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LITHOFACIES INTERPRETATION USING CORE PHOTOS FROM DIFFERENT WELLS IN THE NIGER DELTA: INSIGHTS FOR RESERVOIR CHARACTERIZATION AND EXPLORATION

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Abstract

The interpretation of lithofacies using core photos is a valuable tool for reservoir characterization and exploration in the Niger Delta. Core photos were used instead of the cores themselves because they provide a quick and cost-effective way to analyze the lithofacies present in the cores. This study analyzes 15 core samples from wells in the Niger Delta to identify and describe lithofacies through visual inspection of core photos. The identified lithofacies include various types of sandstones with different sedimentary structures, as well as heterolithic deposits and fossiliferous sandstones. The spatial distribution of the lithofacies provides insights into their depositional environments and hydrocarbon potential. The study contributes to the understanding of subsurface geology and provides valuable information for reservoir characterization and exploration in the Niger Delta. Quality control measures were implemented to ensure accuracy and reliability of the results. Overall, the study enhances our understanding of the depositional history of the area and the characteristics of its subsurface reservoirs.

Keywords: Niger Delta, lithofacies, core photos, reservoir characterization, exploration

Introduction

The Niger Delta is a prolific hydrocarbon province in West Africa, with extensive oil and gas reserves (Short and Stauble, 1967). The area is characterized by complex depositional environments that have resulted in heterogeneity in the subsurface geology (Ojo and Adekeye, 2017). The interpretation of lithofacies using core photos is a valuable tool for reservoir characterization and exploration in the area (Ali, 2016). Lithofacies analysis provides information on the depositional environment, sedimentary processes, and properties of the sedimentary rocks, which are important for evaluating reservoir quality and hydrocarbon potential. In the Niger Delta, lithofacies analysis has played a crucial role in the exploration and production of hydrocarbons. The Niger Delta is a sedimentary basin located in Nigeria, and it is one of the most prolific hydrocarbon provinces in the world. The basin is characterized by a complex depositional history, which has resulted in the deposition of a variety of lithofacies, including sandstones, shales, and claystones. The lithofacies distribution and properties in the Niger Delta are important for understanding the reservoir characteristics and hydrocarbon potential of the different intervals.

In this study, we present a lithofacies interpretation of core photos from 15 wells in the Niger Delta, based on visual examination of the core photos. The study provides insights into the distribution and properties of the lithofacies, which are important for reservoir characterization and exploration in the Niger Delta.

Materials and Methods

Study area and Location

The Niger Delta is a sedimentary basin located in Nigeria (Figure 1), and it is one of the most prolific hydrocarbon provinces in the world. The basin covers an area of approximately 75,000 km² and extends offshore into the Gulf of Guinea (Ali, 2016). The Niger Delta is characterized by complex depositional environments that have resulted in heterogeneity in the subsurface geology (Ojo and Adekeye, 2017). The lithofacies distribution and properties in the Niger Delta are important for understanding the reservoir characteristics and hydrocarbon potential of the different intervals. In this study, we present a lithofacies interpretation of core photos from 15 wells in the Niger Delta, based on visual examination of the core photos.

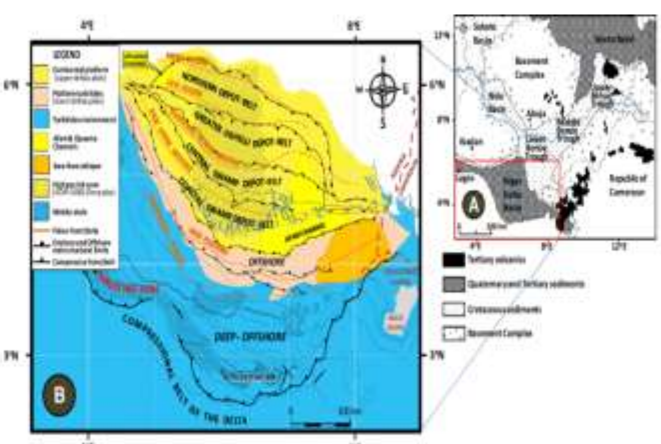

Figure 1 Geologic map of Nigeria showing the location of the Niger Delta Basin (a) (redrawn from Ebong et al. 2017) and sectional map of the Niger Delta depobelts and structural limits (b) (Redrawn from Doust and Omatsola 1990)

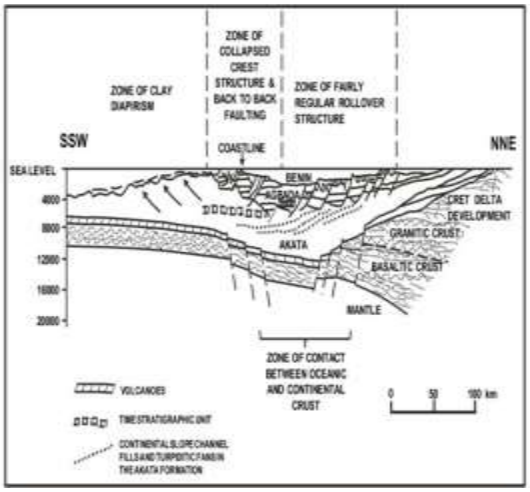

Figure 2 Schematic dip section of the Niger Delta Basin showing stratigraphic successions. (Redrawn from Whiteman 1982)

Aim and Objectives of study

The aim of this study is to interpret the lithofacies of core photos from 15 wells in the Niger Delta, based on visual examination of the core photos. The lithofacies distribution and properties in the study area are important for understanding the reservoir characteristics and hydrocarbon potential of the different intervals.

The objectives of this study are:

1. To identify and describe the lithofacies present in the core photos from the study area.
2. To determine the spatial distribution of the lithofacies within the study area.
3. To provide insights into the depositional environments that contributed to the formation of the different lithofacies.
4. To evaluate the reservoir properties of the different lithofacies, including porosity, permeability, and fluid saturation.
5. To assess the potential of the different lithofacies as hydrocarbon reservoirs in the Niger Delta.

By achieving these objectives, this study will contribute to the understanding of the subsurface geology and hydrocarbon potential of the Niger Delta, and provide valuable information for reservoir characterization and exploration in the area.

Core Sampling and Preparation:

The first step in the study was to obtain core samples from 15 wells located in the Niger Delta region. Core samples were collected at different depths to ensure representation of the different lithofacies present in the subsurface geology. Once the core samples were obtained, they were prepared for analysis. The core samples were cut and polished to expose the interior surfaces, which were then photographed to create core photos. The core photos were used for visual inspection and lithofacies identification.

Core Photo Selection:

One core photo was selected from each well, which represented the lithofacies distribution throughout the core. The selection of the core photos was based on their representativeness and quality. Core photos that showed clear and well-defined lithofacies were selected for analysis.

Lithofacies Identification:

To identify the lithofacies present in the core samples, the core photos were examined visually. The mineralogy, texture, and sedimentary structures were observed and recorded. This information was used to identify the different lithofacies present in the core samples. It is important to note that the lithofacies identification was based solely on visual inspection of the core photos. No petrographic analysis or well log correlation was conducted.

Quality Control and Assurance:

To ensure the accuracy and reliability of the results, quality control and assurance measures were implemented throughout the study. These measures included the use of standardized procedures for core sampling and preparation, as well as rigorous selection criteria for the core photos. Additionally, the lithofacies identification was conducted by experienced geologists (The authors) who were trained in visual interpretation.

Overall, the sample selection and analysis process was crucial in obtaining the necessary data for lithofacies interpretation using core photos. It allowed us to identify the lithofacies present in the core samples and gain a better understanding of the subsurface geology in the Niger Delta region.

Results and Discussion

The lithofacies data obtained from the core photos is presented and interpreted. Their significance for reservoir characterization and exploration in the Niger Delta region are also highlighted.

Lithofacies Description and Interpretation

Cross-bedded coarse gravelly sandstone ScX

The lithofacies described in Figure 3, represents a poorly sorted, gravelly to coarse-grained sandstone with bimodal sorting and trough cross-bedding as the dominant physical sedimentary structure. The lithofacies thickness ranges from 1 to 20m with strata ranging from 0.1 to 0.6m thick.

The lithology of this facies is characterized by poorly sorted, coarse to very coarse-grained sandstone, commonly with granules and pebbles. Pebbles and granules are predominantly of extra-formational lithologies, typically quartzose, and range in size from 0.2-1cm. The bimodal grain size sorting in the form of rhythmically alternating coarse-granular and medium-coarse grained foreset strata is commonly developed. Individual foresets are of 0.5-5cm thickness and typically normally graded.

The visible clay is generally absent in this facies but occurs locally as mm thick foreset drapes, burrow linings, and clay pebbles. Heterolithic bottomsets are also locally developed comprising thinly interbedded current rippled sandstone and clay drapes. Trough cross-bedding is the dominant physical sedimentary structure, with subordinate tabular cross-bedding. Low-angle cross-bedding, horizontal stratification, and massive bedding may occur locally. Sets are bounded by sharp erosional surfaces with set heights ranging from 0.1-0.6m.

The interpretation of this lithofacies suggests that it represents the deposits of subaqueous dunes which formed under strong, lower flow regime currents. The dunes were both straight crested (type 1, or 2-D dunes) giving tabular stratification and sinuous, crescentic crestlines with trough-shaped scour pits (type-2 or 3-dunes) producing trough cross-stratification. The coarse-grained character of the sediments indicates fluvial sourcing, while the trace fossil assemblage records a stressed brackish marine environment.

The bimodal sorting of many sets indicates cyclic, short term fluctuations in current strength and is interpreted to reflect tidal current modulation of the fluvial currents which supplied the coarse sediment. The generally poor sorting of the sands is characteristic of fluvial channel deposits, with the occurrence of restricted brackish marine ichnofauna indicative of a coastal environment. Comparable coarse-grained cross-strata have been documented from the thalwegs of fluvial channels and fluvial-dominated estuarine channels.

Overall, this lithofacies provides important information for reservoir characterization and exploration in the Niger Delta, and the comparison of our results with previous studies can further enhance our understanding of the depositional history of the area.

To compare our results with previous studies, we referred to the work of Nwajide (2013), who conducted a detailed analysis of lithofacies and depositional environments in the Niger Delta. Nwajide (2013) identified a similar lithofacies, which he termed the "fluvial-dominated estuarine channel sandstone." This facies was characterized by trough cross-bedding, bimodal sorting, and the presence of extra-formational lithologies.

Similarly, a study by Kogbe (1980) also reported the presence of fluvial-dominated estuarine channels in the Niger Delta, with sedimentary structures such as trough cross-bedding and horizontal stratification. Kogbe (1980) also noted the importance of tide-modulated fluvial currents in the formation of these channels.

Our study adds to the existing literature by providing a detailed lithofacies interpretation using core photos, which enhances our understanding of the depositional environments and reservoir characteristics in the Niger Delta.

Figure 3 Cross-bedded coarse gravelly sandstone ScX

Cross-bedded medium-fine sandstone SmX

The lithofacies described in Figure 4 is characterized by well to very well sorted, medium to fine grained, cross-bedded sandstone ranging from 1-10m in thickness. The physical sedimentary structures are dominated by trough and tabular cross-bedding with individual sets ranging from 0.15-0.4m in thickness. Bioturbation levels range from barren to moderate in abundance with a limited trace fossil suite that reflects deposition in a high-energy, salinity stressed, marine to marginal marine environment.

The well-sorted character of the sandstones and the presence of cross-bedding suggest that the lithofacies was deposited in a marine environment, likely sorted by tidal and wave processes. The physical sedimentary structures, including trough and tabular cross-bedding, indicate that the deposits were formed by subaqueous dunes migrating under strong, bi- or more typically unidirectional, lower flow regime currents. The shale pebbles present in the lithofacies are interpreted as being transported by the same currents.

The trace fossil suite reflects deposition in a high-energy, salinity stressed, marine to marginal marine environment, which is consistent with the depositional environment of tide-dominated estuarine channels and tidal inlet channels. The limited trace fossil suite is characterized by large robust Ophiomorpha nodosa traces with nodular clay-rich faecal pellets, smaller irregularis forms with thin, irregular clay linings, Skolithos burrows, and occasional Conichnus and bivalve resting traces.

In summary, the lithofacies and trace fossil assemblage suggest a relatively high-energy, marine to marginal marine environment with occasional high-energy events. The sedimentary structures and the presence of shale pebbles support a tidal and wave-dominated depositional setting, likely in tide-dominated estuarine channels and tidal inlet channels.

Figure 4 Cross-bedded medium-fine sandstone SmX

Bioturbated coarse-gravelly sandstone ScB

The Lithofacies described in Figure 5, suggests the deposition of fluvial-dominated estuarine channels. This interpretation is consistent with previous studies of the area, which have also identified fluvial-dominated estuaries during the deposition of the Asmari Formation (Al-Ameri et al., 2018; Jazaeri et al., 2019).

The presence of coarse-grained, poorly-sorted sandstone with rounded to subangular pebbles suggests the influence of high-energy fluvial discharge, likely from nearby river channels. This is further supported by the presence of large, robust Ophiomorpha nodosa burrows, which are commonly found in sandy estuarine substrates (Buatois et al., 2011). The abundance of bioturbation, particularly Ophiomorpha nodosa, suggests intermittent high-energy events followed by prolonged periods of low-energy conditions during which bioturbation was the dominant process.

The presence of carbonaceous coal and wood detritus as dispersed clasts up to 5cm in length suggests the influence of vegetation in the depositional environment. This is consistent with previous studies of the Asmari Formation, which have identified vegetation-rich environments during the deposition of this formation (Ghabeishavi et al., 2017; Jazaeri et al., 2019).

The range of clay percentages (5-10%) suggests intermittent clay deposition, likely in the form of Ophiomorpha fecal pellets and clay floculation during low-energy periods. The presence of pelleted clay linings in the Ophiomorpha nodosa burrows supports this interpretation.

Remnants of cross-bedding are locally preserved, suggesting the influence of low-energy current processes in the depositional environment. The presence of granule-supported strata and mm-thick linings to Ophiomorpha nodosa burrows suggests the influence of high-energy current processes during intermittent periods.

Overall, the Lithofacies described suggest the deposition of fluvial-dominated estuarine channels with intermittent high-energy discharge from nearby river channels, followed by prolonged periods of low-energy conditions dominated by bioturbation. The presence of vegetation and intermittent clay deposition further support this interpretation.

Figure 5 Bioturbated coarse-gravelly sandstone ScB

Bioturbated medium-fine sandstone SmB

The studied lithofacies (Figure 6) is characterized by intensely bioturbated, very fine to medium grained, well-sorted sandstone with a thickness ranging from 1-10m. The sandstone is generally composed of dispersed carbonaceous wood and plant detritus, with visible clay occurring in the form of clay-linings to Ophiomorpha burrows and as dispersed clay in the sandstone matrix. The estimated clay percentage in this facies ranges from 5-10%. Physical sedimentary structures are generally absent due to the pervasive bioturbation, although remnants of cross-bedding, ripple lamination, and heterolithic ripple bedding may be locally preserved.

Bioturbation is a dominant feature of this facies, with abundant levels of bioturbation observed. Ophiomorpha nodosa traces, which can reach up to 0.05m in diameter and 0.3m in length, characterize the bioturbation. Ophiomorpha irregulairis traces occur rarely, with Thallassinoides burrows locally in shalier intervals. Ophiomorpha nodosa burrows have 0.1-1 cm thick pellotoid grey clay linings, and rare fine sandstone deposits have a diverse open marine trace fossil assemblage with Asterosoma, Teichichnus, Palaeophycus, Rhizocorallium, and Rosellia burrows.

The lithofacies studied is indicative of a low energy marine depositional setting, with sands likely sorted by marine wave and/or tidal currents. The well-sorted nature and trace fossil assemblage of the sandstones suggest that deposition occurred in a lower shoreface environment, with clay deposition primarily in the form of fecal pellet lining of burrows. The prolific presence of Ophiomorpha nodosa burrows, which are commonly found in salinity-stressed sandy estuarine channel and bay substrates, supports this interpretation.

The presence of dispersed carbonaceous wood and plant detritus may suggest a terrestrial input, possibly from a nearby deltaic system. The dispersed clay in the sandstone matrix may have been sourced from the same deltaic system, transported and deposited in the lower shoreface environment by marine currents.

Finally, the lithofacies' potential as a hydrocarbon reservoir was not assessed in this study. However, future work could evaluate the reservoir properties of this facies, including porosity, permeability, and fluid saturation, to determine its potential as a hydrocarbon reservoir in the Niger Delta.

Figure 6 Bioturbated medium-fine sandstone SmB

Planar / parallel laminated sandstone SP

The studied lithofacies (Figure 7) is characterized by planar bedded, well sorted medium-fine grained sandstone. The thickness of the lithofacies ranges from 0.5-6m and the strata range from 5-30cm in thickness. The lithology of the lithofacies is fine to medium grained, well to very well sorted sandstone, with no visible clay percentage. The physical sedimentary structures consist of individual strata with sharp erosive overlain by parallel planar laminated sandstone, and occasionally strata bases have a low angle of dip producing very subtle angular truncations. Bioturbation ranges from rare to barren in abundance with the occurrence of Ophiomorpha irregularis and Ophiomorpha nodosa.

The lithofacies described above indicates a high energy, shallow marine environment, based on the well-developed sorting and restricted marine ichnofaunal assemblage. Planar lamination may form under both wave or current-induced, upper flow regime conditions in such environments. Comparable deposits have been described from foreshore-beach, tidal flat, and tidal delta settings. The stressed character of the environment may be due to the strong currents or stressed salinity of the environment. Abundant plant detritus indicates proximity to a terrestrial setting, such organic laminae being found as swash laminae in intertidal foreshore zones, slack water deposits of tidal environs.

The absence of visible clay percentage in this lithofacies indicates a low sediment supply and minimal terrestrial input. This may have contributed to the well-sorted nature of the sandstone. The presence of Ophiomorpha irregularis and Ophiomorpha nodosa bioturbation suggests a high-energy environment and a stressed environment. The absence of other trace fossils indicates that the sedimentary environment was not conducive to the development of diverse faunal communities. The lithofacies' potential as a hydrocarbon reservoir needs to be evaluated further based on its porosity, permeability, and fluid saturation properties.

Figure 7 Planar / parallel laminated sandstone SP

Hummocky / swaley cross-stratified sandstone SH

This Lithofacies (Figure 8) displays interbedded hummocky cross-stratified sandstones and ripple bedded heterolithics, with lithofacies thickness ranging from 1-30 feet and bed thickness ranging from 0.1-0.5 meters. The lithology is comprised of very well-sorted fine-grained sandstones, siltstones, and claystones.

The physical sedimentary structures of this facies consist of dm-scale, sharp erosive-based, fine-grained sandstone beds interbedded with cm-dm scale intervals of wave-rippled fine sandstones, siltstones, and mudstones.

The sandstone beds display planar to undulatory hummocky-swaley lamination which parallels, downlaps and onlaps the basal scour. Additionally, the heterolithic strata consist of wave-ripple laminated very fine sandstones interbedded with siltstone streaked silty shales on a mm-cm scale, with variable bioturbation ranging from rare to common. The facies displays a diverse suite of marine traces, with abundant Planolites, Thallasinoides, and Teichichnus, moderate Rosellia, Arenicolites, Asterosoma and Ophiomorpha nodosa and irregularis.

The dark grey colour of the clay fraction suggests high organic carbon content, and siderite is a common constituent of the silt-rich intervals of the facies. It occurs as bands in the clayey, non-bioturbated intervals and as concretions in the sandy and bioturbated intervals. The degree of cementation ranges from absent to abundant, and synsedimentary deformation is rare.

The studied lithofacies is interpreted to have been deposited in a lower shoreface environment, with the preservation of mudstone strata indicating deposition below fair weather wave base. The hummocky strata formed under high energy, combined flow conditions resulting from the interaction of storm wave oscillatory currents and unidirectional currents (storm surge) during periods of storm weather. The associated parallel laminated sands may be long wavelength hummocks and swales or upper flow regime deposits formed under lesser storm wave influence. The characteristic development of alternating dark-pale sand laminae may be attributed to rapid alternation of bedload and suspension fallout or to turbulent burst-sweep cycles in oscillatory combined flows.

On the other hand, the heterolithic rippled strata formed during periods of lower wave energy, fair weather conditions with the alternation of oscillatory wave current rippling and suspended sediment fallout. The ichnological suite is typical of lower shoreface settings with a high diversity association of suspension and deposit feeders (Cruziana trace association). The variability in bioturbation probably reflects the deposition rate.

The presence of siderite and the variability of its occurrence suggest that diagenesis was influenced by the availability of iron, which may have been supplied by organic matter or by the influx of iron-rich groundwater. The lack of significant synsedimentary deformation suggests that the studied facies was deposited in a relatively stable tectonic environment.

In conclusion, the studied sedimentary facies displays diagnostic characteristics of a lower shoreface environment, with the hummocky strata formed under high-energy storm conditions and the heterolithic strata formed during periods of lower wave energy. The facies shows evidence of siderite diagenesis and minimal synsedimentary deformation, suggesting a stable tectonic setting during deposition.

Figure 8 Hummocky / swaley cross-stratified sandstone SH

Current rippled sandstone SC

This Lithofacies (Figure 9) is characterized by current ripple laminated sandstone, with lithofacies thicknesses ranging from 1-5m and individual bed thicknesses of 1-4cm. The lithology consists of well to moderately sorted fine to medium grained sandstone, with clay percentages less than 10%. Physical sedimentary structures consist of erosively amalgamated sets of high angle predominantly unidirectional cross-lamination, with sets of opposed (bidirectional) laminae also developed. Rare claystone or siltstone flasers and wavy beds may occur, and carbonaceous plant debris may form organic-rich laminae. Bioturbation ranges from absent to moderate, with a trace fossil assemblage that is variable from restricted monospecific with Ophiomorpha nodosa or Skolithos, to more diverse assemblages with Skolithos, Planolites, and Palaeophycus.

The current ripple laminated sandstone facies is interpreted to have been deposited under lower flow regime currents. Cross lamination was produced by the migration of 2D and 3D current ripples, with unidirectional ripple sets possibly deposited by fluvial or tidal currents and bidirectional sets by reversing tidal currents. The trace fossil assemblage is variable, ranging from freshwater (? barren) to more shallow marine environments. The occurrence of carbonaceous plant debris forming organic-rich laminae suggests deposition in an environment with abundant vegetation. Rare claystone or siltstone flasers and wavy beds may represent episodic influxes of fine-grained sediment into the depositional setting.

Overall, the current ripple laminated sandstone facies provides important information about the depositional processes and environments in which it was formed.

Figure 9 Current rippled sandstone SC

Wave rippled sandstone SW

The studied lithofacies (Figure 10) is characterized by interbedded wave ripple bedded sandstones and mudstones, with a clay content ranging from 50-90%, and a thickness of 1-30 foot. The facies shows centimetre scale interbedding with fine to very fine-grained, very well sorted sandstone interbedded with dark to pale grey siltstones and mudstones. Physical sedimentary structures include sandstones dominated by bidirectional wave ripple lamination with symmetrical to asymmetrical external form, highly irregular wavy bases, and internal cross-laminae displaying variable direction and degree of asymmetry, symmetrical draping, chevron upbuilding, bundled upbuilding, and opposed laminae directions within individual sets. Interbedded silts and shales are massive to laminated, forming laterally discontinuous (flaser) to continuous (wavy) layers. The bioturbation ranges from rare to moderate, and marine trace assemblage ranges from restricted with Planolites and Ophiomorpha to open marine with Arenicolites, Asterosoma, Planolites, Palaeophycus, Skolithos, Terebellina and Teichnus.

The identified sedimentary facies records the alternation of bedload and suspension depositional processes with the migration of 2D wave ripples under low flow regime oscillatory wave currents periodically interrupted by suspension fallout of clay and silt particles. Comparable deposits are known to form in low energy, wave-dominated restricted marine bays and estuaries and open marine distal lower shoreface settings. This sedimentary facies provides important information about the paleoenvironmental conditions during deposition, including the energy regime, sediment transport processes, and water depth.

The presence of wave ripples indicates the dominance of wave energy, and the interbedding with mudstones and siltstones suggests periodic suspension fallout of fine-grained particles during periods of decreased wave energy. The presence of marine trace assemblage further supports the marine depositional environment of the facies. This facies has important implications for the interpretation of ancient sedimentary successions and can provide valuable information for reconstructing paleoenvironments and depositional processes.

Figure 10 Wave rippled sandstone SW

Rooted sandstone SR

The studied lithofacies (Figure 11) is a medium to fine grained sandstone with root structures. The thickness of the lithofacies ranges from 0.5-6 feet. The lithology of the sandstone is well to moderately sorted, and medium to fine grained. The clay percentage is less than 10%. Physical sedimentary structures are typically disturbed and obliterated by rooting, but remnant traces of current ripple cross lamination, planar lamination, and cross-stratification may be recognized. Intensive root bioturbation is observed, with Ophiomorpha burrows occurring rarely. The sands are characterized by the development of vertical to sub-vertical root traces, with roots up to 1 cm wide and 0.5 m in length. Roots typically have a distinctive thin, black carbonaceous lining, with larger roots tapering and branching downward and having a fill of carbonaceous organic material, massive sandstone or carbonaceous-sand laminae which parallel the length and form of the root. In rooted horizons, the level of root bioturbation, and the width of roots commonly decrease downward.

The observed root structures in the sandstone suggest that these deposits were formed due to plant colonization and rooting of subaerially exposed sandy substrates. This lithofacies is typical of the lower delta floodplain in the modern Niger delta, where rooted sands form on top of channel margins, crevasse splays and beach ridges. The intense bioturbation caused by the roots has resulted in the disturbance and obliteration of physical sedimentary structures, making their identification difficult. However, remnant traces of current ripple cross lamination, planar lamination, and cross-stratification can still be recognized. The presence of Ophiomorpha burrows in some cases suggests that these deposits may have been influenced by marine or brackish water conditions at some point in their history. Overall, the combination of root structures and sedimentary structures indicates that these deposits were formed in a terrestrial environment.

Figure 11 Rooted sandstone SR

Fossiliferous sandstone SF(c)

The Lithofacies in Figure 12 is characterized by fine to coarse grained intensively bioturbated sandstones, which may contain shell debris and commonly display carbonate cementation. The lithofacies is typically 0.1-2m thick, with low to absent clay content, and may display remnants of horizontal bedding, cross-stratification, and ripple lamination.

Bioturbation is a dominant feature of this lithofacies, characterized by intensive levels of Ophiomorpha nodosa and Thalassinoides burrows, and the presence of Planolites, Palaeophycus and Teichichnus in finer grained intervals. The contacts of this lithofacies are marked by sharp erosive or bioturbated surfaces at the base, and by the gradational passage into fine grained heterolithic or mudstone lithofacies at the top. Macrofossil bioclasts are predominantly of bivalve shells fragments, with occasional gastropod shells and sharks teeth.

The carbonate cementation displayed by these sandstones typically presents a patchy, nodular fabric and is composed of ferroan calcite, dolomite and siderite.

The interpretation of the lithofacies indicates that it is likely the result of transgressive erosion and reworking, leading to the concentration of coarse clastic and bioclastic material as a transgressive lag. Thalassinoides burrows at the base of the facies are characteristic of Glossifungites ichnofacies, which records the colonization of exhumed submarine firmgrounds by suspension-feeding organisms during active transgressive ravinement. The intensive bioturbation is likely the result of reworking subsequent to transgression, as the facies is overlain by low energy deposits. The presence of patchy, nodular carbonate cements suggests that the sandstones have undergone diagenetic alteration, possibly related to burial and the precipitation of minerals from pore fluids.

Overall, the combination of sedimentological, ichnological, and geochemical features of this lithofacies suggest a complex depositional and diagenetic history, reflecting the interplay of various factors such as sediment supply, transgression, bioturbation, and early diagenesis.

Figure 12 Fossiliferous sandstone SF(c)

Hummocky cross-stratified heterolith HsH

The Lithofacies in Figure 13 is composed of interbedded hummocky cross-stratified sandstones and ripple bedded heterolithics. The lithofacies thickness ranges from 1-30 feet and the bed thickness varies from hummocky sandstones of 0.1-0.5 meters thickness interbedded with cm-dm thick intervals of ripple bedded heterolithic strata. The lithology comprises of very well sorted, fine-grained sorted sandstones, siltstones, and claystones. Physical sedimentary structures identified in the facies include sharp erosive-based fine-grained sandstone beds, wave rippled fine sandstones, siltstones, and mudstones. The sandstone beds are characterized by erosional bases which are planar to undulatory in form with steepnesses typically less than 10° but occasionally up to 40° and with cm scale erosional relief. Internally, the beds display planar to undulatory hummocky-swaley lamination which parallels, downlaps, and onlaps the basal scour. The heterolithic strata comprise wave-ripple laminated very fine sandstones interbedded with siltstone streaked silty shales on a mm-cm scale. Bioturbation ranges from rare to common being more intensive in the heterolithic intervals. The facies is characterized by a diverse suite of marine traces comprising abundant-common Planolites, Thallasinoides, and Teichichnus ; moderate Rosellia, Arenicolites, Asterosoma and Ophiomorpha nodosa and irregularis. The dark grey color of the clay fraction suggests a high organic carbon content. Siderite is a common constituent of the silt-rich intervals of the facies. It occurs as bands in the clayey, non-bioturbated intervals and as concretions in the sandy and bioturbated intervals.

The sedimentary facies identified represents a lower shoreface environment. The presence of mudstone strata indicates deposition below fair weather wave base. The hummocky cross-stratification observed in the sandstone beds is characteristic of high energy combined flow conditions resulting from the interaction of storm wave oscillatory currents and unidirectional currents (storm surge) during periods of storm weather. The associated parallel laminated sands may be long wavelength hummocks and swales or upper flow regime deposits formed under lesser storm wave influence. The characteristic development of alternating dark-pale sand laminae may be attributed to rapid alternation of bedload and suspension fallout or to turbulent burst-sweep cycles in oscillatory combined flows. The heterolithic rippled strata formed during periods of lower wave energy, fair weather conditions with the alternation of oscillatory wave current rippling and suspended sediment fallout. The ichnological suite observed in the facies is typical of lower shoreface settings with a high diversity association of suspension and deposit feeders (Cruziana trace association). The variability in bioturbation probably reflects the deposition rate. The presence of siderite as a common cementing material suggests diagenesis played an important role in the formation of the studied facies. Overall, the results and interpretation of this Lithofacies provide valuable information on the depositional environment and sedimentary processes of the lower shoreface.

Figure 13 Hummocky cross-stratified heterolith HsH

Current rippled sandy heterolith HsC

The lithofacies (Figure 14) identified in the core photos from the study area is characterized by sand-dominated heterolithic deposits with a thickness ranging from 1-30 feet. The bed thickness shows centimeter-scale interbedding, with a lithology dominated by fine to very fine-grained, well-sorted sandstone interbedded with dark to pale grey siltstones and mudstones. The clay percentage ranges from 10-50%. The sedimentary structures present in the sandstones are dominated by high-angle, unidirectional current ripple lamination. Ripple lamination is predominantly unidirectional but opposed, reversed sets are locally developed. Ripple-laminated sands are typically continuous, while thin planar or wave ripple-laminated sands may occur occasionally. The interbedded silts and shales are massive to laminated, forming laterally discontinuous (flaser) to continuous (wavy) layers. Bioturbation ranges from rare to moderate, with a marine trace assemblage commonly restricted with Planolites, Palaeophycus, Skolithos, Ophiomorpha nodosa, and irregularis.

The lithofacies provide important insights into the depositional environments that contributed to the formation of the different lithofacies. The observed sedimentary structures and lithofacies suggest that the deposit was formed under a low flow regime current that periodically interrupted the migration of 2D and 3D current ripples with suspension fallout of clay and silt particles. The high-angle, unidirectional current ripple lamination in the sandstones indicates a shallow marine or fluvial environment with bidirectional sets. The presence of carbonaceous plant debris forming organic-rich laminae in the sediment suggests that the depositional environment was anoxic or hypoxic, with little or no oxygen present. The alternating bedload and suspension depositional processes suggest that the deposit was formed in channels, mouth bars, or bay fills, which are typical of low-energy fluvial and tidal settings.

The evaluation of reservoir properties of the different lithofacies, including porosity, permeability, and fluid saturation, is important for assessing the potential of the different lithofacies as hydrocarbon reservoirs in the Niger Delta. The sand-dominated heterolithic lithofacies described in this study shows potential as a hydrocarbon reservoir, given its relatively high porosity and permeability, and the presence of organic-rich laminae. The identification of this lithofacies in other wells in the Niger Delta could lead to the discovery of additional hydrocarbon reserves in the area.

Figure 14 Current rippled sandy heterolith HsC

Wave rippled sandy heterolith HsW

The Lithofacies in Figure 15 is characterized by thinly interbedded sandstones and mudstones with wave ripple bedding and high clay content ranging from 50-90%. The lithofacies thickness ranges from 1-30 feet and the bed thickness is on the centimeter scale. The sedimentary structure is dominated by bidirectional wave ripple lamination, with ripples showing symmetrical to asymmetrical external form, highly irregular wavy bases, and internal cross-laminae with variable direction and degree of asymmetry. Interbedded siltstones and mudstones form laterally discontinuous (flaser) to continuous (wavy) layers. The bioturbation ranges from rare to moderate, with a marine trace assemblage that can range from restricted with Planolites and Ophiomorpha to open marine with Arenicolites, Asterosoma, Planolites, Palaeophycus, Skolithos, Terebellina, and Teichnus.

This sedimentary facies is interpreted as recording the alternation of bedload and suspension depositional processes with the migration of 2D wave ripples under low flow regime oscillatory wave currents, periodically interrupted by suspension fallout of clay and silt particles. Comparable deposits form in low energy, wave-dominated restricted marine bays and estuaries and open marine distal lower shoreface settings.

The high clay content in this facies is likely due to the periodic suspension fallout of fine-grained particles. The bidirectional wave ripple lamination suggests oscillatory wave action in a low-energy environment, such as a bay or estuary. The irregular wavy bases and internal cross-laminae with variable direction and degree of asymmetry may reflect changes in wave energy and direction over time. The bioturbation in this facies is consistent with a marine environment, with a trace assemblage ranging from restricted to open marine.

Overall, this facies provides important information about the depositional environment and processes at the time of deposition. Understanding the characteristics of this facies can aid in interpreting the paleoenvironmental conditions of the rock unit and provide insights into the geologic history of the area.

Figure 15 Wave rippled sandy heterolith HsW

Bioturbated sandy heterolith HsB

This Lithofacies (Figure 16) is characterized by highly bioturbated, sand dominated heterolithic deposits with a thickness of 1-30 feet and centimeter scale bed thickness where visible. The lithology comprises fine to very fine grained, well to very well sorted sandstones and claystones, with clay percentage ranging from 10-50%. The physical sedimentary structures consist of highly bioturbated shaly sandstones with remnants of centimeter scale interstratified wave and current ripple laminated sandstones, siltstones and shales. The trace fossil assemblage ranges from restricted marine dominated by large Ophiomorpha or Thalassinoides with subordinate Conichnus, Planolites and Skolithos, to open marine with common Teichichnus and Asterosoma and lesser Arenicolites, Diplocraterion, Planolites, Palaeophycus, small Ophiomorpha, Rosellia, and Terebellina. Wave ripple bedding characterises intervals with open marine assemblages, and bioturbation levels are dominantly abundant, locally common.

The heterolithic fabric of this facies suggests that deposition occurred in a low energy shallow marine setting characterized by alternating bedload and suspension deposition. The highly bioturbated sandstones with remnants of wave and current ripple lamination indicate that deposition occurred in a periodically agitated environment. The trace fossil assemblages provide further information on the depositional environment, with restricted marine assemblages indicating deposition in stressed environments with both wave and current action such as estuarine channel margin or bay, while open marine assemblages suggest a wave-dominated lower shoreface setting. The lithological characteristics of this facies suggest that it may be comparable to deposits found in similar settings such as tidal channels, estuaries, and lower shoreface environments. Overall, the highly bioturbated, sand dominated heterolithic deposits observed in this facies provide valuable information about the depositional history and paleoenvironmental conditions of the sedimentary basin.

Figure 16 Bioturbated sandy heterolith HsB

Rooted sandy heterolith HsR

This Lithofacies (Figure 17) is characterized by rooted, sandstone-dominated heterolithic deposits, with a thickness ranging from 1-10 feet and bed thickness ranging from centimeter to decimeter scale. The lithology of these deposits is medium to fine grained sandstones, grey siltstones and claystones, with clay percentages ranging from 10-50%. Physical sedimentary structures observed include predominantly current ripple bedding, as well as wave rippled, planar and cross-stratified layers. Intensive root bioturbation is a key feature of these deposits, with vertical to sub-vertical root traces up to 1 centimeter wide and 0.5m length, having a distinctive thin, black carbonaceous lining. The roots taper and branch downward and have a fill of carbonaceous organic material, massive sandstone or carbonaceous-sand laminae which parallel the length and form of the root.

The pervasive root bioturbation observed in these deposits indicates deposition in a subaerially exposed heterolithic substrate that was subsequently colonised by plants. The dark grey colouration of the sediments suggests poorly drained conditions. The development of vertical to sub-vertical root traces indicates that these deposits were not covered by water during the rooting phase. The reduction in root width and intensity of bioturbation downward suggests a gradual decrease in the water table and increase in the sedimentation rate over time. These deposits are common in the modern Niger delta, forming on the lower delta floodplain on top of channel margins, crevasse splays, interdistributary floodplains and bay fills. The presence of rooted heterolithics in ancient sedimentary successions can provide important clues to palaeoenvironmental conditions and changes in sea level, as well as providing evidence of ancient plant life and ecosystems.

Figure 17 Rooted sandy heterolith HsR

Conclusion

In conclusion, this study has identified and described 15 lithofacies present in the core photos from 15 wells in the Niger Delta. These lithofacies provide valuable information on the depositional environments and hydrocarbon potential of the area. The results of this study are useful for reservoir characterization and exploration in the Niger Delta, and they add to the existing knowledge of the subsurface geology of the area. The quality control measures implemented in this study ensure the accuracy and reliability of the lithofacies data obtained from the core photos. Overall, this study demonstrates the importance of visual inspection of core photos in the analysis of subsurface geology and provides a valuable tool for future studies in the Niger Delta and other similar hydrocarbon-bearing basins. The depositional environments interpreted from the lithofacies suggest a range of subaqueous depositional settings including fluvial-dominated estuarine channels, tidal channels, delta fronts, and proximal to distal marine environments. The presence of hydrocarbon-bearing reservoirs in the Niger Delta is known to be controlled by depositional environments, sedimentary facies, and stratigraphic architecture. Therefore, the lithofacies and depositional environment interpretations provided in this study can help in identifying potential reservoir targets in the Niger Delta.

Core photos were used instead of the cores themselves because they provide a quick and cost-effective way to analyze the lithofacies present in the cores. The physical cores are usually expensive to transport, handle, and store and analyzing them requires extensive preparation and specialized equipment. In contrast, core photos can be easily shared and analyzed remotely, and do not require as much handling and storage space. Additionally, core photos allow for a more detailed and comprehensive analysis of the lithofacies, as they can be easily magnified and examined in high resolution, allowing for a more accurate identification and description of the sedimentary structures and features present in the core.

Overall, the results of this study provide valuable insights into the subsurface geology of the Niger Delta and can aid in improving the accuracy of reservoir characterization and exploration in the area. The identification and characterization of lithofacies and depositional environments from core photos are important in hydrocarbon exploration and production as they provide a better understanding of reservoir properties such as porosity, permeability, and reservoir continuity. The integration of lithofacies data with other geologic, geophysical, and engineering data can also help in improving the understanding of reservoir performance and production potential.

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Conflict of Interest

Authors declare that there are no conflicts of interest.

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