Petroleum and Coal

Article **Open Access**

Sequence Stratigraphic Signatures from XEN-1 Well: Key for Understanding Cretaceous–Tertiary Transitional Events in the Northwestern Niger Delta Basin, Nigeria

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Received May 7, 2019; Accepted July 15, 2019

Abstract

In order to evaluate and understand transitional events with stratigraphic elements that characterize the close of the Cretaceous and the onset of the Cenozoic in the north-western part of the Niger Delta Basin, where it overlies the Anambra Basin. Cutting samples of sand and shale from a depth range of 1743 – 2655 m of XEN-1 well drilled in the north-western part of the delta were subjected to qualitative lithological, palynological and geochemical analyses, to define paleodepositional settings, age frame and lithostratigraphic profile for the well section. Interpretation of the paleodepositional proxies indicated that the sediments were deposited in fluctuating paleodepositional settings through time between continental to open marine in a cyclic pattern or relative sea-level oscillatory regimes. Sequence stratigraphic interpretation revealed three lowstand systems tracts (LSTs), seven transgressive systems tracts (TSTs), and six highstand systems tracts (HSTs). Age-sensitive palynomorph species suggested a Maastrichtian to Early Miocene age for the sediments. This revealed a major transgressive event that marks the Cretaceous-Tertiary (K-T) transition that ended in the Ypressian (54.6 Ma MFS). Thus, strengthened the age frame of Paleocene-early Eocene for the Imo Formation as suggested by early workers. But in contrast to the regressive model that advances for the deposition of the Ameki Formation by previous studies. The lower lithological unit was redefined to be the product of a still stand sea-level phase. While the upper unit is to be a product of sea-level fall and the base of which is marked by the 47.2 Ma sequence boundary (SB). This study has shown that K-T lithostratigraphic transitional events were controlled essentially by third-order sea-level rise that transcended the K-T boundary, hence characterized by marine shale facies.

Keywords: *Cretaceous-Tertiary transition; Niger Delta; Ameki Formation; Imo Formations; sequence stratigraphy.*

1. Introduction

Cretaceous stratigraphic events and sequences are contained in two tectonic elements in southern Nigeria. The areas include the Anambra and Dahomey Basins (Fig. 1a). In the Anambra Basin, the stratigraphic pile in the flank areas seems to display stratigraphic signature different from that at the central parts of the basin. Stratigraphically, the Niger Delta Basin rest on the Anambra Basin that is overlying the Abakaliki Basin (Fig. 1b). Older formations of the Niger Delta outcrops in the northern aspects of the delta that falls within the geographic space of the Anambra area. This occurrence has led to serious misconception and misunderstanding among students, academics, and researchers involved in stratigraphic and sedimentological studies in this part of Nigeria. The misunderstanding is hinged on failure to distinguish between geologic (tectonic) and geographic element, hence several formations of the Niger Delta Basin, e.g. the Paleocene Imo, Eocene Ameki, and Oligocene Ogwashi Formations have been erroneously classed as part of the Anambra Basin stratigraphic sequence.

The Atlantic Ocean advanced from the onset of rifting in the Berriasian to open marine conditions in the Albian, at the time depositional of Santo and Campos Basins of Brazil was developing [1], close relatives of southern Nigeria Basins and other West African coastal basins (Figs. 1 and 2). This is attributed to the age of the Asu River Group in Abakaliki sub-basin that is assigned Albian, the oldest subsurface lithostratigraphic unit in southern Nigeria (Fig. 3) [2].

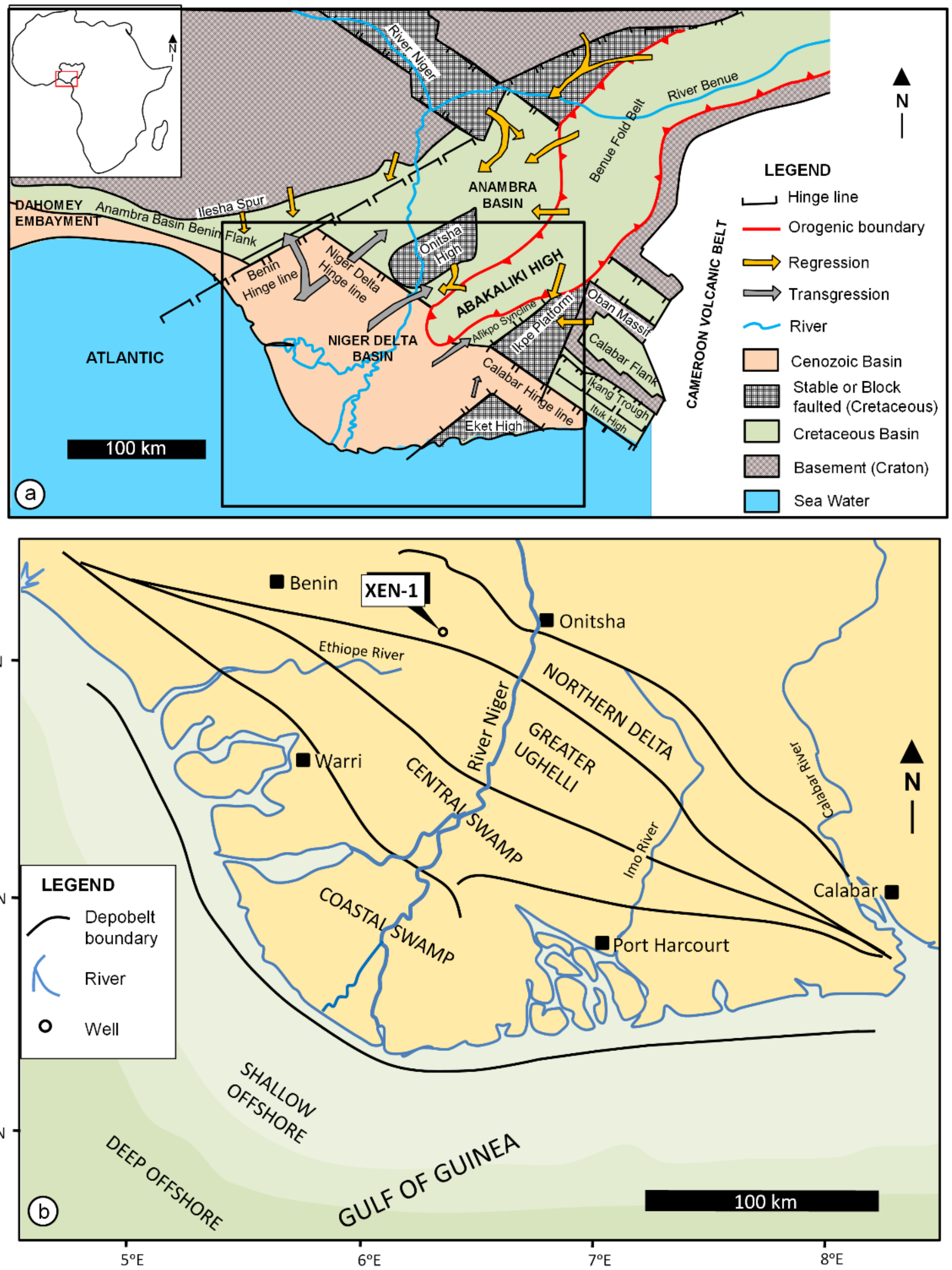

Fig. 1. Location and regional geologic settings of the southern portion (Benue Trough) of Nigeria. (a) Tectonic setting of the Cretaceous and Cenozoic Basins of the Benue Trough showing the boundaries and structural framework of the associated basins (*modified from Murat* [17]*; Ogbe et al.* [18]). Inset map of Africa shows the location of Nigeria and southern Nigeria marked red box. Refer to Fig. 2 for the evolution of the Benue Trough. (b) A simplified Niger Delta map marked black box in Fig. 1b showing the depobelts and XEN-1 well location (*modified from Corredor et al.* [19]). Each depobelt defined by major bounding faults.

It is pertinent to note that the Anambra Basin, adjacent to the Abakaliki sub-basin is strictly a Cretaceous Basin hosting Cretaceous age sediments, while the Niger Delta is a Cenozoic basin containing Cenozoic to Recent sediments (Figs. 1 and 3). The Niger Delta Basin rests unconformably on the Anambra Basin and represents a Cenozoic continuation of southward transportation and deposition of clastics into the coastal Atlantic that commenced since the Late Cretaceous-Early Paleocene (Figs. 1 and 2). Cretaceous sedimentation in southern Nigeria ends and at the Cretaceous-Paleogene boundary popularly known as the Cretaceous-Tertiary (K-T) boundary which may be hosted by the Nsukka Formation that straddles the boundary [3]. Beyond the poor understanding in distinguishing the stratigraphic signatures of both basins, the age range and conditions of deposition call for some adjustments and refinement.

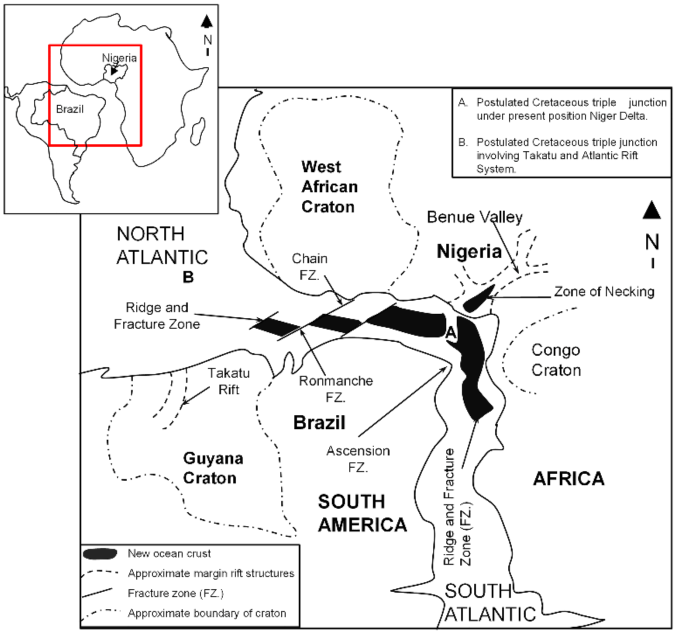

Fig. 2. Schematic diagram showing the development of the Benue Trough and South Atlantic from the onset of rifting in the Early Cretaceous and consequently into open marine conditions *(modified from Burke et al.* [26]), refer to Fig. 1. Note the location of the Nigeria, Brazil, South Atlantic, and Benue Trough marked red box in the inset plate of Africa and South America

SUBSURFACE		SURFACE OUTCROPS			
Niger Delta Basin Stratigraphy	Oldest known Age	Youngest known Age	Southern Benue Trough	Oldest known Age	BASIN
Recent Benin Formation (Afam clay Member)	Oligocene	Plio/Pleistocene	Benin Formation	Miocene	Niger Delta
Recent Agbada Formation	Eocene	Miocene	Ogwashi-Asaba Formation	Oligocene	
		Eocene	Ameki Formation	Eocene	
Recent Akata Formation	Eocene	Lower Eocene	Imo Formation	Paleocene	
		Paleocene	Nsukka Formation	Maastrichtian	Anambra
		Maastrichtian	Ajali Formation	Maastrichtian	
Unknown	Cretaceous	Campanian	Mamu Formation	Campanian	
		Campanian/ Maastrichtian	Nkporo Shale	Santonian	
		Coniacian/ Santonian	Awgu Shale	Turonian	Abakaliki
		Turonian	Eze-Aku Shale	Turonian	
		Albian	Asu River Group	Albian	

Fig. 3. Formations of the Niger Delta Area, Nigeria (Modified from Short and Stauble [2])

Generally and especially in the central northern aspects of the Niger Delta, the Cretaceous-Paleogene transition in the Anambra-Niger Delta province is sedimentologically represented by the Nsukka Formation that unconformably overlies the Ajali Sandstone Formation, and is characterized by sandstone, shale and sub-bituminous coal formed in varied paleodepositional settings ranging from strandplain mash, with occasional fluvial influence to shallow marine [4].

While the Ajali Sandstone Formation is strictly a Cretaceous sedimentological component of the Anambra Basin, the Nsukka Formation straddles the K-T boundary [5] and can partly be ascribed to the Anambra Basin and Niger Delta sequences. Although the many studies on the Cretaceous-Tertiary Boundary (KTB), has left controversies and heated debates on the nature of the events and causal mechanisms of the KTB [6-14], the transition is noted to be heralded by a Late Cretaceous regression and an Early Danian transgression [4-5,15-16]. The two hypotheses advanced so far on the K-T Boundary event are: (1) that the K-T events are the result of catastrophic effects of a large extra-terrestrial body colliding with the earth, and (2) that the K-T extinctions resulted from terrestrial volcanic activities of the Deccan during which gaseous emission affected global climatic system and resulted in annihilation of macro and microfauna, a process which may have been accelerated by a bolide impact at K-T boundary time. Although, Deccan volcanism event could only have caused moderate climatic warming inadequate to drive major sea-level changes [13,16].

This study is aimed at using sequence stratigraphic method to unravel paleosea level signatures prevalent during the Cretaceous-Cenozoic transition in the Anambra-Niger Delta Basin sedimentary pile accessed through a well located in the western parts of the northern depositional belt of the Niger Delta, in order to ascertain the stratigraphic range of the Paleocene Transgressive Event (PTE) in the older stratigraphic sequences of the Niger Delta Basin and to define systems tracts within the Ameki Formation in order to refine and improve on information regarding the depositional condition(s) of the formation. It is expected that this work would provide a basis for further investigation of Cretaceous-Cenozoic sedimentary sequences in similar geologic settings in order to understand sedimentary signatures and events that can offer a better understanding of the end-Cretaceous-Cenozoic transition.

2. Tectonics setting of the Anambra and Niger Delta basins

The Anambra and Niger Delta Basins are both located in Southern Nigeria (Fig. 1). The Niger Delta Basin is located south of the Anambra Basin and situated along the West African coast at the site of a Cretaceous triple junction and lies between longitudes 5° and 8°E and latitudes 3° and 6°N within the coastal area of the Gulf of Guinea (Figs. 1 and 2). Distal aspects of the lithostratigraphic units of the Anambra Basin grade laterally into formations of the Niger Delta at depth.

The Anambra Basin is roughly triangular in shape and covering an area of about 40,000 km^2 [20]. It is bounded at the south by the northern boundaries of the Niger Delta Basin, while the Lower Benue River forms its northern limit (Fig. 1a). The West African Massif and the Abakaliki anticlinorium respectively form the western and eastern boundaries [21]. The basin extends westwards towards Dahomey Basin but separated by the Okitipupa High along the Benin Hinge Line [22], which forms its subsurface boundary to the west (Fig. 1a). The western arm of the Anambra Basin is a narrow tectonic structure that rims the southern limits of the western Basement Complex located in the north of the area (Fig. 1).

The evolution of the Anambra and the Niger Delta Basins is related to the failed arm of a triple junction which evolved during the separation of Africa from South America in the Late Jurassic – Early Cretaceous times (Fig. 2), although the Anambra Basin was formed much later to Paleocene [23-24] and the Niger Delta Basin was formed thereafter in the Paleocene [22]. According to Murat [17] prior to the Santonian thermotectonic event, the megatectonic setting of the southern Benue Trough was characterized by longitudinal fault blocks that preferentially subsided in the eastern half of the trough to become the Abakaliki sub-basin, known as the Southern Benue Trough, while the western parts remained a stable platform until the Santonian. Relative to the western platform area which received thin veneer of clastic and chemical sediments, the subsided eastern part recorded massive clastic sedimentation, thus became the main depocenter (Abakaliki area). The Santonian folding and uplift subsequently caused a flexural inversion that displaced the depocenter to the west and northwest, thereby creating the Anambra Basin. Generally, the thermotectonic basin subsidence in the Southern Benue Trough was by spasmodic mechanism, characterized by the high rate in pre-Albian time, low in Cenomanian, and very high in the Turonian, a phase that is thought to be the initiation of the actual Anambra Basin that climaxed during the Santonian thermotectonic event [25].

The Anambra Basin is sandwiched between the Benue Trough and the Niger Delta Basin in a tied style that is characteristic of West African coastal basins (Figs. 1 and 2) [4]. This probably indicates that a thermal decay occurred after the Santonian thermotectonic event that produced a sagging structure which became the Anambra Basin and continued up to the Paleocene where the formation of the Niger Delta sedimentary pile commenced [4].

Consequently, The Niger Delta builds out into the Atlantic Ocean at the mouth of the Niger-Benue and Cross River drainage systems and extends more than 300km from the proximal to distal ends (Fig. 1) [21]. It prograded from the north to south in the Eocene to Recent, forming successive depositional belts or depobelts: Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp and Offshore Depoblets (Fig. 1). The Niger Delta Basin contains both sedimentary wedges that are dominated by progradational sequences and major marine transgressive sequences (Fig. 1). Climatic variations, proximity, and nature of sediment source areas and sediment-paleo-circulation pattern influenced the gradual change in the shape of the Cretaceous coastline that developed into a bulge with the growth of the Niger Delta, thereby controlled the extent of incursions of the sea [27]. Rapid subsidence <700 m/Ma and progradation of ≈2 km/Ma along three depo-sitional axes that fed irregular, early delta lobes that eventually coalesced characterized the embryonic delta during the Late Eocene – Middle Miocene [28-30]. Late Oligocene to Middle Miocene delta subsidence remained steady at about 700 m/Ma with increased delta progradation of 8–15 km/Ma [31], Progradation of the delta over a landward dipping oceanic lithosphere has steadily occurred from the Middle Miocene onward [2]. The subsequent lateral merging of active depocenters in the eastern sector resulted in an enlarged delta front, which prograded fast and developed into a convex coastline (Fig. 1).

3. Stratigraphy of the Anambra and Niger Delta Basins

Nwajide [4] concluded that the stratigraphic package of the Anambra Basin that ranged in age from Santonian to Early Paleocene (Fig. 3), was deposited by a major and minor marine transgressive events. The major transgression formed the Nkporo Group, while the minor event formed Coal Measures (Fig. 3) [4,32]. The Nkporo Group (Nkporo Shale and lateral equivalents) occur as the basal units of the basin and overlies an angular unconformity that caps the Abakaliki Basin (Fig. 3) [4]. Stratigraphic units of the Nkporo Group (Lafia, Owelli, Enugu, and Nkporo Shale Formations) are of Campanian age that formed the first depositional cycle of the Anambra Basin (Fig. 3). The younger stratigraphic units of the basin such as the Mamu, Ajali, and Nsukka Formations were deposited in the Danian (Maastrichtian to Early Paleocene) by the minor transgression as the second and last depositional cycle of the basin (Fig. 3)". A detailed description of each of these formations and their age ranges are well documented by earlier workers [4,22,32-40].

Stratigraphic units of the Niger Delta Basin are in both subsurface and outcropping. The outcropping Paleocene-Eocene Imo Formation that is predominantly marine shale occurs in the northern part of the Niger Delta, where it overlies the Nsukka Formation (the youngest unit of the Anambra Basin), is lithostratigraphic equivalent and continuous of the subsurface Akata Formation (Figs. 3 and 4) [2,32,41-44]. The Eocene Ameki Formation composes of grey-green sandy clays, sandy claystone, and sandstone in the Southeastern Nigeria, where it unconformably rests on the Imo Formation is lithostratigraphic equivalent and continuous of the Agbada Formation (Figs. 3 and 4) [17,22,32]. The Ameki Formation was deposited in a deltaic and shallow marine paleoenvironment during the Eocene Regression that affected the Anambra Basin [17,22]. Another cropping unit of the Niger Delta is the Oligocene-Miocene Ogwashi Formation that overlies the Ameki Formation [32]. It is composed of white, blue, and pink clays, cross-bedded sands, carbonaceous mudstones, shales, and seams of lignite, which are inferred to be flood plain environment deposits [4].

The subsurface Akata, Agbada, and overlying Benin Formations are the three main lithostratigraphic units which show a typical offlap sequence, comprising time equivalent proximal-to-distal prograding facies (Fig. 4 and Fig.3). The Akata Formation was deposited in the Early Eocene to Recent and occurs as a bottomset with a thickness that ranges from 600 m to 6000 m that is composed of over 90% prodelta marine shale with less than 10% of sandstone [2]. The Agbada Formation of the Late Eocene to Holocene forms the foreset that is composed of delta front lithofacies of mostly shoreface and shallow marine deposits of alternation of sand and shale of near equal proportion, of a thickness ranging from 3000 m to 4500 m [2,45]. The topset

Benin Formation is an upper delta plain lithofacies that consists of over 90% massive continental sands and gravels with clay intercalations, with a variable thickness which generally exceeds 2100 m and ranges in age from Oligocene – Recent [2,22,44-45].

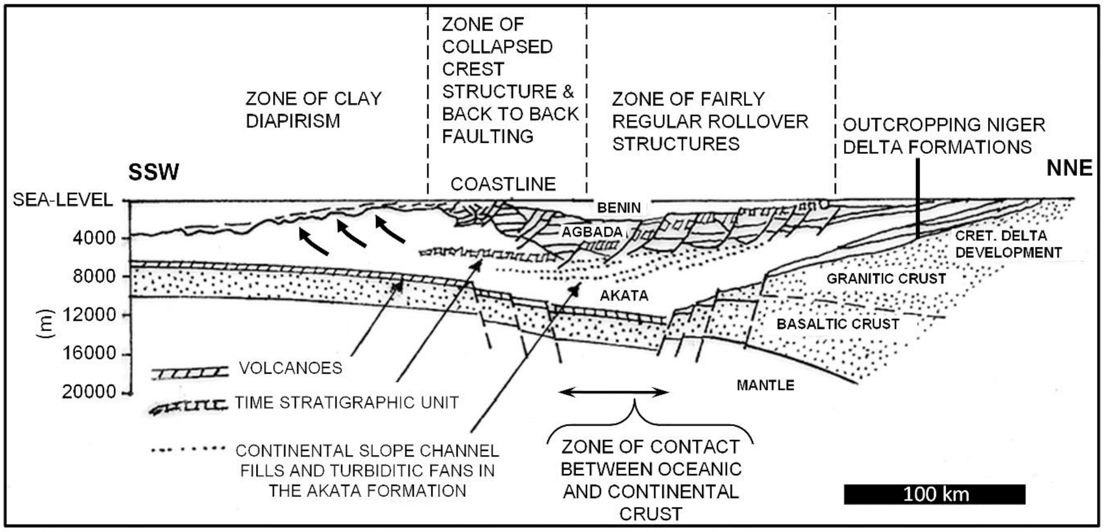

Fig. 4. Schematic stratigraphic cross section of the Cenozoic Niger Delta Basin along depositional dip showing the basin's subsurface and outcropping Formations (*Evamy et al.* [3]). Note the outcropping Cenozoic Niger Delta Formations overlying the Cretaceous sediments of the Anambra Basin in the northern delta

4. Investigative methodology

4.1. Lithofacies and palynological analysis

A total of one hundred and sixty (160) non-composited ditch cutting samples of sand and shale from a depth range of 1743 – 2655 m of the XEN-1 well located in the northwestern Niger Delta Basin (Fig. 1b), were subjected to qualitative whole grain lithological and textural analyses involving stereomicroscopic description to determine gross grain morphology, sorting, color, size distribution, mineralogy and the presence of accessory materials. The well under study belongs to the Shell Petroleum Development Company (SPDC) but is here coded XEN-1well for confidentiality reasons. Generally, the sampling range for lithofacies description is about 5.6 m and an average of 10 m for a palynological purpose. Palynological sample preparation is described in Osokpor and Ogbe [46] in accordance with Traverse [47], while age determination is based on earlier works of the authors [48-49].

4.2. Geochemical analysis

Three subsurface cutting samples retrieved from sections (2380, 2420 and 2545 m) of the Imo Formation in well XEN-1, Northern depobelt, western Niger Delta Basin (Fig. 1b), where geochemically analyzed for biomarker as a complementary proxy for Paleoenvironmental determination in this study. Sediment samples due for analysis were extracted for soluble organic matter using a TECATOR FOSS SOXTEC 2055 extractor during which exhaustive extraction was done for 80 min. at 100°C using dichloromethane. A fractionation of process by column chromatography with 70% silica gel was done for the extracted oils. Elution of the saturate and aromatic hydrocarbons and polar compounds was achieved using n-hexane (20mL), n-hexane/dichloromethane (90:10, v/v/ 40 mL) and DCM/methanol (50:50, 30 mL) respectively.

Saturated hydrocarbon fractions were analyzed by an Agilent 6850 gas chromatography-mass spectrometry (GC-MS) series interfaced with an Agilent 7683 injector series housing an auto-sampler, and equipped with a flame ionization detector. The GC-MS machine, fitted with a capillary column using helium as a carrier gas, was then programmed to run at 35°C to 300°C/min with a flow rate of 1.1mLs/min. Terpanes and steranes were identified using m/z

191 and 217 fragments, respectively. Analyses were carried out at Fugro Robertson Petroleum Geochemistry Laboratory in Llandudno, North Wales United Kingdom.

5. Results

5.1. Lithostratigraphy and biosignals

Lithological characteristics derived through the synthesis of gross lithologic and grain morphologic attributes of well-cutting samples analysis from the well section revealed four main lithotypes (sand, shale, Limestone/lime mud, and coal), and nine lithofacies (very fine – medium sand, medium – coarse sand, coarse sand, sandy limestone, sand shaly limestone, shaly limestone, black coal, carbonaceous shale and sandy shale) displaying a prominent cyclic pattern, a product of probable interplay of auto-allocyclic facies generators (Fig. 5). The lithologic signatures displayed enabled the definition of four lithostratigraphic units in the studied section. These include interbeds of coal and shale punctuated by silty shale intervals at the upper section which occurs as the basal unit and characteristic of the Mamu Formation. The basal unit is overlain by a section composed of thick black shale and is ascribed to the Imo Formation. The Imo Formation is then overlain by limestone lithotype composed of shaly – sandy lime mud facies. The sequence is capped by a section composed of interbeds of sand and shale characteristic of the Agbada Formation.

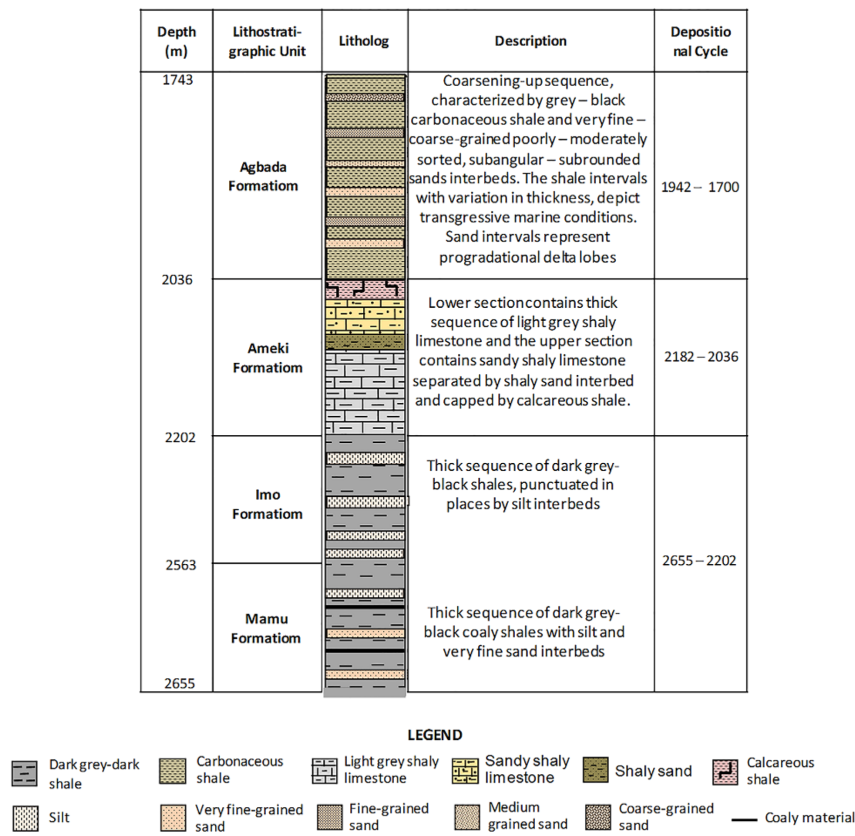

Fig. 5. Lithologic log of the studied section of the XEN-1 well showing the penetrated depositional cycles and formations with depth

Palynomorphs assemblage dominated by land derived species composed of seventy-six (76) well-preserved pollen, thirty-eight (38) spore, and fifteen (15) dinocyst form species were recovered and identified in selected samples from the well section (Fig. 6). Generally, the dinocyst recovery was poor. Due to the long range of the sporomorph and dinocysts assemblages recovered, the pollen assemblage was solely utilized in age-dating the sediments.

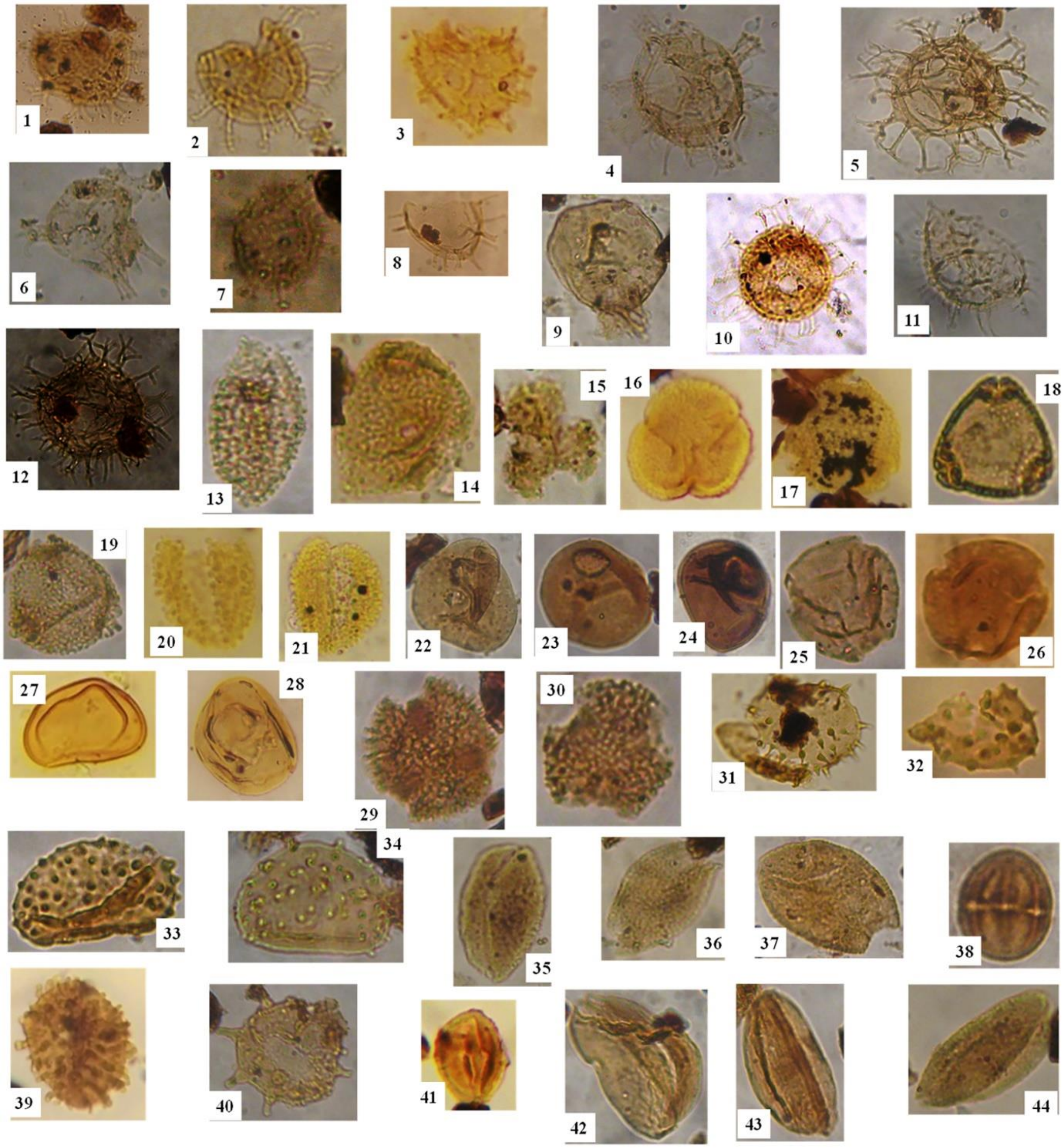

Fig. 6. Some age diagnostic dinocysts and miospore species recovered from XEN-1 well

1. *Hafniasphaera sp.* (L. Maastr.– L. Paleocene), **2.** *Hafniasphaerahyalospinosa.* (L. Maastr. – L. Paleocene), **3**. *Heterosphaeridium sp.* Cookson & Elsenack, 1968 (Sant. – E. Camp. & Oligo), **4.** *Fibrocysta sp.,* **5.** *Spiniferites sp.,* **6.** *Homotriblium sp.,* **7.** *Hystrichosphaeridium sp.,* **8.** *Polysphaeridium sp.* (E. Jurrassic – M. Mio), **9.** *Palynodinium sp.* (L. Cret.), **10.** *Operculodinium centrocarpum.* **11.** *Lingolodinium sp.,* **12.** *Spiniferiteshafnispira,* **13 & 14.** *Arecipitesexilimuratus,* **15.** *Retitricolpites sp.,* **16.** *Perfortricolporitesdigitatus,* **17, 18, 19.** *Retibrevitricolporitesobodoensis,* **20 & 21.** *Racemonocolpiteshians,* **22, 23, 24.** *Monoporitesannulatus,* **25 & 26.** *Psilatricolporitescostatus,* **27 & 28.** *Laevigatosporites sp.,* **29 & 30.** *Gemmatricolporites sp.,* **31.** *Spinozonocolpitesechinatus*, **32.** *Spinozonocolpitesbaculatus,* **33 & 34.** *Verrucatosporitesusmensis,* **35.** *Langapertitesproxapertitiod,* **36.** *Retidiporites sp.,* **37** & **38.** *Sapotaceaepollenites,* **39 & 40**. *Grimsdaleamagnaclavata,* **41.** *Verrutricolporitesscabratus* (L. Miocene), **42.** *Striamonocolpitesundulostriatus,* **43.** *Striamonocolpitesrectostriatus* (Lower Miocene), **44.** *Monocolpopollenitessp* (U. Cret)

5.2. Paleodepositional environment of XEN-1 Well penetrated intervals

The result from the interpretation of paleodepositional environment proxies shows that the sediments were deposited in varying paleodepositional settings through time ranging from continental to open marine in a more or less cyclic pattern occasioned by oscillatory and/or changing relative sea-level. Three major paleodepositional cycles A-C, were established. Sediments in the depth range 2655 – 2202 m (Cycle A), which occupies the lower section of the well and of Maastrichtian – Paleocene age were deposited in a paralic paleoenvironment, probably in a middle - outer neritic zones of the paleo-shelf during the Late Cretaceous to Paleocene transgression that affected the Benin Flank area and created the proto Niger Delta sedimentary pile. This section of the well is composed of black shale devoid of silt, silty shale and coal interbed lithofacies. The black shale is characterized by black coaly and brownish woody fragments suggestive of a transitional fluvio-marine environment [50-51]. This view is strongly supported by biomarker, isoprenoid, and n-alkane data from samples XEN2380, XEN2420, and XEN2545 within this depth range (Fig. 7, Tables 1 and 2).

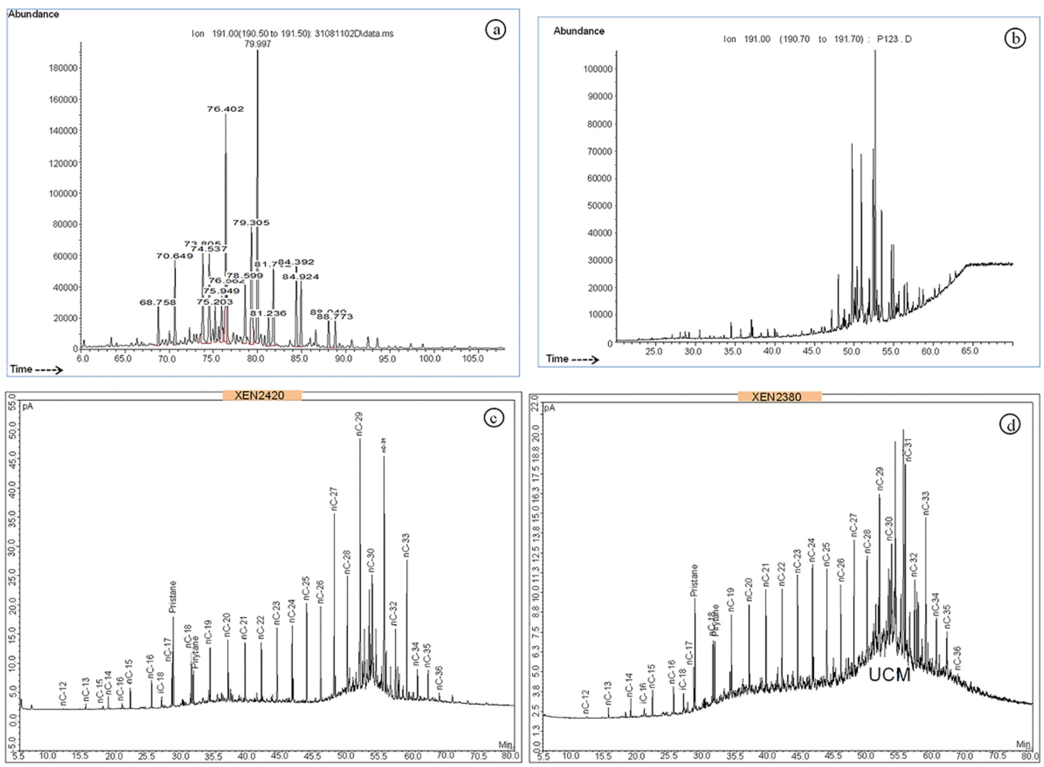

Fig. 7. Chromatogram results of the different samples. (a) High Scan Triterpane mass chromatogram of sample XEN2380. (b) Low Scan Triterpane mass chromatogram of sample XEN2545. (c) Gas Chromatogram for sample XEN2420. (d) Gas Chromatogram for sample XEN2380

The abundance of the C30 pentacyclic triterpanoid, gammacerane, relative to the C30 hopane (Table 1), is a marker for saline environments [52-53]. Within this interval, the Gammacerane index value range from 0.06 to 0.03 (Table 1). This trend ordinarily would indicate a shallowing water condition (Table 2), but the integration of this data with sedimentological and biosignal data reveal a paleosea transgression onto a platform area. Biosignal data of decreasing miospore abundance which indicates a transgression and a bloom of Spiniferites species in this section and known to thrive abundantly in neritic waters [54], supports a deepening trend of the middle neritic condition in the Late Cretaceous to an outer neritic setting in the Paleocene.

Table 1. Paleodepositional environment parameters from the pentacyclic, triterpanes and steranes distribution of the XEN-1 well.

Sample No	Depositional environment S T_7	Salinity T T_{10}
X2380	0.34	0.03
X2545	0.42	0.06

S=(h35S + h35R)/(h34S + h34R) (m/e 191), C_{35}/C_{34} extended hopane ratio
T=G/h30 (m/e 191), Gammacerane/hopane ratio (Gammacerane index)

Table 2. Isoprenoid and n-alkane ratios of XEN-1 well

Sample No.	Depositional environment (A) Pr/Ph	Depositional environment (B) $(Pr+nC_{17})/(Ph+nC_{18})$	Depositional environment (C) $\%C_{25}$ + n-alkane	Interpretation
X2380	1.76	1.34	58.30	Shallow marine. Oxic
X2420	2.92	1.18	66.25	Shallow marine and transitional. Oxic

Sediments in **Cycle B** (depth range 2182 – 2036 m), were also deposited in paralic paleodepositional settings although they mark a still stand and a regressive phase of the paleosea, implying that deposition took place in shallower paleobathymetric domains. The lower section is characterized by whitish carbonate (limestone), sandy shale, shaly limestone and calcareous limestone lithofacies of Eocene age that correlates with the lower lithological section of the Ameki Formation, and capped by an upper section, that is composed of sequences of sandy and calcareous shale lithofacies characteristic of the upper lithological section of the Ameki Formation [22].

The biosignal presented by this interval shows an initial increase in total palynomorphs and pollen percentages and a corresponding decrease in sporomorph percentage. This trend signals a flooding and reduced fluvial influx in the lower section, which may have heralded clear coastal water conditions conducive for the development and growth of carbonate depositional systems, and an initial increase and subsequent decrease in sporomorph percentage indicating a shallowing water condition at the upper section.

This position is strengthened by the occurrence of the shallow water dinocysts species, *Multispinula quanta*, and *polysphaeridium sp.* [54], at a depth of 2050 m.

The depth interval 2036 – 1743 m (**Cycle C**) is marked by thick sequences of dark shale with subordinate very fine to medium-grained sand components in some sections and thin fine to coarse-grained sand interbeds. This interval is characterized by increased pollen and reduced spore percentages, which infer probable luxuriant vegetation occasioned by warm paleoclimate associated with a relative rise in sea-level. The inference for this interval is supported by the occurrence of *Operculodinium centrocarpum* a deep water dinocyst species, at 1817 m.

5.3. Sequences stratigraphy

5.3.1. Systems tracts

Four second-order sequences have been established in XEN-1 well. The sequences range from 2655 – 2202 m (Sequence 1 – 4), 2202 – 1945 m (Sequence 5), 1945 – 1758 m (Sequence 6 – 7) and 1758 – 1700 m (Sequence 7).

Lowstand Systems Tract (LST): Three LSTs were identified in the well. The first LST starts from the 47.2 Ma sequence boundary which marks the Lower Lutetian Stage at a depth of 2097 m within the P440 zone [3], and range up to 2036 m, (LST-1) (Fig. 9). The second LST commences at the 32.4 Ma sequence boundary within the P590 zone of Evamy *et al.* [3] at 1942 m and range up to a depth of 1927 m, which is of a Lower Rupelian Stage (Fig. 9). LST-3 commences at 1893 m and range up to 1840 m, marked at the base by the 27.3Ma sequence boundary of Upper Chatian. It falls within the P620 zone of Evamy *et al.* [3]. Paleo-depositional environment interpretation for these intervals above shows that the three LSTs were deposited in a near-shore to the shallow marine shelfal paleodepositional environment. Definition of these systems tract is based primarily on biosignal, Lithofacies and overall stacking patterns which show a general progradational trend. The LSTs are characterized by the absence of mangrove pollen species, and an abundance of sporomorphs relative to pollen and thick sand interbeds, a reflection of relatively dry climatic conditions probably signaling a lowering sea-level. Van der Zwan *et al.* [55] reported high run-off and extensive sand deposition to result from dry climatic conditions.

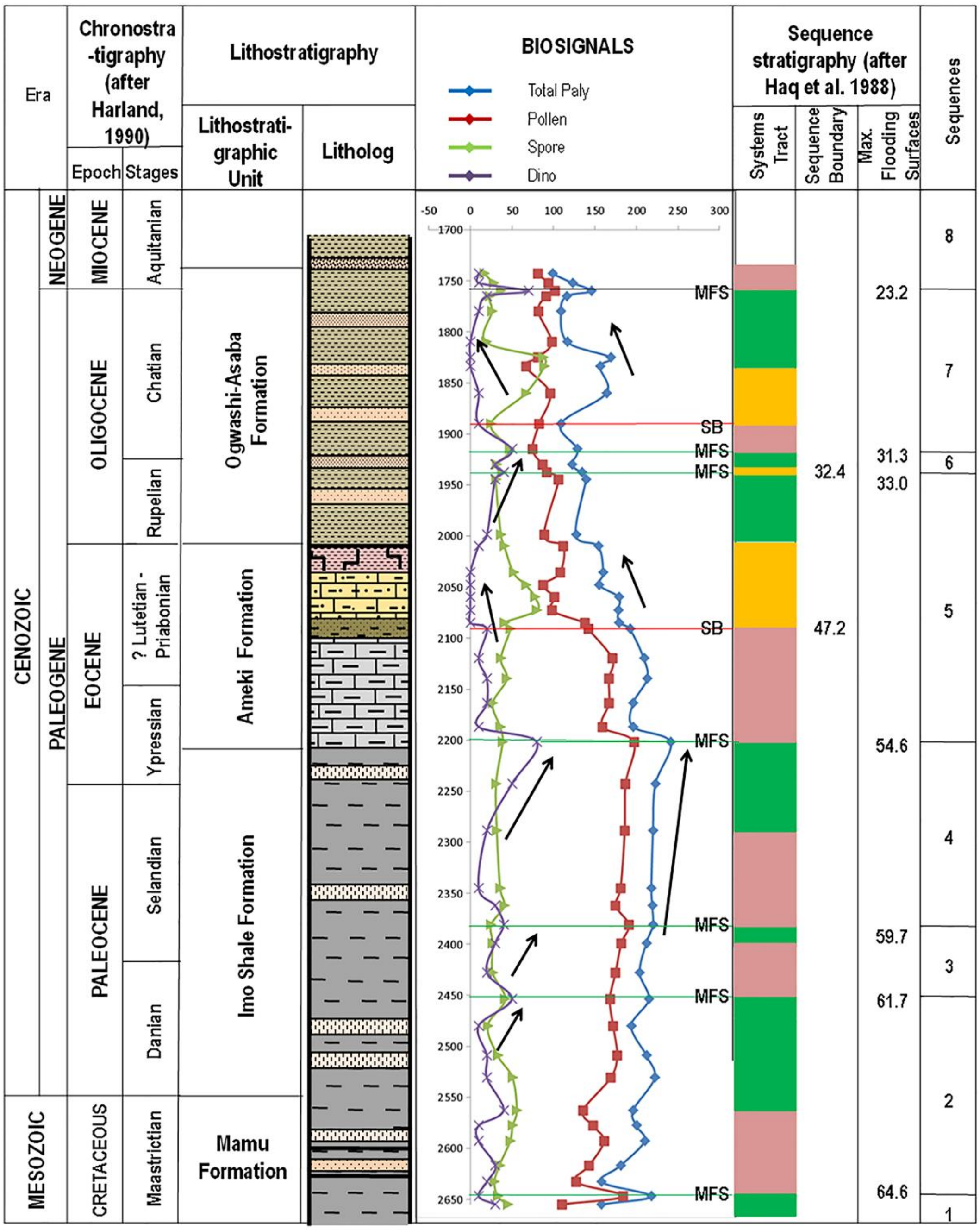

Fig. 8. Quantitative depth plot of biosignals and associated sequence stratigraphic elements correlated with formations and age in the XEN-1 well

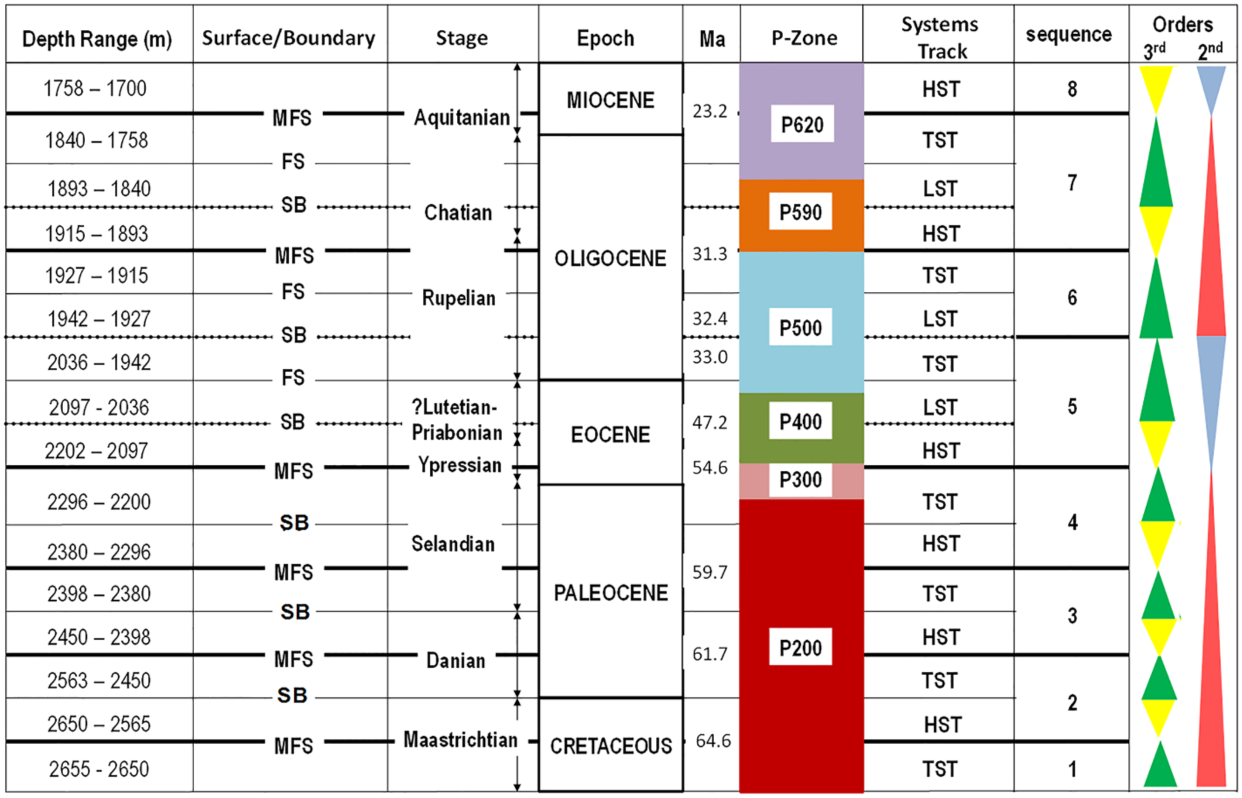

Fig. 9. Sequence stratigraphic summary sheet showing systems tract, major surfaces, Sequence, and P-zones. See Fig. 9, biosignal plot and sequence stratigraphic elements

Low stand systems tract biosignals

LST 1 - Biosignal from LST-1, shows dominance of savanna species (*Retibrevitricolporites-obdoensis, Arecipites sp., Proteacidites sp., Retidiporites sp.* and *Monoporitesannulatus,* etc.) over rainforest species. The interval also displays abundant verrucate spore species sand shallow marine dinocysts assemblages such as *Operculodiniumisrealianium, Polysphaeridium, Lingolodinium,* and *Selenopemphix sp*. (Fig. 6). These signals reveal a climate-driven sea-level change within this interval.

LST-2 - Present savanna ecological group composed of *Graminae, Arecipites sp*., indeterminate trilete spores, abundant *Laevigotosporites* species, and *Elaesguineensis*, a rainforest species, and freshwater swamp forest groups such as *Racemonocolpiteshians, Retitricolporites sp., Perfortricolpitesdigitatus, Magnatrititeshowardi,* and *Acrostrichumaureum* (Fig. 6). These species occur at different intervals in a cyclical pattern indicating a moderately wet and dry fluctuating paleoclimate in the Lower Oligocene (Mid Rupelian Stage) in this section of the well. The occurrence of *Lingolodinium* and different species of *Spiniferites* characteristic of shallow marine paleoenvironment, confirms a shallow marine paleodepositional setting for this interval.

LST-3 - displays a palynomorph assemblage characterized by initially reduced spore abundance relative to pollen at the lower section and a subsequent increase in spore and a reduction in pollen abundance (Fig. 8). Palynomorph species recovered from this interval include *Racemonocolpiteshians, Retitricolporites sp., Stereisporites sp., Gemmatricolpites,* and *Laevigatosporites sp* (Fig. 6).

Transgressive Systems Tract (TST): Seven TSTs were identified in the well, ranging from 2655 – 2650 m (TST-1), 2563 – 2450 m (TST-2), 2398 – 2380 m (TST-3), 2296 – 2200 m (TST-4), 2036 – 1942 m (TST-5), 1927 – 1915 m (TST-6) and 1840 – 1758 m (TST-7) capped by seven Maximum flooding surfaces.

These systems tracts have been defined based on an overall lithofacies which displays retrogradational parasequence stacking patterns, biosignal trend of high pollen and reduced spore percentages, the dominance of rainforest and freshwater swamp forest pollen species and representative pristine/phytane ratios (Pr/Ph) and biomarker ratio datasets (Table 2). Dense tropical vegetation is indicated by the abundance and increase of tropical rainforest pollen species, which may have evolved by wet and warm tropical climatic conditions. Similar studies in the Campos Basin, Brazil, using dinocysts species, indicated high salinity water and warm tropical climate conditions [56]. These infer warm global paleoclimate that probably occasioned the melting of polar ice which may have led to release of melt waters into the ancient seas with a consequent rise in eustatic sea-level leading to the global transgression that affected both the Anambra and Niger Delta Basins (Fig. 1) and some of their relatives in Brazil (e.g. Espírito Santo and Campos Basins).

5.3.1. Maximum flooding surfaces

The first MFS is established at 2650 m and marks the 64.6 Ma Late Cretaceous marine transgression events that deposited the Mamu Formation. The second MFS is at 2450 m and marks the 61.7Ma flooding event in the Danian stage (Early Paleocene) (Fig. 9). The third MFS is the 59.7Ma surface defined at 2380 m, formed during the Early Selandian Stage. The first three MFSs are within the P200 zone of Evamy *et al.* [3] (Fig. 10). Facies dislocation, which points to an abrupt deepening/shallowing and local palynomorph abundance/reduction appropriately interpreted, have been used to indicate the flooding surfaces of the various TSTs.

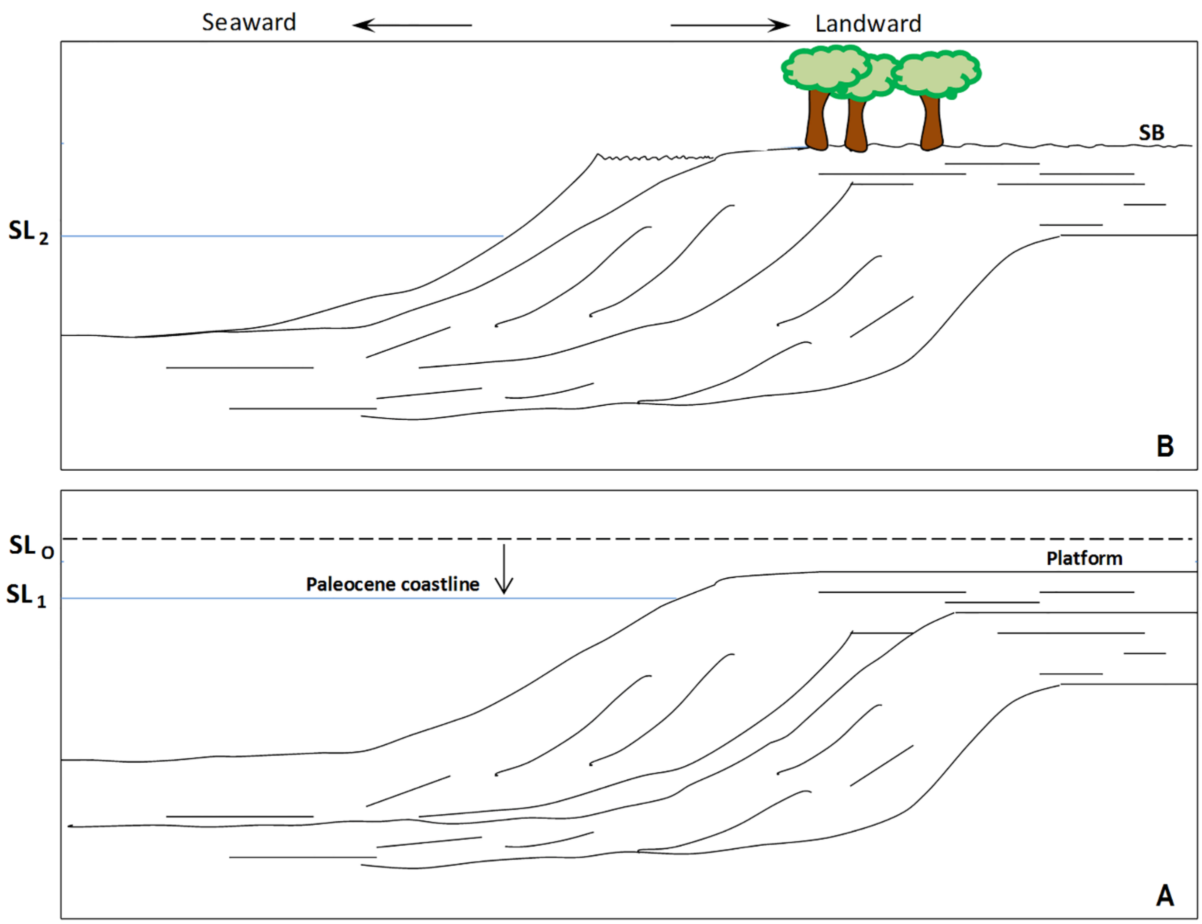

Fig. 10. Eocene-Oligocene paleogeographic conceptual model showing sea-level (SL) cycles during the formation of the Ameki Formation in the Benin Flank area as observed in XEN-1 well. (A) Transgression to highstand showing the relative fall in sea-level. (B) Lowstand, the rate of sedimentation > accommodation

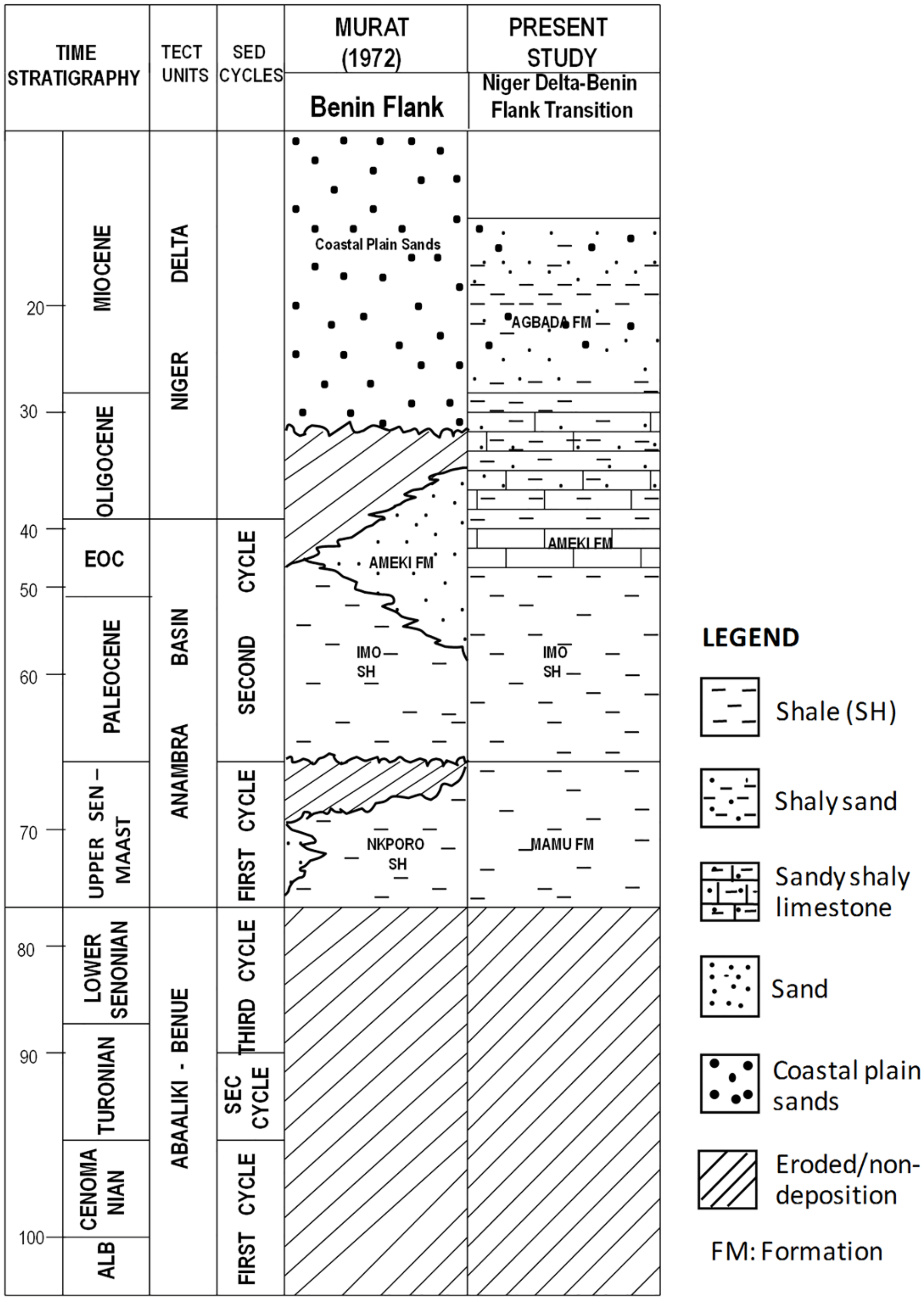

Fig. 11. A comparison of stratigraphic synopsis for Cretaceous and Tertiary formations of Murat [22] and present study in the Niger Delta-Benin Flank Transition from the Xen-1 well penetration

High Stand Systems Tracts: The six High Stand Systems Tracts, (HST) which exhibits a progradational and aggradational stacking pattern were established based on bio- and litho-facies, parasequence stacking pattern, and geochemical data.

Biosignal for these tracts shows a general higher abundance of pollen over spore in all the HSTs. *Spinizonocolpites echinatus* a mangrove forest species occur abundantly. Also, an abundance of *Verrucatosporites usmensis* and *Sporites verrucatus*, spores produced by several families of ferns were recorded, while *Arecipites exilimuratus*, *Laevigatosporites sp.*, and *Psilatricolporites sp.* produced by rainforest and mangrove vegetation (Fig. 6), indicate a warm wet climatic condition which has been variously correlated with sea-level high stand [57]. Shallow marine dinocysts taxa such as *Spiniferites ramosus*, *Homotriblium sp.,* and the freshwater algae *Cymatosphaera* were also recovered. These indicate HST formed in a shallow marine paleoenvironment.

6. Discussion

Results from paleodepositional proxies obtained for the well, indicate deposition in paleodepositional environments ranging from delta plain to shallow marine settings, and assigned ages ranging from Maastrichtian to Early Miocene. Paleodepositional interpretations show a close correlation with relative sea-level changes through time (Figs. 8 and 9), hence instrumental to the nature and type of sedimentary facies and architecture formed.

Results from age determination using an initially generated biozonation scheme for XEN -1 well [48], where the first and last occurrences and ranges of age-diagnostic palynomorphs were drawn, reveal some discrepancies in the age of the Ameki Formation identified in this study and age range presented by Murat [17] and Whiteman [22]. These discrepancies are shown by the sequence stratigraphic interpretations and correlations done for XEN -1 well, (Fig. 8). Integration of palynological signals from the lower sections of the well with lithofacies data, reflects a transgressing sea in a neritic paleoenvironment (Fig. 8) during the Late Cretaceous to Early Tertiary (Maastrichtian – Early Eocene), confirmed by sedimentologic, biosignal and geochemical proxies (Figs. 1, 5, 6, 7 and Tables 1 and 2). Similar sedimentation pattern was observed at the El Kef section by Molina *et al.*, [58], where marine sediments and sedimentation was continuous across the K-Pg boundary.

Lithofacies characteristics correlate the lowermost section of XEN-1 well with the Mamu Shale Formation, while the overlying section correlated with the Imo Formation known to be present in the Benin Flank area [17,22]. These interpretations are supported by palynological age data for this section (Figs. 5 and 11). The salinity index, parameter T10 shows decreasing trend up to the well (Table 1). This trend points to flooding of a platform area where a shallow marine condition probably existed and dilution of seawater was probably caused by fluvial incursion/influence. This view is also affirmed by the isoprenoid and n-alkane ratios for samples XEN2380 and XEN2545 (Figs. 7a and 7b, Table 2). The stratigraphic display revealed in this well supports presentation by Nwajide [4] that the Nsukka Formation is a proximal stratigraphic element, hence disappears in a proximo-distal direction, leaving the more marine Imo Formation resting unconformably on the Mamu Formation.

Towards the close of the Paleocene Transgression, the paleo-sea transgressed onto a sort of platform area (Fig. 10), during which time, strong fluvial influence on coastal deposystems still existed (XEN2420 and XEN2380 %C_{25} + n-alkane) (Figs. 8c and 8d, Table 1), and following which fluvial systems were probably driven landwards and a full marine condition established on the platform area, where carbonate forming biota subsequently thrived, (XEN2380 isoprenoid and n-alkane ratios, Fig. 7a, Tables 1 and 2).

The end-Paleocene transgression is capped by the 54.6 Ma MFS corresponding to Early Ypresian age, marking the end Cretaceous-Tertiary transgression event that affected the Northern Niger Delta Benin Flank area and marked the stratigraphic limit of the Imo Formation. The Imo Formation is overlain by the Ameki Formation in the northern parts of the Niger Delta Basin, interpreted to have been deposited in a deltaic and shallow marine paleoenvironment during the Eocene Regression that affected the coastal areas of southern Nigeria [22]. Murat [17] classed the Paleocene Imo and the Eocene Ameki Formation as part of the Anambra Basin. The Anambra Basin is a Cretaceous tectonic element; hence the stratigraphic limit of the Anambra Basin is the Cretaceous–Paleogene (K-Pg) boundary probably embedded in the lower section of the Nsukka Formation [4].

Systems tracts are predictive [59], and are reflected in the sedimentologic and biosignal characteristics. The transgressive systems tract at the lower section capped by the 54.6 Ma MFS, is overlain by a highstand systems tract interpreted from lithofacies characteristics between 2202 – 2097 m and capped by the 47.2 Ma sequence boundary at 2097 m in the well. Carbonate productivity varies with the sea-level change that can be identified in sequence stratigraphic interpretations of carbonate [60]. Wright and Burchette [60] noted a significant fact, that the bulk of carbonate sediment production occurs in the top 100 m of water column, with by far the highest production rates at depths of less than 20 m of water depth and that if submerged below these depths, rates of carbonate production and the ability of the carbonate system to cope with increases in relative sea-level are significantly impaired.

On most carbonate platforms, sediment production is greatest during sea-level highstands, when the whole platform surface is shallowly submerged (Fig. 10a), then during the intervening LST or transitional phases (Fig. 10b) [61-62], a phenomenon commonly termed 'highstand shedding' [63]. Observations based on sedimentologic, age and sequence stratigraphic interpretations in this present study are consistent with the Burchette and Wright [64], Haak and Schlager [61] and Schlager [62] model for carbonate production. The carbonate facies in XEN-1 well range from 2097 m to 2036 m (≈ 61 m thick). The lower part of this interval overlie the 54.6 MFS of the Early Eocene and is characterized by highstand systems tract carbonate facies, while the upper part is characterized by sandy shale, shaly carbonates and calcareous shale probably formed during carbonate "keep up" phase [65]. The lower part of the carbonate facies interval in XEN-1 well correlates with lithological descriptions of the lower part of the Ameki Formation, while the upper part correlates with the upper part of same formation [17,22]. Deductions based on the above data sets, shows that the lower section of the Ameki Formation in the northwestern area of the Niger Delta was formed in a carbonate platform that was established during a relative sea-level highstand regime in the Late Ypresian to Mid Eocene period (Fig. 10a), while the upper section is a product of a regressive sea level phase, also on a paleo-platform environment following sea-level highstand phase during the Late Eocene to Oligocene period (Figs 9 and 10). This interpretation contrast with conditions of deposition advanced by Murat [17] and Whiteman [22], who showed that the Ameki Formation was solely the product of the Eocene regression event, thus advanced a solely Eocene age for the formation, although Murat [22] without substantiating the Oligocene age limit with biostratigraphic data (Fig. 9), thinks that the age of the Ameki Formation may range from Eocene to Oligocene. Interpretations based on lithofacies and depositional cycles of sequences overlying the Ameki Formation in XEN-1 well shows that the Ameki Formation is overlain by the Agbada Formation. In this well, the section interpreted as corresponding to the Agbada Formation of the Niger Delta, range in age from Early to Late Miocene and overlies the Ameki Formation. This interpretation is also in contrast with interpretations based on Murat [22] stratigraphic synopsis of the Benin Flank, which shows an unconformity spanning the Late Eocene to Oligocene periods over the Ameki Formation and subsequent deposition of the Coastal Plain Sands (Benin Formation) (Fig. 11).

In the central Anambra Basin and eastern areas of the Benin Flank, the Mamu Formation is shown to overlie the Nkporo Shale; while the Ajali Sandstone Formation and Ajali type sandstone in the Fuga area, overlies the Mamu Formation, respectively [4]. A slightly different Late Cretaceous lithostratigraphic succession is observed in the western area of the Benin Flank [17,22]. Murat [22] showed an unconformity overlying the lower Senonian Araromi Shale, correlated with the Nkporo Shale and then deposition of the Paleocene-age Imo Formation (Fig. 11).

In this study, the Late Cretaceous sediments interpreted to correspond with the Mamu Shale are directly overlain by the Imo Formation, with no intervening erosional surface in the form of a sequence boundary or period of non-deposition. Biosignal and lithofacies characteristics from this interval show a Late Cretaceous-Tertiary transgression punctuated by periods of sea-level still stands reflected as highstand systems tracts and renewed rise in sea-levels, reflected as transgressive systems tracts (Fig. 9). Late Cretaceous palynomorphs species abound at the lower section and directly overlain by sediments yielding Early Paleocene species (Fig. 6), which correlates with the Paleocene-age Imo Formation. This fact highlights the limitation of the use of erosional surfaces as sequence boundaries [66], especially in the Niger Delta Basin [44].

7. Conclusions

Data presented in this work has shown that Cretaceous-Tertiary lithostratigraphic transitional events were controlled dominantly by major rising relative sea-level changes that transcended the K-Pg boundary and terminated in the Ypressian, driven by warm climatic conditions. This event created the Late Cretaceous Mamu and Paleocene Imo Formation and was mainly characterized by short sea-level rise pulsations deciphered through systems tract analysis. This could further be used to partly articulate the deposition of the Nsukka Formation in other parts of the Anambra Basin, although not present in this well location.

Integrated sequence stratigraphic results from this study support a Paleocene-Eocene (Ypressian) age range for the Imo Formation. Also, the integrated approach adopted in this work has shed more light on prevalent sea-level conditions under which the Ameki Formation was formed. It shows that the lower lithologic section was formed during a relative sea-level still stand/highstand phase, while the upper lithologic unit was formed as a regressive wedge (LST). The K-T lithostratigraphic transitional events were controlled essentially by third-order sea-level rise that transcended the K-T boundary, hence characterized by marine shale facies.

Acknowledgments

Special thanks to Shell Petroleum Development Company (SPDC) Nigeria for providing the ditch-cuttings of one her wells in the northwestern Niger Delta used for the study and the Tertiary Education Trust Fund (TETFUND) for providing research grants for the laboratory analysis through the Federal University of Petroleum Resources, Effurun (FUPRE) Nigeria. Special thanks to the management and staff of Fugro Robertson Petroleum Geochemistry Laboratory Llandudno, North Wales, United Kingdom, especially Dr. Lucy Costa and Dirby Vosper who have assisted in the geochemical analysis. We also wish to thank the Department of Earth Sciences, FUPRE for making her Laboratories available for the palynological analysis.

References

[1] Wiltshire J and Wright S. Pre-salt of West Africa, twin or distant relative of Brazil sub-surface? Gaffney and Cline Associates, 2016.
[2] Short KC and Stauble AJ. Outline of Geology of Niger Delta. AAPG Bull, 1967; 51: 761-779.
[3] Evamy DD, Haremboure J, Kamerling P, Knaap WA, Molloy FA and Rowlands PH. Hydrocarbon habitat of Tertiary Niger Delta. AAPG Bull, 1978; 62: 1-39.
[4] Nwajide CS. Geology of Nigeria's Sedimentary Basins. CSS Bookshops Ltd, Lagos, Nigeria, 2013.
[5] Mbuk IN, Rao VR and Kumaran KPN. The Upper Cretaceous-Paleocene boundary in the Ohafia-Ozu Abam area, Imo State. J. Mining and Geology, 1985; 22: 105–113.
[6] Alvarez LW, Alvarez W, Asaro F and Michel HV. Extra-terrestrial cause for the Cretaceous–Tertiary extinction: experimental results and theoretical interpretation. Science, l980; 208: 1095–1108.
[7] Bohor BR. A sediment gravity flow hypothesis for siliciclastic units at the K/T boundary, northeastern Mexico. In: Ryder G, Fastovsky D and Gartner S (eds) The Cretaceous–Tertiary Event and other Catastrophes in Earth History. Geol Soc Am, Special Paper, 1996; 307: 183–196.
[8] Keller G, Lopez-Oliva JG, Stinnesbeck W, and Adatt T. Age, stratigraphy, and deposition of near-K/T siliclastic deposits in Mexico: Relation to bolide impact? Geol Soc Am Bull, 1997; 109: 410–428.
[9] Tsujita C. Coincidence in the geological record: from clam clusters to Cretaceous catastrophe. Canad J Earth Sci, 2001; 38: 271–292.
[10] Alvarez W. Comparing the evidence relevant to impacts and flood basalts at times of major mass extinctions. Astrobiology, 2003; 3: 153–161.
[11] Schulte P, Stinnesbeck W, Steuben D, Kramar U, Berner Z, Keller G and Adatte T. Multiple slumped? Chicxulub ejecta deposits with iron-rich spherules and quenched carbonates from the K/T transition, La Sierrita, NE Mexico. Int J Earth Sci, 2003; 92: 114–142.
[12] Keller G, Adatte T, Berner Z, Harting M, Baum G, Prauss M, Tantawy AA and Stueben D. Chicxulub Impact predates K–T boundary: New evidence from Brazos, Texas. Earth and Planet Sci let, 2007; 255(3-4): 339–356.
[13] Schulte P, 40 Others. The Chicxulub asteroid impact and mass extinction at the Cretaceous–Paleogene boundary. Science, 2010; 327: 1214–1218.

[14] Keller G. The Cretaceous–Tertiary Mass Extinction: Theories and Controversies, in, Keller G and Adatte T, eds, The End-Cretaceous Mass Extinction and the Chicxulub Impact in Texas. SEPM Special Publication, 2011; 100: 7–22.
[15] Zachos JC, Arthur MA and Dean WE. Geochemical and paleoenvironmental variations across the Cretaceous/Tertiary boundary at Braggs, Alabama. Paleogeography, Paleoclimatology. Paleoecology, 1989; 69: 245-266.
[16] Self S, Blake S, Sharma K, Widdowson M and Sephton S. Sulfur and chlorine in Late Cretaceous Deccan magmas and eruptive gas release. Science, 2008; 319: 1654–1657.
[17] Murat RC. Stratigraphy and paleogeography of Cretaceous and Lower Tertiary in Southern Nigeria, in, Dessauvagie TFJ, Whiteman AJ, eds, African Geology. University Ibadan Press, Nigeria, 1972; 221– 266.
[18] Ogbe OB, Olobaniyi SB, Ejeh OI, Omo-Irabor OO, Osokpor J, Ocheli A and Overare B. Petrological and structural investigation of rocks around Igarra, southwestern Nigeria. Ife J Sci, 2018; 20 (3): 663–677.
[19] Corredor F, Shaw JH and Bilotti F. Structural styles in the deep-water fold and thrust belts of the Niger Delta. AAPG Bull, 2005; 89: 753–780.
[20] Nwajide CS and Reijers TJA. Sequence architecture in outcrops: examples from the Anambra Basin. NAPE Bull, 1996; 11: 23–32.
[21] Reijers TJA. Selected Chapters on Geology: Sedimentary geology and sequence stratigraphy in Nigeria and three case studies and a field guide. SPDC Corporate reprographic Services, Warri, Nigeria, 1996.
[22] Whiteman AJ. Nigeria: Its Petroleum Geology, Resources, and Potentials. Graham and Trotman, London, 1982.
[23] Agagu O and Ekweozor CM. Source rock characteristics of Senonian shales in the Anambra syncline, southern Nigeria. J Mining and Geology, 1982; 19: 132–140.
[24] Agagu OK, Fayose EA and Petters SW. Stratigraphy and sedimentation in the Senomian Anambra Basin of eastern Nigerian. J Mining and Geology, 1985; 22: 25–36.
[25] Ojoh K. Cretaceous geodynamic evolution of the southern part of the Benue Trough (Nigeria) in the equatorial domain of the south Atlantic: stratigraphy, basin analysis and paleogeography. Bull Centres Recherche Exploration Production, Elf-Aquitane, 1990; 14: 419–442.
[26] Burke K, Dessauvagie TFJ and Whiteman AJ. Openning of the Gulf of Guinea and the Geological History of the Benue Depression and Niger Delta. Nature Physical Sci, 1971; 233: 51-55.
[27] Reijers T.JA, Petters SW and Nwajide, CS. The Niger Delta Basin, in, Selley RC, ed, African basins. Sedimentary Basins of the World (Elsevier, Amsterdam), 1997; 3: 145–168.
[28] Weber KJ and Daukoru E. Petroleum geology of the Niger Delta. Proceedings of the Ninth World Petroleum Congress, 1975; 2: 209–221.
[29] Ejedawe JE. Patterns of incidence of oil reserves in Niger delta basin. AAPG Bull, 1981; 65: 1574–1585.
[30] Ejedawe JE, Coker SJL, Lambert-Aikhionbare DO, Alofe KB and Adoh FO. Evolution of oil-generative window and oil and gas occurrence in Tertiary Niger Delta Basin. AAPG Bull, 1984; 68: 1744–1751.
[31] Knox GJ and Omatsola ME. 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, 1987; 181–202.
[32] Reyment RA. Aspects of the geology of Nigeria. University of Ibadan press, Nigeria, 1965.
[33] Tattam EM. A Review of Nigerian Stratigraphy. Geol. Surv. Nigeria, 1944; 27-47.
[34] Petters SW. An ancient submarine canyon in the Oligocene-Miocene of the western Niger Delta. Sedimentology, 1984; 31: 805–810.
[35] Petter SW. Foraminiferal biofacies in the Nigerian rift and continental margin delta, in, Oti MN and Postma G, eds, Geology of Delta. A.A. Balkema, Rotterdam, 1995; 219-235.
[36] Nuhu GO. Analytical micropaleontology I interpreting paleoenvironment, stratigraphy and floral province of Upper Cretaceous sediments in the Middle Benue Trough, Nigeria. Abstract, 28th Annual Conference, Nig Mining and Geosci Soc., 1992.
[37] Agumanu AE. Diagenetic processes in sandstones of the Cretaceous southern Benue Trough. Nigeria. J Mining Geology, 1990; 26: 207–224.
[38] Ehinola OA, Ekweozor CM and Simonelt BRT. Geological and geochemical evaluation of Lafia-Obi coal, Benue Trough, Nigeria. NAPE Bull, 2000; 15: 92–104.
[39] Zaborski PMP. The Cretaceous and Paleocene transgressions in Nigeria and Niger. J Mining and Geology, 2000; 36: 153–173.

[40] Okoro AU and Nwajide CS. Petrography and mode of formation of the oolitic ironstone beds in the Campano-Maastrichtian Nkporo Formation in Leru, southeastern Nigeria. Global J. Geol Soc, 2008; 6: 57–62.

[41] Berggren WA. Paleocene biostratigraphy and planktonic foraminifera of Nigeria (West Africa). Proceeds 21st Int Geol Congress, Copenhagen, 1960; 6: 41-55.

[42] Ogbe FGA. Stratigraphy of strata exposed in the Ewekoro quarry, Western Nigeria, in, Dessauvagie TFJ and Whiteman AJ, eds, African Geology, University of Ibadan Press, Nigeria, 1972; 305-322.

[43] Arua AI. Episodic Sedimentation: An example from the Nkporo Shale (Campano-Maastrichtian). J Afri Earth Sci, 1980; 7: 72 –759.

[44] Reijers TJA. Stratigraphy and sedimentology of the Niger Delta. Geologos, 2011; 17 (3): 133–162

[45] Avbovbo AA. Tertiary lithostratigraphy of Niger Delta. AAPG Bull, 1978; 62: 295-306.

[46] Osokpor J and Ogbe OB. Facies evolution, paleodepositional environment and sequence stratigraphy of Tertiary sediments, northwestern Niger Delta Basin. Development J Sci and Tech Res, 2017; 6 (2): 9–24.

[47] Traverse A. Paleopalynology. Unwin Hyman, Boston, 1988.

[48] Osokpor J. Petroleum potentials, paleodepositional environment and sequence stratigraphy of Cretaceous-Tertiary sediments in parts of the Benin Flank & Niger Delta Basins. Unpublished PhD. Thesis, University of Benin, Nigeria, 2013.

[49] Osokpor J, Lucas FA, Osokpor OJ, Overare B and Izeze OE. Palynozonation and lithofacies cycles of Paleogene to Neogene age sediments in PML-1 well, northern Niger Delta Basin. Pacific J Sci and Tech, 2015; 16: 286 – 297.

[50] Sittler C. Illustration de l`histoiregeologique du fosse rhenan et de l`Alsace. – Recording the Rhine graben and Alsace history by sketched cross sections. N. JB. Geology of Paleontology Abh, 1992; 186: 255-282.

[51] Sittler C and Ollivier-Pierre MF. Palynology and palynofacies analysis: Some clues to assess and identify West-European Tertiary depositional environments in terms of relative high or lowstands: Application to the case of three Eocene and Oligocene sections in France. Elf Aquitaine Production F-64018, 1994; 475-487.

[52] Peters KE and Moldovan JM. The biomarker guide interpreting molecular fossils in petroleum and ancient sediments. Prentice-Hall, Englewood Cliffs, NJ, 1993.

[53] Peters KE, Walters CC and Moldowan JM. The biomarker guide: Biomarkers and isotopes in the environment and human history, Cambridge. Cambridge University Press, 2005; 1: 471

[54] Harland R. Distribution maps of Recent dinoflagellate cysts in bottom sediments from North Atlantic Ocean and adjacent seas. Paleontology, 1983; 26: 321-387.

[55] Van der Zwan CJ, Van de Laar JGM, Pagnier HJM and Van Amerom HWJ. Palynological, ecological and climatological synthesis of the Upper Carboniferous of the well De Lutte-06 (East Netherlands). Comptes rendus XII ICC-P, 1993; 1: 167-186.

[56] Santos A, Carvalho MA, de Oliveira AD and Filho JGM. Paleoenvironmental changes and influence on Operculodinium centrocarpum during the Quaternary in the Campos Basin, southwestern Brazil. J South Am Earth Sci, 2017; 80: 255–271.

[57] Poumot C. Palynological evidence for eustatic events in the tropical Neogene. Bulletin des Centers de Recherches Exploration-Production, Elf Aquitaine, 1989; 13: 437-453.

[58] Molina E, Gonzalvo C, Ortiz S, and Cruz LE. Foraminiferal turnover across the Eocene–Oligocene transition at Fuente Caldera, southern Spain: No cause–effect relationship between meteorite impacts and extinctions. Marine Micropaleontology, 2006; 58: 270 – 286.

[59] Posamentier H and Allen G. Siliciclastic sequence stratigraphy – concepts and applications. SEPM Concepts in Sedimentology and Paleontology, 1999; 7: 210

[60] Wright VP and Burchette TP. Shallow-Water Carbonate, in, H. G. Reading, ed., Sedimentary environments: Processes, Facies and Stratigraphy. Blackwell Sci, 1996; 325-394.

[61] Haak AB and Schlager W. Compositional variations in calciturbidites due to sea-level fluctuations, Late Quaternary, Bahamas. Geologische Rundschau, 1989; 78: 477–486.

[62] Schlager W. Depositional bias and environmental change – important factors in sequence stratigraphy. Sedimentary Geology, 1991; 70: 109-130.

[63] Schlager W, Reijmer JJG and Droxler A. Highstand shedding of carbonate platform. J Sedimentary Res, B64, 1994; 270-281.

[64] Burchette TP and Wright VP. Carbonate ramp depositional deposits. Sedimentary Geology, 1992; 79: 3-57.

[65] Schlager W. Carbonate Sedimentology and Sequence Stratigraphy. Tulsa: SEPM (Society for Sedimentary Geology). SEPM Concepts in Sedimentology and Paleontology, 2005; 8: 200.

[66] Galloway WE. Genetic Stratigraphic Sequences in Basin Analysis 1: Architecture and Genesis of Flooding-Surface Bounded Depositional Units. AAPG Bull, 1989; 73 (2): 125–142.

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