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A Re-evaluation of the Stratigraphic and Palaeogeographic Evolution of the Paleogene Sedimentary Successions of the Niger Delta

Ogechi Ekwenye[1*], Kingsley Okeke[1], Gloria Otosigbo[2], Ogechukwu Onyemesili[3]

[1]*University of Nigeria, Department of Geology, Nigeria.*
[2]*Alex Ekwueme Federal University, Department of Geology, Nigeria.*
[3]*Chukwuemka Odumegwu Ojukwu University, Department of Geology, Nigeria.*

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Abstract

A critical evaluation of the stratigraphic and paleogeographic evolution of the Paleogene sedimentary successions shows three cycles of sedimentation that are controlled by coastal morphology, basin bathymetry, sediment supply, hydrodynamic processes (dominantly tidal and wave/storm actions), and relative sea-level changes. Early Eocene Imo Formation is of a shallow-marine tidally-influenced environment. Middle Eocene – Late Eocene Ameki Group indicates a continental-marginal marine (estuarine) setting, and Oligocene Ogwashi Formation represents a tidally-influenced coastal-plain environment. Sequence stratigraphic models indicate four major depositional sequences of fluvial, estuarine, coastal-plain and shallow-marine environments that were bounded by unconformities linked to type-1 sequence boundaries (SB1 to SB4), during the Cenozoic. Four systems tracts consisting of the falling-stage systems tract (FSST), the low-stand systems tract (LST), the transgressive systems tract (TST) and the high-stand systems tract (HST) were established. The sequences and systems tracts indicate dominant progressive progradation with periodic retrogradation and aggradation of the Niger Delta Basin sediments. The Paleogene relative sea-level movements in south-eastern Nigeria indicate relative sea-level changes around southern Africa suggesting global relative sea-level fluctuations.

Keywords: Sequence stratigraphy, depositional environments; relative sea-level changes; paleogeography; Paleogene, Niger Delta.

1. Introduction

Several studies which encompass sedimentology, palynology, biostratigraphy, geochemistry, clay and heavy mineral analyses of the Paleogene sedimentary successions in south-eastern Nigeria showed that the strata are mainly of marginal to shallow-marine environments, with occasional fluvial deposition (Reyment, 1965; Adegoke, 1969; Arua, 1986, 1980; Nwajide, 1980, 2013; Anyanwu and Arua, 1990; Oloto, 1984; Oboh-Ikuenobe et al., 2005; Ekwenye et al., 2014, 2015, 2017; Ikegwuonu and Umeji, 2016; Okeke and Umeji, 2016; Ekwenye and Nichols, 2016). However, there are few documented papers on detailed paleogeographic and sequence stratigraphic evolution of the Cenozoic Niger Delta Basin (Oboh-Ikuenobi et al., 2005; Odunze and Obi, 2011; Ekwenye et al., 2017). Oboh-Ikuenobi et al. (2005) focused their study on the Umuahia and environs which is part of the southern region of the study area. Their work focused on the five depositional sequences of the Paleogene and the influence of relative sea- level fluctuations on the depositional cycles. However, no depositional models and relative sea- level curves were constructed to give a visual and deep understanding of the Paleogene paleogeography. Odunze and Obi (2011); Ekwenye et al. (2017) documented and reconstructed the sequence stratigraphic framework of the Imo Formation and Ameki Group respectively.

The need to understand the paleogeography from Paleocene to Oligocene has necessitated a new insight into the stratigraphic successions of Paleogene sediments of south-eastern Nigeria which includes a systematic review of the environment of deposition, palaeocurrent and heavy mineral analyses. In this regard, a paleogeographic evolution is reconstructed, and the relative sea-level changes and the sequence stratigraphic framework of the Paleogene strata are established.

2. Tectonic Setting of The Niger Delta Basin

Tectonic evolution of the Niger Delta basin is closely related to that of the Nigerian Benue. The Niger Delta Basin is geographically situated in the Gulf of Guinea and delineated by latitudes 3° and 6°N and longitudes 5° and 8°E (Nwajide, 2013; Figure 1). The basin is bounded to the west by the Okitipupa Ridge and demarcated from the Anambra Basin to the north by an unconformity. The eastern limit is defined by the Cameroun volcanic line, while the southern limit is the Guinea Abyssal plain. The establishment of the Niger Delta Basin followed the subsidence of the southern area of the Benue Trough during the Danian as a result of thermal contraction of the lithosphere (Sleep, 1971, Turcotte, 1977, Onuoha, 1981, Nwajide, 2013). According to Nwajide (2013), this subsidence induced major marine transgression of the Early Paleocene that paved the way for the accumulation of the basal beds of the Niger Delta basin.

* Corresponding author e-mail: ogechi.ekwenye@unn.edu.ng

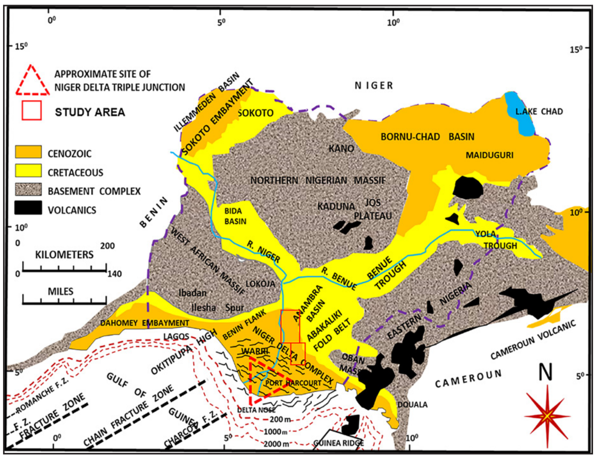

Figure 1. Structural map of the Nigerian Sedimentary Basin showing the chain and Charcot oceanic fracture zone (modified after Murat, 1972).

3. Stratigraphic Setting

The stratigraphic history of south-eastern Nigeria is characterized by three sedimentary phases (Short and Stäuble, 1967; Murat, 1972; Obi et al., 2001) during which the axis of the sedimentary basin shifted. These three phases are: (a) the Abakaliki-Benue phase (Aptian-Santonian), (b) the Anambra-Benin phase (Campanian- Early Palaeocene), and (c) the Niger Delta phase (late Paleocene-Pliocene). The resulting succession of the Niger Delta consists of the Paleogene system which is comprised of the Imo Formation, Ameki Group, and Ogwashi Formation (Figure 2), with a composite thickness of about 3,500 m. The succession begins with the transgressive Imo Formation (Paleocene) consisting of blue-grey clays, shallow-marine shale and sandstone, limestone and calcareous sandstone. The Imo Formation (Reyment, 1965) is the oldest outcropping lithostratigraphic unit of the Niger Delta Basin which is laterally equivalent to the Akata Formation in wells. The type locality of the Imo Formation is at the Imo River with a thickness estimated as 1000 m (Reyment, 1965).

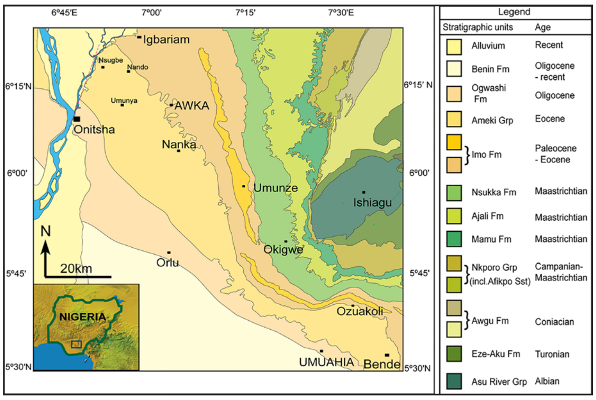

Figure 2. Geologic map of south-eastern Nigeria showing the Paleogene formations.

The Ameki (Ibeku Formation of Ekwenye, 2014), Nanka and Nsugbe formations are the lateral equivalents of the Ameki Group (Nwajide, 1980) the formation conformably overlies the Imo Formation. Reyment (1965) described the type locality of the formation between miles 73 to 87 along the section left behind during the eastern railway construction at Ameki Town. The Ameki Formation, which is composed of rapidly alternating shale, sandy shale, mudstone, clayey sandstone (Adegoke et al., 1980; Arua, 1980; Anyanwu and Arua, 1990) and fine-grained fossiliferous sandstone with thin limestone beds (Reyment, 1965; Arua, 1986), represents most of the Eocene. The age of the formation has been variously considered to be Early Eocene (Reyment, 1965) and Early Middle Eocene (Lutetian) (Berggren, 1960; Adegoke, 1969).The depositional environment has been interpreted as estuarine, lagoonal, and open marine, based on the faunal content. White (1926) interpreted an estuarine environment for the formation because of the presence of certain fish species of a known estuarine affinity. Adegoke (1969), however, indicated that the fish were probably washed into the Ameki Sea from inland waters, and preferred an open marine depositional environment. Nwajide (1980) and Arua (1986) suggested environments that ranged from nearshore (barrier ridge-lagoonal complex) to intertidal and subtidal zones of the shelf environments, whereas Fayose and Ola (1990) suggested that the sediments were deposited in marine waters of depths between 10 m and 100 m. Ekwenye et al. (2017) used the concept of facies analysis and sequence stratigraphy to suggest a tide-dominated estuarine system for the Ameki Group.

The Ogwashi Formation, previously known as Lignite Series (Parkinson, 1907), overlies the Ameki Group conformably with a type locality in Delta State. The Formation correlates with the upper Agbada Formation which is regarded as the down-dip extension of the outcropping Ogwashi Formation, while the lower Agbada Formation correlates with the Ameki Group (Short and Stäuble, 1967). The Ogwashi Formation (Eocene-Oligocene) is comprised of an alternation of coarse-grained sandstone, lignite seams, and light-colored clays of continental origin (Kogbe, 1976). Although Reyment (1965) suggested an Oligocene-Miocene age for the formation, a palynological study by Jan du Chêne et al. (1978) yielded a Middle Eocene age for the basal part of the Ogwashi Formation. Ekwenye and Nichols (2016) proposed a tidally-influenced coastal-plain deposit for the Ogwashi Formation due to the high degree of bioturbation in the basal matrix-supported conglomerate and sandstone facies.

4. Palaeoenvironment of Deposition

The palaeoenvironments of the Paleogene successions of the Niger Delta Basin reveal the interplay of sea-level fluctuations, sediment supply, tide, wave, and storm dynamics during the sedimentation of the Imo Formation, Ameki Group, and the Ogwashi Formation (Figure 3). Although, many variable palaeoenvironmental interpretations exist in the literature for the Paleogene strata; there is a need to harmonise them by integrating research studies on the sedimentology, palynology, and stratigraphy of the Paleogene successions.

The Imo Formation: Littoral to neritic conditions were suggested by Arua, 1980; Anyanwu and Arua, 1990 based on faunal assemblages; foreshore and shoreface zones of beaches and bars (Stevens et al., 2011), while a middle to outer neritic-zone conditions were deduced by Okeke and Umeji (2016) based on the abundance of gonyaulacacean cysts for the Imo Formation. The Costacalista adabionensis

(Adegoke, 1977) along with other foraminiferal and ostracod species (Reyment, 1965; Nwajide, 2013) as well as a shelf to shoreface (shallow marine) setting (Oboh-Ikuenobi et al., 2005) support a neritic environment. A littoral zone is a marginal-marine environment, while the neritic zone is a shallow-marine environment extending from mean low water down to 200-metre depth. Doust and Omatsola, (1990) indicated a high occurrence of microflora and marine planktonic foraminifera, in which foraminifera constitute more than 50% of the microfaunal assemblages suggestive of a shallow-marine shelf deposition. A dominantly shallow-marine shelf deposit for the Imo Formation is also supported by (Ekwenye et al., 2014) who recognized four depositional styles for all the lithofacies components of the formation viz offshore (shelf) shale (Facies association (FA) 1,5), tidal sand waves sandstone (FA 2), shoreface–foreshore (FA 3), and fluvial sandstone (FA 4) (Figure 4).

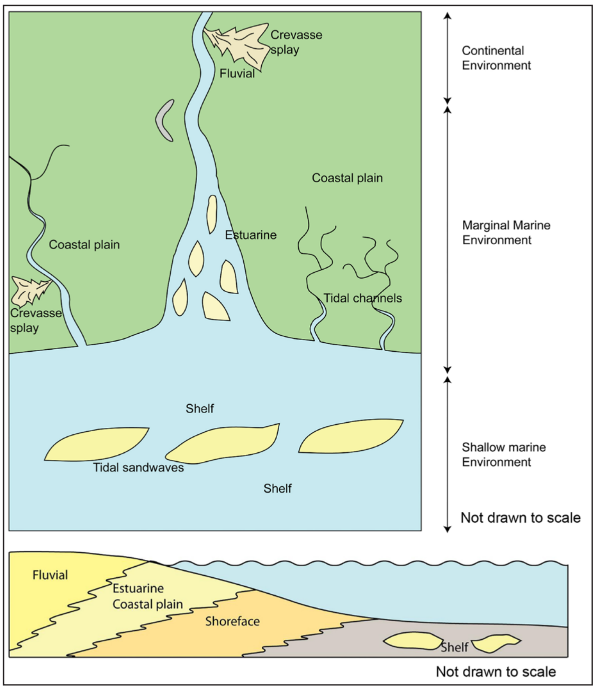

Figure 3. Conceptual model of the various depositional environments that dominated the Niger delta Basin (surface outcrop) during the Paleogene.

Ameki Group: Reyment (1965) suggested a partly marine and partly non-marine to estuary setting, and Adegoke (1969) suggested a shallow-marine setting for the Ameki Formation. This was supported by Ekwenye et al. (2017) who interpreted the Ameki Group as the tide-dominated estuarine system. Similarly, Nwajide, 1980 and Nwajide and Reijers, 1996 unravel the tidal sedimentation of the Ameki and suggested a tidal-influenced environment. The presence of the Pappocetus lugardi invertebrate fauna, foraminifera with Turritella and Siphonochelus nigeriensis invertebrate gastropods exemplifies a tropic shallow marine for the Ameki Formation (Nwajide, 2013). Alternating coastal and inner neritic conditions was recorded by (Okeke and Umeji, 2016) due to the diversity and abundance of terrestrial over marine palynomorph taxa in the formation. According to Okeke and Umeji (2016), the middle to outer neritic taxa are Adnatosphaeridium multispinosum, Hystrichokolpoma rigaudiae, Heteraulacysta pastulata, Eocladopyxis peniculata, Achilleodinium biformoides, Muratodinum fimbriatum. Alternating coastal and inner neritic conditions confirms the partly-marine and partly non-marine settings which are typical of estuarine environments. The dominance of tidal actions during the Eocene implies a tide–dominated estuarine for the Ameki Group.

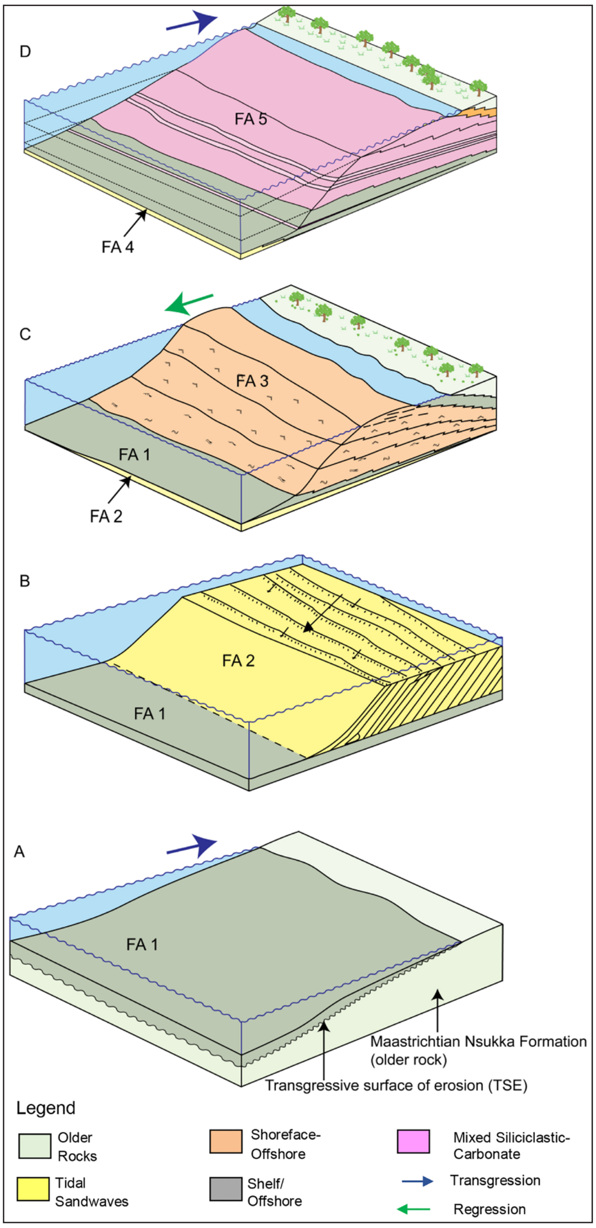

Figure 4. Depositional stages of the Imo Formation showing the **(A)** offshore shale facies (FA 1) which represented a major transgression in the Late Paleocene. **(B)** Tidal sandwaves (FA 2) deposited by an unidirectional tidal current in an offshore environment, whereby the sandwave deposit is encased by the offshore shale (FA 1) (see figure 4c). **(C)** The prevalence of wave action over tides led to the deposition of progradational coarsening-upward succession. Medium to pebbly sandstone. A lagoonal deposit occurs at the backshore. **(D)** A return to transgression is obvious with the deposition of mixed siliciclastic–carbonate sediments in a shelf setting, followed by a highly bioturbated sandstone with mono-specific Thalassinoides boxwork pattern (modified after Ekwenye, 2014; Ekwenye et al., 2015).

Ogwashi Formation: The integrated palynological and sedimentological analysis of the Ogwashi Formation (Umeji, 2003) is indicative of progradational shoreline palaeoenvironments; oscillating between the lower brackish water and upper (fresh water) deltaic plain. Detailed lithofacies and outcrop studies of exposures (Ekwenye and Nichols, 2016) illustrate tidally influenced coastal-plain environments for the formation. Sub-environments such as fluvio-estuarine channels, tidal channels, tidal flats, coastal-plain channels, and coastal flood plain with mire are deposited in the tidally-influenced coastal-plain settings. An upper flood-plain environment was assigned by Nwajide (2013) while Okezie and Onuogu, 1985 attributed the lignite as a product of tropical to semi tropical plants with palm particles. In the southern part of the Ogwashi Formation around Umuahia (Ikegwuonu and Umeji, 2016) noted the occurrence of Monoporites anulatus a savannah pollen, Psilastephanocolporites laevigatus of tropical lowland evergreen forest and Proxapertites operculatus, Longapertites marginatus and Psilatricolporites crassus palmae pollen of brackish water swamp. These indicate palynomorph assemblages of the upper deltaic and lower deltaic-plain environment in conformity with the works of Umeji, (2002). The basal units of Ogwashi Formation is bioturbated matrix-supported conglomerates or conglomeritic sandstones which are typical of coastal-plain channels that are tidally-influenced. Reyment (1965) referred the Ogwashi Formation to coastal-plain deposits. Typically, a delta coarsens upward from prodelta shales to the delta front and delta-plain channels and bay-fills, but these depositional facies were not observed in the Ogwashi lithologic succession.

5. Discussion

5.1 Paleogeographic Evolution of the Paleogene Strata

The paleogeography of the south-eastern Nigeria is linked to the Cretaceous sedimentation that ended with the Maastrichtian-Paleocene Nsukka Formation, also referred to as the upper Coal Measures. Sedimentation ended in the Anambra Basin with the Nsukka Formation (Nwajide, 2005), and this is marked by the Paleocene unconformity.

Stage 1: Paleocene - Early Eocene

During the Paleocene, marine conditions were created due to a major relative sea-level rise (Nwajide, 2005; Oboh-Ikuenobe et al., 2005; Whiteman, 1982), which resulted in an increased accommodation, but the low supply of siliciclastic sediments led to the deposition of the offshore shales of the Imo Formation (Figure 5A) that is considered to be the oldest strata in the Niger Delta sedimentary Basin regime (Petters, 1991). Evamy et al. (1978) noted the deposition of marine shales in most of the southern Nigerian basin during the Paleocene to early Eocene times. The Paleocene transgression is further supported by the presence of nontronite (clay mineral) in the offshore shales (Ekwenye, 2014), which signifies low sedimentation and sea level rise (Thiry and Jacquin, 1993). Furthermore, the presence of dinoflagellates, acritarchs, and foraminiferal test linings in the offshore shales are good indicators of shallow-marine conditions (Ekwenye, 2014). Terrestrial input is indicated by the occurrence of sporomorphs and freshwater algal cysts (Ekwenye, 2014). Subsequently, the predominance of tidal process, and the increase in sediment supply during the Paleocene are indicated by the deposition of thick tidal sand waves (Figure 4B). The tidal currents were strong enough to rework fluvio-deltaic sediments of the Nsukka Formation which formed the sand waves (Ekwenye et al., 2014). The large-scale cross bed foresets (10 - 20 m thick) trend dominantly towards a northwest direction, reflecting sand waves' migration related to the dominant tidal current. The sand waves are classified as quartz arenite, with the dominance of rounded to subrounded quartz grains (Ekwenye et al., 2014). The Cretaceous sedimentary rocks of the Anambra and Afikpo basins are considered to constitute a major recycled sedimentary source (Mode et al., 2019). Mode et al. (2019) demonstrated the presence of heavy minerals such as zircon, tourmaline and apatite, and medium to high-grade metamorphic minerals, which suggest a contribution from igneous and metamorphic sources as well. Kreisa et al. (1986) interpreted similar giant–scale (3 - 12 m) cross-bed sets such as the tidal sand waves' deposit of Rancho Rojo Sandstone in Arizona which they further suggested to be a tide-dominated transgressive shallow-marine environment.

Cessation of the incoming clastic sediments is indicated by the presence of intense bioturbation of the topmost unit of the tidal sand-wave deposit. The presence of monospecific Thalassinoides horizontalis (Ekwenye et al., 2014) suggests a stressed shallow-marine condition. These events may have occurred as a result of a pause in sedimentation and probably lowering of the sea level which ended the deposition of the sand waves. Similar relationships are recorded by Bottjer (1985), where the lowering of the sea level with a pause in sedimentation during the Cretaceous resulted in monospecific Thalassinoides burrow system at the contact between Marlbook Formation and Saratoga Formation in South western Arkansas. A subsequent rise in relative sea level and reduced clastic supply-initiated deposition of the offshore shale of the Imo Formation (Ekwenye et al., 2014) which encased the tidal sand waves. The interplay between sediment supply, relative sea-level changes and hydrodynamic processes affected the stratigraphic succession of the Imo Formation. The deposition of a coarsening upward succession of well-sorted, rippled laminated sandstone suggests a predominance of a wave action and influx of siliciclastics, which indicates progradation. Heavy mineral assemblages (Ekwenye et al., 2015; Mode et al., 2019) suggest a mixed provenance, and that sediments probably originate from pre-existing sedimentary and metamorphic rocks, most probably from the Oban massif (Figure 5B); input may also be derived from the West African massif. This substantiates Dickinson (1985) QtFL and the QmFLt ternary diagrams' interpretation which illustrate that the Paleogene sandstones are a product of mixed sources of cratonic interiors, transitional continental blocks, and recycled orogen, and transitional continental as well as transitional recycled and quartzose recycled origins respectively.

A lagoonal deposit capped the first depositional sequence of the Imo Formation as a result of progradation. The second sequence commenced with coarse-grained sandstone (indicating regression) which is overlain by shale, marl and a thin limestone layer. This suggests the presence of a transgressive period, which may have occurred during the early Eocene. At the onset of the transgression, the Niger Delta Basin became a shelf in which a marine succession (marl, fossiliferous shale facies and structureless calcareous sandstone with subordinate structureless non-calcareous sandstone, bioturbated sandstone and non-fossiliferous dark grey shale facies) was deposited; the deposition of these sediments suggested a pause in sedimentation due to a relative rise in sea level. According to Ekwenye et al. (2014), clay mineral analysis of the Imo Formation indicates the presence of nontronite, illite and kaolinite. Nontronite and illite are common in marine environments, while kaolinite indicates a terrestrial input during transgression. The relatively moderate occurrence of palygorskite suggests a Ca-rich water condition which resulted in the deposition of marl, limestone and fossiliferous sandstone. Palygorskite occurs in a wide range of environments (Weaver, 1989); it is common in alkaline lakes and perimarine environments under arid to semi-arid conditions. It is also documented in deep ocean sediments, brackish-water conditions, and marine sediments.

Shallow-marine conditions prevailing with the deposition of fossiliferous sandstone with fossiliferous limestone layers in the upper Sandstone Member of the Imo Formation indicates the availability of clastic sediments during a gradual relative sea-level rise which created accommodation for clastic accumulation. The occurrence of marl and the fossiliferous nature of the clastic sediments are restricted to the southern part of the study area (Umuahia-Bende region) which indicates variability in sediment supply. Results of the heavy mineral analysis indicate that the most probable source area would be the Oban massif. The high occurrence of coarse-grained garnets is associated with a schistose lithologic unit of the Oban massif that includes quartz-mica schist, garnet-mica schist, garnet-sillimanite schist and kyanite-sillimanite schist (Ekwueme et al., 1991).

A strongly bioturbated fine-grained sandstone capped the Imo Formation in the Umuhia-Bende region. The burrows are dominated by monospecific Thalassinoides paradoxicus (Ekwenye et al., 2014). This suggests a gradual fall in relative sea level and a pause in clastic input that enabled the unit to be colonized by burrowing decapod crustaceans. The top of the horizon forms a major discontinuity surface (Bottjer, 1985; Pemberton et al., 2004) that demarcated the Imo Formation from the Ameki Group.

Stage 2: Middle Eocene – Late Eocene

The Ameki Group which consists of the Nsugbe, the Nanka and the Ameki (Ibeku) formations (that are lateral equivalent) were deposited from the Middle-Late Eocene. During the Middle Eocene, a relative sea-level fall resulted to incision, obvious in the north-eastern part of the study area, and subsequent infill led to deposition of multistorey channels (Ugwu-Nnadi quarry, Nsugbe (Ekwenye et al., 2017). The conglomerate to sandstone of the Nsugbe Formation may have originated from the Western Nigerian massif and pre-existing sedimentary rock: as indicated by the high proportion of euhedral and prismatic ultrastable heavy-mineral suites such as zircon, tourmaline and apatite (Ekwenye et al., 2015) associated with the Nsugbe Formation which suggests a close-by acidic igneous or plutonic source and a basic igneous source (Figure 5C). However, the presence of rounded grains indicates multiple cycles of reworking which was common with the pre-existing sediments. The trough and planar cross-stratified sandstone units have a general trend of south-west palaeoflow direction, indicating a northeast provenance. A subsequent rise in relative sea-level and a strong influence of tidal process created estuarine (brackish-water) conditions (Figure 5C) characterised by tidally-influenced fluvial channels, tidal channels, tidal flats, supratidal, and tidal sand bars in the Ameki Group (Ekwenye et al., 2017). Palynological studies record terrestrial and marine influences in the estuarine deposits. The palynology from the Nanka Formation is nearly barren, with only a terrestrial influence. However, results from Ibeku Formation shows a mixed terrestrial and a shallow-marine input. Furthermore, outcrops around the Aguchi and Awgbu area has Proxapertites spp., Longerpertites marginatus and Echiperiporites species, Wilsonidium nigeriense and Phthanoperidinium alectrolophum Homotryblium tenuispinosum, Homotryblium abreviatum at the onset of the Nanka Formation suggesting a low-saline neritic environment (Okeke and Umeji, 2016).

A similar incised valley succession is recorded in the Aspelintoppen Formation, Eocene Central Basin of Spitsbergen, where fluvial deposits pass upwards into macrotidal tide-dominated estuarine deposits (Plink-Björklund, 2005). Eriksson et al. (2006) also observed fluvial-tidally influenced estuarine sedimentation in high-relief zones of tectonic origin, in the Mesoarchean Moodies Group, South Africa, and they related the succession to absolute sea-level fluctuations. Modern macrotidal estuaries with similar depositional facies are recorded in Seine estuary and Mont-Saint-Michel Bay, English Channel, NW France (Tessier et al., 2011); Minas Basin (Yeo and Risk, 1981) and Cobequid Bay, Bay of Fundy (Dalrymple et al., 1990).

In the study area, the Nsugbe Formation is interpreted as a fluvial channel deposit and marine inundation which occurred over the fluvial deposits resulting in the deposition of tidally- influenced point bar deposits (Nanka Formation). The inclined heterolithic strata of this point bar deposit (Nanka Formation) trend in an eastward direction (with low dip angle of 7°-10°). The eastward direction signifies a dominance of flood tidal current, whereas a minor westward trending inclined heterolithic strata shows a subordinate ebb tidal current. The dominance of flood tidal current over the ebb current supports the interpretation as a tide-dominated estuarine system (Hovikoski et al., 2008). Heavy-mineral analysis (Table 1) of the tidally-influenced point bar suggests that more than 68-78% of the clastics are of acidic igneous or plutonic origins, whereas 20-32% of the clastics suggest a metamorphic origin (Ekwenye et al., 2017). This may imply that more sediment is shed from the granitic unit of the Western Nigeria massif, or that the ultrastable heavy minerals are more resistant to weathering and alteration. Tidal channels exhibit palaeocurrent trends in south-east and north-west directions. The sandstones are quartzarenites to lithicarenites. Heavy minerals (Table 1) from the tidal channel sandstones also show higher clastic input from the acidic igneous bodies. Tidal sand bar units are dominated by southwest trending paleocurrent directions. The sands are dominantly quartzarenites and the heavy-mineral interpretation suggest a more clastic input from the metamorphic source (65-68%) than the acidic igneous source

(25-32%). Variation in the proportion of the heavy-mineral suite may also be attributed to grain-size and hydraulic conditions (heavy minerals occur more in finer grain-size fractions), as well as differential weathering from the source areas.

The changes observed in the clay minerals in the tide-dominated estuarine complex probably suggest an interaction between the terrigenous source and marine-source clay minerals. Clay minerals from the Nanka Formation consist mainly of kaolinite and a mixed illite layer. Insignificant palygorskite and very a limited occurrence of montmorillonite (only observed in one sample) are present. The dominance of kaolinite and a mixed illite layer suggest a greater influence of terrigenous input. The presence of montmorillonite as well as chlorite in minor amounts signifies a marine influence due to a rise in sea level (Thiry and Jacquin, 1993; Weaver, 1989). The composition and distribution of these clay minerals is similar to those of the estuaries along the east coast of the United States though the abundances of the clay minerals differ (Weaver, 1989).

Table 1. Summary of the heavy minerals and their provenances (adapted from Ekwenye et al., 2015).

Formation	Environment of Deposition	Heavy Minerals (Zrn, Tur, Apt, Px) %	Heavy Minerals (Rt, Sil, Kyn, St, Ep)%	Source Area
Nsugbe	Fluvial channel	64.7-66.6%	33.4-35.3%	Mixed sources, but dominantly igneous origin
Nanka	Tidally influenced fluvial channel	68.2-78.5%	20.9-31.8%	Mixed sources, but dominantly igneous origin
Nanka	Tidal channel	54.4-66.8%	33.1-45.6%	Mixed sources, but dominantly igneous origin
Nanka	Tidal Flat	53.6-82.3%	17.2-46.4%	Mixed sources, but dominantly igneous origin
Nanka	Tidal sand bar	28.8-32.5%	67.5-67.8%	Mixed sources, but dominantly metamorphic origin

Stage 3: Oligocene

During the late Eocene, the estuary was filled up with the Ameki Group sediments, leaving a low topography and a low-relief landscape. Probably, the activation of the paleo-Niger River or a relative sea-level fall may have resulted in the fluvial incisions on the low topography coastal-plain environment during the Oligocene. The tidally-influenced coastal plain is considered to be controlled by relative sea-level changes based on the vertical variation in the facies and facies associations from marine to non-marine conditions. The clay mineral suites in the Ogwashi Formation are dominated by kaolinite and mixed layer illite which signifies a continental input. A similar composition, but with varying amounts of kaolinite and illite, which occurs in the Early to Middle Cenomanian sediments of the Iberian strait (Northern Spain) is interpreted as fluviatile and littoral deposits (Floquet, 1991). Results from heavy mineral interpretation indicate mixed proportions of suites of minerals from metamorphic and igneous rocks which suggests the dominant source area to be the Oban Massif, which is comprised of basement rock (metamorphic rock) and granite (igneous rock) with contributions probably from the Western Nigeria basement, as well as recycled sedimentary rocks based on the occurrence of rounded and subrounded grains.

Oboh-Ikuenobe et al. (2005) demonstrated from palynlogical studies that the Ogwashi Formation contains 20-60% unstructured phytoclasts, 14-21% structured phytoclasts, <10% amorphous organic matter (AOM), and 5% fungal remains, but contains no marine palynomorphs. In contrast, Okeke and Umeji (2016) and Okeke (2017) recorded dinoflagellate and acritarch dominated by “Homotryblium tenuispinosum (1%) at Ogbunike, H. abbreviatum, in association with Operculodunium centrocarpum, Cleistosphaeridium? aciculare, Leiosphaeridea sp. and trochospiral foraminiferal test lining from the Ogwashi Formation sections at the conspicuous Ogbunike section (formerly Ogbunike Tollgate). According to Okeke and Umeji, 2016, the marine species are indicative of low salinity near shore or a brackish water environment. However, palynological analysis of the Ogwashi Formation around Umuahia yielded pollen and spore species of Monoporites annulatus, Psilastephanocolporites laevigatus and Psilastephanocolporites, Pachydermites diederixiProxapertites operculatus, Longapertites marginatus and Psilatricolporites crassus. Alnipollenites verus, Schizosporis parvus (Spirogyra), Schizophacus spriggi, Ovoidites parvus, and Ulvella nannie suggestive of fresh-water upper deltaic to the lagoon and or brackish-water lower deltaic plain within the tropical lowland rainforests (Ikegwuonwu and Umeji, 2016). The depositional environment interpretation of Ikeguonwu and Umeji op.cit confirmed the non-marine influences documented by Oboh-Ikuenobe et al. (2005). It seems that the marine influences recorded in the Ogbunike domain by Okeke and Umeji Op.cit were absent around the Umuahia-Bende area or the strata were completely missed by the authors during the geological mapping. The high occurrence of unstructured phytoclasts dominated by AOM may be due to the influence of nearshore marine water. Oboh-Ikuenobe et al. (2005) further suggested that the Oligocene Ogwashi Formation is a non-marine succession. They disregard the presence of low diversity, but a high abundance of Skolithos ichnofacies was found in the basal conglomerate and coarse-grained sandstone of the Ogwashi Formation. The occurrences of Skolithos ichnofacies and the ensued paleoenvironmetal interpretation were validated by the marine taxa recorded by Okeke (2017). Okeke and Umeji (2016) which indicate marine influences in the Ogwashi Formation around the vicinity. MacEachern and Hobbs (2004) indicated that the presence of bioturbation in coarse- grained strata is indicative of a marine influence. Thus, the regressive Ogwashi Formation (Figure 5D) had minor marine inundation that resulted in the high level of bioturbation found in the basal units.

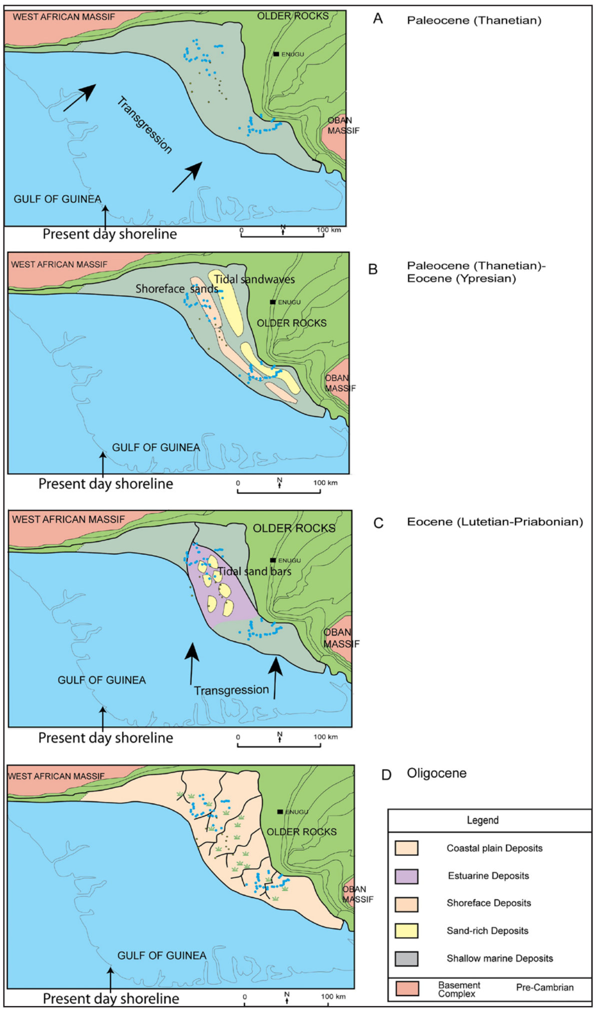

Figure 5. Paleogeographic evolution of the Paleogene strata, south-eastern Nigeria from Paleocene to Oligocene. **(A)** Paleocene transgression resulted in a shallow-marine condition that led to the deposition of bluish to dark grey shale facies interpreted as offshore shale (FA1). **(B)** Sediment influx from most probably pre-existing sedimentary rocks and Oban massif may have resulted in deposition of tidal sandwaves, shoreface/foreshore sandstone and fluvial channel in the Imo Formation. **(C)** Eocene sediments of the Ameki Group are dominantly derived from West African massif and recycled sedimentary rocks. A sea-level rise created an estuarine condition during the Eocene. **(D)** The Oligocene period witness a minor regression that resulted in coastal plain deposits with a minor transgression that led to the deposition of fluvio-estuarine sediments.

5.2 Sequence Stratigraphic Framework

Four depositional sequences are recorded for the Paleogene fluvial, estuarine, coastal-plain and shallow-marine depositional environments (Figure 3). The stratigraphic distribution and the facies' characteristics of the four depositional sequences are controlled by relative sea-level changes, as well as other controlling factors such as sediment supply, tidal processes and basin bathymetry. The cycle chart of the sea-level fluctuations is based mainly on the study of the stratigraphic succession of outcrops (Figure 6) and also contributions from other research works (Avbovbo and Ayoola, 1981; Oboh-Ikuenobe et al., 2005; Nwajide, 2005; Short and Stäuble, 1967). Four systems tracts were delineated: the falling-stage systems tract (FSST), the low-stand systems tract (LST), the transgressive systems tract (TST), and the high-stand systems tract (HST). However, the FSST deposits are not observed; the FSST corresponds to the sequence boundaries (SB 2 - 4).

The stratigraphic sequences are bounded by unconformities (type-1 sequence boundaries) as a result of relative sea-level changes. These sea-level changes can be correlated to other parts of the world (Figure 7). This is not an easy task though, due to the inadequacy of high-resolution chronological data for the study area. Despite this, the timing of the Paleogene sea–level movements around southern Africa (Siesser and Dingle, 1981) is observed to be approximately close to the timing established for sea-level changes in south-eastern Nigeria (Reyment, 1980; Reijers et al., 1997; Petters, 1995). Attempts have been made by Oboh-Ikuenobe et al. (2005) and Odunze and Obi (2011) to analyse the sequence stratigraphy in terms of the global sea- level curve of south-eastern Nigeria, but there are still inconstancies in the location of sequence boundaries, the interpretation of depositional facies and systems tracts.

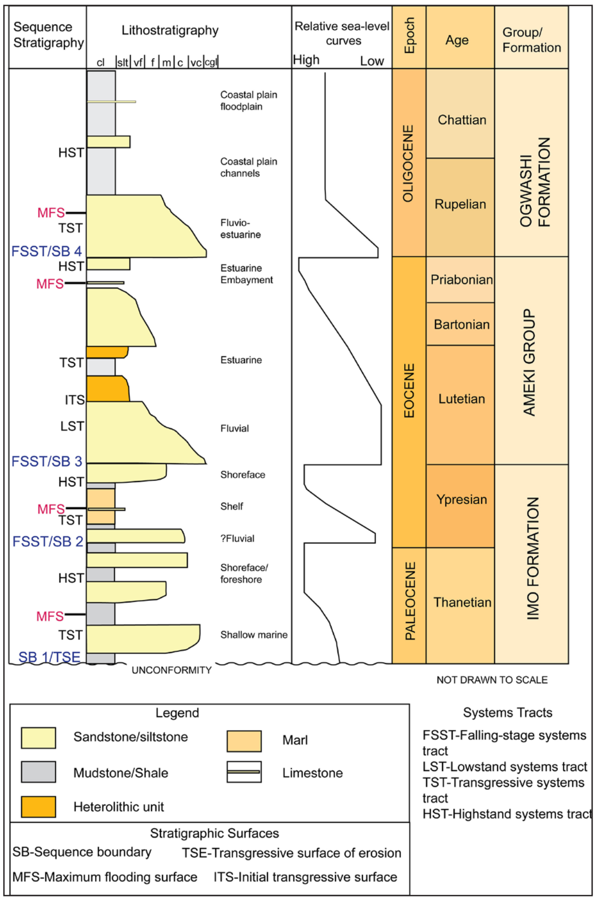

Figure 6. Sequence stratigraphic interpretation and relative sea-level changes of the Paleogene strata in south-eastern Nigeria.

5.2.1 Paleocene-Early Eocene Sequence

The first sequence boundary (SB1) occurs as an unconformity between the Nsukka Formation and the overlying Imo Formation (Avbovbo and Ayoola, 1981). The unconformity coincides with the transgressive surface of erosion which heralded the onset of a relatively rapid sea-level rise during the Paleocene. This Paleocene transgression initiated with the deposition of the offshore/shelf shale/ mudstone of Imo Formation. The transgressive surface of erosion (TSE) coincides with the first sequence boundary (SB1) (Figure 6). The lowstand deposit is absent in the first depositional sequence. The offshore/shelf shale/mudstone and tidal sand wave deposits signifies the transgressive systems tract, while the highstand systems tract is represented by shoreface-foreshore and lagoonal deposits. The Paleocene transgression in the study area is correlated to other regions of the world such as north-western and western Africa (Reyment, 1980), Argentina (Bertels, 1969), Brazil (Ponte and Asmus, 1978), South Africa (Siesser and Dingle, 1981) as well as in the northern and southern areas of eastern Europe and West Siberia as evidenced by the Peri-Tethys (Radionova et al., 2003). The Paleocene transgressions in southern Nigeria and South Africa are suggested to be as a result of tectono-eustacy or relative sea-level changes (Reyment, 1980; Reyment and Mörner, 1977; Siesser and Dingle, 1981; Oboh-Ikuenobe et al., 2005). The Imo Formation succession suggests that the Paleocene transgression continued into probably early Eocene times, with a minor regression pulse that resulted to the second sequence boundary (SB2). This long-term sea-level rise is related to the global sea-level fluctuations (Figure 7) as observed in the South African sea-level curve illustrated by Siesser and Dingle (1981). The regression resulted in a thin bedded, coarse to medium-grained sandstone (that represents fluvial deposits) which reflects a lowstand systems tract. An increase in relative sea-level resulted in the deposition of a thick succession of shale, marl with limestone layers (that represents shelf deposits) which represents the transgressive systems tract. The highstand systems tract is typified by coarsening upward fossiliferous sandstone (that represents shoreface deposits).

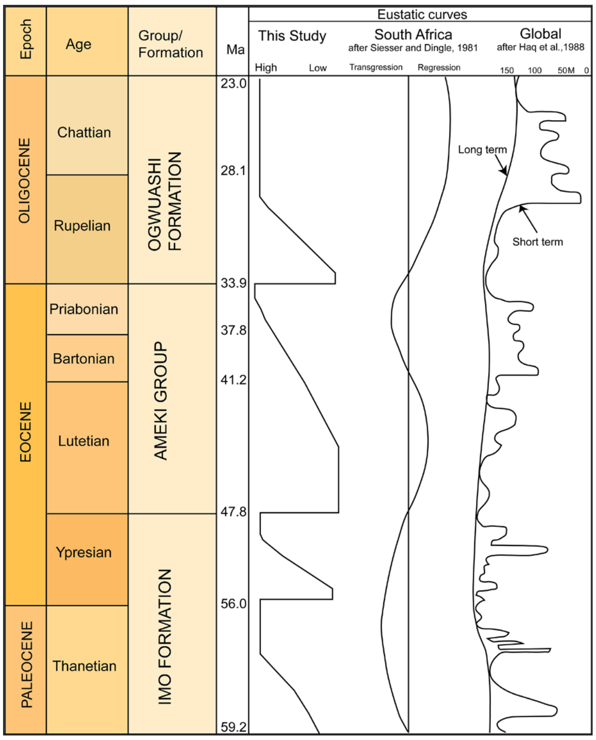

Figure 7. Comparison of south-eastern Nigerian and South African (Siesser and Dingle, 1981).

5.2.2 Middle-Upper Eocene Sequence

Siesser and Dingle (1981) recorded a series of transgressions and regressions during the Paleogene in South Africa and these events correlate approximately to the relative sea-level changes in south-eastern Nigeria (Figure 7). During middle Eocene times (Kogbe, 1976; Oloto, 1984), the Ameki Group was deposited and this corresponds to a regressive pulse which occurred during the middle Eocene in Southern Africa (Siesser and Dingle, 1981). The Ameki Group commenced with an initial regressive fluvial deposit of the Nsugbe Formation which forms the third sequence and the sequence boundary occurs at the base of the fluvial channel (SB3) or tidally influenced fluvial deposit in areas (such as Nando) where the tidal deposits rest directly on the Imo Formation deposits. The regression was followed subsequently by transgression that resulted in the estuarine condition and deposition of the Nanka Formation and the Ibeku Formation. The marine incursion marks the marine flooding surface and landward movement of the bayline which separates the regressive fluvial deposit from the transgressive estuarine deposits. The transgressive systems tract (TST) consists of thick successions interpreted as tidally influenced fluvial channels, tidal channels, tidal flats and tidal sand bars. This implies the availability of accommodation and sediments' supply, which may be due to regional subsidence and eustasy. Major global transgression in the Eocene is recorded by Flemming and Roberts (1973) and Siesser and Dingle (1981). This Eocene transgression may have affected sediments of the surface outcrop in the Niger Delta Basin, resulting in the estuarine conditions of the Ameki Group. The highstand systems tract is more pronounced in the Umuahia-Bende region. It is characterised by marine influence as the sea level gradually increases, which forms an inner tidal sand bar in the Enugwu-Ukwu region and estuarine embayment deposits in the Umuahia-Bende area. Siesser and Dingle, (1981), likewise suggested a regressive pulse during the middle Eocene in Southern Africa, which is represented by intense erosion that led to the absence and scarcity of middle Eocene rocks and subsequent transgression in late Eocene times.

5.2.3 Oligocene Sequence

The Oligocene strata in south-eastern Nigeria are characterised by tidally-influenced coastal- plain deposits which suggest a period of regression. The fourth sequence boundary (SB4) is marked by an unconformity, typified by basal erosive channels that are filled with fluvio-estuarine deposits. The fluvio-estuarine deposit constitutes the transgressive systems tract, while the tidal channel and coastal-plain deposits sensu stricto which include mud-filled channels and floodplain/mire form the highstand systems tract. Likewise, Siesser and Dingle (1981), recorded regression throughout the Oligocene time; marine influence was also noted in the Oligocene strata (Flores, 1973). This sequence is similar to the Oligocene Ogwashi deposit in southern Nigeria that commenced with regressive sequence of thick conglomerate, which was later reworked by shallow-marine infaunal organisms that indicate a marine influence.

6. Conclusions

The Paleogene succession in south-eastern Nigeria includes the Paleocene-Eocene Imo Formation, the Eocene Ameki Group and the Oligocene Ogwashi Formation which were deposited in a shallow-marine environment, a continental-marginal marine (estuarine) setting and a coastal-plain environment respectively. Three major paleogeographic stages were established based on the stratigraphic distribution of the sediments, sedimentation pattern and presence of regional scale discontinuities. These include:

1) The Paleocene-Early Eocene stage during which marine conditions were created due to a major relative sea-level rise. This resulted in increase in accommodation, low siliciclastic influx and the deposition of the offshore facies of the Imo Formation. The presence of thick tidal sand waves within the Imo Formation indicates that tidal processes were active.
2) The middle Eocene-late Eocene stage, during which a relative sea-level fall resulted to incision and subsequent deposition of multi-storey channelized, trough and planar cross-stratified sandstone with general south-west and northeast-directed palaeocurrent patterns. A subsequent rise in relative sea-level and a strong influence of tidal process created estuarine (brackish-water) conditions characterised by tidally-influenced fluvial channels, tidal channels, tidal flats, supratidal and tidal sand bars in the Ameki Group.
3) The late Eocene-Oligocene stage, during which a tidally-influenced coastal-plain regime prevailed, leading to the accumulation of the coastal-plain sands of the Ogwashi Formation.
4) Four depositional sequences characterized by four systems tracts were delineated: the falling-stage systems tract (FSST), the low-stand systems tract (LST), the transgressive systems tract (TST), and the high-stand systems tract (HST). The internal arrangement of these depositional sequences reflect a progressive progradation with periodic retrogradation and aggradation of the Niger Delta Basin sediments during the Paleogene.

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