Depositional facies, sequence stratigraphy and reservoir potential of the Eocene Nanka Formation of the Ameki Group in Agu-Awka and Umunya, southeast Nigeria

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ABSTRACT

A sedimentological investigation was carried out in Agu-Awka and Umunya localities to interpret the facies, depositional environment, sequence stratigraphy, reservoir potential, and architecture of the outcropping Eocene Nanka Formation of the Ameki Group in southeast Nigeria. Petrographic analysis reveals that the sediments are composed of predominantly subangular to subrounded recycled quartz grains with a minor amount of rock fragments. It indicates that the sediments are texturally submature and mineralogically mature. Lithofacies analysis indicates that the formation is composed of fine to coarse-grained, trough and planar cross-bedded sandstone with clay-drape units, interpreted to be a subtidal bar facies, and a minor mudstone interval with sand to muddy heterolith interpreted to be a tidal mudflat facies. This suggests that the formation is of mixed environments, such as a tidally influenced high-energy fluvial and low-energy marsh to lagoonal settings. The lower sand unit of the subtidal bar facies (fine to coarse-grained cross-bedded sandstone with clay-drape) represents a highstand systems tract. The sharp base sandy heterolith lithofacies that forms the upper unit of the subtidal facies, and the overlying tidal mudflat facies that comprises a bedded mudstone and overlying wave rippled sandy heterolith intervals represent a transgressive systems tract. The reservoir quality of the sandstone facies is predicted to be moderate to good based on textural statistical analysis. The various relationships of the sedimentological parameters of the outcrops revealed by this study may assist and contribute to the prediction and understanding of the reservoir stratigraphic heterogeneity and properties of the subsurface depositional facies of the Nanka Formation.

1. Introduction

This work is based on a detailed lithofacies analysis of measured sub-section of the Nanka Formation of the Ameki Group at Umunya and Agu-Awka, southeastern Nigeria. The study analyzes the facies heterogeneity, textural characteristics, and architecture, and deduces the depositional environments. As a prelude to interpret the sequence stratigraphy of the Ypresian (Early Eocene) formation (Reyment, 1965; Nwajide, 1980, 2013).

The formation outcrops cover an area of more than 1,400 km² in the eastern part of the Niger Delta Basin (Nwajide, 2013). The outcrop is delimited by latitudes 5° 45' N to 6° 17' N and longitudes 6° 45' E to 7° 15' E (Figure 1). Good exposures of the formation are visible in the Agu-Awka and Umunya areas and constitute a stratigraphic equivalent of the subsurface sandstone of the Agbada Formation in the central and southern reaches of the Niger Delta Basin (Figure 2). Extensive areas of the formation have been so deeply gullied as to expose the fresh outcrop within Nanka town and other places are covered by thick lateritic soil development (Nwajide, 2013). Outcrops in the Nanka locality, and other gully and road cut exposures of the Nanka Formation have been studied by several workers (Reyment, 1965; Nwajide and Reijers, 1996; Umeji, 2003; Nwajide, 2013).

Sedimentological studies within the Nanka Formation by the aforementioned workers have shown that the reservoir facies distribution is unclear due to the depositional complexity of the formation and they revealed that the challenges of predicting the reservoir properties are obscurely related to the heterogeneity of the facies, architecture and depositional environment. The primary aim of this work, therefore, is to provide a sedimentological description of the outcrops that would help to resolve the challenges and improve the understanding of the reservoir characteristics. Also, to examine the textural characteristics of the formation.
sediments using available sedimentological and petrographic data to construe the facies distribution and depositional environment of the Nanka Formation at an outcrop scale. This may provide a better understanding of reservoir stratigraphic heterogeneity and prediction of reservoir facies quality and architecture in its subsurface equivalent in the Niger Delta Basin. While this study is carried out within the Niger Delta Basin the approach, method and result can be applied and/or adopted in studying other sedimentary basins of similar depositional settings. The results can be related in terms of geological implications on subsurface studies that may be of benefit to the geoscience community in both academia and industry.

2. Geologic setting

Outcropping parts of the Cenozoic Niger Delta Basin can be found in the northeastern part of the region, where they overlie sediments of the

Figure 1. Simplified geologic map of the outcropping Nanka Formation and part of other outcropping formations of the Cenozoic Niger Delta Basin (Modified from Nwajide, 1980; 2013). Inset map of Nigeria showing the location of the Niger Delta (black box), and the map of Niger Delta showing the location of the study area (red box), respectively. Location NE-SW cross-section in the inset map for Figure 2 is marked.

Figure 2. Schematic northeast (NE) – southwest (SW) cross-section of the Cenozoic Niger Delta Basin showing the subsurface formations and their outcropping stratigraphic equivalents overlying the Cretaceous sediments of the Anambra Basin in southeastern Nigeria (Reprinted from Ogbe, 2020). Note the NE-SW line location is shown in Figure 1 and the position of the vertical line A-B cutting through the outcropping formations of the Niger Delta Basin marked in Figure 3.
Anambra Basin (Figures 1 and 2). The evolution and stratigraphy of the Abakaliki, Anambra and the Niger Delta Basins, which are often referred to as the southern Nigeria basins, have been well established (Reyment 1965; Short and Stauble, 1967; Burke et al., 1971; Murat, 1972; Weber and Daukoru, 1975; Wright, 1981; Nwajide, 2013). The tectonic evolutions of these basins are related to the separation of the African and South-American plates that were formed as a result of continental rifting of the Precambrian basement terrain that developed into the ridge-ridge-ridge (R-R-R) triple junction from Late Jurassic to Cretaceous (Reyment, 1965; Short and Stauble, 1967; Burke et al., 1971; Murat, 1972; Wright, 1981; Nwajide, 2013)
The Nsugbe Formation, is mainly sands and minor calcareous clay/mud with heterolithic and calcareous clay intercalations (Reyment, 1965; Arua, 1986; Ekwenye et al., 2015). The Imo Formation is the mappable equivalents of the Akata Formation and the Ameki Group and the Ogwashi Formation (Nwajide, 2013).

The facies of the Ameki Group conformably overlies the Imo Formation and contains three stratigraphic components: the Ameki Formation, the Nanka Formation and the Ngwure Formation (Figure 3), which pinch out in both westwards and eastwards (Nwajide, 1980, 2013). The Imo Formation is the mappable equivalents of the Akata Formation and the Ameki Group and Ogwashi Formation are the mappable equivalents of the Agbada Formation of the subsurface stratigraphic units of the Niger delta (Short and Stauble, 1967) (Figure 2). The Imo Formation is the oldest stratigraphic unit in the Niger Delta Basin (Short and Stauble, 1967; Petters, 1991) and is composed of blue-grey shales with sand lenses, marl and fossiliferous limestones (Reyment 1965; Short and Stauble, 1967; Nwajide, 2013). The Ameki Formation is estimated to range from 1200 to 1900 m; the Ogwashi Formation is predominantly sands with some conglomerate bands, estimated to be about 1000 m thick (Nwajide, 2013). The Ogwashi Formation comprises alternating coarse sands, silts, and clays with thin to thick lignite seams (Kogbe, 1976; Nwajide, 2013). The Benin Formation, which is the youngest stratigraphic unit of the Niger Delta Basin (Short and Stauble, 1967) (Figure 3) is composed of coastal plain sands with lenses of clay and mud (Tattam, 1944; Simpson, 1955). The Benin Formation exists in both outcrops and the subsurface (Figure 3) and occupies an extensive area of southern Nigeria (Reyment, 1965; Short and Stauble, 1967; Nwajide, 2013) (Figure 2).

Nwajide (2006) established that Abakiliki anticlinorium is one of the sources of sediments for the Anambra and Abakiliki (Akpko) Basins, which later became contributors to the Cenozoic Niger Delta Basin fills that advanced from the Tethyan onwards (Figure 3). Eastern Nigerian Oban Massif is also an important source for the Cenozoic sediments of the Niger Delta Basin (Ekwenye, 2015). The Ameki Group (Ameki, Nanka and Ngwure Formations) sediments were laid down in an estuarine, tidal, barrier ridge-lagoon complex and open marine systems after the major Paleocene marine transgression of the second depositional cycle at the site of the rift triple junction (Short and Stauble, 1967; Nwajide, 2013; Ekwenye et al., 2014). The sediments were deposited under semi-humid to humid paleoclimatic conditions (Ekwenye et al., 2015). Hence, the present study is an attempt to unravel the stratigraphic heterogeneity of the Nanka Formation. This may further help to understand the depositional facies relationship and distribution of the sedimentary pile of the Formation.

3. Materials and methods

The descriptive aspects of this paper are based largely on the textural and lithofacies characteristics of the outcropping sections of the Nanka Formation of the Ameki Group in the southeast Nigeria. The exposed sections of the formation at Umunya locality is about 500 m in length with an average thickness of 20 m and at Agu-Awka is approximately 300 m in length with an average thickness of 12 m. These were logged and representative samples were obtained for sieve analysis. They were also examined under a polarizing microscope for mineral grain size analysis. The analyses were carried out at the Department of Earth Sciences Sedimentological Laboratory, Federal University of Petroleum Resource, Effurun, Nigeria. A total of 10 samples of sandstone obtained from the exposed sections of the formation were analyzed for textural attributes such as mineral grain size and sorting. The samples were air-dried under a controlled temperature and disaggregated using porcelain mortar and pestle. This was homogenized using a coning and quartering procedure. 100 g of each of the dried samples was weighed by means of a highly sensitive electrical weighing balance (Mettler Teledo, PL602-S) and passed through a suitable sets of stacked sieves progressively, with electromechanical Ro-tap machine, based on the procedure of Friedman (1967). Textural parameters such as grain size and sorting were computed using the statistical formulae of Folk and Ward (1957) to obtain the grain size statistical parameters such as geometric mean size, standard deviation (sorting), and geometric mean, which were used to estimate permeability values of the sandstone empirically using Krumbine and Monk (1942) permeability equation \( K = C_0 D_m \) where \( C_0 \) is the standard deviation (grain diameter in \( \mu m \)); \( D_m \) is the geometric mean of grain diameter in \( mm \), where \( \phi = \log(D_m) \); \( \sigma \) is the standard deviation of grain diameter in \( \phi \) units; and \( K \) = permeability, expressed in millidarcy (mD). A total of 4 samples of unconsolidated sand facies representing each lithofacies, were obtained from the exposed sections of the Nanka Formation and impregnated in the consolidated sand with epoxy resin in order to make the samples consolidated. These were then thin-sectioned for petrographic studies under an optical microscope. Directional (paleocurrent) data such as attitudes (azimuths and dip amounts) of the forest planes of cross-bedded sand facies of the formation were obtained with the aid of a compass clinometer. Anemometers such as (azimuths and dip amounts) of the forest planes of cross-bedded sand facies of the formation were obtained with the aid of a compass clinometer. Anemometers such as (azimuths and dip amounts) of the forest planes of cross-bedded sand facies of the formation were obtained with the aid of a compass clinometer. Anemometers such as (azimuths and dip amounts) of the forest planes of cross-bedded sand facies of the formation were obtained with the aid of a compass clinometer.

4. Results

4.1. Sedimentological characteristics of the Nanka Formation

A detailed lithofacies description was carried out on the outcrop at Agu-Awka and Umunya localities in the eastern part of Nigeria (Figure 4). The thickness of these outcrops ranges from 14 to 20 m. The outcrops are located along terraced road-cuts and sand quarry sites (Figure 4). Four lithofacies were identified from the base to the top: fine to coarse-grained cross-bedded sandstone with clay-drape; sharp base sandy heterolith, bedded mudstone and wave rippled sandy heterolith. Based on lithology and depositional structures two assemblages of...
genetically related lithofacies associations were established, the subtidal bar and tidal mudflat.

4.1.1. Subtidal bar facies association

The fine to coarse-grained cross-bedded sandstone with clay-drape and the sharp base sandy heterolith lithofacies belong to the subtidal bar facies association. The fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies forms the basal section of the outcropping Nanka Formation at Agu-Awka and Umunya localities. The lithofacies is composed of fine to coarse-grained sandstone with varying thickness across the outcrop but attains a maximum thickness of about 8 m in the Umunya section. It is demarcated by a ferruginous erosional surface from an overlying facies that is delimited in Agu-Awka location. The facies consists of predominantly white and brownish-yellow subangular to subrounded, moderately spherical sand grains. Statistical analysis revealed a moderately to well sorted grains with less than 10% clay content, which qualifies it to be texturally submature, in agreement with a previous work on the formation (Nwajide, 2013). Nevertheless, it is mineralogically mature on account of its mineral composition that consists of quartz as the main framework mineral. It ranges from 90 – 97% and a minor amount of rock fragment that ranges from 2 – 8% with a near zero amount of feldspar (Figure 5a), as revealed by micro-petrographic analysis. It suggests that the sandstones are essentially quartz-arenite (Figure 5b). The mineral framework comprises of both monocrystalline and polycrystalline quartz grains. The monocrystalline quartz grains amount >50% and it is characteristically associated with the sharp base sandy heterolith lithofacies. While the polycrystalline quartz grains average 45% and is predominant in the fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies (Figure 5a).

The facies is deposited in beds of few centimeters to meter scale thick foresets (Figure 6), characterized by unidirectional high angle tabular cross-beds with average of 055° and trough cross-beds with intervening clay-drapes, bounded by reactivation surfaces that are sub-planar to curvilinear geometry (Figures 6 and 7). The clay-drapes within bedsets merge across the cross-beds. The foreset thicknesses vary in a regular manner of more than a centimeter to about 10 cm interval (Figures 6 and 7). This facies displays abundant Ophiomorpha of Skolithos ichnofacies (Figure 7). The fine-grained and clay sediments within the facies are dominated by burrows of Chondrites of Cruziana ichnofacies (Figures 7 and 8). This ichnofacies assemblage is most common in the fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies unit and sparsely noticeable in the sharp base sandy heterolith lithofacies unit. This suggests that the fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies unit was possibly deposited in an oxic environment setting.
Figure 5. Petrographic composition of the sandstone facies of the Nanka Formation at Aku-Awka and Umunya. (a) Representative thin section photomicrographs of the subtidal bar (reservoir) facies of the Nanka Formation, which reveals that quartz as the major mineral grains and minor rock fragments with little or no feldspar content. Snapshot: Scopetmage software interface (I) Fine to coarse-grained cross-bedded sandstone with clay-drape displays polycrystalline quartz grains that show sutured boundaries with a high-order pink and green interference colors (metamorphic source). (II) Sharp base sandy heterolith displays a monocrystalline quartz grain that shows a high-order pink interference color with fluid inclusions (igneous source). (b) Ternary diagram plot of quartz, feldspar and rock fragment composition of the sandstone of the Nanka Formation at Aku-Awka and Umunya (After Fols, 1980). It reveals that the sandstone is a quartz-arenite type, which suggests that it is a mineralogically mature sandstone.

Figure 6. Composite log through the Nanka Formation exposed at Umunya (N 6° 12' 05"; E 6° 50' 00"), showing stratigraphic relationships between facies associations in the study area. Note the lithofacies legend, it also represents for Figure 8 composite log explication.
The fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies is present in the locations (Figures 6, 8, and 9). It is friable in Agu-Awka, in contrast to Umunya outcrops that are relatively consolidated (Figure 4a), indicating different rates of lithification at the various localities. This has attracted quarry activities to the Agu-Awka localities (Figure 4b). Sharp base sandy heterolith lithofacies with a thickness of about 1.8 m at Umunya and 6 m at Agu-Awka directly overlies the fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies (Figures 6 and 8). It is the dominant lithofacies in the outcropping section at Agu-Awka and least frequency at Umunya (Figure 9a). It consists of beds of poorly laminated shale and well consolidated ferruginous sandstone composed of very fine to coarse-
grained, angular to subangular poorly sorted sediments (Figure 8). This facies consists of more brownish to a yellowish sand component that constitutes more than 70% of the net-to-gross ratio. Herringbone cross-bedding structure is conspicuous in the Agu-Awka outcrop section (Figure 7). Flaser bedding, parallel horizontal bedding and lamination with wave ripples and other depositional structures such as slumped structures and Liesegang bands. The Liesegang bands have partly obliterated the primary structures they associated with in the facies. These were observed towards the upper portion of this facies, essentially composed of fine-grained sands (Figure 7).

### 4.1.2. Tidal mudflat facies association

The bedded mudstone and the wave rippled muddy heterolith are components of the tidal mudflat facies association. The bedded mudstone lithofacies is about 6 m at Umunya (Figure 6). It is a well consolidated mudstone deposit that is composed of a light gray bedded siltstone, clay laminae and poorly laminated shale (Figure 10). The clay component is more than 60% and the silt is about 40% with quartz framework. The facies is characterized by a few lenses of coarse sands with parallel laminations. Within the fine to coarse-grained cross-bedded sandstone with clay-drape, about 2.5 m thick bed of a mudstone and muddy siltstone is conspicuous at Agu-Awka location (Figure 9b). Wave ripples and small scale horizontal planar bedding to massive structure, together with burrows of *Crustiana* ichnofacies were found in the mudstone units of this facies (Figures 8 and 10). Other subunits of this facies such as the siltstone, heterolith, and clay/shale are predicted to have been developed in a quiet environment, ascribed to the absence of *Crustiana* ichnofacies assemblage in the deposits. This suggests that the mudstone units of this facies were possibly deposited in an oxic paleoenvironment setting.

The wave rippled sandy heterolith lithofacies occurs as the upper facies unit of the Nanka Formation. It is composed of more than 5 m thick of beds ranging from 5 to 10 cm of an alternating poorly laminated mudstone and wavy ripple laminated fine to medium-grained ferruginous sandstone (Figure 10). These beds are near horizontal and trends approximately north-south. Mudstone constitutes more than 45%, and sand accounts for about 55% of the facies characterized by wave ripple laminations (Figure 10). Quartz grains form the framework of the sandstone beds, consisting of a mixture of rounded and subrounded grains. An upward increase in sand net-to-gross ratio with a corresponding upward thickening in beds is observed within the sandstone beds (Figures 6 and 10). The facies shows a complete absence of trace fossils. This lithofacies is absent in the outcropping section of the formation at Agu-Awka (Figure 9).

5. Discussion

### 5.1. Depositional environment and setting

The fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies suggests that the sediment was deposition under mixed environments such as fluvial and tidal settings, tidally influenced fluvial deposits. The fluvial origin is demonstrated by the presence of a wide range of sediment grain size distribution, moderate to well sorted grains, graded fining-upward cycles, unidirectional planar, trough cross-bedding, and erosional channel surfaces. While the depositional features that suggest a tidal origin include flaser bedding, clay-drapes, laminated wave ripples, bi- and unidirectional planar structures, and reactivation surfaces (Figure 7). The occurrence of clay-drapes within the
bedsets that merge across cross-beds and foresets in a regular manner, suggests that the Nanka sand deposit experienced cycles of high and low tides, as reported by previous works (Murty, 1977; Nanayama and Shigeno, 2006; Shiki et al., 2008; Abdulkadir and Abdullatif, 2013; Abouessa et al., 2014). The presence of trace fossil assemblages within the fine to coarse-grained cross-bedded sandstone with clay-drape lithofacies indicate fluctuations in energy of the sedimentary environment that was under oxic conditions. High-energy environment with a

Figure 9. Pie diagrams of the depositional facies frequency in the exposed section of the Nanka Formation. (a) Spatial distribution of the lithofacies at the Umunya section. (b) Spatial distribution of the lithofacies at the Agu-Awka section.
Figure 10. Sedimentary structures in tidal mudflat facies. (a) Wave ripple-laminated sandstone within heterolith unit. (b) Wave ripples, undulose laminated in burrowed mudstone unit. (c) Poorly laminated claystone showing a convolute lamination. (d) Siltstone lenticular bedding in a mudstone interval. (e) Small-scale horizontal planar bedding in a muddy siltstone interval.

Figure 11. Rose diagrams presenting the paleocurrent directions for subtidal sand facies of Nanka Formation. (a) Measurement obtained at Umunya outcrop elucidating a unidirectional paleocurrent, southwest. (b) Measurement obtained at Agu-Awka outcrop elucidating a bi-direction paleocurrent, northwest and northeast provenances. N = number of readings.
sandy-shifting substrate in foreshore zone has been interpreted to favor the Skolithos ichnofacies. In contrast, the Cruziana ichnofacies indicates soft-ground substrate developed under low energy environment such as in lagoon/shelf/offshore zone (Shingaly, 2016). The presence of reactivation surfaces within the facies also suggest a high energy environment such as wave actions (Figures 6 and 7). In that sense, earlier deposited sediments were eroded by a high current intensity and subsequently followed by deposition of new bedsets. The co-occurrence of these depositional features suggest that more than one aspect of the hydrodynamic processes prevalent. The characteristics of the sharp base sandy heterolith lithofacies revealed that the sediments were deposited in a quiet and well oxygenated continental marshy environment such as a lagoonal setting. The characteristic indicators of this lithofacies association are common in a subtidal and intertidal settings (Prothero and Schwab, 1996; Nwachukwu et al., 2011).

The cross-bedding palaeocurrent measurements and analysis revealed the foresets dip in the range of 10° to 30° with azimuths that is unidirectional in the dominant range in northeast (Figure 11a), and bi-directional in the southwest and southeast directions with a little variance (Figure 11b). These indicate southwest, northwest, and northeast were the provenances, while depositions were in the northeast, southeast and infrequent in southwest directions, respectively through tidal, and wave actions (Figures 11 and 12). Though in a tidal setting, paleocurrents are unreliable as a provenance indicator (Miall, 1978; Nwajide, 2013). The sedimentological and petrographic analysis suggest that sediments of the subtidal facies and the tidal mudflat facies were possibly derived from recycled sediments of sedimentary rocks that are of both igneous and metamorphic origins (Figure 5).

The bedded mudstone and wave ripple sandy heterolith ichnofacies are likely to have been deposited in a mixed environment such as still water and stressed environments. This is ascribed to the presence of borrow and absence of flow structures in the bedded mudstone deposit and the absence of borrow in the sandy heterolith deposit. Muds are typical of still water bodies in the coastal domain such as a lagoon environment (Figure 12). The rapid alternation of sands and muds of the wave ripple sandy heterolith ichnofacies, suggests a deposition by an alternation of bedload and suspension load sediments. Their depositional characteristic structures indicate a tidally influenced deposit, such as the types obtained in lagoonal settings (Figure 12).

5.2. Sequence stratigraphy of the Nanka Formation

The sequence stratigraphic framework for the sediments was established based on the vertical relationship between the various lithofacies and their stacking patterns. The lower lithofacies (the fine to coarse-grained cross-bedded sandstone with clay-drape) is interpreted to be a tidally influenced fluvial deltaic deposit and represents a highstand systems tract (HST). The sharp base sandy heterolith (the bedded mudstone lithofacies and the wavy ripple laminated muddy heterolith lithofacies) represents a transgressive systems tract (TST) (Figure 13), indicating an increase in the rate of coastal retrogradation and a rise in sea-level. The surface between the fine to coarse-grained cross-bedded sandstone with clay-drape and the sharp base sandy heterolith lithofacies is interpreted to be an erosion surface, possible a sequence boundary (SB). This suggests that there was probably a lowstand systems tract deposit that has been eroded before the onset of an accommodation space buildup accompanied by a low rate of sedimentation of a tidal and lacustrine facies (Figure 13b). It could be observed in some areas as a SB landward of where the rate of influx of sediment is high over a transgressive surface of erosion (TSE) and merges with a maximum flooding surface where the rate of influx of sediment is low over the TSE (Mitchum, 1977; Catuneanu, 2002). The sequence stratigraphic evolution of the Nanka Formation is related to an episode when the rate of sedimentation of the subtidal bars facies association was greater than the rate of an accommodation space that was succeeded by an erosion (Ogbe et al., 2020) and an abrupt rise in sea-level with retrogradation of the tidal mudflat deposit. Deposition of the subaerial plain on the shallow marine facies suggests that there was a progradational shoreline translation within the ancient tidal and fluvial influenced deltaic systems (Vos, 1977). The pattern of the vertical succession of the facies associations and depositional environments indicates a facies dislocation in the outcropping Nanka Formation (Nwajide, 1980, 2013), elucidating the seaward shift in facies as the shallow marine facies is capped by coastal plain deposit tracts (Figure 13b) (Van Wagoner et al., 1990; Emery and Myers, 1996; Nwajide, 2013). The pattern of the ichnofacies distribution and the
| Genetic unit | Systems tract | Lithofacies                                      | Facies association | Depositional environment |
|-------------|---------------|-------------------------------------------------|-------------------|-------------------------|
| 20m         | TST           | Wavy ripple muddy heterolith lithofacies        |                   | Lagoonal                |
| 15m         |               | Bedded mudstone                                 | Tidal mud flat    |                         |
| 10m         |               | Sharp base sandy heterolith                      | Marsh to marine   |                         |
| 5m          | HST           | Fine to coarsegrained cross-bedded sandstone    | Subtidal bars     | Flood tidal             |
|             |               | with clay-drapes                                |                   | Tidal fluvial deltaic   |

Possible outcrop position:
- **TST**: Transgressive Surface
- **HST**: Highstand System Tract
- **LST**: Lowstand System Tract
- **Maximum Flooding Surface**: Flooding surface
Table 1. Reservoir characteristics: Grain-size statistical analysis and permeability evaluation of the sandstone facies of the exposed sections of the Nanka Formation.

| Location     | Sample No. | $\phi$ | $\sigma$ | $D_m$ (mm) | Interpretation | $K = C_0 D_m^{-1.33\sigma}$ (Krumbein and Monk, 1942) | Qualitative evaluation (Levorsen, 1967) |
|--------------|------------|-------|--------|-----------|----------------|-------------------------------------------------|--------------------------------------|
| AGU-AWKA     | Al-1       | 1.15  | 0.72   | 0.45      | Medium grained, moderately sorted sand          | 59.93                                           | Good                                 |
|              | Al-2       | 1.12  | 0.53   | 0.46      | Medium grained, moderately well sorted sand     | 80.32                                           | Good                                 |
|              | Al-3       | 0.60  | 0.84   | 0.66      | Coarse-grained, moderately sorted sand          | 110.15                                          | Good                                 |
|              | AI-4       | 2.10  | 0.67   | 0.23      | Fine-grained, well sorted                       | 16.71                                           | Moderate                             |
|              | Al-5       | 1.16  | 0.75   | 0.45      | Medium grained, well sorted sand                | 57.62                                           | Good                                 |
| UMUNYA       | U1-1       | 0.98  | 1.28   | 0.48      | Coarse-grained, well sorted sand                | 32.74                                           | Moderate                             |
|              | U1-2       | 2.85  | 0.39   | 0.14      | Fine-grained, well sorted sand                  | 8.94                                            | Poor to fair                         |
|              | U1-3       | 2.56  | 0.38   | 0.17      | Fine-grained, well sorted sand                  | 13.35                                           | Poor to fair                         |
|              | U1-4       | 1.94  | 0.46   | 0.26      | Medium grained, well sorted sand                | 28.12                                           | Moderate                             |
|              | U1-5       | 1.96  | 0.61   | 0.25      | Medium grained, moderately sorted               | 21.36                                           | Moderate                             |

$C_0$ is an empirical constant (760 Darcy/mm²); $D_m$ is the geometric mean of grain diameter in mm, where $\phi = -\log_2 (D_m)$ as the graphic mean; $\sigma$ is a standard deviation of the grain diameter in phi unit.

Various lithofacies characteristics suggest that both static and dynamic elements of depositional environments played a role in the development of the sequence of the Nanka Formation. Depositional environment affected the sedimentation pattern and stratigraphic base level facies association, where it attained a shallow sea-level when an accommodation space was limited by an erosion and subsequently, the facies starts deepen gradually with a slow rate of coastal retrogradation (Figures 12 and 13). The stratigraphic association of episodes of an increase in fluvial deltaic sediment supply, and lacustrine facies variability with the SB, suggests a tectonic control on the Niger Delta Basin climate and development (Mckie and Garden, 1996; Osokpor and Ogbe, 2019; Ogbe et al., 2020). These have probably played a role in the sequence stratigraphy of non-marine/coastal sediments of formations of the passive margin of southern Nigeria basins (Reyment; 1965; Oboh-Ikuenobe et al., 2005; Nwajide, 2013). The microscopic study reveals that the reservoir quality potential than the Umunya locality (Table 1). This is attributed to the variation in the spatial distribution of net-to-gross sand ratio, ferruginous materials, architectural and depositional structural elements between Umunya and Agu-Awka outcrops (Table 1). Generally, in the highly compartmentalized reservoir facies of the Nanka Formation, the burrows in the ichnofacies within the formation may possibly improve the connectivity by piercing the clay beds possibly a third-order SB. This is attributed to the extensive areal of the surface. The Nanka Formation could be described as deposits of systems tract; TST (Modi et al., 2003) and Nwajide (2006) assigning Priabonian to Miocene age to the formation and the work of Umeji (2013) established that the erosional surface may be a fourth-order SB or possibly a third-order SB. However, we suggest that the erosional surface is a regional stratigraphic marker, possibly a third-order SB. This is attributed to the extensive areal of the surface. The Nanka Formation could be described as deposits of third-order sequences. This is based on the work of Reyment (1965), which assigned Ypresian age to the formation and the work of Umeji (2003) and Nwajide (2006) assigning Priabonian to Miocene age to the overlying Ogwashi Formation (Figure 12).

5.3. Prediction of the reservoir quality and architecture of the Nanka Formation

Based on the net-to-gross ratio, textural characteristics, and the composition of the various lithofacies, the subtidal bar facies is interpreted to be the most potential reservoir of the Nanka Formation. These variables are inherent in most depositional environments, and they may possibly affect hydrocarbon extraction processes. The study shows that petrographic characteristics (grain size, sorting, sphericity, matrix, cement and mineral composition), palaeobiogenic, diagenetic processes, and depositional environments are all considered to be factors affecting the architecture and reservoir quality of the facies of the Nanka Formation. Here, the computed permeability is a function of porosity in evaluating the reservoir quality of the facies (Table 1).

The facies architecture changes from proximal to distal, attributed to lateral facies changes and variability in environment of deposition within the Nanka Formation (Figures 6 and 8). The thickness, net-to-gross ratio, sand continuity and connectivity, sand-body geometry and mudstone lithofacies exhibit variations. These are predicted to affect the lithofacies’ vertical and lateral stacking pattern distribution in the subsurface (Figures 6 and 8). Reservoir quality, architecture and heterogeneity observed in outcrops are expected to change and may possibly be affected at different scales, from finer to larger scales (Miall, 1988; Abdulkadir and Abdullatif, 2013).

Permeability average values derived from statistical parameters of the reservoir facies of the Nanka Formation in Agu-Awka and Umunya outcrops are 64.95, and 20.90 mD, respectively (Table 1). The formation porosity value is predicted to correspond with the permeability (Ma and Morrow, 1996). Reservoir characteristics evaluated have revealed that the sediments of the Agu-Awka localities have better reservoir quality potential than the Umunya locality (Table 1). This is attributed to the variation in the spatial distribution of net-to-gross sand ratio, ferruginous materials, architectural and depositional structural elements between Umunya and Agu-Awka outcrops (Table 1).

5.4. Prediction of the facies and reservoir quality in the subsurface

It should be specified here that the reservoir facies heterogeneity, quality and architecture observed at outcrops are expected to change and may be affected at different scales in the subsurface (Miall, 1968, 1996; Abdulkadir and Abdullatif, 2013). Based on outcrop data from this study, the composition of the facies in the subsurface is predicted to be from proximal to distal, medium to coarse-grained quartz-arinite sandstone (Figure 5b), and the sediment is expected to be texturally immature and moderately mineralogically mature. It could be envisaged that the sediment in the subsurface is poor to moderately sorted due to the size range and finer grains distribution in the outcrops studied. The net-to-gross ratio is conceptualized to increase proximally, and the lateral and vertical connectivity is expected to be good, being ascribed to the high

Figure 13. Sequence stratigraphic analysis of the outcropping Nanka Formation of the Ameke Group that is based on lithological stacking patterns and facies. (a) Synoptic description illustrating the sequence stratigraphy, facies and depositional environment of the sediments. (b) Sequence stratigraphy physiological model showing the possible position of the synoptic vertical succession of facies of the outcropping Nanka Formation, where a shallow marine facies, HST is capped by a coastal plain deposit, TST (Modified from Van Wagoner et al., 1990). Note the position of the vertical red line marked. HST = highstand systems tract; LST = lowstand systems tract; TST = transgressive systems tract.
6. Conclusions

1. The lithofacies analysis points out that the interpreted subtidal bar facies association was deposited in mixed environments, such as fluvial-tidal deltaic settings influenced by wave actions with high intensity. While the interpreted tidal mudflat facies association was deposited in a marsh to marine environment that was characterized by wave actions with relative low intensity.

2. The paleocurrent pattern elucidates one major sediment dispersal compartment within the fluvial system from a source area located in the southwest transported to the northeast direction. In the tidal setting, the sediments are distributed from the northwest and northeast to southeast and infrequent in the southwest direction. The tidal imprints characteristically found in most of the depositional facies of the Nanka Formation studied, step-up the uncertainties of the paleocurrent analysis in prediction of the sediments provenance though.

3. Variation in the shape of the sand grains and the presence of reactivation surfaces in the Nanka Formation indicate the facies have been recycled and/or reworked by wave actions on the sediments that were sourced from both igneous and metamorphic rocks.

4. The various lithofacies characteristics and pattern of ichnofacies distributions indicate that both dynamic and static elements of depositional environments played a role in the sedimentation and sequence developments of the Nanka Formation. Similarly, the relationship between the various lithofacies associated with the exposed erosional surface of the formation at the two locations, suggests that the surface is a regional stratigraphic marker and possibly a third-order sequence boundary.

5. The statistical parameters indicate that the reservoir quality is moderate to good in the outcrop. While in the subsurface is predicted to be poor to moderate. The reservoir quality may possibly be improved by the presence of the ichnofossils within the formation.

6. The study reveals that textural properties, depositional environments and/or facies heterogeneity are predicted to be the factors controlling the architecture and reservoir quality of the facies of the Nanka Formation. Post-depositional processes may also be factors.

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