Iranian Journal of Science (2023) 47:73–90
https://doi.org/10.1007/s40995-023-01411-z

RESEARCH PAPER

Depositional Facies and Palynofacies Provenance of Clastic Deposits: Insight from Paleocene Strata in Southeast Region, Nigeria

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Received: 8 July 2022 / Accepted: 3 January 2023 / Published online: 27 January 2023

Abstract

Detailed sedimentary facies and palynofacies provenance studies were carried out on clastic deposits outcropping around the Awka area within the Imo Formation (Paleocene) of the Niger Delta Basin. Seven facies were systematically recognized based on the textural parameters, sedimentary structures and palynological constituents. Interpretation of the prevailing paleoenvironments, palynofacies provenance and depositional mechanisms were derived from the hydrodynamic controls. The sedimentary facies include shales, mudstones, siltstones, heteroliths, cross-bedded sandstones and matrix-supported conglomerates. The palynofacies showed preponderance of amorphous organic matter, marine taxa, opaque particles, with few structured phytoclasts and terrestrial microflora. These palynological microflora constituents are grouped into palynofacies association A and B based on the composition and proportion of the organic particles, stratigraphic position and paleoenvironments of the strata. Facies analysis indicates that the mudrock facies (e.g. shale, mudstone and siltstone) are deposits of deep marine depositional settings with terrestrial input while the sandstones mimic deposits associated with tidal sand waves in shallow sandy seas, braided river and tidally influenced distributary channels. The facies and palynofacies provenance model suggest dominance of terrestrially influenced shallow to deep marine environment evidenced from the abundance of amorphous organic matter and presence of gonyaulacacean dinoflagellate species, *Glaphyrocysta ordinata, G. exuberans,* and pollen of *Proxapertites operculatus, Retitricolporites irregularis* with other accompanying marine forms. In addition, the presence of texturally mature coarse- to fine-grained sandstones, variable sedimentary structures, internal bed geometries and nature of bedding are suggestive of tidally dominated shallow marine settings including distributaries channel network deposits.

Keywords Depositional facies · Palynofacies provenance · Paleocene · Niger Delta Basin · Palynofacies hydrodynamics

1 Introduction

Over the past two decades new studies in palynofacies and facies analysis have resulted in higher resolution palynostratigraphy, microflora origin and provenance with depositional environment interpretations. Sedimentary facies analysis takes into account the physical and chemical characteristics of rocks along with the fossil floral and faunal content of strata, in deciphering the sedimentary processes of deposition which allows a better paleoenvironmental reconstruction (Abbas et al. 2019; Kwetche et al. 2018, Miall 2016; Dalrymple et al. 2012; Nichols 2009; Mial 2006, Reading and Levell 1996). Elsewhere in other areas of the world (Murthy et al. 2019; Isamel and Orhan 2019; Ekwenye et al. 2015), it was established that the emplacement of lithofacies and palynological microfossils are governed by the oxidizing (oxygen depletion), dysoxic and anoxic conditions prevalent during sediment accumulation.

The palynofacies analysis of Combaz (1964), Whitaker (1982, 1984), Whitaker et al. (1992), Tyson (1993, 1995) as well as other numerous investigations have discussed various palynofacies schemes applied in geological studies.

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Palynological and palynofacies remains studies have been carried out on the outcropping Niger Delta Basin (Germerrad et al. 1968; Jan du Chêne et al. 1978; Umeji 2003; Okeke and Umeji 2016; Okeke 2017, Okeke, and Umeji 2018). Previous studies show that sedimentary packages of the Imo Formation (composed of shales, sandstones and lenses of limestones) were deposited under tropical littoral to neritic conditions based on macro faunal assemblages with a Paleocene marine horizon containing gastropods, nautiloids, pelecypods as well as *Myliobatis* and *Rhinoptera* fish teeth (Arua 1980; Anyanwu and Arua 1990). Ichnofossils (*Aulichnites, Ophiomorpha* and *Palaeophycus*) in the sandstone facies indicate deposits of foreshore and shoreface zones of beaches and bars (Stevens et al. 2011; Okeke 2017). Palynofacies content of the Imo Formation shows dominance of structureless organic matter (amorphous organic matter), dinoflagellate cysts and other marine derived microfossils. Other less abundant palynofacies components include pollen and spores, structured phytoclasts, opaque particles, cuticle and resin debris. The organic matter is mainly a mixture of kerogen types II and III (Bustin 1988, Okeke et al. 2021; Okeke 2017). The Paleocene dinoflagellate cysts, *Diphyes bifidum*, *Achomosphaera quadrata, Ifecysta fusiforma,* and *Palaeocystodinum* sp. were described in the Alo-I well by Antolinez and Oboh-Ikuennobe, (2007). Ghafor, (2000), Rull (1997), and Jervey (1992) reported that the boundary of palynological zones help to locate and date sequence stratigraphic surfaces. The palynostratigraphy and palynofacies analysis of Barremian-Maastrichtian Bahariya Formation, northern Egypt indicated that the preponderance of spores and translucent phytoclasts signify regression and shallow marine deposition (Aboul et al. 2019).

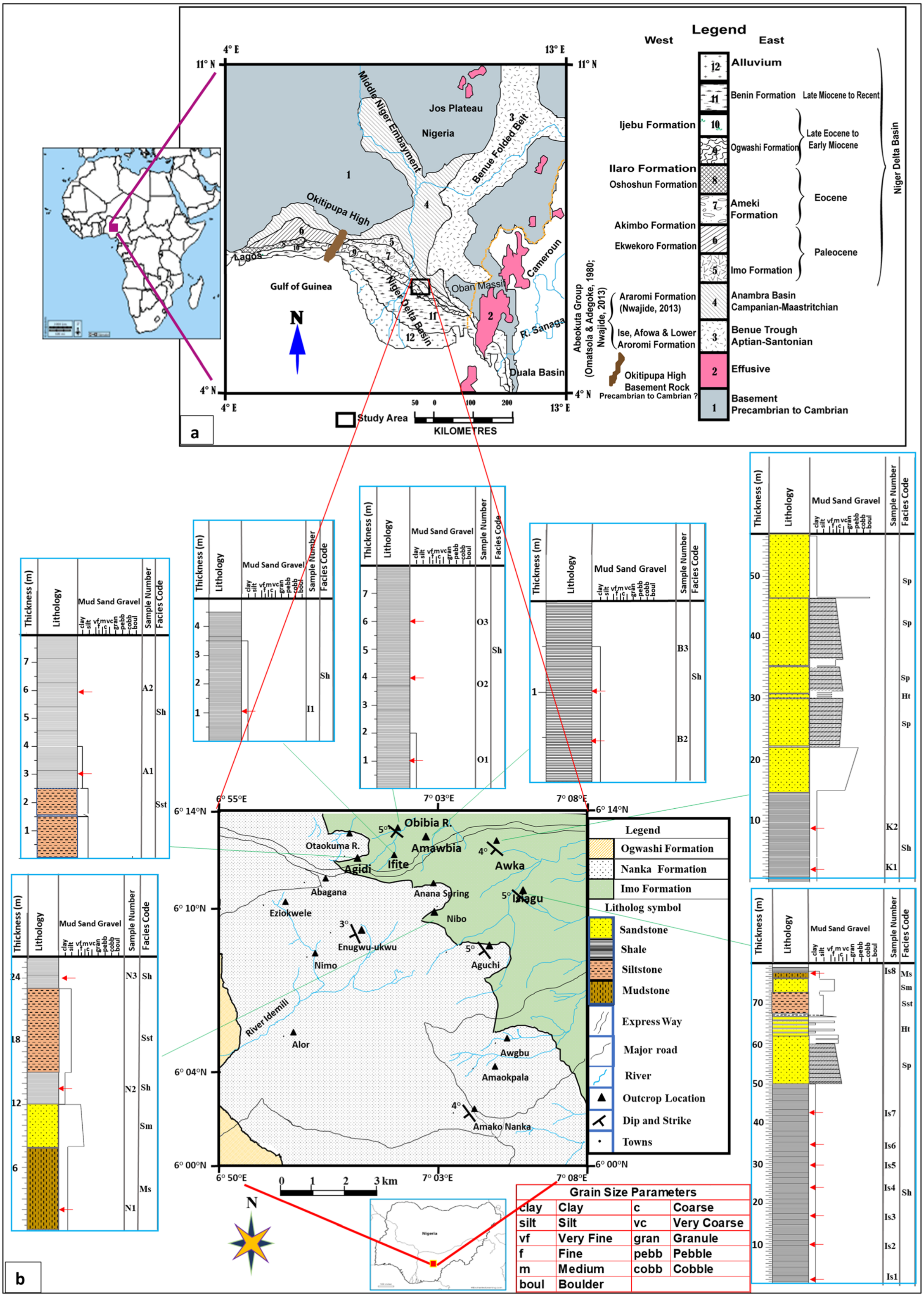
The geological units of the basin on the eastern province are the Imo, Ameki, Ogwashi and Benin formations from north to south, respectively (Fig. 1a). Offshore, the subsurface units are the Akata, Agbada, and Benin formations. The ages and southwestern lithostratigraphic counterparts of these formations were correlated as shown in Fig. 1a (Reyment 1965; Murat 1972; Nwajide 2013; Burke et al. 1971; Onuoha 1981; Wright et al. 1985; Doust and Omatsola 1990). This study tries to interpret the interplay of lithofacies and palynofacies changes and their implications to the depositional environments and provenance prevalent during the Paleocene. The lithologies were not built into facies association since several authors (Anyanwu and Arua 1990; Oboh-Ikuenobe et al 2005; Ekwenye et al. 2015, 2014) have extensively addressed that.

This study introduces detailed facies, palynofacies analysis and its hydrodynamic signatures for the first time in the provenance and paleoenvironment interpretations of the formation in the Awka area. It applies the integration of sedimentary facies and palynofacies approaches in order to elucidate the depositional processes, depositional settings, palynofacies provenance and other geological events during the Paleocene. The specific objectives of the work are: (I) to demonstrate the hydrodynamic implications of the palynofacies associations of the clastic strata; (II) to discuss the palynofacies associations of the Imo Formation and the paleoenvironmental implications. (III) to discuss the high resolution paleoenvironmental processes of the geological models prevalent during the emplacement of the Imo Formation.

Fig. 1 **(a)** The regional geology of southern Nigeria showing the ▶ Niger Delta Basin compared to the western arm of the basin (Modified after Okeke and Umeji 2018). **(b)** The geological map of the study area showing outcrop locations, dip and strike, accessibility and the lithologic logs of the studied sections of the Imo Formation

2 Materials and Method

The study involved systematic field mapping, sedimentary logging with palynological and palynofacies analysis. The palynofacies sedimentary samples are eminently unoxidized, inherent in shales while oxidized sandstones are devoid of palynological elements. The study area is part of the outcropping sections of the Niger Delta Basin, southeastern Nigeria (Fig. 1b). Its boundaries are Latitude −06° 00' to 06° 14' and Longitude −6° 55″ to 7° 08', with an outcropping calculated area coverage of about 728.75 km^2 (Fig. 1b). Detailed sedimentological logging of seven outcrop sections (Fig. 1b) were carried out to obtain the sedimentary facies types, sedimentary structures, rock geometries, nature of bedding and texture of the different rock types in order to reconstruct the paleoenvironmental conditions prevalent during sediment deposition. The ichnofossils with their abundances were also noted. After cleaning, and crushing, each 10 g of sediments from twenty-one rock samples were digested. The samples were treated by the palynological acid maceration technique using hydrochloric (HCl) and hydrofluoric (HF) acids for carbonate and silicates removal, respectively. The 5 g equivalent aliquots for palynofacies studies was dispersed in polyvinyl alcohol, mounted on glass slides and analysed with biological microscope after which a minimum of 200 palynofacies debris were counted in each slide. The detailed field examination and hydrodynamic implications of the various sizes and shapes of the opaque debris, amorphous organic matter (AOM), resin and structured phytoclasts with palynomorph elements of the palynofacies and sedimentary rock types were integrated in the lithofacies interpretation, provenance and reconstruction of the paleoenvironmental settings.


a
b
Legend
West
East
Alluvium
Benin Formation
Late Miocene to Recent
Ijebu Formation
Ogwashi Formation
Late Eocene to Early Miocene
Ilaro Formation
Oshoshun Formation
Ameki Formation
Eocene
Akimbo Formation
Ekwekoro Formation
Paleocene
Imo Formation
Niger Delta Basin
Araromi Formation (Nwajide, 2013)
Ise, Afowa & Lower Araromi Formation
Abeokuta Group (Omatsola & Adegoke, 1980; Nwajide, 2013)
Anambra Basin Campanian-Maastrichtian
Benue Trough Aptian-Santonian
Effusive
Okitipupa High Basement Rock Precambrian to Cambrian ?
Basement Precambrian to Cambrian
Jos Plateau
Nigeria
Middle Niger Embayment
Benue Folded Belt
Okitipupa High
Lagos
Gulf of Guinea
Niger Delta Basin
Oban Massif
Cameroun
R. Sanaga
Duala Basin
Study Area
KILOMETRES
Thickness (m)
Lithology
Mud Sand Gravel
Sample Number
Facies Code
Legend
Ogwashi Formation
Nanka Formation
Imo Formation
Litholog symbol
Sandstone
Shale
Siltstone
Mudstone
Express Way
Major road
River
Outcrop Location
Dip and Strike
Towns
Obibia R.
Otaokuma R.
Amawbia
Awka
Agidi
Ifite
Abagana
Anana Spring
Isiagu
Eziokwele
Nibo
Enugwu-ukwu
Nimo
Aguchi
River Idemili
Alor
Awgbu
Amaokpala
Amako Nanka
Grain Size Parameters
clay Clay
silt Silt
vf Very Fine
f Fine
m Medium
boul Boulder
c Coarse
vc Very Coarse
gran Granule
pebb Pebble
cobb Cobble

3 Results and Discussion

Table 1 summarizes the lithofacies defined for the studied sections of the Imo Formation around Awka area. They are defined based on sedimentary structures and palynofacies evidence named: shale (Fcm), mudstone (Fm); siltstone (Fm) heteroliths (Fl), cross-bedded sandstone (Sp), matrix-supported gavel (Gmg), and other subfacies shown in Table 1. The sedimentary structures, textural characteristics and the palynofacies composition of the sections were also used to interpret the depositional process as well as the depositional environment. The attributes and hydrodynamic implications of these palynofacies elements as well as the sedimentary particles gave insights into the provenance of the sediments (Figs. 2, 3 and Table 1).

3.1 Palynofacies Assemblages

The percentage frequencies of the palynofacies assemblages from the studied sections is shown in Fig. 4b. They include the seven sections studied, in which twenty-one palynofacies samples were analysed. Field and laboratory evidences have shown dearth of the mudrock facies of the outcrops of the Imo Formation in northern area in terms of micropaleontologic forms, especially foraminifera. But this work documents an explore and visibility of palynofacies in depositional facies systems of the outcrops of the Niger Delta basin. The prolific intervals yielded very high frequencies of amorphous organic matter (AOM), palynomorphs, cuticles, structured and unstructured phytoclasts (Fig. 4b). Figure three presents the palynofacies count attributes of the Isiagu section as a representative section. The palynofacies marine components were gonyaulacacean dinoflagellate cysts species of *Glaphyrocysta ordinata, G. exuberans* whereas the terrestrially derived pollen species are *Proxapertites operculatus, Retitricolporites irregularis* and spores which accounted for about 2% of the total sedimentary organic matter content (Fig. 5). From these palynofacies components two palynofacies assemblages were deduced namely, Palynofacies Association A and Palynofacies Association B (Fig. 3).

Palynofacies Association A from the Selandian interval is associated with high frequencies of amorphous organic matter (64%), opaque particles (28%), structured and unstructured phytoclasts (accounted for 1%) each, presence of *Glaphyrocysta ordinata*, *G. exuberans, Proxapertites operculatus, Retitricolporites irregularis* palynomorph taxa. Interpretations from the palynofacies and lithofacies attributes (Table 1 and Fig. 4b) suggest a deep marine environment with pronounced terrestrial input.

The Thanetian strata of the study, regarded as Palynofacies Association B is marked by a decrease in AOM (49%) and opaque particles (3%), incidence of equant (or equidimensional) opaque particles (14%), 5% of unstructured phytoclasts (resin and degraded wood), terrestrial pollen and spores with marine palynomorphs (21%). These palynofacies assemblages and lithofacies signatures of the formation indicate an offshore marine with terrestrially influenced depositional environment (Table 1). The percentage frequencies of other palynofacies assemblages are shown in Figs. 4 and 5.

3.2 Lithofacies Interpretation

Seven lithofacies were described and interpreted based on the grain size parameters and sedimentary structures, whereas the hydrodynamic implications of the amorphous organic matter (AOM), opaque particles, structured phytoclasts with other palynofacies constituents as well as the sedimentary components were synthesized into depositional environments and sediment transport mechanisms that deposited the strata. The lithofacies recognized are shales (Fcm), matrix-supported conglomerate (Gmg), cross-bedded sandstones (Sp), mudstones (Fm); siltstones (Fm), heteroliths (Fl), structureless sandstone (Sm) (Fig. 2). The facies codes and the sample numbers with the lithologies of the studied outcrop sections are indicated in Figs. 2 to 3 and Table 1. The results of the mechanisms of deposition, depositional environments, palynofacies constituents and other sedimentary indices of each lithofacies are shown in Table 1.

3.2.1 Shale Facies (Fcm)—Deep marine

The Fcm facies architectural element is the dominant lithology in the study area and the Imo Formation in general. Excellent well-preserved outcrops of the shale facies (Fcm) were studied at Agidi, Nibo, Ifite, Awka, Nibo and Isiagu (Fig. 1a). The facies occur in association with black carbonaceous shale and blue grey shale (Fcm), non-fossiliferous siltstone (Fm), mudstone (Fm) and fine to medium grained structureless sandstone (Sm).

3.2.1.1 Description and Interpretation The shale (Fcm) facies are dark grey, occasionally carbonaceous but commonly non-carbonaceous, fissile, micaceous, texturally very fine-grained and non-fossiliferous (Figs. 2f and 3c). The lithologic architectural element is laminated and grades from carbonaceous black shale at the bottom to grey at the top around Isiagu. It is overlain with a sharp contact by a 10 m thick, well-sorted white, very coarse to fine-grained sandstone having small-scale planar cross-bedding (Sp2) (Fig. 2c). The variations in the organic content of the

Table 1 Results of the processes of deposition and microenvironments of each lithofacies in the Imo Formation. Fluvial facies code scheme see (Miall 2006, 2016, 1987)

Lithology/ Facies	Facies code	Subfacies	Sedimentary structures	Textural characteristic	Palynofacies composition	Depositional mechanism	Depositional environment
Clay, mud	Fcm		Dark grey and grey fissile shale, wavy- lenticular laminae, regular, parallel-laminated with veins of siltstone	Dark grey, non-carbonaceous, fissile, plastic, micaceous, non-fossiliferous	Overwhelming abundant amorphous organic matter, opaque debris, few structured wood, resin, pollen and spores, occurrence of dinoflagellate, trochospiral forams tests	Settling out of suspension due to quiescence in middle to deep marine setting	Offshore marine shale, deep marine
Matrix-supported gravel	Gmg		Structureless unit, normal grading but no clasts imbrications, inverse grading	Matrix-supported, poorly sorted conglomeratic bed, large angular clasts, no sedimentary structures	Barren	Debris flow in a subaqueous environment in absence of turbulence. (Pseudoplastic debris flow-Mial, 2006)	Fluvial channel System (Braided River), debris flow, sheet flood and stream channel fan
Sand, fine to very coarse, may be pebbly	**Sp**	Sp1—High and medium Cross-bedded sandstone	High and medium angle cross-beds, mud pebbles, *Ophiomorpha nodosa* box	Fine–coarse pebbly, moderately to poorly sorted sandstone	Barren	High-energy uni- and bi-directional tidal currents forming 2-D dunes, migration of large flow-transverse Bedforms	Tidal sandwaves in shallow sandy seas, coastal tidal settings, Tidal bars
		Sp—Mud draped planar Cross-bedded sandstone	Single and double mud drapes, inclined master bed, mud clasts	Medium- to coarse-grained mature sandstone, poorly sorted	Same as above	Migration of straight-crested Bedform, slack water mud drapes	Same as above
		Sp2—Low angle planar cross-bedded sandstone	Coarse to medium grained sandstone, poorly to moderately sorted	Fine- to coarse-grained mature sandstone	Same as above	Low amplitude migrating mega ripple for low angle cross-beds, washed out dune	Same as above
Sand, fine to coarse sandstone	**Sm**		Massive, devoid of primary sedimentary structure	Fine-grained, non-fossiliferous, massive or structureless sandstone	Same as above	Gradual aggradation of Sands under steady flows and rapid deposition, Sediment-gravity flow	Tidal channel, flood plain, braided River, Tidal flats

Table 1 (continued)

Lithology/ Facies	Facies code	Subfacies	Sedimentary structures	Textural characteristic	Palynofacies composition	Depositional mechanism	Depositional environment
Mud, Silt	Fm	Fm1—Carbonaceous mudstone	Thickly—thinly laminated dark and brown, mudstone with veins of siltstone and plastic when wet	Carbonaceous mudstone, micaceous with sand grit	Occurrence of amorphous organic matter, dinoflagellate species, opaque particles, unstructured phytoclasts, little pollen and other plant tissues	Continuous and periodic settling of fines out of suspension due to quiescence	Middle to deep marine, Flood plain, Deltaic environments (offshore normal salinity mudstone)
		Fm2—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
		Fm3—Laminated mudstone	laminated mudstone with siltstone, lenticular parallel bedding	laminated mudstone with streaks dark grey siltstone	Same as above	Same as above	Same as above
		Fm4—Siltstone	Massive, non-fissile and absence of lamination	White, grey and green millimetre silt sized particles, non-plastic. slightly friable/ powdery when dry	Few amorphous organic matter, marine and terrestrial palynomorphs with other land derived microfossils	Settling out of suspension due to quiescence in calm waters often grading into shale or sandstone	Same as above
Sand, Silt Mudstone	Fl		Rhythmic succession of millimetre–centimetre mudstone, shale and sandstone, parallel laminations, flaser and Lenticular bedding	Regular alternations of thin or thick, fine- to coarse-grained sandstone and mudrock layers	Barren	Cyclic oscillation of sediment supply and tidal velocity (High tides and slack tide fallout)	Tidally influenced channels, intertidal and subtidal coastlines

shale (Fcm) in the topmost part of the facies is the result of weathering which causes ferruginization due to the leaching iron oxide from the strata; this ravages the outcrops in this area. North-west of Isiagu, similar carbonaceous shale of about 15 m thick was documented. The facies in Agidi and Isiagu have similar features of dark grey colours and lamination with siltstone that are also gradually undergoing weathering. The facies possess wavy—lenticular laminae, regular and parallel lamination with particles of siltstone and very fine gained sandstone texture. The trends of the facies are shown in Fig. 1a. The shale facies are mostly overlain by mudstone (Fm) and non-fossiliferous siltstone (Fm), facies at Isiagu and some other places.

The Fcm (shale) and Fm facies is associated with overwhelming abundant amorphous organic matter, dinoflagellate species, opaque debris and few structured wood fragments categorized as Palynofacies Association A and B (Fig. 4b). Other sedimentary organic matter constituents are resin, pollen and spores, dinoflagellates cysts and trochospiral microforaminiferal linnings. This type of palynofacies synthesis, in association with quality occurrence of gonyaulacaean *Glaphyrocysta ordinata, G. exuberans* taxa and abundance of amorphous organic matter is common in silts and finer (i.e. mudrock facies) sediments of the Imo Formation. The frequency of the palynofacies components and the photomicrographs are shown in Figs. 3 and 5, respectively.

Fig. 2 **a** Facies and architectural elements Conglomeratic lag of the Imo Formation around Awka area (Gmg). **b** Siltstone facies (Fm) interbedded by mm-cm-thick heterolith facies (Fl) of consolidated ironstone and siltstones. **c** Massive coarse to medium grained sandstone (Sm) of the Imo Formation from the study. **d** The heterolith facies (Fl) of the formation at the Isiagu quarry with normal fault. **e** Cross-bedded sandstone facies (Sp) at Isiagu. **f** The shale facies (Fcm) of the Imo Formation

Mud dominated facies are usually abundant in clastic marine offshore and non-marine depositional settings. The shale facies are deposited during the transgressive systems tract (TST) of the formation which forms the dominant sedimentary facies of the formation. The shale facies are deposited from settling out from suspension of fines due to quiescence marine setting (Table 1). In addition, the grey to dark colours of the shales indicate variations in degree of oxygen levels as well as biological remain during deposition. The palynofacies groups of the Imo Formation reflect deposition in offshore marine environment with little terrestrial influence. The terrestrial influences is supported by the occurrence of pollen and spores (2.5%), as well as 1% of cuticle and degraded wood in Association A (Fig. 4b). The hydrodynamic attributes of cuticle phytoclast (Whitaker 1984; Tyson 1995) propels its long-distance transport down to the basin where they are recovered from offshore marine shales. The organic matter content of the shale facies depicts a dysoxic to anoxic environment associated with good preservation of palynofacies debris and other marine forms. The hydrodynamic implication of kerogen in silts and finer sediments is suggestive of a dominantly deep marine setting with terrestrial non-marine influences.

3.2.2 Siltstone Facies (Fm)

Siltstone facies (Fm4) were deposited around Isiagu, Agidi and Obibia River sections as a bed of about 1.5 m thick (Fig. 2b). It occurs in association with carbonaceous

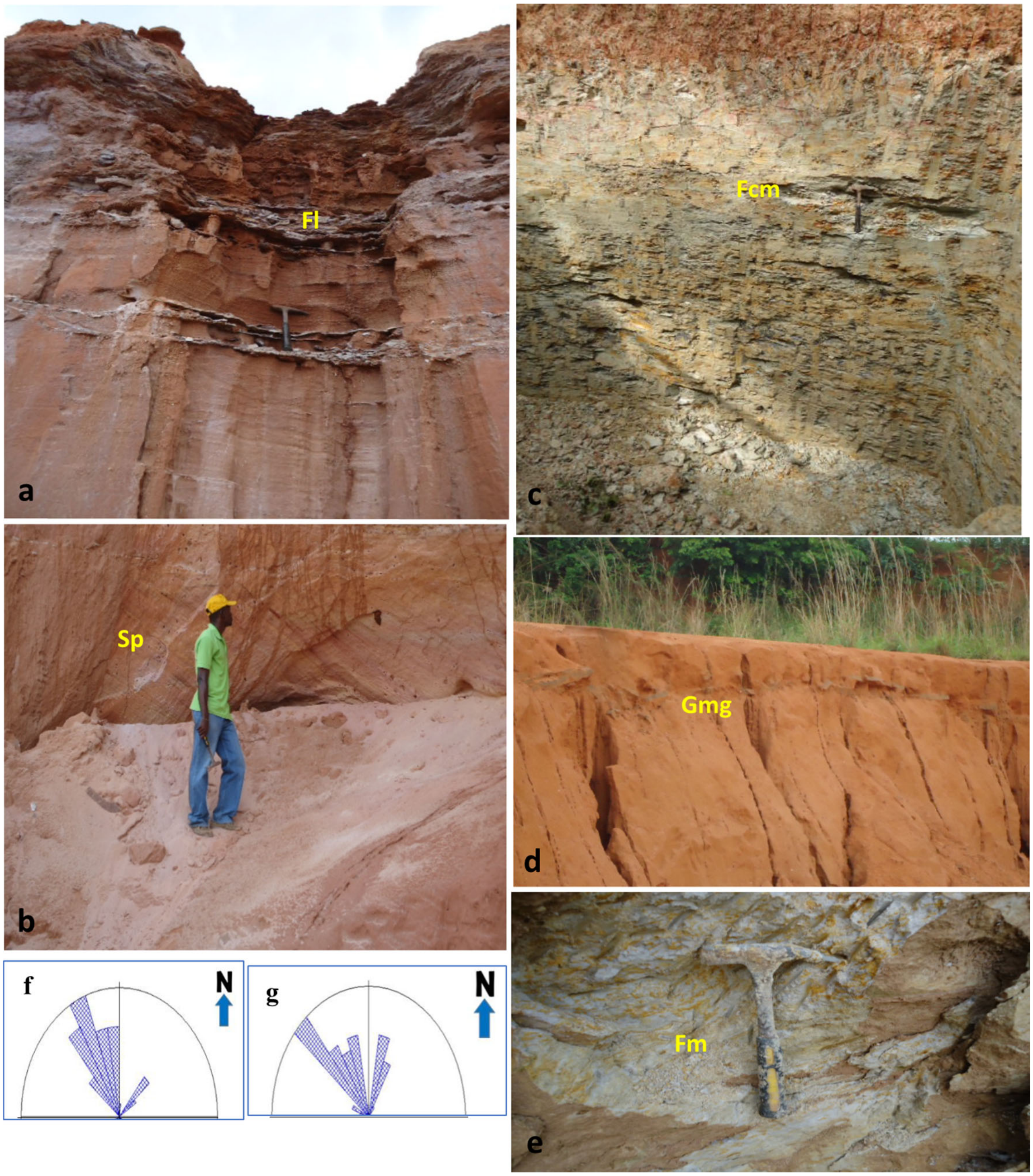


Fig. 3 **a** The heterolithic facies of sandstone and white clay (Fl) of the Imo Formation. **b** High angle cross stratified sandstone facies (Sp) at Awka**.** **c** Shale Facies (Fsh) at the shale mining pit at Agidi showing the mm thick thinly laminated shale. **d** Facies and architectural elements Conglomeratic lag of the Imo Formation around Awka area (Gmg). **e** Light grey mudstone (Fm) of the Imo Formation from the study. **f** and **g** Paleocurrent pattern of the tidal sandwave cross stratified sandstone facies (Sp) in the study from the Awka and Isiagu outcrop

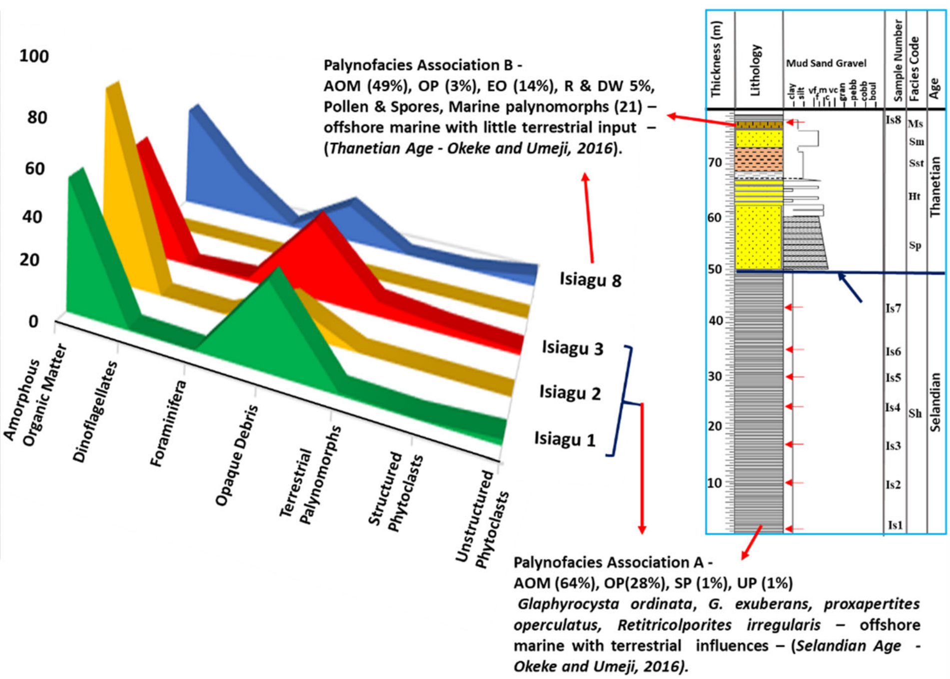
mudrock units of shale and mudstone. The facies at Agidi exhibits white, grey and green millimetre silt sized particles, non-plastic, slightly friable/powdery when dry. The sedimentary structures inherent in siltstone are parallel or wavy lamination, lenticular bedding but the Fm4 facies of the Imo Formation is structureless or massive, non-fissile and non-laminated.

3.2.2.1 Description and Interpretation The hhydrodynamic processes of siltstone facies deposition is engineered by suspension fallout during fair-weather periods. Structureless siltstone are products of rapid deposition of sediments (MacEachern et al. 2008). The wavy—lenticular laminae, regular and parallel lamination with particles of siltstone on the facies indicate mild agitation of the Paleocene waters during the sediment and palynofacies

Palynofacies	Description
Amorphous Organic Matter	Fluffy, yellow-amber and brown structureless dense humic gel-like substances of different sizes, degrees of preservation and shape of about 20 µm to 70 µm. They are of marine in origin formed from the alteration of algal matter.
Resin	Yellow to amber colored stem tissues associated with higher vascular plant with variable sizes of 30 µm to more than 60 µm
Opaque Particles	Opaque particles classified as equidimensional opaque particles, lath- shaped opaque particle and opaque debris. Lath-shaped opaque particles are needle and blade shaped with irregularly shaped sizes while the opaque particles are those without any defined shape. These palynodebris are products of oxidation of translucent woody material during prolonged transport and post-depositional alteration of other terrestrial phytoclast.
Unstructured Phytoclasts	Degraded chemically or bacterially altered irregularly shaped structureless to partly structured phytoclasts without any observable cell structure.
Cuticles	Flat, platy, relatively thin and well-preserved leave remnants that show clear outline of epidermal cells that define its boundaries with distinct upper and lower epidermis still intact. The sizes range from 15 µm to 40 µm.
Structured Phytoclasts	Terrestrially derived structured and relatively structureless lath-shaped and occasional equidimensional well-preserved conducting plants tissues with cellular structures and fringes of structured wood parts of different sizes ranging from 50 µm to > 75 µm.
Marine Palynomorphs	Dinoflagellates, Foraminifera test linings and other remains of marine organisms.
Terrestrial Palynomorphs	Pollen derived from land plants.
Sporomorphs	Embryophytic spores of terrestrial origin susceptible to water logging.

a

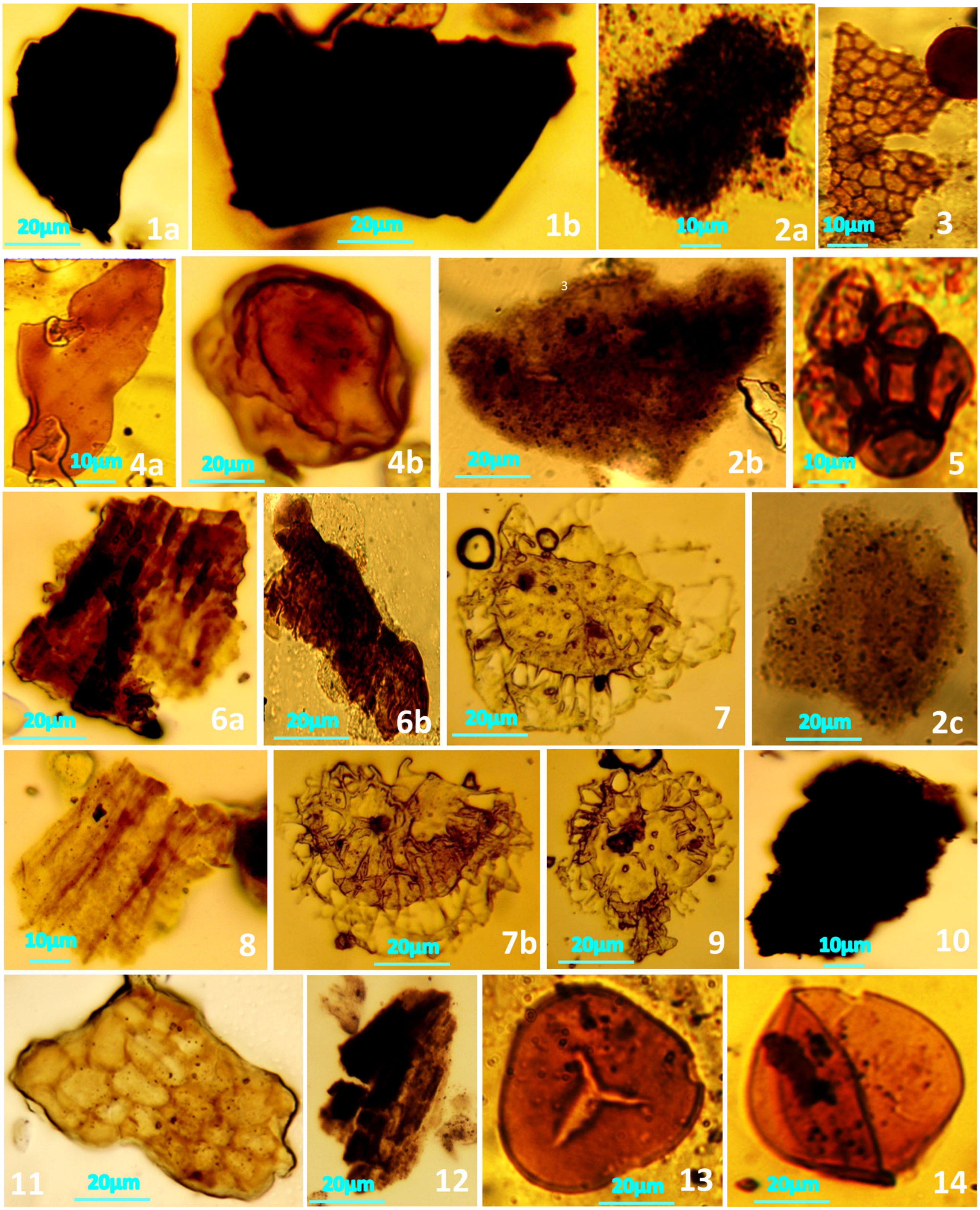
Particulate Organic Matter	Is						
	1	2	3	4	5	6	8
Palynomorphs							
Pollen	1	-	5	-	-		0.3
Spores	-	-	1	-		-	-
Dinoflagellate cysts	0.8	-	-	-	-	-	21
Forams test lining	-	-	1	-	-	-	0.9
Phytoclast (structured)							
Tracheids	0.4	-	0.3	-	-	-	-
Cuticles	-	-	3	-	-	-	-
Plant tissues	-	-	-	-	-	-	0.6
Phytoclast(unstructured)							
Degraded wood	2	-	2	-	-	-	5
Resin	-	-	-	-	-	-	5
Amorphous Organic Matter							
Fluffy- Transparent	10	45	25	-	-	-	20
Yellow - brown	26	40	15	-	-	-	15
Black brown	20	-	11	-	-	-	13
Opaque debris (Opaque)							
Opaque	37	13	35	-	-	-	3
Equant opaque	-	-	-	-	-	-	14
Lath Shaped Opaque	-	-	-	-	-	-	-



b

Fig. 4 a The palynofacies constituents of the Imo Formation sediments with their respective microscopic characteristic. **b** On the left is the abundance percentage frequency distribution of palynofacies components of the representative section of the Imo Formation at Isiagu; the viewgraph

deposition. The siltstone facies grades into shale, mudstone or sandstone in some outcrop sections which demonstrates the mild agitation of the water ream in middle to deep marine environment amidst settling out of suspension due to quiescence in calm waters. High abundance and diversity of palynofacies components of amorphous organic matter, opaque debris along with presence of structured and unstructured phytoclasts and palynomorph taxa (Fig. 5) denote Palynofacies Association B in the siltstone facies. These palynofacies elements of the microflora group suggest a relative offshore marine depositional environment with little terrestrial input.


20µm
1a
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2a
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3
10µm
4a
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4b
20µm
2b
10µm
5
20µm
6a
20µm
6b
20µm
7
20µm
2c
10µm
8
20µm
7b
20µm
9
10µm
10
11
20µm
20µm
12
20µm
13
20µm
14

◀ **Fig. 5** Palynofacies assemblages from the Imo Formation. (Magnifications: × 40). 1a & b. Equidimensional opaque particles. 2a-d. Amorphous organic matter. 3. Dispersed cuticle showing regular rectangular outline. 4a & b. Resin particle Foraminifera Test lining. 6a & b. Degraded structured phytoclasts. 7. *Glyphyrocysta ordinata* Stover and Evitt, 1978. 8. Structured phytoclast. 9. *Glyphyrocysta* sp *cf Adnatosphaeridum multispinosum* Williams & Downie in Davey et al. 1966. 10. Opaque phytoclast. 11. Dispersed cuticle showing regular rectangular outline. 12. Structured phytoclasts. 13. *Cyathidites australis* Couper, 1953. 14. *Triplanisporites sinuosus* Pflug, 1953

3.2.3 Cross-Bedded Sandstone Facies (Sp)—Tidal Sandwaves

The cross-bedded sandstones facies is composed of large-scale high angle cross-bedded sandstone (Sp1), small-scale low angle planar cross-bedded sandstone (Sp2) and mud draped planar cross-bedded sandstone (Sp) sub facies along with heterolith (Fl) facies. The sandstone (Sm) body encountered at the Nibo section is structureless.

3.2.3.1 Description and Interpretation Planar cross-bedded sandstone (Sp) facies were deposited as texturally mature fine—coarse pebbly, moderately to poorly sorted sandstone of various thicknesses and geometry around the Isiagu and Awka areas (Fig. 2a, c, and e). The sedimentary structures include high and low angle cm-thick large-scale cross-stratification (Sp1, Sp2) with foreset dip angle range of 10° to 38° (Fig. 3), mud pebbles and mud drapes (Sp) with few *Ophiomorpha nodosa* ichnofossils. The cross-stratifications are dominated by planar and inclined types formed by 2-D dunes that migrated northwestwards based on the predominant paleocurrent pattern (Fig. 3f, g). Although herringbone and trough cross-beds were uncommon in the study, they have been reported around Ebenebe and Ugwuoba few kilometres west and north of the present study by Ekwenye et al (2014). The mud drapes were deposited between stacked sets of cross-strata on the dune foresets or bottomsets while the paleocurrent pattern shown in Fig. 3f, g, are predominantly unimodal with minor bimodal paleoflow pattern. Other internal structures are small-scale cross-beds, mudclasts, inclined master cross-bedding with millimetre to centimetre cross-beds and occasional minor parallel laminations (Figs. 2e and 3b). The Planar cross-bedded sandstone facies (Sp), is laterally extensive and forms part of the Ebenebe ridge which extends more than 25 km across the formation and terminate at Umunze area southerly. At Isiagu 10 m thick, well-sorted white, very coarse to fine-grained sandstone with small-scale planar cross-beds (Sp2) overlie marine carbonaceous shale facies (Fcm) and underlie marine mudstone (Fm) with a sharp contact. A normal fault cuts across it with a slight displacement of the sand body (Fig. 2d). At Awka area, 8 m and 10 m thick planar cross-bedded medium- to coarse- grained sandstone with mud drapes and *Ophiomorpha nodosa* burrows interbedded by a heterolithic bed of clay and sandstone was deposited in a coarsening upward fashion. The beds strike NE-SW with varying dip amount inclined in SW direction (Fig. 1). Apart from *Ophiomorpha nodosa,* low activities of other ichnofossil fabrics of *Paleophycus heberti, Planolites* sp. and boxworks of *Thalassinoides horizontalis* with well-preserved polygonal structures were previously recorded by Ekwenye et al. (2014).

The dominant large-scale, high (Sp1) and low angle planar cross-beds (Sp2), mud pebbles, mud draped inclined cross-bedding (Sp3), large-scale foresets and master cross-beddings with *Ophiomorpha nodosa* box indicate tidal sandwave deposits accumulated in sandy marine environmental settings. The tidal sandwave sandstones deposits of the study are encapsulated by the enfolding of the sandstone bodies in-between mudrock facies. The sandwaves represent the mesoforms transverse bedforms (2-D dunes) of Miall (1985) originated from 'dynamic flood events during storm-induced run off'. The predominant unidirectional current with minor bimodal paleoflow pattern (Fig. 3f, g) were interpreted to suggest north-west regional net sand transport direction (Ekwenye et al. 2014). The nature of the cross-stratifications was interpreted as tidal current sandwaves by Dalrymple (1984) in the facies analysis of the Bay of Fundy. Mud drapes on the small-scale cross-beds (Sp2) were denoted by Allen (1992) and Olariu et al. (2012) in sandwaves strata. The sandstone units of the study are barren of palynomorph and palynofacies components. The thickness of the sandstone body and the various sedimentary structures reflects variable environmental mechanisms associated 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 (Figs. 2b and 3b). The occurrence of various mud drape thicknesses is an indication of repeated slack water period associated with a tidal environmental setting (Nio and Yang 1991), while succession of stacked cross-strata mimics the same tidal environment limited to the marine realm (Dalrymple and Rhodes 1995; Longhitano 2011). Mud drapes (Sp) on the dune foresets, and presence of compound dunes were noted by Olariu et al. (2012) while Miall (2006, 1985, 1987) illustrated the event of mud drapes dominance in the sandy braided strata as indicating standing of water pools at low stage channel dissertation indicating distal flood plain facies. The 3 m to more than 4 m thick lengths of the cross-beds at Awka area indicate migration of sandwaves in the direction of the predominant tidal current (Fig. 3b). The presence of plane parallel-laminated cm-thick mud beds within the sandstone body indicates periods of low flow velocity of the dunes during tidal current reversals. The long cross-stratification on the sandstone is similar to those produced in large sandbars formed in rivers, since this type of environment and tidal sandwave are capable of exhibiting tidal signatures (Johnson and Baldwin 1996). However, several smaller dunes can form a compound dune in the offshore area where they can reach heights of more than 10 m. The sand bodies' (dune crests) tidal currents are parallel or oriented at low angle with the paleo shorelines. The absence of oscillatory (wave-generated) sedimentary structures such as hummocky cross-stratification suggests protected marine environment, such as a strait or protected embayment that accentuated the currents and inhibited the formation of large waves (Olariu et al. 2012). The sandstones are weakly burrowed with *Ophiomorpha* biogenic structures associated with the environmentally wide-ranging *Glossifungites* ichnofacies consistent with firm, unlithified substrates (Pemberton, et al. 1992; Pemberton and Frey 1985).

3.2.4 Mudstone (Fm)—Shallow Marine

Mudstone facies were deposited around Isiagu, Agidi and Obibia River sections. The facies elements consist of laminated and flaser structured grey carbonaceous mudstone facies (Fm1), massive mudstone facies (Fm2), laminated mudstone facies (Fm3), grey siltstone facies (St), fine-grained sandstone facies and heterolith facies (Fl).

3.2.4.1 Description and Interpretation At the Isiagu section, carbonaceous mudstone (Fm1) was deposited as 2 m thick bed overlain by partly weathered shale. At the Obibia River the mudstone facies (Fm) are carbonaceous (Fm1) and massive (Fm2) as well as thickly—thinly laminated, slightly shaly with thinly laminated siltstones and ichnofacies genera deposited at the Isiagu section. Along Onitsha-Enugu expressway, the siltstones are blue-green, interbedded with consolidated sandstone at the base and gradually grades into the overlying shale. The mudstone (Fm) and siltstone facies are usually underlain by sandstone facies, forming a predominant fining upwards cycle.

Sedimentary structures in mudstones (Fm) are obvious and well pronounced when very fine-grained sands are deposited with mudstone. The predominant structures in the mudstones are thick to thin lamination suggestive of weak suspension currents associated with deposition of muds. They are also emplaced laterally to the main tidal currents where weak currents and long slack water periods aid mud accumulation in normal marine environment (Olariu et al. 2012). The Fm and siltstone facies have abundant amorphous organic matter (49%), opaque debris, structured and unstructured phytoclasts and palynomorph taxa (Fig. 5) associated to Palynofacies Association B. The characteristic sizes and shapes of the palynofacies elements of the microflora associations suggest deposits of offshore marine environment with little terrestrial input. The evidence of terrestrial influences is observed in the presence of pollen and spores (0.3%), degraded wood (5%), plant tissues (1%) and others shown in Fig. 5. The high content and preservation of palynofacies constituents of the organic matter reflect anoxic environment which favour organic matter preservation. The preponderance amorphous organic matter (49%) together with foraminiferal linings (1%) and dinoflagellates support a marine setting.

3.2.5 Heteroliths Faceis (Fl)—Tidal Rhythmites

The heterolithic (Fl) facies is made up of interlamination of medium-fine sandstone and shale, muddy heteroliths of sandstone and mud. They crop out around the Isiagu and Awka area.

3.2.5.1 Description and Interpretation The Fl facies (Table 1) were described as rhythmic interbeds of various amounts of medium to fine sand, mud and clay; forming wavy, flaser and lenticular bedding structures as well as parallel laminations. At Isiagu (Figs. 2d and 3a) the sandstone unit grades vertically into horizontal bands of medium grained sand body at the base and heteroliths of white fine-grained sands caped by thin white clay at the top (Fig. 2d)—a fining upwards motif. The textures of heterolithic (Fl) beds in the study are regular alternations of thin and thick, fine- to coarse-grained sandstone and mudrock. Similar heterolithic structure of Isiagu was observed at Awka area but here, the unit grades into 1 m thick heteroliths of grey clay and very fine sandstone that started with clay bands and terminates with the normal faulted heterolithic unit (Fig. 2d).

The sandwaves facies (Sp) of the formation is overlain by heterolith facies (Fig. 3a). Sandwaves and other shallow marine facies are usually overlain or underlain by coastal, deltaic, estuarine or deeper marine facies (Nichols 2009). The fining upwards heterolithic (Fl) facies is formed from alternating flood-ebb tidal currents and slack water suspension fallout in lower tidal flat (Nichols 2009; Nio and Yang 1991). The heterolithic facies, display flaser or lenticular lamination depending on the sand and mud ratio (Nichols 2009) similar to those observed in the Imo Formation in the study. The sedimentary structures of the facies (Fig. 3d) are attributes of tidally influenced channels or intertidal and subtidal coastlines. Mud drapes, herringbone cross-stratification, reactivation surfaces and heteroliths are strong indicators of tidally influenced transport and deposition (Abouessa et al. 2014). The facies is palynologically barren of organic matter debris.

3.2.6 Matrix-Supported Gravel Facies (Gmg)—Debris Flow, Stream Channel Fans and Braided River

These facies is less common and only outcrops in the Awka section where these deposits were exposed in a quarry. The conglomerates occurred on a poorly weathered unit on top of the outcrop underlain by the coarse gained planar cross-bedded sandstone (Sp). The facies are structureless, coarse to medium grained, unbioturbated and very poorly exposed.

3.2.6.1 Description and Interpretation In this study, the matrix-supported conglomerate facies (Gmg) occur on the 58 m thick quarry section underlain by medium to coarse-grained planar cross-bedded sandstone (Sp). The bed is a 10 m poorly weathered sandstone, interbedded with a 0.2 m of poorly sorted, matrix-supported conglomerate with crudely aligned angular clasts of up to 20 cm (Figs. 2a and 3d). The sandstone unit is structureless, massive with normal grading. The clasts are not in contact with each other and are almost entirely separated by sand matrix (Fig. 2a). The clasts were deposited in a NW–SE direction similar to the paleo current direction (Fig. 3f, g). In hand specimen, the sandstones are medium- to coarse-grained, moderately to poorly sorted without any recognizable structure. The contact between the facies and the underlying bed depicts a sharp contact due to the change in rock colour variations and structures. The matrix-supported gravel (Gmg) facies is barren of particulate organic matter along with ichnofacies fabrics.

Matrix-supported gravel (Gmg) can be formed by debris flow, sheet flood and stream channel fans (Nichols 2009). The high strength-debris flow of the facies triggered the lateral sharp contacts between the sediments of this origin and the underlying bed. The features of the matrix-supported gavel (Gmg) unit are similar to Miall (1992, 2006) model which indicated that the Gmg facies with sandy, mottled, brown clay are deposits of pseudoplastic debris flow (braided fluvial) channel framework whereas Mulder and Alexander (2001) denoted cohesive debris flow for the facies architecture. Matrix-supported conglomerate were also discussed as mud- and debris-flow deposits connected to alluvial fan setting (Collinson 1986; Blair and MacPherson 1992). Similarly, Kwetche et al. (2018) interpreted similar conglomeratic facies from the Duala Basin (Cameroon) as fluvial channel environment sediments. The Gmg facies colour is as a result of ferruginous (Fe^{2+}) indicium synonymous with the tropical rain forest areas especially in quarry sites (Fig. 2a).

The matrix-supported conglomerate (Gmg) unit of the Imo Formation has the features of braided river channel deposits with thickly bedded channelized matrix-supported clasts as well as normal grading signifying braided channel. Usually, coarsest materials are deposited on the channel floor to form an accumulation of larger coarse lag (Figs. 2a and 3d). Among the features of braided river succession (Nichols 2009) is an erosion surface indicating the base of the channel overlain by a basal lag of coarse clast deposit. Similar features of this facies were noted by Abbas et al. (2019) in the Himalayan foreland basin Pakistan, where the stratified gravel and matrix-supported gravel marks erosive basal units and onset of fining upward successions interpreted as braided fluvial units emplaced along the Indus River channel.

3.3 Paleoenvironment Interpretation

Considering the lateral and vertical variations of the facies with the abundance of palynofacies associations linked with the dominance and dynamics of amorphous organic matter (AOM) and other marine forms, it is evident that the studied mudrock facies (Fcm, Fm) of the Imo Formation were deposited in an offshore marine environment amidst terrestrial influences. The mudrock facies of the Imo Formation is the major outer neritic deposits of the outcropping Niger Delta Basin. The basal mudrock strata (Fig. 2f) yielded prolific AOM (64%), marine palynomorphs and opaque debris. The richness of amorphous organic matter (AOM) results from suboxic-anoxic conditions, and low-energy environments associated with deposition of clay and silt sized materials (Simonetta et al. 2018; Tyson 1995). The paucity of the degraded wood (5%) and plant tissues of terrestrial origin demonstrate relative distal deposition far from the reaches of the land vegetation ecosystem. In each lithofacies section, palynofacies signatures vividly reflected the lithofacies variations. The sedimentary organic matter is absent in coarse to fine-grained sandstone (Sp, Sm) and clayey heterolithic units (Fl) and abundant in the shale, siltstone and carbonaceous mud facies (Table 1). This effect is linked to environmental fluctuations resulting from changes in water energy and oxygen content along with deposition away from the parent vegetation. The energy intensity and well oxygenated conditions of the coarser sandstone fractions led to no deposition or the destruction of the amorphous organic matter, which outweighed the preservation rate of particulate organic matter (POM) in the area.

The mudrock facies of the Imo formation are overlain by the sandstone facies (Table 1) strongly affected by the interaction of tide, storm and wave dynamics. The sandstone strata are conspicuously swatheing in-between the lower and upper mudrock facies (Fcm, Fm). The sedimentological characteristics of the sandstone body with inherent large-scale high and low angle cross-beds, mud drapes, inclined cross-bedding, large-scale foresets and master cross-beddings with ichnogeneric fabrics illustrate tidal sandwaves sediments accumulated in sandy marine settings or proximal marine setting. The tidal imprints are inherent in the mud draped high and low angle cross stratified sandstones with paleocurrent direction showing a predominant unimodal pattern (Figs. 2e and 3b). This signifies unidirectional advancement of the tidal currents. Debris flow in alluvial fans, stream channel or braidplain environment is evident from the conglomeratic facies (Gmg) associated with river/stream channel settings, braided river as reconstruct from the heterolithic units. However, various reports (Anyanwu and Arua 1990; Oboh et al. 2005) suggested delta front and fluvial channel of an estuarine fill for the sandstones of the Imo Formation. Recently Ekwenye et al. (2014) argued that the lithofacies and stratigraphic succession of the Imo Formation displayed tidal signatures and marine ichnofossils; noting that the sandstone bodies were enclosed in shallow marine shales and thus, mirror tidal sandwave sediments deposited in marine environment.

The sea level dynamics during the sandwave sediment (Sp) deposition gradually gave way for the outer neritic upper mudrock facies starting with the heterolithic facies of sandstone and white clay (Fig. 2d). The wavy-lenticular laminae, regular and parallel lamination with particles of siltstone facies on the shale facies indicate mild agitation of the Paleocene waters during the sediment deposition. This also point to the influence of wave or tidal action during the deposition of the strata. The Palynofacies Association B tied to the upper mudrock facies (Fcm, Fm) is characterized by a slight drop in AOM to 49% when compared with the constituents of Palynofacies A. Prolific occurrence of dinoflagellate cysts (21%), and other marine forms as well as paucity of terrestrially derived microflora of the assemblage, signify marine shale deposited in a quiet water environment. The decline in the amorphous organic matter in this part although abundant does not necessarily illustrate gradual shallowing up, and relatively oxygenated waters since the dinoflagellates peaked at this point. Mathematically, the amorphous organic matter abundance adjusted to the increased marine forms accentuated by dinoflagellate cyst values which were few in the Palynofacies Association A. The results of Palynofacies Associations A and B show preponderance of gonyaulacacean type dinocysts which thrive most in areas of upwelling where availability of nutrients is evident. This is supported by the black carbonaceous nature of the mudrock facies produced in areas least affected by fluvial input and oxygenation. The abundance of open marine gonyaulacacean cysts, gonyaulacacean/peridinacean ratio, dinoflagellate/pollen and spore ratio and other sedimentological evidence imply open marine environment with terrestrial influences for the Imo Formation (Okeke 2017). This implies a predominant distal marine deposition for the shale units which is substantiated by paucity of terrestrial pollen and spores (0.3%) and other terrestrially derived particulate organic matter. The signatures of the debris flow, sheet flood and stream channel processes are domiciled in the matrix-supported gravel (Gmg) facies interpreted as alluvial fan, braided river channel deposits or marine gravel of Mulder and Alexander (2001) comprising thickly bedded channelized matrix-supported conglomerates.

3.4 Palynofacies Hydrodynamics and Provenance Interpretation

The hydrodynamic implications of the amorphous organic matter, opaque debris, structured and unstructured phytoclast and other sedimentary organic matter particles together with the sedimentary grain size and structures of shale (Fcm), mudstone (Fm) and siltstone facies were integrated to interpret the provenance and depositional mechanisms since the sandstone facies are barren of sedimentary organic matter. The Imo Formation is a predominantly transgressive mudrock formation with a regional progradational sandstone facies of various thicknesses, shades of colour, varying sedimentary geometries and structural intensities across the basin (Figs. 2 and 3). Changes in the relative abundance of sedimentary organic matter in palynofacies assemblages are linked to environmental and climatic mechanisms prevalent during sediment provenance, transport and deposition. Studies in the Niger Delta Basin have shown that the distribution and abundance of sedimentary organic matter is associated with the age and facies changes of the strata. This is because facies changes (vertical or lateral) associated with biological, chemical and physical component attributes of the formations are the distinguishing features of the Niger Delta Basin (Fig. 1b). The paleoenvironment reconstruction based on palynofacies is majorly sustained on the forms recovered from the shale (Fcm), siltstone and mudstone (Fm) facies (discussed above under lithofacies analysis section), the only palyniferous lithofacies of the formation (Table 1) since the sandstone components are barren of sedimentary organic matter.

The organic components are dominated by amorphous organic matter (64%) and other marine palynomorphs (0.8%) associated with relatively reduced salinity marine environment (Fig. 4b). Abundance of amorphous organic matter in modern marine sediments is indicative of dysoxic to anoxic conditions (Caratini et al. 1983; Tyson 1995). This is similar to the depositional environment interpreted in the formation. Studies in Peru indicated that Cenozoic sediments were swamped by finely particulate amorphous organic matter as a result of anaerobic bacteria degradation and productivity at the water realm analogous to events in the study and other tropical zones (Ten Haven et al. 1990;

Powell et al. 1990). The high occurrence of amorphous organic matter which were considered to be of low buoyancy because of their large sizes and high specific gravity with their spongy nature rendering it susceptible to water logging (Whitaker 1982; 1984; Whitaker et al. 1992) confirmed that the fine-grained facies of the Imo Formation accumulated in a quiet anoxic environmental setting. The equivalent allochthonous amorphous organic matter (AOM) of terrestrial origin in high-energy environment, which have undergone transportation, would have been readily destroyed since they are susceptible to physical abrasion. Besides, the high occurrence of amorphous organic matter in the Cretaceous sediments from Drazia-1 well, Abu Roash Member North Egypt were recently interpreted as distal dysoxic-anoxic shelf environment deposits based on microfloral ternary diagram plots (Nabil et al. 2019; Isamel and Orhan 2019).

The absence of these equidimensional particles and the abundance of opaque debris (Figs. 4b and 5) is environmentally driven and indicates that the recovered equidimensional opaque particles are mostly of marine origin. This is because sediments with opaque particles of terrestrial origin (i.e. charcoal) would have been swamped by lath opaque debris and associated equidimensional opaque particles considered to be virtually of high buoyancy because of their spindle sizes, sharp angles and very low specific gravity. Elsewhere in Wardha Valley coalfield Maharashtra, the presence of opaque and equidimensional debris indicates near shore oxidizing conditions (Murthy et al. 2019). The lack of lath shaped opaque debris (Fig. 5) also suggests very low winnowing activity but the presence of few rounded shaped opaque particles in the mud (Fm) and siltstone facies are indicative of reworking, where sediments previously deposited in the shale facies (Fcm) were regurgitated during the onset of the emplacement of the mud (Fm) and siltstone facies. In a research carried out by one of the authors integrated provenance and paleogeography examination of the Imo Formation, it was substantiated that sediments of the unit in general are eroded and reworked from the Cretaceous older Anambra Basin. All the same, reworking of the sediments is possible since the sandstone members of the formation interpreted as dominant tidal sandwave with diagnostic mud drapes and other accompanying sedimentary structures are deposits of tidal settings (Table 1). The sediments are overwhelmed by erosion and subsequent redeposition of strata. This shows the presence of active tidal current in the Paleocene sea.

The hydrodynamic attributes of few structured phytoclasts of vegetal origin in shale (Fcm) and mudstone (Fm) facies dominated by cuticles and tracheid (1%) depict slight terrestrial influences. This type of plant debris, categorized as palynomaceral 3 (Whitaker 1982, 1984), are considered the most buoyant of the organic matter constituents of sedimentary rocks. The low numbers and sizes (15–40 μm) of these terrestrial phytoclasts show that they have undergone significant transport down the basin where they were deposited away from their parental vegetation. The paucity of terrestrially derived particulate organic matter in shale (Fcm), siltstone and mud (Fm) facies were validated by palynofacies and field evidence. The low occurrence and sizes of these land derived palynological organic matter also reflect long-distance transport away from the parent plant but also the absence of thick forest vegetations. Sedimentological and palynological evidence suggest lateral facies changes of the formation southwards due to the basin geometry (not discussed in details in this work) around Umuasua (ie location of the K/Pg boundary) and Bende area where the strata are completely more marine with an exclusive very black pelagic carbonaceous shale facies (Fig. 1b).

Pollen, spores, dinoflagellate cysts and other marine and non-marine elements recovered after the acid palynological processing techniques have been established as an unequivocal paleoenvironmental tool in the evaluation of the depositional settings. There is paucity of terrestrial pollen and spores in the shale (Fcm), siltstone and mud (Fm) facies, which buttressed the marine setting with terrestrial influences for the formation. The occurrence of *Proxapertites operculatus* currently encountered in the Palmae Province (Herngreen and Chlonova 1981) in conjunction with Amanoa type *Retitricolporites irregularis* suggest mangrove swamp environment associated with warm and humid climate. The terrestrial influences attributed to the formation are evident in the presence of few resin (5%) particles. The most prolific producers of resin are tropical and subtropical evergreen forest tress (Larson, 1978). Resin was associated with reworked and redistributed sediments by flash floods, fluvial and runoff processes (Fraquet, 1987). It is also associated with high-energy environment in Africa (Litwin and Ash 1991), commonly recovered from beaches and ancient oxbow lakes. The small sizes and few resin particles recovered from the Imo Formation were transported down the basin through rivers, notwithstanding their acclaimed resistance to physical abrasion and more importantly high specific gravity which makes them prevalent in high-energy setting and peat forming environment (since they can be reworked and redistributed in sediments). However, the depositional facies and palynofacies provenance analysis shows that the bulk of sediments of the studied formation were transported through fluvial processes, which supported a possible reworking and redeposition of some strata by tide and storm processes.

The occurrence of dinoflagellate cysts species is important in deciphering the depositional environment and provenance of a given sediment. The marine dinoflagellate cysts taxa (21%) dominated by the gonyaulacalean *Glaphyrocysta ordinata* and *G. exuberans* suggests (open marine) deepening of the basin during the Thanetian (Fig. 4). Batten and Stead, (2005) had posited that open marine associations are dominated by palynomorphs of marine origin together with subordinate organic matter of aquatic habitat. It is a well-known fact that marine forms vary in abundance in area of oceanic upwelling and are equally scarce in regions where the organic matter is consumed by marine organisms and degraded by oxygen. This type of environment is similar to that of Imo Formation where the presence of the gonyaulacalean *Glaphyrocysta ordinata,* and *G. exuberans* and the abundance of amorphous organic matter, common in silts and finer sediments (i.e. mudrock facies) is suggestive of a deep marine setting. The trochospiral foraminifera test linings (Fig. 5) uphold the marine environment for the formation and have been associated with this type of setting in old and modern sediments especially in waters least affected by fresh water inflow.

4 Conclusions

The hydrodynamics of the palynofacies and lithofacies attributes of the studied strata were integrated in the reconstruction of the provenance, depositional mechanisms and environmental conditions of the formation. Seven facies were described and interpreted based on the palynofacies constituents, textural parameters and sedimentary structures synthesized into paleoenvironments in addition to processes that deposited the strata. Various depositional mechanisms interpreted for the strata includes accumulation through settling out of suspension due to quiescence for the mudrock facies while the sandstones majorly show varying degrees of high-energy uni- and bi-directional currents, migrating large flow-transverse bedforms, slack water mud drapes, low amplitude migrating mega ripples for low angle cross-beds. The conglomerates and heteroliths mimic debris flow in a subaqueous environment in absence of turbulence as well as cyclic oscillation of sediment supply and tidal velocity (i.e. high tides and slack tide fallout), respectively. Palynofacies A and B were deduced from the study of amorphous organic matter, opaque organic matter, structured and unstructured phytoclast and palynomorphs. The abundance of amorphous organic matter in the sediments in conjunction with gonyaulacalean *Glaphyrocysta ordinata, G. exuberans* chorate cysts and *Proxapertites operculatus* and *Retitricolporites irregularis* terrestrial taxa and other supplementary marine species, indicate a dominantly deep marine environment with relative stagnant bottom and minor terrestrial influences for the mudrock facies. In the light of this, the depositional environments of the sandstone bodies were dominated by tidal sandwaves in shallow sandy marine and other tidally influenced environments interpreted for the sandstone bodies. Palynofacies and sedimentary facies interpretations elucidated the provenance, depositional environments and cycles associated with dynamic micro environments and palynofacies events associated with the phytoecological space of the Imo Formation water realms.

Acknowledgements The authors appreciate the reviewers and journal editors for the painstaking, diligent and unflagging revision of the work. We are grateful to Mary Rosa Mystica, colleagues, and friends in the Department of Geology, University of Nigeria, Nsukka, for their support, suggestions and encouragement.

Author contributions O.P.U conceptualized and supervised the study. K.K.O., O.P.U., N.A.U. and O.C.U. carried out the field work, laboratory analysis and the palynofacies provenance interpretations of the work. C.P.D., O.C.E. and C.O.M. are the sedimentology specialists who dealt with the depositional facies interpretation of this research.

Funding The authors declare that no funds, grants or other supports were received from any source during this research.

Declarations

Conflict of interest The authors declare that they have no conflict of interests to disclose.

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