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ORIGINAL PAPER

Depositional facies and palynofacies provenance reconstruction of the Danian Nsukka Formation, Southeastern Nigeria

Kachikwulu Kingsley Okeke[1]

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Abstract

A combined detailed palynofacies and lithofacies analysis was carried out on the Nsukka Formation outcropping Danian (Palaeocene) lithostratigraphic units in the Ikpankwu domain (SE Nigeria) for the first time. Lithological characteristics of grain size textural attributes, sedimentary structure and microflora palynofacies elements were instrumental in deciphering eight lithofacies: carbonaceous shale facies (Shfc), claystone facies (Csf), mudstone facies (Mfm), cross-bedded sandstone facies (Spt), siltstone facies (Fmt), heterolith facies (Fls), structureless sandstone facies (Smc), plane parallel laminated sandstones facies (Pls) and seven sub-facies deposited within low- to high-energy environment. These lithofacies and palynofacies-induced sedimentary attributes were grouped into three facies association (FA1, FA2 and FA3) and palynofacies types to delineate the principle palaeoenvironments, palynofacies provenance and depositional mechanisms triggered by hydrodynamic antics of the Nsukka Formation. The palynomaceral elements display superiority of large to medium-sized well-preserved brown to dark brown Palynomaceral 2 phytoclasts and terrestrial sporomorphs, Palynomaceral 4 and limited number of Palynomaceral 1 and Palynomaceral 3. The lithofacies and palynomaceral hydrodynamic array indicate that the mudrock facies of shale, mudstone and siltstone are deposits of lower deltaic plains or Lagoon with high terrestrial microflora input, while the sandstone facies depicts sediment of the upper deltaic plain (upper shoreface) or coastal tidal settings with overall effective oscillation tendency from tidal flat, lagoon to nearshore with open marine-influenced setting. The lithofacies and palynomaceral provenance prototype suggest terrestrially dominated shallow marine and tidally influenced outer neritic environment signalled from the quality and quantity of land-derived palynofacies components in association with few AOM and *Kenleyia* spp. and *Spiniferites ramosus* dinocysts, foraminifera test lining along with *Laevigatosporites* sp., Longerpertites group and other pollen and spore microflora. Lithofacies and palynomaceral organic matter in fluvial and inner neritic deep marine-influenced paralic strata of the study exhibit a perfect model for appreciating the lithological changes associated with a larger diversity of palynomaceral elements in marine and non-marine settings along with those of fluctuating salinity in the water realm.

Keywords Palynofacies · Palynomaceral · Palaeoenvironment · Lithofacies · Microflora · Danian Nsukka Formation

Introduction

The study area contains the outcropping sedimentary rocks of the Nsukka Formation of the Anambra Basin, southeastern Nigeria located around the Ikpankwu and Okigwe areas. It is bounded by latitudes 5°00′ N and 6°00′ N and longitudes 7°15′ E and 7°30′ E (Fig. 1). The Nsukka Formation is the Latest Maastrichtian to Danian deposit in the Anambra Basin, Southeastern Nigeria, that is overlain by the Imo Formation and chronostratigraphically underlain by the Late Maastritchian fluvial dominated deposits of the Ajali Formation (Fig. 1).

Sedimentology, foraminifera and palynology analysis of the formation were previously conducted to access the age and depositional environments of the Nsukka Formation. This was indicated as paralic to inner shelf (Simpson 1954; Reyment 1965), fluvial with marine incursions in shoreface settings (Nwajide and Reijers 1996), lagoon or bay to shoreface (upper-lower) and proximal offshore (Mode and Odumodu

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✉ Kachikwulu Kingsley Okeke
kachikwulu.okeke@unn.edu.ng

[1] Department of Geology, University of Nigeria, Nsukka, Enugu, Nigeria

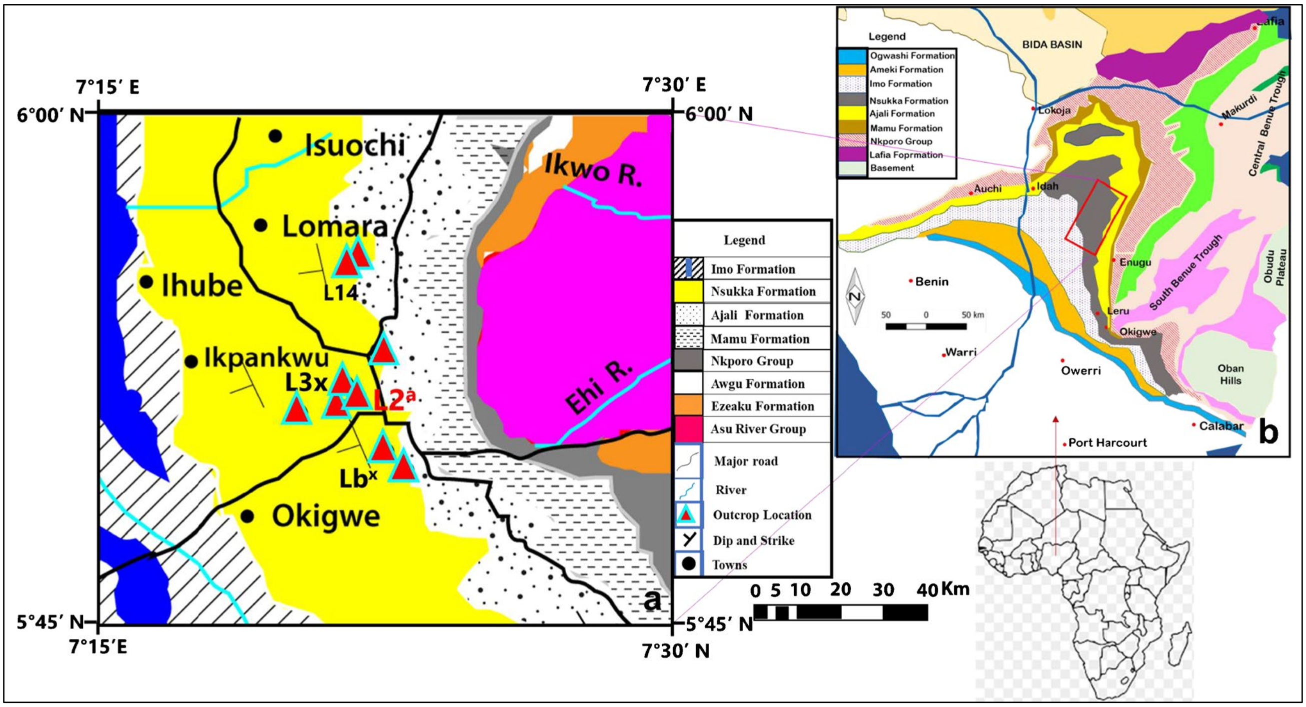


Fig. 1 **a** Enlarged view of the study area showing the geological map of the study area displaying outcrop locations, dip and strike and accessibility of the studied Nsukka Formation within Ikpankwu and Okigwe vicinity. **b** Geologic map of Southeastern Nigeria showing the study area and map of Africa (modified after Nigerian Geological Survey Agency, 2009)

2014) and beach with fluvial influences (Odumodu and Ephraim 2008). Other micropaleontologic evidence revealed paralic and marine settings (Okeke et al. 2024; Mode 2004, Oboh-Ikuenobe et al. 2005 and Umeji and Nwajide 2007). However, the lateral extent of the formation is broadened by an ancient shoreline which traversed in a North–South direction from south of Dekina to south of Okigwe and Calabar River in a continuous south-eastern ward marine line (Umeji and Edet 2008; Rayment 1965). At this juncture, the sandstone (coal) prone facies sequences of the formation are absent due to the marine conditions of the Nkporo Group depositional cycle, prevalent throughout the Maastrichtian stage in the Calabar Flank. The depositional style of the formation is prevalent westwards across the River Niger towards the Okitikpukpa basement high where an angular unconformity with the Nsukka Formation is inherent (Fig. 1).

The concept and introduction of palynofacies analysis to the scientific world and integration of the new science to geology interpretations and exploration instigated the palynofacies analysis schemes of Combaz (1964), Whitaker (1982, 1984), Whitaker et al. (1992) and Tyson (1993, 1995) which were elaborated and applied in geological investigations.

Lithofacies analysis considers the macro fossils, microfossils and physical and chemical features of sedimentary rocks in interpreting the sedimentary processes of deposition and palaeoenvironment of sediments (Okeke et al. 2023; Farouk et al. 2023; Talebmorad and Ostad-Ali-Askari 2022; Ghashghaie and Ostad-Ali-Askari 2022; Ghashghaie et al. 2022; Baioumy et al. 2020; Abbas et al. 2019; Ali et al. 2019; Kwetche et al. 2018; Miall 2022, 2016; Dalrymple et al. 2012; Nichols 2009; Reading and Levell 1996). Grain sizes, sorting variations and sedimentary structures are the lithofacies' specific physical features produced by variable depositional processes of energy input and sediment supply. However, some palaeoenvironment statuses are products of many depositional processes previously reported in contrasting category of depositional settings (Whitaker et al. 1992). In this case, integration of palynofacies and lithofacies analysis is a confirmation technique for accurate palaeoenvironment reconstruction since unaided lithofacies analysis slows exact palaeoenvironment reconstruction. The combined palynofacies and lithofacies analysis proposes a universal revolution for evaluation and revolution of the sedimentary processes, rock mechanics and biological hydrodynamic arrays in resolving the depositional environment attributes of the oscillating upper deltaic and lower deltaic depositional environment of the Nsukka Formation.

The coal and mudrock facies of Nsukka Formation yielded stratigraphic significant species that were previously used to assign a Latest Maastrichtian to Danian age to the studied sections of the Nsukka Formation (Figs. 2

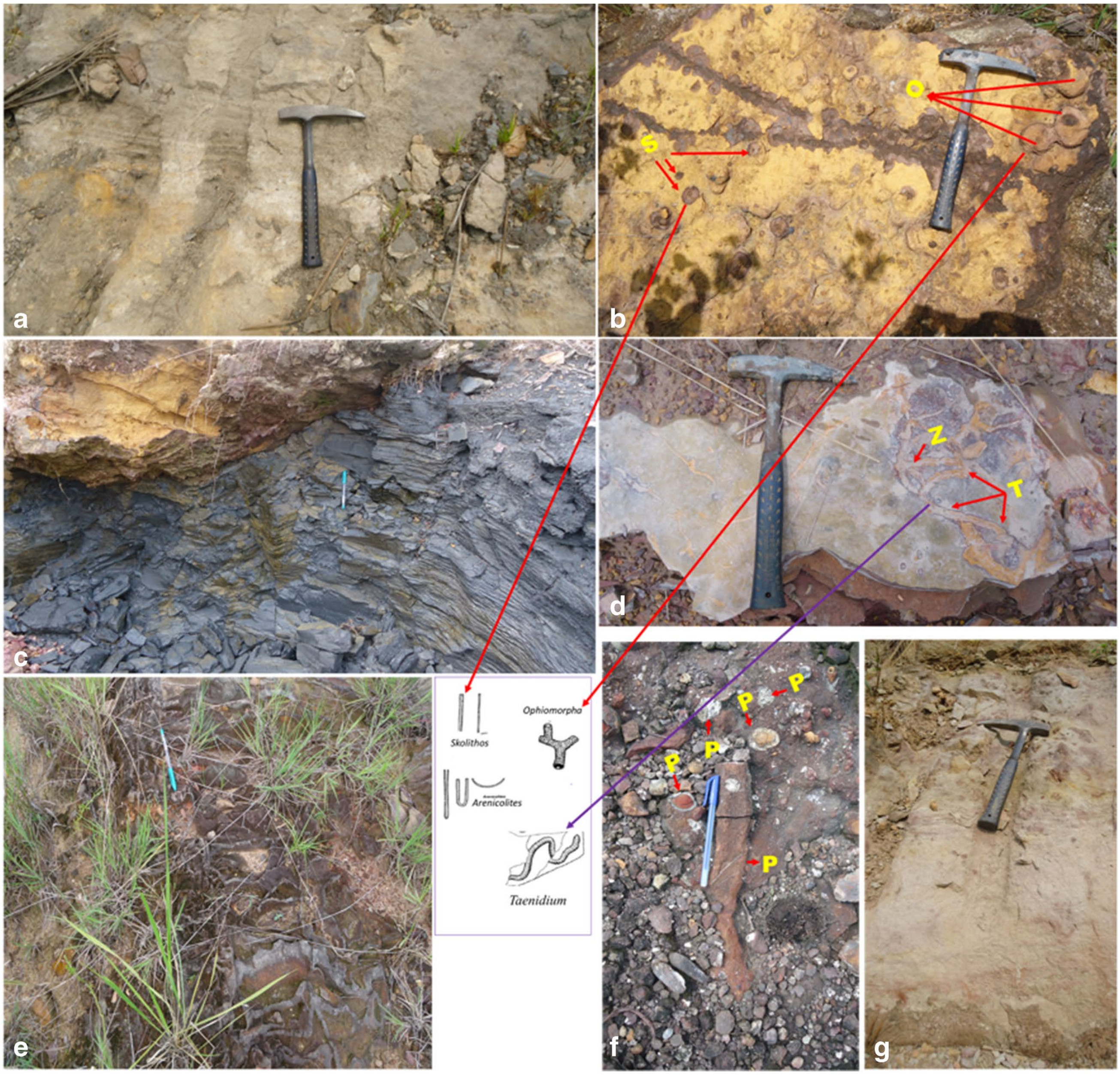


Fig. 2 **a** Low angle mud draped cross-stratified partly consolidated sandstone facies (Spt) at Ihube road cut. **b** Consolidated bioturbated structureless sandstone (Smc2), Ichnofossil suite includes Skolithos (S), *Ophiomorpha nodosa* (O). **c** Carbonaceous black shale facies (Shfc) of the Nsukka Formation overlain with sharp contact by a sandstone facies. **d** Consolidated bioturbated siltsone facies (Fmt2), Ichnofossil suite includes Taenidium *serpentinium* (T), Zoophycos (Z). **e** Partly distorted and weathered massive horizontally laminated siltstone facies (Fmt3) observed at the top of the Ikpankwu unit. **f** Consolidated bioturbated structureless sandstone facies (Smc2), Ichnofossil suite includes *Planolites montanus*. **g** Siltstone facies (Fmt) at the outcrop section at Ihube

and 3). The microflora species of *Spinizonocolpites* group, *Longapertites* group, *Scabratriporites annellus, Retitricolpites americana, Retidiporites magdalenensis, Retidiporites adegokei* and *Proteacidites dehaani* were the chronostratigraphic diagnostic palynomorph typical of the northern and southern sections of the formation (Okeke et al. 2024; Bankole and Ola-Buraimo 2017; Umeji 2000; Umeji and Nwajide 2007; Umeji and Edet 2008; Van Hoeken Klinkenberg 1964, 1966; Reyment 1965).

The synthesised lithofacies and palynomaceral analysis herein present detailed conceptualised depositional facies, palynomaceral exposé and its hydrodynamic signatures for the first time in the provenance and paleoenvironment interpretations of sedimentary rock. The various sizes, shapes

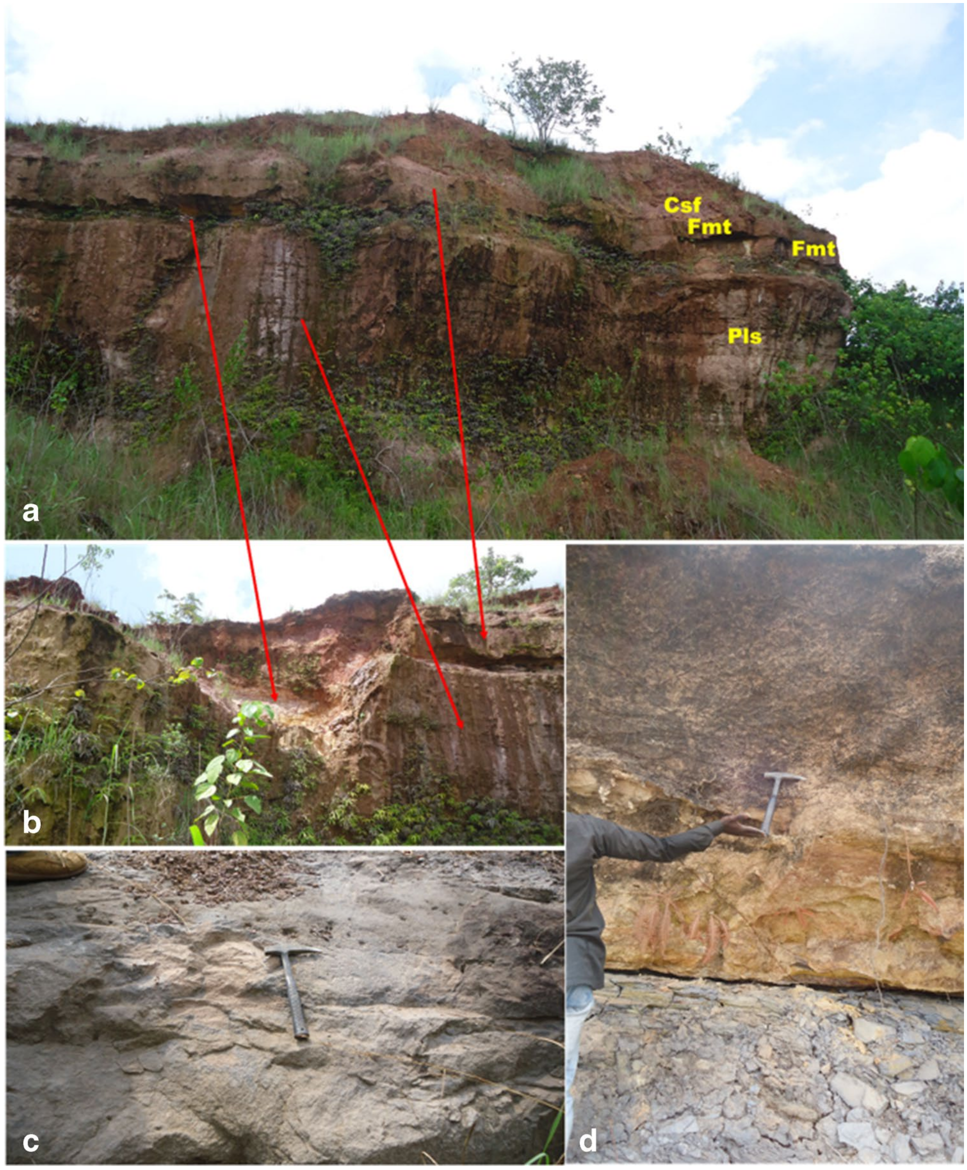


Fig. 3 **a** An overview of the outcropping section at Ikpankwu depicting a general oscillating depositional sequences of fining and coarsening upward sequences. **b** Normal fault system showing fault-bedded horizon of the Ikpankwu outcrop displaying reddish brown to pink claystone facies (Csf), plane planar laminated sandstone facies (Pls) and consolidated siltstone facies (Fmt). **c** Consolidated structureless sandstone facies (Smc1). **d** Carbonaceous black shale facies (Shfc) of the Nsukka Formation overlain with sharp contact by a partly consolidated fine-grained sandstone to siltstone facies

and preservation criteria of the palynomaceral are similar to the sandstone hydrodynamic technique and grain size depositional system of sedimentary rock. Sizes and shapes are the key events of the palynomaceral hydrodynamic system which correlates to sandstone saltation dynamics substantiated in fluctuating depositional environment changing aspect of the Late Maastrichtian to Danian deposits of the Nsukka Formation. This pinpoints the lower and upper deltaic plains oscillating synthesis of the Nsukka Formation for the first time for proper delineation of the sedimentary processes paradigms. At this juncture, the integration of lithofacies and palynomaceral approaches is key to proper clarification of the depositional processes, depositional environment, palynomaceral hydrodynamics and provenance along with other geology evolution mechanism during the Danian sedimentation processes. The specific objectives of this research details include the following: (i) to demonstrate the palynomaceral component sizes, disintegration and frequency inherent in the prototype marine space, (ii) to discuss the oscillating depositional environment dynamics of the study, (iii) to examine the effective depositional processes of the sedimentary lithofacies model during deposition of Nsukka Formation and (iv) to explain the hydrodynamic aspect of the particulate organic matter and authenticate its provenance.

Materials and method

Detailed sedimentary rock outcrop studies and desktop description of micro and macro sedimentary structures, along with sandstone grain sizes and measured lithological thickness were substantial in the clarification of the depositional environment and hydrodynamic system of the plant materials and sandstone sequences of the formation. The studied sections of the Nsukka Formation are accessible in the vicinity of Ikpankwu (L3x), Ihube ($L2^a$) down to Uturu (Lb^x) and cover an areal extent of more than 50 km^2. The sedimentary outcrop sequences are well-preserved with good details of the sandstone fabrics. The sandstone depositional processes are essential in sedimentological logging, nature of bedding contacts, along with dips and strikes orientation (Fig. 1) and lateral extent of the outcrop sections. The diversity attributes of the trace fossils, size, ichnofacies ethology, ichnofacies distribution and intensity of bioturbation were also analysed.

The sedimentary mudrock facies is key in the adequate acid maceration laboratory analytical techniques for better result of palynofacies elements. The sequential diligent acid maceration of particulate organic matter with HCl and HF in palynological analysis was achieved after systematic field mapping, sedimentary logging and sample collection from the studied outcrops. The selected well-preserved sandstone samples underwent cleaning and crushing before 20 g of sediment were digested in hydrochloric (HCl) and hydrofluoric (HF) acids for the removal of carbonate and silicates, respectively. The sample underwent palynofacies acid maceration techniques in the presence of a carbonate-free sample which negates the hydrochloric (HCl) maceration procedure. Twenty grams of equivalent aliquots for palynofacies studies was dispersed in polyvinyl alcohol, mounted on glass slides and examined with a transmitted light biological microscope. The palynomaceral groups are standardised in this work in a systematic code language as P1, P2, P3 and P4 designated as Palynomaceral 1, Palynomaceral 2, Palynomaceral 3 and Palynomaceral 4, respectively. The palynofacies terminology (Tyson 1993, 1995; Whitaker 1982, 1984) and palynomaceral classification working scheme of Whitaker 1982 and 1984 are utilised in the exhibition of the palynomaceral model of the Nsukka Formation for the first time. The particulate organic matter terminologies of Tyson (1993, 1995) and Combaz (1964) standardised as amorphous organic matter (AOM), opaque debris, resin and structured phytoclasts as well as dinocysts and pollen and spores palynomorph were amicably incorporated to buttress the emphasised palynomaceral significance. The Stratabugs software of StrataData Ltd. is vital in statistical frequency charts of the palynomaceral forms (Fig. 4). The Sedlog lithology imprint of the Ikpankwu outcrop and other outcrops section logs were merged with the Stratabugs data to demonstrate the sample intervals and palynomaceral abundance mark as indicated with an arrow index as shown in Fig. 4.

Background of key palynomaceral elements

Palynofacies components of the palynomaceral scheme of Whitaker (1982, 1984) is made up of terrestrial input of woody debris and palynomorph microflora of marine dinocyst and pollen and spore of terrestrial origin subdivided into four categories namely, Palynomaceral 1, Palynomaceral 2, Palynomaceral 3 and Palynomaceral 4 (P1, P2, P3 and P4) according to their origin, buoyancy and degradation features (Fig. 5). The hydrodynamic concept of the outlined palynomaceral groups is similar to the sedimentary rock hydrodynamic standard of sandstone grains suggestive of palaeoenvironment. The origin of the palynomaceral components is essential in this palynofacies interpretations to precisely clarify the provenance, depositional environment mechanics related to the microenvironments and palynofacies arrays linked with the Late Maastrichtian to Danian phytoecological space of the Nsukka Formation water realms.

Palynomaceral 1 comprises amorphous organic matter (AOM) palynofacies component made up of black-brown, yellow–brown and fluffy-coloured structured and structureless irregularly shaped material with variable preservation and dense appearance (Fig. 5). They are made up of structured plant debris, humic gel-like substances, resinous substances and algal detritus (Whitaker et al. 1992, van der Zwan et al. 1993). They are considered to be less buoyant, prone to waterlogging and easily distorted in high-energy medium. The amorphous organic matter (P1) of the Nsukka Formation is few and similar to the terrestrial origin form of Staplin (1969), Masran and Pocock (1981). The degradation process ranges from poorly degraded-degraded phytoclasts-amorphous organic matter. This illustrates that they are product of alteration other than primary products (Staplin 1969). Their colour ranges point to terrestrial origin (Masran and Pocock 1981).

Palynomaceral 2 consists of well-preserved structured phytoclasts, cuticle and relatively structureless light-brown phytoclasts (Okeke, 2017; Whitaker et al. 1992, van der Zwan et al. 1993 Fig. 5). In its well-preserved conducting tissues form, they exhibit lath (spindle) shape with occasional equidimensional shapes. They are terrestrial input of woody debris of relatively high buoyancy due to its thinner and lath-shaped nature. They are more buoyant than P1.

Palynomaceral 3 is made up of degraded and partly degraded phytoclasts of all palynofacies particles (Whitaker et al. 1992, van der Zwan et al. 1993). They are relatively thin, irregularly shaped, normally structured and relatively unstructured with variable rages of distortion and size ranges. The small to medium size of P3 along

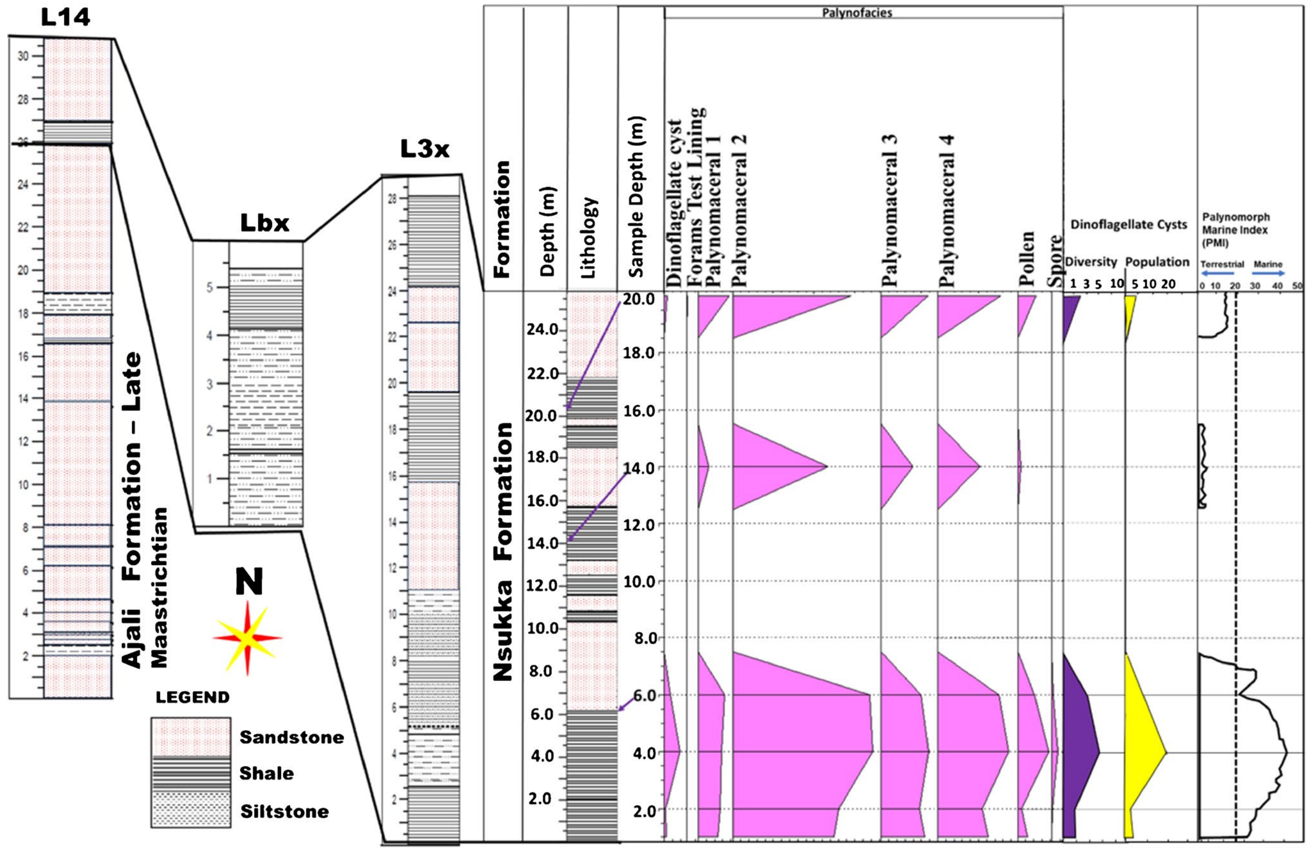


Fig. 4 Summary of the palynomaceral distribution chart of the relative abundance of particulate organic matter at the Ikpankwu outcrop section in the southern flank of the Nsukka Formation, Anambra Basin, showing pollen and spore frequencies, palynomaceral index, dinoflagellate cyst indices and abundances, lithostratigraphic surfaces, and Palynomorph Marine Index (PMI) significance

with the structured and unstructured character of P3 initiated its very high buoyancy than Palynomacerals 1–3. It includes all palynofacies components of P1, P2 and P4 namely, AOM, structured phytoclasts, cuticle and opaque particles.

Palynomaceral 4 elements are products of the oxidation of translucent woody material during prolonged transport or post-depositional alterations. It is equally produced as charcoal during natural wildfires (Okeke, 2014; Tyson 1993). They are usually black, nearly black coloured with different grades of brown-dark brown circumference colour, equidimensional, lath (blade/needle)-shaped material that are nearly uniformly opaque and structureless. The hydrodynamic relative comparison of the equant and lath-shaped opaque debris denoted that the latter is extremely buoyant with long-distance transport character whereas the former is relatively of lesser buoyancy due to the shape. However, all are resistant to degradation and significant in the transport mechanism of sediment in high-energy palaeoenvironments.

Results

Palynomaceral mark

The statistical percentage frequencies of the palynomaceral groups from the studied outcrop lithologies are shown in Fig. 4. The palynomaceral plant remain standard components of amorphous organic matter (AOM), opaque particles, structured and unstructured phytoclasts with other palynomaceral constituents were recovered in the study (Fig. 5).

Figure 4 portrays the palynomaceral percentage abundance of forms encountered in the Nsukka Formation. P2 (46%) and P3 (17%) phytoclast groups are the most dominant particulate organic matter type with an overwhelming abundance of 63%, while the Palynomaceral 1 (9%) and dinoflagellate species (1.6%) accounted for 10.6% statistical value. However, the fluctuating abundance of palynofacies groups was illustrated as a product of environmental and climate changes during sediment deposition (Okeke and Umeji 2018). Pollen and spores (5.5%) and Palynomaceral 4 particles (22%) were also recovered (Figs. 4 and 5).

Sedimentary facies

The depositional facies synthesised principle of lithology, grain sizes, texture, sedimentary structures, bed unit geometry and palynomaceral hydrodynamic status of the Nsukka Formation that outcropped in the study area revealed eight lithofacies. Scientific analysis of these facies endows a geologic platform to unravel the sedimentary components and propose the depositional environments and sediment transport mechanisms inherent in the pronounced oscillating depositional system of the formation. Palynomaceral 1 to Palynomaceral 4 hydrodynamic dynamics were purposeful in reconstructing the provenance of the sedimentary components. The studied lithofacies are shales (Shfc), claystone (Csf), cross-bedded sandstones (Spt), mudstones (Mfm), siltstones (Fmt), heteroliths (Hts), structureless sandstone (Smc) and plane planar laminated sandstone (Pls) as shown in Figs. 2 and 3. The facies codes, lithologies and synthesised results of the depositional mechanism and environments along with palynofacies components and other sedimentary models of each lithofacies are recoded in Tables 1 and 2 and Figs. 2 and 3.

Carbonaceous shale facies (Shfc)

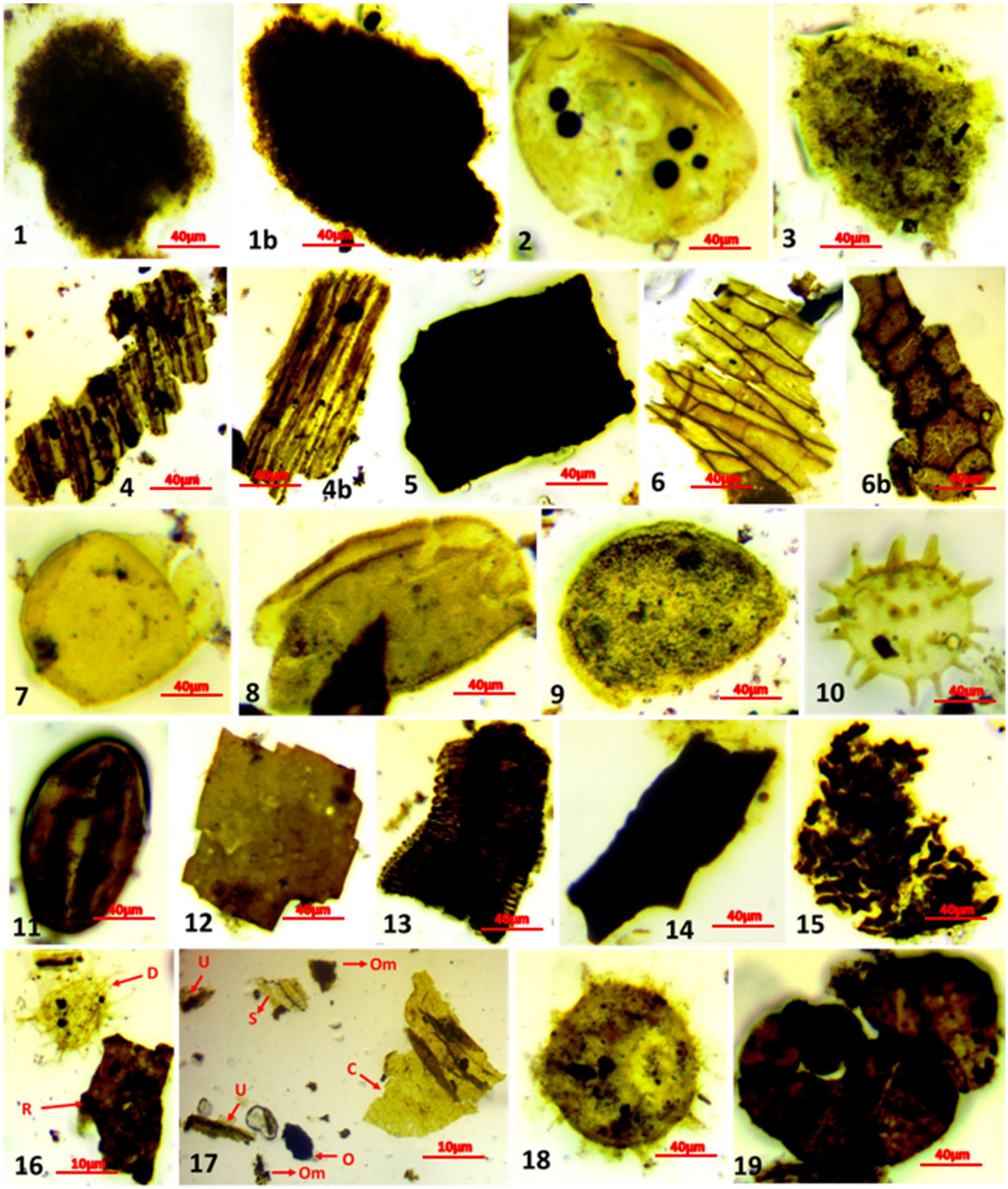
Shcf-deposited strata comprise dark grey to black carbonaceous fissile shale with abundant ironstone concretionary horizons and thicknesses ranging from 30 cm to 6 m. Well-preserved low land outcrops of the shale facies at Ihube, Ikpankwu, and Ihube PortHarcout-Enugu road were mostly found at the basal and topmost sections (Figs. 2c and 3d). The facies occur in association with black carbonaceous shale and blue-grey shale, non-fossiliferous siltstone (Fig. 2g), mudstone and fine- to medium-grained structureless sandstone (Fig. 3d). At the Ikpankwu, the facies is overlain by plane planar laminated sandstone and other sandstone signatures as shown in Fig. 3a, whereas at Ihube, this facies is overlain and underlain by siltstone and slightly consolidated planar cross-bedded sandstone that is fractured in some places. The shale (Shfc) facies are mostly black to grey coloured, carbonaceous but commonly non-calcerous, fissile, micaceous, texturally very fine-grained (Fig. 2c). Wavy-lenticular laminae, regular and parallel lamination with siltstone bands and particles of siltstone along with very fine-grained sandstone texture is obvious in hand specimen and outcrop studies. There is an absence of trace fossils with some remnants of opaque particle plant remains in the shale. Some sections of the facies are undergoing weathering and ferruginisation due to the leaching iron oxide from the strata in the tropics. The shale facies palynomaceral analysis exhibits high abundance, good quality and quantity of well-preserved palynomaceral elements with a high occurrence of Palynomaceral 2 (45%) and Palynomaceral 4 (22%) along with pollen and spore (1%) microflora and dinocysts taxa (1%). Other palynomaceral constituents encountered in the Shfc facies are P1 and P3 as shown in Figs. 4 and 5.

Interpretation

The black colour, opaque particles of Palynomaceral 4, fine-grained, non-calcareous character and other constitution of Shfc are a result of the high particulate organic content inherent in the shale facies. This composition attributes of the shale facies (Fig. 2c) are products of suspension sediment fallout in an anoxic, low-energy, shallow to offshore marine environment (Miall 2000). It was also noted as a deposited product of settling out from suspension of fines due to quiescence marine setting (Okeke et al. 2023). The shale facies is associated with overwhelming abundant large- to medium-sized Palynomaceral 2 and Palynomaceral 4, few medium- to small-sized P1 and fragments of P3, dinoflagellate cysts and high diversity and abundance of pollen and spores obtainable in palynofacies events (Figs. 2 and 3). The frequency of the palynomaceral arrays, in association with quality and quantity occurrence of *Laevigatosporites* sp. cf *javanicus, Proxapertites operculatus, Longapertites vanendeenburgi, Spinizonocolpites echinatus, Ephedripites regularis* pollen and spore and dinocyst species of cf *Kenleyia lophophora,* cf *Kenleyia leptocerata* and gonyaulacacean dinoflagellate cysts taxa of cf *Spiniferites ramosus* marine palynomorphs, as well as benthonic trochospiral forams test lining is common in silts and finer grained mudrock sediments of the Nsukka Formation as shown in the photomicrographs (Fig. 5). The palynomaceral elements of the Nsukka Formation illustrate shallow marine environment with deep marine influences (Table 1) supported by *Spiniferites ramosus* gonyaulacacean taxa and AOM (12%) indicative of fluctuating salinity endowment in the water realm. The hydrodynamic attributes of palynofacies components in silts and finer sediments reflect relatively lower deltaic plain setting (shallow marine) with profound terrestrial palynofacies input and outer neritic salinity influences.

Claystone facies (Csf)

Claystone facies includes thin bands of reddish, reddish brown to dark grey clay and 20 cm to 35 cm white clay or kaolinitic claystone bands prominent at the Ikpankwu quarry. At Ihube, these facies alternate with the black carbonaceous shale (Fig. 3a, b) and siltstone that is considerably thicker than the claystone units, but



in Ikpankwu, the facies is displayed as bands of mud drapes of slack water origin which may be as a result of the quarry events. The facies is devoid of sedimentary structures.

Interpretation

The whitish and reddish colour ranges of this facies is mostly a result of weathering and ferruginisation due to the leaching iron oxide that devastate outcrops in

◂**Fig. 5** Photomicrographs of particulate organic matter in the Nsukka Formation; r, resin; o, opaque debris; s, structured phytoclast; U, unstructured phytoclast; c, cuticle; D, dinoflagellate cysts; om, organic mass. 1. Amorphous organic matter – Palynomaceral 1, 2. *Laevigatosporites* sp. cf *javanicus* Takahashi 1982, 3. Dinoflagellate cyst cf. *Kenleyia lophophora* Cookson and Eisenack 1967, 4. Well-preserved structured phytoclasts – Palynomaceral 2, 5. Equant opaque particle—Palynomaceral 4, 6. Cuticle—Palynomaceral 2, 7. *Proxapertites operculatus* Germeraad et al. 1968, 8. *Longapertites vanendeenburgi* Germeraad et al. 1968, 9. *Longapertites marginatus* Van Hoeken-Klinkenberg 1964, 10. *Spinizonocolpites echinatus* Muller, 1968, 11. Ephedripites regularis Van Hoeken-Klinkenberg 1964, 12. Resin particles, 13. Unknown structured phytoclasts—Palynomaceral 2, 14. Lath shaped opaque particle—Palynomaceral 4, 15. Degraded black-brown phytoclast—Palynomaceral 3, 16. Resin particle and dinoflagellate cysts cf *Spiniferites ramosus* (Ehrenberg 1838) Loeblich and Loeblich 1966, 17. Particulate organic matter elements of the Nsukka Formation, 18. Dinoflagellate cysts cf *Kenleyia leptocerata* Cookson & Eisenack 1967, 19. Trochospiral forams test lining

tropical to subtropical areas due to the intensity of the sun. The red colour prototype of the claystone facies was also regarded as haematite-grown coatings and crystals intergrown with clay (Odu et al. 2021). The colour attributes of the facies, non-carbonaceous and absence of organic matter in Csf depict in situ oxic depositional environment associated with flood plain, shoreface marine and deltaic depositional settings with non-preservation of palynofacies debris due to oxygenation of the water realm. Csf facies also denote hydrodynamic episode in low- to high-energy depositional system within floodplain. However, some section of the Csf depicts weathering and pedogenesis of existing facies attributed to palaeosol.

Mudstone (Mfm)

Mudstone facies (Mfm) are poorly exposed within the study area but it outcropped at the Ihube section. Msfm elements consist of black to grey-coloured laminated and flaser mudstone (Mfm1), massive mudstone facies (Mfm2), carbonaceous siltstone facies, very fine-grained sandstone facies and heterolith facies. At the Ihube section, the mudstone facies are deposited as a black to grey carbonaceous laminated and interlaminated (Mfm1) 2-m thick mudstone, weathered in some places, massive (Mfm2), thinly laminated with shale and siltstone bands. They are usually underlain and overlain by heterolith facies (Hts) with sharp contacts at the top and the base. The palynomaceral attributes of the mudstone facies (Mfm) are dominated by well-preserved medium- to large-sized Palynomaceral 2 and Palynomaceral 4 (Fig. 4). P1 (9%) and P3 (14) along with pollen and spore taxa of *Laevigatosporites* sp. cf *javanicus* and *Proxapertites operculatus* along with cf *Kenleyia lophophora* and dinoflagellate species and others shown in Figs. 4 and 5 were recorded.

Interpretation

The mudstone facies are massive (Mfm2) but consist of very thin laminations (Mfm1) indicative of weak suspension currents, related to the deposition of mudstone. It was reported that the dynamics of weak currents and long slack water periods support the deposition of mud in normal marine settings where Mfm is deposited laterally to the main tidal currents (Olariu et al. 2012). The palynomaceral components of the facies are dominated by large- to medium-sized well-preserved Palynomaceral 2 and Palynomaceral 4 along with few medium- to small-sized Palynomaceral 3 and relatively large Palynomaceral 1, indicative of terrestrial microflora occurrences in shallow marine settings. The frequency of the palynofacies groups and palynomorph species suggests a lower deltaic plain paleoenvironment with deep marine influences but dominant of large-sized palynomaceral elements illustrates excellent preservation of palynofacies, perfect anoxic environment and little distance transport prior to deposition.

Cross-bedded sandstone facies (Spt)

The cross-bedded sandstone model of the Nsukka Formation consists of high- and medium-angle planar cross-bedded sandstone facies (Spt) with mud pebbles and mud drape. The Spt contains white-yellowish coarse- to fine-grained mud draped low angle cm-thick planar cross-stratification, slightly ferruginised, semi-consolidated and moderately sorted sandstone (Fig. 2a) that is slightly massive in a short distance. Spt facies was encountered in the part of a slightly dipping road outcrop at Ihube along the PortHarcout-Enugu road. The studied sandstone facies with 2 m maximum bed thickness is devoid of ichnogeneric burrows but the cross-stratification attributes of the studied Spt facies are substantiated with a series of typical planar foresets with angular bases and tangential (asymptotic) or concave toesets (Fig. 2a).

Interpretation

The mud drape architecture of the planar cross-bedded sandstone (Spt) facies conceptualised the migration of straight-crested bedforms as products of the middle part of the lower flow regime event. The dominance and intensity of mud drapes in the sandy braided strata suggest active standing of water pools at low-stage channel dissertation, indicative of distal flood plain facies (Miall 2006, 1985, 1987). With respect to the intensity of flow over the crest, weak flows form angular forests, while strong flows produce tangential forests (Collinson et al. 2006), inherent in the Ihube outcrop section. The sandstone facies is void of palynomorph and palynomaceral elements. Abundant and regular mud drapes

Table 1 Facies description, processes and mechanism of deposition and microenvironments of each lithofacies and palynomaceral assemblages in the Nsukka Formation

Lithology/facies	Facies code	Subfacies	Sedimentary structures	Textural characteristic	Palynomaceral composition	Depositional mechanism	Depositional environment
Shale	Shfc		Black and dark grey shale, fissile, wavy-lenticular laminae, regular, parallel laminated with veins and bands of siltstone	Back to dark grey, carbonaceous, fissile, plastic, sand grit, micaceous, non-fossiliferous	Few P1, medium to small sized P3, overwhelming abundant large to medium sized P2, P 4 pollen and spores, dinocysts, foraminifera test lining	Settling out of suspension due to quiescence in shallow marine-lower deltaic plain	Lower deltaic plain
Claystone	Csf		Reddish brown to pink, white clay, band, parallel laminated	White, non-carbonaceous, plastic on wetness, non-fossiliferous	Barren	Settling out of suspension due to quiescence in floodplains	Floodplains, deltaic settings, paleosol
Siltstone	Fmt	Fmt1-Carbonaceous siltstone	Massive, non-fissile and undulating lamination, bioturbated	White, light to grey millimeter silt-sized particles, non-plastic. slightly friable / powdery	Little P1, medium to small sized P3, overwhelming abundant large to medium-sized P2, P 4, pollen and spores, dinocysts	Settling out of suspension due to quiescence in calm waters often grading into shale, mudstone or sandstone	Flood plain, shallow marine, deltaic environments
		Fmt2-bioturbated siltstone	Consolidated, massive, bioturbated	Slightly very fine-grained to silty, fossiliferous, massive or structureless sandstone when dry	Barren	Settling out of suspension due to quiescence in calm waters often grading into shale, mudstone or sandstone	Flood plain, shallow marine, deltaic environments
		Fmt3-laminated siltstone	Consolidated, massive, distorted	Massive or structureless with possible very fine- to medium-grained, sandstone grains	Same as above	Same as above	Same as above
Cross-bedded sandstone	Spt	Sp-Mud-draped planar cross-bedded sandstone	Medium angle cross-bed, single and double mud drapes, inclined master bed, mud clasts, mud pebbles, void ichnofacies	Medium to fine-grained mature sandstone, poorly sorted, semi-consolidated, slightly massive	Barren	Migration of straight-crested bedform, slack water mud drapes	Tidal sand waves in shallow sandy seas, coastal tidal settings, Tidal bars
Structureless sandstone	Smc	Smc1–structureless sandstone	Consolidated, massive	Coarse- to fine-grained, non-fossiliferous, massive or structureless sandstone	Same as above	Gradual aggradation of sands under steady flows and rapid deposition	Tidal channel, flood plain, braided river, tidal flats
		Smc2–bioturbated structureless sandstone	Consolidated, massive, bioturbated	Medium- to fine-grained, fossiliferous, massive or structureless sandstone	Same as above	Gradual aggradation of sands under steady flows and rapid deposition	Tidal channel, flood plain, braided river, tidal flats

Table 1 (continued)

Lithology/facies	Facies code	Subfacies	Sedimentary structures	Textural characteristic	Palynomaceral composition	Depositional mechanism	Depositional environment
Mudstone	Mfm	Mfm1-laminated mudstone	Laminated mudstone with siltstone, lenticular parallel bedding	Laminated mudstone with streaks of dark grey siltstone	Few P1, medium to small-sized P3, overwhelming abundant large to medium-sized P2, P 4, pollen and spores, dinocysts	Continuous and periodic settling of fines out of suspension due to quiescence	Lower deltaic plain, shallow marine
		Mfm2-massive mudstone	Structureless to very thinly laminated dark grey mudstone with siltstone	Massive micaceous mudstone with micaceous siltstone, with sand grits	Same as above	Episodic settling of mud and silt from suspension	Same as above
Heteroliths	Hts		Rhythmic succession of mm-cm mudstone, shale and sandstone, parallel laminations, flaser and lenticular bedding	Regular alternations of thin or thick, fine- to coarse-grained sandstone and mud-rock layers	P1, medium to small sized P3, abundant large- to medium-sized P2, P 4, pollen and spores, dinocysts	Cyclic oscillation of sediment supply and tidal velocity (high tides and slack tide fallout)	Tidally influenced channels, intertidal and subtidal coastlines
Plane planar laminated sandstone	Pls		Parallel lamination, periodic oscillation of sandstone interbedded with white clay	Regular alternations of thin or thick medium- to coarse-grained sandstone, white	Barren	Same as above	Same as above

Table 2 Summary of lithofacies description, facies association and interpretation of depositional environment

Lithofacies	Lithofacies association	Sedimentary structures	Depositional microenvironment array
1. Carbonaceous shale facies (Shfc) 2. Mudstone (Mfm)-laminated, mudstone (Mfm1), massive mudstone (Mfm2) 3. Carbonaceous siltstone facies (Fmt1) 4. Heteroliths facies (Fls)	FA1	Shale facies display back-dark grey colour with carbonaceous, fissile, plastic, sand grit, micaceous and non-fossiliferous structures and structureless in some beds. Mudstones are laminated with siltstone, lenticular parallel bedding. Siltstone is partially massive, non-fissile with undulating lamination and bioturbated. Heteroliths contain rhythmic succession of mm-cm mudstone, shale and sandstone and exhibit parallel laminations, flaser and lenticular bedding. High abundance of P2 and P4, presence of P1 and P3, pollen and spores, dinoflagellate cysts and trochospiral benthic foraminifera text linings	Lagoonal, coastal swamp, brackish water, lower deltaic plain, marginal marine, near-shore open marine deposit
1. Structureless sandstone facies (Smc)-structureless sandstone (Smc1), bioturbated structureless sandstone (Smc2) 2. Siltstone facies- bioturbated siltstone (Fmt2), laminated siltstone (Fmt3) 3. Plane planar laminated sandstone facies (Pls) 4. Heterolith facies (Hts)	FA2	*Ophiomorpha* burrows are common in the bioturbated structureless sandstone while Smc1 facies is massive and consolidated. Siltstone facies are laminated, micaceous, fairly consolidated and moderately bioturbated. Hetrolithic facies are non-bioturbated with rhythmic succession of millimeter-centimeter siltstone, shale mudrock and sandstone facies. Barren of palynomaceral elements	Lower shoreface deposit, lower deltaic plain
1. Cross-bedded sandstone facies (Sp) 2. Bioturbated structureless sandstone (Smc2) 3. Plane planar laminated sandstone facies (Pls) 4. Heterolith facies (Hts)	FA3	High and medium-angle planar cross-bedded sandstone with mud pebbles, mud drape and extra-formational clasts. Intensely-moderately bioturbated. Barren of palynofacies group	Upper shoreface (Upper deltaic plain), fluvial-distributary channels? Coastal tidal settings, tidal bars

in sandstone units are a precise pointer of a tidally influenced environment (Dalrymple et al. 1992; Nichols 2009). The high-energy marine process within the delta front is substantiated by tidal imprints of tide-dominated delta where sediments are reworked and winnowed with a variety of grades of crossbedded sandstone strata (Boggs, 2006). This is substantiated by the presence of dinoflagellate species in Shfc facies confirming tidal depositional setting for Spt facies and deep marine-influenced setting of the Nsukka Formation shale facies.

Siltstone facies (Fmt)

The siltstone facies is composed of carbonaceous siltstone (Fmt1), consolidated bioturbated siltstone (Fmt2) and laminated siltstone facies (Fmt3) deposited around Ihube and Ikpankwu sections. The thickness of the studied Fmt bed size ranges from 50-cm to 1-m thick (Fig. 3d) units that are overlain and underlain by carbonaceous shale facies and mudrock facies, respectively, with sharp contacts. Fmt consists of white and dark grey millimetre silt-sized particles of non-fissile and laminated consolidated to non-consolidated siltstone units (Fig. 2g). The Fmt3 at Ikpankwu exhibits a distorted enclosed clay-like pipes that are generally broken, but the content of the broken pipes resembles medium to fine-grained sandstone particles (Fig. 2e). The consolidated facies are structureless or massive, non-laminated in hand specimen and bioturbated. The bioturbation intensity in Fmt2 ranges from moderate to intense at the topmost unit of the Ikpankwu outcrop. The siltstone facies recorded the occurrence of large-sized to relatively medium-sized P2 and P4 (21%). The Palynomaceral 1 and Palynomaceral 3 were also recorded with the presence of *Spinizonocolpites echinatus, Laevigatosporites* sp. and other palynomorph species shown in Figs. 1 and 4.

Interpretation

Siltstone facies of the study are overlain by shale facies and mudstone facies with a sharp contact in some sections which displays mild agitation of the shallow water realm (lower deltaic plain) amidst settling out of suspension due to quiescence in calm waters. The hydrodynamic nature of Fmt is responsible for the suspension fallout during fair-weather periods. The suspension fallout was regarded as the deposits of waning stage flood deposition, in the overbank areas (Hjellbakk 1997). This facies architecture of micaceous and enclosed clay-like pipes, broken at intervals, was reported in the formation at Inyi vicinity (Odu et al. 2021) as deposits of suspension settling with little bed-load transport engineered by weak currents. Series of undulating lamination inherent in the siltstone facies of the formation illustrates sediment reworking by strong wave action in a shallow marine environment. The abundance and quality of well-preserved palynofacies components of large to medium well-preserved P2 and P4 in addition to a few relatively small-sized P3 and P1 depict the shallow marine environment with increased terrestrial particulate organic plant remains. Fmt1 and Fmt2 facies are barren of palynomaceral particulate organic matter. These palynomaceral elements indicate a relatively shallow marine depositional environment with little deep marine input.

Heteroliths facies (Fls)

The heterolithic (Fls) facies is a predominant lithologic units of the Nsukka Formation around Okigwe and Ihube vicinity. They are the product of hydrodynamic episode of medium- to fine-grained sandstone and shale, muddy heteroliths of sandstone and mud, engineered into interlamination of sandstone particles. Fls facies comprises regular alternation of thin beds of wavy, flaser and lenticular bedding with dissimilar lithologies of sandstone, siltstone and shale siliciclastic rocks that are interbedded with obvious sharp contacts. The thickness of the beds varies from 50 cm to 1 m in places and was directly overlain and underlain by shale facies or siltstone facies and sandstone in the studied outcrop sections. The palynomaceral remains of the Danian heterolith facies recorded the abundance of large to medium-sized well-preserved Palynomaceral 2 and Palynomaceral 4 along with palynomorph diversity and abundance recorded in Figs. 4 and 5 of the study. Small-sized degraded Palynomaceral 3 with few Palynomaceral 1 elements were encountered during the visual microscopic study (Figs. 4 and 5).

Interpretation

Fls facies sedimentary structures of regular alternation, wavy, flaser and lenticular bedding inherent in the Danian units of the Nsukka Formation are indicative qualities of tidally influenced channels or intertidal and subtidal coastlines. Heterolithic deposits and sedimentary structures of the Nsukka Formation depict tidal rhythmites and deposits of tidally influenced settings and sediment accumulation in a brackish water environment. Fls was also reported as rhythmic interbeds of numerous grain size ranges of medium- to fine-grained sandstone, shale, mud and clay, forming wavy, flaser and lenticular bedding structures in addition to parallel laminations (Okeke et al. 2023). The rhythmic pattern and cyclic deposition of the heterolithic units were explicit and well-documented (Reineck and Singh 1980; Nichols 2009; Abouessa et al. 2014). The omnipresent Fls facies in Nsukka Formation outcrop sections demonstrate the shallow marine facies prototype of the formation and sand waves fit in the normally overlain or underlain by coastal, deltaic, estuarine or deep marine setting facies paleoenvironment scenario of

Nichols (2009). Varieties of parallel laminations and heterolith facies denote regular alternating low- and high-energy events (Kvale 2006) in shallow marine with deep marine wave and current actions. Summarily, heterolith deposits of the Nsukka Formation are tidally influenced lithofacies unit of the formation which accumulated in a lagoon or brackish water space. The presence of quality palynofacies constituents and the consistency of large to medium well-preserved Palynomaceral 2 and Palynomaceral 4 in addition to a few relatively small-sized Palynomaceral 3 and Palynomaceral 1 in all the mudrock-oriented units depicts the lower deltaic plain settings with well-pronounced terrestrial palynomaceral input. These palynomaceral elements confirmed the shallow marine depositional environment with little deep marine input attributes of the formation.

Structureless sandstone facies (Smc)

Structureless sandstone facies (Smc) is made up of structureless sandstone (Smc1) and bioturbated structureless sandstone (Smc2) studied at Ihube and Ikpankwu sections with bed size range of 50 cm to 4 m thick (Fig. 3c). Smc2 was deposited as thin 0.5 m (Fig. 2b), intensely to well-preserved bioturbated, medium to fine-grained consolidated brown to dark brown-coloured sandstone. The reddish, reddish-brown, or dark brown colour adventure of the lithofacies unit exhibits ferrogunised surfaces. There is complete absence of sedimentary structures at Ikpankwu due to the intensity of *Ophiomorpha* burrows bioturbations within the lithology. Smc1 is highly consolidated (Fig. 3c) but grades from well-consolidated rock to partly consolidated sandstone unit at the Ihube express road cut section. A maximum bed thickness of 4 m with sharp contacts at the top and base was observed. The lithofacies unit is dark-brown to dark in colour with crystals of quartz grains. The hand specimen of Smc facies is partly consolidated with quartz grains and the absence of sedimentary structures.

Interpretation

The structureless sandstone units of the study accumulated through gradual aggradation of sands under steady flows and rapid deposition, as the natural deposition of the Smc, but the colour varieties of the facies are products of weathering and ferruginisation of sedimentary rocks prominent in the tropical to subtropical regions. They could have been deposited in tidal channel, flood plain, braided river or tidal flats. The pronounced dominance of *Ophiomorpha* burrows suggests a high- and moderate-energy state of sedimentation whereas prevalence of vertical shafts (Fig. 2b) indicated periodic sedimentation as the major cause of successive upward extension of shafts (Howard and Frey 1984). The marked intensity of trace fossils at the topmost part of the outcrop at Ikpankwu indicates the prevalence of post-storm trace marker species. Well-preserved trace fossils and diligent cover-up of the original sedimentary structures confirm periods of bottom stability (Mode and Odumodu 2014; Mode et al. 2018).

Plane planar laminated sandstone (Pls)

Plane parallel laminated sandstones facies (Pls) is made up of laminated white to light medium- to coarse-grained sandstone (Fig. 3a). The plane limitations are separated by mudstone bands with variable-sized mud chips and grey to brick red colour in some areas of the outcrop. Pls facies has a characteristic bed thickness of 2 m in the middle part of the outcrop.

Interpretation

Plane parallel laminated sandstone facies (Pls) exhibits a systematic regular alternation of relatively thick medium- to coarse-grained sandstone units interlaminated by white clay facies. Tidally influenced channels and intertidal and subtidal coastlines suggest the depositional environment system of the facies.

Discussion

The detailed synthesised palynomaceral and lithofacies investigation of the study upheld the palynomaceral hydrodynamics, provenance and depositional environment inherent in the sedimentary conditions and the interaction between the water real and terrestrial components of the Nsukka Formation deposits. The various sedimentary analytical approaches based on the lithological characteristics of grain size textural attributes, sedimentary structure and microflora particulate organic matter elements of the studied outcrops substantiated (a) the facies association and palynofacies depositional environment and (b) palynofacies hydrodynamics and provenance reconstruction. These validated sedimentary processes in this research are dynamic in the palaeoenvironment system and sequence stratigraphic dimensions of sedimentary basins.

Facies association and palynofacies depositional environment

A combined palynofacies and lithofacies palaeoenvironment of the Nsukka Formation is vital in reconstructing the microenvironment pattern of the upper deltaic plain and lower deltaic plain in addition to marginal marine-influenced outer neritic macroenvironment attributes of the formation. The continental setting-induced palaeoenvironment of the northerly lower facies of the formation indicated in the proposed type area of Umeji and Edet (2008) was documented as lower and upper deltaic plains oscillating from a tidal flat, lagoon, tidal bar, raised bog and reed swamp, while the southerly upper facies of marginal marine-influenced outer neritic conditions of this study was noted as nearshore open marine conditions. These microenvironments are substituted by majority of the eight lithofacies groups inherent in this study which, when combined with the palynofacies phytoclasts, elaborates the depositional environments and sediment transport mechanisms correlative of sandstone saltation. The Nsukka Formation displays traits of high and low energy processes in gradually coarsening upward sequences (FA3) with arrays of oxic and winnowed sea bottom (Fig. 6) from relative sea level drop and intercalation of anoxic fining upwards transgressive shale sequences (FA1). These stratigraphic sequences create an open sea and a higher energy wave/current or tide-influenced shallow marine settings synonymous to lagoonal/brackish water or swamp deposit (Fig. 6 and Tables 1 and 2).

Facies association 1 (FA1) portrays the lagoonal or brackish water/swamp deposit of the shallow marine on-delta macro environment with deep marine influences that comprise black carbonaceous shale facies, carbonaceous mudrock facies, carbonaceous siltstone facies and heterolithic facies. This correlates to palynofacies types XIII, XI/XIII and XI designated as lagoon and lagoon margin in low energy on-delta sub environment, as well as palynofacies types VII, VI, V and VIII designated as upper shoreface, lower shoreface and delta front of relatively enclosed lower energy shelf of Whitaker (1982, 1984) and Whitaker et al. (1992). However, the palaeoenvironment dynamics of the Nsukka Formation mimic on-delta sub-environment in addition to the shore and offshore relatively low energy closed sea of Whitaker (Op. cit.). This was ascertained due to the variable depositional environment obscure of northerly upper and lower deltaic plain, southerly shallow marine with deep marine influences (Okeke et al. 2024; Umeji and Nwajide 2007; Umeji and Edet 2008), western marginal marine to continental setting (Bankole and Ola-Buraimo

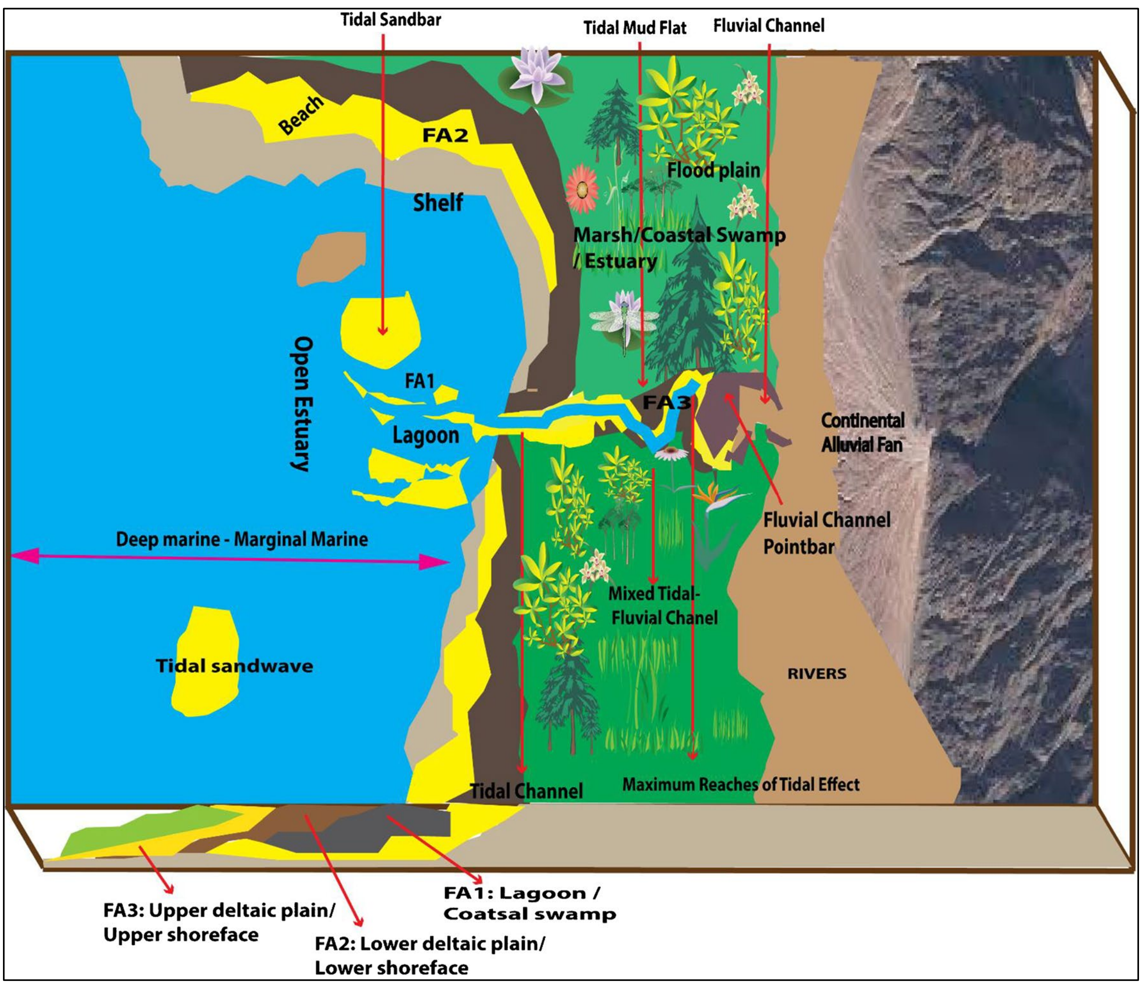


Fig. 6 Conceptual spatial (3-D) and lithostratigraphic stacking packages of the Nsukka Formation facies depositional model of the study area

2017) and shallow marine with deep marine influences in Calabar Flank (Edet and Nyong 1993, 1994) of Nigeria. This is analogous to creating an open sea way of the Trans-Saharan sea. The maximum thickness of the FA1 is 6 m at the Ikpankwu section. The frequent sandstone, siltstone and shale interbeds in the study (Figs. 2 and 3) indicate deposition under fluctuating high and low-energy conditions while the carbonaceous shale normally caps many flood plain pond sequences. The dark grey colour, abundant spindle and equant shaped particles of Palynomaceral 4, the overwhelming abundance of medium- to large-sized well-preserved Palynomaceral 2 and medium- to small-sized brown to dark brown P3 and P1 depict high carbon content in the carbonaceous shales, siltstone and mudrock facies. This is indicative of a well-vegetated and wet palaeoenvironment linked to the lower reaches of a fluvial stream system or lower deltaic plain with deep marine influences. These environment indices are strengthened by the Palynomorph Marine Index (PMI) values (Fig. 4), abundance and diversity of pollen and spore species of *Longapertites* group, *Laevigatosporites* sp. cf *javanicus, P. operculatus, Spinizonocolpites echinatus, Ephedripites regularis* and gonyaulacacean dinocyct species of cf *Kenleyia lophophora,* cf *Kenleyia leptocerata* and other gonyaulacacean dinoflagellate cysts taxa of cf *Spiniferites ramosus* as well as trochospiral forams test lining in the FA1 facies. The pollen and spore microflora are dominated by monocolpate species of the *Longapertites* group, *Spinizonocolpites echinatus* and *Spinizonocolpites echinatus* allocated to the Palmae group that prevailed during the warm-humid tropical climatic conditions during deposition in the Palmae Province. Diversity imprints of terrestrial microflora in the palaeoenvironment of deposition denoted that the highest diversity of palynomorphs of lagoonal settings of Carboniferous and other stratigraphic deltaic deposits (Neves et al. 1973) is indigenous to the ecological space. The typical palynofacies series of the study is similar to the on-delta sub-environment model of Whitaker (1982, 1984) and Whitaker et al. (1992). The absence of any tectonic event during the deposition of the Nsukka Formation, the palynomorph marine index (PMI) value and the high frequency of terrestrially derived phytoclasts of the study confirmed the palynofacies abundance events and indicative of close proximity to the palaeoshoreline. Such events have been reported in many other places, e.g. in the Niger Delta (Oboh 1992), North Atlantic (Habib 1979), Côte D'Ivoire-Ghana transform margin (Oboh-Ikuenobe et al. 1998) and Southeast Region of Nigeria (Okeke et al. 2023).

Facies association 2 (FA2) has an erosional or compression contact with the underlying shale facies of FA1 at the Ihube PortHarcourt-Enugu roadcut (Fig. 3d) typifying the lithostratigraphic architectural modification of the Nsukka Formation as the essence of oil and gas expulsion of the source rock triggered by compressional force. FA2 is made up of siltstone facies, structureless sandstone facies, plane planar laminated sandstone facies and heterolith facies. It consists of medium- to very fine-grained, wave-ripple laminated sandstones, claystone kaolin clay of variable bed thickness range of 10 cm to 4 m and colour fluctuation of white to reddish due to the intense weathering and ferruginisation of the tropics due to sun light. This FA2 is barren of palynomaceral components notwithstanding that the palaeoenvironment synthesis of the lower shore face affirms excellent particulate organic matter and other micropaleontologic tools thrives and preservation. However, the availability of oxygen and sunlight in the 200 m depth of the sea physiography space, which is imbued with abundant macro and microorganism that destroys the organic matter mass which completes the food chain and food web of biological organisms. The trace fossil assemblage in the bioturbated sandstone facies is generally moderate to intense. This FA2, interpreted as a lower shoreface deposit contains the heterolith facies that is distinctively unborrowed, whereas FA2 lithofacies sequences depict a fining upward sequence grain-size profile (Fig. 3a). It was reported that the fine and laminated quality of heterolith facies portrays low-energy depositional environment (Nichols et al. 2016; Dim et al. 2016).

The Upper shoreface FA3 consists of cross-bedded sandstones, bioturbated sandstone, plane planar laminated sandstone and heterolith facies that are barren of palynomaceral elements due to oxygenations and decomposition of plant remains. FA3 is made up of white-yellowish to brown medium- to fine-grained unbioturbated sandstone linked to ferruginisation and weathering effect of sunlight. However, *Ophiomorpha* and *Thalassinoides* were reported from the roadcut outcrop section near Ihube in the hypostratotype of the Nsukka Formation of Umeji and Nwajide, (2007) and other outcrops in the vicinity of Okigwe (Mode and Odumodu 2014). The mud drape thicknesses denote repeated slack water period in tidal environmental setting (Nio and Yang 1991) inherent in upper shoreface deposit. FA3 cross-bedded sandstone consists of planar and inclined types formed by 2-D and 3-D dunes created by strong unidirectional currents in a high-energy, storm-wave-dominated, upper shoreface setting. Sandstone body thicknesses and variable sedimentary structures are indicative of many environmental processes linked with high-energy uni- and bi-directional current, migration of large flow transverse bedforms, slack water mud drapes and low amplitude migrating mega ripple for low angle cross-beds (Okeke et al. 2023) inherent in the study (Fig. 2a). The reported *Ophiomorpha* ichnofacies trace fossils depicts high energy settings present in both shoreface and foreshore sequences. Non-occurrence of macro and microscopic plant debris confirms oxygen attributes of the FA3 reported above and the non-preservation model of the offshore events during sediment deposition (Fig. 6). The evidence of trace fossils in siltstone (Fmts) and sandstone (Smc2) suggest rapid deposition of mass flow indicative of fining upward sequence model observed at Ikpankwu section.

Palynofacies hydrodynamics and provenance reconstruction

The abundance and quality of particulate organic matter in lithofacies depict grain size parameters, sedimentary structures and the hydrodynamic implications of palynofacies in a given lithology. The hydrodynamic implications of P1 to P4 palynomaceral elements (Fig. 5) of structured and unstructured phytoclast, AOM, opaque debris and other particulate organic matter particles with the textural and structural features of shale (Shfc), mudstone (Mfm) and siltstone (Fmt) facies were combined to interpret the depositional mechanisms and provenance. The relationship of low (9%) occurrence of AOM (P1) and high (46%) abundance of terrestrially derived palynofacies groups (P2) and PMI significance reflects changes in the marine environment and verse versa, as recorded in the oscillating non-marine and marine events of the Nsukka Formation (Fig. 4). These relative changes are linked to environmental and climatic mechanisms predominant during sediment provenance, transport and deposition.

The phytoclast essentials of the study are dominated by well-preserved large-sized frequency of P2 (46%) and P4 (22%) and a small number of relatively small-sized P3 and P1, along with pollen and spores (5.5%) and forams test limning and dinocysts (1.6%). The occurrence and abundance of amorphous organic matter (P1) in modern marine sediments support dysoxic to anoxic conditions of the marine realm (Caratini et al. 1983; Tyson 1995). This is because organic matter is better preserved in the absence of oxygen and destroyed in the presence of oxygen due to the biodegradation effect of biological organisms in their ecosystem with respect to the palaeoecology food system. The presence of well-preserved phytoclasts of land and marine origin in the Danian unit of the Nsukka Formation deposits indicates a relative absence of oxygen during deposition. Production, taphonomy and preservation nature of sedimentary rocks denote that the quicker the rate of deposition, the better the prospect of preservation (Coleman, et al 1979; Curtis 1980).

The variable sizes of P1 and PMI values of the Nsukka Formation illustrate transportation and deposition of low buoyant Palynomaceral 1 due to its relatively large sizes and high-specific gravity with its spongy nature which renders it vulnerable to water logging (Whitaker 1982; 1984; Whitaker et al. 1992). Amorphous organic matter of algal detritus (degraded *Botryococcus*) which is made up of degraded material is usually well preserved in areas with mild duration and extent of aerobic degradation (Tyson 1987, 1989). This strengthens the fact that the fine-grained mudrock facies of the Nsukka Formation was deposited in a quiet anoxic environment. However, the allochthonous Palynomaceral 1 of terrestrial source in high-energy environment having undergone long transportation were easily destroyed by virtue of their medium to small sizes since they are prone to physical abrasion. Resin particles which are amongst the famous element of plant debris are an essential particulate organic matter of terrestrial origin. The irregular shape of spindle, equant and slightly rounded forms of the physical disintegration and high marine energy resistance of resin particles are the keys to its high abundance in all the palynofacies-prone strata of Nsukka Formation. Resin particulate organic matter is more abundant and well preserved in tropical and subtropical evergreen forest plant tress (Larsson 1978) ecological space. The abundance and tenacious hydrodynamic diligence of resin in reworked and redistributed sediments of flash floods, fluvial and runoff processes (Fraquet 1987) posit its resistance to physical abrasion and high specific gravity due to its prevalence in high-energy environment and peat-forming settings. They are also profound in high energy environment in Africa (Litwin and Ash 1991), usually encountered in beaches and ancient oxbow lake deposited strata. However, weathering and transport processes of the sandstone facies along with palynomaceral element provenance mechanism analysis reflect fluvial processes which substantiates reworking and redeposition of the sediments by tide and storm activity as the effective main depositional procedure active in the Nsukka Formation depositional settings.

The large- to relatively medium-sized Palynomaceral 4 forms denote its terrestrial origin, sourced from charcoal remains of forest fire since they are virtually of high buoyancy because of their spindle sizes, sharp angles and very low specific gravity of the opaque debris. P4 particles of equidimensional and lath-shaped opaque forms in Wardha Valley Coalfield Maharashtra suggest near-shore oxidising conditions (Murthy et al. 2019). The occasional cellular structure of some opaque and semi-opaque debris (Fig. 5) of the Nsukka Formation posits that the effect of geothermally fusinized and deep burial thermal alteration of P4 particles are mostly on palynofacies of terrestrial plant origin. The hydrodynamic features of large- to medium-sized well-preserved Palynomaceral 2 debris of vegetal origin in shale (Shfc) siltstone (fmt) and mudstone (Mfm) facies are characterised by cuticles (14%) and tracheid which reflects little or no distant transport from terrestrial source before deposition. The P3 plant debris were reported as the most buoyant of the organic matter particle of sedimentary rocks (Whitaker 1982, 1984). This is because the constituents of P3 are the medium to frequently small-sized P1–P4 debris with all the attributes of buoyancy and biodegradation resistance.

Pollen, spores, dinoflagellate cysts and other marine microflora are effective particulate organic matter palaeoenvironmental tool in the reconstruction of the depositional settings and provenance of sandstone units. A good frequency statistical (1.6%) value of dinoflagellate cyst species of cf *Kenleyia* cf. *K. lophophora,* cf *Kenleyia leptocerata* and gonyaulacacean dinoflagellate cysts taxa of cf *Spiniferites ramosus* and trochospiral forams test lining were encountered amidst terrestrial pollen and spores microflora in the shale (Shfc), siltstone (Fmt) and mud (Mfm) facies. These species buttressed the shallow marine setting with deeper marine dinoflagellate influences for the formation. The benthonic trochospiral foraminifera taxa recorded in this study confirmed the marine palaeoenvironment and the provenance of the formation. This type of species has been linked with sediments deposited in waters least affected by fresh water inflow. The microflora dynamics of the Nsukka Formation at Ikpankwu and Ihube area revealed a relatively high diversity, and regular occurrence of monocolpate pollen species of *Proxapertites operculatus, Longerpertites* group, *Spinizonocolpites echinatus* which are frequently recovered in the Palmae Province (Herngreen and Chlonova 1981) suggests mangrove swamp environment consistent with warm and humid climate.

Conclusion

- The combined detailed palynofacies and lithofacies analysis of the formation illustrates eight depositional lithofacies and seven sub-facies of carbonaceous shale facies, claystone facies, mudstone facies, cross-bedded sandstone facies, siltstone facies, heterolith facies, structureless sandstone facies, and plane parallel laminated sandstones facies deposited within low- to high-energy environment. These lithofacies attributes were grouped into three facies associations (FA1, FA2, and FA3) based on the integrated lithofacies and palynomaceral sedimentary synthesis.
- These lithofacies association upheld the depositional model of sediment packages deposited in lagoons and coastal swamps of shallow marine, and lower to upper shoreface environments/upper to lower deltaic plain with outer neritic influences and other distributaries channel network.
- Palynomaceral elements display quality and quantity large- to medium-sized well-preserved P2 and P4 and a limited number of P1 and P3 along with other marine and terrestrial palynomorphs. These palynomaceral dynamic sizes and shapes key events fall within the palynomaceral hydrodynamic system similar to sandstone saltation dynamics significant in the interpretation of the provenance and oscillating palaeoenvironment changing aspect of the Nsukka Formation anoxic depositional space.
- The facies and palynofacies provenance model revealed terrestrial phytoclast dominated shallow marine with tidally influenced outer neritic setting signalled from the quality and quantity of land-derived palynomaceral components in association with few AOM and palynomorphs. Lithofacies, palynofacies provenance and distribution of phytoclasts in fluvial and shallow to deep marine paralic strata of the Nsukka Formation exhibit a perfect geological interpretation model for appreciating the lithological changes associated with sedimentary facies in addition to larger and few diversities of palynofacies in marine and non-marine settings as well as fluctuating salinity events in the water realm.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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