age model. This step is very necessary and crucial to minimise the potential false variation in SR over short periods which could have resulted from diachronous (hiatus) biostratigraphic datum events (FAD and LAD). In doing so, the bottom of the GCs is marked by the **FAD or FOC** of *Gephyrocapsa oceanica* <3µm (20 ka), middle of the GCs is marked by the **FAD or FOC** *Emiliana huxleyi* (11–8.5 Ka), and the uppermost part of the GCs is marked by the **LAD or LOC** of *Emiliana huxleyi* (6.5 ka) (Figures 5.6a-c).

Step 5: Finally in addition to step 4, an estimated error limit of 4-5 cm per each GC was considered and recorded to accommodate any error or degree of uncertainty for an approximate age range between 200-500 years in accordance with the position of the event datums during interpretation (represented with a blue asterisk Figures 4.6-4.8).

Table 3.4 Summary Table of the Sedimentation Rates (SR)

Gravity core	Datum/Age	GC1	SR cm/ka	GC2	SR cm/ka	GC3	SR cm/ka
Depth (cm)	LAD/6.5 ka	0-40	6.2	0-40	6.2	0-40	6.2
Depth (cm)	LAD/11-8.5 ka	40-184	72.0	40-142	51	40-142	51
Depth (cm)	LAD/20 ka	184-272	9.8	142-266	13.8	142-260	13.1

4.5.1 Sedimentation Rates in GC1

The sedimentation rates at the bottom of GC1 are less rapid compared to those from age comparable intervals in GC2 and GC3 (Figures 4.6-4.8; Table 3.1). According to the biostratigraphic data used to define the key datums, a high sedimentation rate was observed at the bottom (272cm) of the Late Pleistocene compared to the remaining part of the GC1. From the FOC of *Gephyrocapsa oceanica* <3 μ m to the FAD of *Emiliana huxleyi*, the sedimentation rate is 9.8cm/ kyr during the Late Pleistocene. After this datum, to the middle of the GC, the sedimentation rates increase and then decline progressively up-hole between 51 to 6.2 cm/kyr to the LOC abundant increase of *Emiliana huxleyi* during the mid-Holocene (Figures 4.6-4.7; Table 3.1).

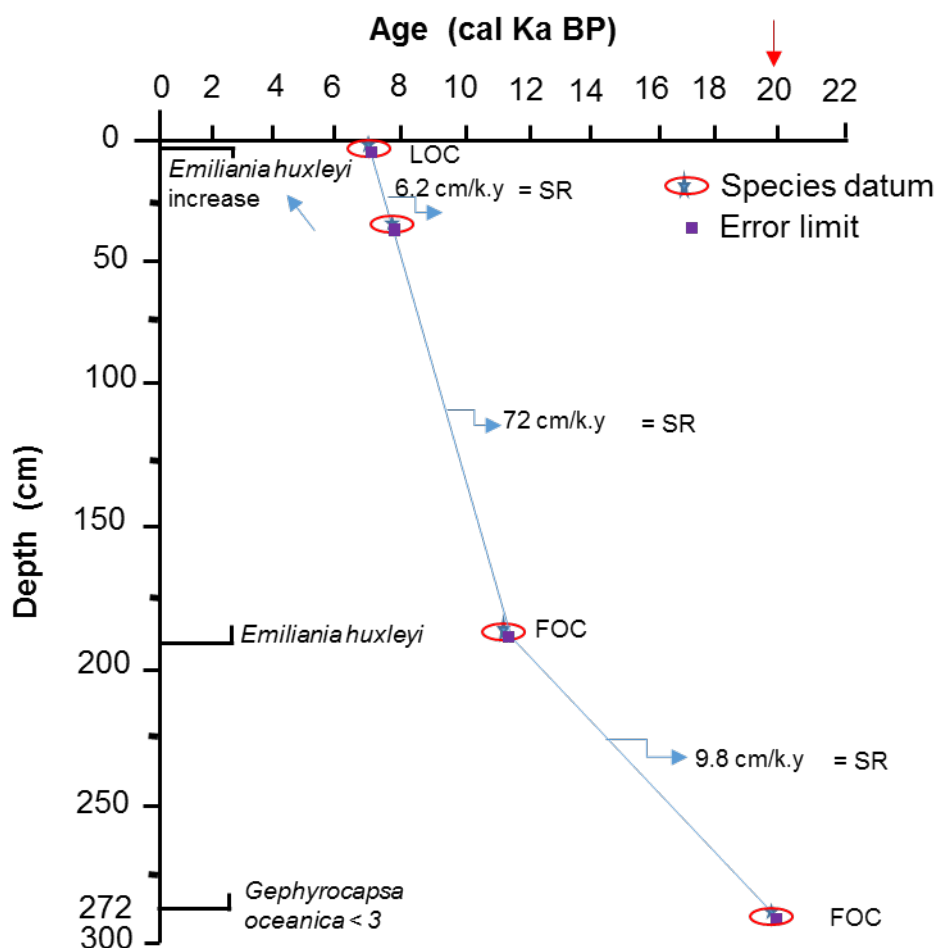


Figure 4.7. Sedimentation Rate (SR) and age-depth model for GC1.

Note: FOC = first occurrence in core, LOC = last occurrence in core

4.5.2 Sedimentation Rates in GC2

The SR in GC2 (Figure 4.7) shows variance when compared with GC1 and GC3. At the sampled lower part of the Late Pleistocene interval, *Gephyrocapsa oceanica* <3 μ m FAD or FOC event has been used as a calibration datum point to interpolate the sedimentation curve. Extrapolation of the data from 184 to 266 cm (thickness of strata between the two datums) indicates a sedimentation rate of 13.8cm/kyr down-hole during the Late Pleistocene (Figure 4.7). From the middle part of the GC2, the sedimentation rate increases up-hole from 51 cm/kyr from the FAD or FOC of *Emiliana huxleyi* during the Early Holocene, and then decreased to 6.2cm/kyr associated with the LAD or LOC abundant increase of *Emiliana huxleyi* in mid-Holocene at the topmost part of the GC2 cored sequence.

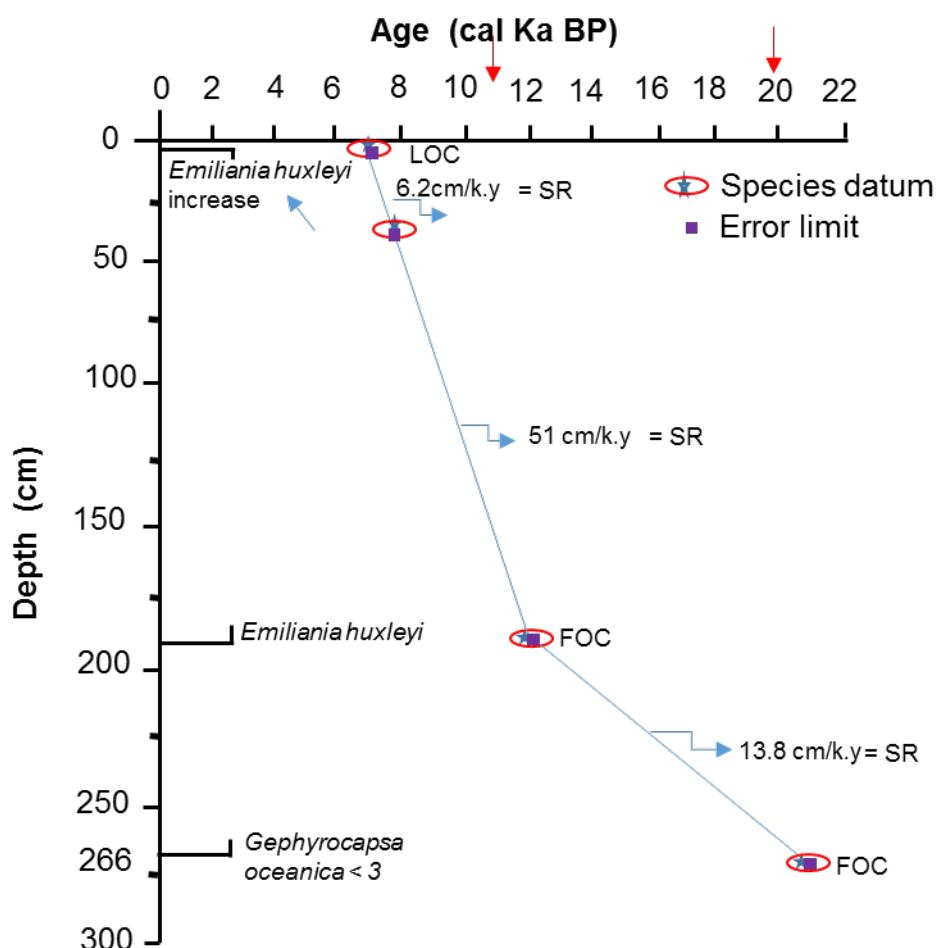


Figure 4.8. Sedimentation Rate (SR) and age-depth model for GC2

4.5.3 Sedimentation Rates in GC3

The SR increases at the bottom (184-260 cm) of the GC3 cored interval when compared with the GC1 due to a postulated different depositional setting in the location. At the bottom of GC3 a sedimentation rate of 13.1cm/kyr was recorded during the Late Pleistocene (Figure 4.8). From the middle part of the GC3, the sedimentation rate progressively increases up-hole from 51cm/kyr at the FAD or FOC of *Emiliana huxleyi* during the Early Holocene and decreased to 6.2cm/kyr associated with the LAD or LOC abundant increase of *Emiliana huxleyi* in mid-Holocene at the topmost part of the GC3. This result is similar to the SR at the middle of GC2, but, different from GC1 (Figures 4.6)

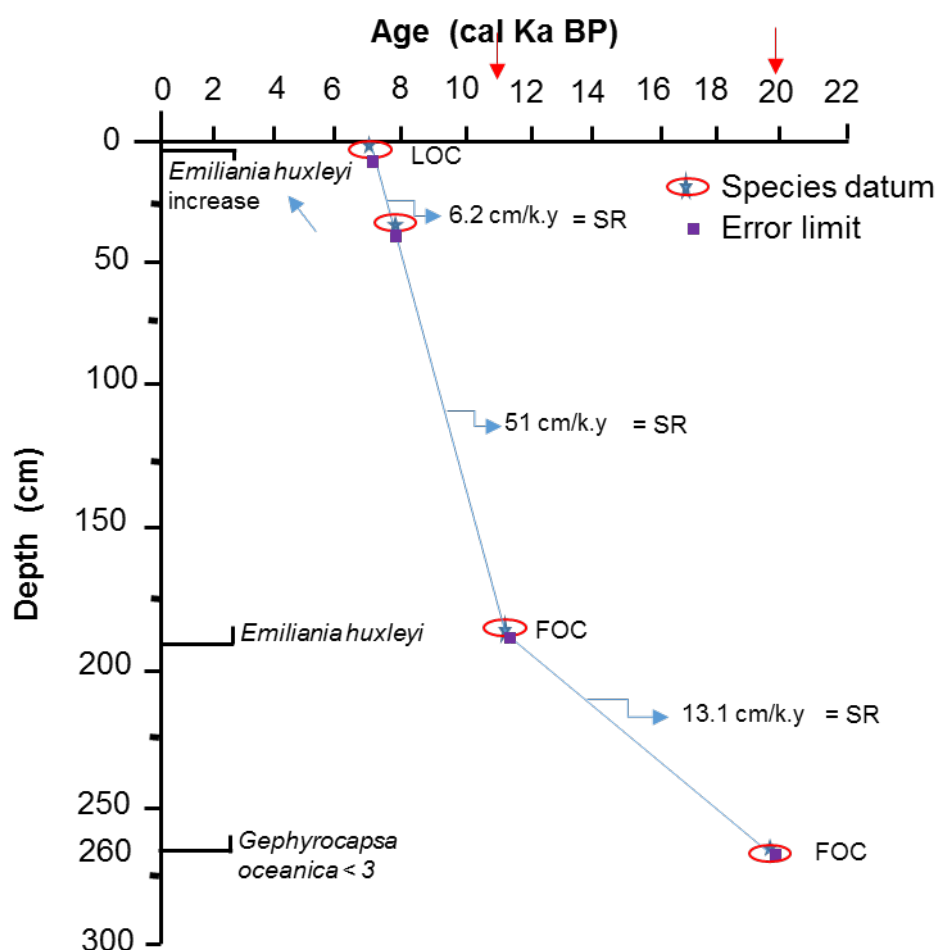


Figure 4.9. Sedimentation Rate (SR) and age-depth model for GC3

The SR investigation of the three cores has a similar trend to the MD03–2708C core located in the Ogooue fan, West Equatorial Africa (Kim *et al.*, 2010) and the ERCS 17 cores in Niger Delta (Riboulot *et al.*, 2012) in which radiocarbon dates have been used to constrain the stratigraphy. The bottom of the three GCs shows similar influx of sedimentation rates, whereas the middle - uppermost parts shows a longer/slower sedimentation rate (Figures 4.6 a-c; Table 3.4).

Also, significant influx of sedimentation rate at the bottom of the gravity cores equating with the 20-11 Ka period suggests a major response of the Benue and Niger rivers confluence system (Figure 2.8) to one or more strong forcing factors (high fluvial input within the catchment area), similar to that postulated by Marret *et al.* (2001) for the Congo River palaeodischarge model. This control could be local (e.g. a period of intense tectonism) or regional (e.g. climate change) both contributing to the discharge of large volume of sediment through the Benue and Niger systems across the Niger Delta. The constant SR at the middle of the GC2 and GC3, and at the topmost part of the three cores, indicates a similar depositional setting perhaps influenced by a local factor such as sea level change representing a return to lower palaeodischarge (Barusseau *et al.*, 1995).

4.6 Conclusions

- Three local sedimentation rates were classified (Table 4.4). Different rates of sedimentation were observed at the GCs, including 72 to 51 cm/kyr between 11 and 8.5 ka, which is one of the highest that has been observed in this study.
- Nannofossils offer the most precise dating method in the Niger Delta given their resistance to diagenetic alteration (Raffi, 1979).
- In well-preserved sediments recovered away from upwelling areas, nannofossils and planktonic foraminifera are habitually abundant.
- Nannofossils are present in the shallow water column and so minimize potential bias between sites, both locally and globally.
- A very small amount of material is needed, so that these microfossils (nannofossil and foraminifera) are perfect for obtaining high-resolution biostratigraphy during the Quaternary (Raffi, 1979).

- Considering the similar case study from Zaire River (Core KZai 02), this study also noted that the dating of Core KZai 02 was also successful using an age reference from a nearby core based on the same marker species of nannofossils (*Gephyrocapsa oceanica* <3 μ m and *Emiliana huxleyi*) (Dalibard *et al.*, 2014).
- Given the above, this study is the second piece of research in Africa to use nannofossil and planktonic foraminifera for dating complex deltaic environments during the 'late Quaternary'.
- Based on the similar age interpretation obtained from the two regions: Zaire River (KZai 02) and Niger Delta (GC), the current study suggests coherency using biostratigraphic dating (NN19 = Late Pleistocene, NN20 and NN21 = Holocene) to date the 'late Quaternary' sedimentary succession of the Niger Delta.

Chapter 5: Results

Highlights

- An array of data descriptions using physical, chemical and structural accessory of sedimentary components on four multi-proxy based on the conventional guide were analysed reflecting the inherent properties of the cores
- The results from sedimentological and foraminiferal components were described in response to their variance and morphological descriptions, whereas and geochemical proxy were based on their influx and concentration rates
- Analyses of these multi-proxy results enable each core to be subdivided into four distinct intervals that indicate a temporal related evolving environment below

5.1 Introduction

Based on the sedimentology methodological approach as discussed in Chapter 3, the GCs were studied for their visual characteristics. In context, the cores were logged and investigated to establish the lithological components. Therefore, this chapter aimed to apply a detailed grain size analysis, geochemical ratios (Ti/Zr & Fe/S elements), and benthic and planktonic foraminiferal results in conjunction with a detailed lithofacies analysis to generate robust palaeoenvironmental evolution interpretation in the subsequent chapter. The general observation of the lithofacies results of the cores suggests dominance of mudstone lamination intercalation with pulses of fine-medium-grained sand.

5.2 Lithological Description of the GCs

A detailed lithological description at the scale of 1:10 cm (interval per unit length) was undertaken, while a synopsis of the various lithological components at different depth intervals was discussed based on the different units identified in each GC (Figures 5.1-5.3).

The observable muddy features in the gravity cores were described using the approach of Nichole (2011), and the Shell Petroleum Development Company lithofacies description guide (conventional guide) (see Appendix 4 for all core photos).

The sedimentology description of the cored sequences focussed on the following visual criteria: lithology (grain size), accessories (mineral particles, e.g. siderite, pyrite; shell fragments, e.g. gastropods), bioturbation, sedimentary structures and depositional environments (Figures 5.1-5.3). The sedimentology was used to define each characteristic lithological unit in order to interpret the broader picture of depositional history and sedimentary evolution (succession). The basic description was achieved on each of the GC based on the following units in Table 4.1 (detailed lithological descriptions are archived on the accompanying CD).

Table 4.1 GCs Lithological Units Subdivision

Core	Total length (cm)	Units/intervals
GC1	275	GC1-Z, GC-Y, GC-X & GC-W
GC2	266	GC2-A, GC-B, GC-C & GC-D
GC3	260	GC3-U, GC-T, GC-S & GC-R

Table 4.2 Summary of Characteristics Relative to Lithofacies Types

Code	Lithology	Sedimentary structure	Interpretation
MS	Very fine to medium sand; rare clay	Wavy lamination and cross bedding; sideritic nodules	Low flow regime, typical distal to pro-delta deposit
SF	Silty fine sand, dominantly silty clay; thick grey and green soft mudstone	Moderately bioturbated wavy lamination; moderate lenticular bedding	Subaqueous delta front characterised by near shore deposit, intermediate energy regime
FS	Muddy silty stone with spots of circular white clay alternation	Laminated lenticular, silty fine sand and clay prone	Lagoonal to coastal swamp deposit/delta, typical higher energy regime

5.2.1 GC1 Lithological Descriptions

Four units were visually identified as follows and are shown/described in Figure 5.1; Plate C; Table 4.2.

Unit GC1–Z (272 - 185 cm)

This unit comprises of a section beginning with lithofacies (MS), starting with a medium sand towards the base of GC1. The medium sandy facies is overlain by fine sand and grey clay. The grain size is silty, medium-fine sand, and rare clay associated with an overall fining-upward sequence. The fabric consists of small sized gastropod shells (I), minor (< 2%) accessory component of shell fragments, and traces of siderite nodules. Minor to moderate bioturbation is also observed. The sedimentary structures consist of wavy lamination and cross bedding (J).

Unit GC1-Y (185 - 120 cm)

The lithofacies (SF) which overlies the above section shows a gradational lower boundary with the underlying deposits, and is made up of a repetitive, very silty fine sand, a thick succession (35cm) of grey to green soft mudstone with indeterminate gastropod fragments. The lithology over this interval is predominantly siltstone with traces of very fine sand. There are subtle wavy laminae (H) within the very fine sand component, which is also affected by a moderate degree of bioturbation (G). Mica flakes and shell fragments are present in the siltstone.

Unit GC1-X (120 - 60 cm)

The lithofacies (FS) consists of muddy siltstone with white lenticular clay alternations. Traces of shell fragments were not visible or present when compared to the units below. Mica flakes and bioturbation were also not present .

Unit GC1-W (60 - 0 cm)

This unit consists alternation of lithofacies (SF and FS) of very fine and silty sandstone. Shelly content increases in this unit (topmost part) as well as the accessory contents such as pyrite nodules and mica. Siderite traces are rare with the occurrence of some macrofossil content of pteropods and gastropods. However the sedimentary

structure are not always clearly visible, but where described, the structures consist of traces of cross-bedding (D) and lenticular wavy lamination (E).

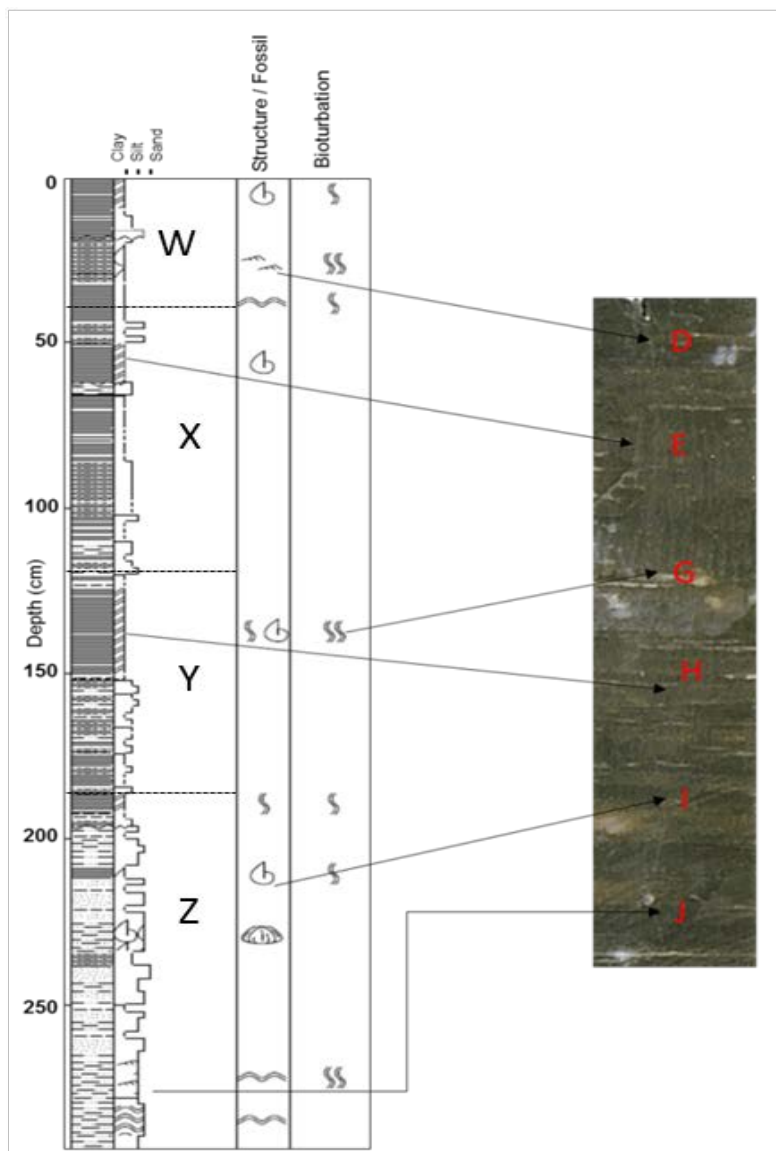
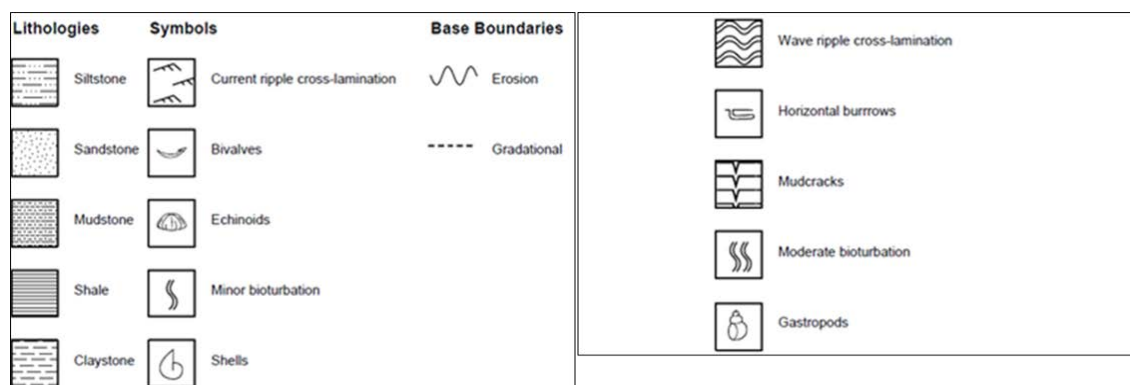


Figure 5.1. Description of the GC1.



Note: This legend is applicable to all the GCs litho-logs.

5.2.2 GC2 Lithological Descriptions

Four units were visually identified as follows and are shown/described in Figure 5.2; Plate C; Table 4.2

Unit GC2-A (266 - 220 cm)

The unit consist of lithofacies (SM) and heterolithics consisting of 70% mud and 30% fine to medium sand. The sand occurs as lenses (46cm thick) and is usually overprinted by circular white traces of siderite, mica flakes and shell debris, associated with thin sandstone. *Thalassinoides* burrows and minor bioturbation (e.g. echinoderms - C) were observed towards the bottom of the core. The sedimentary structures in this unit consist of the preservation of cross-bedding and wavy lamination as well. The traces of macrofossil content present consist of gastropods and echinoderms (C) but were not well preserved.

Unit GC2-B (220 - 135 cm)

This unit consists of lithofacies (SF) and a complex sequence of silts and clays supplemented by fine sand. The colour of the silt content decreases from light grey to dark brown (75%) while clay (5%) content increases (dark grey) up-hole. The laminated siltstones with rare bioturbation (B) were more prominent than clay content. The observed sedimentary structure is made of discontinuous wavy laminations (B).

Unit GC2-C (135 - 70 cm)

This unit consist of prominent lithofacies (FS) of siltstones with very fine brown/light grey sand (30%). Wavy ripple, clay laminae (mm-scale), which do not drape, were observed. The accessory content is slightly different from Unit B. Bioturbation was observed between 70-105 cm with some tiny vertical burrows (~ 4cm) (B). There are limited differences in the sedimentary structures recognised when compared with the underlying unit B. Gastropod and bivalves shells were observed from the uppermost part of this unit.

Unit D (70 - 0 cm)

Lithological components observed from this unit consist of lithofacies types SF and FS, and is mostly a mudstone fining-upward sequence composed of dark - grey to brown (75%) siltstones. The observed accessories are mostly disseminated wood organic matter, mica flakes, broken shell fragments, traces of glauconite, and shell debris (including gastropods, bivalves) (A). Bioturbation is quite rare, with traces of *Ophiomorpha* and *Thalassinoides* burrows present within 10-20 cm from the uppermost part of the GC2. The observed sedimentary structures in the uppermost part of the core (0-20 cm) are rare discontinuous wavy laminations and cross bedding.

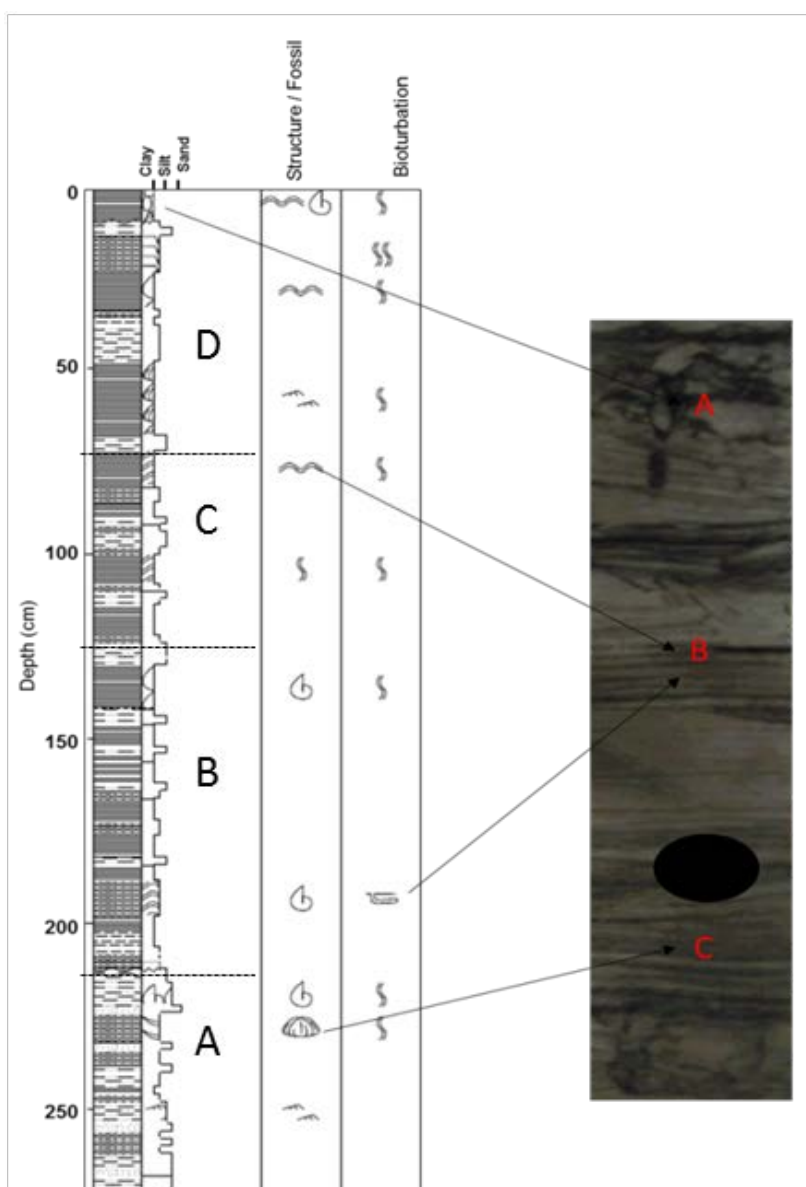


Figure 5.2. Description of the GC2.

5.2.3. GC3 Lithological Descriptions

Four units were identified visually as follows (Figure 5.3; Plate C; Table 4.2).

Unit GC3-R (260 - 220 cm)

The lithofacies (MS) in this unit is predominantly siltstones with medium sandstones (30%) sand and clay (5%). The dominant colour is dark grey. The accessory content is mostly shell debris, (but not well preserved when compared to the similar intervals in the other cores), mica flakes and siderite. Gastropod and *holothurian* type of echinoderms remains (P) between 196–200 cm were quite rich. Bioturbation is rare to absent but, there is a presence of minor traces of *Thalassinoides* burrows noted.

Unit GC3-S (220 - 160 cm)

This unit consist of lithofacies (SF) of homogeneous grey silty clay (75%) increasing upward with alternations of very fine sand bodies, about 10cm thick, with associated moderate wood fragments. Lithological components are dominantly mudstones, with moderate very fine sand, coloured mostly dark to light brown. The accessory materials and the biotic contents were not visible. Bioturbation and sedimentary structures were not observed from this interval except for a minor presence of burrow similar to that of the crustacean trace fossil (N).

Unit GC3-T (160 – 70 cm)

The lithofacies (FS) in this unit is predominantly silty fine sand (65%) with rare clay content in which the colour is dark grey and light brown. Accessory content is mostly shell debris and traces of siderite. The macrofossil content consists of gastropods and unrecognisable echinoderms. Bioturbation is similar to vertical and horizontal burrows of *Skolithos* (M & N).

Unit GC3-U (70 - 0 cm)

The lithofacies (SF and FS) in this unit consists of a homogeneous succession of extremely soft, grey clays (5%) and siltstones (65%) irregularly interrupted by thin fine sandy layers (commonly less than 20cm) and disseminated plant remains. The colour of the very fine sand is predominantly light brown. Shell fragments and traces of

siderite were noticed at the bottom and top end of this interval. Bioturbation consists of minor to moderate burrows of gastropods and echinoderms (k). The sedimentary structures are not so obvious, but traces of wavy lamination were recognised at the uppermost part of the unit (L).

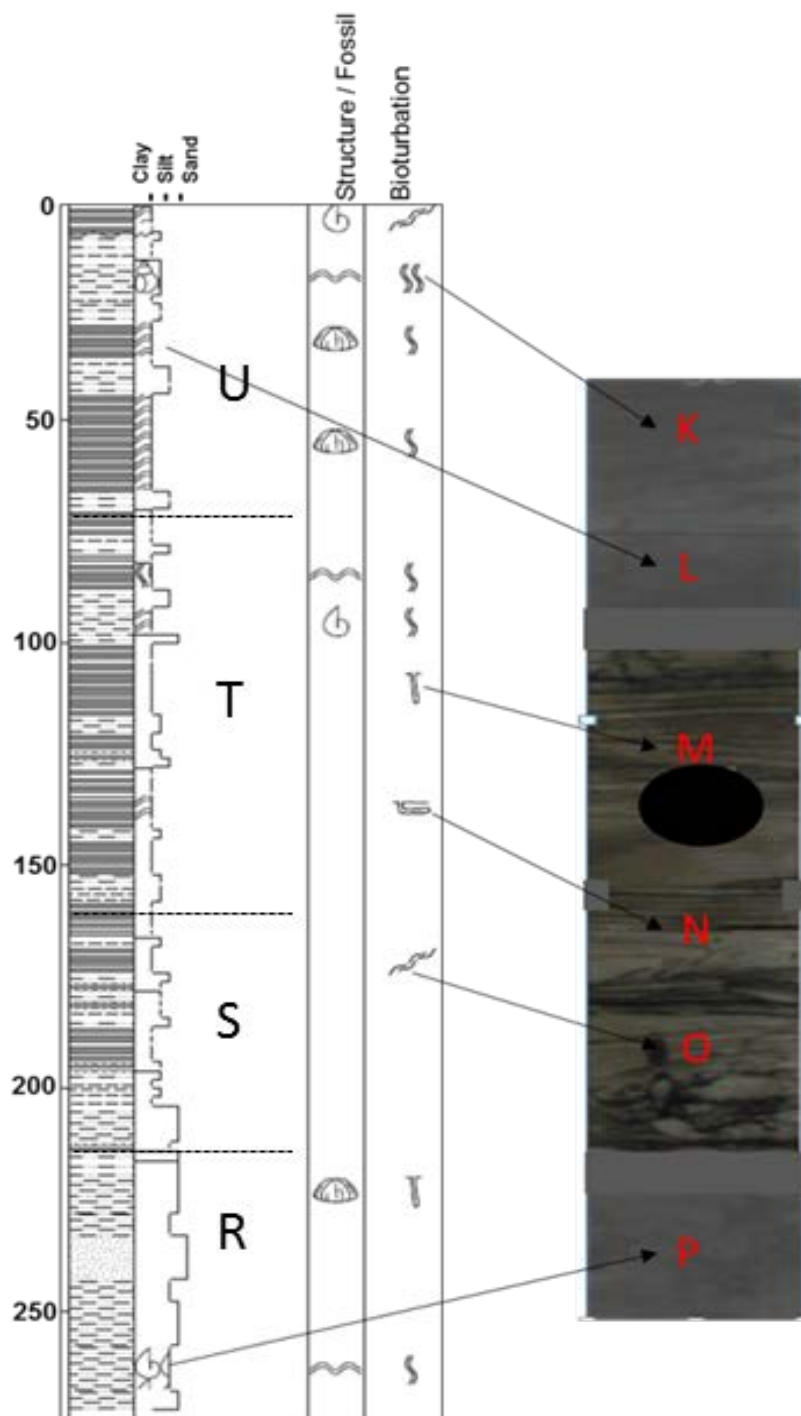


Figure 5.3. Description of the GC3.

5.3 Grain Size Analysis

Results of particle size measurements (LPSA) are presented in percentages in the narrative below (Figures 5.4-5.6).

5.3.1 GC1 Grain Size Distributions

The grain size distributions are plotted in percentages. These percentages represent certain points within the intervals cited or running averages across the intervals with the three GCs.

GC1 (272 - 185 cm)

The bottom of this unit is predominantly 69% silt-grade sediments. The percentages of sand and clay are low when compared to the silt, with 35% and 11% respectively.

GC1 (185 – 130 cm)

This unit consists of dominant silt-grade percentages as well. Silt accounts for 77% of the total sample size. The percentages of sand and clay are low when compared to silt, with 18% and 5% respectively.

GC1 (130 – 40 cm)

Within this unit, the percentages of silt increase more when compared to other units. 80% silt is noted, whereas 18% and 2% of sand and clay respectively is recorded.

GC1 (40 - 0 cm)

The uppermost part of this unit consists of 77% silt-grade, 22% sand and 1% of clay. Much change in the percentage of silt was significantly observed through this unit similar to other units in the GC1 (Figures 5.4-5.6).

5.3.2 GC2 Grain Size Distributions

GC2 (266 - 230 cm)

The lowest unit interval consists of 65% dominant silt-grade material. The percentages of sand and clay are low consisting of 30% and 5% respectively.

GC2 (230 - 145 cm)

Across this unit the percentages of sand, silt, and clay-grade are as for the lowermost interval.

GC2 (145 - 45 cm)

This unit shows a greater predominance of silt-grade material fraction. Silt accounts for 71% of the total sample which is higher than the lower two units. The percentages of sand and clay are low when compared to silt. They consist of 19% and 10% of the overall total sample respectively.

GC2 (40 - 0 cm)

The uppermost unit consists of 77% silt fraction. Similar to interval 145-230 cm of GC2, 22% of sand and an exceedingly low 1% of clay were deposited at the same time, similar in the uppermost unit in GC1 (Figures 5.4-5.6).

5.3.3 GC3 Grain Size Distributions

GC3 (260-230 cm)

This unit consists more of silt-grade components which account for 60% of the total grain size. The percentages of sand and clay are low when compared to silt, but show very similar percentages with the equivalent units in the GC1 and GC2. They consist of 18% and 5% respectively.

GC3 (230-135 cm)

In this unit silt increase up-hole to 70%. The percentages of sand and clay are low consisting of 25% and 5% respectively. The percentage of silt is higher than when compared to the previous unit.

GC3 (135–35 cm)

This unit consists predominantly of 67% silt. The percentages of sand and clay are higher when compared to the previous unit (230-135 cm) consisting of 30% and 3% respectively. The percentages of silt decreases slightly when compared with the previous records of silt percentages.

GC3 (35–0 cm)

The topmost part of this unit consists of 77% silt, 22% sand and 7% clay. Within this interval it is observed that there are numerous higher frequency percentage changes associated with the silt proportion. The percentage of clay in this unit of the GC3 is quite different when compared to the topmost units of the GC1 and GC2 (Figures 5.4-5.6).

5.4 Geochemical Composition of the GCs

In this section, two geochemical elemental ratio data plots are presented demonstrating various concentration changes throughout the three GCs. The value of Ti/Zr ratio is much significant and increases down-hole (140-80) at the intervals (depths) especially at the bottom of the GCs. The value of Fe/S is low (between 0-6) throughout the same intervals at the bottom of the GCs due to the low presence of organic matter and relative formation of pyrite. However, from the middle to uppermost intervals of the three GCs, the value of the Ti/Zr decreases (5-65) but the value of Fe/S increases (4-45) across the same relative intervals in the three GCs (Figures 5.4-5.6). Based on these characteristics, below is the summary of the concentrations of the Ti/Zr and Fe/S from the GCs.

Table 4.3: GC1 Geochemical Results

Depth (cm)	Ti/Zr	Values	Fe/S	Values
185-272	90	High	0-6	Low
130-185	40	Intermediate	4-30	Intermediate
40-130	30	Low	15-35	High
0-40	40	Low	11-40	High

Table 4.4: GC2 Geochemical Results

Depth (cm)	Ti/Zr	Values	Fe/S	Values
185-266	110	High	5-7	Low
130-185	20-65	Intermediate	6-12	Intermediate
40-130	20	Low	15-16	High
0-40	25	Low	15-35	High

Table 4.5: GC3 Geochemical Results

Depth (cm)	Ti/Zr	Values	Fe/S	Values
185-260	80	High	8	Low
130-185	5-35	Intermediate	15	Intermediate
40-130	6	Low	45	High
0-40	30	Low	16	High

5.5 Foraminiferal Data from the GCs

Foraminiferal data sets are divided into benthic and planktonic species. The description below provides the abundance of the species distributions and summary of each interval or change observed from the graphical plots of the benthic and planktonic dataset (Figures 5.4-5.6). These results show that foraminiferal percentages vary with depth across each of the GCs.

5.5.1 GC1 Foraminiferal Distributions

GC1 (272-185 cm)

In this unit the benthic versus planktonic counts were high (up to 80%). *Elphidium* sp., *Lagena* sp. and *Ammonia beccarii* initially dominated the count accounting for 80% of the total foraminifera. Planktonic species are present, but in low quantities. Only *Globorotalia truncatulinoides* accounts for between 5-20% of the total foraminiferal assemblage.

GC1 (185-130 cm)

This unit contains increased numbers of benthic species such as *Ammonia beccarii*, *Cibicides* spp., *Melonis* spp., *Uvigerina* spp. and *Bolivina* spp. accounting for 10–20% of the total foraminiferal count. However, the planktonic group including *Globigerinoides ruber* and *Globorotalia* spp. constitutes 75% of the foraminiferal count. This percentage increases more when compared to the previous unit. There is a complete diametric shift in relative numbers of benthics and planktics.

GC1 (130-40 cm)

In this unit the benthic species decreases but, the miliolids benthic group including *Quinqueloculina buena*, *Triloculina* sp. replace the calcareous benthics constituting between 5-25%. Planktonic species decrease, but the percentage of *Globorotalia tosaensis* begins to dominate, accounting for 65-75% of the total foraminiferal count.

GC1 (40-0 cm)

The benthic species in this unit disappear up-hole, especially the benthic miliolids but, calcareous and porcellaneous types such as *Uvigerina* spp., *Bolivina* spp. and *Loxostomoides* spp. respectively increase up-hole accounting for about 35-45% of the total foraminiferal. *Globorotalia tosaensis* percentage increases more among the planktonics in this unit, accounting for about 70% of the total foraminiferal assemblages (Figures 5.4-5.6).

5.5.2 GC2 Foraminiferal Distributions

GC2 (266-230 cm)

In this unit the benthic species, especially the miliolids such as *Quinqueloculina buena*, *Triloculina* sp. and calcareous benthics including *Elphidium* sp., *Ammonia beccarii* increase accounting for between 25-70% of the total foraminiferal count. The species of the planktonic decrease up-hole, with *Globorotalia truncatulinoides* and *Globigerinoides ruber* accounting for 20-25% of the total foraminiferal count.

GC2 (230-145 cm)

This unit contains a low number of benthic species such as *Quinqueloculina* sp., *Cibicidoides* spp., *Melonis* spp., *Triloculina* spp. and *Cassidulina* spp. accounting for 30-40% of the foraminiferal count. However, the planktonics including *Globigerinoides ruber* and *Globorotalia truncatulinoides* account for about 25-50% of the total foraminiferal count. This percentage increases more when compared to the previous unit.

GC2 (145-45 cm)

In this unit the benthic species such as *Uvigerina* sp. and *Bolivina* sp. account for 10-20% of the foraminiferal count. However, the planktonic including *Globigerinoides ruber* and *Globorotalia* spp., which account for 45-50% of the total count, increase more up-hole when compared to the previous unit.

GC2 (45-0 cm)

Within this interval, the benthic species decreases suggesting significant reduction, as exemplified by the dramatic drop in number of the miliolids up-hole whereas calcareous such as *Ammonia beccarii* and *Cassidulina* sp., appear accounting for 0-25% of the total benthic foraminiferal assemblages. *Globorotalia tumida* and *Globigerinoides ruber* percentages are higher in this unit accounting for about 75% of the total planktonic foraminiferal assemblages (Figures 5.4-5.6).

5.2.3 GC3 Foraminiferal Distributions

GC3 (260-230 cm)

This unit contains shallower water benthic species such as *Ammonia beccarii* and *Melonis* spp., accounting for 50-55% of the benthic foraminiferal count. However, the planktonics, including *Globorotalia* spp., accounting for 45-50% of total foraminiferal are fairly well represented.

GC3 (230-135 cm)

The shallow water benthics are present, but only in low quantities. Only *Uvigerina* sp. and *Lagena* sp. account for 5-35% of the total foraminiferal set. In this unit the planktonic percentage counts are high with only *Globigerinoides ruber* initially dominating the total foraminiferal accounting for 50-65% of the total count.

GC3 (135-35 cm)

Benthics species in this unit such as *Uvigerina* sp. and *Bolivina* sp. account for 35-40% of the total foraminiferal count. However, the planktonic component including *Globigerinoides ruber* and *Globorotalia* spp., which account for 50-55% of the total percentages, increase more up-hole when compared to the previous interval.

GC3 (35-0 cm)

The benthic species in this unit are greatly reduced, especially the calcareous types except for the *Uvigerina* sp. and *Lagena* spp., which account for about 30-45% of the total benthic count. *Globorotalia tumida* and *Globigerinoides ruber* percentages increase more in this unit accounting for about 55-60% of the total foraminiferal assemblages. The number increases more when compared to the previous unit (Figures 5.4-5.6).

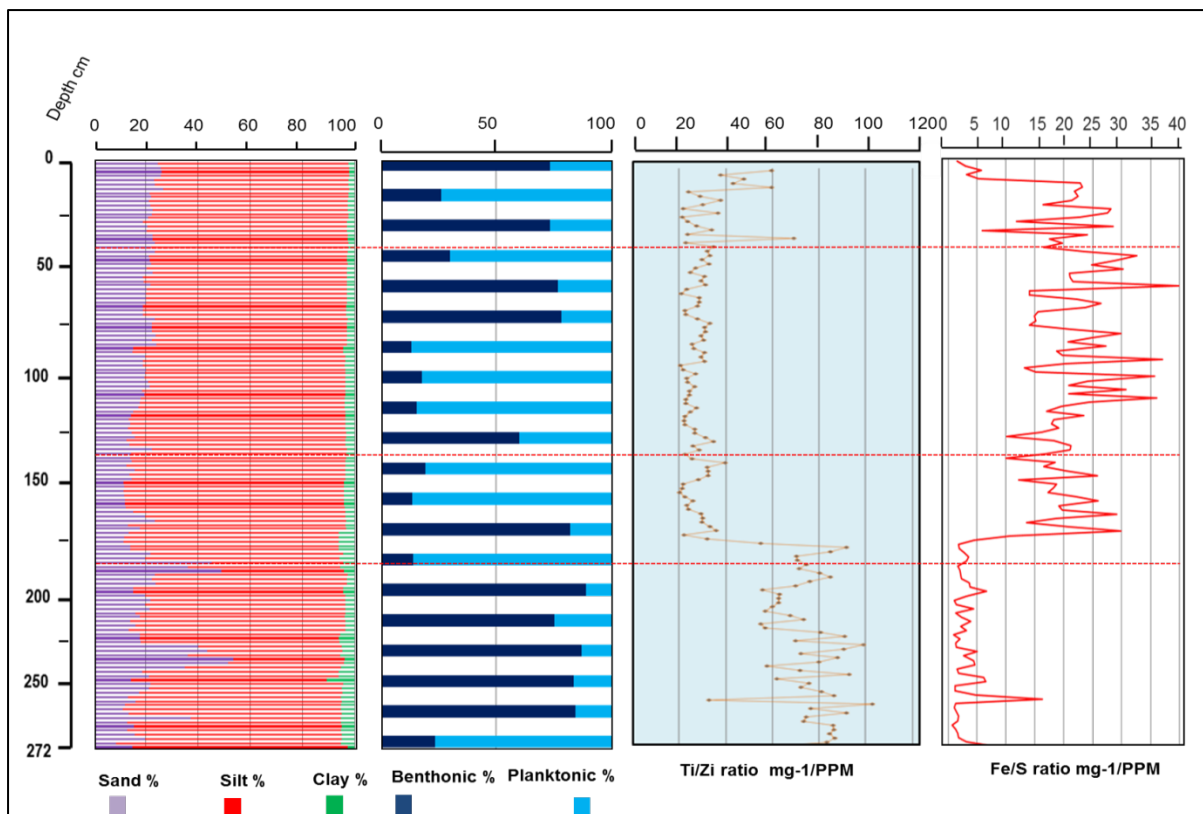


Figure 5.4. Summary diagram for Grain Size, Benthic and Planktonic Foraminiferal assemblages, and geochemical data for GC1.

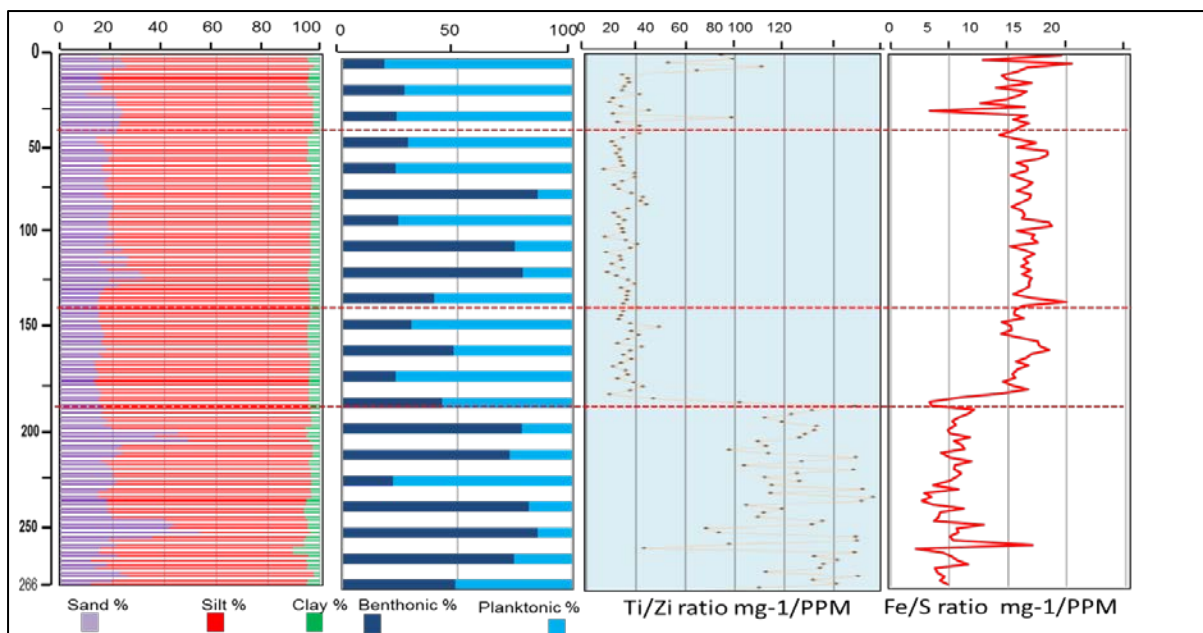


Figure 5.5. Summary diagram for Grain Size, Benthic and Planktonic Foraminiferal assemblages, and geochemical data for GC2.

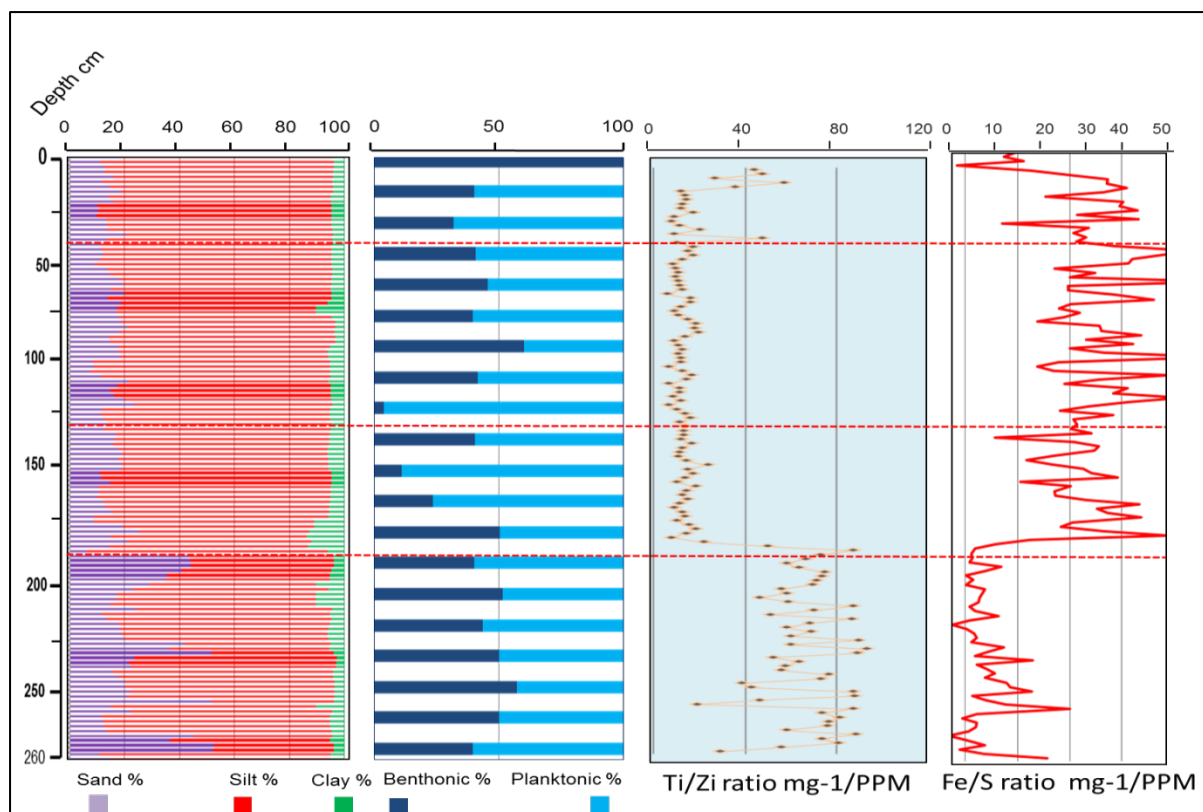


Figure 5.6. Summary diagram for Grain Size, Benthic and Planktonic Foraminiferal assemblages, and geochemical data for GC3.

5.6 Palynomorphs Recovered from the Gravity Cores

A high number of palynomorph components, including pteridophyte/bryophyte spores, gymnosperm pollen, angiosperm pollen, Foraminiferal Test Linings (FTLs), freshwater algae and fungal spores were recovered from the three studied gravity cores. Plant tissue, such as cuticle, xylem-cell, stomata, insect-derived and palynodebris were also abundantly present (Appendix 1- Plate 4).

The computation of the pollen sum discussed in Chapter 3 is a very important step in any percentage calculation since the results have major implications for the interpretation of deltaic palaeovegetation and landscape evolution. Of the recovered components, terrestrially derived forms (pollen and spores) constitute approximately 92% of the total palynomorph assemblages, whereas less than 2-3% are of marine origin (dinoflagellate cysts, FTLs). Freshwater algae, fungal spores and other types represent the remaining 6% of the total NPPs from the three GC. On average, 25

families representing 60-80 palynomorph species (excluding dinoflagellate cysts, unrecognised pollen and fungi) were identified (Appendix 1-Plates 4 to 5).

As discussed previously (Chapter 3-Section 3.5) similar family names exist as indicators of different ecosystem habitat groups, but vary from species to species in each of the palaeovegetation belts identified (e.g. Polypodiaceae and Euphorbiaceae belong to more than one ecosystem habitat group) (Appendix 1, Plates 1 to 5).

Given this, in this study both the morphological and botanical affinities for the identification of each species to their family level were considered (Appendix 1). In order to relate the ecological dynamics of the vegetation types to the prevailing mechanisms controlling the variations of each species in different regions (hinterland vs. littoral source) and seasonal inferences (arid vs. humid), the family-based nomenclature was adopted (e.g. *Rhizophora* = Rhizophoraceae) to reduce the biased interpretation that could have resulted from similar species identification (Poumot, 1998; Rull, 2001). Given this insight, species were grouped into family affinities to deduce their ecological affinity as stated above (Appendix 1). Thus, in this study, the table below is the summary annotation of the particular species and their related families.

Table 4.6. Family & Botanical Nomenclature relating to Morphogenic/Species Nomenclature – example (in colour) within the same family and vegetation habitat applicable in the GCs study.

	Botanical affinity	Pollen/Spore taxon		Family	Vegetation group	Plate number	Figure number	Figure page number	Descriptions page no
1									
2									
3	<i>Rhizophora</i>	spp.	<i>Zonocostites ramonae</i>	Rhizophoraceae	Mangrove Swamp	1	16, 18-24,	230	215
4	<i>Acrostichum</i>		<i>Acrostichumsporites</i> sp	Pteridaceae	Mangrove Swamp	2	65	232	222
5	<i>cf. Ipomoea</i>		<i>Echiperiporites</i> sp	Convolvulaceae	Mangrove Swamp	2	41,42	232	218
6	<i>Avicennia</i>	<i>germinans</i>	<i>Foveotricolporites crassixinus</i>	Avicenniaceae	Mangrove Swamp	2	36, 37	232	215
7	<i>Chamaecrista</i>		?	Fabaceae	Mangrove Swamp	1	38, 39, 40	230	216
8									
9	<i>Cyperus</i>		<i>Cyperus</i> sp	Cyperaceae	Fresh Water Swamp	2	35	232	219
10	<i>Symphonia</i>	<i>globulifera</i>	<i>Pachydermites diderixi</i>	Clusiaceae	Fresh Water Swamp/lowland rainforest	1	25-28	230	217
11	Arecaceae		<i>Psilate / Monocolpites</i> spp	Arecaceae	Fresh Water Swamp	1	33	230	218
12	<i>Nymphaea</i>	aff. <i>Lotus</i>	<i>Zonosulcites / Psilamonoprites</i> sp	Nymphaeaceae	Fresh Water Swamp	2	46	232	219
13									
14	<i>Tabernaemontana</i>		<i>Psilatricolporites crassus</i>	Apocynaceae	Lowland Rainforst / Open forest	1	8,9	230	213
15	<i>Celtis</i>		<i>Momipites africanus</i>	Cannabaceae	Lowland Rainforst / Open forest	1	12	230	214
16	<i>Anthonotha/ Berlinia/ Isoberlinia</i>		<i>Striatocolpites</i> sp	Caesalpinioideae	Lowland Rainforst	1	30, 31	230	216
17	<i>Amanoa</i>		<i>Retitricolporites irregularis</i>	Euphorbiaceae	Lowland Rainforst	1	7	230	214
18	<i>Vernonia</i>		<i>Spinizonocolpites</i> sp.	Asteraceae	Lowland Rainforst / Open forest	1	32	230	215
19	<i>Alchornea</i>	aff. <i>cordifolia</i>	<i>Psilatricolporites operculatus</i>	Euphorbiaceae	Lowland Rainforst	1	14, 15	230	213
20	Fern spores		<i>Laevigatosporites</i> sp	Pteridophyta	Lowland Rainforst / Open forest	3	66-68	234	220
21	<i>Lycopodium</i>	sp	<i>Lycopodiumsporites</i> sp	Lycopodiaceae	Lowland Rainforst / Open forest	2	57	232	223
22	Moss spores	sp	<i>Stereisporites</i> sp	Bryophyta	all open habitats	2	60	232	223
23	aff. <i>Hibiscus</i>	sp	<i>Echiperiporites estalae</i>	Malvaceae	all open habitats	1	29	230	218
24	Polypodium		<i>Polypodiaceoisporites</i> sp. (<i>Verrucatosporites usmensis</i>)	Polypodiaceae	Lowland Rainforst / Open forest	3	69, 70	234	221
25	Borreria (Spermacoce)		<i>Stephanocolpites</i> sp	Rubiaceae	Lowland Rainforst / Open forest	2	43, 44, 45	232	217
26	Fern spores		<i>Polypodiaceoisporites</i> sp	Pteridophyta	Lowland Rainforst / Open forest	2	62-64	232	221
27									
28	<i>Graminidites</i>	sp	<i>Monoporites annulatus</i>	Poaceae	Savannah	1	1-6	230	212
29									
30	<i>Podocarpus</i>		<i>Podocarpites</i> sp	Podocarpaceae	Afromontane	2	47-50	232	219

The pollen and spores were classified into their indicator groups following their climate, sea level and ecological affinities of the taxa and related plants as follows:

- I. Mangrove - Coastal Swamp;
- II. Freshwater Swamp - Palmae;
- III. Lowland Rainforest - Open Forest (semi arid, sub-humid and humid tropics);
- IV. Savannah - Afromontane;
- V. Non-pollen palynomorphs (NPPs).

Furthermore, given that material is remobilised and transported from the floodplain and coastal swamp environments to offshore environments, pollen and spores can be grouped into two more regional indicators of derivation/source (Poumot, 1989; Morley, 1995; Rull, 2002):

- a. Hinterland (upland) indicators (i.e. fern from lowland rainforest, open forest; savannah – afromontane);
- b. Littoral (lowland) indicators (i.e. mangrove, coastal swamp, freshwater swamp, Palmae).

The hinterland pollen indicators therefore suggest distant terrestrial sediment transport to the marine offshore basin, whereas the littoral pollen indicators suggest short coastal marine sediment transport to the offshore basin. A full list of species (taxa) indicating botanical affinities and the potential habitat or ecological niche including author references is listed in Table 1 and Appendix 1 - Plates 1 to 5.

In addition to the regional indicators, the NPPs (non-pollen palynomorphs) were not grouped among the pollen taxa and the indicators. Among the types discussed, this study considered foraminiferal test linings; freshwater algae and cuticles because of their environmental significance (Appendix 1- Plates 3 to 5).

5.6.1 Assemblage Zonations

Based on interpretation of the data arrays and the cluster analysis performed with CONISS, four assemblage zones can be recognised in the Gravity Cores studied (see GC1, GC2 and GC3 figures below). The CONISS analysis was performed with TILIA software and based on the percentages of pollen taxa calculated on a sum that excluded Rhizophoraceae.

Rhizophoraceae is deliberately excluded from the zones and indicator pollen group "Mangrove & Coastal Swamp" in the total sum of the pollen percentages, concentration and flux values separately, to avoid a biased record due to the over representation of Rhizophoraceae pollen (Scourse *et al.*, 2005). This approach aided in the original quantitative representation of other taxa in the determination of the prevailing palaeoenvironmental change.

5.6.1.1 Description of the Palynomorph Assemblages from GC1

The following four subdivisions of the palynomorph assemblages in the GC1 are given from bottom to top depth order to reflect the adopted zonation, cluster scheme and chronology (Figure 5.7).

Zone GC1-A1 (275-210 cm)

This zone is characterised by the strong dominance of a hinterland component, namely Lowland Rainforest (Lycopodiaceae, Bryophyta, Pteridaceae, Rubiaceae ~ 5-

40 %) as well as an intermediate proportion of Savannah - Afromontane (Poaceae, ~ 25%) and NPPs (cuticles ~25%).

The pollen concentrations and influx rate from the hinterland component are relatively very high, consisting of 45,000 grains.cm⁻² and 870 grains.cm⁻²yr⁻¹ values respectively. The littoral component representation, especially Mangrove – Coastal and Freshwater Swamp indicators is very low over this interval. Less than ~ 1% of the Freshwater Swamp indicators group was observed in this zone. The percentage of Rhizophoraceae decreases as well (20%).

The Freshwater Swamp indicators were also fairly represented with the exception of Cyperaceae constituting ~ or > 20%. The pollen concentrations and influx rates from the littoral vegetation are relatively very low when compared to the hinterland vegetation in this zone, ranging between 120,000 grains.cm⁻² and 380,000 grains.cm⁻²yr⁻¹ among the indicator groups respectively (Figure 5.7).

Zone GC1-A2 (210-145 cm)

This interval is characterised by high values of littoral composition with a gradual up-hole representation of the Mangrove – Coastal Swamp indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae, ~ < or > 5-75 %) dominating with the close association of low to intermediate representation of Freshwater Swamp indicators (Cyperaceae, Clusiaceae and Arecaceae Nymphaeaceae ~ 3-20 %). With the exclusion of Rhizophoraceae, Avicenniaceae and Cyperaceae dominates throughout the zone. The percentage of Rhizophoraceae increases more (75 %).

The pollen concentrations and influx rates from the littoral component are high. They consist of 365,000 grains.cm⁻² and 770,000 grains.cm⁻²yr⁻¹ respectively. The hinterland vegetation in this zone is characterised by the strong reduction, specifically in the proportion of the Savannah - Afromontane (Poaceae, Podocarpaceae ~ 2-7 %) and NPP (cuticles ~15%). The Lowland Rainforest (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta,

Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 5-20%) is fairly represented by the appearance of Apocynaceae and Bryophyta.

The pollen concentrations and influx rates from the hinterland vegetation are fairly low. This consists of 93,000 grains.cm⁻² and 271,000cm²yr⁻¹ within this interval zone respectively (Figure 5.7).

Zone GC1-A3 (145-85 cm)

Throughout this interval, a different vegetation pattern is observed, which begins with an intermittent increase in the littoral component with the gradual expansion of different floral families of the Mangrove – Coastal Swamp vegetation (Rhizophoraceae, Pteridaceae [*Acrostichumsporites*], Convolvulaceae, Avicenniaceae, ~ 5-65 %). This representation is the most prominent and consistent in this zone. The percentage of Rhizophoraceae increases more compare to other components (~65 %).

The representation of the indicators for Freshwater Swamp vegetation is not too different when compared to Zone GC1-A2 (Cyperaceae, Nymphaeaceae Clusiaceae, and Arecaceae ~ 5-15 %).

The pollen concentrations and influx rate from the littoral component in this zone are about 300,000 grains.cm⁻² and 127,000 grains.cm⁻²yr⁻¹ respectively.

The hinterland component in this zone is characterised by the specific reduction in the percentage indicators for Lowland Rainforest (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 4-21 %). The indicator for Savannah-Afromontane vegetation (Poaceae, Podocarpaceae ~ 3-16 %) is similar to the previous zones. NPPs (cuticles ~8%) decrease, showing a different relationship when compared with the underlying intervals.

The pollen concentrations and influx rates from the hinterland vegetation decrease. They consist of 61,000 grains.cm⁻² and 470,000 grains.cm⁻²yr⁻¹ respectively (Figure 5.7).

Zone GC1-A4 (85-0 cm)

The uppermost zone is characterised by the most abundant and prominent peak of littoral vegetation, with an abrupt expansion of the different floral families associated with Mangrove – Coastal Swamp vegetation indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae Fabaceae, ~ 5-75 %), except the Convolvulaceae family. The Rhizophoraceae count increases consistently (~80%). The representation of the Freshwater Swamp vegetation indicators is low when compared with the indicators of Mangrove-Coastal Swamp vegetation except the Clusiaceae and Arecaceae.

The pollen concentrations and influx rates from the littoral vegetation in this zone are 510,000 grains.cm⁻² and 270,000 grains.cm⁻²yr⁻¹ respectively.

The hinterland vegetation in this zone is characterised by the sharp and consistent decline in the percentages of the indicators for Lowland Rainforest (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 3-18 %) with the exception of Bryophyta and Apocynaceae which peaked slightly. There is a coeval decline in the peak of the Savannah – Afrotropical vegetation indicators (Poaceae~ 2-3 %). NPPs (cuticles ~ 9%) value is similar to Zone GC1-A3.

The pollen concentrations and influx rates from the hinterland vegetation decreased. The values are 146,000 grains.cm⁻² and 220,000 grains.cm⁻²yr⁻¹ respectively (Figure 5.7).

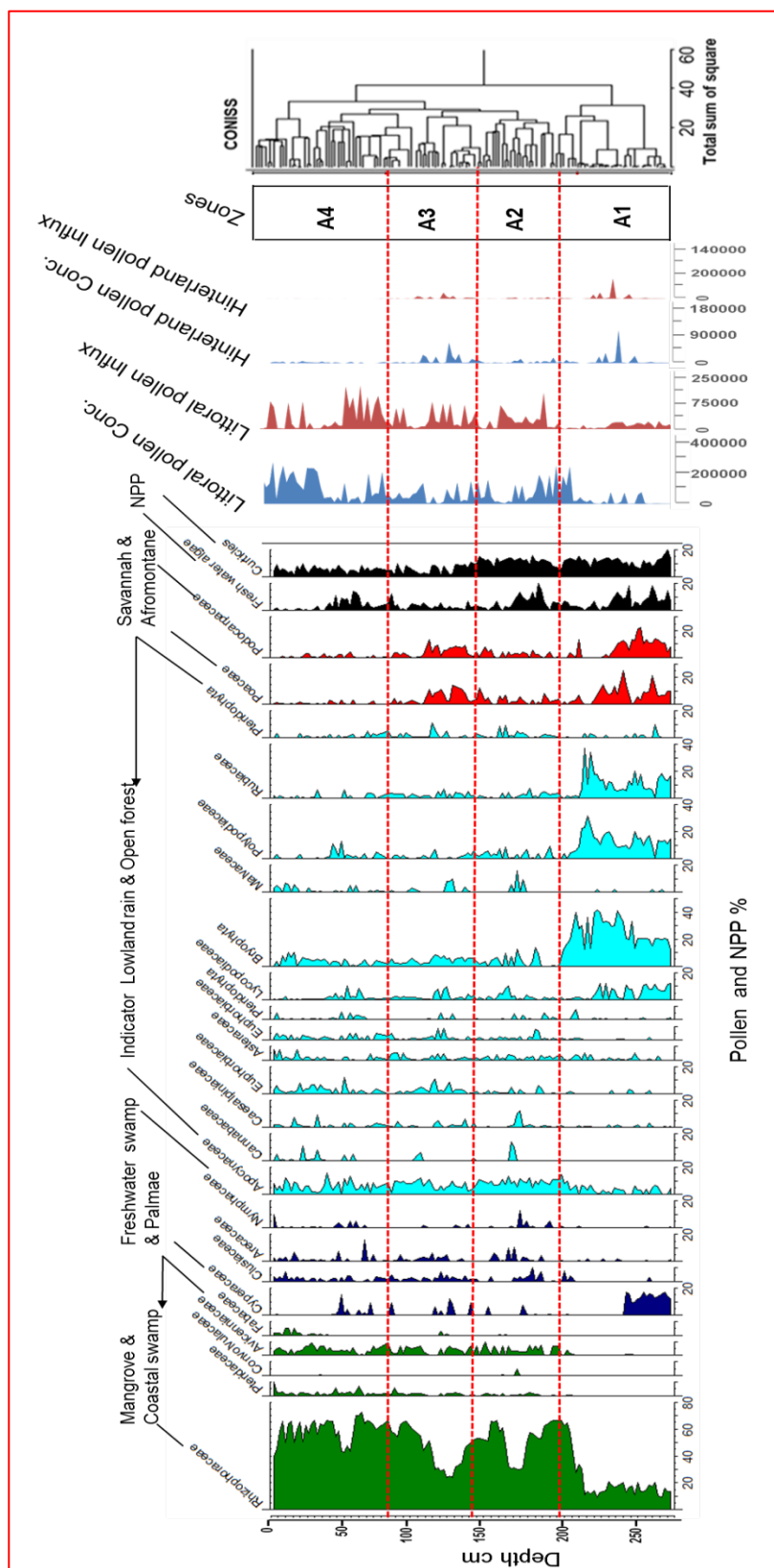


Figure 5.7. Relative Palynomorph Distribution diagram and proposed zonation for GC1. Note that Rhizophoraceae percentages were calculated on a total pollen sum basis, whereas other pollen taxa percentages were calculated on the pollen sum excluding Rhizophoraceae. Footnote on family and species diagram (see Table 4.6 and Section 5.4) for more details.

5.6.1.2 Description of the Palynomorph Assemblages from GC2

The following four subdivisions of the palynomorph assemblages in the GC2 are given from bottom to top depth order to reflect the adopted zonation, cluster scheme and chronology (Figure 5.8).

Zone GC2-B1 (266-205 cm)

The lowermost interval zone of the GC2 includes a prominent peak in the hinterland component, especially the Lowland Rainforest vegetation (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 5–60 %). The peak of the Savannah – Afromontane in the GC2 (Poaceae, Podocarpaceae ~ 5-25 %) increases in proportion, but not as close to the percentage of Lowland Rainforest vegetation. The percentage of the NPPs (cuticles ~ 8%) begins with a brief increase at the base of this zone.

The pollen concentrations and influx rates from the hinterland component increase similarly to Zone GC1-A1, ranging between 26,500 grains.cm⁻² and 14,600 grains.cm⁻²yr⁻¹ respectively. Littoral vegetation begins with an intermittent decline in the Mangrove –Coastal Swamp vegetation indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae ~ 0-20 %). The contribution of Rhizophoraceae is also low on average in this interval (21%).

Percentages of aquatic taxa - indicators for Freshwater Swamp vegetation (Cyperaceae, Nymphaeaceae Clusiaceae, and Arecaceae ~ 0-20 %) increased especially the Cyperaceae (~ 28%). The pollen concentrations and influx rates from the littoral vegetation in this zone are very low when compared to the average, ranging between 1,380 grains.cm⁻² and 1,400 grains.cm⁻²yr⁻¹ respectively. Other species from the littoral and hinterland vegetation not mentioned in this zone were absent or show very low concentrations deemed to be of no significant value (Figure 5.8).

Zone GC2-B2 (205-160 cm)

This zone, unlike the underlying zone, is characterised by a gradual increase of littoral components beginning with Mangrove – Coastal Swamp vegetation indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae ~ 5 - 65%). The percentage of Rhizophoraceae increases as well (65%). The indicators for Freshwater Swamp vegetation (Cyperaceae, Nymphaeaceae Clusiaceae, and Arecaceae ~ 5-10%) are well-spread throughout this zone, but the percentages of the dominant Cyperaceae declines.

The pollen concentrations and influx rate from the littoral vegetation in this zone are very high when compared on the average, ranging between 1,340 grains.cm⁻² and 12,000 grains.cm⁻²yr⁻¹ respectively.

The prominent hinterland component among the Lowland Rainforest vegetation (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 5 - 20%) declines within this zone, but Apocynaceae and Bryophyta were fairly represented among other species. The Afromontane – Savannah vegetation indicators (Poaceae, Podocarpaceae ~ 2-12%) and the NPPs (cuticles 5%) also is constant in proportion.

The pollen concentrations and influx rates from the hinterland vegetation decreases, with the values 1,800 grains.cm⁻² and 850 grains.cm⁻²yr⁻¹ respectively (Figure 5.8).

Zone GC2-B3 (160-98 cm)

Following the B2 Zone, this interval is characterised by a slight decline of the littoral components beginning with the Mangrove-Coastal Swamp vegetation indicators during the presumed interglacial period (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae ~ 5-20 %). The percentages of Rhizophoraceae increase and decrease as well (20-40 %). The Freshwater Swamp vegetation

(Cyperaceae, Nymphaeaceae Clusiaceae, and Arecaceae ~ 2-9 %) show a slight increase.

The pollen concentrations and influx rate from the littoral vegetation in this zone are not high. These consist of 1,200,000 grains.cm⁻² and 9,200 grains.cm⁻²yr⁻¹ respectively. The hinterland component in this zone intermittently increases and then decreases. The Lowland Rainforest vegetation (Bryophyta, Polypodiaceae, Apocynaceae, Rubiaceae~ 3-22%) increased in this zone along with other families such as Euphorbiaceae and Apocynaceae being fairly represented among the species. The indicators for Afromontane – Savannah vegetation (Poaceae, Podocarpaceae ~ 2-3 %) increased slightly, along with the intermittent peak of NPPs (cuticles 3%).

In this zone, pollen concentrations and influx rates from the hinterland vegetation increased on average within the zone. These include 4,900 grains.cm⁻² and 3,900 grains.cm⁻²yr⁻¹ respectively (Figure 5.8).

Zone GC2-B4 (98-0 cm)

This zone commences with the highest and dominant peak of the littoral component with a rapid expansion of Mangrove – Coastal Swamp vegetation indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae, Fabaceae ~ 4-60%) with the exception of Convolvulaceae that are not recorded. The percentage of Rhizophoraceae increases up-hole, to its highest record of 65% followed by Fabaceae family.

The representation of the Freshwater Swamp vegetation indicators decreases (Cyperaceae, Nymphaeaceae Clusiaceae, and Arecaceae ~ 5-20 %) with all the families being present within the zone. The pollen concentrations and influx rates values consist of 1,050,000 grains.cm⁻² and 10,400 grains.cm⁻²yr⁻¹ respectively.

The hinterland component in this zone is characterised by the sharp and consistent decline in the percentages of the lowland rainforest vegetation indicators (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioidea, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae,

Polypodiaceae, Rubiaceae ~ 4 – 20%). In all the families, Apocynaceae and Asteraceae increase slightly, suggesting this trend is clearly different within this interval, when compared with the other intervals above. There is also a consistent decline in the peak of Savannah- Afromontane vegetation indicators (Poaceae and Podocarpaceae ~ 3-5 %). NPPs (cuticles ~ 4%) decreased in abundance. The pollen concentrations and influx rates from the hinterland vegetation decreased. The values are about 1,000,900 grains.cm⁻² and 1,800 grains.cm⁻²yr⁻¹ respectively (Figure 5.8).

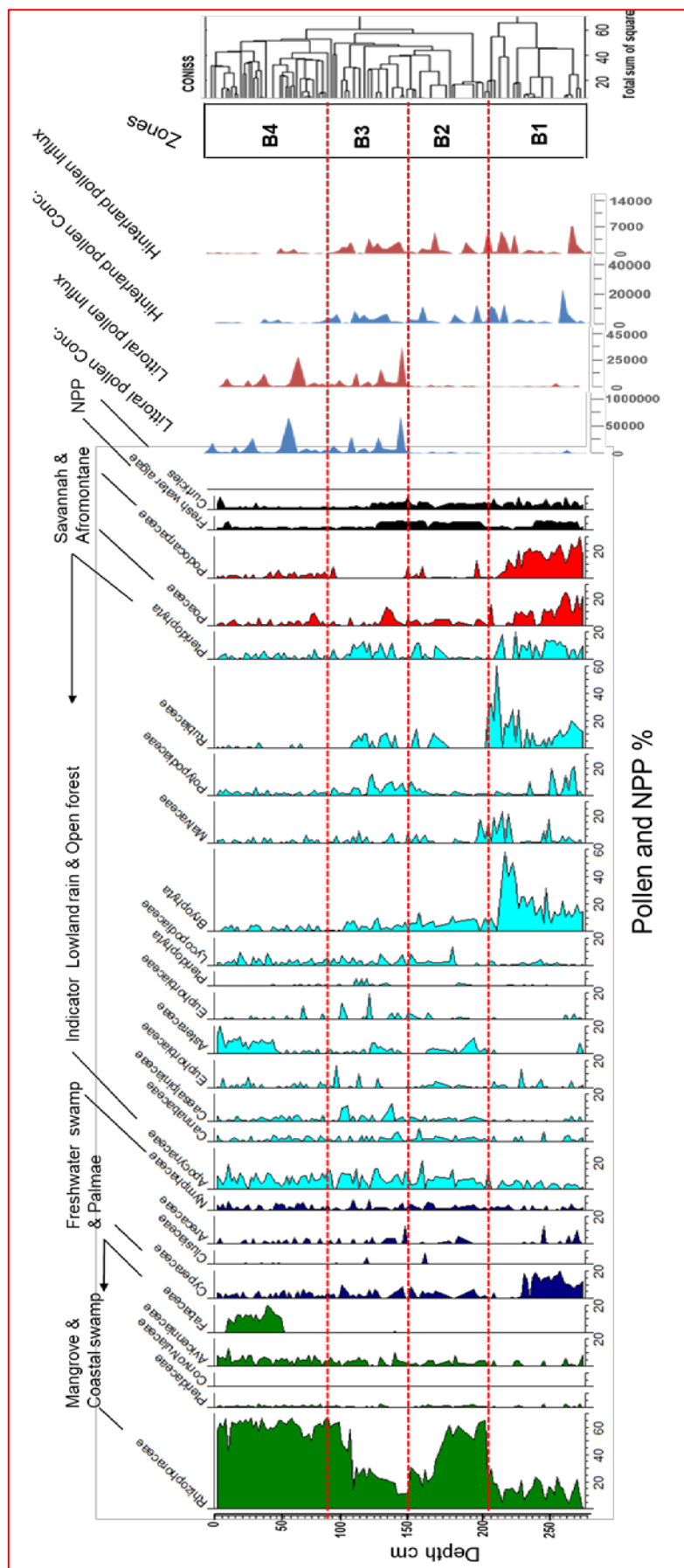


Figure 5.8. Relative Palynomorph Distribution diagram and proposed zonation for GC2. Note that Rhizophoraceae percentages were calculated on a total pollen sum basis, whereas other pollen taxa percentages were calculated on the pollen sum excluding Rhizophoraceae.

5.6.1.3 Description of the Palynomorph Assemblages from GC3

The following four subdivisions of the palynomorph assemblages in GC3 are given in bottom to top depth order to reflect the adopted zonation and cluster scheme (Figure 5.9).

Zone GC3-C1 (260-190 cm)

This zone is also characterised by the prominent expansion of the hinterland component consisting of the Lowland Rainforest and Afromontane – Savannah vegetation. The Lowland Rainforest vegetation (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 5-35%) increased more in comparison to other families. Therefore, in this zone, the peak of Savannah – Afromontane (Poaceae, Podocarpaceae ~ 5-25%) increases in proportion, as well as, the percentage of Lowland Rainforest vegetation. The percentage of the NPPs (cuticles ~ 7%) also increases in this zone.

The pollen concentrations and influx rates from the hinterland vegetation increase relative to the total pollen count. These consist of 42,000 grains.cm⁻² and 1,800 grains.cm⁻²yr⁻¹ respectively.

The littoral vegetation begins with a sporadic decline in the Mangrove – Coastal Swamp vegetation indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae ~ 0-20 %). The Rhizophoraceae is low as well (20%) at this interval.

The percentage of the aquatic taxa - Freshwater Swamp vegetation indicators (Cyperaceae, Nymphaeaceae Clusiaceae, and Arecaceae ~ 0-30 %) (as hydrophytic adapted plants) increases in this zone proportionately.

The pollen concentrations and influx rates from the littoral vegetation in this zone are very low when averages are compared to their equivalent units in the GC1 and GC2. These consist of 27,000 grains.cm⁻² and 290 grains.cm⁻²yr⁻¹ respectively (Figure 5.9).

Zone GC3-C2 (190-140 cm)

This zone recorded a gradual increase of the littoral component beginning with the Mangrove–Coastal Swamp vegetation indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae ~ 5-70 %). Rhizophoraceae count increases gradually (60-70%) up-hole.

The Freshwater Swamp vegetation indicators (Cyperaceae, Nymphaeaceae, Clusiaceae, and Arecaceae ~ 3 – 6 %) decline up-hole. The pollen concentrations and influx rates from the littoral vegetation in this zone are very high when averages are compared with the other equivalent sections. They consist of 79,000 grains.cm⁻² and 640 grains.cm⁻²yr⁻¹ values respectively.

The prominent hinterland component in the Lowland Rainforest vegetation declines, but the three families (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 5-21%) present in this zone increase slightly, when compared with other families in the same group. The Afromontane - Savannah vegetation indicators (Poaceae, Podocarpaceae ~ 2-5 %) also declined along with the NPPs (cuticles ~ 5%), but Podocarpaceae increases slightly among the two families.

The pollen concentrations and influx rates from the hinterland vegetation decrease. These include 1,130 grain.cm⁻² and 550 grains.cm⁻²yr⁻¹ in this zone respectively (Figure 5.9).

Zone GC3-C3 (140-75 cm)

This zone is characterised by an intermittent decline and increase of the littoral component beginning with the Mangrove–Coastal Swamp vegetation indicators (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae ~ 5- 40 %). Percentage counts of Rhizophoraceae decline slightly as well (40%). The indicators of Freshwater Swamp vegetation (Cyperaceae, Nymphaeaceae, Clusiaceae, and

Arecaceae ~ 5-40 %) increased relative to the underlying interval zone. Cyperaceae increased relatively when compared to the previous interval.

The pollen concentrations and influx rates from the littoral component in this zone are fairly high when compared on the average. These include 100,800 grains.cm⁻² and 26,600 grains.cm⁻²yr⁻¹ respectively.

The hinterland component in this zone consisting Lowland Rainforest vegetation (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 5-25 %) decreased in this zone except Apocynaceae and Euphorbiaceae. The Afromontane – Savannah vegetation indicators (Poaceae, Podocarpaceae ~ 2-4 %) reciprocally decreased with alternating higher peaks of some hydrophytic adapting pollen (e.g. Asteraceae), whereas the NPPs continued to decline (cuticles ~5 %).

The pollen concentrations and influx rates from the hinterland component decreased and then increased against a slight average within the zone, ranging between 760 grains.cm⁻² and 600 grains.cm⁻²yr⁻¹ respectively (Figure 5.9).

Zone GC3-C4 (75-0 cm)

The highest interval of this core begins with the most abundant and noticeable peak of littoral components with an abrupt expansion of the Mangrove – Coastal Swamp vegetation indicators, with the exception of Convolvulaceae and Fabaceae families which were not recorded (Rhizophoraceae, Pteridaceae, Convolvulaceae, Avicenniaceae ~ 4-80 %). The recovery of Rhizophoraceae increases more when compared to other zones (up to 80%).

The representatives of the Freshwater Swamp vegetation indicators decrease (Cyperaceae, Nymphaeaceae, Clusiaceae, and Arecaceae ~ 3-18 %) with all the families being present in this interval zone.

However, the reappearance of Cyperaceae and Nymphaeaceae may suggest a different source of vegetation input within this zonal interval. The pollen concentrations

and influx rates from the littoral component in this zone consist of 900,800 grains.cm⁻² and 140,800 grains.cm⁻²yr⁻¹ respectively.

Whereas the hinterland component in this zone is characterised by the sharp and consistent decline in the percentages of the indicator Lowland Rainforest (Apocynaceae, Asteraceae, Lycopodiaceae, Cannabaceae, Caesalpinioideae, Euphorbiaceae, Pteridophyta, Euphorbiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae ~ 2 – 26%), overall the families increase slightly. It was also noticed that there was a slight peak in Apocynaceae and Euphorbiaceae families when compared with other families in this same zone.

Furthermore, there is a consistent decline in the peak of the Savannah – Afromontane vegetation indicators (Poaceae, Podocarpaceae ~ 2-4 %), whereas the percentage of Polypodiaceae decreases slightly when compared to other families in the zone.

NPPs (cuticles ~ 4%) consistently decline in this zone. The pollen concentrations and influx rates from the hinterland component decrease. They consist of 660 grains.cm⁻² and 480 grains.cm⁻²yr⁻¹ respectively (Figure 5.9).

5.6.2 Conclusions

- In this chapter, four results from the sedimentological, geochemical, micropalaeontological (foraminiferal) and palynological analysis of each of the GCs were described based on their physical, structural, botanical and morphological criteria. Analyses of these multi-proxy results enable each core to be subdivided into four distinct intervals that indicate a sequential related evolving environment to provide the basis for interpretation/discussions in subsequent chapters.
- Moreover, similar family names exist as indicators of different ecosystem habitat groups, but variation from species to species in each of the palaeovegetation belts were identified. This method is among the recent study from the Niger Delta to adopt this exclusive method to reduce bias interpretation that could arise due to

the diverse nature of tropical pollen. This will form the yardstick for the palynomorph interpretation in subsequent chapters as well.

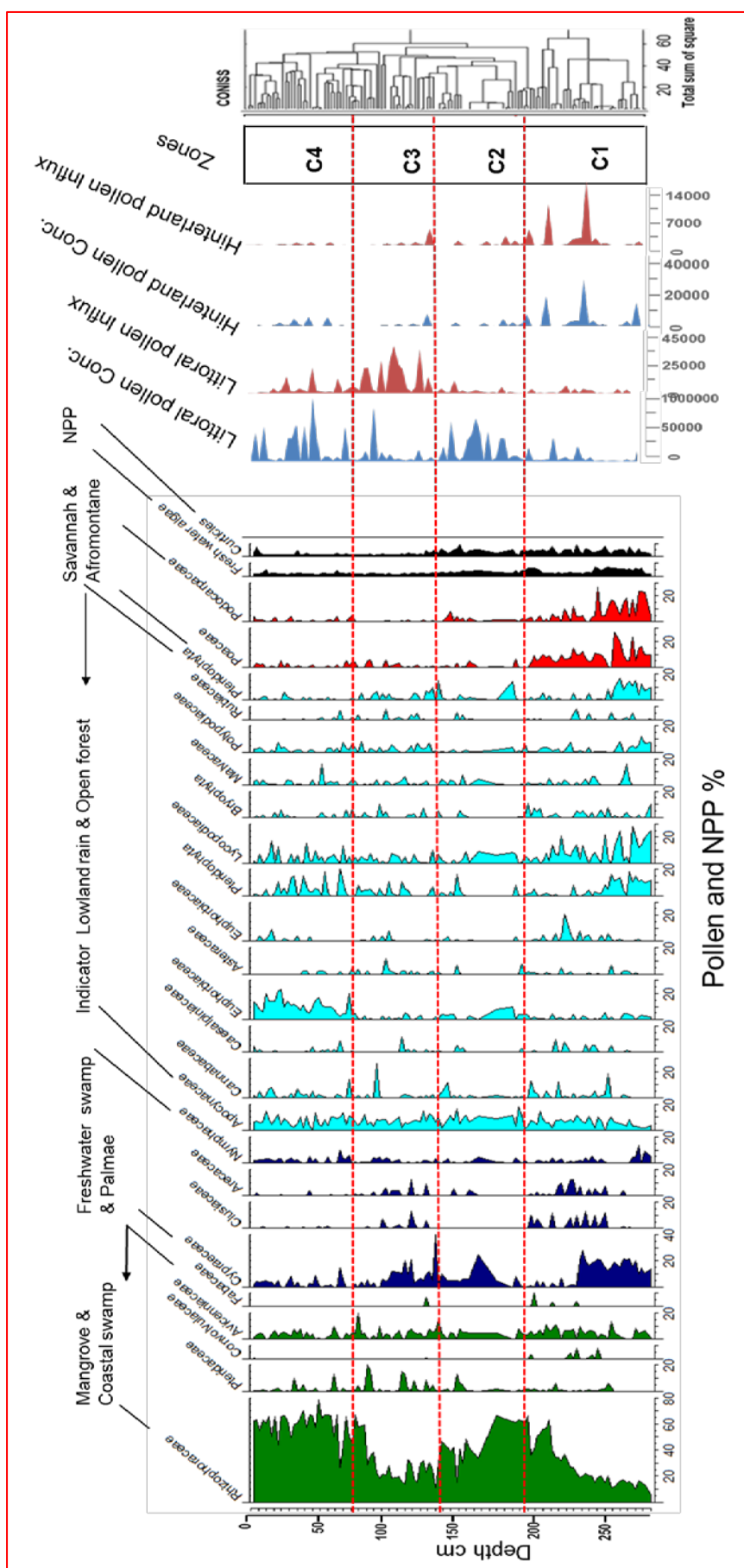


Figure 5.9. Relative Palynomorph Distribution diagram and proposed zonation for GC3. Note that Rhizophoraceae percentages were calculated on a total pollen sum basis, whereas other pollen taxa percentages were calculated on the pollen sum excluding Rhizophoraceae.

Chapter 6: Interpretation of Physical Properties and Calcareous Microfossil records

Highlights

- The interpretations of each proxy apart from the palynomorph data were robustly evaluated here
- Linked to the interpretations, a summary of the sedimentology, geochemistry, foraminiferal and grain size of the three GCs is provided in graphical form
- Datasets from each proxy linked to different controls (e.g. sea level, sediment supply) and the chronostratigraphy demonstrate their impacts on the sedimentary environments and coastal evolution of the Niger Delta
- Environmental change in the present context was driven by sea level change and sediment supply after ~20ka in relation to the strength of the monsoon
- These sporadic controls and connections between physical inputs and outputs of sediments/microfossil components studied here enable the reconstructions of two regional evolutionary stages of sedimentary budgets in this region

6.1 Interpretation of Results

Studies of the Late Quaternary Niger Delta have categorised different sedimentary units based on lithofacies alone (Allen, 1964; Oomken, 1974). Since this time, an array of techniques has been developed to provide a more detailed insight into the spatial correlation of sedimentary sequences and palaeoenvironments, which can afford us the ability to unlock past physical and natural processes with more confidence and rigour.

Three key sedimentary palaeoenvironments have been identified from the GCs study on the basis of the lithofacies and other proxies. It is very important to emphasise that the use of the foraminifera in this study was initially meant for the age evaluation of the GCs but, drawing the models of Murray (1991) that can be applied to the datasets it was later applied for environmental interpretations of GCs.

Other data considered in this Chapter are the geochemistry and Grain Size Analysis results from the GCs (Tables 4.3-4.5). Both Ti/Zr vs. Fe/S ratios are very

helpful in fingerprinting terrestrial and marine sources. High values of Ti/Zr ratio suggest a fluvial discharge from the terrestrial catchment, whereas high values of Fe/S ratio indicate an inherent marine environment and *vice versa* (Tables 4.3-4.5). This is because Ti and Zr components are obtained from the weathering of basaltic granites during wetting and drying of the rock during seasonal climate variations. On the other hand, Fe elements are deposited during post-weathering and transportation of felsic rocks, whereas S is released by marshes, mud volcanoes, hot springs and other places on land, and in oceans where biogenic decay and marine sedimentation is taking place (Marius and Lucas, 1991; Doktrogrades, 2004).

In addition, the geochemistry of the GCs was also interpreted along with the sedimentary grain size. The interpretation undertaken is to determine the control and source of direction of the sediment supply at the prevailing period. Fine-grained silt and clay are usually indicative of calm shallow water, lagoonal and shoreface deposits which are important sea level indicators. The distinction between fine and medium fractions provides the basis applied in the interpretation and discussion of the particle size results. Medium-grained sand indicates a highly energetic fluvial regime. Fine-grained sand suggests normal conditions of a low energy sedimentary environment or an overall quiet depositional environment influenced by settling processes. The intercalation of sands and silt indicates an aggrading process and generally quiet environment influenced by settling processes. The distinction relates in a way to the energy regime of the depositional setting which has been shown to differentiate between calm, settling conditions, storm episodes and fluvial discharge during sea level rise and could also disappear in some cases during sea-level fall and siltation (Kakroodi *et al.*, 2012).

6.1.1 GC1 Lithological Interpretation

GC1-Z (272 - 185 cm)

The geochemical record shows high values of Ti/Zr and low values of Fe/S ratios in this unit. This suggests a fluvial transport of terrestrial sediment from the continental setting into the Niger Delta (source-to-sink). Originally deposition of sediments took place under continental conditions but, were subsequently remobilised and redeposited within the marine realm basin (Adegbie *et al.*, 2003) (Table 4.3).

Based on the description and interpretation of the data above, and the observed characteristics of this unit from the sedimentary succession (Lithofacies Type: MS), the depositional environment could be inferred as middle neritic/pro-delta due to the occurrence of *Elphidium* sp., *Lagena* sp., *Ammonia beccarii*, and *Globorotalia truncatulinoides* microfaunas (Adegoke, 1975; Murray, 1991) (Figures 6.1; 6.2; Plate C).

GC1-Y (185 – 120 cm)

Geochemical records throughout this unit shows intermediate values of Ti/Zr and Fe/S ratios, suggesting a mixing of transported sediments within the marine realm (Adegbie *et al.*, 2003) (Table 4.3).

The combination of the geochemistry, sedimentological facies (Lithofacies Type: SF) with the presence of *Ammonia beccarii*, sporadic appearance of *Globigerinoides ruber*, *Globorotalia* spp., *Cibicidoides* spp., *Melonis* spp., *Uvigerina* spp. and *Bolivina* spp., suggests a tidal flat series of depositional environments (inner – middle neritic or delta front *sensu* Allen, 1965) (Figures 6.1, 6.2; Plate C).

GC1-X (120 - 60 cm)

This unit shows a decrease in the values of Ti/Zr ratio, whereas the Fe/S ratio increases thereby influencing a mixing of transported sediments within the marine setting (Zabel *et al.*, 2001) (Tables 4.3).

Based on the foraminiferal ratios, geochemical concentrations and sedimentological results (Lithofacies Type: FS), the environment of deposition is suggested to be middle neritic due to the presence of a miliolid microfauna

(*Quinqueloculina buena*, *Triloculina* sp.), *Globorotalia* sp., *Uvigerina* spp. The lower part of this unit indicates a sequencetial short-lived, highly organic rooted swamp environment, characterised by temporarily inundated conditions and preservation (Allen, 1964 and Cattaneo *et al.*, 2004) (Figures 6.1, 6.2; Plate C).

GC1-W (60 - 0 cm)

The geochemical concentration results for this unit show a low Ti/Zr ratio, whereas the Fe/S ratio increases. These variations suggest marine dominated sediments, and a complete shift to a marine based depositional setting (Adegbeie *et al.*, 2003). This condition relates to a period of anoxia due to the increase in the concentration of Fe and S contents (Table 6.3). The combination of the interpreted data set with sedimentology (Lithofacies Types: SF and FS) and the occurrence of *Glorobotalia tumida*, *Uvigerina* spp., *Bolivina* spp., *Loxostomoides* spp. and *Globorotalia* spp. suggest a lagoonal to coastal plain/delta plain depositional environment (Allen, 1964; Murray, 1991) (Figures 6.1, 6.2; Plate C).

6.1.2 GC2 Lithological Interpretation

GC2-A (266 - 220 cm)

The geochemical results over this unit show a high Ti/Zr ratio, whereas Fe/S ratio decreases, indicating a fluvial sedimentary transport source from weathered soil component in the marine setting (Adegbeie *et al.*, 2003) (Table 4.4).

Interpretation of these results, sedimentological description (Lithofacies Type: MS) and the foraminiferal assemblages entirely represented by euryhaline benthic species such as *Elphidium* sp., *Ammonia beccarii*, Miliolidae (*Quinqueloculina* sp. and *Triloculina* spp.) indicate a similar environment when compared with GC1 Unit Z. Although planktonic foraminiferal types *Globigerinoides ruber* and *Globorotalia truncatulinooides* were present, they are very rare. The combined presence of these relative facies (lithofacies, chemofacies and biofacies) suggests a middle neritic or (pro-delta) environment (Adegoke 1975, Murray, 1991) (Figures 6.1, 6.3; Plate C).

GC2-B (220 - 135 cm)

The sediment source in this unit consists of intermediate values of Ti/Zr and Fe/S ratios. These similar ratios suggest a transition of sedimentary source typical of the continental and marine setting (Zabel *et al.*, 2001) (Table 4.4).

Combination of the geochemical, sedimentological (Lithofacies Type: SF) and foraminiferal ratios suggests a lagoonal - inner neritic or delta front based on the presence of *Globigerinoides ruber*, *Globorotalia tumida*, *Quinqueloculina buena*, *Triloculina* spp., *Cassidulina* sp., and *Melonis* sp. (Allen, 1964; Cattaneo *et al.*, 2004) (Figures 6.1, 6.3; Plate C).

GC2-C (135 - 70 cm)

The geochemical concentrations of the sediments in this unit demonstrates a decrease in the Ti/Zr and increase in Fe/S ratios. This attribute indicates a sedimentary source typical of the marine setting (Zabel *et al.*, 2001) (Table 4.4).

The above interpretation, in combination with the sedimentary core descriptions (Lithofacies Type: FS), and the foraminiferal ratio suggests a lagoonal depositional environment or delta plain based on the presence of *Bolivina* sp., *Globigerinoides ruber*, *Globorotalia tumida* and *Uvigerina* sp. (Adegoke, 1975; Cattaneo *et al.*, 2004) (Figures 6.1; 6.3; Plate C).

GC2-D (0 - 70 cm)

In this unit the Ti/Zr ratio decreases whereas the Fe/S ratio increases towards the uppermost part of the GC2 core (Table 4.4). This variation suggests a marine deposited sedimentary source (Adegbie *et al.*, 2003).

The combination of sedimentological descriptions (Lithofacies Types: SF and FS) in this unit with the foraminiferal assemblages such as *Ammonia* sp., *Cassidulina* spp. *Globigerinoides ruber* and *Globorotalia tosaensis* suggests a lagoonal to coastal plain or delta plain depositional environment (Adegoke, 1975; Murray, 1991) (Figures 6.1, 6.3; Plate C).

6.1.3. GC3 Lithological Interpretation

GC3-R (260 - 220 cm)

The Ti/Zr ratio increases, whereas the Fe/S ratio decreases in this unit, suggesting a fluvial sedimentary source to the marine setting (Zabel *et al.*, 2001) (Table 4.6).

The combination of geochemical concentration and sedimentological descriptions (Lithofacies Type: MS), and the co-occurrence of consistent traces of calcareous nodules suggests a low-energy depositional environment. The presence of very small benthic foraminifera such as *Melonis* spp., *Ammonia beccarii*, with the preservation of *Globorotalia tumida* species that occur exclusively in mangrove marshes and brackish water ponds suggests a middle neritic (pro-delta front) depositional environment (Allen, 1965; Cattaneo *et al.*, 2004) (Figures 6.1, 6.4; Plate C).

GC3-S (220 - 160 cm)

The Ti/Zr ratio increases, whereas the Fe/S ratio in the sediments decreased in this unit, suggesting a fluvial controlled sedimentary source (Zabel *et al.*, 2001) (Table 4.5).

The combination of the sedimentological description (Lithofacies Type: SF) and the presence of *Uvigerina* spp., *Globigerinoides ruber*, *Globorotalia tumida* and *Lagena* spp., links this unit to either a lagoonal to inner neritic or deltaic front setting, indicating high energy depositional environment (Adegoke, 1975; Murray, 1991) (Figures 6.1, 6.4; Plate C).

GC3-T (160 - 70 cm)

The geochemical concentration of the sedimentary source shows a decrease in the Ti/Zr ratio, whereas the Fe/S ratio increases in this unit, suggesting a marine sedimentary source (Zabel *et al.*, 2001).

Combination of the geochemical elemental concentrations, sedimentological descriptions (Lithofacies Type: FS) with foraminiferal ratios suggests an delta plain depositional environment based on the presence of *Uvigerina* spp., *Bolivina* spp., *Globigerinoides ruber*, *Globorotalia* spp. (Murray, 1991, Cattaneo *et al.*, 2004) (Figures 6.1, 6.4; Plate C).

GC-U (70 - 0 cm)

In this unit the Ti/Zr ratio decreased, whereas the Fe/S ratio increases towards the upper most part of the core, indicating a marine sedimentary source (Adegbe *et al.*, 2003).

Combining the above result with the sedimentological description (Lithofacies Types: SF and FS), and with the occurrence of *Uvigerina* spp., *Globigerinoides ruber*, *Globorotalia tumida* and *Lagena* spp., this facies indicates a lagoonal or coastal plain (delta plain) depositional environment (Adegoke, 1975; Murray, 1991). (Figures 6.1, 6.4; Plate C).

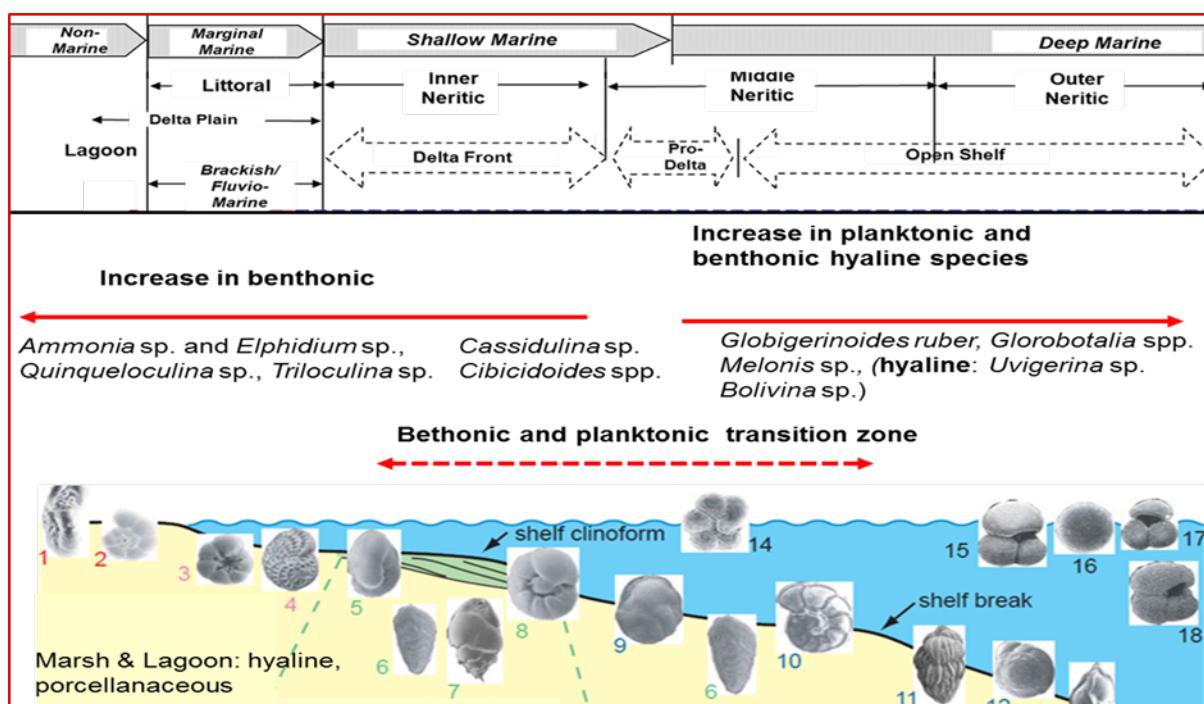


Figure 6.1. Schematic expression of gross sedimentary environments and foraminiferal distributions: (1-3 *Ammonia beccarii*, 4 *Elphidium* sp., 5 *Cassidulina* sp., 6 *Bolivina* sp., 11 *Uvigerina* spp., 12 *Cibicidoides* sp., 8 *Globorotalia inflata*, 18 *Globigerinoides ruber*) (modified after Allen, 1964 and Cattaneo *et al.*, 2004).

6.2 Discussion

The morphological characteristics and the evolution of any fluvio-deltaic embayment system are determined by the interaction of several factors, including the precursor geomorphology of the receiving basin, tidal current, wave regime, storms, sediment supply and the fluvial discharge (Plater and Kirby, 2011; Figure 2.10). To

forecast future changes, the understanding of what has occurred in the past and what is happening at the present, a multi-proxy dataset consisting of sedimentology, micropalaeontology and geochemistry facies (bio-geofacies) components were integrated to discuss the coastal lithostratigraphic evolution of the region. Therefore, the section below establishes how these changes could be modelled to deduce the coastal evolutionary history of the Niger Delta in time and space.

6.2.1 Controls on the Chronostratigraphic Evolution of the Niger Delta

Following the aforementioned interpretation of the physical properties and calcareous microfossil records, this section examines the deltaic facies evolution with particular attention to the interplay between the major driving mechanisms of sediment supply and the Late Quaternary stratigraphic succession of the Niger Delta (Study Objective 5). These discussions are outlined in order of their chronological successions as follows:

- Late Pleistocene (20-11 ka)
- Early Holocene (11-8.5 ka)
- mid-Holocene (8.5-6.5 ka)

6.2.1.1 Late Pleistocene Record (20-11 ka)

It was observed that increasing grain size has a significant influence on the Ti/Zr and benthic/planktonic ratios preserved during this time (Figures 6.3-6.5). A possible interpretation of an external source (e.g. fluvial transport) of influence on the marine setting of the Niger Delta could be suggested during this time frame (Figure 6.5). The record from the age models in Chapter 4 suggests sedimentary influx during this period (GC1 = 9.8cm/kyr; GC2 = 13.8cm/kyr; GC3 = 13.1cm/kyr) (Figures 4.6-4.8). The combined multi-proxy dataset interpreted during this period suggests that Lithofacies Type MS is most likely of middle neritic or pro-deltaic depositional origin (Figure 6.1). Contrary to these records, the South East Asia region, sitting in a low latitude setting like the Niger Delta, suggests that similar particle size (medium sandstone) is more of fluvio – tidal source (Huang and Zong, 1982). This discrepancy may be due to the pattern and timing of sea level change affecting each region.

In addition, this study records have also shown that GC1 and GC3 contain predominantly benthic foraminifera with 10% to 25% of planktic species during this time. This trend varies differently with the GC2 data. In the GC2, benthic and planktic ratio is about 50% (Figures 6.3-6.5). Perhaps it could be suggested that the discrepancy between the values recorded is due to some of environmental conditions mentioned above, and also as stated in Chapters 2 and 4.

Given this condition during this time frame, an increase in the Ti/Zr ratio and decrease in the Fe/S ratio has also been recorded. Consequently, it can be assumed that the increase in the Ti/Zr ratio from the three GCs indicates an increase in the fluvial discharge to the Niger Delta from a similar provenance through rapid sedimentation rates (Figures 6.3-6.5) during the sea level lowstand (Figures 6.2-6.4). This similar fluvial discharge is possibly related to an abrupt palaeodischarge change which was first recorded in West Africa from the Congo Fan (GeoB 1007-4) by Marret *et al.* (2001). The reflection from the Ti/Zr ratio and Lithofacies Type MS (medium sand and sedimentary structure) during the fresh water runoff could be linked to the influence of a weak monsoon and seasonal migration of the ITCZ with a mean position around 13° N and further 10° S during the last glacial maxima (Leroux, 1993).

6.2.1.2 Early Holocene Record (11–8.5 ka)

The Early Holocene lithofacies record in this study is defined by Lithofacies Type SF (soft silty very fine sand and rare clay) sequence (Figures 5.1-5.3). This sequence consists of fine grained sediments deposited in an intermediate to low energy sedimentary system with accumulation rates of: GC1 = 72 cm/kyr; GC2 = 51 cm/kyr; GC3 = 51 cm/kyr, pulsated by eustatic sea level rise (Fletcher, 2005) (Figures 4.6-4.8). Absence of medium sand during this period relates to reduced fluvial control on the GCs sediments and significantly weaker control from tidal currents. Traces of marine bioturbation provide an indication of biologically active conditions characteristics of low energy deltaic environment with burrowing of gastropods and echinoderms.

Moreover, during this period the planktonic foraminiferal percentage increases more (over 60%) when compared to the benthic foraminifera (Figures 6.2-6.4). From our records, this transition also witnessed a sharp decrease in the value of Ti/Zr and increase in the Fe/S ratios indicating a shift from glacial (MIS2) to interglacial (MIS1)

conditions marking the onset of sea level transgression and slow sedimentation rates. (Figures 4.6-4.8) (Adegbie *et al.*, 2003; Lucas and Marius, 1991). Consequently, this study therefore proposes that the resultant environment suggests a change from pro-delta to delta front environment (Figure 6.1). In other words, it could also indicate a period of gradual shelf transgression which indicates an onset of the marine influence and incursion on the coastal Niger Delta triggered by the intensification of summer insolation and WAM (Weldeab *et al.*, 2007).

6.2.1.3 Mid-Holocene Record (8.5–6.5 ka)

Following the successive periods above is another episode linked to the regional sea level inundation across the West African coast. During this period our record suggests sedimentary succession of Lithofacies Types SF and FS (an intercalation of silty clay and fine sand) which is slightly different from that recorded from the Early Holocene. This period is punctuated with similar changes in the depositional environments at the three GCs, with change to high energy regime conditions. The observation from the sedimentation rate suggests a consistent deceleration in accumulation rate but, with increased thickness after 8.5ka with short-term sedimentation rates of: GC1 = 6.2cm/kyr; GC2 = 6.2cm/kyr; GC3 = 6.2cm/kyr. (Chapter 4). Consequently, the lithological features suggest a major change in depositional system from a gradual to episodic trend (Fletcher, 2005) (Figure 6.1). Given this, the period suggests a shift from low energy to tidal conditions/higher energy current conditions (Allen, 1964; Oomkens, 1974). Although, these distinct changes were observed from the intervals recorded above (Figures 6.2-6.4), it is difficult however to describe the sedimentary sequences recorded between these intervals.

This is because there is not much change observed from the lithofacies descriptions when compared to the previous Early Holocene and subsequent Late Pleistocene time periods. In addition, it is very important to highlight that the retrograding sediment which has also been observed from the sedimentary settings in the Mississippi, Yangtze Delta and Ganges-Brahmaputra Deltas have such a distinctive change like the Niger Delta (Zong *et al.*, 2009; Reijers, 2011). Interpreting such an environment under this condition is complex because of the mixed nature and prograding delta (Reijers, 2011). Therefore, it should be suggested that the best

possible way that the successive environments could be interpreted in this situation (mixed nature and prograding delta) is through the application of marine microfossils.

Notwithstanding, given the preposition above, the mid-Holocene records have shown a progressive change in grain size values and benthic/planktonic, Ti/Zr and Fe/S ratios between the intervals delineated above (Figures 6.2-6.4). The critical observation above suggests consistent and dominant lithofacies types SF and FS in the GC2 and GC3. However, this differs from the GC1 during this period. An interpretation was enabled in addition to the observation recorded above with the reduction of the benthic and increase in the planktonic foraminifera (about 70%) in the GC2 and GC3, but quite different in the GC1 record (Figures 6.2-6.4). In addition to the above difference in the GCs, this study presumes that these distinct changes observed between the GCs during this time frame was controlled by the optimum Mid-Holocene sea level rise affecting the delta plain to pro-delta environmental succession (Lezine *et al.*, 2005; Reijers, 2011) (Figure 6.1). Similar to the present records, transgressive deposits and features of this type have also been observed in cores from the Holocene Rhine and Rhone Deltas (Oomkens, 1974) (Figures 6.2-6.4).

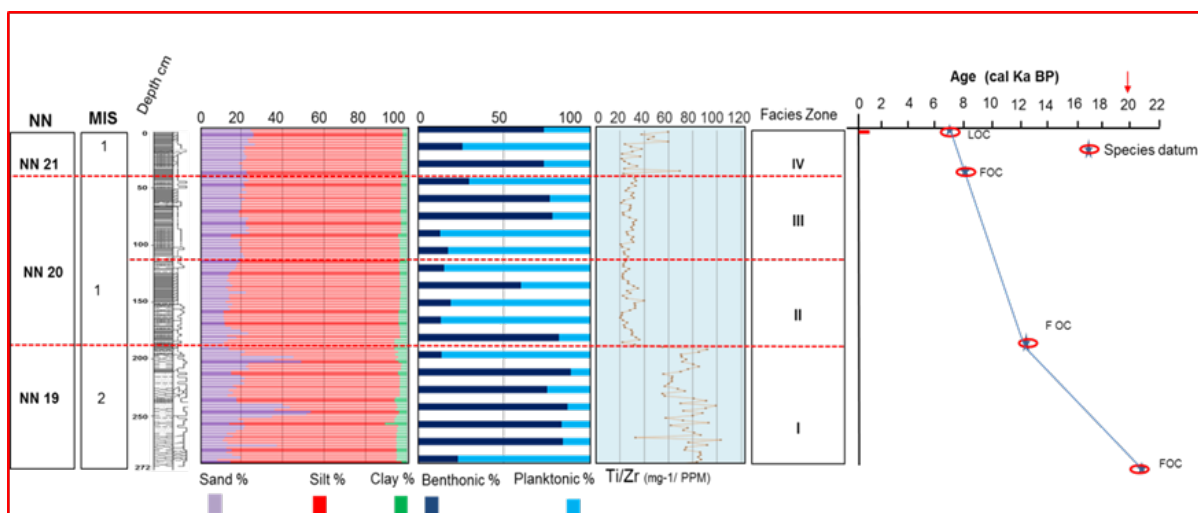


Figure 6.2. Stratigraphic evolution of the lithofacies, biogeochemical and sedimentation rate records for GC1.

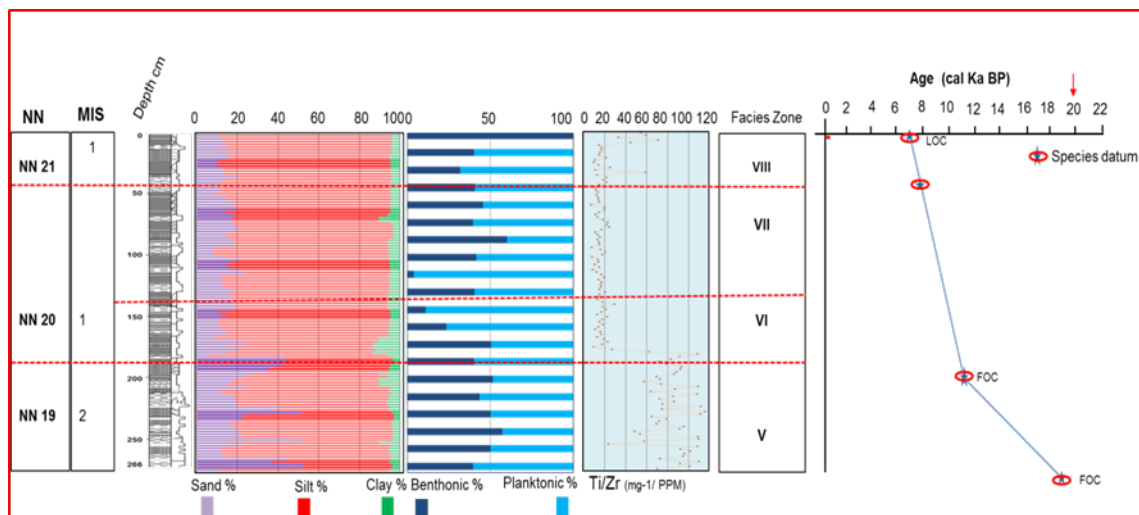


Figure 6.3. Stratigraphic evolution of the lithofacies, biogeochemical and sedimentation rate records for GC2.

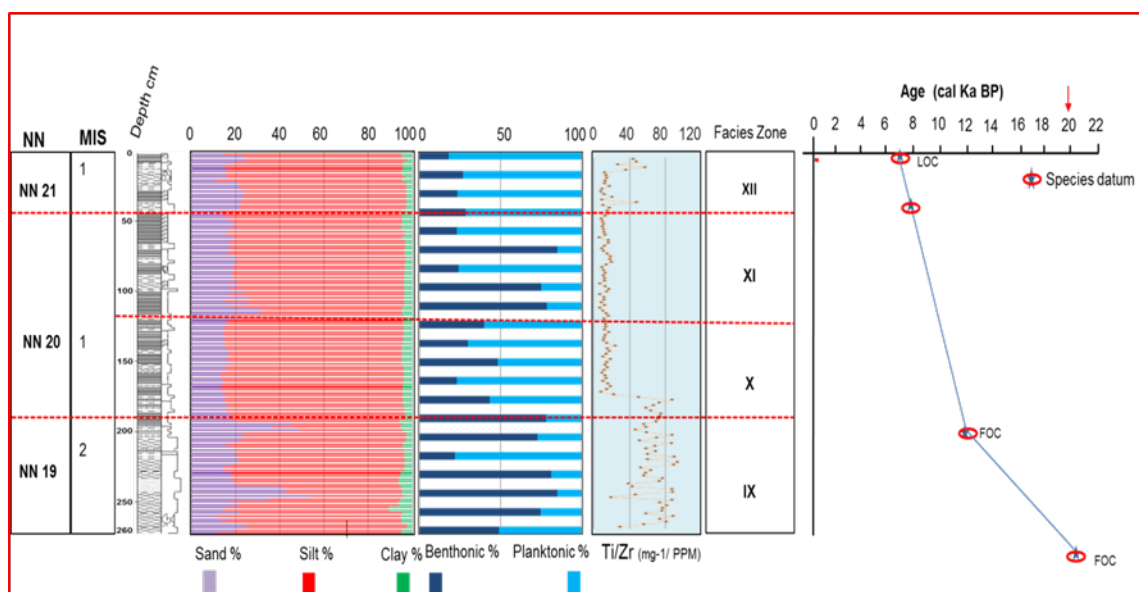


Figure 6.4. Stratigraphic evolution of the lithofacies, biogeochemical and sedimentation rate records for GC3.

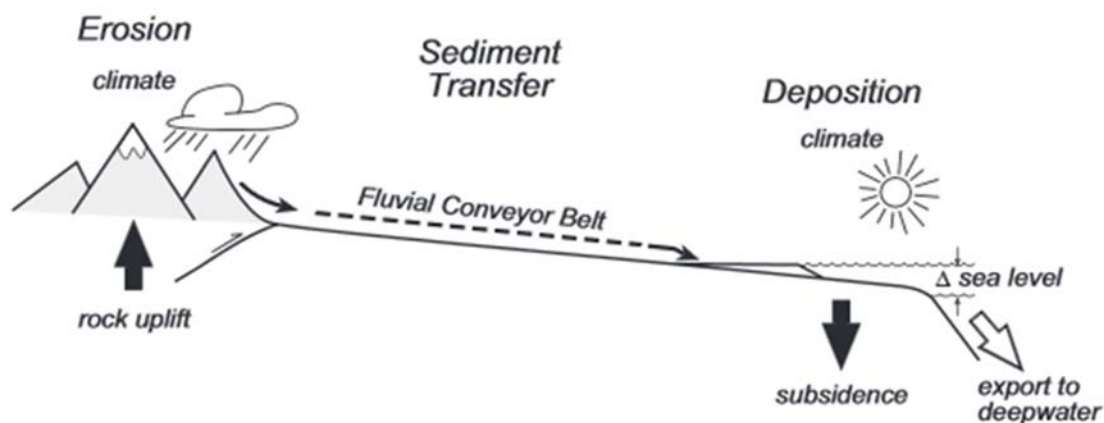


Figure 6.5. Source-to-sink concept in sediment supply, showing tectonic hinterland source where the sediment is produced, the fluvial transportation process that convey the sediment to the continental shelf (shoreface) and basin floor fan (modified after Castellort and Van Den Driessche, 2003).

Given the above discussions through time, the sedimentological features and grain size components consisting of sand/silt layers at the base of the GCs show some fining-upward sequence trends are considered to be quite distinct when compared with the middle and uppermost parts of the cores (Figures 5.1-5.3). The addition of foraminiferal and geochemical results combined with the grain size data also show many similarities, but with a slight difference between the deltaic environments interpreted from the three GCs. The chronostratigraphic diagrams show the position of the shoreline through time, indicating the migration distance of sedimentary deposits (Figures 6.2-4).

In addition, this section proposes that the source of the fluvial transport to the Niger Delta sedimentary environment observed from the GCs could be linked to intermittent weathering up-river triggered by the prevailing climate (Castellort and Van Den Driessche, 2003) (Figure 6.5). The source of this sediment could also have been influenced by the wet and dry climate variables of the south eastern Mamfee embayment of Nigeria, Oban Massif and Cameroon volcanic rock provinces considering the similar observation from their geochemical characteristics (e.g. Adegbe et al., 2003) (Figure 2.14).

6.2.2 Comparison of GC Data with other Deltas during Post-Glacial Periods

This section presents a summary on the comparison of the data derived from the Gravity Cores with those from other regions where it is suggested that climate and depth of water controlling the delta progradation are the major factors controlling delta evolution are evaluated here (Morgan, 1970; Doust and Omatsola, 1990; Reijers, 2011). Similar to the records shown in the previous section, where the sedimentary succession has shown a complex dominance of silty sand and pulses of laminated clay, Oomkens (1974) and Allen (1964) have also proposed such models in the past (e.g. Rhine, Rhone and Mississippi deltas). The similarities from both records indicate that the Niger Delta sedimentation pattern could have been forced or controlled by the same global factors (hydrodynamic, climate and sediment supply) driving other deltas such as the Mississippi and Rhine.

Furthermore, core sections in the Mississippi Delta have shown an abundant supply of fluvial sediment and river mouth bar shoreface characteristics, descending towards the basin during delta progradation (Gould, 1970; Gosian *et al.*, 2005). For the Rhone Delta, a similar trend was recorded from the cyclic sedimentation patterns triggered by post-glacial sea level regression and transgression. In this study, the data suggests that amongst the sandy-silt deposits with the fine sandy-clay removed, fluvio-estuarine processes could have triggered the subsequent erosion, through lateral transportation and re-deposition within coastal barriers on the delta plain reaffirming the control of coastal deposition by wave - tidal processes (Oomkens, 1974; Reijers, 2011).

Given this comparison with the similar records observed from the GCs data, this study suggests similar depositional control during the post-glacial sea level rise across the Niger Delta. Finally, in relation to the previous discussions (Section 6.3), and the comparisons among the deltas reviewed, it can be assumed that the morphology or geometry of the lithofacies types developed in the deltas were strongly dependent on the amount of sediment transported into the riverine channels and the surrounding delta through time. (e.g. Riboulot *et al.*, 2012).

6.2.3 Controls and impacts on Sediment Supply on the Coastal Evolution on the Niger Delta

In this section, the information obtained from this chapter based on the integration of multiple data sets (micro and macrofossils, geochemistry and sedimentology), in which every data set complements each other, represents a powerful tool for the understanding of the lithostratigraphic evolution of the Niger Delta. It also becomes clear that the deltaic palaeoenvironments evolution of the Niger Delta could be better understood using different proxies instead of a singular method based upon sedimentological criteria alone (e.g. Allen, 1964 and Oomkens, 1974). Moreover, in this section, different controlling mechanisms were explored to determine those considered to be influencing the sedimentary and geochemical records of the Niger Delta (Chapter 2), but among the controlling types, sea level change and sediment supply seem very promising to substantiate the evidence that the Niger Delta progrades during the Late Pleistocene, whereas it retrogrades in the Holocene (Figure 6.6). The coherence of the integrated dominant facies shows significant variations at the middle to the topmost part of the three GCs. Given this, a possible suggestion on the impact of the mid to Early-Holocene transgression could have triggered the dominant facies change during the interglacial period (MIS1), supporting the assumption of a strengthened WAM, “subsequent delta retrogradation and sea level retreat” (Figure 6.6). Conversely, during the Late Pleistocene regression, the bottom of the GCs sequences shows a contrasting facies variations during the late glacial period (MIS2) supporting the assumption of a weakened WAM, linked to the episode of “palaeodischarge and delta progradation” (Figure 6.6). In a nutshell, understanding the potential variability of WAM linked to ancient deltaic sequences where there is no potential control prominent in the Quaternary could be substantial value in decoding the past signals more thoroughly.

Given the above precepts, this study identified two sedimentary sequence orders consisting pro-delta to delta plain in the stratigraphic architecture of the Eastern to Western Niger Delta and calibrated their biostratigraphic ages into absolute ages (Figure 6.6). Comparing the records from GCs with those from other deltas has entertained the opportunity to discussed casual relationships and proposes that the key influence on the shift in delta depositional patterns was climate-driven sea level

change impacting sediment supply for the two time-periods in relation to the variation of WAM (20-11 ka; and 11-6.5 ka)

Thus, in addition to past studies (e.g. Jermannaud *et al.*, 2010) in the region, two relative episodes of sediment supply controlling the evolution of the coastal margins of the Niger Delta during the time frame are:

- 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 11ka;
- Global sea level change (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) (Figure 6.6).

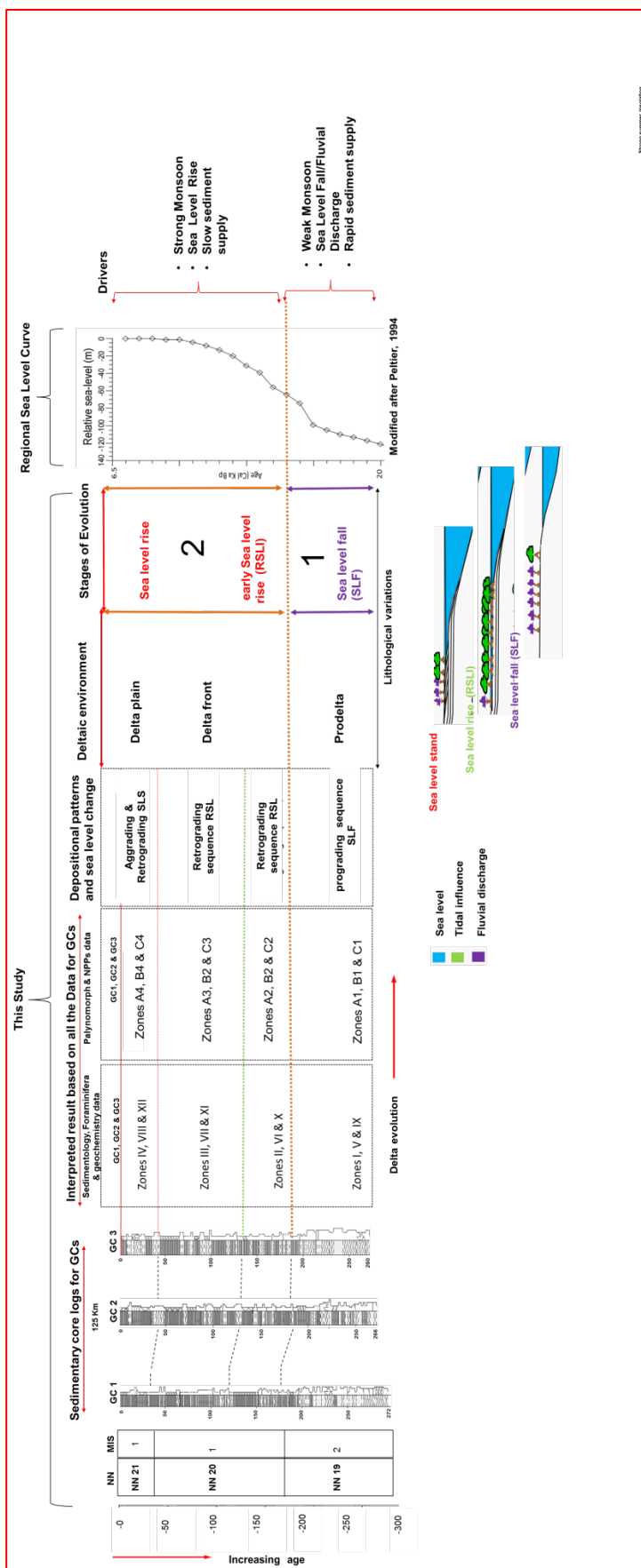


Figure 6.6. Schematic expression of the lithostratigraphic evolution of the Niger Delta in relation to the regional sea level changes and sediment supply based on GCs data.

Note:

All the zones consist of the data evaluated from geochemistry, foraminifera, grain size and sedimentology (See Result Chapter 5)

Given the two episodes above, it becomes imperative to confirm that the rate of sea-level rise after the post-glacial period discussed earlier could be non-linear, and on the global trend, linked to the initial period of rapid rise, and subsequently by the sporadic sea rise (Peltier, 1994) (Figure 6.6). Therefore, because the depositional architecture of the Late Pleistocene coastal system probably evolved from a prodelta to a delta front lower shoreface deposit, it becomes obvious that the deltaic plain-upper shoreface in response to relative sea-level fall and rise (20ka to 6.5Ka) impacted on the sediment supply of the Niger Delta signifying that there was no significant shift in the deltaic lobe after 11 ka (Jermannaud *et al.*, 2010) (Figure 6.6).

This complex process leads to variations in recession rates as the shoreface setting of the Niger Delta retreats, so even with constant sea levels, erosion rates may vary with time (and places). It can be suggested that the multiple proxy results contributed to the long term evolution of the littoral coastline, and in particular the influence of underlying core-lithologies on sediments and starved systems. A sediment starved coastline can be defined as a coastline where the sediment supply is inadequate to build up a protective shoreface capable of regulating recession rates. Whereas transported sediments is when the sediment supply is sufficiently transported to build up the protective littoral continental shoreface. Within a coastal environment the rate of change of sedimentation is dependent on the amount of transport into the system versus the amount of sediment that leaves the system.

Drawing on the conclusions above, the wider consequences of these findings based on sediment supply are considered here. The main contribution is related to the improved understanding of transgressive and lowstand shoreface interactions observed between the evoked climate-sea levels driving or controlling the littoral-coastal sediments of the Niger Delta, with variable lithological facies (GCs) changes in relation to the chronostratigraphy and strength of West African Monsoon system (Figure 6.6). These inputs and outputs of sediments then equate to the balance of the system, and frequently reflect the amounts of erosion or accretion affecting the coastal morphology. Notwithstanding, the present study exclusively observed an average shift in the deltaic lobe during the studied time frame. However, the current shift in the paradigm of exploration activities from onshore to offshore Niger Delta would rather impact on the coastal succession due the continuous pressure resulting from human

interference and heavy equipment (e.g drilling rig). Consequently, the future trend or shift of the coastal Niger Delta may increase unequivocally in the region. Thus, ahead of time this study perhaps provides two stages of input and output of sediments for the past 20ka which could be used as a yardstick for future study and prediction.

Moreover, this relationship should perhaps be important for the reconstructions of sedimentary budgets and coastal management especially the Eleme and Bonny areas (beehive of activities for crude oil refining) of the Niger Delta currently facing aggressive flooding, land loss and coastal erosion or incision.

6.3 Conclusions

- This chapter concludes by highlighting the impact of sea level and sediment supply variations on the littoral swamp and deltaic environments based on micro and macrofossils, geochemistry and sedimentology, linking the timing and nature of changes in shallow coastal succession during the early Holocene to mid-Holocene, and Late Pleistocene development of the Niger Delta.
- As a further contribution to the future preservation and sustainable development of the deltaic coastline, it becomes significant that constraining the littoral coastal stratigraphy and sedimentary evolution of the Niger Delta should improve our understanding of the main control (WAM) processes, response and shift in the depositional environment to the near shore coastline during the sea level rise (Figure 6.6).
- This finding could serve intergovernmental and local planning agencies concerned with coastal shifts and exploration of the environment in a wider regional perspective by informing policies to protect and mitigate any adverse effects of sea level change due to global warming in the region ahead of time.

Chapter 7: Interpretation of the Palynomorph records

Highlights

- Spatial observation of the changes in palaeovegetation patterns on the basis of hinterland vs. littoral vegetation and NPPs results evolved during MIS1 and MIS2
- The chronological interpretation of palynomorph data enabled the deduction of warm and dry climatic intervals from the GCs, and the factors controlling their evolution / mode of transportation/dispersal from their catchments
- The role of climate drivers (ITCZ and WAM) in relation to the variations of palynomorph/geochemical data shows evidence of terrestrial and marine record across the Niger Delta through time
- Observable interpretations permit a re-evaluation of the controls in relation to the two stages in palaeovegetation and coastal evolution of the Niger Delta

7.1 Interpretation of Palynomorph Records from the GCs

The following pollen taxa and NPPs types below have been selected in association with other pollen families to increase the reliability of the new pollen families adopted for the study of palaeoenvironmental interpretation. They are follows:

Cyperaceae pollen

This is a freshwater swamp and aquatic pollen (White, 1983). Their presence in marine sediments can be explained by fluvial remobilisation from the river mouth during arid climate phases. In the West African Margin, influx of Cyperaceae pollen has been recorded in sediments from the Gulf of Guinea (e.g. Niger Delta) (Dupont and Weinet, 1996). The terrestrial source area is indistinguishable due to the fact that it grows in both open grassland and savannah or marshy environment (Dupont and Agwu, 1991).

Podocarpus Pollen

This type of pollen is initially dispersed by wind, and then can be fluvial born, or rafted in marine realm. Its higher occurrence in the marine sediments is indicative of hinterland sediments and dry climates (Dupont *et al.*, 2007). These characteristics have aided in its application in the reconstruction of atmospheric trade winds and aridity (Shi and Dupont, 1997).

Rhizophoraceae Pollen

High representation of *Rhizophora* pollen in marine setting can be explained or discussed by its high pollen production locally, and retention sediments in greater numbers per gram per cm³ of sediment due to its small size (van Campo and Bengo, 2004). Its variation in the marine setting in tropical areas is indicative of sea level change (Morley, 1995; Rull, 2002; Scourse *et al.*, 2005). Association of other mangrove families with *Rhizophora* pollen (e.g. Euphorbiaceae) are related to warm climate and rise of the sea level (Poumot, 1989).

Charred Grass Cuticle

The presence of charred grass cuticles reflects or indicates prevalent wildfires that have occurred during seasonal arid/dry conditions (Morley and Richard, 1993). They are usually dispersed by wind and transported into the marine settings through fluvial processes.

Freshwater Algae

The types of freshwater algae found in this study are *Pediastrum*, *Botryococcus* spp., *Pseudoschizaea ozeanica* and *Ovoidites* sp. Their presence in marine sediments are indicative of fresh water input into the marine realm in which most freshwater algae are distributed in the marine sediments (Morley, 1995).

7.2 GCs Palynomorph records

The section below interprets and discusses the palynomorph records from each of the GCs, which have been divided into four zones, as described in Chapter 6, to distinguish the change in specific indicator groups linking vegetation patterns in relation to their stratigraphic position.

7.2.1 GC1 Palynomorph Record

NN19 = MIS2 (20-11 ka)

The beginning of the Late Pleistocene is marked by a good representation of cold taxa (e.g. Podocarpaceae, Poaceae) that signify cold/dry palaeo-environmental conditions. The taxa (e.g. Podocarpaceae, Poaceae, Lycopodiaceae, Bryophyta, Polypodiaceae, Rubiaceae) that signify cold/dry climate during this time (Figure 7.1). The interval between 275-210 cm is accompanied by significant and rapid expansion of Afromontane Forest (Podocarpaceae), Savannah (Poaceae), Lowland Rainforest (Lycopodiaceae, Polypodiaceae, Bryophyta, Rubiaceae) and presence of dry-land derived charred grass cuticles. Cyperaceae and NPPs also develop synchronously with the expansion of this hinterland vegetation. This period indicates a drier/cooler climate with significant presence of open vegetation during the ~ 20ka (Dupont *et al.*, 2007; Kim *et al.*, 2010; Marret *et al.*, 2013). However, components of Mangrove Swamp vegetation and most of the Fresh Water Swamp vegetation apart from Cyperaceae contribution (thermophilous taxa) decline sharply during this period. The presence of low mangrove pollen is related to the relative lower sea level (~112-135 m) below the present day level (Peltier, 1994; Lezine *et al.*, 2005; Punwong *et al.*, 2013).

NN20 = MIS1 (11-8.5 ka)

At the beginning of the Early Holocene, the period is characterised by a gradual rise of Mangrove–Coastal Swamp vegetation (Rhizophoraceae, Avicenniaceae) and a higher representation of pioneer warm taxa (Rhizophoraceae), whereas those of Lowland Rain–Open forest, Freshwater Swamp–Palmae (Cyperaceae), Savannah–Afromontane and Charred Grass Cuticles showed a marked decline except Apocynaceae (Figure 7.1). The step 1 increase (Phase 1) records the onset of the transition between warm/intermediate climate conditions as indicated by a slight decrease of Mangrove vegetation and reappearance of hydrophitic lowland rainforest plants (Dalibard *et al.*, 2014) (Figure 7.1). An episode in which Lowland Rainforest

partly replaces less water-dependent Savannah-Afromontane and Freshwater Swamp vegetation was observed at the onset of the warm and relatively wetter period. This period signifies a transition from arid to humid conditions during the early Holocene (Lezine and Vergnaud-Grazzini, 1993; Dupont *et al.*, 1998; Scourse *et al.*, 2005; Marret *et al.*, 2013). The significant reduction in Poaceae, Cyperaceae and Podocarpaceae pollen in the GC1 suggests declines in grassland, herbaceous communities and Afromontane forest (Davis and Brewer, 2009).

NN21 = MIS1 (8.5-6.5 ka)

The beginning of the Middle Holocene is characterised by a palynomorph record reflecting an expansion in littoral coastal vegetation (Figure 7.1). This period of rapid increase in Mangrove vegetation trend has been recorded from other African core locations (Dupont and Weinelt, 1996). Step 2 increase (Phase 2) shows a consistent rapid expansion of Mangrove vegetation, and a short-lived expansion of limited warm Lowland Rainforest vegetation controlled by the rise of the sea level during the Hypsithermal event (Lezine and Vergnaud-Grazzini *et al.*, 1993; Scourse *et al.*, 2005).

7.2.2 GC2 Palynomorph Records

NN19=MIS 2 (20-11.7 ka)

Similar to GC1, the distribution of vegetation patterns and NPPs during the glacial period (Late Pleistocene) in GC2, shows comparable major trends. The beginning of NN19=MIS2 is also marked by a good representation of the pioneer cold/dry taxa, whereas those of warm/wet taxa declined similar to the GC1 profiles (Figure 7.2).

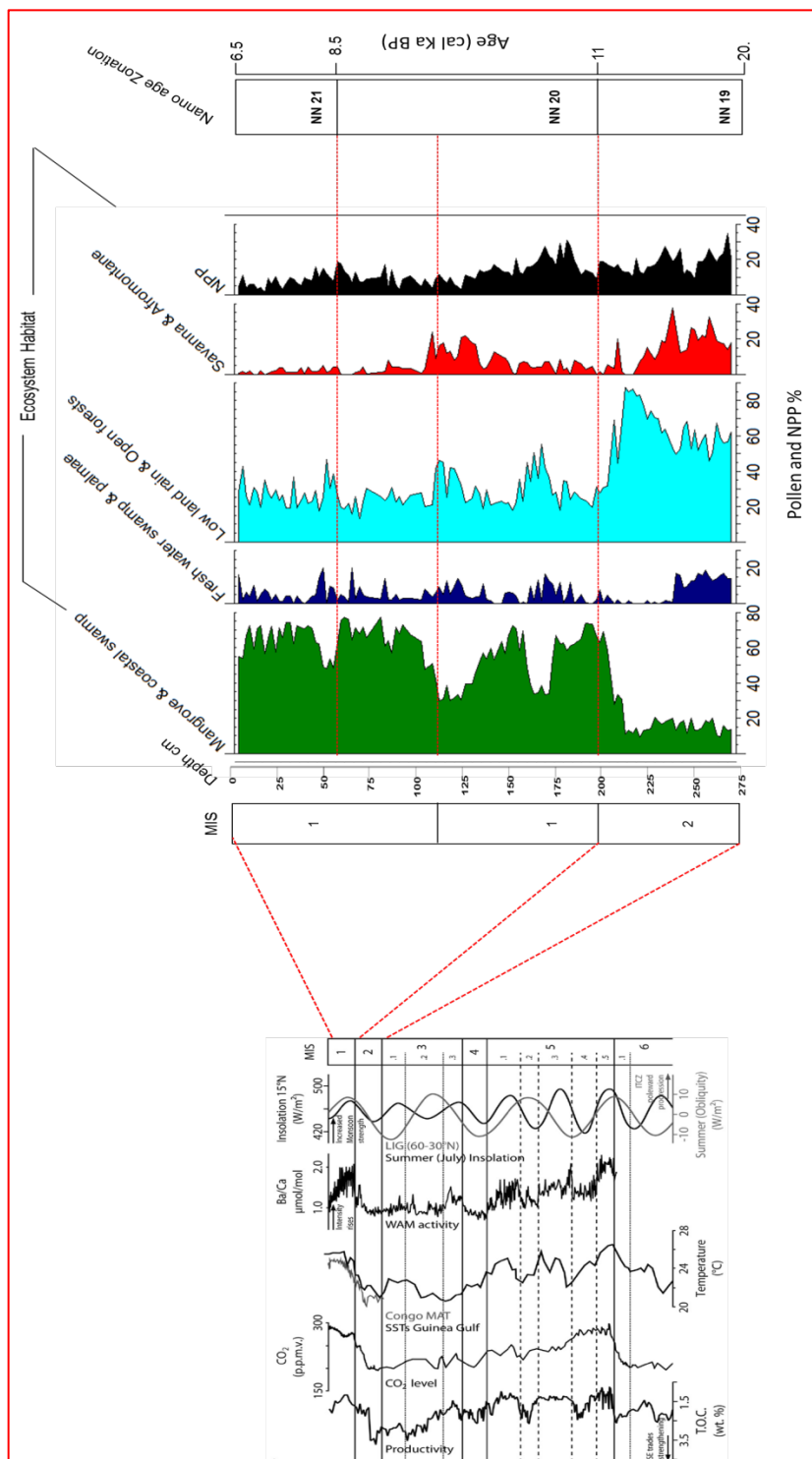


Figure 7.1. Vegetation dynamic diagram of GC1 correlated to MIS 1 & 2 summer LIG 60⁰–30⁰ (Davis and Brewer, 2009); summer insolation curve at 15°N (Berger and Loutre, 1991); WAM system curve of Ba/Ca ratio (Weldeab *et al.*, 2007); Gulf of Guinea SSTs (Schneider *et al.*, 1997) Congo Mean Annual Temperature; Vostok CO₂ level curve (Petit *et al.*, 1992).

The interval between 266-195 cm is characterised by the expansion in the Afromontane forest (Podocarpaceae), Savannah (Poaceae), Lowland Rainforest (Podocarpaceae, Poaceae, Lycopodiaceae, Bryophyta, Malvaceae, Polypodiaceae, Rubiaceae, Pteridophyta) and Charred Grass Cuticles during the Late Pleistocene. Cyperaceae, Clusiaceae, Arecaceae and NPPs also increase with the expansion of a hinterland vegetation similar to GC1. This period suggests a dry climate, with increased aridity. The increase in abundance of Afromontane and Savannah grassland pollen in the sediments might indicate long distance transport of pollen by enhanced atmospheric circulation (Maley, 1991; Jahns, 1996; Shi and Dupont, 1997). During this time, Mangrove Swamp vegetation and most Fresh Water Swamp vegetation (thermophilous taxa) apart from Cyperaceae and Arecaceae decline rapidly relative to the postulated low sea level and corresponding well with past records derived from Western Equatorial Africa (e.g. Lezine and Vergnaud-Grazzini, 1993) (Figure 7.2). Dry and cold Afromontane forest development in central Equatorial Africa has been reported during the time frame from the Niger Delta and Cameroon (Brenac, 1988; Dupont and Weinelt, 1996)

NN20=MIS 1 (11-8.5 ka)

The Early Holocene (NN20=MIS1) is characterised by the gradual rise of Mangrove–Coastal Swamp vegetation (Rhizophoraceae, Avicenniaceae) and a better establishment of pioneer warm taxa. Step 1 increase records indicate a transition between warm/intermediate climate conditions denoted by the slight decrease of the Mangrove vegetation and reappearance of the hydrophitic Lowland Rainforest plant communities (Dalibard *et al.*, 2014) (Figure 7.2). This period suggests warm climatic condition in relation to sea level rise and local expansion of halophytic vegetation which indicates marsh terrestrialisation and encroachment of brackish environments within lagoonal–marsh settings (Fletcher, 2005, Morley, 1995). During this time-frame, hinterland contributing indicators decreased except the Bryophyta, Malvaceae, Rubiaceae, Apocynaceae (Figure 7.2). It is also a period in which the Lowland Rainforest slightly replaces some of the water-dependent Savannah-Afromontane and Freshwater Swamp vegetation. A significant decline in those vegetation types similar to the GC1 suggests a region under grassland, herbaceous communities and Afromontane forest (Poumot, 1989; Davis and Brewer, 2009) (Figure 7.2).

NN21=MIS1 (8.5-6.5 ka)

At the onset of the mid-Holocene, the pollen record in GC2 indicates a two step relative increase in vegetation changes similar to those recognised in GC1 (Figures 7.2). Step 2 increase in GC2 is slightly different from that observed in GC1, whereby it shows an expansion of Mangrove-Coastal Swamp vegetation (Rhizophoraceae, Avicenniaceae) during sea-level rise, coinciding with the Hypsithermal event (Scourse *et al.*, 2005; Marret *et al.*, 2013; Dalibard *et al.*, 2014). Apocynaceae, Asteraceae slightly increases. This period indicates a wetter climate in relation to the rising sea level flooding the adjacent location (Kim *et al.*, 2010).

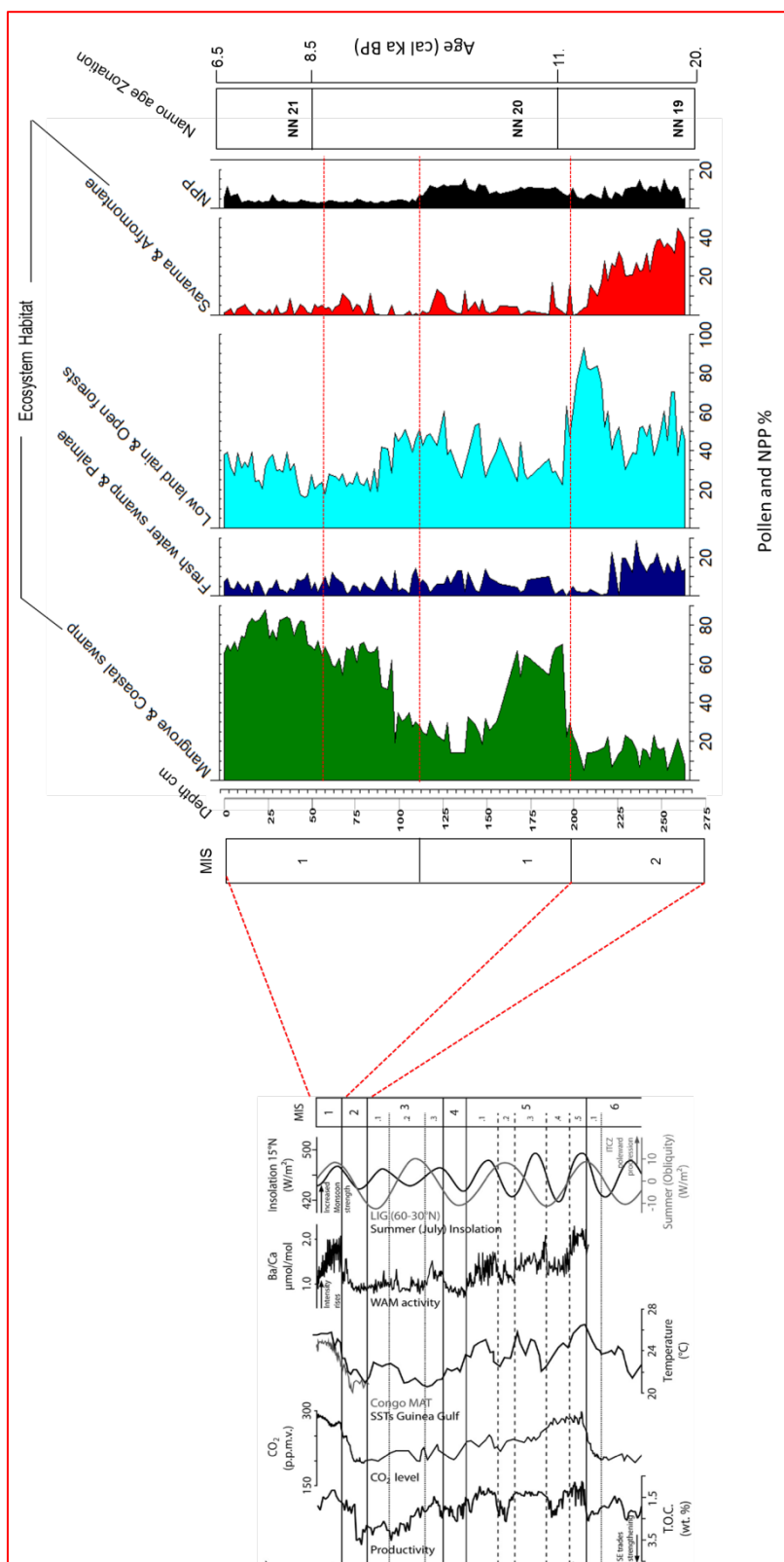


Figure 7.2. Vegetation dynamic diagram of GC2 correlated to MIS1 & 2 summer LIG 60⁰-30⁰ (Davis and Brewer, 2009); summer insolation curve at 15⁰N (Berger and Loutre, 1991); WAM system curve of Ba/Ca ratio (Weldeab *et al.*, 2007); Gulf of Guinea SSTs (Schneider *et al.*, 1997); CO₂ curve (Petit *et al.*, 1992).

7.2.3 GC3 Palynomorph Records

NN19=MIS 2 (20-11 ka)

As with the records and interpretations for GC1 and GC2, similarly the vegetation and NPPs records during the glacial period (Late Pleistocene) in the GC3 show an increase in dry taxa at the base of the cored sequence. This period (NN19=MIS2) is represented by a good record of pioneer cold/dry taxa that were abundant during the Late Pleistocene. The warm/wet taxa show a similar decline up-hole as recorded in GC1 and GC2 (Figure 7.3). This period is accompanied by a rapid expansion in the Afromontane forest (Podocarpaceae), savannah (Poaceae), Lowland Rainforest (Apocynaceae, Bryophyta, Polypodiaceae, Lycopodiaceae, Pteridophyta) and charred grass cuticles during the glacial period.

However, dissimilar to GC1 and GC2, Freshwater Swamp indicators and NPPs from this core increase up-hole. Grassland and open forest existed along the adjacent continent during that time as a source area for recorded pollen and spores families (Dupont and Agwu, 1991). This period is associated with cold/arid climatic conditions.

Furthermore, as discussed previously regarding the GC1 and GC2, Mangrove Swamp vegetation and most Fresh Water Swamp vegetation (thermophilous taxa) also reduce, but with the exception of some of the taxa in GC3 (such as Figure 7.3). The low percentage of mangrove pollen in this period corresponds well with past pollen studies from West Equatorial Africa that identify mangrove expansion, corresponding with exposure of the continental shelf during sea level fall (Dupont, 2000; Scourse *et al.*, 2005). Considering the larger recovery of many pollen types belonging to hinterland habitats and the high values of savannah grass pollen found in the modern marine sediments (e.g. Dupont and Agwu, 1991), the percentages of mangrove pollen obtained in the present study during the glacial time are low. This may be due to the arid conditions prevailing during this time.

Similar to the GC1 and GC2, this result from the dry taxa indicates an expansions of Open forest, Afromontane and Savannah vegetation on the adjacent continent suggesting that the glacial drying/cooling climate prevailed during the LGM in the West Equatorial African regions (e.g. Maley and Brenac, 1998).

NN20=MIS 1 (11-8.5 ka)

After the glacial period, the Early Holocene (NN20=MIS 1) interval is marked by the rapid rise of Mangrove–Coastal Swamp vegetation (Rhizophoraceae, Avicenniaceae) and the establishment of warm taxa coinciding with the warm/wet climate conditions during an interglacial time (Rull, 1997). Step 1 increase of the mangrove vegetation indicates an onset of the Early Holocene showing a transition between warm/intermediate climate conditions denoted by a slight decrease of the Mangrove-Coastal Swamp vegetation and a sporadic reappearance of hydrophitic Lowland Rainforest plant components (Dalibard *et al.*, 2014) (Figure 7.3). Similar to the GC1 and GC2, there was also a significant decline in Savannah and Afrotropical palynomorph records. These similarities among the three GCs described above (pages 105, 110 and 116) suggest a decline of grassland cover in the region (Poumot, 1989; Rull, 2002; Davis and Brewer, 2009). This arid-humid transition is almost similar to the increase of mangrove pollen in Ogouée Fan core MD03-2708 marking the onset of eustatic sea level rise after the Late Pleistocene (Kim *et al.*, 2010).

NN21=MIS1 (8.5-6.5 ka)

The mid-Holocene is characterised again by a two step increase in vegetation change similar to those documented already for GC1 and GC2 (Figures 7c). Similar to the GC1 and GC2, the Step 2 increase offers an interpretation for a rapid expansion of the mangrove vegetation during the Hypsithermal event (Scourse *et al.*, 2005; Marret *et al.*, 2013; Dalibard *et al.*, 2014). A similar pattern has been observed from the mangrove pollen off the Niger Delta, Congo and Angola during this time period (Lezine *et al.*, 2005, Scourse *et al.*, 2005; Kim *et al.*, 2005). This expansion in mangrove vegetation indicates a reduced fluvial input and related monsoon circulation punctuated by lower river discharge during the sea level rise (Marret *et al.*, 2013; Punwong *et al.*, 2013).

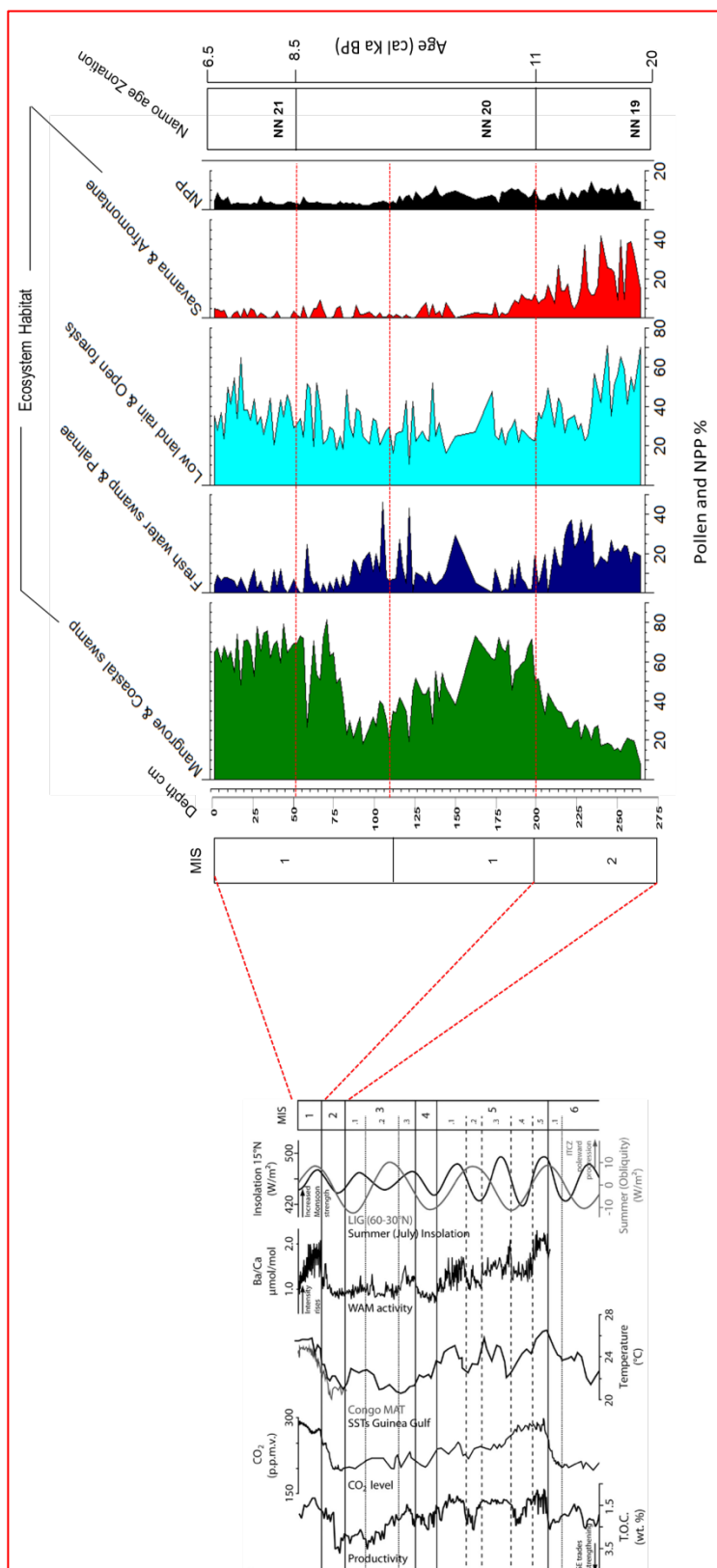


Figure 7.3. Vegetation dynamic diagram of GC3 correlated to MIS 1 & 2 summer LIG 60° – 30° (Davis and Brewer, 2009); summer insolation curve at 15°N (Berger and Loutre, 1991); WAM system curve of Ba/Ca ratio (Weldeab *et al.*, 2007); Gulf of Guinea SSTs (Schneider *et al.*, 1997); CO₂ curve (Petit *et al.*, 1992)

7.3 General Discussions on the GCs Palynomorph Records

7.3.1 Preservation and Dispersal of Palynomorphs

Given the interpretation above, this section presents the significance of palynomorph preservation in relation to the studied GCs. Preservation varies greatly between taxa, and is significantly controlled by ecological and climate factors (Fletcher, 2005). These differences are related to the categories of pollination, palaeoecology and climate factors. In general, a representation of pollen families with increasing distance from the source area is clearly explained (Dafni, 1992), but the actual method of pollen dispersal is controlled by the characteristics of diverse pollen species and the habitat types which control their size, aerodynamic, hydrodynamic and taphonomic (Dupont *et al.*, 2007).

Although, preservation of pollen is of great concern for the interpretation of pollen records, in practice, anaerobic sediments have more potential for pollen preservation (Fletcher, 2005). This is because oxygen was insufficient during anoxia thereby promoting less impact of bacteria degradation on pollen components. On the other hand, severe influence of bacteria degradation on some pollen types in a sedimentary record due to intensive or rapid decay may underscore their absence. In this study, if the above statements hold true, it is not surprising to observe from the studied GCs that Convulaceae and Fabaceae pollen families, which are common littoral pollen in proximal marine records are poorly represented due to this effect biodegradation, whereas Rhizophoraceae, Apocynaceae, Avicenniaceae and Adiantaceae families are very dominant due to their ability to withstand prevailing biodegradation (Fletcher, 2005).

Furthermore, other schools of thought suggest an absence of entomophily (insect pollinated activity) as suggested for the Gulf Coast (e.g. Jardine and Harrington, 2008), as well as the ability of pollen taxa to withstand rigours of higher sedimentation rates, anemophilous (wind pollinated), restricted high flux of charcoal resulting from wildfires, and burning of the palynomorph reproductive organs during pollen germination (Zobba *et al.*, 2011). Given these conditions, it could be concluded that Convulaceae and Fabaceae pollen families from the GCs are susceptible to deterioration under such sedimentation rates during lithification or diagenetic processes as well, when

compared with other mangrove families (Phumphumirat *et al.*, 2009). Thus, it becomes important to consider these factors in the dispersal and preservation of palynomorph in the future for an effective pollen interpretation pollen discussed above (Figures 7.1-7.3).

7.3.2 Controls of Climate Drivers on Palynomorph Records

This section reviews the detail pollen and vegetation records from the GCs in relation to the impact of climate drivers from the Late Pleistocene to the mid-Holocene. The last glacial (Late Pleistocene) and interglacial periods (Holocene) have been marked with significant shifts between extreme climate conditions (wet and dry) in relation to the dynamics of the oceanic and atmospheric circulations (Hessler *et al.*, 2010). The consequence of this interaction in the North Atlantic causes an increase in the average temperature of the surface waters of the North or South Atlantic Ocean. This effect may coincide with a southward shift of the Intertropical Convergence Zone (ITCZ) (EPICA members, 2006; Dupont *et al.*, 2008; Collins *et al.*, 2010). The temperature relationship between oceans and the atmosphere has influenced vegetation distribution in tropical regions, at least after the post-glacial period (e.g. Gasse *et al.*, 2008; Hessler *et al.*, 2010).

Given this relationships (oceanic and atmospheric circulations), the section below discusses how do ITCZ migration and WAM circulation play dominant role on the distributions of palynomorph records in the tropics of West Africa.

This question presents the importance and role of climate drivers (ITCZ and WAM) and sea level in examining the relationship between the tropical West Africa and Niger Delta vegetation dynamic. These discussions will be based on the following bullet points in relation to the terrestrial palynomorph records from the three GCs:

- Migration of the ITCZ and WAM, and their impact on the evolution of vegetation within the Niger Delta.
- Control on the *Rhizophora* and coastal littoral vegetation of the Niger Delta.
- Control and evidence of fluvial palaeodischarge/terrestrial influx on the Niger Delta sedimentary succession.

7.3.2.1 Migration of the ITCZ and WAM, and their Impacts on the Evolution of Vegetation in the Niger Delta

The global climate and vegetation configurations are mainly affected by the position and direction of the ITCZ and the strength of the African Monsoon (Chapter 2; Shannahan *et al.*, 2007). Ocean-atmosphere interaction regulates the position of the ITCZ and thus rainfall patterns and river systems ('the hydrological regime') in tropical provinces (e.g. West Africa) (Graham and Barnett, 1987; Leroux, 1993). The current GCs study clearly records a transition from dry to wet climate (East-West of the Niger Delta) which is inferred to coincide with the hypothesis of WAM circulation and ITCZ migration during the Late Pleistocene to Mid Holocene.

During the last glacial and deglacial period (20-11 ka), the ITCZ migrated towards the southern hemisphere promoting an arid/dry climate and facilitated the expansion of hinterland vegetation and fluvial transportation of grassland pollen (Hessler *et al.*, 2010) (Figures 6 & 7.1-7.3). This expansion from the GCs (depths ~ 272-202 cm) is associated with weak WAM activity presumably causing aridification in the region. In addition to this successive scientific fact the lowland and warm ocean air circulation contributed further to continental aridity influencing dry climates during the Late Pleistocene (Lezine *et al.*, 2005; Kim *et al.*, 2010; Marret *et al.*, 2013). The abundance of grass cuticles from the GCs during this period could also be related to an induced wildfire activity, and sequential fluvial discharge through the Benue and Niger Rivers confluence and out across the Niger Delta (Richard and Morley, 1993) (Figures 5.7-5.9).

On other hand, at the onset of the present interglacial period (11-6.5 ka) the climate patterns become wet/warm due to strengthening of the summer insolation. This causes an increase in WAM activity as the evoked ITCZ migrates northwards towards the equator (Marret *et al.*, 2001). The hinterland vegetation declined during this time (Morley, 1995; Shi *et al.*, 2001; Dalibard *et al.*, 2014) (Figures 7.1-7.3). The expansion of the littoral vegetation during this time, as identified in this study, is similar to the Central and West African records, probably related to rise in sea level in response to melting of ice at polar regions (e.g. Shackleton, 1987; Lezine *et al.*, 2005; Scourse *et al.*, 2005; Marret *et al.*, 2013; Dalibard *et al.*, 2014).

Given this seasonal circulation, transition from dry to wet conditions following the end of the LGM (MIS2), as observed in all three GCs in this study and from other locations (Dupont, 2000) in the subequatorial West Africa, is most likely due to the migration of the ITCZ and WAM (e.g. Gasse *et al.*, 2008; Hessler *et al.*, 2010; Weijers *et al.*, 2007; Marret *et al.*, 2013). Looking forward, in this section the vegetation records recognised through pollen and NPPs of the GCs offer to evaluate the relationship between monsoonal and ITCZ dynamics. The coherence from the interpretation of the palynomorph records of GCs exclusively substantiates previous evidence, and has also contributed to the “recent dialogue on the strength and importance of the tropical monsoon” in controlling the regional climate of West Africa (Guilderson *et al.*, 1994; Blunier *et al.*, 1998).

7.3.2.2 Controls on *Rhizophora* and Coastal Littoral Vegetation of the Niger Delta

Control of sea level

Generally mangrove pollen grains are considered as a good stratigraphic marker of sea-level changes within the tropical regions of the world. Pollen produced by mangrove species is observed to be present in shallow subtidal and intertidal settings (Scourse *et al.*, 2005).

Further to the previous discussions (Chapter 7; Sections 7.2.1 to 7.2.3), this section highlights the importance of mangrove data and what has actually provoked or controlled the strongly comparative increases across the three GCs. The similar expansion in the mangrove pollen in the GCs (GCs depth of ~ 202-0 cm) is due to vegetation change as a result of sea-level rise during the Early to mid-Holocene, and erosion and reworking of old mangrove sediments that were deposited on the sea floor of the Niger Delta (Morley, 1995) (Figures 7.1-7.3). Given this, the observed increase in mangrove (GCs depth of ~ 202-0 cm) is not exclusively due to forest expansion, but due to transportation and redeposition of previous mangrove pollen sediments onto the continental shelf during sea-level rise (Scourse *et al.*, 2005; Kim *et al.*, 2005; Dupont *et al.*, 2007) (Figure 7.4). Similar to other regions like Australia, mangrove expansion has been termed the “big swamp phase” as a result of sea-level rise (Schmidt, 2008). Moreover, this episode could suggest a regional or local control (e.g. uplift) of enhanced wet climate patterns influencing the Niger Delta sediments

coinciding with the strengthening of the summer insolation and intense WAM system (Morley, 1995; Lezine and Denfle, 1997).

However, it is appropriate and logical to observe and suggest that the slight decline in the *Rhizophora* pollen data presented (GCs depth of ~175-75 cm) after the Early Holocene, close to the mid-Holocene could be due to the influence of intermittent or gradual sea-level rise transgressing the shoreline, or perhaps, other local factors that our data cannot sufficiently explain in this study (Ellison, 2000) (Figure 7.4). It appears that the presumed decline in the mangrove vegetation after the Early Holocene is not truly an evidence of a change in the vegetation but rather a false decline in the graphical peak resulting from lack of higher recovery of *Rhizophora* pollen within those intervals (Figure 7.4). This is because previous analysis (BGS) resulted in the shortage of samples to be analysed within the specific intervals (10 intervals). Thus, no significant samples were left for further analysis in order to compensate for the shortfall of the mangrove data (See Figure 7.4 especially GCs 2 & 3 *Rhizophora* pollen plots).

Apart from the direct evidence of the sea level rise contributing or controlling mangrove expansion or higher recovery of *Rhizophora*, two factors are also suggested to have influenced the abundance of *Rhizophora* and coastal littoral vegetation expansion in the Niger Delta. These are:

- the nature of the coastal morphology of the continental shelf; and
- the effects of soil geochemistry (edaphic nutrient composition) on mangrove vegetation.

Nature of the coastal morphology of the continental shelf

The local influence of the rise in sea level controlling the expansion of Rhizophoraceae has been proposed to depend on the lower gradient of the shelf morphology by different authors (e.g. Jaramillo and Bayona, 2000; Kim *et al.*, 2010). Unlike the Gulf of Tribuga, the northern Colombia Pacific coastal setting where the marine shelf is presumably narrow thereby recording less Rhizophoraceae preservation during sea level transgression (Jaramillo and Bayona, 2000), studies from the Gulf of Guinea (e.g. Sanaga Fan, Congo and Ogooue Delta, Gabon), have shown that the continental shelf is assumed to develop a lower gradient and more

laterally extensive providing a platform for the evoked sea level rise to transgress across the shelf (Kim *et al.*, 2010). The philosophical drive behind this hypothesis is logical; however, in this study of the Niger Delta, there is limited cogent information on the proposed hypothesis discussed above. In the future, this study recommends further investigation on the ensued “morphology of the continental shelf in relation to sea level and mangrove expansion” in both active (e.g. Gulf of Tribuga) and passive margins (e.g. Gulf of Guinea) of South America and West Africa respectively to validate the science.

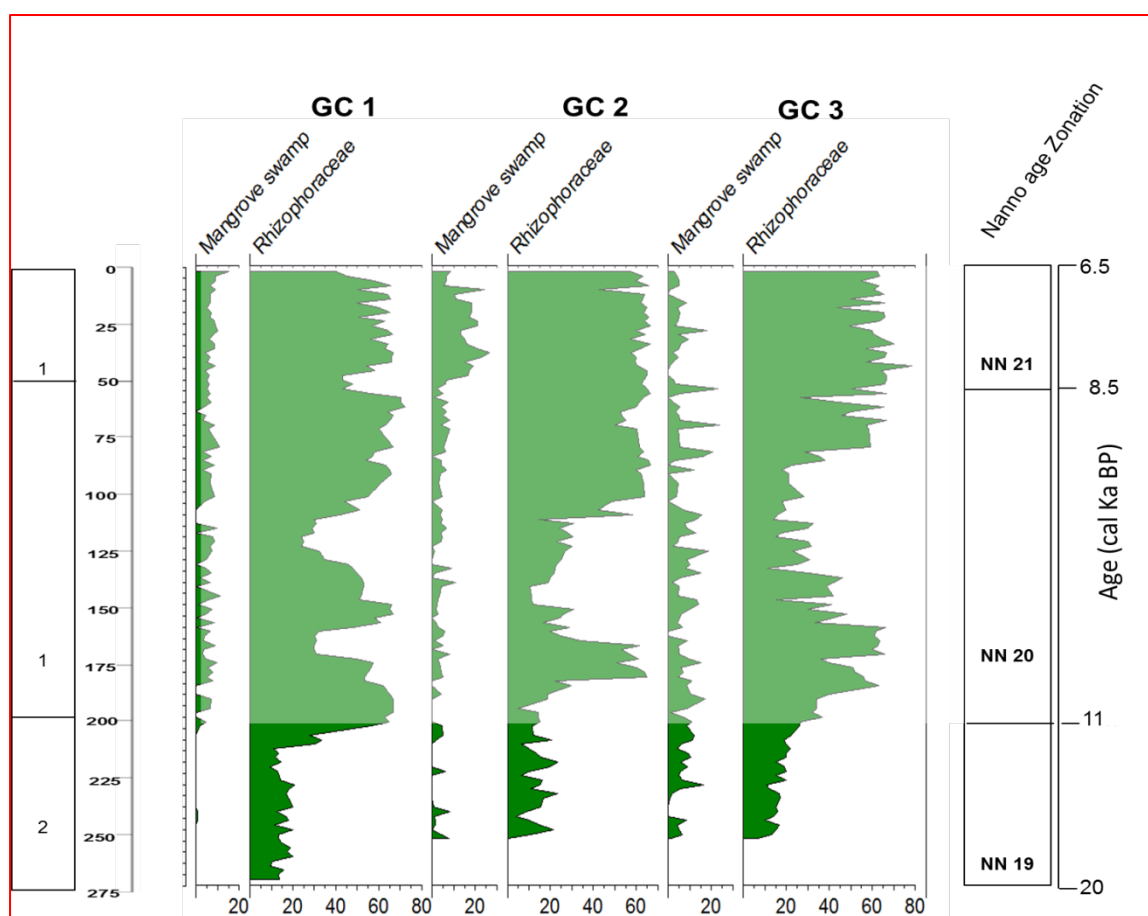


Figure 7.4. Diagram demonstrating similar phase of Mangrove fluctuations (% calculated on a total sum excluding Rhizophoraceae) and with Rhizophoraceae percentages for the GCs. Grey band represents an interglacial period of increased mangrove pollen.

Effects of soil geochemistry (edaphic nutrient enrichment)

In addition to the review of aforementioned controls, this study has reviewed and obtained coherent information on the detailed study on the decomposable geochemical compositions present in the littoral sediments enhancing mangrove vegetation development along the West African and South America coasts (Marius and Lucas, 1991; Mendoza, 2007) respectively.

Given the above theory and possible inferences, the present study on mangrove data presumably shows evidence of a sharp increase in the *Rhizophora* and associated mangrove vegetation in relation to high concentration of Fe/S ratios at (GCs depth of ~202-0 cm) during the Early to mid-Holocene (11.7-6.5 ka) when compared to the glacial-deglacial period (20-11 ka, ~273-202 cm) (Figure 7.5). Although, Fe/S ratio spike seems to be focused with the total mangrove data abundance from the graphical representation below, however it is imperative to presume that this rationale is only proposing evidence that natural biodegradable constituent also have a significant role on the growth of coastal littoral vegetation (Marius and Lucas, 1991). This is because all littoral plants (mangrove vegetation) depend on decomposable organic matter for their consistent nutrient enrichment usually supplied from the marine realm by the major geochemical elements. In addition, mangrove systems entrap decaying vegetation better because of the high proliferation of rhizomes thus creating high bacterial breakdown (Punwong *et al.*, 2013). Given this relationship and logical inclination, it appears that the abundant formation of FeS₂ (Pyrite) could have also supported the development of the mangrove vegetation along the littoral coast of the Niger Delta (Marius and Lucas, 1991; Mendoza, 2007). Therefore, it becomes obvious that the susceptible biodegradation of the organic matter inclined to the marine conditions (acidity and salinity) inevitably could have contributed or controlled the nutrient enrichment supporting the development of mangrove vegetation in the two sedimentary basins as well (West Africa and South America).

Presumably, in addition to the logical hypothesis on the “sea level transgression and the morphology of the shelf” suggested by other authors (e.g. Kim *et al.*, 2010), this study presents further data and insightful contributions to the “geochemistry of the organic matter decay” from the coastal Niger Delta for further study (Figure 7.5).

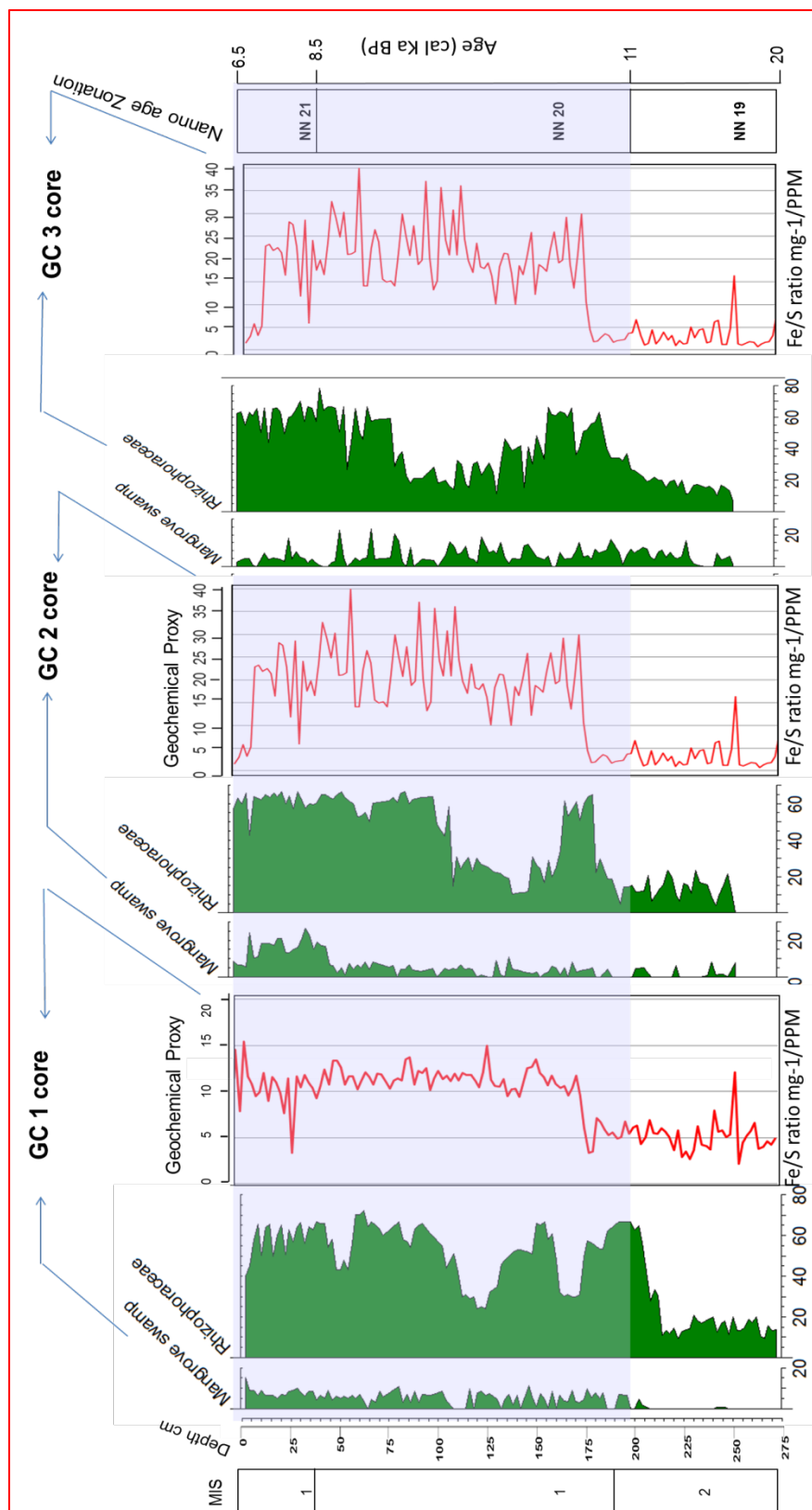


Figure 7.5. Diagram comparing the Fe/S ratio curves with % of Mangrove (calculated on total sum excluding Rhizophoraceae) and % of Rhizophoraceae for the three GCs. Grey band represents a period of increased mangrove pollen and Fe/S ratio.

7.3.2.3 Controls and Evidence of Fluvial Palaeodischarge/Terrestrial Influx on the Niger Delta Sedimentary Succession

During the glacial period (MIS2), several records in Africa (e.g. T89-16; MD03-2708; GeoB-4905 (Kim *et al.*, 2010; Marret *et al.*, 2001)) show significant change in dry pollen taxa, charred grass cuticles and freshwater algae (*Pediastrum*) due to the alteration in atmospheric and oceanic circulation. This can be taken to provide evidence of palaeodischarge because such palynomorph records listed above are usually transported into the basin during fluvial run off (Dupont and Agwu, 1991).

As a further contribution to the “logical palaeodischarge evidence in core T89-16” in the region, the current study presents this evidence of fluvial palaeodischarge from the bottom of the GCs (~272-202 cm) based on abundant occurrence of Cyperaceae, Poaceae and *Podocarpus* pollen data during the Late Pleistocene (NN19 = 20-11 ka). Significant evidences are sequentially suggested in this study due to higher occurrence of pollen data, charred grass cuticles, *Pediastrum*, geochemical ratio (Ti/Zr ratio) and rapid sedimentation rate (GC1 = 9.8cm/kyr; GC2 = 13.9cm/kyr; GC3 = 13.1 cm/kyr) of medium sand recorded at ~ 272-202 cm dept in GCs in the Late Pleistocene (Figures 6.2-6.4; 7.6).

Control on the terrestrial evidence is limited to the amount of precipitation during the prevailing time frame in relation to the seasonal migration in rainfall over the continental catchment area during the austral winter (Figure 2.1). Looking forward, from the seasonal migration of the ITCZ, it becomes imperative to logically suggest that the palaeodischarge events may have been provoked from latitudinal migration of the mean ITZC from its southerly position, resulting in the extension of monsoonal conditions over the Niger Delta during LGM (MIS2). During this time, the ITCZ position in January during the LGM was to the south of the Africa basin (Street-Perrott and Roberts, 1983).

Thus, increase in the fluvial discharge reflected from this studied data is linked to the seasonal latitudinal migration of the ITZC with a mean annual position assumed to be around 13°N positioned further south (10°S) during the LGM (MIS2) based on similar records from the West African coast (Leroux, 1993; Marret *et al.*, 2001) (Figure

2.1). The rationale behind the control evoking the terrestrial changes recorded in this study (Figure 7.6) is indicative of increased fluvial input linked to the confluence of the Niger and Benue Rivers (Figure 2.8). These rivers constitute the main conduit through which terrestrial materials are transported to the Niger Delta (Adojoh and Dada, 2015).

In context of other regional African settings, the potential event of palaeodischarge from the Niger Delta Rivers (Figure 7.6) may also be linked to an episode known as the “Ogolian regression” in North West Africa, and the Amazon River discharge in the US. It is a period of sea level fall and fluvial discharge in North West Africa during the LGM period (Barusseau, 1988; Barusseau *et al.*, 1995; Lezine *et al.*, 2005). Importantly, in this section the knowledge of controls and evidence of fluvial palaeodischarge/terrestrial influx on the Niger Delta sedimentary succession based on pollen and geochemistry data provides an understanding of how the terrestrial pollen records and sedimentary influx in the marine terrain could be evaluated from the regional perspective in the future.

7.4 Conclusions

- It is important to conclude from this Chapter that in marine sediments, tropical or Lowland Rainforest families (e.g. Lycopodiaceae, Sphagnaceae and Polypodiaceae) consist of the most numerical greatest diversity of pollen and spore records (Poumot, 1989; Gajewski *et al.*, 2002; Dupont, 2011). This scenario necessitated the adoption of a new method in assigning pollen data to their botanical families which in a way reduced bias within interpretation that could have resulted from their complex diversity (Rull, 1998; Fletcher, 2005; IPC, 2012).
- In addition, another significant conclusion which can be taken from this Chapter is that the synchronous shift of palynomorph records across the GCs during these periods are evoked by dry and wet climatic during Late Pleistocene and Early-mid Holocene conditions respectively. The synchronous shift supports the hypotheses of ITCZ and WAM leading to understanding of what is actually inciting or controlling the changes in the vegetation (sea level, climate and edaphic factors (geochemistry)).

- The study of palynomorph records in marine sediments is very insightful for the reconstructions of palaeovegetation variations on the adjacent continent thus, overriding processes control the pollen abundance and preservation records in relation to the regional gradient of the studied area.
- Finally, to complement the aforementioned controls on pollen records, the effect of “palaeodischarge or freshwater pluming” should be investigated, as well as the impact on the distribution of the littoral phytoplankton (e.g. dinoflagellate cysts-few record was found) and vegetation for an effective management and conservation of the coastal palaeoecological habitat of the region in the future.

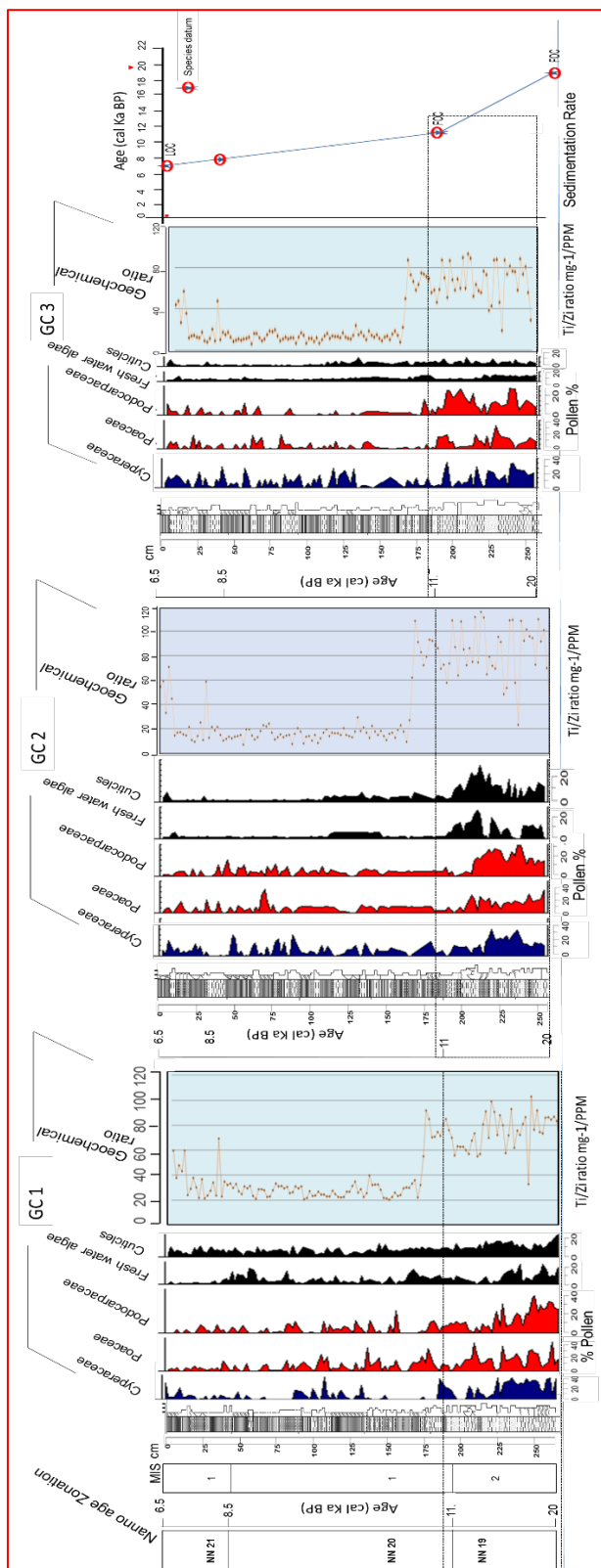


Figure 7.6. Integrated diagram showing evidence of terrestrial influx (Highlighted in dotted band) based on higher occurrence of Pollen Data, Non Pollen Palynomorph, Geochemical Ratio (Ti/Zr ratio) and Rapid Sedimentation Rate of medium sand at the base of the GCs ~ 272-202 cm depth

Chapter 8: Implications and Contributions of the Integrated Multi-proxy Dataset on the Niger Delta environment

Highlights

- Palaeoenvironmental evolutionary stages of the Niger Delta were reconstructed based on the multi-proxy records during the 20-6.5 ka
- The sequential records of multi-proxy data assemblages especially mangrove pollen outlined suggest their application as a practical tool for the future study of sequence stratigraphy and climate-driven sea level rise
- The palaeoenvironmental evolutions outlined in this context confirm a direct and regional link between the vegetation dynamics (pollen) and sediment supply on the Niger Delta sedimentary succession
- Integrated controlling or driving factors and insights that accommodate the complete evolution of the coastal deltas in different time frame resulted in an improved understanding on the gradual shift of the coastal Niger Delta region

8.1 Implications of the Study

This Chapter will explore the significance of the detailed integrated multi-proxy dataset to reconstruct the coastal evolution of the Niger Delta setting looking at the aforementioned controls in Chapters 6 and 7. This will deepen understanding of the ways in which integrated multiproxy data can be used to distinguish which controlling factors were prominent in the evolution of the Niger Delta depending on the prevailing glacial (MIS2) or interglacial (MIS1) conditions. Moreover, this will also provide a new coastal palaeoenvironmental study from the Niger Delta, where very little information is known about the coastal dynamics and further contribute to the body of knowledge affecting the depositional succession of the region through the impact of climate and sea level fluctuations. Importantly, this chapter will not only apply those controls and concepts but, provides the confirmation of the strength on the discussed hypotheses (ITCZ and WAM) interacting with the region. Implications and contributions of this study are highlighted into three bullet points below:

- Impact of climate change on the littoral mangrove ecosystems of the Niger Delta.

- Implications and Controls of shelf transgression in relation to the biosequence stratigraphic studies.
- Broad palaeoenvironmental evolution of the Niger Delta.

8.2 Impact of Climate Change on the Littoral Mangrove Ecosystems of the Niger Delta

This section addresses the impact of a warm climate on sea level through response seen as the expansion of the coastal mangrove vegetation. Case studies on mangrove ecosystems along the West African coastline from 1997 to 2015 (Chapter 7) will be used as a modern analogy to the Quaternary dataset in this section in relation to the fourth objective of this study. The present deforestation, reclamation and water logging within the region have affected the long term survival of mangrove vegetation characterised by a very dynamic but, complex sedimentary environment in most regions worldwide. Thus, the concern for the future is how do previous studies support future conservation of the mangrove ecosystem within the region.

In context, this study on mangrove vegetation expansion derived from the GCs (GCs depth of ~202-0 cm) through the Early to mid-Holocene (11–6.5 ka) due to the sea-level rise during the warm to hypsithermal climate period indicates a past period of marine incursion on the coastline (Punwong *et al.*, 2013) (Figure 7.4). Presumably, the synchronous relationship between the expansions of mangrove pollen from the three GCs across the East–West Niger Delta suggests a uniform rise of the sea level, regional responses to environmental influences, similar controls on sediment accumulation and evidence of dominant mangrove vegetation within the region (Figure 7.4).

Given that the present is the key to past processes (Lyell, 1830, p. 33), it implies that the past Niger Delta palaeoshoreline could be interpreted using indicator mangrove pollen as well as to forecast the future sea level scenario. To this effect, the current study has confirmed the dynamic response of coastal vegetation to sea level and climate conditions in the Niger Delta after 11 ka, and reinforces the need for coastal and sustainable management of the mangrove vegetation along coastal zones which are now centres of national and international research planning activities (Ogadinma, 2013). Consequently, increasing awareness of global warming relative to

its potential impact on sea-level rise and coastal morphology, increase in water temperature, and quantity of the continental or terrestrial runoff becomes a significant question meriting further study in relation to mangrove vegetation (Nicholls and Cazenave, 2010).

To take a step ahead, as a further contribution to the Nigerian economy, it is imperative to assess the impact of climate change and sea-level change on the Niger Delta because of the current global consequences resulting in the risk of flooding, environmental degradation, drought and for the future sustainability of the region since evidence have been shown from the GCs at 11-6.5 ka on past sea-level rise. However, since climate, geosystems and ecosystems control the development of human society, the feedback between these driving forces is critical to creating predictive scenarios for the development of the socio-economic system of the region (IPCC, 2013; Massuanganhe, 2016).

Overall, this section provides an insight into how a changing climate is likely to influence the development of mangrove ecosystems through past study on sea level rise at 11.7-6.5 ka resolved from the depth of GCs ~ 202-0 cm (Figure 7.4). With the on-going aggressive flooding resulting from the impact of global warming affecting the ecosystems within the Niger Delta region (e.g. Eleme and Bonny refineries locations), these findings hint at the need to consolidate and expand the initiatives to protect this valuable coastal and vegetational ecosystem, observed to be ever present in the region, and focused in particular on combining traditional conservation efforts with adaptation to climate impact in the future (Nicholls and Cazenave, 2010; Ogadinma, 2013). Conservation of mangrove ecosystems should be of utmost importance to the present decision making process affecting marine coastal systems and their ability to sustain future generations in the region. This becomes an important necessity, because mangroves play a key role as a signal for recognising sea level transgression, ability to swiftly absorb CO₂, buffering strong winds and offering coastal protection (BBC science/environmental news, 2016).

8.3 Implications and Controls of Shelf Transgression in Relation to the Biosequence Stratigraphic Studies

The knowledge that mangrove assemblages (e.g. *Rhizophora*) can be linked to stages of sea-level change as discussed in the previous section 8.2 through the sequential history of the coastal Niger Delta over 20ka using different systems tracts (ST) is echoed in this section (see Appendix 2/3 for this terminology “ST” and basis for the sequence stratigraphy- pages 247-251).

Under this premise, the designation of an increase in *Rhizophora* pollen to Highstand Systems Tract (HST) or Transgressive Systems Tract (TST) during the sea-level transgression has been the subject of debate by different authors (e.g. Scourse *et al.*, 2005). However, with the current update from the GCs study, the debate may be reinforced if either of the two of the systems tracts (HST or TST) are carefully linked to the integration of selected proxies (i.e geochemistry vs. foraminifera) with Rhizophoraceae pollen (Figure 8.1).

Given these arrays of datasets, the current study provides a novel testing of models and concepts by interpreting high resolution multi-proxy data components to differentiate between each element of the system tracts as proposed in the third objective of the study. During the Early to mid Holocene the transgression (notionally the TST) was interpreted from the GCs around about 11-6.5 ka (GCs depth of ~202-0 cm). This period suggests slower sedimentation of mudstone lithofacies correlative with the expansion of coastal mangroves, as well as, an increase in the Fe/S ratio and planktonic foraminifera in the intertidal zone of the Niger Delta (Figure 8.1). Presumably, this consistent trend from the GCs during the interglacial period is in agreement with the TST model proposed by Scourse *et al.* (2005) and Morley *et al.* (2011). This study interprets this phase to be a function of both rapid spread of the coastal littoral zone associated with sea-level rise but linked to the gently sloping shelf where sedimentation takes place through transgression, leading to delta plain expansion and mangrove ecosystem development which produces the *Rhizophora* pollen (Morley, 1995; Rull, 2002; Adojoh *et al.*, 2015; Adojoh *et al.*, 2016). This will consequently result in an increase in marine-linked sediments (tidal influence) when compared to the lowstand systems tract (LST) (GCs depth of ~272-202) (Figure 8.1). As most sediments are deposited in the Coastal Mangrove Swamp region, it implies

that mangrove pollen abundance in intertidal and tidal settings would be much lower than in the LST (Poumot, 1989; Morley, 1995; Rull 2002; Punwong *et al.*, 2013) (Figure 8.1).

As a further contribution to sequence biostratigraphic studies, the synchronous relationships established from the GCs at different locations, this offers a robust correlation tool, which permits the opportunity to create distinctions between system tracts, i.e. the HST, TST and LST. It is suggested that by adopting the combined increase in the planktonic foraminiferal and *Rhizophora* sp. as proxies linking the marine transgression (TST), both offer information regarding palaeobathymetry and distance from the marine coast (Torricelli *et al.*, 2006). However, to the given debates concerning the recognition of the two systems tracts (TST or HST) there must be a clear distinction between the two systems tracts. The correlation of mangrove pollen, planktonic foraminifera and Fe/S ratio peaks is explicitly related to marine transgressions, whereby providing a contribution that mangrove pollen type *Rhizophora* is acknowledged as an indicator of the Transgressive Systems Tract (e.g. Bergren *et al.*, 1995; Scourse *et al.*, 2005; Morley *et al.*, 2011), rather than the presumed HST by other authors (e.g. Fredoux and Tastet, 1976; Poumot, 1989; van der Zwan and Brugman, 1999) (Figure 8.1). Therefore, in review this may allow a synchronous correlation of multiple proxies with possible global bioevents (Armentrout *et al.*, 1999; Morley and Morley, 2011).

Overall, the knowledge and understanding of how systems tracts recognised through mangrove pollen evidence in this study could be applied to other deltaic coastlines that are also sensitive to changes in sea level rise where this concept has been misconstrued (e.g. Orinoco Delta-South America; Sarawak Basin-South East Asia, and West Africa). Finally, the major impact here is where only palaeovegetation profiles are available for future researchers reviewing similar questions, this work can help provide a robust comparison. By implication, the sequential records of fossil pollen assemblages can be turned into a practical tool for the future study of sequence stratigraphy, its impact and their phases, which are linked to particular depositional systems tracts (Figure 8.1). Thus, in addition to previous studies in the region (e.g. Pomout, 1989; Morley, 1995; Armentrout *et al.*, 1999), this should provide an understanding of the potential variability of ancient deltaic sequences where there is limited control in Quaternary sequences to decode past signals more thoroughly.

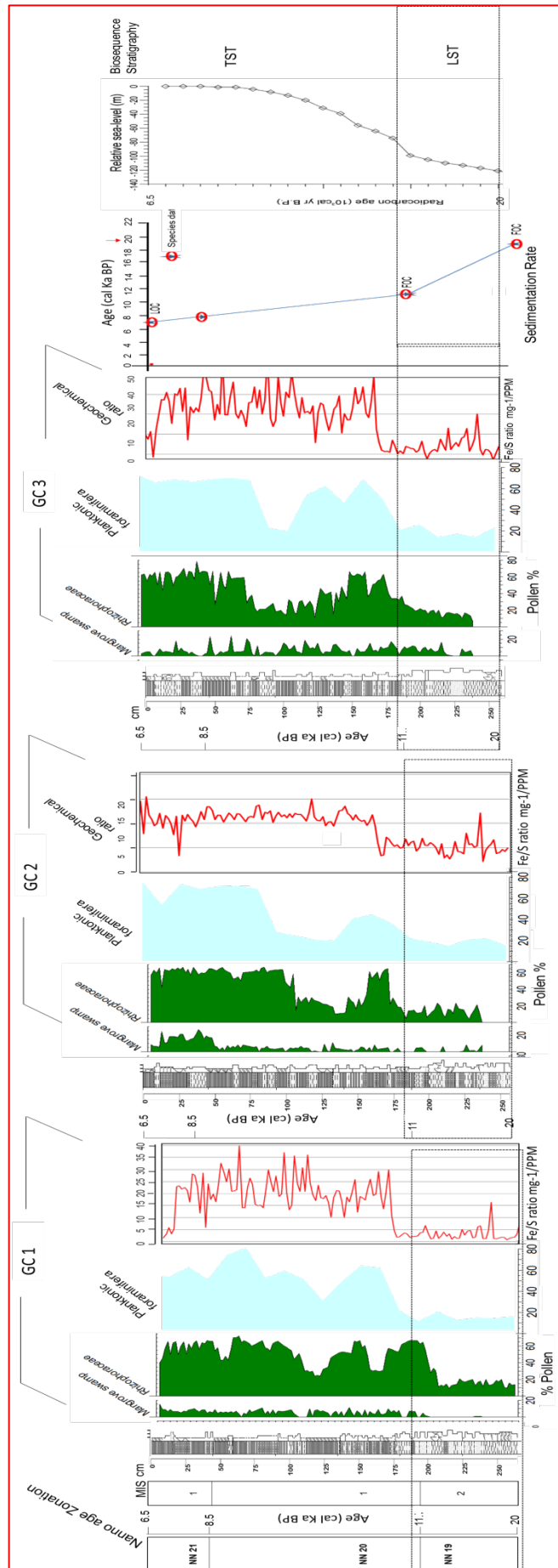


Figure 8.1. Integrated and correlated multi-proxy component and their systems tracts appraisal for the GCs linked to the regional sea level curve (Peltier, 1994).

8.4 Palaeoenvironmental Evolution of the Niger Delta

An understanding of sedimentary budgets and palaeoenvironmental evolution as partly discussed in Chapter 6 is an important tool for the reconstruction of ecological balance and coastal management in most regions of the world due to the sporadic impact of sea level inundation linked to the menace of global warming. Given these insights, this study probe further to reconstruct the evolution of the Niger Delta environment and to present a model that explains the interplay between all the driving mechanisms, palaeoenvironment, sea-level and climate change based biotic and abiotic evidence (Fifth Study Objective). Therefore, this section links the evolutionary stages of the littoral coastal margin of Niger Delta to the deltaic landscape architecture from 20 to 6.5 ka into two principal stages based on evidence derived from the integrated multi-proxies. These stages are as follows:

- Stage 1 - Prograding (advancing) Delta (20-11 ka);
- Stage 2 - Retrograding (retreating) Delta (11-6.5 ka)

Stage 1: Prograding Delta (NN19=MIS2)-(20-11.7 ka)

During this time, the GCs data confirm the emergence of the continental shelf in response to a lower than present day sea level (Figure 8.1). The littoral environment (mangrove and coastal swamp) is subaerially exposed, sedimentation and fluvial transport, is by mass movement incited by the weak West African Monsoon (WAM) (Morley, 1995; Reijers, 2011; Zong *et al.*, 2009). The GCs records indicate the predominance of hinterland pollen (Savannah/Afromontane) and freshwater pollen (Cyperaceae) during this time (Figures 7.1-7.3). The pollen types extend beyond the littoral coastal zone representing a strong signal of the prevalent arid conditions and rapid sedimentation rates (GC1 = 9.8 cm/ kyr; GC2 = 13.9 cm/ kyr; GC3 = 13.1 cm/ kyr) (Figures 4.4-4.5). The high value of Ti/Zr ratio of the sediments indicates fluvial or terrestrial transport, and the sedimentology indicates a shift towards a higher fluvial regime during the lowstand (Zabel *et al.*, 2001; Adegbeie *et al.*, 2003). The foraminiferal (benthic and planktic) results, combined with the grain size data show a slight difference between the deltaic environments interpreted. This possibility suggests a distal offshore-lower shoreface prodeltaic environment based on the dominance of

benthic foraminiferal and hinterland pollen assemblages (Adegoke, 1975; Murray, 1991) (Figures 6.4a-b) (Figure 8.2).

Given this similar interpretation at the bottom of the GCs, the prograding Stage 1 of the Niger Delta (period of regressive deposition) can be correlated to a period of an enhanced discharge or sediment supply “Ogalian Regression” and “rapid Palaeodischarge” in Senegal and Congo respectively; defining a period through which the fluvial sediments are transported through to the deltaic marine shores (Petters, 1984; Knox and Omatsola, 1987; Barousseau, 1988; Barousseau *et al.*, 1995; Marret *et al.*, 2001) (Figures 7.6; 8.2).

Stage 2: Retrogradation (NN20=MIS1; 11-6.5 ka)

Following the Stage 1 is the succession of the Niger Delta retreat attributed to sea-level rise. The period of an onset of the Early Holocene sea-level rise coincides with an episode of shore-line retreat. During this stage, similar attributes were recorded from each of the GCs based on the visible fine grained lithofacies components. These components were deposited under a high energy regime that prevailed at the coastal margin of the Niger Delta throughout the Early to mid-Holocene evoked by the strong West African Monsoon (WAM) (Figure 8.2) (Zong *et al.*, 2009). This period is related to a high tidal influence associated with fine grain size suspension load reflecting the proximity of turbidity currents. High values of littoral mangrove pollen (e.g *Rhizophora*) and the Fe/S ratio suggest a reducing environment with the potential of rapid post-dissolution of pyrite minerals and organic rich sulphur content (Fletcher, 2005; Mendoza, 2007). These predictive interpretations suggest a proximal-upper shoreface deltaic front palaeoenvironment based on the occurrence of planktonic foraminifera and mangrove pollen assemblages (Figure 8.1). This Stage of the tidal and wave processes becomes the mechanisms of sediment transport shaping the delta (Chapter 2).

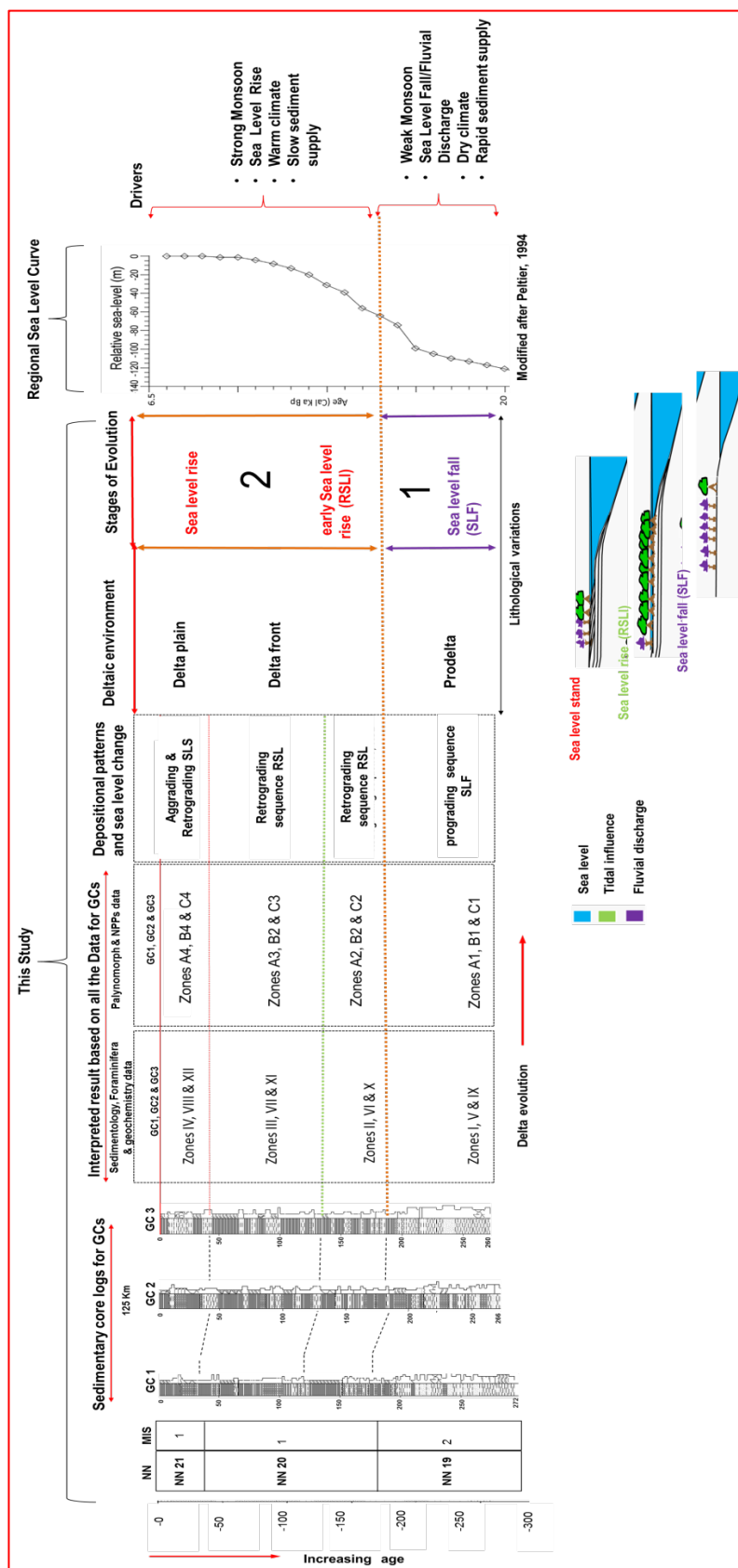
Moreover, deposition during Stage 2 (relative coastline retrogradation) is principally driven by the interaction between the creation of accommodation space and reduction in sediment discharge into the deltaic basin (Posamentier and Allen, 1999). The delta sedimentation resolved from the GCs data switches from a prodelta to delta front, then delta plain (Figure 8.2). Sequence of delta front sedimentation patterns are exclusively over represented as well (Weber, 1971; Knox and Omatsola, 1990). Given

this, the ability for the tidal processes to erode during this period would strongly depend on the marine grain size of the delta infill at different relative sea levels (Oomeken, 1974; Knox and Omatsola, 1990). Regionally, Stage 2 during this time frame correlates to the period of sea-level rise linked to the North West Africa margin known as the “Nouakchottian transgression” recorded in Senegal and Mauritania (Barusseau, 1988; Barusseau *et al.*, 1995; Lezine and Deneffe, 1997; Dalibard *et al.*, 2014) (Figure 8.1). It is imperative to propose that the Stage 2 scenario may echo a reduction in monsoon-driven fluvial discharge on the Niger Delta (Zong *et al.*, 2009).

Finally, given the above discussions (Sections 8.2-8.4), this section concludes the general discussions on the principal controls of the coastal evolution of the shallow offshore Niger Delta (Stages 1 and 2) have been controlled by several factors. However, based on the data evaluated linked to the Stages (1 and 2) evidence has shown three principal factors to be crucial to the findings of this study. These are:

- Climate change;
- Sea level change;
- Sedimentary dynamics.

Given that two stages evolved, the stratigraphic landscape and evolution of the Niger Delta was controlled by the fluvial sediment supply and relatively sea level variations linked to the Late Quaternary climate changes (Figure 8.2). In a nutshell, it is imperative to acknowledge that Stage 1 provides an insight into the influx of sedimentary budget, shoreface palaeoenvironment, hinterland pollen and nutrient components that could be anticipated at the interphase of the coastal-oceanic boundary of the marine Niger Delta about 20ka. On the other hand, impact of the coastal retreat observed in Stage 2 will significantly increase the awareness that Niger Delta shoreface is gradually shifting due to erosion or monotonic sea level incursion after 11ka. Among these factors, sea-level change is considered to be more active on the coastal evolution of the Niger Delta during this time frame. This is because evidence from mangrove data shows that sea-level rise (Stage 2) controlled the evolution of coastal ecosystems and sediment supply at 11-6.5 ka in relation to the strong alteration of the main climate drivers (ITCZ and WAM) (Chapters 5, 6 and 7) (Figure 8.2).



Note: All the relative changes interpreted from the result Chapter 5 were inserted into the Figure 8.2 based on the observable zones of the GCs data.

Stage 1 consists of high abundance of medium sand, Ti/Zr elements, Benthic foraminifera, hinterland pollen and spores (Figure 8.2).

Stage 2 comprises of high abundance of silty-fine sand, Fe/S elements, Planktonic foraminifera, Mangrove pollen and spores (Figure 8.2).

Figure 8.2. An end-point of the broad palaeoenvironmental evolution of the Niger Delta and their controlling mechanisms from the GCs data (integrating all proxies).

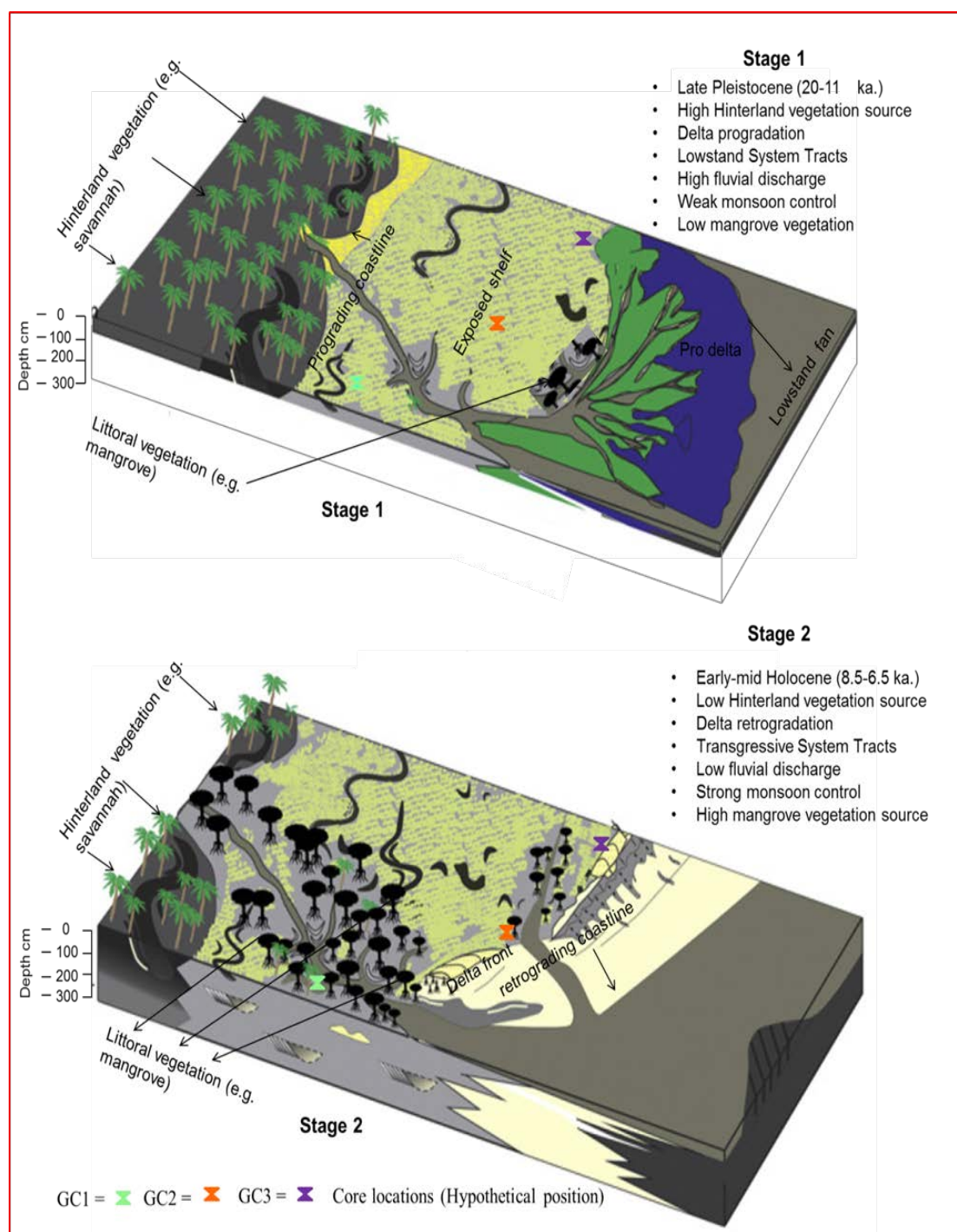


Figure 8.3. Two evolutionary stages of vegetation dynamic and depositional settings as observed from Figure 8.2 modified into the landscape of the Niger Delta (modified after, Cohen *et al.*, 2014) (GC1 = East of Niger Delta, GC2 = Central Niger Delta, GC3 = West of Niger Delta).

Note: More hinterland vegetation dominates during the **Stage 1**, whereas littoral coastal vegetation dominates at the **Stage 2** during the post-glacial time (MIS1&2) depicting the notional controls on changes to expect during the evolution of the Delta.

In addition, given the two diagrams above (Figures 8.2; 8.3), it becomes essential to link the resulting signals or responses from this study to the understanding of the environmental conditions leading to adaptation in the ecosystem organisation (vegetation), composition of the coastal landscape and depositional settings. Moreover, in contribution to the devastating scenario emanating from the coastal encroachment by sea-level change, this evolutionary model could possibly help predict future environmental changes of the coastal settings of Nigeria to ensure the sustainability of the region especially in areas facing coastal slump and retreat (e.g. Bonny gas platform, East of Niger Delta, Eleme Refinery, West of Niger Delta and Lokoja municipal). Thus, the current study permits a re-evaluation of the controls of climate, sea level and sediment supply contributing to the understanding of the stages in palaeovegetation and the littoral/coastal evolution of the region.

8.5 Conclusions

- The overall aim of this chapter provides an integrated evolutionary framework of the coastal margin of the Niger Delta during the Late Quaternary in relation to the alteration of the main climate drivers. This, in relation to the stratigraphic evolution has resulted in the reconstructions of two regional coastal delta shoreface Stages namely: Delta advancing (1) and retreat (2) (Figure 8.2).
- There is a clear regional temporal pattern shift of the Late Quaternary palaeoenvironmental change either side of the Niger Delta (East to West), however comparison of the multiple data revealed significant difference in the two Stages suggesting a direct and regional link between the vegetation dynamics (pollen) and sediment supply (Figure 8.3).
- Thus, in addition to previous studies in the region (e.g. Pomout, 1989; Morley, 1995; Armentrout *et al.*, 1999), this should provide an understanding of the potential variability of ancient deltaic sequences where there is limited control in Quaternary sequences to decode past evolutionary signals more thoroughly in order to predict the future shifting scenario of the Niger Delta.

Chapter 9: General Conclusions, Broader Implications, Future Research and Recommendations

9.1 General Conclusions

The main scientific aim of this study was to determine and understand the driving factors influencing the palaeoenvironmental change through the detailed reconstruction of vegetation and sediment supply of the coastal offshore of Niger Delta during the Late Pleistocene to mid-Holocene. The aim of this chapter is to provide an overall summary of results and to conclude the main findings, limitations, future research and broader impacts of the study from Niger Delta. The objectives to be achieved were as follows:

- To constrain an age model for the complex deltaic setting of the Niger Delta (Coastal offshore) based on samples taken from three strategically positioned Gravity Cores.
- To reconstruct the vegetation patterns and delta shift of the Niger Delta during the post-glacial period (MIS1 & MIS2) through investigation of the palynomorph and core-lithology records.
- To determine and compare the timing of mangrove vegetation (*Rhizophora* sp.) expansion in relation to sea level rise (transgression) and apply the signal to biosequence stratigraphy studies.
- To evaluate the Holocene warm climate impact on littoral vegetation for the future sustainability and management of littoral/coastal zone of the Niger Delta.
- To probe further and reconstruct the evolution of the Niger Delta environment and to present a model that explains the interplay between the controlling mechanisms, palaeoenvironment, sea-level and climate change based on biotic and abiotic evidence.

In these general conclusions, the main hypotheses tested were the interactions between the position of the ITCZ and the strength of the WAM on explaining fluctuations in the palynomorph records of the Niger Delta. At present the hypotheses of ITCZ and WAM are quite promising in this study, and perhaps played a leading role to a better understanding of the vegetation evolution and coastal shift of the Niger Delta, similar to other regions in West Africa (e.g. Sanaga, Congo, Senegal and Ogooué deep sea deltas). Thus, palynomorph distribution in marine delta indicates a good representation in latitudinal occurrence of sporomorphs (pollen and spores) between terrestrial-source and the marine-sink, hence providing the basis for reconstructing different biomes over the time frame.

Based on the discussions from Chapters 7 and 8, it can now be concluded that the hinterland versus littoral pollen plots from the GCs records have enabled an understanding of an ecosystem response (vegetation dynamics) to the various control (dry versus wet climate, sea level and edaphic factor) due to the alteration of the climate drivers (ITCZ and WAM). It is suggested that the interpreted expansion of the hinterland vegetation within this region is coincident with arid/cold climatic, low sea level and weak monsoon conditions in relation to the southerly position of the ITCZ during the 20-11 ka (NN19=MIS2), whereas the expansion of littoral vegetation is linked to sea level rise during humid/wetter climate conditions in relation to northern migration of the ITCZ at 11-6.5 ka (NN20 and NN21=MIS1).

Given these conditions, it is important to emphasise that the similar relationship obtained from the GCs palaeovegetation (palynomorph records) and core-lithology provides strong evidence that are correlative to the timing of arid and humid transitions during the Late Pleistocene–mid Holocene respectively. This causative correlation using multiple proxies has been made in the Niger Delta region for the first time. Therefore, it can now be confirmed and concluded that the palaeoenvironmental evolutionary Stages (1 and 2) of the Niger Delta region is linked to the timing of the establishment of the WAM in relation to the migration of the ITCZ.

9.2 Key Findings

In addition to the principal and regional findings discussed above, other key findings from the study are outlined below by combining the results derived from the methodological techniques and the multi-proxy data.

1) Among the multi-proxies used, mangrove pollen and *Rhizophora* data offer many insights to this study. Given this, the extensive littoral mangrove pollen recorded between 20-11 ka in GCs offers a key potential for future investigation on the impact of climate on sea-level change along the coastal shoreface of Niger Delta. Abundant percentage recovery of mangrove pollen from the three GCs, especially the *Rhizophora* family, was due to the application of the correct methodology using a 5µm sieve (Scourse *et al.*, 2005). The results have demonstrated and confirmed the importance of mangrove pollen grains, as a good stratigraphic marker of sea level change in West Africa, Gulf of Guinea (8.5-6.5 ka). If properly managed, these mangrove ecosystems could play a key role in absorbing CO₂ and buffer to strong wind and offering coastal protection in the future.

2) The GCs data have exclusively shown to conform to the schools of thought which suggest that mangrove or Rhizophoraceae peaks can be linked to marine transgressions (TST) (for the Gulf of Guinea and South America). However, to make a clear distinction from the debate and confusion (misnomers) on the applicable systems tracts (TST or HST), a consequential observation from the GCs has further established that an integration of other proxies (e.g. foraminifera and geochemistry) with the increase of Rhizophoraceae should cogently be adopted for future study.

3) Evidence of fluvial discharge reflected from the hinterland pollen, Ti/Zr ratio and cuticle components are linked to the seasonal latitudinal migration of the ITZC about 20-11 ka (NN19). This shows evidence of palaeodischarge in the coastal setting of Niger Delta similar to the T89-16 core (Congo River) and Amazon River. The abundance of those components often reflects the amounts of transport into the system vs. the amount of biodegradable nutrient supply to the coastal system. This study proposes this relationship as an important tool for the reconstruction of sedimentary budgets, ecological balance and for coastal management.

4) The combination of foraminifera with the grain size data shows significant slight differences between the interpreted deltaic environments. The use of foraminifera has enabled the environmental interpretation of the GCs ranging from the upper to lower shoreface environment which was erroneously interpreted as a lagoonal to delta front environment from the Niger Delta by previous authors (e.g. Allen, 1964). Accurate interpretation and preservation of the shoreface through foraminifera-based study has many impacts on the coastal evolution studies and management policy.

5) In relation to the stratigraphic evolution, two regional coastal delta shoreface stages namely delta advancing (1) and retreat (2) were reconstructed. Implications of this development provide evidence on the average shifting of the coastal delta over the past 20ka. Because the past processes guide the future, it becomes imperative that a published piece of work on this finding will contribute to the socio-economic awareness of host communities on the ongoing coastal pressure, erosion or sporadic sea level incursion (e.g. Eleme Refinery and Bonny LNG projects areas). In other words, understanding of past evolutionary stages of the Niger Delta would inform the intergovernmental policy makers in planning adaptive and migration measures to coastal region against aggressive flooding due to induced climate-sea level rise in the future.

6) Dating technique in this study was successful because of the combination of both nannofossils and foraminiferal biostratigraphic disciplines. Nannofossils were exclusively successful for dating here because studies have shown that it has one of the best precision in dating disturbed settings, and also they are more resistant to diagenetic changes over time (dissolution and overgrowth) (Raffi, 1979). In addition, in well-preserved sediments recovered away from upwelling areas, nannofossils and planktonic foraminifera are habitually abundant. Thus, the combination of these microfossils has enabled a successful relative dating of the GCs.

7) As an addendum, it is important to conclude that this study records low occurrences of dinoflagellate cysts. Possible suggestions from previous findings made it clear that the siliciclastic influx (sedimentation rate) of palaeodischarge on Niger Delta could have affected on their preservation due to overburden sedimentary stress (e.g. Bankole *et al.*, 2014). In addition, the effects of “freshwater plumes” and “tidal inundation” originating from the ocean-land boundary have been documented to provoke the hydrologic control impacting stress on their preservation in northwest

Borneo, Mississippi Delta, Amazon Delta and southern New England (USA) basins (Simmons *et al.*, 1999; Pospelova *et al.*, 2004).

9.3 Broader Implications and Summary of all the Conclusions

Environmental studies have responded positively to issues arising from sustainable management on socio-ecosystems. The discipline of palaeovegetation in this study has produced useful knowledge which has been applied to set up management initiatives in a coastal deltaic environment and ensure the preservation of the ecosystem which has contributed directly as a service (coastal protection and sea level rise recognition) to society and the nation at large (Nigeria). However, the emerging question related to the impacts of climate change challenges these in context of the longer term, and in some instances where extreme weather conditions are affecting the Present Day deltaic processes of the Niger Delta. Between 20ka to 6.5ka, a deltaic system evolved in response mainly to the sea level fall and rise resulting to Stage 1 and Stage 2 respectively. Although, the studied stratigraphic succession is compatible with the trend of the global sea level fall and rise (e.g. Peltier, 1994) (Figure 8.2), there was not much shift in the coastal Niger Delta over the time frame as reported by previous researchers (e.g Allen, 1964; Oomken, 1974; Riboulot *et al.*, 2012). Given this finding, this study has contributed in this direction by discussing the links through which climate and sea level related events may affect and control the deltaic environment, and through that interplay, play an essential role in vegetation and delta evolution in the future.

Notwithstanding “the closed door policy” to research within the region due to the existence of oil and gas companies, it represents one of the first attempts to study the delta evolution using multiple dataset since the last glacial period where an original approach has been applied through the use of deltaic sediments, necessitated by the absence of natural lakes in the region. A combination of the GCs multiple dataset permits the identification of three factors controlling the palaeoenvironmental change in the course of this study from East, Central and Western part of the Niger Delta. These factors provide a case study that illustrates a stratigraphic sequence linked to the development of deltaic systems and coastal shoreface occupied by littoral vegetation, and an interplay of regional sea level changes after 20ka. Certainly, this

implies the future of ecosystem development will largely depend on the potential to which climate-related impact changes within the region.

Given these precepts, this study suggests that the current stages of delta advance and retreat (Stages 1 and 2), and vegetation are considered as compulsory inputs for potential lowstand, transgressive sediments and palaeogeographical evolutionary models in future studies. This is because of the importance of the shoreface in evaluating stabilisation of the coastal cliff and mangrove vegetation development. Coastal shoreface cliff of the Niger Delta is very significant to the region because it serves as platforms or beehives of activities for the Onne shipping companies, wind turbine, site for the Eleme petrochemicals, exit for oil and gas companies's workers to the offshore sites, recreational and tourist center for local and foreign investors. Therefore, adverse sea level impact and anthropogenic pressure on the coastal shoreface cliff and littoral vegetation could also have impact on Nigeria's natural resources along the coastline, agricultural land, aquatic life and fisheries possibly exposed to vulnerability of climate change. A long term adverse effect would significantly impact Nigeria's GDP in the future because the main source of revenue (oil and gas) for the government comes from the region (Niger Delta).

Finally, to take a step forwards towards the improvement of coastal delta management policies, it is necessary to apply the lessons learnt from studies of long-term developments and controls of delta evolution under the timeframe. This study calls for a change in the way that the coastal deltas are currently viewed and managed by society. Thus, integrated controlling or driving factors and insights that accommodate the complete evolution of the coastal deltas in different timeframe could result in an improved and sustainable management of the vegetation and coastal setting of the region in the future. Therefore, this study hypothesised that the dynamics of the summer monsoon and sea level fluctuation played a major role in shaping the landscape in the Niger Basin and adjacent coastal regions during the time frame.

9.4 Limitations

- Techniques such as radiometric dating were considered for this study, but due to the lack of suitable materials (wood, shells and clastic sediments), poor recovery of mono-specific planktonic foraminiferal, catchment preference and

poor preservation it was not possible to apply them in this particular study. It is important to know also that even the radiometric dating could provoke lots of noise or erroneous information during the interpretations due to different transporting source of sediments linked to this setting of the Niger Delta terrain.

- Company restrictions (“Closed door policy”) have also affected acquiring other data set such as wireline logs, seismic, contour maps and more gravity core samples.

9.5 Future Research and Recommendations

In the future, defining the stratigraphic evolution of the delta at the regional scale is a key challenge because the Niger Delta is an outstanding natural repository of wider interest for large scale depositional systems globally. It is important that future research should take the form of the following recommendations:

- It is significant to obtain the late Holocene deposits in order to study the impact of anthropogenic factors or control on the palynomorph records and sediment supply of the region in the future.
- In the future, informed predictive numerical models should be complemented with this type of study on the coastal shift and response to sea level changes.
- Finally, more gravity core locations (at least 6 core locations) should be acquired to probe further the controls (factors) and hypotheses discussed above with the hope of correlating array of similar peaks of dataset from the present studied GCs to decode past signals more thoroughly in the deep offshore.

References

References

- Adegbie, A. T., Schneider, R., Röhl, U. and Wefer, G., 2003. Glacial millennial-scale fluctuation in central African precipitation recorded in terrigenous sediment supply and fresh water signals offshore Cameroon. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **197**, 323-333.
- Adegoke, O. S., du Chêne, J. R. E., Agumanu, A. E. and Ajayi, P. O., 1978. Palynology and age of the Kerri-Kerri Formation, Nigeria. *Revista Española de Micropaleontología*, **X**, 267-283.
- Adegoke, O. S., 1975. Foraminifera fauna of the polyhaline lagoons of the Gulf of Guinea. *Journal Mining and Geology*, **12**, 1-8.
- Adekanmbi, O. H. and Ogundipe, O. T., 2009. Pollen grains of Lagos lagoon swamp and hinterland vegetation. *International Journal of Botany*, **5**, 270-278.
- Adeonipekun, P. A., Sowunmi, A. M. and Richards, K., 2015. A new Late Miocene to Pleistocene palynomorph zonation for the western offshore Niger Delta. *The Palynology*, pp 1-15.
- 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. and 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., Grimes, S., Watkinson, M., Fitzpatrick, Hart, M. and Osterloff, P., 2012. Applied palynodebris associations: Inferred systems tracts, palaeoenvironmental reconstructions and implications from the EA-DP-C Gravity Core, EA field, shallow offshore Niger Delta, Nigeria. 13th International Palynological Conference (IPC)/9th International Organisation of Palaeobotany Conference, Tokyo, Japan. *Abstract Japanese Journal of Palynology*, **58**, 3-4.
- Adojoh O., Marret, F. D., Duller, R. and Osterloff, P., 2016. Relative impact of sea level change and sediment supply on shallow offshore Niger delta margins from palynodebris and lithofacies data. *Quaternary International*, 404, 178.
- Adojoh, O. and Osterloff, P., 2010. Phytoecological reconstructions of Eocene-Pliocene sediments, Niger Delta. 3rd NAPE/AAPG regional Deepwater African offshore conference, Abuja. Abstract A 6.

References

- Aizebeokhai, A. P., 2011. Potential impacts of climate change and variability on groundwater resources in Nigeria. *African Journal of Environmental Science and Technology*, **5**, 760-768.
- Amorosi, A., Antonioli, F., Bertini, A., Marabini, S., Mastronuzzi, G., Montagna, P., Negri, A., Rossi, V., Scarponi, D., Taviani, M., Angeletti, L., Piva, A. and Vai, G. V., 2014. The Middle - Upper Pleistocene The Middle - Upper Pleistocene Fronte section, Taranto, Italy ronte section, Taranto, Italy: An exceptionally preserved marine record of the Last Interglacial. *Global and Planetary Change*, **119**, 23-38.
- Alexandre, A., Meunier, J. D., Lézine, A. M., Vincens, A. and Schwartz, D., 1997. Phytoliths: indicators of grassland dynamics during the late Holocene in intertropical Africa. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **136**, 213-229.
- Allen, J. R. L., 1964. The Nigerian continental margin: Bottom sediments, submarine morphology and geological evolution. *Marine Geology*, **1**, 289-332.
- Allen, J. R. L., 1965. Late Quaternary Niger Delta and adjacent areas: sedimentary environments and lithofacies. *Bulletin of the American Association Petroleum Geologists*, **49**, 547-600.
- Allen, J. R. L., 1970. Sediments of the modern Niger Delta: a summary and review, In: *Deltaic Sedimentation* (Ed. J. P. Morgan), Special Publications Society of Economic Palaeontologists Mineralogy, **15**, 138-151.
- 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.
- Anthony, E. J., 2002. Long-term marine bedload segregation and sandy versus gravelly Holocene shorelines in the eastern English Channel. *Marine Geology*, **187**, 221-234.
- Arbuszewski, J. A. deMenocal, P. B., Cléroux, C., Bradtmiller, L. and Alan, M., 2013. Meridional shifts of the Atlantic intertropical convergence zone since the Last Glacial Maximum. *Nature Geoscience*, **6**, 959-962.
- 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. & Simmons, M. D. (eds.) *Biostratigraphy in production*

References

- and development geology. Geological Society, London, Special Publications, **152**, 259-290.
- Aslan, A. and Whitney, J. A., 1999. Evolution of the Holocene Mississippi River floodplain, Ferriday, Louisiana: Insights on the origin of fine grained floodplains. *Journal of Sedimentary Research*, 800-815.
- Austin, D. F. and Cavalcante, P. B., 1982. Convolvulaceas de Amazonia. *Publication Avulsas*, **36**, 134.
- Avbovbo, A. A., 1978. Tertiary lithostratigraphy of Niger Delta. *American Association of Petroleum Geologists Bulletin*, **62**, 295-396.
- Backman, J., Fornaciari, E. and Rio, D., 2009. Biochronology and paleoceanography of late Pleistocene and Holocene calcareous nannofossils across the Arctic Basin. *Marine Micropaleontology*, **72**, 86-98.
- 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.
- Banner, F. T. and Blow, W. H., 1965. Progress in the planktonic foraminiferal biostratigraphy of the Neogene. *Nature*, **208**, 1164-1166.
- Barry, R. G. and Chorley, R. J., 2003. *Atmosphere, weather and climate*, 8th edition. Routledge, London.
- Barousseau, J. P., Bâ-diar, A. M., deScamps, C., diOp, H. S., Giresse, P. and Saos J. I., 1995. Coastal evolution in Senegal and Mauritania at 103, 102 and 101-year scales: natural and human records. *Quaternary International*, **29**, 61-73.
- Barousseau, 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.
- Batten, D., J. and Lister, J. K., 1988. Evidence of freshwater dinoflagellates and other algae in the English Wealden (Early Cretaceous). *Cretaceous Research*, **9**, 171-179.
- BBC, 2016. British broadcasting cooperation news on mangrove vegetation.
- Bell, A., 1983. *Dung Fungi. An illustrated guide to the Coprophilous fungi in New Zealand*. Victoria University Press, Wellington.
- Bennett, K., D., 1994. Confidence intervals for age estimates and deposition times in late-Quaternary sediment sequences. *The Holocene*, **4**, 337-348.

- Berger, A. and Loutre, M. F., 1991. Insolation values for the climate of the last 10 million years. *Quaternary Science Reviews*, **10**, 297-319.
- Berggren, W. A., Hilgen, F. J., Langereis, C. G., Kent, D. V., Obradovich, J. D., Raffi, I., Raymo, M. E. and Shackleton, N. J., 1995. Late Neogene chronology: new perspectives in high-resolution stratigraphy. *Geological Society of American Bulletin*, **107**, 1272-1287.
- Berné, S., Rabineau, M., Flores, J. A. and Sierro, F., J., 2004. The impact of quaternary global changes on strata formation: exploration of the shelf edge in the Northwest Mediterranean sea. *Oceanography*, **17**, 92-103.
- Bhattacharya, J. P. and Walker, R. G., 1992. Deltas. In: *Facies Models - response to Sea Level Change* (ed. R.G. Walker and N.P. James). Geological Association of Canada Bulletin, 157-177.
- Bhattacharya, J. and Giosan, L., 2003. Geomorphology of wave influenced deltas: Implications for facies interpretation. *Sedimentology*, **50**, 187-210.
- Blaauw, M., 2010. Methods and code for 'classical' age-modelling of radiocarbon sequences. *Quaternary Geochronology*, **30**, 1-6.
- Blunier, T., Chappellaz, J., Schwander, J., Dallenbach, A., Stauffer, B., Stocker, S. T., Raynaud, D., Jouzel, J., Claussen, H. B., Hammer, C. U. and Johnsen, S. J., 1998. Asynchrony of Antarctic and Greenland climate change during the last glacial period. *Nature*, **394**, 739-743.
- Bouimetarhan, I., Dupont, L., Kuhlmann, H., Pätzold, 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.
- Braconnot, P., Joussaume, S., de Noblet, N. and Ramstein, G., 2000. Mid - Holocene and Last Glacial Maximum African monsoon changes as simulated within the Paleoclimate Modelling Intercomparison Project. *Global and Planetary Change*, **26**, 51-66.
- Bralower, T. J., Leckie, R. M., Sliter, W. V. and Thierstein, H. R., 1995. An integrated Cretaceous microfossil biostratigraphy. In: Berggren, W.A., Kent, D.V., Aubry, M.-P. & Hardenbol, J. (eds.) *Geochronology, Time Scales*. SEPM Special Publication 54.
- Branonnot, P., Marzin, C., Gregoire, L., Mosquet, E. and Marti, O., 2008. Monsoon response to changes in Earth's orbital parameters: Comparisons between simulations of the Eemian and of the Holocene. *Climate of the Past*, **4**, 281-294.

References

- Brown, E. T., Johnson, T. C., Scholz, C. A., Cohen, A. S. and King, J. W., 2007. Abrupt change in tropical African climate linked to the bipolar seesaw over the past 55,000 years. *Geophysical Research Letters*, **34**, 1-5.
- Bruce, C. H., 1973. Pressured shale and related sediment deformation: Mechanism for development of regional contemporaneous faults. *American Association Petroleum Geologists Bulletin*, **57**, 86-878.
- Brenac, P., 1988. Evolution de la végétation et du climat dans l'Ouest-Cameroun entre 25 000 et 11 000 ans BP. Actes X Symposium Association des Palynologues de langue franc-aise, Inst. Fr. Pondichery, Science Technology, **25**, 91-103.
- Burke, K. B., 1972. Longshore drift, submarine canyons and submarine fans. *American Association Petroleum Geologists Bulletin*, **56**, 1975 -1983.
- Bujak, J. P., Downie, C., Eaton, G. L. and Williams, G. L., 1980. Dinoflagellate cysts and acritarchs from the Eocene of southern England. *Special Papers in Palaeontology*, **24**, 100.
- Bustin, R. M., 1988. Sedimentology and characteristics of dispersed organic matter in Tertiary Niger Delta: Origin of Source Rocks in a Deltaic Environment. *American Association of Petroleum Geologists*, **72**, 277-298.
- Carpenter, M. C., 1990. Feedback mechanism in climate: World meteorological organization intergovernmental panel on climate change, "Climate Change: The IPCC Scientific Assessment". Cambridge Press.
- Castelltort, S. and vanDen D. J., 2003. How plausible are high-frequency sediment supply-driven cycles in the stratigraphic record? *Sedimentary Geology*, **157**, 3-13.
- Castradori, D., 1993. Calcareous nannofossil biostratigraphy and biochronology in eastern Mediterranean deep-sea cores. *Riv. Italian Paleontological Stratigraphy*, **99**,107-126.
- Cattaneo, A. and Steel, R. J., 2003. Transgressive deposits: A review of their variability. *Earth Science Reviews*, **62**, 187-228.
- Cattaneo, A., Trincardi, F., Langone, L., Asioli, A. and Puig P., 2004. Cliniform generation margins. *Oceanography*, **17**, 104 -117.
- CGG, 2015. A Laboratory procedures of the CGG Robertson Research Company, UK (In house training).
- Chang, Y., 1967. Accuracy of fossil percentage estimate. *Palaeontology*, **41**, 500-502.

References

- Chase, M. W., Salamin, N. and Wilkinson M., 2005. Land plants and DNA barcodes: short-term and long-term goals. *Philosophical Transactions of the Royal Society B: Biological Sciences*, **360**, 1889-1895.
- Christopher, R. A., 1976. Morphology and taxonomic status of *Pseudoschizaea Thiergart* and *Frantz* ex. R. Potonié emend. *Micropaleontology*, **22**, 143-150.
- Chukwueke, C., Thomas, G. and Delfaud, J., 1992. Sedimentary processes, eustatism, subsidence and heat-flow in the distal part of the Niger Delta. *Bulletin des centres de recherches exploration-production Elf Aquitaine*, **16**, 137-186.
- Cita, M. B., 1975. The Miocene/Pliocene boundary: history and definition. In Saito, T., Burckle, L., H., (Eds.), *Late Neogene Epoch Boundaries. Special Publication. Micropaleontology*, 1-30.
- Clemens, S. C., Prell, W. L., and Sun, Y., 2010. Orbital-scale timing and mechanisms driving Late Pleistocene Indo-Asian summer monsoons: Reinterpreting cave speleothem $\delta^{18}O$. *Paleoceanography*, **25**, 4207,
- Cohen, H. A., and McClay, K. R., 1996. Sedimentation and shale tectonics of the north western Niger Delta front: *Marine and Petroleum Geology*, **13**, 313-328.
- Cohen, L. C. M., França, M. C., Rossetti, F. D., Pessenda, R. C. L., Giannini, F. C. P., Flávio L. L., Buso-Junior, A. A., Castro, D., and Macario, K., 2014. Landscape evolution during the late Quaternary at the Doce River mouth, Espírito Santo State, Southeastern Brazil. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **415**, 48-58.
- 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., Zariess, M., and Wefer, G., 2010. Interhemispheric symmetry of the tropical African rainbelt over the past 23,000 years. *Nature Geosciences*, **4**, 42-45.
- Couper, R. A., 1958. British Mesozoic microspores and pollen grains. *Palaeontographica*, **103**, 75 -179.
- Cowling, S., A. and Sykes, M. T., 1999. Physiological significance of low atmospheric CO₂ for plant-climate interactions. *Quaternary Research*, **52**, 237-242.
- Curran H. A., 1985. Biogenic Structures: Their use in interpreting depositional environments. *Society of Economic Palaeontologists Mineral*. pp. 347.
- Curtis, D. M., 1970. Miocene deltaic sedimentation, Louisiana Gulf Coast. (In:) J.P. Morgan (Ed.): *Deltaic sedimentation – modern and ancient. SEPM Special Publication*, **15**, 293-308.

- Dafni, A., 1992. Pollination ecology: a practical approach. Oxford, Oxford University Press.
- Dalibard, M., Popescua, S., Maley, J., François 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.
- Damuth, J.E., 1977. Late Quaternary sedimentation in the western equatorial Atlantic. *Geological Society American Bulletin*, **88**, 695–710.
- Davis, B. S., and Brewer, S., 2009. Orbital forcing and role of the latitudinal insolation/temperature gradient. *Climate Dynamics*, **32**, 143-165.
- Delcourt, A. and Sprumont, G., 1955. Les spores et grains de pollen du Wealdien du Hainaut. *Mémorie Society Belgium Géologis*, **5**, 1-73.
- d'Orbigny, A. D., 1839. Foraminifères. In: *Histoire Physique, Politique et Naturelle de l'île de Cuba*. Atlas **8**, 1-12. Eds: de la Sagra, 1-224.
- Doktorgrades, E., 2004. Reconstruction of sedimentary environment and climate conditions by multi-geochemical investigations of Late Palaeozoic glacial to postglacial sedimentary sequences from SW-Gondwana. Dissertation submitted to Universität Bonn, Germany, 96 - 117.
- Dow, W. G. and Pearson, D. B., 1975. Organic matter in Gulf Coast sediments: Offshore Technology Conference Proceedings, **3**, 2343 - 10.
- Doust, H. and Omatsola, E., 1989. The Niger delta: AAPG Memoir, **48**, 201-238.
- 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 Bulletin, **45**, 201-238.
- Dovlo E. K., 2016. Seasonal variations in temperature and salinity in the Gulf of Guinea. *Journal of Aquaculture and Marine Biology*, **4**, 2.
- 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.
- Dupont, L., 2011. Orbital scale vegetation change in Africa. *Quaternary Science Reviews*, **30**, 3589-3602.
- 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.

References

- Dupont, L. M. and Agwu, C. O., 1992. Latitudinal shifts of forest and savanna in N.W. Africa during the Brunhes chron: Further marine palynological results from site M16415 (9°N, 19°W). *Vegetation History and Archaeobotany*, **1**, 163-175.
- Dupont, L. M., Behling, H., Jahns, S., Marret, F. and Kim, J. H., 2007. Variability in glacial and Holocene marine pollen records offshore from west southern Africa. *Vegetation History and Archaeobotany*, **16**, 87-100.
- Dupont, L. M., Beug, H. J., Stalling, H. and Tiedemann, R., 1989. First palynological results from Site 658 at 21°N off northwest Africa: Pollen as climate indicators. In: Ruddiman, W., Sarnthein M., *et al.* (Ed.), *Proceedings of the Ocean Drilling Program, Scientific Results*.
- Dupont, L. M., Jahns, S., Marret, F. and Ning, S., 2000. Vegetation change in equatorial West Africa: Time-slices for the last 150 ka *Palaeogeography, Palaeoclimatology, Palaeoecology*, **155**, 95-122.
- Dupont, L., M., Marret, F. and Winn, K., 1998. Land-sea correlation by means of terrestrial and marine palynomorphs from the equatorial East Atlantic: phasing of SE trade winds and the oceanic productivity. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **142**, 5-84.
- Dupont, L., M. and Weinelt, M., 1996. Vegetation history of the savanna corridor between the Guinean and the Congolian rain forest during the last 150,000 years. *Vegetation History and Archaeobotany*, **5**, 273-292.
- Edet, J. J. and Nyong, E. E., 1994. Palynostratigraphy of Nkporo shale exposures (late Campanian-Maastrichtian) in the Calabar flank S.E. Nigeria. *Review of Palaeobotany and Palynology*, **80**, 131- 147.
- Ekweozor, C., M. and Daukoru, E., M., 1994. Northern delta depobelt portion of the Akata-Agbada petroleum system, Niger Delta, Nigeria, In: Magoon, L.B., and Dow, W.G., eds. *The Petroleum system from source to trap*: Tulsa, American Association of Petroleum Geologists, 599-614.
- Ellis, M., B., 1976. *More dematiaceous Hyphomycetes*. Commonwealth Mycological Institute, Kew, Surrey.
- Ellison, J., C., 2000. How South Pacific mangroves may respond to predicted climate change and sea level rise. Chapter 15, pp. 289-301. In: A. Gillespie and W. Burns, eds. *Climate change in the South Pacific: Impacts and responses in Australia, New Zealand, and Small Islands States*. Kluwer Academic Publishers, Dordrecht, Netherlands.

References

- Emery, Y. D. and Myers, K. J., 1996. Sequence Stratigraphy. *Geological Magazine*, **134**, 575-582.
- Emiliani, C. and Shackleton, N. J., 1974. The Brushes Epoch: Isotopic palaeotemperature geochronology. *Science*, **183**, 511-514.
- EPICA Community Members, 2006. Eight glacial cycles from an Antarctic ice core. *Nature*, **429**, 623-628.
- Erdtman, G., 1966. Pollen morphology and plant taxonomy (An introduction to palynology 1) Angiosperms, Almquist and Wiskell, Stockholm, Chronica Botanica Co. Waltham Mass 239.
- Ericson, D. B., and Wollin, G., 1968. Pleistocene climates and chronology in deep-sea sediments. *Science*, **162**, 1227-1234.
- Evamy, D. D., Haremboure, J., Kamerling, P., Knaap, W. A., Molloy, F. A. and Rowlands, P. H., 1978. Hydrocarbon Habitat of Tertiary Niger Delta. *AAPG Bulletin* **6**, 21-39.
- Fischer, G., Karakas, G., Blaas, M., Ratmeyer, V., Nowald, N., Schlitzer, R., Helmke, Davenport, R., Donner, B., Neuer, S. and Wefer, G., 2009. Mineral balast and particle settling rates in the coastal upwelling system off NW Africa and the South Atlantic. *International Journal of Earth Sciences*, **98**, 281-298.
- Fleming, K., Johnston, P., Zwartz, D., Yokoyama, Y., Lambeck, K., Chappell, J., 1998. Refining the eustatic sea-level curve since the Last Glacial Maximum using far- and intermediate-field sites *Earth and Planetary Science Letters*, **163**, 327-342.
- Fletcher, W. J., 2005. Holocene Landscape History of Southern Portugal. Doctoral thesis. Cambridge University Press, 159-172.
- Frederiksen, N. O., Carr, D. R., Lowe, G. D. and Wosika, E. P., 1983. Middle Eocene palynomorphs from San Diego, California; Part I: Introduction, spores and gymnosperm pollen. *American Association of Stratigraphic Palynologists, Contributions Series*, **12**, 8-31.
- Fredoux, A. and Tastet, J. P., 1976. Analyse pollinique d'une carotte marine au large de la Côte d'Ivoire. Variations de la végétation et du climat depuis 225 000 ans BP. *Palynosciences*, **2**, 173-188.
- Fredoux, A., 1994. Pollen analysis of a deep-sea core in the Gulf of Guinea: vegetation and climatic changes during the last 225,000 years B.P. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **109**, 317-330.

- Gajewski, K., Lézine, A. M., Vincens, A., Delestan, A. and Sawada, M., 2002. Modern climate vegetation pollen relations in Africa and adjacent areas. In: African pollen database. *Quaternary Science Reviews*, **21**, 1611-1631.
- Galloway, W. E., 2001. The many facies of submarine erosion: Theory meets reality in selection of sequence boundaries. American Association Petroleum Geologists. Hedberg research conference on "Sequence Stratigraphic and Allostratigraphic Principles and Concepts", Dallas, 26-29.
- Galloway, W. E., 1975. Process framework for describing the morphologic and stratigraphic evolution of deltaic depositional systems, In: *Deltas: models for exploration* (ed. M.L.Broussard), Houston Geological Society.
- Gartner, S., 1977. Calcareous nannofossil biostratigraphy and revised zonation of the Pleistocene. *Marine Micropaleontology*, **2**, 1-25.
- Garzoli, S. L., Gordon, A. L., Kamenkovich, V., Pillsbury, D. and Ducombe-Rae, C., 1996. Variability and sources of the south-eastern Atlantic circulation. *Journal of Marine Research*, **54**, 1039-1071.
- Gasse, F., Chalié, F., Vincens, A., Williams, M. A. J. and Williamson, D., 2008. Climatic pattern in equatorial and southern Africa from 30,000 to 10,000 years ago reconstructed from terrestrial and near-shore proxy data. *Quaternary Science Reviews*, **27**, 2316-2340.
- Gehrels, W. R., 1999. Middle and Late Holocene sea-level changes in Eastern Maine reconstructed from foraminiferal saltmarsh stratigraphy and AMS ¹⁴C dates on basal peat. *Quaternary Research*, **52**, 350-359.
- Giesen, W. S., Wulffraat, M. and Scholten, L., 2006. Mangrove guidebook for Southeast Asia. Food and agricultural organisation of the United States and Wetlands International, Bangkok, Thailand. pp 769.
- Gelorini, V., Verbeken, A., van Geel, B., Cocquyt, C. and Verschuren, D., 2011. Modern non-pollen palynomorph (NPP) diversity in East African lake sediments. *Review of Palaeobotany and Palynology*, **164**, 143–173.
- Germeraad, J. H. and Hopping, C. A., Muller, J., 1968. Palynology of Tertiary Sediments from Tropical Areas. *Review of Palaeobotany and Palynology*, **6**, 189-348.
- Gifford R. M., 1995. Whole plant respiration and photosynthesis of wheat under increased CO₂ concentration and temperature: long-term vs. short-term distinctions for modelling. *Global Change Biology*, **1**, 385-396

References

- Giosan, L. and Bhattacharya, J., 2005. River Deltas: Concepts, Models, Case Studies, SEPM Special Publication, 83.
- Giosan, L., Donnelly, J. P., Vespremeanu, E. and Buonaiuto, F. S., 2005. River delta morphodynamics: Examples from the Danube delta, In: River Deltas: concepts, models, examples (ed. L. Giosan and J. Bhattacharya), SEPM special publication **83**, 393-411.
- González-Guzmán, A. E., 1967. A Palynological study on the Upper Los Cuervos and Mirador Formations (Lower and Middle Eocene; Tibú area, Colombia). E.J. Brill, Leiden, Netherlands, pp 68.
- Goodbred, S. L., 2003. Response of the Ganges dispersal system to climate change: a source-to-sink view since the last interstade. *Sedimentary Geology*, **162**, 83-104.
- Goodfriend, G. A. and Stanley, D.J. 1996. Reworking and discontinuities in Holocene sedimentation in the Nile delta: Documentation from amino-acid racemization and stable isotopes in mollusk shells. *Marine Geology* **129**, 271-83.
- Goremykin, V. V. and Hellwig, F. H., 2005. Evidence for the most basal split in land plants dividing bryophyte and tracheophyte lineages. *Plant Systematics and Evolution*, **254**, 93-103.
- Gosling, W., Miller, C. and Livingstone. D. A., 2013. Atlas of the tropical West African pollen flora. *Review of Palaeobotany and Palynology*, **199**, 1-135.
- Gould, H. R., 1970. The Mississippi Delta complex. In: *Deltaic Sedimentation* (By J.P Morgan Ed.) Special Publications of Society for Economic Palaeontologists Mineralogy **15**, 3-30.
- Graham, A., 1991. Studies in Neotropical paleobotany. The Pliocene communities of Panama-composition, numerical representations and paleocommunity paleoenvironmental reconstructions. *Annual Missouri Botany Garden*, **78**, 465-475.
- Graham, A., 1995. Diversification of Gulf/Caribbean mangrove communities through Cenozoic time. *Biotropica*, **27**, 20-27.
- Graham, N. E., and Barnett, T. P., 1987. Sea surface temperature, surface wind divergence and convection over tropical oceans. *Science*, **238**, 657-659.
- Gradstein, F. M., Ogg, J. G. and Schmitz, M. D., 2012. *The Geologic Time Scale* Boston, USA, Elsevier.

References

- Grimm, E. C., 1987. CONNISS, a FORTRAN 77 programme for stratigraphically constrained cluster analysis by the method of incremental sum of squares. *Computers and Geoscience*, **13**, 13–35.
- Grenfell, H. R., 1995. Probable fossil Zygnematacean algae spore genera. Review of *Palaeobotany and Palynology*, **84**, 201-220.
- Griffiths, J. F., 1972. Climate of Africa: Seasonal changes cause a moist inflow of monsoonal air towards the low-pressure center over North Africa in summer: (In) *Earth's climate - past and future*. Amsterdam – Elsevier, **9**, 195.
- Guilderson, T. P., Fairbanks, R. G. and Rubenstone, J. L., 1994. Tropical temperature variations since 20,000 years ago: Modulating interhemispheric climate change, *Science*, **263**, 663-665.
- Hammond, A. P., Goh, K. M., Tonkin, P. J. and Manning, M. R., 1991. Chemical pre-treatments for improving the radiocarbon dates of peats and organic silts in a grey podzol environment: Grahams terrace, North Westland. *New Zealand Journal of Geology and Geophysics*, **34**, 191-194.
- Hanlin, R. T., 1990. *Illustrated genera of Ascomycetes*. The American Phytopathological Society, St. Paul, Minnesota.
- Harding, I. and Sam, M., 2012. Identifying the Palaeocene-Eocene Thermal Maximum (PETM) in a new core from Arctic Spitsbergen: The nature of organic carbon burial and a palaeoenvironmental reconstruction. Abstracts of TMS (Palynology Group) meeting, 3.
- Harff, J., Hay, W. W. and Tetzlaff, M. D., 2007. Coastlines as zones of interaction among geological processes, climate change, and socioeconomic development-Modeling opportunities. In: Harff, J., Hay, W.W, and Tetzlaff, D.M., eds., *Coastline Change: interaction of Climate and Geological Processes*. Geological Society of America Special Paper, **426**, 1-4.
- Harland, W. B., Armstrong, R. L., Cox, A. V., Craig, L. E., Smith, A. G. and Smith, D. G., 1989. *A Geologic Time Scale*. The British Petroleum Company plc., London,
- Harrison, S. P. and Prentice, C. I., 2003. Climate and CO₂ controls on global vegetation distribution at the last glacial maximum: Analysis based on palaeovegetation data, biome modelling and palaeoclimate simulations. *Global Change Biology*, **9**, 983-1004.

References

- Hartnett, H. E., Keil, R. G. and Hedges, J. I., 1998. Devol Influence of oxygen exposure time on organic carbon preservation in continental margin sediments. *Nature*, **391**, 572-575.
- Hastenrath, S., 1988a. *Climate and circulation of the tropics*. Reidel, Dordrecht, Boston, Lancaster, Tokyo, Second Printing, pp 455.
- Hastenrath, S., 1988b. Prediction of Indian monsoon rainfall; further exploration. *J. Climate*, **1**, 298-304.
- Hessler, I., Dupont, L., Bonnefille, R., Behling, H., González, C., Helmens, K. F., Hooghiemstra, H., Lebamba, J., Ledru, M. P., Lézine, A. M., Maley, J., Marret, F. and Vincens, A., 2010. Millennial-scale changes in vegetation records from tropical Africa and South America during the last glacial. *Quaternary Science Reviews*, **29**, 2882-2899.
- Heusser, L., 1978. Spores and pollen in the marine realm. In: B.U. Haq and A Boesam (eds.) *Introduction to Marine Micropalaeontology*. 327-339.
- Holdridge, L. R., Grenke, W. C., Hatheway, W. H., Liang, T. and Tosi, J. A., 1971. *Forest environments in tropical life zones: A pilot study*. Pergamon Press, Oxford.
- Hooghiemstra, H., Agwu, C. O. and Beug, H. J., 1986. Pollen and spore distribution in recent marine sediments: a record of NW-African seasonal wind patterns and vegetation belts. *Meteor-Forschungsergebnisse*, **40**, 87–135.
- Hooghiemstra, H., Lezine, A. M., Leroy, S. A., G., Dupont, L. and Marret, F., 2006. Late Quaternary palynology in marine sediments: A synthesis of the understanding of pollen distribution patterns in the NW African setting. *Quaternary International*, **148**, 29-44.
- Huang, Z., Li, P., Zhang, Z., Li, K. and Qiao, P., 1982. *Zhujiang (Pearl) Delta* (in Chinese). General Scientific Press, Guangzhou.
- Huang, Z. and Zong, Y., 1982. Grain size parameters and sedimentary facies of the Quaternary sequences in the Zhujiang (Pearl) Delta, China. *Tropical Geography*, **2**, 82-90.
- Ige, O. E., 2009. A late Tertiary pollen record from Niger Delta, Nigeria. *International Journal of Botany*, **5**, 203 -215.
- Ige, O. E. and Sowunmi, M. A., 1997. Reconstructing past vegetation through palynological analysis. *African Journal of Science*, **1**, 135-145.
- IPC, 2012. *International Palynological Congress and Palaeobotany Conference*, Tokyo, Japan. Conference Proceedings, Special Issue, **58**.

- IPCC, 2013. Climate Change 2013: The physical science basis. Contribution of working group I to the fourth assessment report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge and New York.
- Iyayi, F., 2004. An integrated approach to development in the Niger Delta. A paper prepared for the Centre for Democracy and Development (CDD).
- Jahns, S., 1996. Vegetation history and climate changes in West Equatorial Africa during the Late Pleistocene and Holocene based on a marine pollen diagram from the Congo fan. *Vegetation History and Archaeobotany*, **5**, 207-213.
- Jahns, S., Hu, I., M. and Sarnthein, 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. *Review of Palaeobotany and Palynology*, **102**, 277-288.
- Jan du Chene, R. E. and Salami, M. B., 1978. Palynology and micropaleontology of the Upper Eocene of the well Nsukwa-1, Niger Delta, Nigeria. *C.R. Des Seances SPHN Geneve*, **13**, 5-9.
- Jaramillo, C. A. and Dilcher, D. L., 2001. Middle Paleogene palynology of central Colombia, South America: A study of pollen and spores from tropical latitudes. *Palaeontographica*, **6**, 87-213.
- Jaramillo, C. and Bayona G., 2000. Mangrove distribution during the Holocene in Tribuga Gulf, Colombia. *Biotropica*, **32/1**, 14-22.
- Jaramillo, C. and Oboh-Ikuenobe, F. E., 1998. Sequence stratigraphic interpretations from palynofacies, dinocyst and lithological data of Upper Eocene-Lower Oligocene strata in southern Mississippi and Alabama, U.S. Gulf Coast. *Palaeogeography, Palaeoclimatology, Palaeoecology*, 259 - 302.
- Jardine, J. and Harrington, G., 2008. A diverse floral assemblage from the late Palaeocene of Mississippi. *Palynology*, **32**, 261-262.
- Jarzen, D. M. and Elsik, W. C., 1986. Fungal palynomorphs recovered from recent river deposits, Luangwa Valley, Zambia. *Palynology*, **10**, 35- 60.
- Jermannauda, P., Roubya, D., Robina, C., Nalpassa, T., Guillocheau, 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
- Johnson, H. B., Polley, H. W. and Mayeux, H. S., 1993. Increasing CO₂ and plant-plant interactions: effects on natural vegetation. *Vegetation* **104/105**, 157-170.

References

- Kakroodi, A., Leroy, A., Kroonenberg, S. A., G., Lahijani, S. B., Alimohammadian, H., A. K., Boomer, I. and Goorabi, A., 2015. Late Pleistocene and Holocene sea-level change and coastal paleoenvironment evolution along the Iranian Caspian shore. *Marine Geology*, 361, 111–125
- Kalgutkar, J., 2000. AASP Contribution Series, **39**.
- Kamptner, E., 1943. Zur Revision der Coccolithineen-Spezies *Pontosphaera huxleyi* Lohm. Anzeiger der (Kaiserlichen) Akademie der Wissenschaften. Mathematische-Naturwissenschaftliche Klasse, Wien. **80**, 73-49.
- Kar, R. K., 1992. Occurrence of *Acrostichum* spores from the Langpar Formation Early Palaeocene of Meghala, India. *Geophytology*, **22**, 33-36.
- Kar, R. K. and Saxena, R. K., 1976. Algal and fungal microfossils from Matanomadh formation (Palaeocene), Kutch India. *Palaeobotanists*, **23**, 1-15.
- Kennett, J. P. and Srinivasan, S., 1983. Neogene planktonic foraminifera: a phylogenetic atlas. Hutchinson Ross, New York, pp. 265.
- Key, J. Shell International Research (personal communication).
- Kim, J. H., Dupont, L., Behling, H. and Versteegh, G. J. M., 2005. Impacts of rapid sea-level rise on mangrove deposit erosion: application of taraxerol and *Rhizophora* records. *Quaternary Science*, **20**, 221-225.
- 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, M., E., 1987. Development of the Cenozoic Niger Delta in terms of the escalator regression model. (In:) Proceedings of the KNGMG symposium coastal lowlands-geology and geotechnology. Kluwer Academic Publishers, 181-202.
- 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.
- Krutzsch, W., 1962. Atlas der mittel- und jungtertiären dispersen Sporen- und Pollensowie der Mikroplanktonformen des nördlichen Mitteleuropas. Lieferung I. Veb Gustav Fischer Verlag Jena, **108**.

- Krutzsch, W., 1967. Atlas der mittel- und jungtertiären dispersen Sporen- und Pollensowie der Mikroplanktonformen des nördlichen Mitteleuropas. Gustav Fischer Verlag Jena, **232**.
- Kuehl, S. A., Allison, M. A., Goodbred, S. L. and Kudrass, H. 2005. The Ganges-Brahmaputra delta, In: River Deltas: Concepts, models, examples (ed. L. Giosan and J. Bhattacharya), SEPM Special Publication **83**, 413-434 In: Marine Geology, **361**, 111-125.
- 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.
- Lecal, J. and Bernheim, A., 1960. Microstructure du squelette de quelques Coccolithophorides. Bulletin of Society for Historical Nature, **57**, 273-297.
- Legoux, O., 1978. Quelques especes de pollen caracterique du Nigeria. Centre for Exploration Production Elf Aquitaine, 265-317.
- 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.
- Lewis, S. L., Lopez-Gonzalez, G., Sonke, B., Affum-Baffoe, K., Baker, T. R., Ojo, L. O., Phillips, O. L., Reitsma, J. M., White, L., Comiskey, J. A., Djuikouo K, M. N., Ewango, C. E .N., Feldpausch, T. R., Hamilton, A. C., Gloor, M., Hart, T., Hladik, A., Lloyd, J., Lovett, J. C., Makana, J. R., Malhi, Y., Mbago, F. M., Ndangalasi, H. J., Peacock, J., Peh, K. S. H., Sheil, D., Sunderland, T., Swaine, M. D., Taplin, J., Taylor, D., Thomas, S. C., Votere, R. and Wöll, H., 2009. Increasing carbon storage in intact African tropical forests. Nature, **457**, 1003-1006.
- Lezine, A. M. and Casanova, J., 1989. Pollen and hydrological evidence for interpretation of past climates in tropical West Africa during the Holocene. Quaternary Science Reviews, **8**, 45–55.
- Lezine, A. M. and Cazet, J. P., 2005. High resolution pollen record from core KW31 Gulf of Guinea, documents the history of the lowland forests of West Equatorial Africa since 40,000 year ago. Quaternary Research, **64**, 432-443.
- Lezine, A. M., Cazet, J. P. and Duplessy, J. C., 2005. West African monsoon variability during the last deglaciation and the Holocene: Evidence from fresh water algae, pollen and isotope data from core KW31, Gulf of Guinea. Palaeogeography Palaeoclimatology, Palaeoecology, **219**, 225-237.

References

- Lézine, A. M. and Denèfle, 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.
- Lézine A. M. and Vergnaud-Grazzini, G., 1993. Evidence of forest extension in West Africa since 22,000 BP: A pollen record from the eastern tropical Atlantic. *Quaternary Science Reviews*, **12**, 203-210.
- Lorente, M. A., 1990. Textural characteristics of organic matter in several subenvironments of Orinoco Upper delta. *Geologie en Mijnbouw*, **69**, 263-278.
- Lorente, M., 1986. Palynology and palynofacies of the Upper Tertiary in Venezuela. Dissert. Botany. (Gebrüder Borntraeger, Berlin) **99**, 1-222.
- Lyell, C., 1830, 33. The principles of geology. Murray, London. vol. 2, Chapter 2.
- MacIntyre, C. and McIntyre, S., 2009. Zanzibar 7th travel guide. Bradt travel guides, UK, pp. 390.
- Mahmoud, M. S. and Schrank, E., 2007. Late Cretaceous spores, pollen and dinoflagellates from two boreholes (Nuqra-1 and 3) in the Aswan area, southeastern Egypt. *Revue de Paléobiologie*, **26**, 593-613.
- Maley, J., 1991. The African rain forest vegetation and palaeoenvironments during the late Quaternary. *Climate Change*, **19**, 79-98.
- Maley, J. and Brenac, P., 1998. Vegetation dynamics, palaeoenvironments and climatic changes in the forests of western Cameroon during the last 28,000 years B.P. *Review of Palaeobotany and Palynology*, **99**, 157-187.
- 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., Kim, S. Y. and Scourse, J., 2013. A 30,000 ka yr record of land–ocean interaction in the eastern Gulf of Guinea. *Quaternary Research*, **80**, 1-8.
- Marret, F., Scourse, J., Jansen, J. and Schneider, R., 1999. Climate and palaeoceanographic changes in west Central Africa during the last deglaciation: palynological investigation. *Comptes-Rendus de l'Académie des Sciences de Paris, Earth and Planetary Science*, **329**, 721-726.
- Marret, F., Scourse, J., Kennedy, H., Ufkes, E., and Jansen, J. H .F., 2008. Marine production in the Congo-influenced SE Atlantic over the past 30,000 years: A novel dinoflagellate cyst based transfer function approach. *Marine Micropaleontology*, **68**, 198-222.

References

- 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,
- Martini, E., 1971. Standard Tertiary and Quaternary calcareous nannoplankton zonation. In Farinacci, A. (Ed.), *Proc 2nd Int. Conf. Planktonic Microfossils Roma: Rome* (Ed. Tecnosci.), **2**, 739-785.
- Martinson, D. G., Pisias, N. G., Hays, J. D., Imbrie, J., Moore, T. C. and Shackleton, N.J., 1987. Age dating and the orbital theory of the ice ages: Development of a high-resolution 0 to 300,000 year chronostratigraphy. *Quaternary Research*, **27**, 1-29.
- Massuanganhe, E. A., Westerberg, L. O., Risberg, J., Preusser, F., Bjursäter, S. and Achimo, M., 2016. Geomorphology and landscape evolution of Save River delta, Mozambique. Thesis Manuscript, 1-21.
- McKee, B. A., Aller, R. C., Allison, M. A., Bianchi, T. S., and Kineke, G. C., 2004. Transport and transformation of dissolved and particulate materials on continental margins influenced by major rivers: Benthic boundary layer and seabed processes. *Continental Shelf Research*, **24**, 899-926.
- Meade, R. H., 1996. River-sediment inputs to major deltas. In: *Sea level rise and coastal subsidence* (ed. J.D. Milliman and B.U. Haq). Kluwer Dordrecht, 63-85.
- Mendoza, U. M., 2007. Dynamics of phosphorus and sulphur in a mangrove forest in Bragança, North Brazil. PhD thesis, University of Bremen 1-16.
- Mikkelsen, N., Maslin, M., Giraudeau, J., Showers, W., 1997. Biostratigraphy and sedimentation rates of the Amazon fan. In: Flood, R.D., Piper, D.J.W., Klaus, A., and Peterson, L.C. (Eds.), 1997. *Proceedings of the ODP, Scientific Results*, College Station, TX (Ocean Drilling Program), 155, 579-581.
- Mibey, R. K., and Kokwaro, J. O., 1999. Two new species of *Meliola* from Kenya. *Fungal Diversity*, **2**, 153-157.
- Miller, C. S. and Gosling, W. D., 2014. Quaternary forest associations in lowland tropical West Africa. *Quaternary Science Reviews*, **84**, 7-25.
- Miller, H. S., 2011. Assessing the viability of using foraminifera from Mersey Estuary saltmarsh sediments to reconstruct former sea level. PhD thesis, University of Liverpool.

References

- Miller, K. G., Sugarman, P. H., Browning, V. J., Kominz, M. A., Hernández, J. S., Olsson, R. K., Wright, J. D., Feigenson, M. D. and vanSickel, W., 2003. Late Cretaceous chronology of large, rapid sea-level changes: Glacioeustasy during the greenhouse world. *Geology*, **31**, 585-588.
- Morgan, J. P., 1970. Depositional process and products in the deltaic environment. In: *Deltaic sedimentation* (Ed. By J.P Morgan), Special Publications of Society for Economic Palaeontologists Mineralogy, **15**, 31-47.
- Morley, R. J. and Flenley, J. R., 1987. Late Cainozoic vegetational and environmental changes in the Malay Archipelago. In: *Biogeographical evolution of the Malay Archipelago*. Edited by T., C., Whitmore. Oxford Monograph on Biogeography, **4**, Oxford Scientific Publications, 50-59.
- Morley, R. J., 2000. *Origin and evolution of tropical rainforest*. Wiley. 288-299.
- 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., 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*.
- 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.
- Mudie, P., J., Leroy, S., A., G., Marret, F., Gerasimenko, N., P., Kholeif, S., E., A., Sapelko, T. and Filipova-Marinova, M., 2011. Non-pollen palynomorphs: Indicators of salinity and environmental change in the Caspian-Black Sea-Mediterranean corridor. In: I. V. Buynevich, V. Yanko-Hombach, A. S. Gilbert, & R. E. Martin (Eds.), *Geology and Geoarcheology of the Black Sea Region: Beyond the flood hypothesis*. Boulder: The Geological Society of America, **473**, 89-115.
- Mudie, P. J., Aksu, A. E. and Yasar, D., 2001. Late Quaternary dinoflagellate cysts from the Black, Marmara and Aegean seas: Variations in assemblages, morphology and paleosalinity. *Marine Micropaleontology*, **43**, 155-178.
- Mudie P. J., Rochon A., Aksu. A. E. and Gillespie, H., (2002) Dinoflagellate cysts, freshwater algae and fungal spores as salinity indicators in Late Quaternary cores from Marmara and Black seas. *Marine Geology*, **190**, 203–231.

References

- Mulitza, S., Prange, M., Stuut, J., B., W., Zabel, M., von Dobeneck, T., Itambi, A., C., Nizou, J., Schulz, M., Wefer, G., 2008. Sahel megadroughts triggered by glacial slowdowns of Atlantic meridional overturning. *Palaeoceanography*, **23**, 1-11.
- Murray J. W., 1991. Ecology and palaeoecology of benthic foraminifera. Amsterdam, Elsevier. 397 pp.
- Nagy, E., 1985. Sporomorphs of the Neogene in Hungary. *Geologica Hungarica - Series Palaeontologica. Fasciculus* **47**, 471 pp.
- Nnamani, C. V. and Nwosu, M. O., 2012. Pollen Morphology of Some Members of Nigerian Clusiaceae and Its Taxonomic Significance. *International Journal of Pharmacy and Biological Sciences*, **3**, 14-19.
- Nelson, G. and Hutchings, L., 1983. The Benguela upwelling area. *Program of Oceanography*, **12**, 13-7.
- Newnham, R. M., Vandergoes, M. J., Garnett, M., Lowe, D. J., Prior, C. and Almond, P. J., 2007. Test of AMS ¹⁴C dating of pollen concentrates using tephrochronology. *Journal of Quaternary Science*, **22**, 37-51.
- Nicholls, R. J. and Cazenave, A., 2010. Sea-level rise and its impact on coastal zones. *Science*, **6**, 329-628.
- Nichole, G. 2011. Sedimentology and stratigraphy. Second Edition, 5-9.
- Niger Delta Consortium, 2000. Stratigraphic resolution on the Niger Delta Depobelt (Proprietary data of multinational oil companies, Nigeria).
- Njock, J. C., 1985. La Pêche démersale au Cameroun et ses tendances actuelles. *Revue science et technique. Limbé, Station de Recherches Halieutiques*, pp 30.
- Oboh, F. E., 1995. Sedimentological and palynological characteristics of the E2.0 Reservoir (Middle Miocene) in the Kolo Creek Field, Niger Delta. In: *Geology of Deltas*, Oti, M.N. and G. Postma (Eds.). Balkema Publishers, Rotterdam, 243-256.
- Oboh, F. E., Salami, M. B. and Chapman, J. L., 1992. Palynological interpretation of the palaeoenvironments of Miocene strata of the well Igbomotoru-1, Niger Delta. *Journal of Micropalaeontology*, **11**, 1-6.
- Ogadinma, A., 2013. To assess the hydrological impact of climate change on Niger Delta, Nigeria. 2nd International Conference on Earth Science and Climate Change Las Vegas, NV, USA, **4**, 69.
- Okada, H. and Bukry, D., 1980. Supplementary modification and introduction of code numbers to the low-latitude coccolith biostratigraphic zonation: In Bukry, 1973; 1975). *Marine Micropaleontology*, **5**, 321-325.

References

- Okada, H. and Honjo, S., 1973. The distributions of oceanic coccolithophores in the Pacific. *Deep Sea Research*, **20**, 355–374.
- Okonkwo, N. P., Kumar L. and Taylor, S., 2015. The Niger Delta wetland ecosystem: What threatens it and why should we protect it? In: Map of Niger Delta showing, rivers, states and vegetation zones, Ugochukwu and Ertel (2008). *African Journal of Environmental Science and Technology*, **9**, 455.
- Olago, D., O., 2001. Vegetation changes over palaeo-time scales in Africa. *Climate Research*, **17**, 105–121.
- Olson, D. M., Dinerstein, E., Wikramanayake, E. D., Burgess, N. D., Powell, G. V. N., Underwood, E. C., D'Amico, J. A., Itoua, I., Strand, H. E., Morrison, J. C., Louks, C. J., Allnutt, T. F., Ricketts, T. H., Kura, Y., Lamoreux, J. F., Wettengel, W. W., Hedao, P. and Kassem, K. R., 2001. Terrestrial ecoregions of the world: a new map of life on Earth. *Vegetation changes over palaeo time scales in Africa. Climate Research*, **17**, 105-121.
- Oomkens, E., 1974. Lithofacies relations in late Quaternary Niger delta complex. *Sedimentology*, **21**, 195-222.
- Osterloff. Comm (Unpublihsed Shell Internal Report)
- Overeem, I., Syvitski, J. P. M. and Hutton, E. W. H., 2005. Three-dimensional numerical modelling of deltas. In: *River Deltas: concepts, models, examples* (ed. L. Giosan and J. Bhattacharya). *SEPM Special Publication*, **83**, 13-30.
- Peck, J. A., Green, R. R., Shanahan, T., King, J. W., Overpeck, J., T. and Scholz, C. A., 2004. A magnetic mineral record of Late Quaternary tropical climate variability from Lake Bosumtwi, Ghana. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **215**, 37-57.
- Peltier, W. R., 1994. Ice age paleotopography. *Science*, **265**, 195-201.
- Peterson, R. G. and Stramma, L., 1991. Upper level circulation in the South Atlantic Ocean. *Program Oceanography*, **26**, 1-73.
- Petit, J. R., Jouzel, J., Raynaud, D., Barkov, N. I., Barnola, J. M., Basile, I., Bender, M., Chappellaz, J., Davisk, M., Delaygue, G., Delmotte, M., Kotlyakov, V.M., Legrand, M., Lipenkov, V. Y., Lorius, C., Pepin, L., Ritz, C., Saltzmark, E. and Stievenard, M., 1992. Climate and atmospheric history of the past 420,000 years from the Vostok ice core, Antarctica. *Nature*, **399**, 429-436.
- Petters, S. W., 1984. An ancient submarine canyon in the Oligocene-Miocene of the western Niger Delta. *Sedimentology*, **31**, 805-810.

References

- Phumphumirat, W., Dallas C. M. and Choathip, P., 2009. Pollen deterioration in a tropical surface soil and its impact on forensic palynology. *The Open Forensic Science Journal*, **2**, 34-40.
- Pidwirny, M., 2006. Surface and subsurface ocean currents: Ocean current map. *Fundamentals of physical geography*, 2nd Edition.
- Plater, A. J. and Kirby, J. R., 2011. Sea-Level change and coastal geomorphic response. Elsevier Inc., **3**, 39.
- Posamentier, H. W., Jervey, M. T. and Vail, P. R., 1988. Eustatic controls on clastic deposition. I. Conceptual framework. In: Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C. (Eds.), *Sea Level Changes – An Integrated Approach*. SEPM Special Publication, **42**, 110-124.
- Posamentier, H. W. and Allen, G. P., 1999. Siliciclastic sequence stratigraphy - concepts and applications. *Concepts in sedimentology and palaeontology, Sedimentary Geology*, Tulsa, 204.
- Posamentier, H. W. and Kolla, V., 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. *Journal of Sedimentary Research*, **73**, 367-388.
- Pospelova, V., Gail, L. C., Henry A. W., 2004. Environmental factors influencing the spatial distribution of dinoflagellate cyst assemblages in shallow lagoons of southern New England, USA. *Review of Palaeobotany and Palynology*, **128**, 7-34.
- Potonié, R., 1960. Synopsis der Gattungen der Sporae dispersae II Teil: Sporites. *Beihefte Geologische Jahrbuch*, **39**, 1-189
- Poumot, C., 1989. Palynological evidence for eustatic events in the tropical Neogene. *Centres for Research Exploration Production Elf Aquitaine*, **13**, 437-453.
- Prager, A., Barthelmes, A., Theuerkauf, M. and Joosten, H., 2006. Non-pollen palynomorphs from modern Alder carrs and their potential for interpreting microfossil data from peat. *Review of Palaeobotany and Palynology*, **141**, 7-31.
- Prell, W. L., and Damuth, J. E., 1978. The climate related diachronous disappearance of *Pulleniatina obliquiloculata* in Late Quaternary sediments of the Atlantic and Caribbean. *Micropaleontology*, **3**, 267-277.
- Punt, W., Hoen, P. P., Blackmore, S., Nilsson, S. and Le Thomas, A., 2007. Glossary of pollen and spore terminology. *Review of Palaeobotany and Palynology*, **143**, 1-81

References

- Punwong, P., Marchant, R. and Selby, K., 2012. Holocene mangrove dynamics and environmental change in the Rufiji Delta, Tanzania. *Vegetation History and Archaeobotany*, **12**, 1-16.
- Punwong, P., Marchant, R. and Selby, K. A., 2013. Holocene mangrove dynamics from Unguja Ukuu, Zanzibar. *Quaternary International*, **298**, 4-19.
- Raffia, I., and Rio, D., 1979. Precision and accuracy of nannofossil biostratigraphic correlation. *Special Publications of Royal Society London*, **357**, 1975 -1993.
- Raffia, I., Backman, J., Fornaciari, E., Pälike, H., Rio, D., Lourens, L. and Hilgen, F. J., 2006. A review of calcareous nannofossil astrobiochronology encompassing the past 25 million years. *Quaternary Science Reviews*, **25**, 3113-3137.
- Ratmeyer, V., Balzer, W., Begametti, G., Chiapello, I., Fischer, G. and Wyputta, U., 1999. Seasonal impact of mineral dust on deep-ocean particle flux in the eastern subtropical Atlantic Ocean. *Marine Geology*, **159**, 241-252.
- Regali, M. S. P., Uesugui, N. and Santos, A. S., 1974. Palinologia dos sedimentos mesocenoicos do Brasil. *Technology Petrobras*, **17**, 263-302.
- Reijers, T. J. A., 2011. Stratigraphy and sedimentology of the Niger Delta. *Geologos*, **17**, 133-162.
- Riboulot, V., Cattaneo, A., Berné, 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.
- Riboulot, V., Cattaneo, A., Lanfumey, V., Berné, S., Voisset, M. and Cauquil, E., 2011. Morphological signature of fluid flow seepage in the Eastern Niger Submarine Delta. OTC, Houston, Texas, USA. pp 21744.
- Ridente, D., Trincardi, F., Piva, A., Asioli, A. and Cattaneo, A., 2008. Sedimentary response to climate and sea level changes during the past approximately 400 ka from borehole PRAD1-2 (Adriatic Margin): Geochemistry, Geophysics, Geosystems, **3**, 9.
- Rio, D., Raffi, I. and Villa, G., 1990. Pliocene-Pleistocene calcareous nannofossil distribution patterns in the Western Mediterranean. In: Kastens, K.A., Mascle, J., *et al.*, Proc. ODP, Sci. Results, 107: College Station, TX (Ocean Drilling Program), 513-533.
- Robert W. D. and Kyungsik C., 2007. Morphologic and facies trends through the fluvial–marine transition in tide-dominated depositional systems: A schematic

- framework for environmental and sequence-stratigraphic interpretation. *Earth Science Reviews*, **81**, 35-174.
- Rosignol, M., 1962. Analyse pollinique de sediments marins Quaternaries en Israel. II Sediments Pleistocenes. *Pollen et spores*, **4**, 121-148.
- Ruddiman, W. F., 2001. *Earth's climate-past and future*. Freeman and Company 8-16, 34.
- Rull, V., 1998. Middle Eocene Mangroves and Vegetation Changes in the Maracaibo Basin, Venezuela. *PALAIOS*, **13**, 287-296.
- Rull, V., 1997. Quaternary palaeoecology and ecological theory: Bolten de la Sociedad Venezolana de Geologos, **46**, 16-26.
- Rull, V., 2001. A quantitative palynological record from the Early Miocene of western Venezuela, with emphasis on mangroves. *Palynology*, **25**, 109-126.
- Rull, V., 2002. High impact palynology in petroleum geology. Applications from Venezuela (northern South America). *American Association of Petroleum Geologists Bulletin*, **86**, 279–300.
- Saad, S. J. and Ghazaly, G., 1976. Palynological evidence in Nubia Sandstone from Khnaga oasis. *Pollen et Spores*, **18**, 407-470.
- Sageman, B. B., Rich, J., Arthur, M. A., Birchfield, G. E. and Dean, W. E., 1997. Evidence for Milankovitch periodicities in Cenomanian-Turonian lithologic and geochemical cycles, western interior, U.S.A. *Journal of Sedimentary Research*, **67/2**, 286-301.
- Sah, S. C. D., 1967. Palynology of an Upper Neogene profile from Rusizi Valley (Burundi). *Koninklijk Museum voor Midden-Afrika Tervuren, Belgie Annalen Reeks in 8° Geologische Wetenschappen*, **57**, 173.
- Saito, T., 1962: Eocene planktonic foraminifera from Hahajima (Hillsborough Island). *Transocean Proceedings of the Paleontological Society, Japan*, **45**, 209-225.
- Sanfilippo, A. and Blome, C. D., 2001. Biostratigraphic implications of mid-latitude Paleocene-Eocene radiolarian faunas from Hole 1051A, ODP Leg 171B, Blake Nose, western North Atlantic. In: Kroon, D., Norris, R.D., and Klaus, A. (Eds.), *Western North Atlantic Palaeogene and Cretaceous Palaeoceanography*. Geological Society Special Publication, **183**, 185-224.
- Salard-Cheboldaeff, M., 1978. Sur la palynoflore Maestrichtienne et Tertiaire du basin sédimentaire littoral du Cameroun. *Pollen et Spores XX*, 218 -260.

- Salard-Chebouldaëff, M., 1979. Palynologie maestrichtienne et tertiaire du Cameroun. Etude qualitative et répartition verticale des principales espèces. Rev. Palaeobot. Palynology, **28**, 365-388.
- Salard-Chebouldaëff, M., 1990. Intertropical African palynostratigraphy from Cretaceous to late Quaternary times. Journal of African Earth Sciences, **11**, 1-24.
- Salard-Chebouldaëff, M. J. M. and Brunet, M., 1992. Paleoflore tertiaire du bassin d'anloua plateau de l'adamaoua, camboun. Revista Espanola Micropaleontol., **12**, 131-162.
- Salzmann, U., Hoelzmann, P. and Morczinek, I., 2002. Late Quaternary Climate and Vegetation of the Sudanian Zone of Northeast Nigeria. Quaternary Research, **58**,
- Samant, B., Phadtare, N. R., 1997. Stratigraphic palynoflora of the early Eocene Rajpardi lignite, Gujarat and the lower age limit of the Tareswar Formation of south Cambay Basin, India. Palaeontographica, **245**, 73-83.
- Sanfillipo, A., and Blome, C. D., 2001. Biostratigraphic implications of mid-latitude Palaeocene–Eocene radiolarian faunas from Hole 1051A, ODP Leg 171B, Blake Nose, western North Atlantic. In Kroon, D., Norris, R.D., and Klaus, A. (Eds.), Western North Atlantic Paleogene and Cretaceous Paleooceanography. Spec. Publication of Geological Society London, **183**, 185-224.
- Sandberg, C., A. and Ziegler, W., 1996. Devonian conodont biochronology in geologic time calibration. Senckenbergiana Lethaea, **76**, 259-265.
- Sato, T., Kameo, K. and Takayama, T., 1991. Coccolith biostratigraphy of the Arabian Sea. Proceedings of the Ocean Drilling Program. Scientific Results **117**, 37-54.
- Sato, T. and Takayama, T., 1992. A stratigraphically significant new species of the calcareous nannofossil *Reticulofenestra asanoi*. Centenary of Japan Micropaleontology, 457-460.
- Schmidt, D., P. 2008. A palynological and stratigraphic analysis of mangrove sediments at Punta Galeta, Panama. (Ph.D., University of California, Berkeley) **3331783**, 2-29.
- Schneider, R. R., Price, B., Muller, P. J., Kroon, D. and Alexander, I., 1997. Monsoon related variations in Zaire (Congo). Sediment load and influence of fluvial silicate supply on marine productivity in the east equatorial Atlantic during the last 200,000 years. Paleoceanography, **12**, 463-481.
- 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

References

- reveals significance of mangrove pollen and biomarkers as indicators of shelf transgression. *Quaternary Research*, **64**, 57-69.
- Sexton, W. J. and Murday, M., 1998. The Morphology and Sediment Character of the Coastline of Nigeria - the Niger Delta. *Journal of Coastal Research*, **10**, 959–977.
- Shackelton, N. J., 1987. Oxygen isotopes, ice volume and sea level. *Quaternary Science Reviews*, **6**, 183-190.
- Shanahan, T. M., McKay, Nicholas, P. H., Konrad A., Overpeck, J. T., Otto, B., Bette, H., Clifford, W., King, J., Scholz, C. A. and Peck, J., 2015. The time-transgressive termination of the African Humid Period. *Nature Geoscience*, **8**, 140-144.
- Shanahan, 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.
- Shell, 2011. Location of map of Niger Delta and core positions (GC cores).
- Shell Petroleum Development Company, Nigeria. 2000. Palynomorph Atlas (Unpublished report).
- Shi, N. and Dupont, L., 1997. Vegetation and climatic history of southwest Africa: a marine palynological record of the last 300,000 years. *Vegetation History Archaeobotany*, **6**, 117-131.
- Shi, N., Schneider, R. R., Beug, H. J. and Dupont, L. M., 2001. Southeast trade wind variations during the last 135 kyr: Evidence from pollen spectra in eastern South Atlantic sediments. *Earth Planetary and Science Letters*, **187**, 311-321.
- Short, K., C. and Stauble, A.J., 1967. Outline of geology of Niger Delta. *American Association of Petroleum Geologists Bulletin*, **51**, 761-779.
- Simmons, M. D., Bidgood, M. D., Brenac, P., Crevello, P. D., Lambiase, J. J. and Morley, C. K., 1999. Microfossil assemblages as proxies for precise palaeoenvironmental determination, an example from Miocene sediments of North-West Borneo. In: Jones, R. W. & Simmons, M. D. (eds.), *Biostratigraphy in production and development geology*. Geological Society, London, Special Publications, **152**, 219-241.
- Skinner, L. C., 2008. Revisiting the absolute calibration of the Greenland ice-core age-scales. *Climate of the Past*, **4**, 295-302.
- Smart C. W., 2002. A comparison between smaller (>63 µm) and larger (>150 µm) planktonic foraminiferal faunas from the Pleistocene of ODP Site 1073 (Leg 174A),

References

- New Jersey margin, NW Atlantic Ocean. *Journal of Micropalaeontology*, **21**, 137-147.
- Smith, A. R., Pryer, K. M., and Schuettpelz, E., Korall, P., Schneider, H. and Wolf, P. G., 2006. A classification for extant ferns. *Taxon*, **3**,705-731.
- Sowunmi, M. A., 1981. Aspects of Late Quaternary vegetational changes in West Africa. *Journal of Biogeography*, **8**, 457-474.
- Sowunmi, M. A., 1995. Pollen morphology in the Palmae with special reference to trends in aperture development. *Review of Palaeobotany and Palynology*, **7**, 45-53.
- 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.
- Stanley D. J., 1988. Low sediment accumulation rates and erosion on the middle and outer Nile delta shelf off Egypt. *Marine Geology*, **84**,111–17.
- Stanley, J., 2001. Dating modern deltas: Progress, problems, and prognostics. *Annual Review Earth Planetary Science*, **29**, 257-294.
- Steffen, D. and Gorin, G., E., 1993. Palynofacies of the Upper Tithonian - Berriasian deep sea carbonates in the Vocontian (SE France). *Centres Recherché Exploration Production Elf-Aquitaine Bulletin*, **17**, 235-247.
- Stefano, E., 1998. Calcareous nannofossil quantitative biostratigraphy of Holes 969e and 963b (Eastern Mediterranean) In: Robertson, A. H. F., Emeis, K. C., Richter, C., and Camerlenghi, A. (Eds.). *Proceedings of the Ocean Drilling Program, Scientific Results*, 160, 100-110.
- Stoll, H. M., Klaas, C., Probert, I., Encinar, J. R. and Alonso, J. I. G., 2002. Calcification rate and temperature effects on Sr partitioning in coccoliths of multiple species of coccolithophorids in culture. *Global Planetary Change*, **34**, 153–171.
- Stramma, L. and England, M., 1999. On the water masses and mean circulation of the South Atlantic Ocean. *Journal of Geophysical Research*, **104**, 20863-20883.
- Street-Perrott F. A. and Roberts N., 1983. Fluctuations in closed-basin lakes as an indicator of past atmospheric circulation patterns. In: *Variations in the Global Water Budget*, Street-Perrott F.A. *et al.* (eds). Reidel: Dordrecht, 331-345.
- Stuchlik, L., 2001 (ed.). *Atlas of pollen and spores of the Polish Neogene*. Spores W. Szafer Institute of Botany. Polish Academy of Sciences, **1**, pp 158.

References

- Sullivan, H. J. and Marshall A. E., 1990. Visean spores from Scotland. *Micropaleontology*, **12**, 265-285.
- Swenson J., B., Paola, C., Pratson, L., Voller, V., R., Murray, A., B., 2005. Fluvial and marine controls on combined subaerial and subaqueous delta progradation: Morphodynamic modeling of compound clinof orm development. *Journal of Geophysical Research*, 110.
- Syvitski, J. P. M., Harvey, N., Wollanski, E., Burnett, W. C., Perillo, G. M. E. and Gornitz, V., 2005. Dynamics of the coastal zone. In: *Coastal change and the Anthropocene*. Springer.
- Syvitski, J. P. M., Kettner, A. J., Overeem, I., Hutton, E. W. H., Hannon, M. T., Brakenridge, G. R., Day, J., Vörösmarty, C., Saito, Y., Giosan, L., Nicholls, R. J., 2009. Sinking deltas due to human activities: *Nature Geoscience*, **2/10**, 681-686.
- Takahashi, K. and Jux, U., 1989. Palynology of Middle Tertiary lacustrine deposits from the Jos Plateau, Nigeria. *Bull. Fac. Liberal Arts, Nagasaki Univ. (Nat. Sci.)*, **29**, 181–367.
- Thiergart, F. and Frantz, U., 1962. Some spores and pollen grains from Tertiary brown coal deposit in Kashir. *Palaeobotany*, **10**, 84-86.
- Tjallingii, R. M., Claussen, J. B. W., Stuut, J., Fohlmeister, A., Jahn, T., Bickert, F. and Röhl, U., 2008. Coherent high and low-latitude control of the northwest African hydrological balance. *Nature Geoscience*, **1**, 670-675.
- Thomson, P. W. and Pflug, H. D., 1953. Pollen und des mitteleuropaischen Tertiars. *Palaeontographica*, **94**, 1-138.
- Tooley, M. J., 1978. *Sea level changes North-west England during the Stage Clarendon* Press, Oxford.
- 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.
- Tyson, P. D. and Preston-Whyte, R., A., 2000. *The weather and climate of Southern Africa*, Oxford University Press South Africa, Cape Town, pp 396.
- Tyson, R. V., 1995. *Sedimentary Organic Matter: organic facies and palynofacies* Chapman and Hall, London, 615.
- University of Arizona, Heberium collection, 2011.

References

- Uyigue, E. and Agho, M., 2007. Coping with Climate Change and Environmental Degradation in the Niger Delta of Southern Nigeria. CREDC 5.
- Van Campo, E. and Bengo, M. D., 2004. Mangrove palynology in recent marine sediments off Cameroon. *Marine Geology*, **208**, 315-330.
- van Geel, B. and Aptroot, A., 2006. Fossil ascomycetes in Quaternary deposits. *Nova Hedwigia*, **82**, 313-329.
- van der Hammen, T., 1954. El desarrollo de la flora Colombiana en los periodos geologicos, 1. Maastrichtiano hasta Terciario mas inferior. *Geology*, **2**, 49-106.
- van der Hammen, T., 1957. Climatic periodicity and evolution of South American Maastrichtian and Tertiary floras. *Boletín Geológico*, **5**, 49-91.
- van der Hammen, T. and García de Mutis, C., 1966. The Paleocene pollen flora of Colombia. *Leidse Geologische Mededelingen*, **35**, 105-116.
- van der Hammen, T. and Wymstra, T. A., 1964. A palynology study on the Tertiary and Upper Cretaceous of British Guiana. *Leidse. Geol. Meded.*, **30**, 183-241.
- van der Zwan, C. J., 2002. The impact of Milankovitch scale climatic forcing on sediment supply. *Sedimentary Geology*, **147**, 271-294.
- van der Zwan, C. J. and Brugman, W. A., 1999. Biosignals from the EA Field, Nigeria. In: Jones, R., W. and Simmons, M., D. (eds.), *Biostratigraphy in production and development geology*. Geological Society, London, Special Publications, **152**, 291- 301.
- van Hoeken-Klinkenberg, P. M. J., 1966. Maastrichtian Paleocene and Eocene pollen and spores from Nigeria. *Leidse geologische Mededelingen*, **38**, 37-48.
- Vánky, K., 1994. *European Smut Fungi*. Gustav Fischer Verlag. Stuttgart, Jena, New York.
- van Wagoner, J. C., Posamentier, H. W., Mitchum, R. M., Vail, P. R., Sarg, J. F., Loutit, T. S. and Hardenbol, J., 1988. An overview of sequence stratigraphy and key definitions. In: Wilgus, C., K., Hastings, B., S., Kendall, C., G., C., Posamentier, H., W., Ross, C., A., Van Wagoner, J., C., (Eds.), *Sea Level Changes - An Integrated Approach* SEPM Special Publication **42**, 39-45.
- Vegetation map of Nigeria, Veg 1979.jpg.
- Vella, P., 1964. Biostratigraphic units, *New Zealand Journal of Geology and Geophysics*, **3**, 615-625.

References

- Versteegh, G. J. M., Schefuss, E., Dupont, L., Marret, F., Sinninghe Damste, J. S. and Fred Jansen, J. H., 2004. Taraxerol and Rhizophora pollen as proxies for tracking past mangrove ecosystems. *Geochimica et Cosmochimica Acta*, **68**, 411–422.
- Vincens, A., Garcin, Y. and Buchet, G., 2007. Influence of rainfall seasonality on African lowland vegetation during the Late Quaternary: Pollen evidence from Lake Masoko, Tanzania. *Journal of Biogeography* **24**, 1274-1288.
- Wall, D., 1967. Fossil microplankton in deep-sea cores from the Caribbean Sea. *Palaeontology*, **10**, 95-123.
- Wang, Y., Cheng, H., Lawrence E. R., He, Y., Kong, X., An, Z., Wu, J., Kelley, M. J., Dykoski, A. and Li, X., 2005. The Holocene Asian monsoon: links to solar changes and north Atlantic climate. *Science*, **308**, 854-857.
- Weber, K. J., 1971. Sedimentological aspects of oil fields in the Niger Delta. *Geologie en Mijnbouw*, **50**, 559-576.
- Weber, K. J., 1986. Hydrocarbon distribution patterns in Nigerian growth fault structures controlled by structural style and stratigraphy. *American Association of Petroleum Geologists Bulletin*, **70**, 661-662.
- Weber, K. J., 1987. Hydrocarbon distribution patterns in Nigerian growth fault Structures controlled by structural style and stratigraphy. *Journal of Petroleum Science and Engineering*, **1**, 91-104.
- Weber, K. J., Daukoru, E., 1975. Petroleum geology of the Niger Delta. *Proceedings of the Ninth World Proceedings of the Ninth World Petroleum Congress*, **2**, 209-221.
- Wedepohl, P. M., Lutjeharms, J. R. E. and Meeuwis, J. M., 2000. Surface drift in the south-east Atlantic Ocean, *South African Journal of Marine Science*, **22**, 71-79.
- Weijers, W. J., Schefub, E., Schouten, S. and Sinninghe Damste', J. S., 2007. Coupled thermal and hydrological evolution of tropical Africa over the last deglaciation. *Science*, **315**, 1701–1704.
- Weinelt, M., Sarnthein, M., Pflauman, U., Schulz, H., Jung, S. and Erlenkeuser, H., 1996. Ice-free Nordic seas during the last Glacial Maximum? Potential sites of deepwater formation. *Paleoclimates*, **1**, 283-309.
- 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.

References

- Wright, L. D. and Coleman, J. M., 1973. Variations in morphology of major river deltas as functions of ocean wave and river discharge regimes. AAPG Bulletin, 57, 370-398.
- White, F., 1983. The vegetation of Africa: A descriptive memoir to accompany the UNESCO/AETFAT/UNSO vegetation map of Africa. Natural Resources Research, 20, 1-356.
- Willis, K. J., Kleczkowski, A., Briggs, K. M. and Gilligan, C. A., 1999a. The role of sub-Milankovitch climate forcing in the initiation of the northern hemisphere glaciation. Science, 285, 568-571.
- Willis, K. J., Kleczkowski, A. and Crowhurst, S. J., 1999b. 124,000 year periodicity in terrestrial vegetation change during the late Pliocene epoch. Nature, 397, 685-688.
- Wilson, G., J. and Clowes, C., D., 1982. *Arachnodinium*, a new dinoflagellate genus from the Lower Tertiary of Antarctica. Palynology, 6, 97-103.
- Winship, T., Hongqi, L., Jeremy, D., Fred, J., Fago, D. Z. J. and Michael, M., 2005. Biogeochemical evidence for the presence of the angiosperm molecular fossil oleanane in Paleozoic and Mesozoic non-angiospermous fossils. Paleobiology, 32, 179-190.
- Wolff, E. W., Chappellaz, J., Blunier, T., Rasmussen, S. O. and Svensson, A., 2010. Millennial-scale variability during the last glacial: the ice core record. Quaternary Science Reviews, 29, 2828-2838.
- Wright, L. D. and Coleman, J. M., 1973. Variations in morphology of major river deltas as functions of ocean wave and river discharge regimen. American Association of Petroleum Geologists Bulletin, 57, 370-398.
- Xiao, H. and Suppe, J., 1992. Origin of rollover anticline. American Association of Petroleum Geologists Bulletin, 76, 229-509.
- Yildiz, A., Toker, V., Demircan, H. and Sevim, S., 2003. Paleoenvironmental interpretation and findings of Pliocene - Pleistocene nannoplankton, planktic foraminifera, trace fossil in the Mut Basin: Application and Research Centre of Hacettepe University. Bulletin of Earth Sciences, 123-144.
- Yildiz, A. and Toker, V., 2006. Pleistocene to Holocene calcareous nannofossil biostratigraphy of core samples from The Northeastern Sea of Marmara, Fenerbahçe Pendik, NW Turkey. Journal of Asian Earth Sciences, 27, 835-846.

References

- Young, J. R., 2003. A guide to extant coccolithophore taxonomy. *Journal of Nannoplankton Research*, **1**, pp 125.
- Young, J. R. and Westbroek, P., 1991. Genotypic variation in the coccolithophorid species *Emiliana huxleyi*. *Marine Micropaleontology*, **18**, 5-23.
- Zabel, M., Schneider, R. R., Wagner, T., Adegbe, 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.
- Zachos, J., Pagani, M., Sloan, L., Thomas, E. and Billups, K., 2001. Trends, rhythms, and aberrations in Global Climate 65 Ma to Present. *Science*, **292**, 686-693.
- Zobaa, M. K., Zavada, M. S., Whitelaw, M. J., Shunk, A. J. and Oboh-Ikuenobe, F. E., 2011. Palynology and palynofacies analyses of the Gray Fossil Site, eastern Tennessee: Their role in understanding the basin-fill history. *Palaeogeography, Palaeoclimatology, Palaeoecology*, **308**, 433-444.
- 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.
- Zong, Y., Lloyd, J., M. Leng, M. J., Yim, W. W. S. and Huang, G., 2006. Reconstructions of Holocene monsoon history from the Pearl River estuary, southern China, using diatoms and carbon isotope ratios. *The Holocene*, **16**, 251-63.

Appendix 1

Data Collection Techniques: Taxonomy and Palaeoecological Records

Highlights

- This appendix outlines the technique(s) used to describe the taxa identified in this study based on the identification, recording of the key species through a photo montage of palynomorphs, and non-pollen palynomorph components using a Nikon microscope. It also present the raw data-set applied in various chapters.
- The generic groups of taxa identified in this study are: angiosperm pollen, gymnosperm pollen, pteridophyte spores, bryophyte spores and non-pollen palynomorphs (NNPs).
- The results formed the foundation for a detailed (analysis) interpretation of the palynomorph records.

Introduction to Appendix 1

The identification of palynomorph taxonomic nomenclatures and palaeoecological analyses employed in the present study are based primarily on Germeraad *et al.* 1968, Legoux, 1978, Sowunmi, 1981, Oboh *et al.*, 1992, Shell, 2000, unpublished, Rull, 2002, Punt *et al.*, 2007, Mudie, 2011 and Miller and Gosling, 2014. The identification of taxa is by the examination of the grains, shape, size, wall structure, arrangement of the pores and furrows (after Miller and Gosling, 2014). Routine descriptive analytical processes adopted was to describe most of the key taxa identified. Importantly, this study considered the grouping of each species under their family/botanical affinity (Chapter 3) for the interpretation of the palynomorphs records, except the indeterminate group (Plate 5). For further comprehensive review of each taxon, consultation can be made from the published work of the authors assigned to each species identified at the web page below:

<http://www.kendallhunt.com/store-product.aspx?id=22467>

<http://www.sinauer.com/plant-systematics-a-phylogenetic->

<http://www.sciencedirect.com/science/book/9780123743800>

<http://onlinelibrary.wiley.com/doi/10.1111/j.1095-8339.2009.00996.x/abstract>

<http://www.ville-ge.ch/musinfo/bd/cjb/africa/index.php?langue=an>

<http://www.mobot.org/MOBOT/research/APweb/welcome>.

[http:// the Tropicos database](http://theTropicos.org)

<http://www.tropicos.org/>

<http://biogeodb.stri.si.edu/jaramillo/palynomorph/>

Generally, the generic nomenclature for the foraminifera and fungal spores follows Adegoke, 1975 and Gelorini *et al.*, 2011 respectively. No detailed description was made of their identification, whereby such identification has been achieved using technical expertise of known specialists, and comparative data through photographs.

The section below describes the various palynomorphs identified from the Gravity Cores. Discussion follows thereafter based on angiosperm, gymnosperm, bryospores and NPPs as follows:

I. Angiosperm Pollen

These are derived from non-vascular plants, whereby the mature seed is usually enclosed in the ovule. They have very large group of plants that includes those that have flowers and produce seeds that are encased within a carpel, such as many shrubs and most trees (Chase *et al.*, 2005). Examples are *Rhizophora* sp., *Graminidites* sp., etc.

I-a. Monoporate Pollen types:

Family/Botanical Affinity: Poaceae (Gramineae) Pl. 1, figs. 1 - 6

Description: Monoporate pollen grains are often referred to as *Graminidites* or *Monoporites*. The pore is rounded with the distinct granulate annulus (5µm). The exine is smooth and circular in shape. The size ranges between 20 and 25 µm in most cases.

Morphogenic affinity: *Graminidites annulatus* (*Monoporites annulatus*).

Palaeoecology: Savannah grassland.

Remark and References: A ubiquitous pollen that evolved throughout the Cenozoic in Nigeria and Cameroon, belonging to the family Poaceae (Gramineae). It has a uniform

morphology and possesses one distinct annulate pore (van der Hammen, 1954; Germeraad *et al.*, 1968; Salard-Chebolddaeff, 1990).

Reference Materials: GC1 (250-252 cm); GC2 (238-240 cm); & GC3 (24-26 cm) samples.

I-b. Tricolporate Pollen types:

i) Family/Botanical Affinity: *Tabermaemontana*/ Apocynaceae; Pl. 1, Figs. 8 – 9

Description: The outline in polar view is rounded triangular. Endexine is 2µm thick, with the tectum psilate to finely perforate, about 1.5µm thick; the colpus is 25 to 30 µm long (tapering very sharp towards the costate of about 4.5µm).

Morphogenic affinity: *Psilatricolporites crassus*

Palaeoecology: Mangrove swamp vegetation

Remark and References: Ubiquitous pollen within the Cenozoic and very common in Nigeria, Cameroon and Venezuela (van der Hammen and Wijmstra, 1964; Germeraad *et al.*, 1968; Lorente, 1986).

Materials: GC1 (50-52 cm), GC2 (24-26 cm) & GC3 (48-50 cm) samples.

ii) Family/Botanical Affinity: Euphorbiaceae/*Alchornea*; Pl.1, figs. 15

Description: This type is similar to *Psilatricolporites crassus* except that it has a distinct operculum of about 2-2.5µm. The entire size is elongated at the equator, and with a finely perforated exine of *Alchornea cordifolia* ~ 2.5µm thick. The size is about 25 to 30µm.

Morphogenic affinity: *Psilatricolporites operculatus*

Palaeoecology: Lowland rainforest

Remark and References: Occurs throughout the Cenozoic (van der Hammen and Wijmstra, 1964).

Materials: GC1 (40-42 cm), GC2 (34-36 cm) & GC3 (28-30 cm) samples.

iii) Family/Botanical Affinity: Euphorbiaceae/*Amanoa*; Pl. 1, fig. 7

Description: This is a tricolporate pollen presented with a circular polar view. The colpus is 2µm thick and pointed towards the end of the costae. The endexine is less than 1µm; bacules are about 1.5µm thick, supporting single rows of curvilinear reticulum. The lumina are irregular in shape and are up to 6µm in length. The size of *Amanoa oblongifolia* is between 32 to 33 µm.

Morphogenic affinity: *Retitricolpites irregularis*

Remark and references: The taxon evolved through the Eocene to Recent in Nigeria and Venezuela (Germeraad *et al.*, 1968; Lorente, 1986).

Palaeoecology: Lowland rainforest

Materials: GC1 (200-202cm), GC2 (234-236cm) & GC3 (228-230cm) samples.

iv) Family/Botanical Affinity: Euphorbiaceae?; Pl. 1, figs. 11, 13, 14

Description: The exine is thicker, about 2.3µm. The size is between 25-30µm. The shape is oval to broad – ellipsoidal or prolate shape.

Morphogenic affinity: *Momipites africanus*

Palaeoecology: Lowland rain forest

Remark and References: Common in Nigeria from the mid-Cenozoic (Takahashi & Jux, 1989).

Materials: GC1 core (200-202cm) sample.

v) Family/Botanical Affinity: Cannabaceae/Celtis; Pl. 1, fig 12

The exine is thicker, about 2.4µm. The size is between 23-32µm. The shape is slightly oval to broad – ellipsoidal shape.

Morphogenic affinity: Triporites?

Palaeoecology: Lowland rain forest/Open forest

Remark and References: Common in Nigeria from the mid-Cenozoic (Takahashi & Jux, 1989).

Materials: GC1 core (200-202cm) sample.

vi) Family/Botanical Affinity: Rhizophoraceae/Rhizophora Pl.1, figs. 18-24

Description: Pollen grain with a circular to rounded triangular shape in polar view. The texture of the exine is punctate to minutely reticulate. The dimension of the pollen is 17-20 μm . The perforation is less than 0.5 μm wide and the exine is less than 2.0 μm for most species. The specimens display a variety of forms and ranges in the size and coarseness subtypes (species) were identified, but were grouped as *Rhizophora*, as the taxonomy is similar and the interest of focus is to use their gross morphology to define the palaeoecology and palaeoenvironmental change. Few types observed are *Rhizophora racemosa*, *Rhizophora mucronata* and *Rhizophora mangle*.

Morphogenic affinity: *Zonocostites ramonae*.

Palaeoecology: Mangrove swamp vegetation.

Remark and References: *Rhizophora* evolved through the Cenozoic in Nigeria, Venezuela, Cameroon and Borneo (Germeraad *et al.*, 1968; Evamy *et al.*, 1978; Lorente, 1986; Oboh *et al.*, 1992; Morley, 1995).

Materials: GC1 (66-68 cm), GC2 (72-74 cm) and GC3 (80-82cm) samples.

vii) Morphological Affinity: ?Tricolporate: Pl. 1, fig. 34

viii) Family/Botanical Affinity: Asteraceae/Vernonia-type; Morphological Affinity: Tricolporate fenestrate; Pl.1, fig. 32

ix) Family/Botanical Affinity: Asteraceae/Tubliflorae; Morphological Affinity: Tricolporate echinate; Pl. 2, fig. 56

X) Family/Botanical Affinity: Avicenniaceae/Avicennia; Pl.1, figs. 36, 37

Description: Pollen grains in monads, medium, oblate spheroidal to subprolate, isopolar, circular amb; 3-colporoidate (more common), 3-colporate or 3-colpate. 31 to 33 μm in size. 2 μm wide ectoaperture, lolongate endoaperture, narrow in the first and wide in the second type; exine heterobrochate with interrupted muri, thick in the mesocolpium.

Morphogenic affinity: *Avicennia* spp.

Palaeoecology: Mangrove swamp vegetation

Remark and references: Noted to evolve during Eocene to Recent sediments in some parts of Nigeria, Borneo, Indonesia, Venezuela (Germeraad et al., 1968; Takahashi and Jux, 1989).

XI) Family/Botanical Affinity: Fabaceae/Chamaecrista; Pl.1, figs. 38, 39, 40

Description: Pollen grains of small size between 5 to 10 μm , isopolar, of radial symmetry, subprolate, amb subcircular slightly sinu-aperturate, 3-colporate, longiaperturate, colpi with pointed apices, with psilate margo, with central constriction, sexine slightly thicker than the nexine.

Morphogenic affinity: *Chamaecrista* spp.

Palaeoecology: Mangrove swamp vegetation

Remark and references: Noted to evolve during Eocene to Recent sediments in some parts of Nigeria, Cameroun, Benin Republic, Brazilian Amazon (Salard-Cheboldaef et al., 1992).

I-c Tricolpate Pollen types

- i. **Striatocolpites spp.: Caesalpinioideae/Anthonotha, Berlina-type; Pl. 1figs. 30-31**

Description: Tricolpate pollen with an outline view of prolate shape. The proximal face is striated throughout and anchored by one to several rows of bacules and lirae. The exine is finely striated and the overall size is between 30 to 36 μm on the equatorial view.

Morphogenic affinity: *Striatocolpites* spp.

Palaeoecology: Lowland rainforest

Remark and references: Noted to evolve during Eocene to Recent sediments in some parts of Nigeria, Borneo, Cameroon (Germeraad et al., 1968; Takahashi and Jux, 1989).

Materials: GC1 (56-58cm)

I-d. Stephacolpate Pollen types

Family/Botanical affinity: Rubiaceae/Spermacoce (Borreria) sp Pl. 2, figs. 43-45

Description: Polycolpate pollen grain with a circular polar view. Exine of numerous tectate-baculae distinctly stratified and sculptured. Grains range in size between 38 to 41 μm for the identified species. The exine is about 4-5 μm in thickness and stout baculae are 3-5 μm long and 0.7 μm thick.

Morphogenic affinity: *Stephanocolpites* sp.

Palaeoecology: Lowland rain forest.

Remark and References: Late Miocene to Recent sediments in some parts of Nigeria, North West Poland and Cameroon (Salard-Cheboldaef *et al.*, 1992; Regali *et al.*, 1974).

Materials: GC1 (50-52cm) sample.

I-d. Polyporate Pollen types

i) Family/Botanical Affinity: Clusiaceae/Symphonis globulifera Pl.1, figs. 26–28.

Description: Tetraporoidate to Tetraporate pollen grain with four to six apertures in most cases. Their sizes (diameter) are 42-44 μm , the ektenxinous pore is 6-7.5 μm in length/thickness and the endexinous pore characteristically demarcated for most taxa. Exine is finely vermiculate to punctate. It has a smooth and comparatively thin tectum for tetraporate pollen. The endexine is very thick and perforated at the apertures for all forms identified at the moment.

Morphogenic affinity: *Pachydermites diderixi*.

Remark and References: Eocene to Recent in Nigeria, Cameroon, Venezuela (Germeraad *et al.*, 1968; Salard–Cheboldaeff, 1978; Legoux, 1978; Lorente, 1986; Obot *et al.*, 1992).

Palaeoecology: Fresh water swamp/Lowland rain forest

Materials: GC1 (24-26 cm), GC2 (28-30 cm) & GC3 (40-42 cm) samples.

ii) Family/Botanical Affinity: Malvaceae/Hibiscus Pl. 1, fig. 29

Description: This morphotype is a polyporate pollen grain with oval or circular outline. The size is 30-45 μm , spines are 5-6 μm long and pores are 3-4 μm wide. The coarseness of the wall structure and spines varies depending on the species.

Morphogenic affinity: *Echiperiporites estelae*.

Remark and References: The type evolved through the Eocene to Recent in Nigeria and Cameroon (Germeraad *et al.*, 1968; Salard–Cheboldaeff, 1979; Legoux, 1978; Jan du Chene and Salami, 1978).

Palaeoecology: Open forest

Materials: GC1 (34-36 cm), GC2 (48-50 cm) & GC3 (60-62 cm) samples

iii) Family/Botanical Affinity: cf Ipomoea/Convolvaceae Pl. 2, fig. 41

Palaeoecology: Mangrove swamp

iv) Family/Botanical Affinity: Palmae/Arecaceae Pl. 1, figs. 33

Description: There is not much literature coverage for this morpho-type, as suggested by Salard–Cheboldaeff, (1979). However, an attempt to the look at the colpi relationships along with other descriptions has been taken into consideration. The generic size of Arecaceae is 58 to 60 μm with a mono colpi which is 15-20 μm long.

Morphogenic affinity: *Psilamonocolpites* sp.

Palaeoecology: Palmae, fresh water swamp/riverine.

Remark and References: The morpho-group is known to have evolved during the Eocene to Recent in Nigeria and Cameroon (van derHammen & García de Mutis, 1966; Salard–Cheboldaeff, 1979).

Materials: GC1 (32-34 cm), GC2 (42-44 cm) & GC3 (50-52 cm) samples.

II. Gymnosperm Pollen

II. Gymnosperms: These are plants that generate seeds that are encased in an ovule (Chase *et al.*, 2005). The plants comprises of a seed bearing mechanism which has been unprotected by an ovary. It usually remains evergreen throughout the year

(Chase *et al.*, 2005). Examples of this type are *Podocarpus* sp. (bisaccates), *Striatocolpites* sp.

i) Family/Botanical Affinity: Podocarpaceae/ Podocarpus; Pl. 2, figs. 47 - 50

Description: Bisaccate pollen with the sacci firmly attached to the body, rounded and of different apertural sizes. They are monosulcate pollen with the sulcus wide open in most species. The exines are thin and finely granulated. Their sacci are coarsely granulated. Size varies between 25 to 30 μm . The sacci are between 10 to 15 μm for the types identified.

Morphogenic affinity: *Podocarpus clarus*, *Podocarpus* sp.

Palaeoecology: Afromontane vegetation.

Remark and references: Mid-Miocene to Recent in Burundi; Cameroun; Nigeria (Germeraad *et al.*, 1968; Legoux, 1978; Salard-Cheboldaeff, 1990).

Materials: GC1 (32-34 cm), GC2 (42-44 cm) & GC3 (50-52 cm) samples.

III. Other Pollen types

i) Family/Botanical Affinity: Nymphaeaceae/Nymphaea type lotus Pl. 1 fig. 46

Description: Zonosulcate pollen characterised by a circular to elliptical outline. The size of the pollen ranges from 38 to 53 μm . The sulcus is conspicuously broad and covers most of the pollen grain. Nymphaeaceae has a partly smooth and psilate exine.

Morphogenic affinity: *Psilamonoporites* sp.

Palaeoecology: Fresh water swamp

Remark and references: Nymphaeaceae evolves through the Late Miocene to Recent sediments in most West African settings and Europe (Erdtmann, 1966). Presence in Nigeria is uncommon. The complexity of the outline means that the actual description of the outline seems to be difficult for many researchers to identify.

Materials: GC1 (24-26 cm); (82-84 cm); GC2 (194-196 cm)

ii) Family/Botanical Affinity: Cyperaceae Pl. 1 fig. 35

Description: Elongated pollen grain with granulate apertures. The size is about 19 to 22 μm . The overall morphology flattens as spheroidal, narrowing towards the dorsal view.

Morphogenic affinity: *Cyperus* sp.

Palaeoecology: Fresh water swamp

Remark and References: Recorded through the Miocene to Recent sediments in Nigeria (Niger Delta Consortium, 2000 (Unpublished stratigraphic data))

Materials: GC3 (202-204 cm) sample.

iii) Family/Botanical Affinity Arecaceae/ Borassus type; Pl. 2 fig. 52

IV. Pteridophyte

Pteridophytes: These vascular plants that are reproduced and dispersed through spores (Gifford, 1995). They do not produce seed, hence denoted as cryptogams (Smith *et al.*, 2006). This group comprises of fern spores such as *Lycopodium* sp., *Polypodiaceoisporites* sp., *Acrostichum* sp., *Corrusporis* sp.

In this study, all spores belonging to these group were separated into the following types: Alete, monolete and trilete spores.

a) Pteridophytes, Alete Spores

b) Pteridophytes, Monolete Spores

i) Family/Botanical Affinity: Pteridophyta; Pl. 3, figs. 66 – 68

Description: Monolete spores with size ranging from 15 to 25 μm in length/diameter. Spores are similar in shape to kidney beans. The monolete mark ranges in length from 6 to 8 μm for the species identified. The length of Polypodiaceae ranges from 45 to 64 μm for most species observed.

Morphogenic affinity: *Laevigatosporites* spp.

Palaeoecology: Lowland rain forest/open forest.

Remark and References: It evolved through Eocene to Recent sediments in most cases. It has been documented to have existed in Indonesia, Nigeria, East Europe, East China Sea and Colombia (Krutzsich, 1967; Takahashi and Jux, 1989).

Materials: GC1 (264-266 cm), GC2 (24-26 cm) & GC3 (50-52 cm) samples

ii) Family/Botanical Affinity: Polypodiaceae Pl. 3 figs. 69 - 70

Description: Monolete spore with an outline in polar view - elliptical in shape. It is of similar shape to the laevigate spores above (kidney bean shape) in equatorial view. It has a verrucate exine sculpture. The size ranges from 35 to 48 μm for the species identified. The exine is coarsely and densely spaced (diameter 2.5 μm). The current taxonomic nomenclature documents that this species should be renamed as *Polypodiaceoisorites* sp. (Frederiksen *et al.*, 1983). However, some other authors still refer to it as *Verrucatosporites usmensis*.

Morphogenic affinity: *Polypodiaceoisorites* sp. (aka *Verrucatosporites usmensis*).

Palaeoecology: Lowland rain forest/Open forest

Remark and references: It is ubiquitous pollen that evolved through the Eocene to Recent in Nigeria, Western Europe (Germany) and Borneo (Germeraad *et al.*, 1968; Sah, 1967; Krutzsich, 1967; Salard-Cheboldaeff, 1990).

Materials: GC1 (50-52 cm), GC2 (24-26 cm) & GC3 (50-52 cm) samples

c. Pteridophytes, Trilete Spores

i) Family/Botanical Affinity: Pteridophyta/fern spores? Pl. 2, figs. 58 - 59

Description: Trilete spore similar to *Polypodiaceoisorites* sp. It has a thicker exine. The size ranges from 34 to 35 μm . It has smooth exine about 1.6 μm thick.

Morphogenic affinity: *Undulatisporites* sp.

Palaeoecology: Lowland rain forest/Open forest

Remark and References: Very common in Germany during the Pliocene (Krutzsich, 1962; Stuchlik, 2001). They are known to occur between the Eocene and Recent in Nigeria (Bankole *et al.*, 2014).

Materials: GC1 (50-52 cm).

ii) Family/Botanical Affinity: Pteridaceae/Acrostichum; Pl. 2, fig. 65

Description: A trilete spore with distinct spherical or ellipsoidal shape in some specimens. The exine is irregular fairly covered with verrucate sculpture. The size of Polypodiaceae ranges from 62 to 67 μm in most of the species measured. The length of the trilete mark is 3 μm for either side.

Morphogenic affinity: *Acrostichumsporites* sp.

Palaeoecology: Mangrove swamp vegetation

Remark and References: Revolved throughout the Miocene to Recent in very few African countries like Cameroon, Congo and some North African countries (Kar, 1992). This species is recorded in modern and ancient sediments in NW Borneo. It sits behind the brackish water mangrove vegetation, where fresh water collects in the middle of mangrove islands, with slightly raised elevations, above HWWM (Osterloff, pers. comm.).

iii) Family/Botanical Affinity: Polypodiaceae Pl. 2, figs. 62 - 64

Description: They are sub-circular to triangular shaped in distal and proximal view. The size of Polypodiaceae ranges from 30 to 32 μm . The trilete mark is 4 μm when critically viewed. The exine is about 1.6 μm in thickness/length.

Morphogenic affinity: *Polypodiaceoisporites* sp.

Palaeoecology: Lowland rainforest

Remark and References: Evolved throughout the Early Miocene to Recent in Germany, in a few African countries like Cameroon, Congo and some North African countries (e.g. Tunisia, Morocco) (Sah, 1967; Krutzsch, 1967; Nagy, 1985).

Materials: GC1 (44-46 cm), GC2 (28-30 cm) & GC3 (42-44 cm) samples.

iv) Family/Botanical Affinity: Lycopodiaceae Pl. 2 fig. 57

Description: A trilete spore with a triangular outline view. The side of the exine is slightly straight and concave in polar view. The exine is smooth and heaving-like in the

overall thickness. The size of the equatorial diameter ranges between 25 to 26 μm . The trilete or laesurae arms are almost bifurcating the radius.

Morphogenic affinity: *Lycopodium* sp.

Palaeoecology: Lowland rain forest.

Remark and References: It evolves through the Late Oligocene to Recent sediments in some parts of Nigeria, Benin and Cameroon (Sullivan and Marshall, 1990; Salard-Cheboldaef *et al.*, 1992).

Materials: GC1 (100-102 cm) sample.

d. Bryophyte: Denote all embryophytes that do not have real vascular tissue (Goremykin *et al.*, 2005). *Stereisporites* sp.

Family/Botanical Affinity: Bryophyta; Pl. 2 fig. 60

Description: The outline of these taxa is similar to *Biretiosporites* sp. It is usually triangular to sub-triangular in polar view. The laesurae arms are 5 μm long and nearly taper at the equator. The margin of the laesurae arms is slightly thickened, but less than 1 μm . The size is between 25 to 35 μm . Most of the species viewed have a smooth exine of about 2 μm .

Remark and References: Evolves throughout the Oligocene to Recent in some parts of Europe, Nigeria, North West Poland, Cameroon (Salard-Cheboldaef *et al.*, 1992; Stuchlik, 2001).

Morphogenic affinity: *Stereisporites* sp.

Palaeoecology: Lowland rain forest/ Open forest

Materials: GC1 (50-52 cm), GC2 (24-26 cm) & GC3 (24-26 cm) samples.

V. Non-Pollen Palynomorphs (NPPs)

a. Dinoflagellate Cysts

i. *Polysphaeridium* sp. Pl. 5, fig. 105

Remark and References: It evolves through the Paleogene in Colombia and Miocene to Recent in West Africa (Bujak *et al.*, 1980; Jaramillo and Dilcher, 2001). Observed size ranges between 34.1 to 47 μm .

Materials: GC1 (2-4 cm) sample.

ii. *Lingulodinium* sp. Pl. 5, fig. 106

Remark and References: It evolves through Oligocene to Pleistocene sediments as described by many authors in different parts of the world (Wall, 1967). Its size ranges between 61.4 to 65 μm .

Materials: GC1 (2-4 cm) sample

iii. *Tuberculodinium vancampoe* Pl. 5, fig. 107

Remark and Reference: A typical neritic species which evolves through the Pliocene to Recent sediment (Wall, 1967). The size is about 96 μm depending on the view.

Materials: GC1 (2-4 cm) sample.

b. Foraminiferal Test Linings (FTLs); Pl. 3 figs. 70 (2)-75

c. Algae

i. *Botryococcus* spp.; Pl. 3 fig. 81 (80)

ii. *Pseudoschizaea ozeanica*; Pl. 3 figs. 76-77

iii. *Ovioidites parvus*; Pl. 3 figs. 78-79

iv. *Pediastrum* spp.; Pl. 3 figs. 81

d. Fungi; Pl4. Figs. 88-99

i. *Dyadosporites* sp.,

ii. *Ustulina deusta*,

iii. *Thielaviopsis* sp.

iv. Hypha, *Inapertisporites* sp.

v. *Striadopites* sp.

vi. *Hypoxylonites* sp.

vii. *Haplographites xylophagus*

e. Palynodebris elements 82-87; 100-104

i. Cuticles/plant cell

ii. Amorphous organic matter,

iii. Translucent

iv. Opaque phytoclasts

Conclusion

- In conclusion, angiosperm family pollen types (tricolporate, tricolpate polyporate pollen) constitute the most abundant (70%) component of the palynomorphs recovered from the three Gravity Cores (Plates 1 and 2).

Palynomorphs Photomontage

All scale bars are at 20µm except for Rhizophoraceae which is 10µm.

See taxonomy discussion section for reference depths and descriptions of some of the important taxa which required detailed measurements.

Plate 1

A) Angiosperm Pollen			
Figure	Family name	Morphological name	References
1 - 6	Poaceae	<i>Graminidites annulatus</i>	van der Hammen, 1954, Potonié, 1960
7	Euphorbiaceae	<i>Retitricolporites irregularis</i>	van der Hammen and Wijmstra, 1964
8 - 9	Apocynaceae	<i>Psilatricolporites crassus</i>	Sah, 1967
10	Euphorbiaceae/Rubiaceae	<i>Retibrevitricolporites obodoensis</i>	Legoux, 1978; Germeraad <i>et al.</i> , 1968
11,13, 14	Euphorbiaceae?	<i>Momipites africanus</i>	van Hoeken-Klinkenberg, 1966
12	Cannabaceae	Celtis	Legoux, 1978;
15	Euphorbiaceae/ <i>Alchornae</i>	<i>Psilatricolporites operculatus</i>	van der Hammen and Wijmstra, 1964
16	Rhizophoraceae	<i>Rhizophora</i> sp.	Germeraad <i>et al.</i> , 1968
17	?	<i>Inaperturotetradites reticulatus</i>	Salard-Cheboldaeff, 1978
18-24	Rhizophoraceae	<i>Rhizophora</i> spp.	Germeraad <i>et al.</i> , 1968
25-28	Clusiaceae	<i>Pachydermites diderixi</i>	Germeraad, <i>et al.</i> , 1968
29	Malvaceae	<i>Echiperiporites estelae</i>	Germeraad <i>et al.</i> , 1968
30-31	?Arecaceae/Anthonotha	<i>Striatocolpites</i> spp.	González Guzmán, 1967; Takahashi & Jux, 1989
32	Asteraceae	Vernonia-type	Erdtman, 1969; Adekanmbi, 2009
33-34	Arecaceae	<i>Psilamonocolpites</i> sp.	van der Hammen, 1954

Plate 1

A) Angiosperm pollen

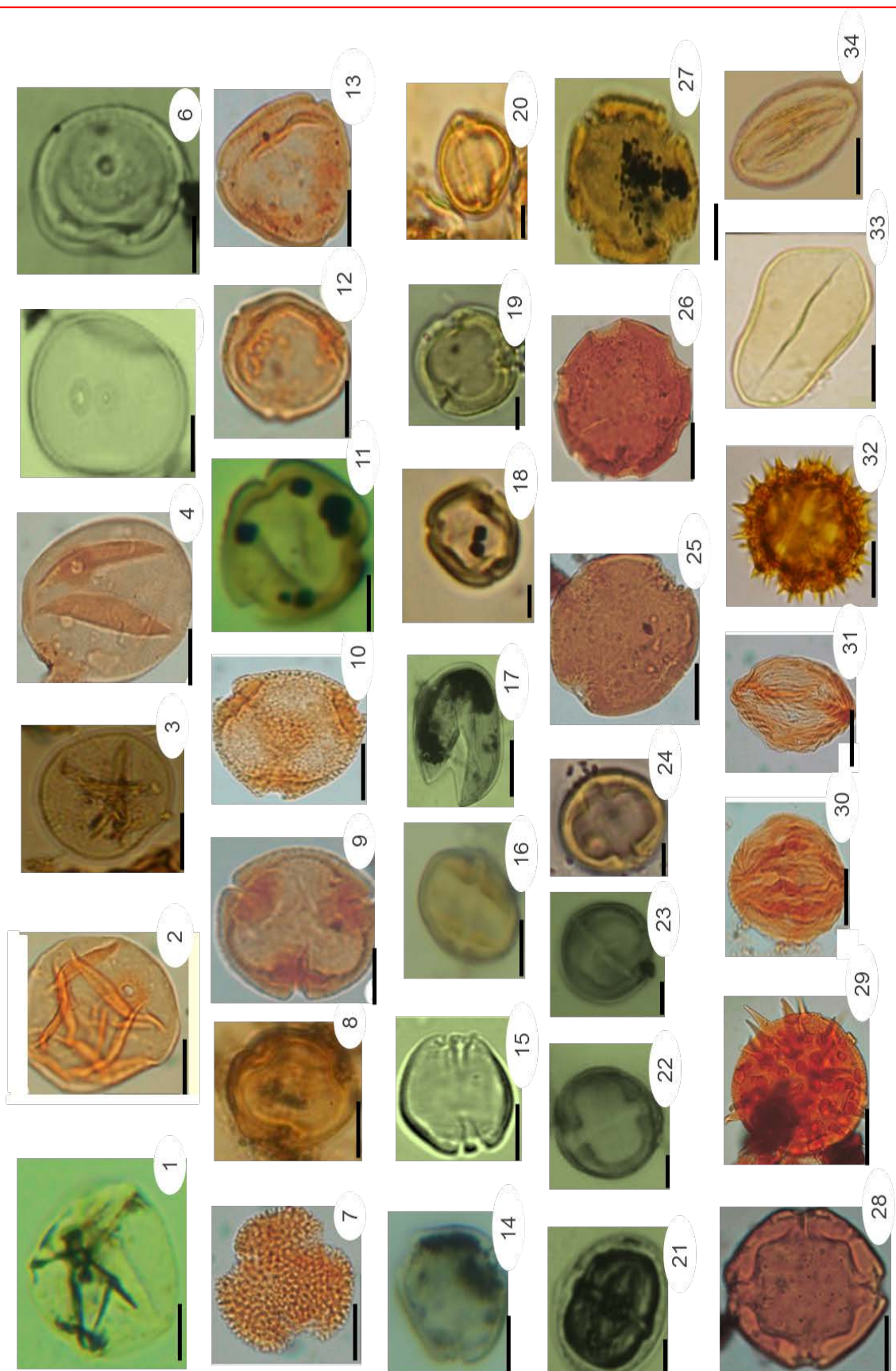
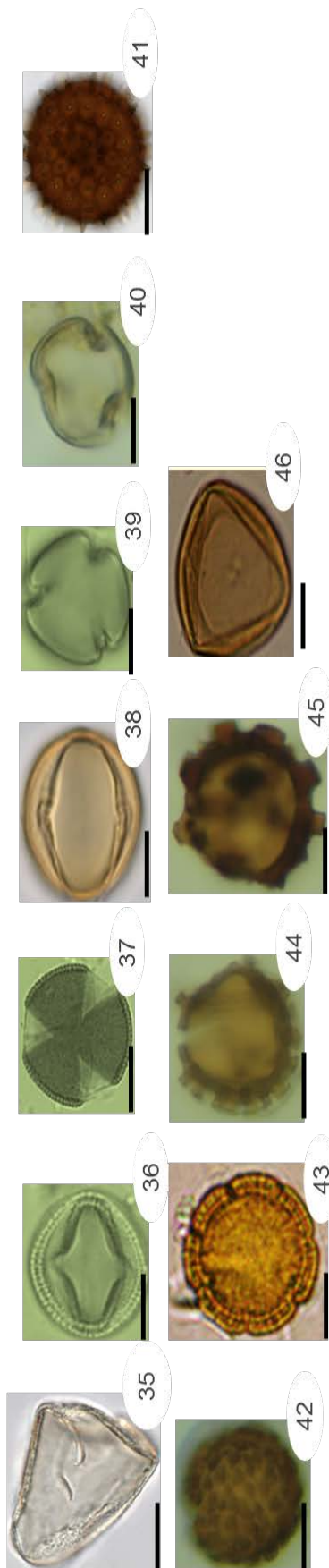


Plate 2

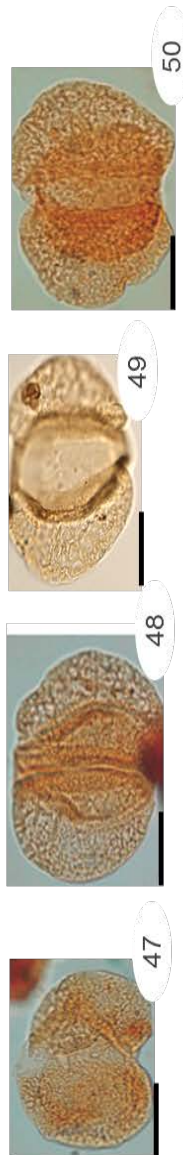
Figure	Family name	Morphological name	Reference
35	Cyperaceae	<i>Cyperus</i> sp.	Germeraad <i>et al.</i> , 1968
36-37	Avicenniaceae	<i>Avicennia</i> sp./ <i>Foveotricolpites</i> spp.	Rull, 2001
38 -40	Fabaceae	<i>Chamaecrista</i> spp.	Miller and Gosling, 2014
41	Convolvulaceae/cf Ipomoea	<i>Echiperiporites</i> sp.	University of Arizona Herbarium, 2011
43-45	Rubiaceae/ Spermaceae (Borreria)	<i>Stephanocolpites</i> sp.	Regali <i>et al.</i> 1974
46	Nymphaeaceae	<i>Nyphaea lotus</i> type/ <i>Psilamonoporites</i> sp.	Saad and Ghazaly, 1976; Miller and Gosling, 2014
B) Gymnosperm Pollen (Bisaccate Pollen)			
47-50	Podocarpaceae	<i>Podocarpidites</i> sp.	Germeraad <i>et al.</i> , 1968
49	Podocarpaceae	<i>Podocarpidites clarus</i>	Sah, 1967
C) Pteridophyte and Bryophyte			
51-56	Asteraceae	<i>Tubliflorae</i> sp.	Krutzsch, 1967
52	Arecaceae	<i>Borassus</i> type	
57	Lycopodiaceae	<i>Lycopodiumsporites</i> sp.	Sowunmi, 1995
58 -59	Polypodiaceae?	<i>Undulatisporites</i> sp.	Delcour & Sprumont, 1955; Krutzsch, 1962
60	Bryophyta	<i>Stereisporites</i> sp.	Salard-Cheboldaef <i>et al.</i> , 1992
62 -64	Polypodiaceae	<i>Polypodiaceoisporites</i> sp.	Sah, 1967
65	Pteridaceae/Acrostichum	<i>Acrostichumsporites</i> sp.	Kar, 1991

A) Angiosperm pollen

Plate 2



B) Gymnosperm pollen (Bissacate pollen)



C) Pteridophyte and bryophyte spores

i) Trilete spores

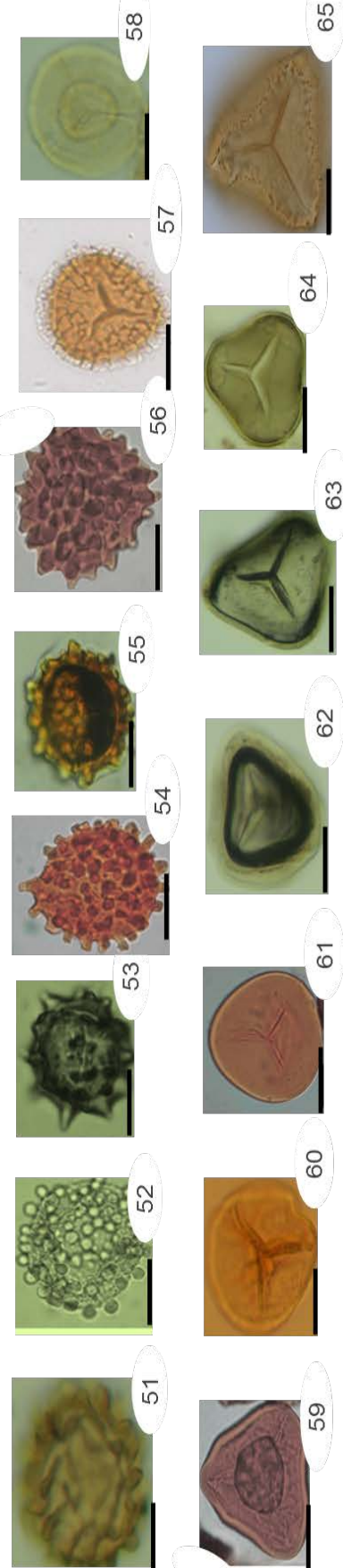
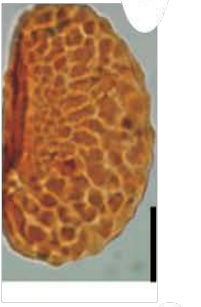
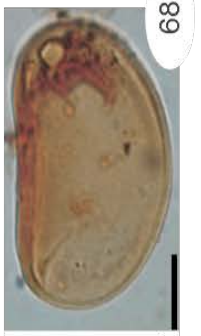


Plate 3

Figure	Family name	Morphological name	Reference
66-68	Pteridophyta	<i>Laevigatosporites</i> spp.	(Potonié & Venitz) Thomson & Pflug, 1953
69-70	Polypodiaceae	<i>Polypodiisporites</i> sp./ <i>Verrucatosporites</i> <i>usmensis</i>	van der Hammen 1957; Rull, 1998, 2001
D) Non-Pollen Palynomorphs (NPPs)			
71-72	Foraminifera	Planospiral FTL	Tyson, 1995
73-74	Foraminifera	Biserial/Triserial FTL	Tyson, 1995
75	Diatom	Diatom	-
76 -77	Fresh water algae	<i>Pseudoschizea</i> sp.	Thiergart & Frantz, 1962
78-79	Zygnemataceae	<i>Ovoidites parvus</i>	Thiergart & Frantz, 1962
80	Brackish water algae	<i>Botryococcus</i> sp.	Batten and Lister, 1988
81	Fresh water algae	<i>Pediastrum</i> sp.	Gelorini <i>et al.</i> , 2011
82-85	Graminae	Grass cuticles	Morley and Richards, 1993
86-87	Plantae	Plant cells	Tyson, 1995

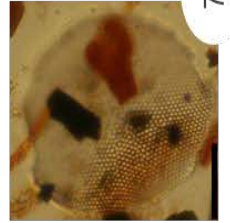
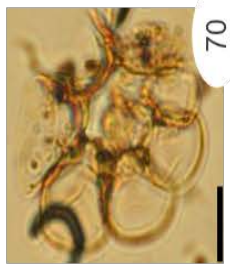
Plate 3

ii) Monolete spores

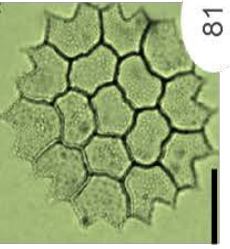
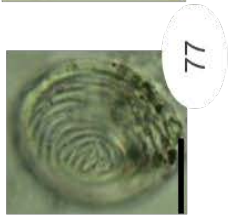


D) Non Pollen Palynomorphs (NPPs)

i) Foraminifera Test Lining (FTL)



iii) Fresh / brackish water algae



iv) Cuticles

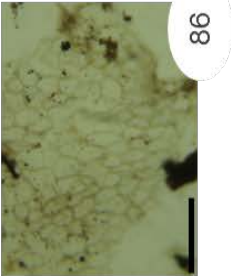
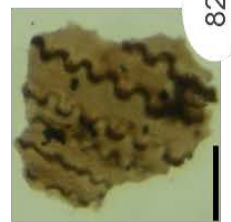


Plate 4

Figure	Family name	Morphological name	Reference
88	Fungi	<i>Ustulina deusta</i>	Van Geel and Aptroot, 2006
89	Fungi	<i>Acroconidiellina</i> sp.	Ellis, 1976
90	Fungi	<i>Ascodesmis</i> sp.	Hanlin, 1990
91	Fungi	<i>Dyadosporites</i> sp.	Gelorini <i>et al.</i> , 2011
92	Fungi	<i>Thielaviopsis</i> sp.	Prager <i>et al.</i> , 2006
93	Fungi	<i>Kutchiathyrites</i> sp.	Gelorini <i>et al.</i> , 2011
94	Fungi Hyphae	<i>Haplographites xylophagus</i>	Kalgutkar and Jansonius, 2000 (AASP Contribution Series #39)
95	Fungi	<i>Hypoxylonites</i> sp. Probably a conidia of cf. <i>Arthrinium</i> sp.	Kalgutkar and Jansonius, 2000
96	Fungi	<i>Meliola</i> sp.	Mibey and Kokwaro, 1999
97	Fungi	<i>Sordaria</i> sp.	Hanlin, 1990
98	Fungi	<i>Cercophora</i> sp.	Bell, 1983
99	Fungi	<i>Urocystis</i> sp.	Vanky, 1994
100-101	-	Stomates on leaf cuticles	-
102	Palynodebris	Amorphous organic matter	Oboh, 1992; Tyson, 1995
103	Palynodebris	Opaque phytoclasts	Oboh, 1992; Tyson, 1995
104	Palynodebris	Translucent phytoclasts	Oboh, 1992; Tyson, 1995

Plate 4

vi) Fungi



88



89



90



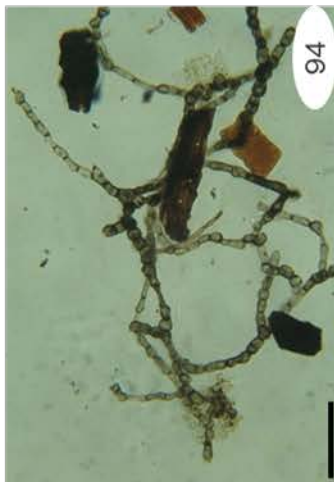
91



92



93



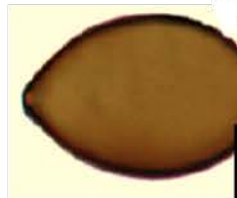
94



95



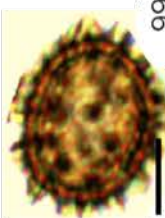
96



97

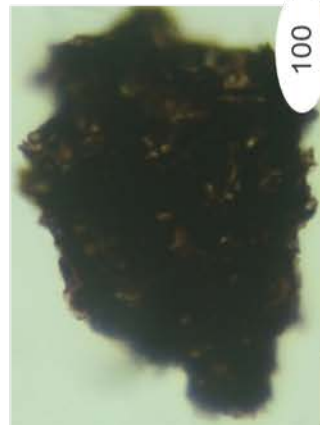


98



99

v) Plant stomates on leaf cuticles



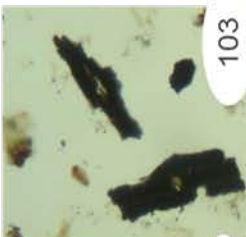
100



101



102



103



104

vi) Palynodebris

E) Dinoflagellate Cysts			
105	Dinoflagellate	<i>Polysphaeridium</i> sp.	Bujak <i>et al.</i> , 1980
106	Dinoflagellate	<i>Lingulodinium</i> sp.	Wall, 1967; Wilson and Clowes, 1982
107	Dinoflagellate	<i>Tuberculodinium</i> sp.	Rosignol 1962, Wall 1967

Plate 5

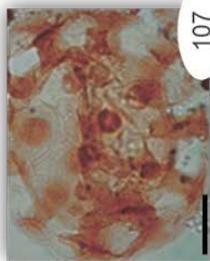
E) Dinoflagellates



105



106

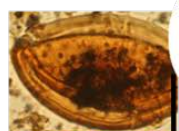


107

F) Indeterminate groups



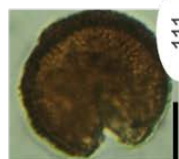
108



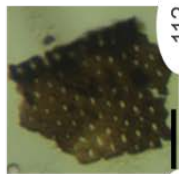
109



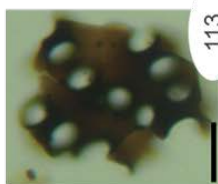
110



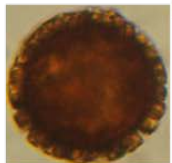
111



112



113



114



115



116



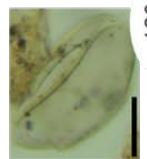
117



118



119



120



121



122



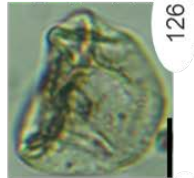
123



124



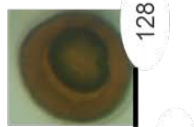
125



126



127

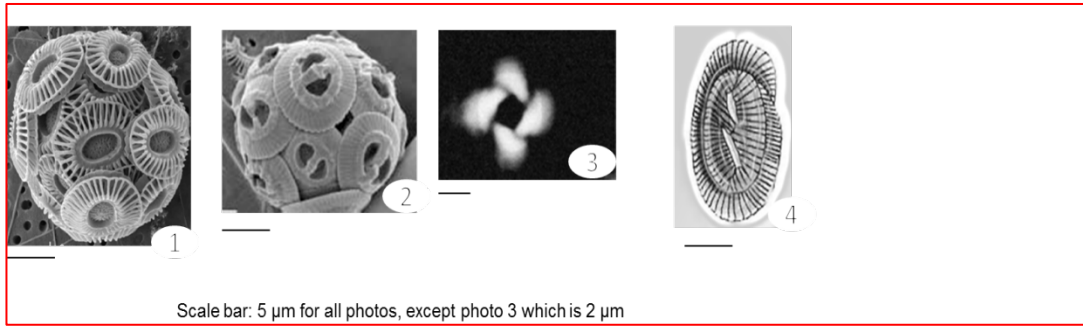


128



128

Plate B: Nannofossils Photomontage



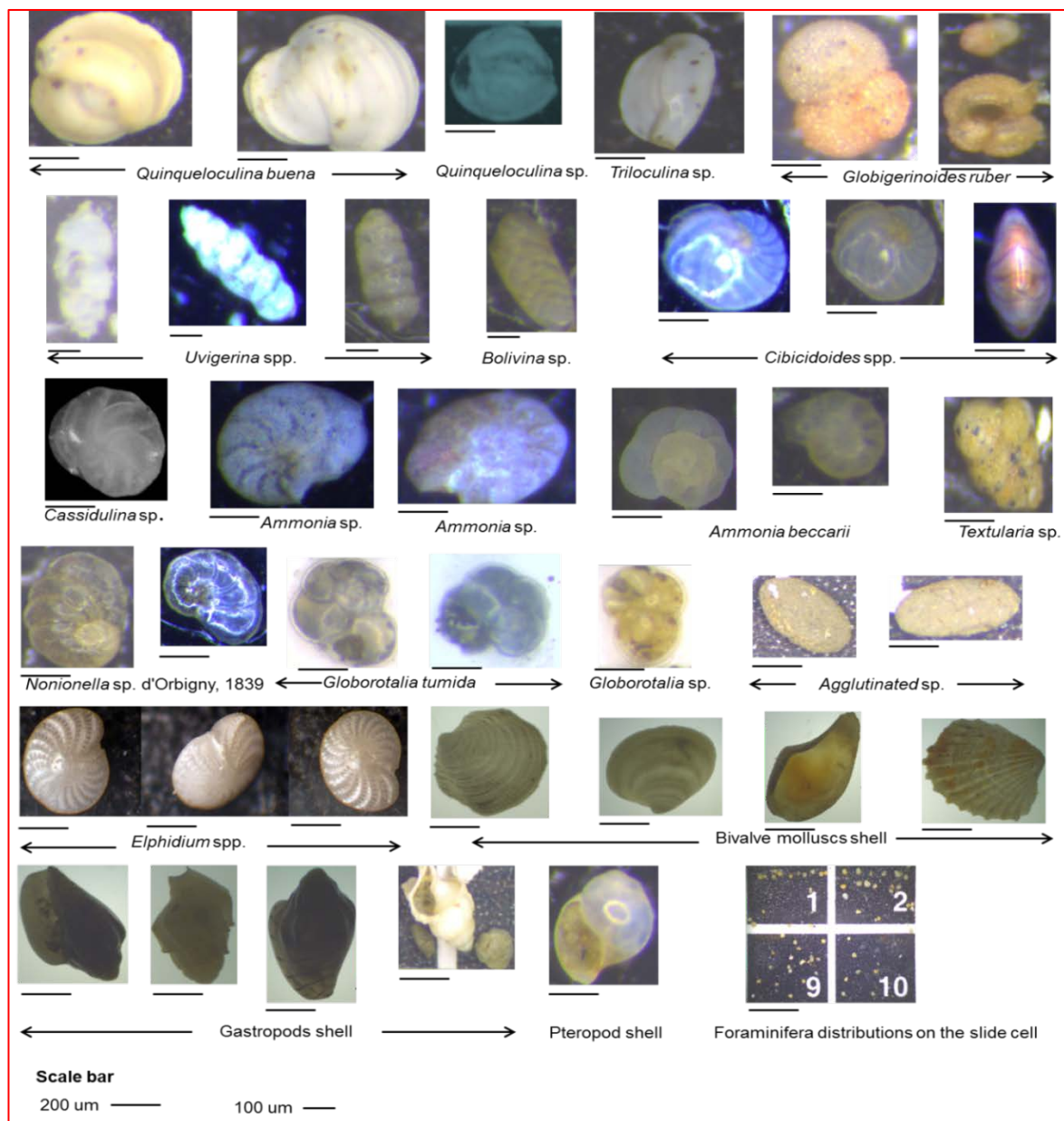
1) *Emiliana huxleyi*

2) *Gephyrocapsa oceanica*

3) *Reticulofenestra asanoi*

4) *Helicosphaera sellii*

Plate C: Foraminifera and Macrofossil Photomontage



Appendix 2

Key words and terminology applied in the thesis.

Phytoecology:

Phytoecology is related to the nature of the fossil record relative to the original plant niche. It is based on organic evolution, which is directional and nonreversible. Indeed, global first and last appearance datum (FADs, LADs) is unique and has chronological meaning. Phytoecological groupings established, the abundance of species is controlled by several factors such as eustasy, climate, edaphic, restricted condition, subsidence, productivity trend, salinity trend etc.

Palynomorph groupings:

Mangrove and Coastal Swamp Indicators:

These groups of pollen/spores are found in the narrow strip of vegetation immediately adjacent to the ocean. It consists of swampy land crossed by sandy ridges. The mangrove environment is noted for developing a rich source rock accumulation (e.g. Mahakam Delta, Eastern Kalimantan – various references). It has an abundance of organic materials which are proteinaceous and fatty. These groupings consist of pollen derivatives from mangrove swamps, tidal estuaries/creek sub-environments (Table 1). The generic environment is one of a salt tolerant intertidal marsh which has a characteristic vegetative type recognised to have covered approximately 75% of tropical coastlines. *Rhizophora* spp. is an important component of mangrove habitats in southern America (Grahma, 1995; Rull, 2002); in West Africa (Germeraad *et al.*, 1968; Poumot, 1989; Morley, 1995), and across Borneo and Indonesia (Morley *et al.*, 2011), Kenya, Oman and the eastern and northern sea-boards of Australia. Other mangrove pollen groups include Apocynaceae, Euphorbiaceae, Avicenniaceae and Anacardiaceae

Freshwater Swamp and Palmae Indicators:

Pollen and spores belonging to this group are associated with mixed fluvial alluvial plain and marine/tidally influenced coastal swamps, particularly in shallow water where the plants develop (Rull, 2001). Estuaries form a transition zone between river and oceanic (marine) environments and are subject to both marine influences,

such as tides, waves, the influx of saline waters; and riverine influences, such as fresh water plumes and pervasive sediment input. The inflow of both seawater and freshwater provide high levels of nutrients in both the water column and sediment, making estuaries among the most productive natural habitats in the World. Some prominent pollen found in these groups are Hypericaceae, Clusiaceae, Malvaceae, Asteraceae and Cyperaceae. Armentrout *et al.* (1999) refer the same pollen to open freshwater taxa. *Palmae* is a common name for an ornamental and economically valuable palm tree, native to western Africa and widespread throughout the tropics.

Lowland Rainforest - Open Forest Indicators:

These relative hinterland groups of pollen/spores are quite dominant indicating that a good number of plant families thrive well in rainforest environments in tropical settings (Poumot, 1989). Large quantities of fossil pollen (mostly angiosperms) with botanical affinities assigned to tropical rain forest plants were recovered from the three GCs. These pollen (Nymphaeaceae), and spores corresponding to their existing parent assemblages are listed in Table 1. Prominent examples among these are fern spores, Polypodiaceae, Lycopodiaceae and Sphagnaceae (Chapter 4).

Savannah and Afromontane indicators:

These groups of pollen/spores belong to tropical grasslands with a scattering of shrubs and small and large trees. Savannah environments may be linked from soil conditions, from periodic fires caused by lightning or set by humans, or from climatic influences. Savannahs as found in western and south-western Africa, develop in regions with marked wet and dry seasons, where rainfall ranges between 100 and 400 mm (4 and 16 in) a year (Poumot, 1989). The most important contributor to this group is tropical grass pollen, Poaceae, which belongs to the Poaceae family, restricted principally to more open vegetation. Morley and Richards (1993) in their study from the Niger Delta recorded a significant amount of charred cuticles from the Cenozoic sedimentary deposits in the Niger Delta (Plate 3). Afromontane groups consist predominantly of the bisaccate pollen group belonging to the family of Podocarpaceae. Their morphology and buoyancy (saccates) allow them to be transported far and wide through both wind and water mediums (Chapter 4).

Non-Pollen Palynomorphs (NPPs) Indicators:

NPPs consist of non-pollen palynomorphs which were not grouped among the pollen taxa. Among the types discussed, our study considered Foraminiferal Test Linings, fresh water algae and cuticles because of their environmental significance (Plates 3-5). They consist of the following sub-groups:

Foraminiferal Test Linings (FTLs): These are test materials from assumed juvenile foraminifera usually made of carbonaceous, porcelaneous and mineral from inner lining of the chambers.

Brackish water algae indicators: These are sets of algae thrive in water columns that have more salinity than fresh water, but not as much as sea water. They may result from mixing of sea water with fresh water, as in estuaries, or it may occur in fossil brackish water aquifers. Technically, brackish water contains between 0.5 and 30 grams of salt per litre - more often expressed as 0.5 to 30 parts per thousand (ppt or ‰). Therefore, “brackish” covers a range of salinity regimes and is not considered as being precise in its definition (Batten and Lister, 1988; Morley, 1995).

Fresh water algae indicators: Refers to algae that are microscopic free-floating plants. These algae are normal and essential inhabitants of sunlit surface waters. A common form of algae in ponds is planktonic algae. Planktonic algae, known as green water (chlorophytic) algae or pea soup algae are microscopic and free floating that give ponds their green colour. Some of planktonic algae recognised from the GCs are *Pediastrum* spp., *Pseudoschizaea ozeanica*, and *Ovoidites parvus* belong to the freshwater green algae family Zygnemataceae (Thiergart and Frantz, 1962) (Plate 4).

Fungal spore hyphae indicators: Fungi are a varied group of generally small organisms that derive their food from living or dead organic matter. They germinate from reproductive cells called spores, which often have a thick, resistant outer coat that protects against unfavorable environmental conditions (Plate 4).

First Downhole Occurrence (FDO) and Last Downhole Occurrence (LDO):

Ranges of individual taxa are often indicated by reference to **first (evolutionary) occurrences (FO)** and **last (evolutionary) occurrences (LO)**. However, in the commercial world, drilling practices usually do not permit the confident selection of first

occurrences (evolutionary inceptions), as downhole contamination of younger sediments (cavings) obscures these events.

Palynodebris:

These are structured and structureless organic matter excluding those that are actually palynomorphs, e.g. wood fragments, plant, insect, cuticle, biotic remains. They are grouped into four. This includes translucent, opaque phytoclasts and amorphous organic matter and is usually transported by wind, water and birds into the sea/river.

Intertropical convergence zone (ITCZ):

Intertropical convergence zone (ITCZ), also called equatorial convergence zone, belt of converging trade winds and rising air that encircles the Earth near the Equator. The rising air produces high cloudiness, frequent thunderstorms, and heavy rainfall; the doldrums, oceanic regions of calm surface air, occur within the zone. The ITCZ shifts north and south seasonally with the sun.

Depositional Sequences:

A depositional sequence is defined as a relatively conformable succession of genetically related strata bounded by unconformities or their correlative conformities (Armentrout *et al.*, 1999). What the definition does emphasise is that every sequence is bounded above and below by unconformities or by correlative conformities that correlate up dip to an unconformity. Every depositional sequence is the record of one cycle of relative sea level. In a vertical succession a depositional sequence is composed of the following elements in the order: Sequence Boundary (SB), Low-stands Systems Tract (LST), Transgressive Surface, Transgressive Systems Tract (TST), Maximum Flooding Surfaces (MFS), High-stand Systems Tracts (HST) and the next Sequence Boundary (SB) (Posamentier *et al.*, 1988).

Lowstand Systems Tract (LST):

The Low-Stand Systems Tract is the set of depositional systems active during the time of relative low sea following the formation of a sequence boundary. If a distinct shelf-slope break exists and relative sea level has fallen sufficiently, the low-stand systems tract consist of basin floor fan, slope fan and a lowstand wedge.

Transgressive Systems Tract (TST):

TST is characterized by a set of back stepping parasequences of fourth-order sequences. The base of the systems tract is the first major flooding surface above low-stand system tracts. The top of the systems tracts is the maximum flooding surface (Posamentier *et al.*, 1988). The transgressive systems tract is interpreted to form during the maximum rate of relative sea level rise. In each succession of parasequence, the shoreline backsteps in a landward direction across the shelf until the point of maximum marine flooding is reached.

Highstand Systems Tract (HST):

This is commonly widespread on the shelf and is characterized by early aggradational to later progradational parasequence sets (Posamentier *et al.*, 1988). The system tract is interpreted to have formed during the latter part of the relative rise of sea level when the rate of relative sea level was decreasing.

Maximum Flooding Surfaces (MFS):

Maximum Flooding Surface caps the transgressive systems tract and marks the turn around retrogradational stacking pattern in the transgressive systems tract to aggradation or progradational stacking in the high stand systems tract. The maximum flooding surface marks the last of the significant flooding surfaces found in the transgressive systems tract and is commonly characterized by extensive condensation and widest landward extent of the marine condensed facies. Many sedimentary features can indicate condensation that is the preservation of relatively long geologic time spans in a relatively thin layer of sediment. Condensation or slow net deposition allows more time for diagenetic reactions to proceed, so condensed sections are commonly enriched in normally rare authigenic minerals such as glauconite, phosphate, pyrite and siderite (Posamentier *et al.*, 1988).

Appendix 3 Basis for biosequence stratigraphy from the impact of “Wetter” vs. “drier” sea level cycles for the studied GC cores

The climate and sea level of an area is mirrored by its vegetation type because climate signals are strongly recognised on basis of vegetational stacking patterns (Birks and Birks, 1990; Bankole *et al.* 2014). Variations in plant communities or

changes in composition / abundance of an assemblage or individual ecosystem species are regularly, partly a direct consequence of the change in climate and/ or palaeoenvironment (Rull, 2002). The consequence of this variation on palyno-floral groups depends on whether such a prevailing climate / sea level change encourages or affects the prevailing plant community. Qualitative and quantitative evaluations of the various groups of palynomorphs were evaluated from the GC cores. This is meant for deducing the climate and sea level phase and the kind of palaeoenvironments which prevailed during the deposition of the Late Quaternary sediments of most regions. The recognition can be modified to reflect the variation of savanna grassland (hinterland) and mangrove forest (littoral). The data plotted generically, suggest a changing climate and sea level during the prevailing palaeoclimatic period (palynocycles).

Sea level / Climatic cycles are recognised as successive phases of humid vs. arid designated as a relative predominance of littoral (mangrove / *Rhizophora* pollen) and hinterland taxa (savannah pollen) (Poumot 1989; Morley and Richards, 1993; Armentrout *et al.*, 1999). Perhaps, these successive phases could be linked to the recurrent palynological sequences reflecting vegetational changes (e.g mangrove / *Rhizophora* pollen) determine by cyclic sea level oscillations and the associated climatic variations (Rull, 2001; Adojoh *et al.*, 2015).

During a dry sea level / climate, the savanna pollen dominated while mangrove pollen (*Rhizophora*) decreased. This interval phase is designated as a low sea level / dry climate and Lowstand System Tracts (LST). Furthermore, when climate becomes wetter, sea level rises and the mangrove vegetation (*Rhizophora* pollen) will expand further into the flood plain while savannah pollen decreases (Morley, 1995). This phase is related to sea level rise / warm climate and Transgressive System Tracts (TST).

In the pollen records, these variations in climate / sea level are related in terms of quantitative changes in the vegetation obtained from the arid region (Van der wan *et al.* 1985). On the other hand, in the tropics, these climatic / sea level variations are indicated in the changes in the relative frequency between savannah pollen and mangrove pollen (Morlye and Richards, 1993).

Therefore, this global variation in climatic / sea level signals recognised from the controlling factors can be related to the savanna and mangrove pollen sediment sources to express their synchronous relationship and thus provide a means or basis for reliable **sequence chronostratigraphic** correlation between vegetation types, littoral pollen, **systems tracts** and delta evolution (Riboulot *et al.*, 2012).

Based on the above premise, this section has proposed an evolutionary and sequence stratigraphic basis for the history of the Niger Delta over the last 20, 000 Bp yrs by probing into the integrated interpretations of vegetation types (pollen records), sediment discharge and geochemical interaction observed from our records under the influence of the major climatic / sea level control. Therefore, the integration of sedimentological, geochemical, vegetation (mangrove / *Rhizophora* pollen) and micropalaeontology (planktonic) interpretation which complement each other representing a powerful tool for the identification of key **systems tracts components** and **sequence stratigraphy** in place of an approach based on lithofacies methods.

Thus, it becomes reliable to adopt the combined increase in the planktonic foraminifera and *Rhizophora* sp. which is interrelated to palaeobathymetry and distance from the marine coast as proxies linking the marine transgression / sea level rise (Torricelli *et al.*, 2006).

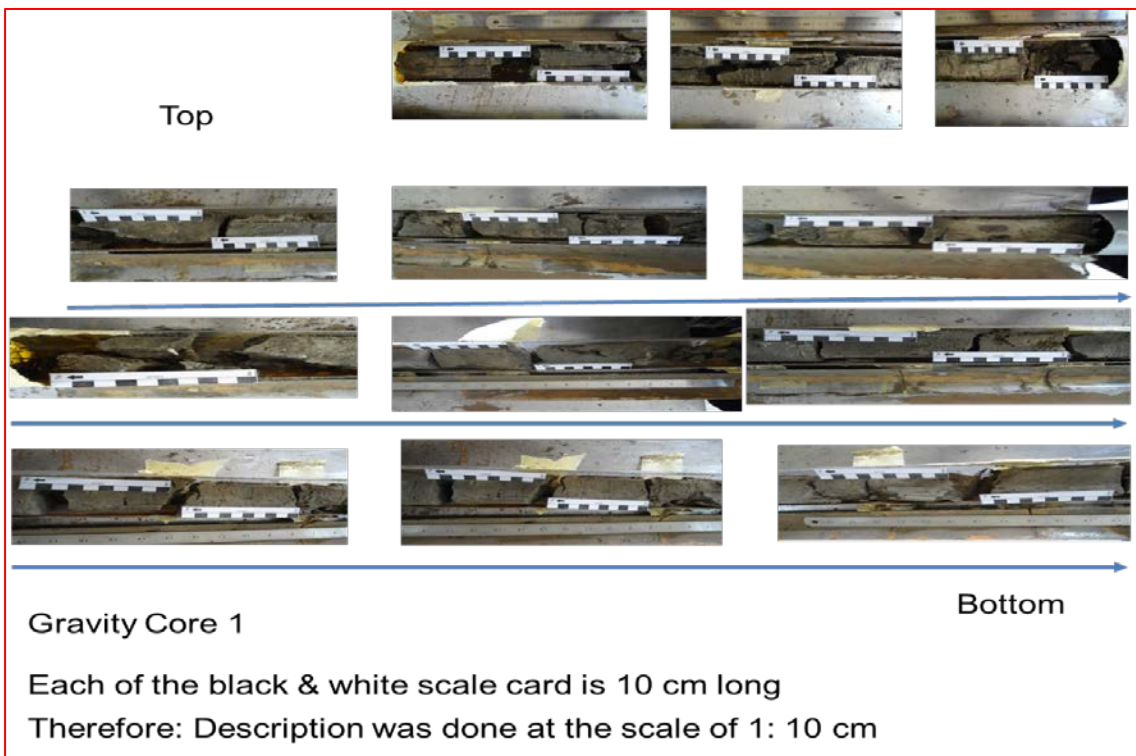
In this regards, we have used most of these models and concepts in evaluating the present GCs study by interpreting a high resolution multi-proxy data as a basis for interpreting **sequence stratigraphy** by combining both the abiotic and biotic components to define each candidate of the **systems tracts** (LST, TST, HST) based on the understanding of the climatic and sea level control.

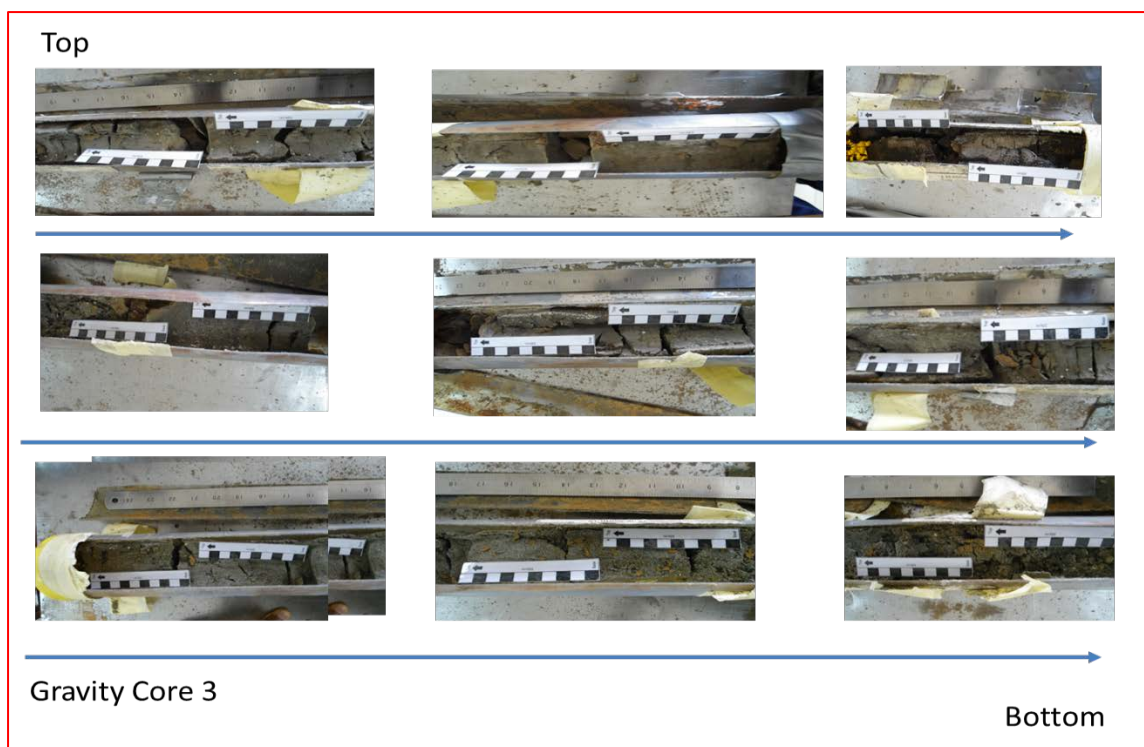
More encompassing and fascinating was the application of Fe/S ratio and planktonic foraminifera (e.g. *Globorotalia* spp.) data integrated with *Rhizophora* sp. to interpret the LST and TST from the GCs records (Amorosi *et al.*, 2014) (Figure 8.1 / Chapter 8). In principle, even though there was no records of seismic data from the studied GCs, the ability to link the available multi-proxy data (e.g mangrove / *Rhizophora* pollen, planktonic foraminifera, Fe/S ratio) to the global bioevent (e.g sea level rise), makes this present study relevant and auspicious to probe for further studies on **biosequence stratigraphy** using the current approach into the deep offshore of the Niger Delta and other regions in the future.

Appendix 4

Published abstracts from the GCs data presented at different conferences
(www.researchgate.net/profile/Onema_Adojoh) (drafted in view for academic publications)

Appendix 5 Photographs of the three Gravity Cores





Curriculum Vitae

Name: Adojoh, Onema Christopher

Education:

- University of Liverpool, UK
Dsc Quaternary Geology and Environmental Change
- University of Benin, Edo, Nigeria
MSc Petroleum Geology, 2009
- Abubakar Tafawa Belwa University of Technology, Bauchi, Nigeria
B. Tech. (Hons), Applied Geology, 2005
- Plymouth University, UK
Micropalaeontology (foraminifera), 2012

Graduate Teaching Associate Certificate in learning and teaching, UK higher education qualification, 2012

- University of Utrecht, the Netherlands
M.Sc. summer school training (palynology and palaeoclimate studies), 2013
- University of Bremen, Germany
Visiting guest, pollen taxonomy, 2014

Professional Experience

- Universities of Plymouth and Liverpool, Research staff demonstrator 2012-2016
- CCG Robertson Research, UK – Intern Stratigrapher, 2015
- Salem University, Nigeria – Lecturer, 2010 - 2011
- Shell, Nigeria, Intern Geologist/Palynologist/Stratigrapher, 2009-2010
- Rued Environmental, Nigeria, EIA and Pollution control officer, 2009
- Nigerian National Petroleum Development Cooperation, IT Geologist, 2003-2004

Others: Relevant leadership, presentation and communication skills

- Attended and made presentations at 18 conferences both home and abroad
- (www.researchgate.net/profile/Onema_Adojoh/publications)
- ✓ **Awards received:** NAPE/CGG Veritas award for the best poster presentation at the NAPE/AAPG conference, Abuja, Nigeria, 2010
- Nigerian Petroleum Technology Development Fund of Nigeria (PTDF), PhD scholarship award, 2011
- Geological Society of London travel grant for the Sedimentology of Paralic reservoir conference, London, UK, 2015
- Quaternary Research Association conference award, US, 2015
- London Petrophysical Society travel grant award, London, 2015
- Geological Society of America, travel grant, 2016
- NABG / National Science Foundation, US conference support , 2016
- ✓ **Email Contact:** christopheradojoh@yahoo.com