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Sequence stratigraphy

Sedimentology and sequence stratigraphy of the Nkporo Group (Campanian−Maastrichtian), Anambra Basin, Nigeria

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Abstract Integration of sedimentologic and sequence stratigraphic interpretations of the Nkporo Group has provided the basis for a basin-wide framework for prediction of potential source, seal and reservoir rocks in the Anambra Basin, Nigeria. Lithofacies and biostratigraphic data show that the Nkporo Group in the Anambra Basin contains three main facies associations (fluvio-deltaic facies, estuarine central basin/shallow shelf facies and estuarine channel fill facies) that determine the reservoir containers, flow units and seals. The units are arranged to form two stratigraphic sequences represented by the Nkporo Shale−Owelli Sandstone and Owelli Sandstone−Enugu Shale successions, respectively. The transgressive systems tract in each sequence comprises coarse-grained fluvio-deltaic sandstone and an overlying open marine black carbonaceous mud rock. The highstand systems tracts comprise delta front deposits with average porosity, permeability and net-to-gross values estimated in the ranges of 30%, 3000 md and 0.9, respectively. The fluvio-deltaic and delta front facies which are encased in organically rich estuarine central basin/shallow shelf mud rocks are likely the potential reservoirs. Trapping capacity is enhanced by the presence of several N−S trending normal faults, and other microstructures related to the post-Santonian tensional regime in the Benue. The new information presented in this paper on potential seal, source and reservoir lithofacies within the Nkporo Group should serve as a useful contribution to the geological modelling of reservoirs within the Late Cretaceous−Paleocene succession in the Anambra Basin.

Key words fluvio-deltaic facies, estuarine central basin, estuarine channel, sequence stratigraphy, reservoir, Nkporo Group, Late Cretaceous−Paleocene, Anambra Basin, Nigeria

1 Introduction

The marginal-shallow marine Nkporo Group is the basal lithostratigraphic unit of the Late Campanian−Maastrichtian successions of the Anambra Basin, Nigeria (Figs. 1, 2). A sequence stratigraphic model for the Group was developed by Nwajide and Reijers (1996), on the basis of stratigraphic analysis of a composite section located at Leru, near Okigwe (Fig. 1). Recent studies by Obi (2000) have led to some revision in the stratigraphic framework. The new stratigraphic synthesis presented in this paper differs significantly from that developed by Nwajide and Reijers (1996). One major difference is that the previous model did not recognize a channel-fill facies that underlies the basal Nkporo Shale (Fig. 3), but placed a type-one sequence boundary at the contact between the estuarine mudstones of the Nkporo Shale and shallow marine facies of the Abakaliki Basin. Juxtaposition of the estuarine shales over shallow marine shales reflects neither erosion, nor any significant facies dislocation that should be consistent with the definition of a type-one sequence boundary

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(Haq *et al.*, 1988; Van Wagoner *et al.*, 1990).

Besides the differences in interpretation, the single-outcrop approach adopted in the stratigraphic analysis of the Nkporo Group presented by Nwajide and Reijers (1996) did not permit determination of large-scale stratigraphic distribution patterns and their correlation. The exact geometries, lateral extent/continuity and sedimentary characteristics of the potential source rocks, seal and reservoir lithofacies identified within the Nkporo Group (Nwajide and Reijers, 1996), were therefore not established.

This paper attempts to:

1) re-evaluate the sedimentology and architecture of the Nkporo Group, using data obtained from well-spaced outcrops and boreholes;

2) present a new sequence stratigraphic interpretation and

3) integrate the sedimentologic and sequence stratigraphic interpretations into a depositional model that may be used as a regional framework for a basin-wide prediction of source, seal and reservoir lithofacies.

2 Geologic setting of the Nkporo Group

The study area is located in the southern part of the Anambra Basin (Fig. 1) and covers about 2200 km[2]. The basin is bounded to the south by the Niger Delta hinge line. It extends north-westward into the Niger Valley, northward to the Jos massif and north-eastward as far as Lafia. The eastern and western limits of the basin are defined by the Abakaliki Anticlinorium and Ibadan massif, respectively (Fig. 1). The structural evolution of the Anambra Basin has been described by Ojoh (1988), Popoff (1990), Binks and Fairhead (1992), Obi *et al.* (2001), and Obi and Okogbue (2004). The origin of the basin is generally believed to be linked to the Santonian tectonics of the Abakaliki-Benue Basin, during which an N−S compression between the African and Europeans plates folded the Abakaliki Anticlinorium (Olivet, 1984; Maluski *et al.*, 1995; Burke,

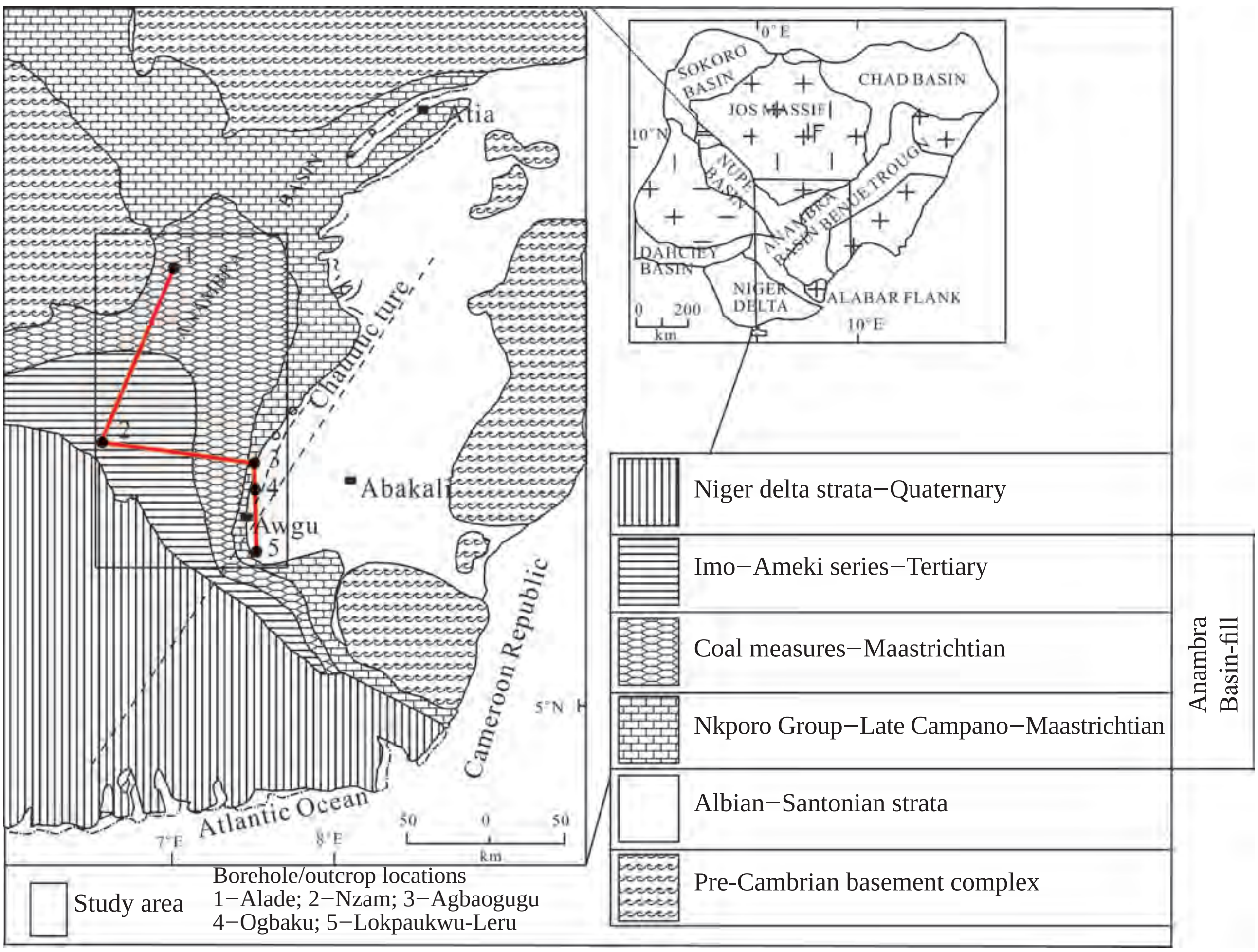


Fig. 1 Geological map of southeastern Nigeria showing the study area, relevant borehole/outcrop locations and line of section (shown in red) (modified after Obi, 2000).

1996). Prior to the tectonic event the Anambra Basin was a platform that was only thinly covered by sediments. The folding of the Anticlinorium laterally shifted the depositional axis into the Anambra platform which then began to accumulate sediments shed largely from the Abakaliki Anticlinorium (Murat, 1972; Hoque and Nwajide, 1985; Amajor, 1987). The Anambra basin-fill comprises over 2500 m of sediments that accumulated during the Campanian−Paleocene period.

The lithostratigraphic framework for the Early Cretaceous−Paleocene strata in southeastern Nigeria has been summarized by Nwajide (1990; Fig. 2). The Campanian−Maastrichtian period is represented by the Nkporo Group comprising the Nkporo Formation, Owelli Sandstone (including Lokoja and Lafia Sandstones) and Enugu Shale (Reyment, 1965). The Nkporo Formation with an estimated subsurface thickness of 1000 m (Agagu and Ekweozor, 1982; Agagu *et al.*, 1985) outcrops mainly in the area south of Awgu (Fig. 4), where it consists of a succession of ammonite-bearing marine shale, limestone lenses and sandstone that successively overstep the Coniacian−Santonian Awgu Formation, Turonian Ezeaku Formation and the Albian Asu River Group. North of Awgu the Nkporo Group is represented by the Owelli Sandstone and the Enugu Shale. The Owelli Sandstone consists of medium- to coarse-grained, prominently cross-stratified, feldspathic sandstone that unconformably overlies the Awgu Formation (Agumanu, 1993). In the region north of Awgu the Owelli Sandstone is directly overlain by the Enugu Shale comprising soft greyish-blue or dark grey carbonaceous mudstone and fine-grained sandstone that are well exposed along the Port Harcourt—Enugu Highway between Agbaogugu and Enugu. The Enugu Shale is associated with extensive synsedimentary deformation structures (Nwajide and Reijers, 1996; Obi and Okogbue, 2004).

South of Awgu, the Nkporo Formation is directly succeeded by the basinal facies of the coaly Mamu Formation (Reyment, 1965). The latter comprises rhythmic alternation of thick carbonaceous shales and oolitic sandstones that pass upward into mainly fine grained, well sorted

Age (my)		Abakaliki−Anambra Basin	Afikpo Basin
30	Oligocene	Ogwashi−Asaba Formation	Ogwashi−Asaba Formation
54.9	Eocene	Ameki/Nanka Formation/Nsugbe Sandstone	Ameki Formation
65	Paleocene	Imo Formation Nsukka Formation	Imo Formation Nsukka Formation
73	Maastrichtian	Ajali Formation Mamu Formation Nkporo/Owelli Sandstone/Enugu Shale (Including Lokoja Sandstone and Lafia Sandstone)	Ajali Formation Mamu Formation Nkporo Shale/Afikpo Sandstone
83	Campanian		
	Santonian	Agjbani Sandstone/Awgu Shale	Non−deposition/erosion
87.5	Coniacian		
88.5	Turonian	Ezeaku Group	Ezeaku Group (Including Amasiri Sandstone)
93	Cenomanian−Albian	Asu River Group	Asu River Group
100			
119	Aptian Barremian Hauterivian	Unamed units	
Precambrian		Basement complex	

Fig. 2 Lithostratigraphic framework for the Early Cretaceous−Tertiary period in southeastern Nigeria (after Nwajide, 1990).

sandstones (Obi, 2000). The presence of *Libycoceras dandense* (Howarth) in marine facies of the Nkporo Shale about 35 m below the Nkporo−Mamu contact in the Lokpaukwu−Leru section demonstrates that in this area the Nkporo Group−Mamu Formation contact approximates to the Campanian−Maastrichtian boundary (Zaborski, 1983).

3 Methodology

The scarp slope of the Enugu Cuesta in the Ozalla−Okigwe area provides complete and easily accessible outcrops of the Nkporo Group in the Anambra Basin. Three representative outcrops located at Agbaogugu, Ogbaku and Leru (Fig. 1), were measured in detail, with emphasis on lithologic variations, texture, sedimentary structures and physical surfaces within the facies succession. The three outcrops were then correlated with sections of the Nkporo Group penetrated by SPDC exploratory oil wells sited at Alade and Nzam, approximately 120 km and 100 km, respectively from the locality of the outcrops (Fig. 1).

Five representative shale samples (two from the Nkporo Formation and three from the Enugu Shale) were collected at regular intervals from the Leru outcrop where the intervals are well developed. Palynological separations and identifications were carried out at the Nigerian National Petroleum Corporation Laboratory, Port Harcourt, while the Foraminifera content was analyzed at the SPDC laboratory, Warri. The samples were analyzed for abundance and diversity counts in palynomorphs, and Foraminifera. Interpretation of the acquired palynological and micropaleontology data followed the method of Leckie *et al.* (1990). The results were then combined with lithologic characteristics, sedimentary structures, and trace fossils, to identify the depositional environments, stratigraphic sequences and their bounding surfaces.

Unconformities were readily observed in the measured sections and were therefore employed in defining sequence boundaries. Sequence stratigraphic interpretations followed the method of Van Wagoner *et al.* (1990).

4 Lithostratigraphy and lithofacies

Three lithostratigraphic formations, the shaly Nkporo Formation, Owelli Sandstone and the Enugu Shale (Reyment, 1965) represent the Nkporo Group in the study area.

4.1 Nkporo Formation

The Nkporo Formation encountered in the study area is subdivisible into two lithostratigraphic units, namely, a lower sandstone and an overlying carbonaceous mud rock unit (Fig. 3).

The basal sandstone unit is composed of ferruginized, poorly-sorted, coarse-medium grained and pebbly sandstone that rests unconformably on the tilted Coniacian−Turonian Formations. In boreholes at the proximal Alade and Nzam localities (Fig. 1) the unit is up to 150 m thick, while in the more basinal Ogbaku and Leru sections where the unit oversteps the Pre-Campanian Formations, the thickness decreases to less than 10 m (Fig. 3). This trend is consistent with a wedge-shaped geometry. In all the outcrops studied, the sandstone exhibits high-angle planar cross-stratified beds with mud drapes on toe-sets at the lower levels. Cross-stratified bed measurements and paleocurrent analysis (Fig. 5) reveal a dominant westerly (260°) paleocurrent direction. The upper part of the unit exhibits strong bioturbation and contains marginal marine trace fossils including Arenicolites, Planolites, Rhizocorallium, and Teichichnus.

The overlying carbonaceous mud rock unit is better developed in the more basinal area south of Awgu, where it begins with grey, bioturbated mudstone that is characterized by concretionary pyritic layers 5−10 cm in thickness. The interval passes upward into nodular, fossiliferous black carbonaceous, fissile shale inter-bedded with grey, to milky-white, sharp-based beds of limestone and very fine grained sandstone/siltstone (Fig. 6). Limestone occurs both as nodules and thin primary bands composed largely of bivalve- and gastropod shells embedded in lime-mud. The sandstone/siltstone lenses are micaceous and wave rippled. Body fossils recovered from the interval by previous workers include ammonites (represented by *Libycoceras dandense*, and *Sphenodiscus*) which dominate the lower levels (Reyment, 1965; Zaborski, 1983) and pelecypod (*Inoceramus*) which occur mainly in the sandstone/siltstone lenses at the upper levels (Arua, 1988; Okoro, 1995).

4.2 Owelli Sandstone

Sedimentology: Outcrop sections of the Owelli Sandstone can be distinguished into two lithofacies, namely, a basal, fossiliferous siltstone-sandstone and an overlying planar cross-stratified sandstone (Fig. 3).

The fossiliferous siltstone-sandstone lithofacies of the Owelli Sandstone is well exposed at the foot of the Enugu Escarpment between Ogbaku and Leru. The interval maintains a gradational contact with the Nkporo Formation and consists of interbedded well-sorted and wave-ripple laminated, fossiliferous siltstone and fine grained sandstone.

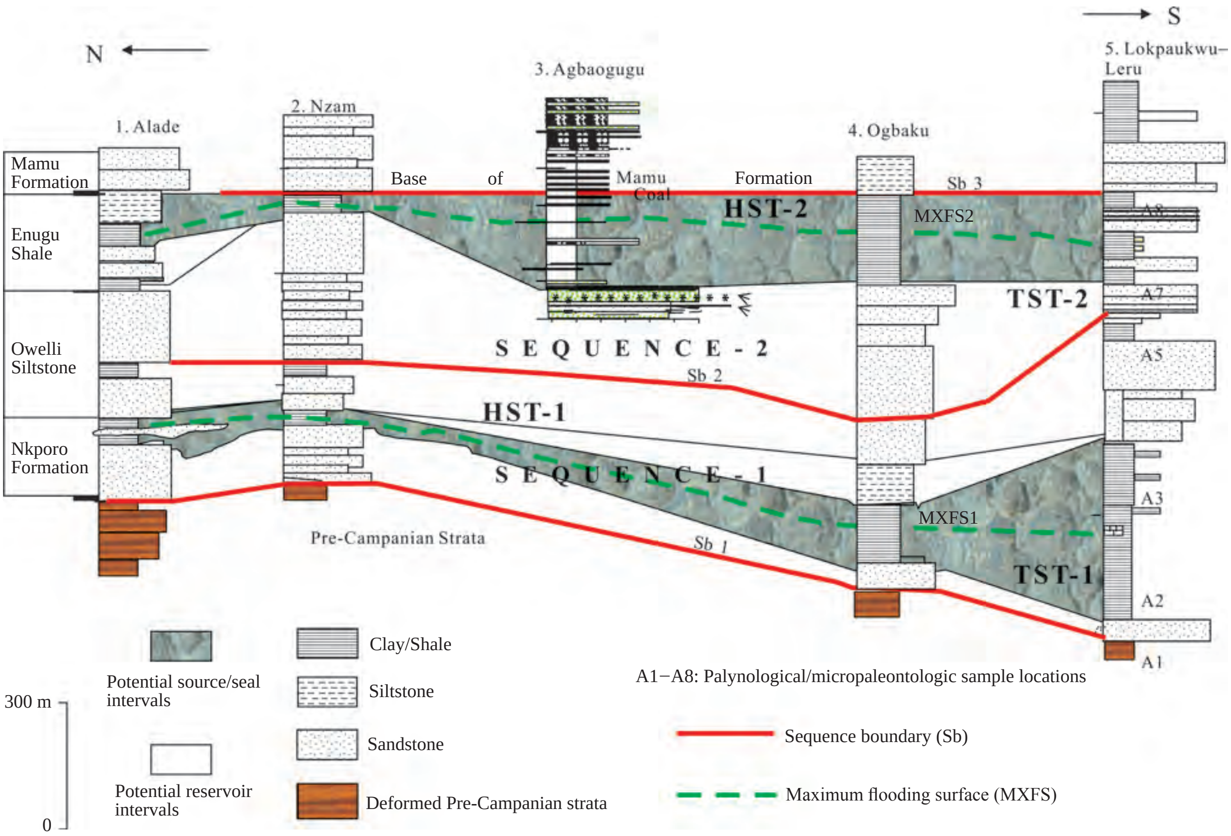


Fig. 3 Basin-wide stratigraphic correlation across the Anambra Basin using base of the Mamu Formation as a datum.

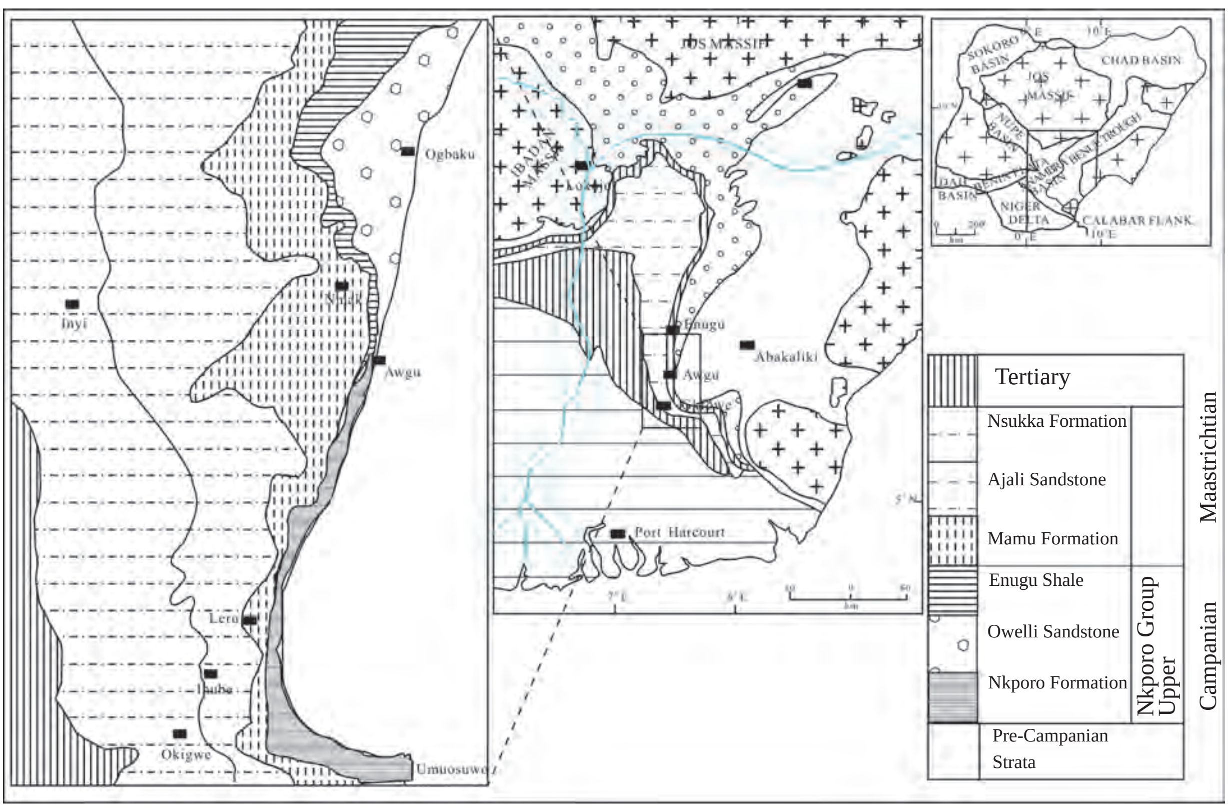
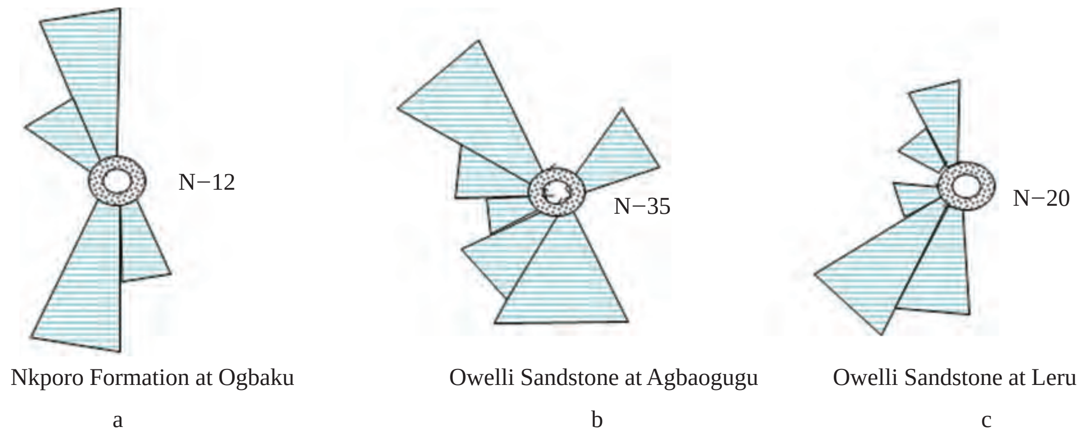


Fig. 4 Map showing the major geologic units in the Ogbaku−Leru region of the Anambra Basin.



Locality	Lithostratigraphic unit	Pattern	MVA	Variance	Vector strength	Environmental implication
Leru	Owelli Sandstone	Perpendicular bimodal	232.4°	2568.4	0.71	Fluvio-deltaic
Agbaogugu	Owelli Sandstone	Perpendicular bimodal-bipolar	270.0°	4518.6	0.45	Fluvio-deltaic
Ogbaku	Nkporo Formation	bipolar	260.0°	6530.8	0.29	Shallow marine

Fig. 5 Paleocurrent data for the Nkporo Group. a−Rose diagram for the basal sandstone member of the Nkporo Formation at Ogbaku; b−Owelli Sandstone at Agbaogugu; and c−Owelli Sandstone at Leru.

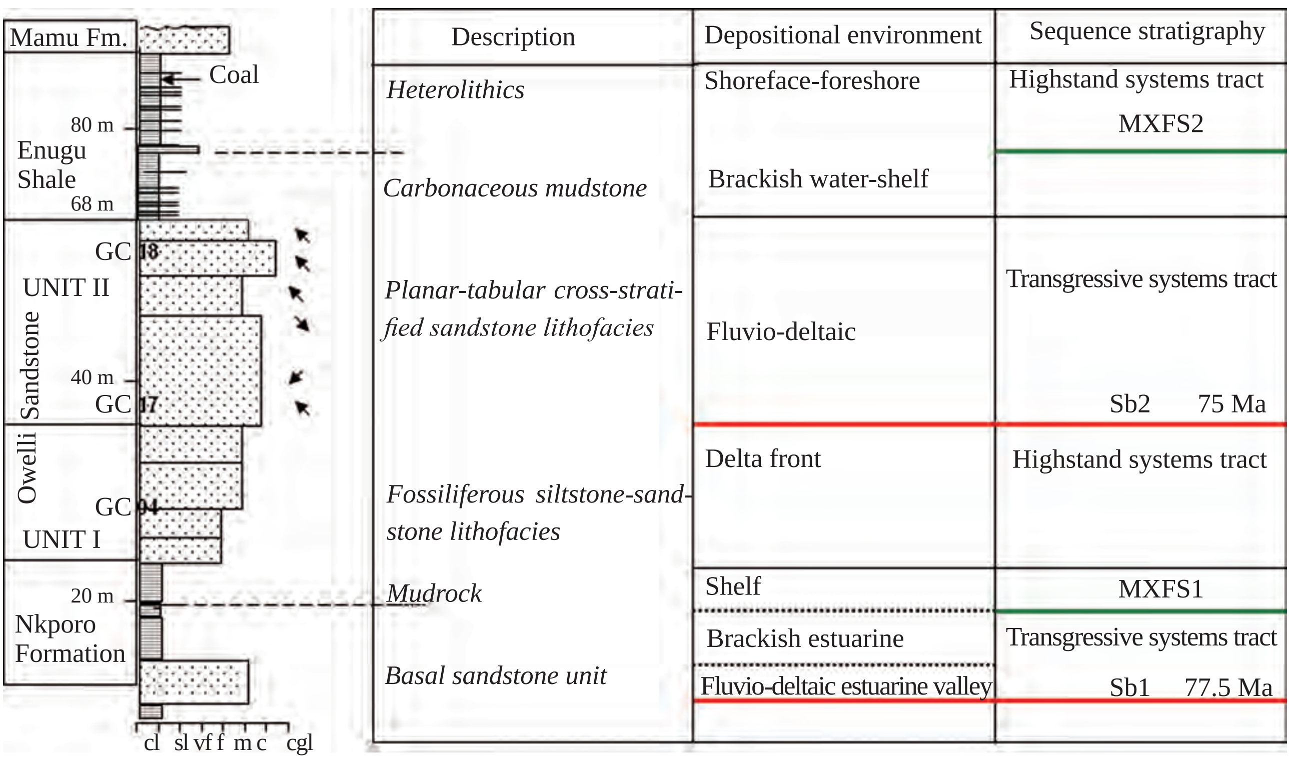


Fig. 6 Stratigraphic profile of the Nkporo Group at the Ogbaku section showing environmental and sequence stratigraphic interpretations. GC 04 to GC 18 are sieve sample numbers. Sb−Sequence boundary.

The basal part of the lithofacies is dominated by inter-laminated 3−10 mm lenses of sandstone and bioturbated siltstone separated by paper-thin mud. The interval gives way upward to sharp-based, coarsening upward, fine-grained micaceous sandstone containing impressions and moulds of the pelecypod *Inoceramus* (Fig. 7a) and the gastropod *Turritella*, as well as slender shafts and tunnels of *Ophiomorpha nodosa*. Estimated outcrop thickness is in excess of 10 m, while bed thickness within the interval varies between 20 cm and 70 cm.

The Planar cross-stratified sandstone lithofacies is best developed in the Ogbaku and Agbaogugu localities. It comprises amalgamated, generally friably to weakly cemented, channelized sandstone units 2.0 m−7.0 m thick (Figs. 6, 8). The base of each sandstone unit is sharp and irregular and commonly associated with clasts of various sizes. Cross-beddings including both low- and high-angle planar-tabular and herringbone types are common. Horizontal lamination, reactivation surfaces, and mud draped foresets are also present. Cross-bed sets range from 25 cm to 80 cm in thickness. Over-turned foresets are present locally (Fig. 9). In the more proximal Agbaogugu sections, the topmost part of the planar-tabular cross-stratified sandstone comprises lateritized, channelized, cross-bedded, coarse-grained sandstone (Fig. 8). At the Leru section the sandstone contains abundant clay clasts and exhibits sole marks at the basal contact with the underlying unit (Fig. 9). Palaeocurrent measurements and analysis indicate a

Fig. 7 a−Well-sorted, micaceous and fossiliferous siltstone−fine-grained sandstone at Ogbaku, containing impressions and moulds of the Pelecypod *Inoceramus*; b−Enugu Shale at Enugu showing massive mud rock facies (below) and parallel-laminated heterolithics (above).

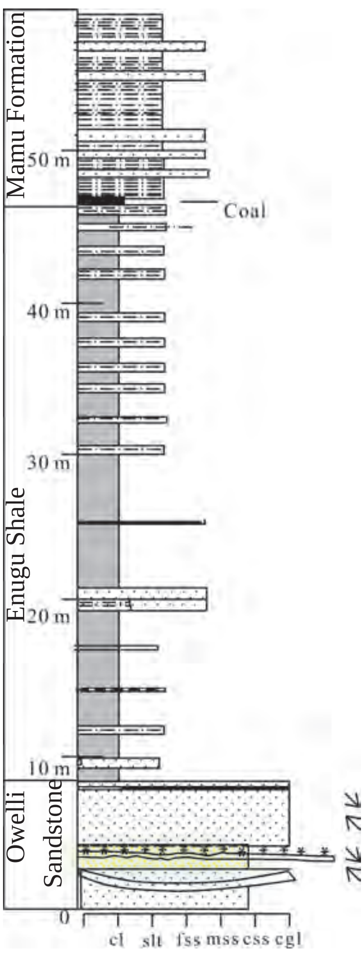
bimodal azimuthal pattern with a principal westerly transport direction (Fig. 5).

Grain size analysis of the Owelli Sandstone shows that grain size ranges from pebbly to fine, with a general coarsening upward trend characterized by abrupt variations in mean grain size, from fine sand to coarse sand. Sorting is generally moderate at the lower levels but fluctuates from moderately-sorted to poorly-sorted at the upper levels. Bioturbation is moderate with *Ophiomorpha verticalis* as the most common trace fossil. Certain intervals may contain large sigmoid-shaped foresets lined with bladed/discoid extra-formational quartzite pebbles (sphericity between 0.7 and 0.75). Log-probability plots for sand samples from the Owelli Sandstone at Ogbaku reveal a grain-size distribution that is characterized by a small, poorly-to-fairly well sorted traction load, and a saltation subpopulation that ranges from −0.5 phi to 2.9 phi, with saltation-suspension junction occurring between 1.5 phi and 3.0 phi (Fig. 10). According to Obi (2000), porosity and horizontal permeability of the Owelli Sandstone generally range between 20% and 30%, and 200 md and 5000 md, respectively.

4.3 Enugu Shale

The Enugu Shale is composed of massive carbonaceous mudstone, laminated mudstone and interlaminated very fine-grained sandstone/siltstone, with total outcrop thickness of over 50 m. Typical sections of the Enugu Shale (Figs. 6, 8) are characterized by even/wavy lamination, flaser- and lenticular-bedding, synsedimentary faults, folds and slump structures/contorted intervals (Obi and Okogbue, 2004), as well as ubiquitous concretions characterized by sideritic cores and pyritic rims. For descriptive purposes, the exposed part of the Enugu Shale is subdivided into carbonaceous mudstone (at base), and heterolithic facies.

The carbonaceous mudstone sharply overlies the fluviatile top of the Owelli Sandstone (Fig. 3). The basal part of the unit is over 10 m thick and comprises massive carbo-



Description	Depositional environment	Sequence stratigraphy
		Sb3 73 Ma
Carbonaceous mudstone alternating with sharp-based siltstone and very fine-grained sandstone, with thickness ranging between 40 cm and 1.5 m	Back-stepping shoreface-foreshore	Highstand systems tract MXFS2
Massive carbonaceous and gypsiferous mudstone beds, 40 cm−150 cm thick, alternating with thinner siltstone beds	Shallow shelf brackish estuarine Fluvio-deltaic	Transgressive systems tract Sb2 75 Ma
Medium- to coarse-grained quartz sandstone Micaceous sandstone and thin shale layers	Tidally influenced channel	Highstand systems tract

Fig. 8 Graphic log of the Agbaogugu outcrop. Sb−Sequence boundary; MXFS−Maximum flooding surface (modified after Obi and Okogbue, 2004).

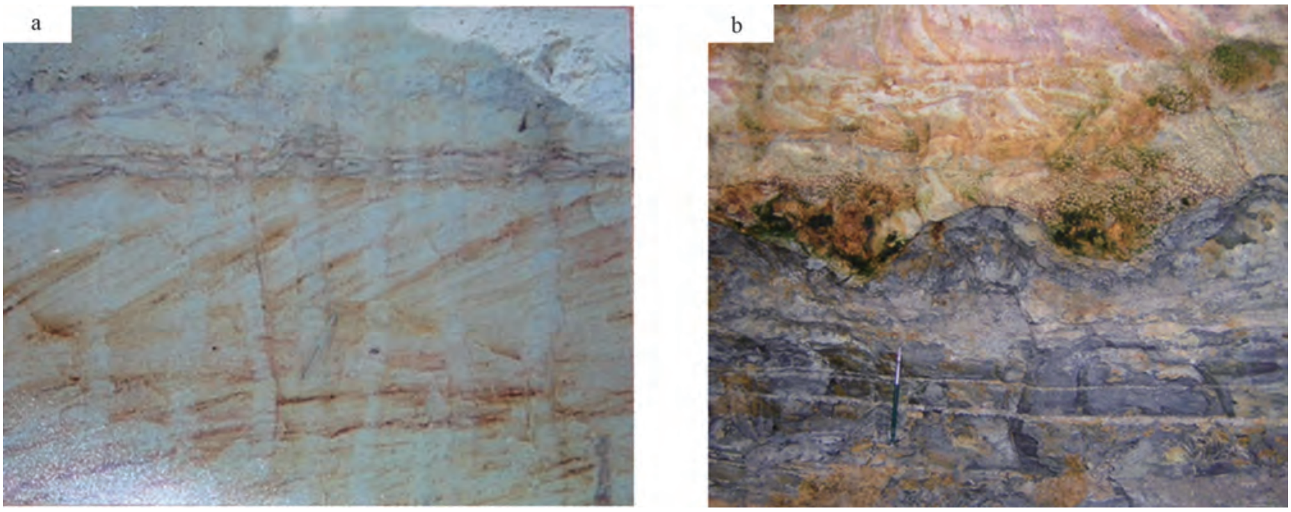


Fig. 9 a−Low-angle (below) and high-angle planar-tabular cross-stratification in the Owelli Sandstone at Ogbaku; b−Sharp and irregular contact (with sole marks) between sandstone lithofacies and underlying mudstone at Leru. Note over-turned foresets within the sandstone lithofacies. Pen is 16 cm in length.

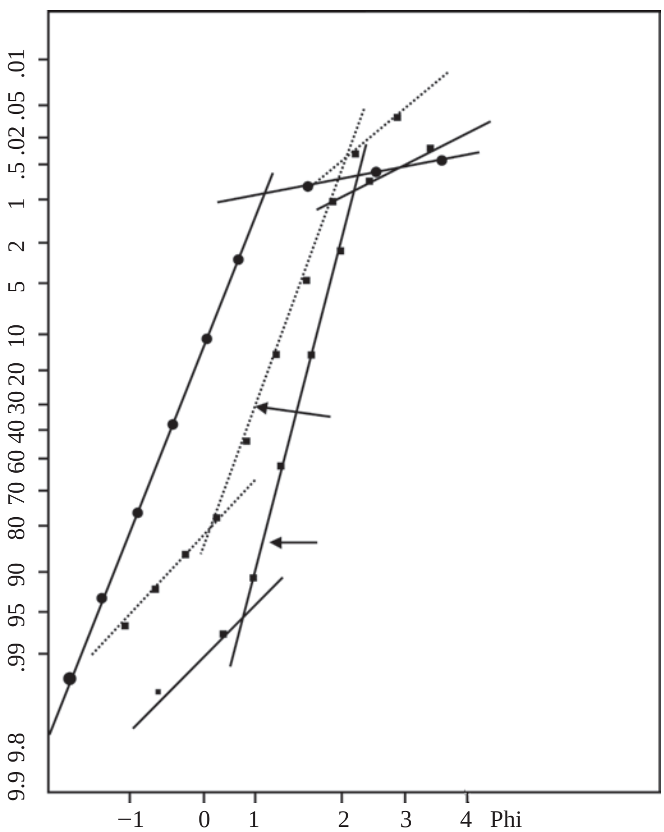


Fig. 10 Cumulative plots for the planar-tabular cross-stratified sandstone lithofacies at Agbaogugu.

naceous and gypsiferous mudstone beds 40 cm−150 cm thick, alternating with thinner siltstone beds. Gypsum occurs in thin flakes, and as crusts along the bedding planes. Laterally persistent silty/sideritic concretions, hardly more than 20 cm in thickness and characterized by sideritic cores and pyritic rims, occur at intervals of between 50 cm and 200 cm. Trace fossil assemblage includes *Teichichnus* and *Planolites*.

The overlying heterolithic facies comprises carbonaceous mudstone alternating with sharp-based siltstone and very fine-grained sandstone (Fig. 7b), with thickness ranging between 40 cm and 1.5 m. Siltstone beds are characterized by lenticular bedding, wavy and parallel lamination, whereas sandstones contain planar-tabular and herringbone cross-stratification, flaser bedding, and reactivation surfaces. Mud drapes occur on foreset planes of the cross-stratified strata. Leaf imprints occur in places.

The transition from the Enugu Shale to Mamu Formation in the more proximal sections is marked by a silty interval containing spindles of vitrinite and sub vertical carbonaceous root traces. In the more basinal sections the transition is marked by an exhumed substrate characterized by the *Glossifungites* ichnofacies including *Arenicolites*, *Rhizocorallium*, *Gastrochaenolites* (?), *Planolites*, and *Thalassinoides* (Obi, 2000).

5 Biostratigraphy

5.1 Palynology

Table 1 presents the distribution, frequency and species diversity of microspores, pollens, dinoflagellates and fungi /algae in the Nkporo Group, Anambra Basin.

The samples record a relatively higher diversity counts in land-derived spores and pollen than in the dinoflagellates where generally low counts in species number are recorded. There is a sharp up-section decrease in the number of dinoflagellate species within the Nkporo Shale (from 4 species in sample A1 to A2 species in A3). The basal beds (A5) of the Enugu Shale record very low dinoflagellate species diversity, compared to the underlying Nkporo samples (A1−A3; Table 1). There is also a marked increase in the number of specimens of continental palynoflora in the Enugu Shale samples relative to the underlying Nkporo Shale samples.

5.2 Micropaleontology

All the Foraminifera species identified in the samples from the Nkporo Group (A1−A8) are agglutinated, with the benthonic *Haplophragmoidos* genera dominating. As was observed in the case of palynomorphs, samples from the Nkporo Shale (intervals A1−A3) are generally marked by very low species diversity, both in terms of type and number (Table 2). Samples from the lower portion of the Enugu Shale (A5−A7) record relatively higher population and diversity counts. The absence of planktonic forms in all the samples is also notable. Similar observations were made for the Nkporo Group by Akaegbobi *et al.* (2009) who reported a low-diversity Foraminifera assemblage that is dominated by the benthonic forms.

6 Depositional interpretation

In Figure 3, outcrop data from the measured sections were combined with well logs to show the stratigraphic relations of the Campano−Maastrichtian Nkporo Group in the Anambra Basin. The lithologic and sedimentological characteristics of the various units are summarized in Table 3.

6.1 Nkporo Shale

Nkporo Shale: The Nkporo Shale documents the transgressive event that followed the Santonian deformation in the Anambra Basin (Murat, 1972; Obi, 2000; Obi and Okogbue, 2004). The coarse-grained sandstone at the base of the Nkporo Shale is interpreted as paleovalley because it clearly cuts erosionally into the older, genetically unrelated Awgu, Ezeaku and Asu River Groups. The basal contact is therefore an erosional unconformity (type-1 sequence boundary) formed by subaerial exposure and fluvial inci-

Table 1 Distribution, frequency and species diversity of microspores, pollens, dinoflagellates and fungal/algae in the Campanian−Maastrichtian strata, Anambra Basin

Formation	Sample number	Spores		Pollens		Dinoflagellates		Fungal/algal cists		Environment
		NS	NSP	NS	NSP	NS	NSP	NS	NSP	
Enugu Shale	A8	10	82	23	366	3	120	3	67	Brackish water
	A7	12	194	18	200	5	157	2	65	Open marine
	A5	7	72	24	186	1	6	2	50	Estuarine
Nkporo Shale	A3	6	66	29	198	2	32	3	94	Brackish water
	A1	9	33	8	36	4	51	2	45	Estuarine

NS = Number of species; NSP = Number of specimens.

sion during a fall of relative sea level (Weimer, 1984; Van Wagoner *et al.*, 1990), which is coincident with the regional Santonian deformation. The lithologic characteristics and biogenic sedimentary structures of the sandstone and its stratigraphic relationship with the overlying carbonaceous shale subunit, suggest that the sandstone accumulated as a fluvio-deltaic fill of the inner estuarine valley.

The general palynological criteria used for environmental prediction (*i.e.* the degree of marine influence) are shown in Table 4. The low Foraminifera and dinoflagellate species diversity observed in samples (samples A1−A2) from the mudstone unit directly above the coarse grained sandstone reflects deposition in restricted brackish water estuarine condition (Leckie *et al.*, 1989). The overlying shale unit (sample A3) contains many features that suggest deposition in an inner neritic environment with a normal salinity and oxygen content. Even though the overall assemblage is still dominated by land derived spores and pollen grains, dinoflagellate diversity within this interval is higher due to increased salinity. The Foraminifera and dinoflagellates species diversity and the occurrence of ammonites are evidence of normal salinity and oxygen content. Evenly laminated and sparsely burrowed black shale, thinly intercalated with silt, sand and lime mud reflects deposition in a quiet water/muddy shelf (Davis *et al.*, 1989; Walker and Plint, 1992).

6.2 Owelli Sandstone

Sediments of fossiliferous siltstone-sandstone (unit I) are considered to be delta front facies representing the deposit of a prograding river-dominated delta. The observed upward coarsening and improvement in sorting from the muddy Nkporo Shale suggests that shallower, higher energy conditions prevailed during deposition of the lithofacies. The characteristic occurrence of beds of clean sand alternating with beds of highly bioturbated, muddy siltstone can be attributed to intermittent, high energy storm events and rapid deposition that alternated with periods of slow deposition during fair weather when burrowing organisms extensively reworked the substrate. The stratigraphic relationship with the open marine Nkporo Shale and the presence of sharp-based progradational parasequences are consistent with deposition in estuarine channels (Allen, 1993). Shallow marine bivalves, gastropods and *Ophiomorpha nodosa*, are typical of near shore, possibly lower shoreface conditions (Curran and Frey, 1977; Frey and

Table 2 Distribution and frequency of Foraminifera in shales of the study area

Sample number	Species	Calcareous	Agglutinated	Benthonic	Diversity	Others
A8	*Haplophragmoides saheliense*		3		4	
	Haplophragmoides sahariense		2	16		
	Haplophragmoides spp.		11	66		
	Arenaceous spp.					
A7	*Haplophragmoides sahariense*		50	14	5	
	Haplophragmoides saheliense		400	490		
	Haplophragmoides spp.		5			
	Haplophragmoides talokaense		10	133		
	Arenaceous spp.		35			
A5	Haplophragmoides spp.		26	24	2	
	Arenaceous spp.		9	147		
A3	Arenaceous spp.		4	5	1	
A2	*Haplophragmoides sahaliense*		6	20	3	
	Haplophragmoides sahariense		7	10		
	Arenaceous spp.		1	12		
A1	Haplophragmoides spp. Gastropod		3	32	1	2

Table 3 Sedimentologic characteristics of the Nkporo Group

Formation	Lithology	Sedimentary structures	Interpretation
Enugu Shale Heterolithics	Carbonaceous mudstone alternating with sharp-based siltstone and very fine-grained sandstone, with thickness ranging between 40 cm and 1.5 m	Wave ripples, soft sediment folds / faults, planar-tabular, flaser and herringbone cross-stratification, and reactivation surfaces. Low dinoflagellates species diversity *Teichichnus*, *Planolites*, *Arenicolites* and *Rhizocorallium*;	Mud zone located between upstream fluviatile and downstream marine sand zones of the estuary
Carbonaceous mudstone	Massive carbonaceous and gypsiferous mudstone beds, 40−150 cm thick, alternating with thinner siltstone beds	Gypsum, low dinoflagellates and Foraminifera species diversity	
Owelli Sandstone Planar-tabular cross-stratified sandstone lithofacies	Medium- to coarse-grained quartz sandstone	Planar cross-bedding, festoon and herringbone structures, gutter casts, over-turned cross-beds, scour surfaces and extraformational pebbles;	Sandy bar within a channel located in the fresh water-dominated upper portion of an estuary
Fossiliferous siltstone-sandstone lithofacies	Micaceous sandstone and thin shale layers	Wave-ripple cross-stratification, moderate bioturbation, *Skolithos*, *Ophiomorpha* and bivalve shells	Estuarine-channel fills
Nkporo Shale Mud rock	Shale, micaceous sideritic siltstone and biomicrite	Even lamination, ammonites, Foraminifera, ostracods and echinoid spines;	Open marine environment
Basal sandstone unit	Light colored, poorly-sorted, coarse-to-medium-grained and pebbly sandstone	High-angle planar cross-beds mud drapes. The upper part is strongly bioturbated and contains *Arenicolites*, *Planolites*, *Rhizocorallium* and *Teichichnus*.	Inner estuarine valley fill

Table 4 General palynological indicators of degree of marine influence (Leckie *et al.*, 1990)

Environment	Descriptions
Continental	Palynoflora composed exclusively of land-derived microspores and pollen
Slightly brackish water	Slight introduction of saline water in essentially fresh-water environment, *e.g.*, coastal lakes with outlets to the sea, inlets, upper estuaries, and interdistributary channels. Littoral contains rare specimens of ceratioid dinoflagellates (*e.g.*, *Nyktericysta*, *Vesperopsis* and *Balmula*) and a few acritarchs. Land-derived spores and pollen abundant
Brackish water	Marginal marine conditions found in bays, estuaries, lagoons, and barrier-associated backwaters. Increase in saline water, dinoflagellate species diversity low, certain species of ceratioid or peridinioid dinoflagellates (*e.g.*, *Palaeoperidinium cretaceum*, *Luxadinium primulum*) appear in abundance, assemblage often monospecific, land-derived spores and pollen abundant
Nearshore marine	Inner neritic environment, shallow marine, dinoflagellate diversity higher due to increased salinity but assemblage still dominated by land-derived spores and pollen grains
Open marine	Outer neritic environment, close to the margin of the shelf, fully saline water, dinoflagellate diversity highest, land-derived spores and pollen grains reduced in quantity, assemblage dominated by dinoflagellates

Howard, 1985; Martino and Curran, 1990).

The overlying planar-tabular cross-stratified sandstone is interpreted as a high-energy active channel deposit based on the texture and sedimentary structures. Cumulative frequency plots of grain size distribution for this unit are characterized by both two- and three-segment curve (Fig. 10) that reflects deposition in fluvio-marine setting (Visher, 1969; Obi, 1998). The observed log-probability trends are very similar to the characteristics obtained for sandstone samples from the Almond and Lance Formation (Visher, 1969), which Weimer (1965) interpreted as being of deltaic origin. The characteristics are believed to be produced by strong tidal currents in areas where the surface creep population has been removed probably in shallow water, or on bars in the tidal channel.

The observed high-angle cross-stratification results from the migration and aggradation of moderate-scale bed forms and is consistent with deposition from strong, dominantly unidirectional currents on bars in a channel (Miall, 1992). Herringbone cross-bedding and reactivation surfaces provide evidence of bidirectional flows in a subtidal setting (Smith, 1988). These features and the association with *Ophiomorpha verticalis*, which provides a more conclusive evidence of brackish water and tidal influence (Bowen and Weimer, 2004), suggest that this part of the Owelli Sandstone was formed as a sandy bar within a channel located in the freshwater-dominated upper portion of an estuary.

The channelized, uni-directionally cross-bedded, coarse-grained sandstone that caps the sandbody in the proximal sections is interpreted to be of fluvial origin. Large bladed/discoid extra-formational quartzite pebbles with their flattened surfaces dipping in a general westerly (265°) direction (Obi, 2000), presumably were originally derived from the Oban massif, east of the study area (Amajor, 1987). The juxtaposition of the fluvial channel deposit on the underlying tidal/marginal marine facies of the Owelli Sandstone indicates a regressive depositional Owelli sequence.

6.3 Enugu Shale

The predominance of clay to very fine grain size in the Enugu Shale is consistent with deposition from suspension in a generally low-energy setting. Evidence for brackish water conditions is provided by the overall low dinoflagellates species diversity and a marked increase in the continental palynoflora relative to the Nkporo Shale, as well as the presence of low-diversity, locally high-abundance ichnofossil suite similar to that commonly associated with brackish water conditions (Wightman *et al*, 1987; Pemberton *et al.*, 1992). The common coexistence of siderite and pyrite further supports this interpretation.

Given a brackish water environment in an estuarine setting, much of the Enugu Shale lithofacies is interpreted to have accumulated in a mud zone located between upstream fluviatile and downstream marine sand zones of the estuary (Dalrymple *et al.*, 1992; Allen, 1993; Allen and Posamentier, 1993). In such a setting, thick mud accumulations can occur on tidal flats and in abandoned channels or in active mud-prone channels (Leckie *et al.*, 1989, 1990). Association of rhythmic alternation of mudstone and thin lenses of sandstone with wave-ripple lamination, lenticular bedding and flaser bedding, is typical of sedimentation in subtidal and intertidal systems (Boersma and Terwindt, 1981; Prothero and Schwab, 1996; Oboh-Ikuenobe *et al.*, 2005). The stratigraphic relationship of the Enugu Shale and the underlying tidally influenced Owelli facies is consistent with a relative rise in sea level and the establishment of estuarine conditions (Reineck and Singh, 1980; Dalrymple, 1992). The large-scale contorted bedding, growth faults and other forms of intraformational angular unconformities common in the Enugu Shale, have been attributed to seismically-induced syndepositional downslope slumping (Obi and Okogbue, 2004).

6.4 Sequences and facies succession

Correlation of key stratigraphic surfaces within the Nkporo Group (Fig. 3) reveals two third-order stratigraphic sequences, namely, the Nkporo Formation−Owelli Sandstone (S1) and Owelli Sandstone−Enugu Shale (S2).

The Nkporo Shale−Owelli Sandstone Sequence, *i.e.,* S1 is separated from the strongly deformed Albian-Santonian strata by an angular unconformity (Nwajide, 1996; Obi and Okogbue, 2004). The thickness varies from about 350 m in the Alade well, to over 600 m in the Leru area (Fig. 3). The transgressive systems tract which has a uniform estimated thickness of about 150 m, is composed of the basal coarse-grained fluvio-deltaic sandstone and the overlying brackish water-estuarine to open marine Nkporo Formation. Transition to the overlying estuarine channel sandstones comprising the highstand systems tract, is marked by a maximum flooding surface that is characterized by a relatively high abundance of dinoflagellates and Foraminifera (Table 2; Fig. 11). Thickness of the HST deposits varies from less than 200 m in the Alade and Nzam wells, to about 300 m and over 500 m respectively in the Agbaogugu and Leru areas (Fig. 3). These reservoir sands are generally moderately-well sorted, with average porosity, permeability and net-to-gross values estimated in the ranges of 30%, 3000 md and 0.9, respectively (Obi, 2000). Lower net-to-gross values (0.6−0.7) and a wider range of reservoir quality (porosity ranges from 10%−35% and permeability from 0.1−3000 md) are recorded in the more basinal sections where the Owelli Sandstone interfingers with non-reservoir shales and heterolithics (Fig. 3).

The Owelli Sandstone−Enugu Shale Sequence, *i.e.,* S2 includes the fluvio-deltaic facies of the Owelli Sandstone and the estuarine mud rocks of the Enugu Shale. The transgressive systems tract begins with the medium-coarse grained fluvio-deltaic facies of the Owelli Sandstone and continues upward into grey-black carbonaceous shale and interstratified thin sideritic mudstone facies of the Enugu Shale. The maximum flooding surface within the TST, representing the transition to the HST is probably represented by the thick interval of mud deposition (that is better developed in the Agbaogugu and Ogbaku sections; Fig. 3). This interval is characterized by a relative increase in abundance and diversity of Foraminifera and dinoflagellates (Fig. 11). The HST is truncated above by the third sequence boundary at the Campanian−Maastrichtian transition.

7 Discussion

The Nkporo Group in the Anambra Basin contains three main facies (fluvial facies, estuarine channel fill facies and estuarine central basin/shallow shelf facies) that determine the reservoir containers, flow units and seals. The fluvial facies assemblage occurs basin-wide along the basal axial position of the incised valley-fills and constitutes over 50% of the entire section. The sandbodies, which have as much as 20% porosity (Obi, 2000) are encased in estuarine central basin/shallow shelf mudstone which are considered to be potential source rocks on account of their organic carbon contents (Agagu and Ekweozor, 1982; Akaegbobi *et al.*, 2009). In the more distal sections, the fluvial facies breaks up into several sharp-based fine-to-coarse-grained sandstone lenses that inter-finger with shallow marine shale (Fig. 4). In the Leru section, for example, five discrete sandbodies are present (Fig. 3). The sands are separated by intervals of black shale, which act as barriers to fluid migration. In the more proximal areas, the reservoir sandstones average over 600 m thick (Fig. 4) and contain little or no interbeds of mudstone, showing an architecture that is typical of braided channel systems (Miall and Arush, 2001).

The estuarine central basin facies assemblage overlies the fluvial facies and comprises finely laminated black mudstones with local lenses and interbeds. The facies assemblage dominates the transgressive systems tract and early highstand systems tract. Sequence stratigraphic principles and interpretations have suggested that sediment-starved portions of the transgressive systems tract and early highstand systems tract (*i.e.* the condensed section) have the greatest marine source rock potential (Loutit *et al.*, 1988). Condensed sections, which form during re-

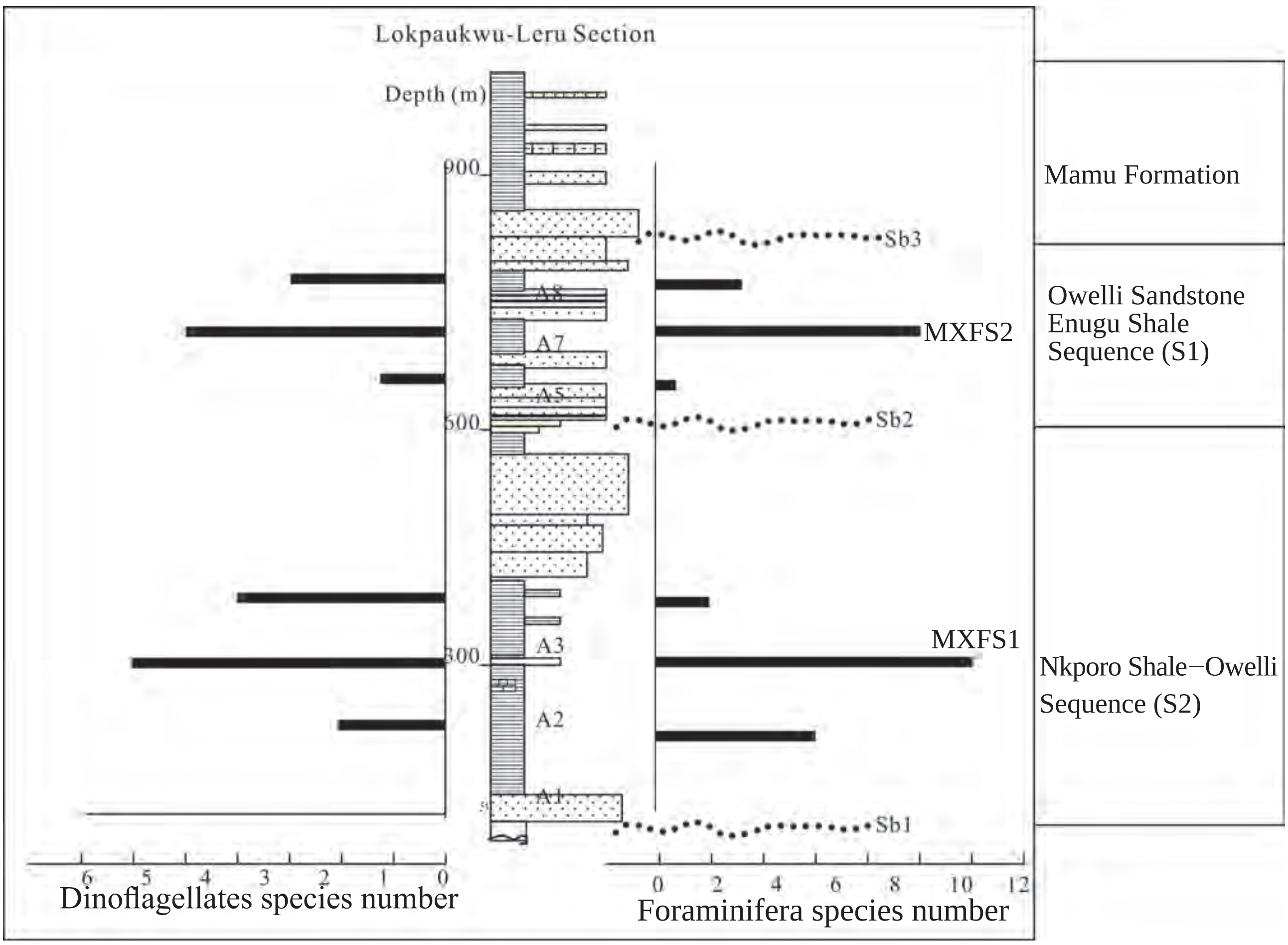


Fig. 11 Stratigraphic profile of the Nkporo Group at the Lokpaukwu-Leru section showing sample locations, plots of dinoflagellates and Foraminifera species abundance and sequence stratigraphic interpretation.

gional transgressions are closely associated with marine flooding surfaces generally considered as having the greatest paleowater depth within a vertical deepening-upward succession. Characteristics of condensed sections include high radioactivity, high pelagic content, and high total organic carbon content. Units belonging to the estuarine central basin facies assemblage of the Nkporo Group have the stratigraphic characteristics of a condensed section in that they are directly above ravinement surfaces, which in turn overlie inner incised estuarine valley-fills. Estuarine central basin facies of the Nkporo Group have been classified as potential source rocks on account of their organic content (Agagu and Ekweozor, 1982). Palynological results obtained in the present work and micropaleontologic results (*e.g.*, Akaegbobi *et al.*, 2009), however, indicate that the bulk of the Enugu Shale was deposited in relatively shallow water, in restricted marginal marine conditions, and that the condensed section is a shallow water variety.

The estuarine channel fill subunits are the second most important reservoir facies in the Nkporo Group. They overlie the fluvial facies and comprise subtidal and tidallyinfluenced facies that dominate the highstand systems tracts. The basal part of the facies assemblage comprises strongly bioturbated shoreface heteroliths. Bioturbation in these units leads to reduction of porosity and permeability because of introduction and mixing of mud between the framework grains of the sandstone. The upper part consists of tidally-influenced sandstones with very good reservoir properties. The Nkporo Group therefore has the capacity to trap hydrocarbons in the reservoir sandbodies. Shale and mudstone facies of the group can act as source and seal lithofacies for the reservoir sands. Trapping capacity is also enhanced by the presence of N−S trending normal faults and microstructures related to the post-Santonian tensional regime in the Benue Trough (Maluski *et al.*, 1995). The structures are particularly visible along the Enugu-Port Harcourt expressway. Open fractures, some partially filled by quartz and/calcite cement are also common. These fracture patterns impact on reservoir permeability and anisotropy and hence play an important part in reservoir fluid flow.

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