LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS OF HYDROCARBON RESERVOIR OF THE LUDO OIL FIELD IN THE COASTAL SWAMP II DEPO-BELT, NIGER DELTA, NIGERIA

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Introduction

The Paleocene marine transgression marked an important stage in the evolution of the Niger Delta. The transgressive event resulted in the southward progradation of the Niger Delta sediments into the Equatorial Atlantic Ocean (Arua, 1980, Obi *et. al.*, 2003, Oboh-Ikuenobe *et. al* 2005). The sediment build-up was accompanied by growth fault tectonics normal to the direction of the progradation, resulting to the formation of parallel, fault-bound Northern, Ugheli, Central Swamp I, Central Swamp II Coastal Swamp I, Coastal Swamp II and the offshore depo-belts that are successively younger from north to south (Ekweozor and Daukoru, 1992; Fig. 1). Each depo-belt contains three thick rock units, which from shallowest to the deepest include (i) fluviatile sand belonging to the Benin Formation, (ii) interbedded sand and shale of the marginal marine-shallow marine Agbada Formation and (iii) marine shale representing the Akata Formation (Reyment, 1965 and Nwajide, 2013). The present study focused on the LUDO Oil field that is located within the Coastal Swamp II depo-belt. The oil field forms part of a north-south trending group of oil fields in the eastern part of the Niger Delta. It contains a single oil reservoir that is buried to a depth of over 8,500 ft. below the surface. There is currently an on-going development activity in the field that involves the updating of information on the reservoir distribution, reservoir heterogeneity and the depositional model.

To contribute to the above initiative, the present study (i) provides detailed record of the lithologic variations, sedimentary structures, textural characteristics and diagenetic aspects of the reservoir; (ii) provides a written summary of each lithofacies interval and lithofacies depth listing, (iii) characterizes and

classifies the reservoir interval using a standard lithofacies scheme and (iv) iinterprets the depositional environments of the reservoir.

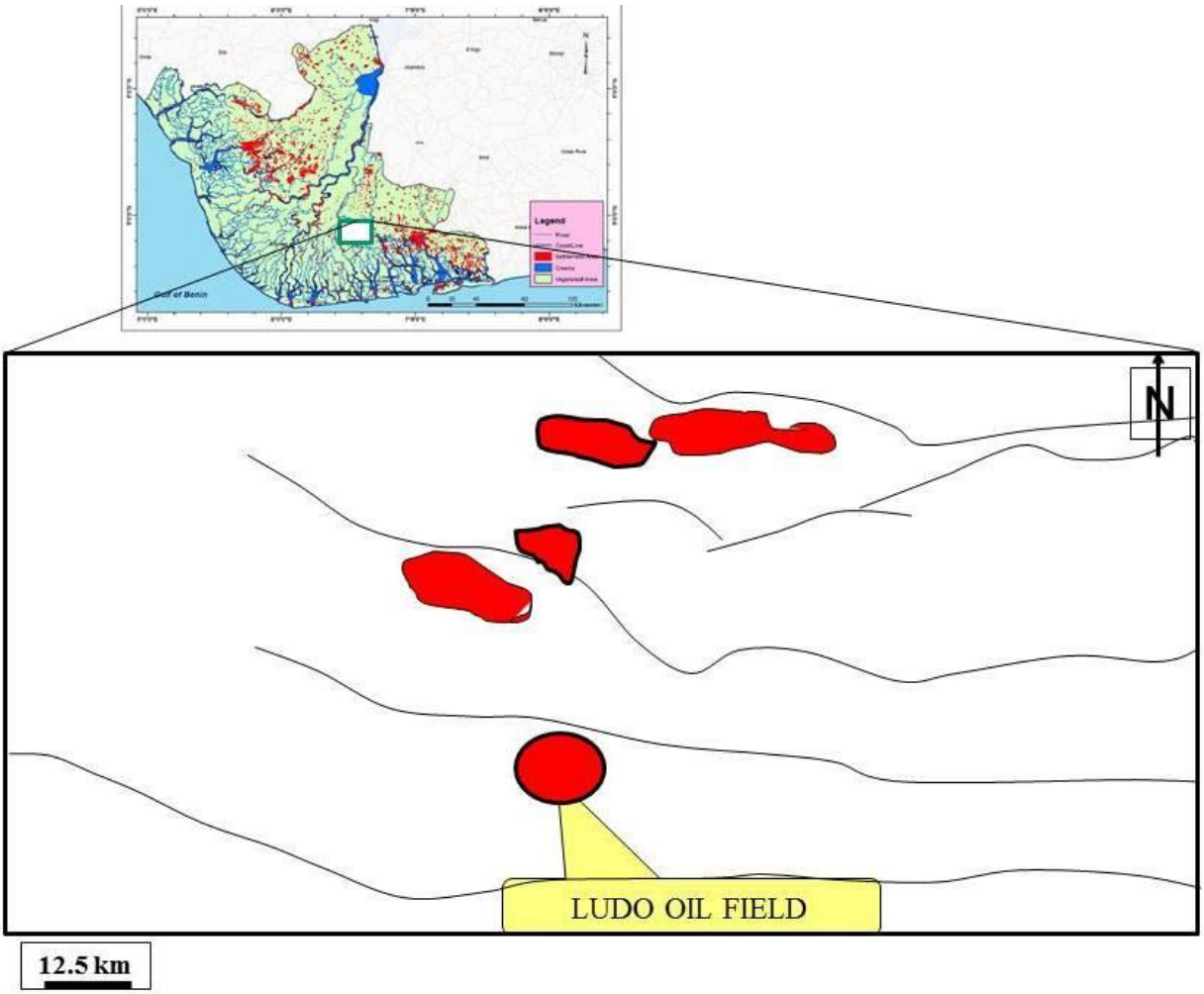

Fig. 1. Play Map Showing the location of the Ludo Oil Field Area

DATA SETS

The sedimentological interpretations presented hereunder are based on the study of 56.16 feet of core slabs taken from depth interval of 8765.80ft to 8821.96ft and arranged in nineteen 3-ft trays. The cores are backed up with the following:

i. Depth manifest for the cored interval,

ii. Spectral core gamma log of the cored interval,

iii. Core photographs on both white light and ultraviolet light, and

iv. Computerized tomography scan images of the core.

METHODS OF STUDY

Textural, compositional and lithological aspects of the cores were estimated by visual examination using the hand lens, dilute acid and standard colour and textural charts. Close-up examination of the cores was then carried out on the core photographs and on the CT-scan images. Sedimentary facies were identified and characterized based on lithology, colour, grain size trend, physical sedimentary structures, types of bed contacts, degree of bioturbation, and faunal content. The slabs were described at a scale of 1: 40 onto Clastic Core Description sheet, using the lithofacies scheme of the SPDC Ltd (Table 1). The schematic lithological log of the cored interval was then matched with the core gamma log signatures and the observed trends were compared with standard deltaic/marginal marine-offshore facies models.

Table 1. Lithofacies scheme used in this study (After Obi and Ebong, 2003)

SEDIMENT TYPE		LITHOFACIES DESCRIPTION	CODE	CLASSIFICATIO N	% Abundance
Sandstone < 20% clay		Pebbly sandstone	PS 1/4	RESERVOIR	
		Fine to coarse grained Cm- scale cross-bedded sandstone	S 2/4x		
		Very fine grained mm-scale Laminated sandstone	S 1/21		
		Very fine to fine grained mm-scale laminated Sandstone with clay drapes/laminae	S 1/2c		
		Bioturbated sandstone	S 1/3b		
Mixed sand and clay (Heteroliths) 20%-80% clay	Sand-rich heteroliths < 20-50% clay	Wavy-bedded sandy heterolith	S 1/2Mw		
		Bioturbated sandy heterolith	S 1/2Mb		
		Glauconitic/shelly muddy sandstone	S 1/4Mshg		
	Mud-rich heteroliths 50-80% clay & silt	Lens-bedded muddy heterolith	Mst	NON-RESERVOIR	
		Bioturbated muddy heterolith	Msb		
Mudstone >80% clay		Bedded or massive mudstone	Mb/Mm		
		Sideritic-bedded mudstone	Msd		
Re-deposited/slumped Sandstone/mudstone & heteroliths		Re-deposited/slumped sandstone	RS 1/4	DEPENDENT ON ORIGINAL SEDIMENT CHARACTERISTICS	
		Re-deposited/slumped mudstone & heteroliths	RM/MS		

Sedimentological Descriptions

The 56.16ft-core extends from a depth of 8765.80ft to 8821.96ft (Table 2). Figure 2 shows that the cored interval is sub-divisible into two major lithologic intervals:

Table 2. Summary of lithofacies depth listing for Ludo oil well

DRILLER'S DEPTH (FT)			LITHOFACIES	DESCRIPTION
TUBE	TOP	BOTTOM	CODE	
1-6	8765.80	8782.20	Sx	Sandstone, dark brown/ferruginized, loose, fine to coarse grained , < 20% clayey, poorly sorted, cm- scale planar & herringbone cross-bedded, clay-draped fore-sets, occasional bioturbation, Thalassinoides, HC stained
6-	8782.20	8783.00	Sl	Dark-brown interval of alternating ,HC-stained, very fine grained, well-sorted sandstone, and clayey siltstone, Thalassinoides along bedding planes,
7-8	8783.00	8788.00	PS	Sand, brown, very coarse grained, pebbly, loose, HC-stained, rests sharply on Fe-stone,
8-9	8788.00	8789.20	PS	Sandstone, strongly ferruginized, coarse, poorly-sorted, iron-bands, HC-stained,
9-10	8789.20	8792.60	Sl	Sandstone, grey-yellow, very fine to fine grained, well-sortd, wave-ripple lamination, H.C-stained,
10	8792.60	8793.40	Mst	Heterolith, mud-rich, grey, lens-bedded,
	8793.40	8795.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic
11	8795.00	8796.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
	8796.00	8798.00	Mb	Heterolith, mud-rich, grey-brown, lens-bedded,
12	8798.00	8800.20	Msb	Heterolith, muddy, grey, strongly bioturbated , crudely laminated, pyritic
12-13	8800.20	8801.50	Mb	Heterolith, mud-rich, light-brown, lens-bedded, , Planolites
13	8801.50	8803.00	Mst	Heterolith, mud-rich, grey, strongly bioturbated, lens-bedded, , Planolites, Thalassinoides, Fe- concretions,
13-16	8803.00	8813.00	Mb	Heterolith, mud-rich, dark-brown, lens-bedded, bioturbated, ferruginized, Psilonichnus,
17	8813.00	8813.9	SMb	Heterolith, sandy, bioturbated , lens-bedded, carbonaceous bands,
	8813.9	8815.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic, Planolites
18	8815.00	8816.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
19	8816.00	8821.96	Mb	Heterolith, mud-rich, dark-brown, lens-bedded,

(a) Iinterval 8821.92-8789.20ft (Tubes 19-9; Fig. 2) is arranged in thickening-and

shallowing upward parasequences (intervals 8821.92-8813.0ft; 8813.0-8803ft and 8803.0-8792.0ft). Each parasequence is capped by a wave-ripple-laminated/bioturbated sandy lithofacies and composed of alternation of dark brown, thinly bedded mud stone (Mb), and lens-bedded (Mst)/bioturbated mud-rich heteroliths (Msb). The interval is generally characterized by members of Cruziana trace suite including the *Arenicolites, Planolites, Thalassinoides, Psilonichnus, Teichichnus, Skolithos and Paleophycus* (Figs. 3 and 4); and

(b) a monotonously sandy and oil-stained interval (8792.6-8765.8ft; Tubes 8-1) that sharply overlies interval-1 and composed of two sub-units: (i) A coarse/pebbly, loose, brown, poorly sorted sandstone (interval 8789.2-8783.0ft) that rests sharply on the ironstone layer; and (ii) A dark brown/ferruginized, loose, fine to coarse grained, < 20%

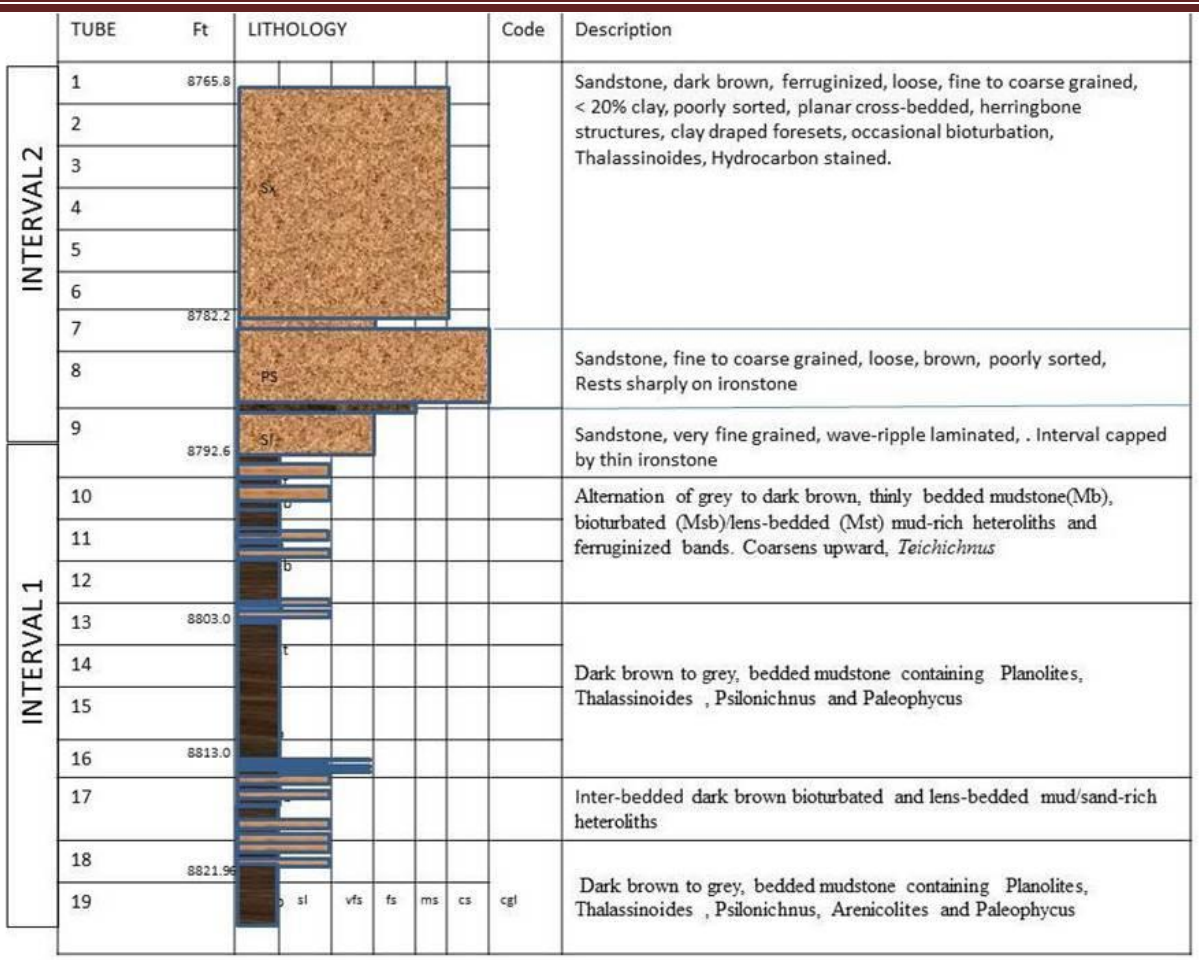

Fig. 2. Vertical facies profile of the cored interval of Ludo oil Well

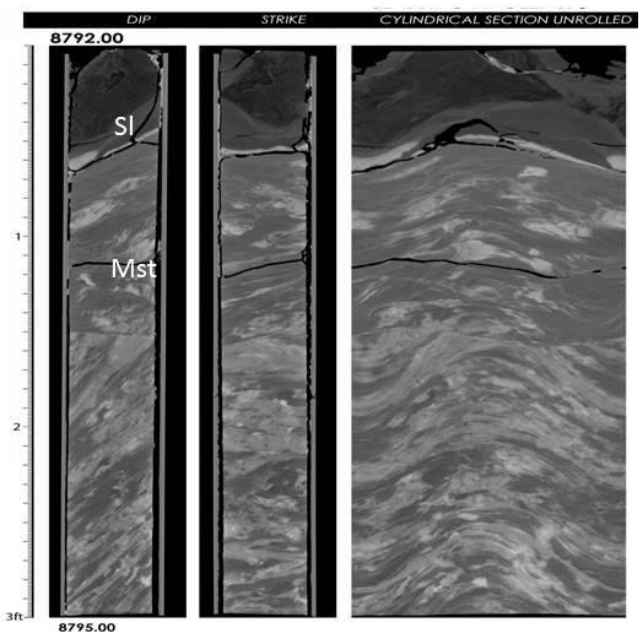

Fig. 3 CT-scan image of strongly bioturbated mud-rich heterolith, Mst (interval 8795-8792.60ft) sharply overlain by fine-grained, well-sorted, wave ripple laminated sandstone, *Sl, (interval 8792.6ft-8792.ft)*

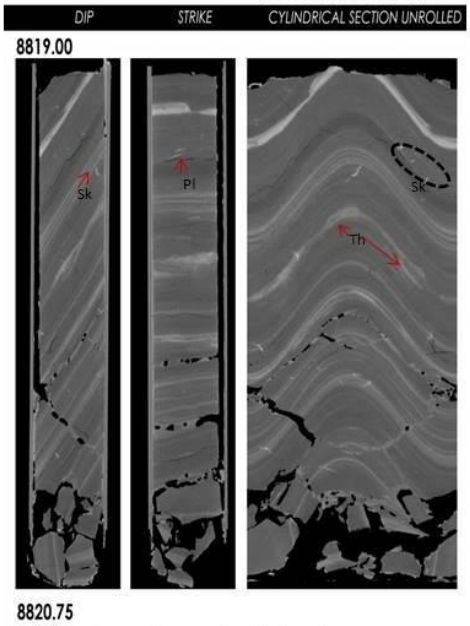

Fig. 4. Tube 19 showing bedded mudstone containing Thalassinoides *(Th)*, aligned horizontal to bedding, Sub-vertical U-tubes of the Skolithos (Sk*)*

clayey, poorly sorted, cm- scale planar & herringbone cross-bedded sandstone (interval 8783.0-8765.9ft), containing strongly ferruginized, clay-draped cross-bed fore-set planes (Fig. 6) and occasionally bioturbated. The two sub-units display a general fining-upward grain-size motif (Fig. 2).

Table 2. Summary of lithofacies depth listing for Ludo oil well

DRILLER'S DEPTH (FT)			LITHOFACIES	DESCRIPTION
TUBE	TOP	BOTTOM	CODE	
1-6	8765.80	8782.20	Sx	Sandstone, dark brown/ferruginized, loose, fine to coarse grained , < 20% clayey, poorly sorted, cm- scale planar & herringbone cross-bedded, clay-draped fore-sets, occasional bioturbation, Thalassinoides, HC stained
6-	8782.20	8783.00	Sl	Dark-brown interval of alternating ,HC-stained, very fine grained, well-sorted sandstone, and clayey siltstone, Thalassinoides along bedding planes,
7-8	8783.00	8788.00	PS	Sand, brown, very coarse grained, pebbly, loose, HC-stained, rests sharply on Fe-stone,
8-9	8788.00	8789.20	PS	Sandstone, strongly ferruginized, coarse, poorly-sorted, iron-bands, HC-stained,
9-10	8789.20	8792.60	Sl	Sandstone, grey-yellow, very fine to fine grained, well-sortd, wave-ripple lamination, H.C-stained,
10	8792.60	8793.40	Mst	Heterolith, mud-rich, grey, lens-bedded,
	8793.40	8795.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic
11	8795.00	8796.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
	8796.00	8798.00	Mb	Heterolith, mud-rich, grey-brown, lens-bedded,
12	8798.00	8800.20	Msb	Heterolith, muddy, grey, strongly bioturbated , crudely laminated, pyritic
12-13	8800.20	8801.50	Mb	Heterolith, mud-rich, light-brown, lens-bedded, , Planolites
13	8801.50	8803.00	Mst	Heterolith, mud-rich, grey, strongly bioturbated, lens-bedded, , Planolites, Thalassinoides, Fe- concretions,
13-16	8803.00	8813.00	Mb	Heterolith, mud-rich, dark-brown, lens-bedded, bioturbated, ferruginized, Psilonichnus,
17	8813.00	8813.9	SMb	Heterolith, sandy, bioturbated , lens-bedded, carbonaceous bands,
	8813.9	8815.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic, Planolites
18	8815.00	8816.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
19	8816.00	8821.96	Mb	Heterolith, mud-rich, dark-brown, lens-bedded,

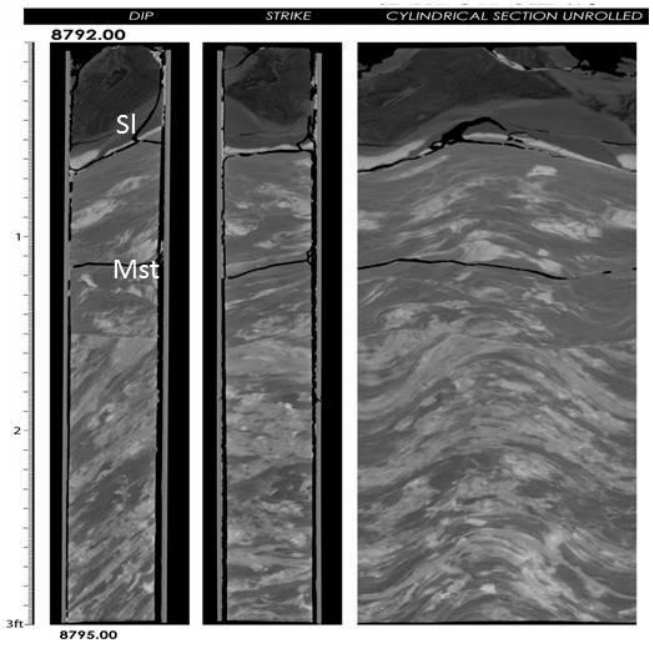

Fig. 3 CT-scan image of strongly bioturbated mud-rich heterolith, Mst (interval 8795-8792.60ft) sharply overlain by fine-grained, well-sorted, wave ripple laminated sandstone, *Sl, (interval 8792.6ft-8792.ft)*

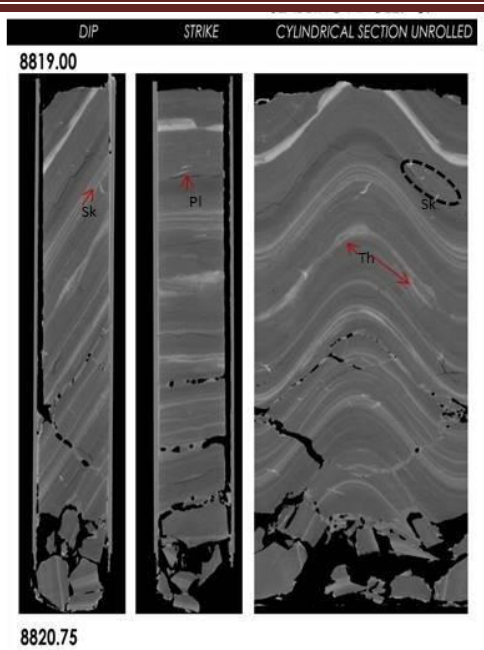

Fig. 4. Tube 19 showing bedded mudstone containing Thalassinoides *(Th)*, aligned horizontal to bedding, Sub-vertical U-tubes of the Skolithos (Sk*)*

Facies Analysis and Classification

Facies analysis and classification reveal that the lithofacies occurring within the cored interval include seven reservoir- and three non-reservoir varieties (Table 3). The reservoir lithofacies include (i) pebbly sandstone (PS), (ii) fine to coarse grained cm-scale cross-bedded sandstone (Sx), (iii) very fine to fine grained mm-laminated sandstone (Sl) , (iv) Very fine to fine grained mm-scale laminated sandstone with clay drapes/laminae (Sc), (v) bioturbated sandy heterolith (SMb) , (vi) bioturbated sandstone (Sb) and (vii) wavy-bedded sand-rich heterolith (SMw) . Non-reservoir lithofacies include: (i) the lens-bedded muddy heteroliths (Mst), (ii) bedded mudstone (Mb), and (iii) bioturbated muddy heterolith (Msb). Reservoir lithofacies makes up 59.32% of the cored interval, while the non-reservoirs constitute the remaining 40.68% (Table 3.). The detailed lithofacies depth listings for the cores are shown in Table 4.

Table 3. Lithofacies Classification Scheme for the Ludo Oil well

SEDIMENT TYPE		LITHOFACIES DESCRIPTION	CODE	CLASSIFICATIO N	% Abundance
Sandstone < 20% clay		Pebbly sandstone	PS 1/4	RESERVOIR	11.04
		Fine to coarse grained Cm- scale cross-bedded sandstone	S 2/4x		29.20
		Very fine grained mm-scale Laminated sandstone	S 1/2l		1.42
		Very fine to fine grained mm-scale laminated Sandstone with clay drapes/laminae	S 1/2c		6.05
		Bioturbated sandstone	S 1/3b		4.45
Mixed sand and clay (Heteroliths) 20%-80% clay	Sand-rich heteroliths < 20-50% clay	Wavy-bedded sandy heterolith	S 1/2Mw		3.56
		Bioturbated sandy heterolith	S 1/2Mb		3.56
		Glauconitic/shelly muddy sandstone	S 1/4Mshg		--
	Mud-rich heteroliths 50-80% clay & silt	Lens-bedded muddy heterolith	Mst	NON-RESERVOIR	10.19
		Bioturbated muddy heterolith	Msb		15.31
Mudstone >80% clay		Bedded or massive mudstone	Mb/Mm		14.249
		Sideritic-bedded mudstone	Msd		--
Re-deposited/slumped Sandstone/mudstone & heteroliths		Re-deposited/slumped sandstone	RS 1/4	DEPENDENT ON ORIGINAL SEDIMENT CHARACTERISTICS	--
		Re-deposited/slumped mudstone & heteroliths	RM/MS		--

Table 4. Summary of lithofacies depth listing for Ludo oil well

DRILLER'S DEPTH (FT)			LITHOFACIES	DESCRIPTION
TUBE	TOP	BOTTOM	CODE	
1-6	8765.80	8782.20	Sx	Sandstone, dark brown/ferruginized, loose, fine to coarse grained , < 20% clayey, poorly sorted, cm- scale planar & herringbone cross-bedded, clay-draped fore-sets, occasional bioturbation, Thalassinoides, HC stained
6-	8782.20	8783.00	Sl	Dark-brown interval of alternating ,HC-stained, very fine grained, well-sorted sandstone, and clayey siltstone, Thalassinoides along bedding planes,
7-8	8783.00	8788.00	PS	Sand, brown, very coarse grained, pebbly, loose, HC-stained, rests sharply on Fe-stone,
8-9	8788.00	8789.20	PS	Sandstone, strongly ferruginized, coarse, poorly-sorted, iron-bands, HC-stained,
9-10	8789.20	8792.60	Sl	Sandstone, grey-yellow, very fine to fine grained, well-sortd, wave-ripple lamination, H.C-stained,
10	8792.60	8793.40	Mst	Heterolith, mud-rich, grey, lens-bedded,
	8793.40	8795.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic
11	8795.00	8796.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
	8796.00	8798.00	Mb	Heterolith, mud-rich, grey-brown, lens-bedded,
12	8798.00	8800.20	Msb	Heterolith, muddy, grey, strongly bioturbated , crudely laminated, pyritic
12-13	8800.20	8801.50	Mb	Heterolith, mud-rich, light-brown, lens-bedded, , Planolites
13	8801.50	8803.00	Mst	Heterolith, mud-rich, grey, strongly bioturbated, lens-bedded, , Planolites, Thalassinoides, Fe- concretions,
13-16	8803.00	8813.00	Mb	Heterolith, mud-rich, dark-brown, lens-bedded, bioturbated, ferruginized, Psilonichnus,
17	8813.00	8813.9	SMb	Heterolith, sandy, bioturbated , lens-bedded, carbonaceous bands,
	8813.9	8815.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic, Planolites
18	8815.00	8816.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
19	8816.00	8821.96	Mb	Heterolith, mud-rich, dark-brown, lens-bedded,

Depositional Interpretation

The ten lithofacies are further grouped into two facies associations based on the gross lithology, association of physical/biogenic sedimentary structures, and vertical arrangement of the facies. These include the wave ripple laminated sandstone and heteroliths at the base, and the cross-bedded, pebbly sandstone at the top. The overall sedimentary characteristics and close similarity to the deltaic model of Coleman and Prior (1982) provide basis for the recognition of the two facies associations as deposits of the delta front and delta plain environments respectively (Fig. 5). The lithofacies depth listing and the depositional interpretations are shown in Table 5.

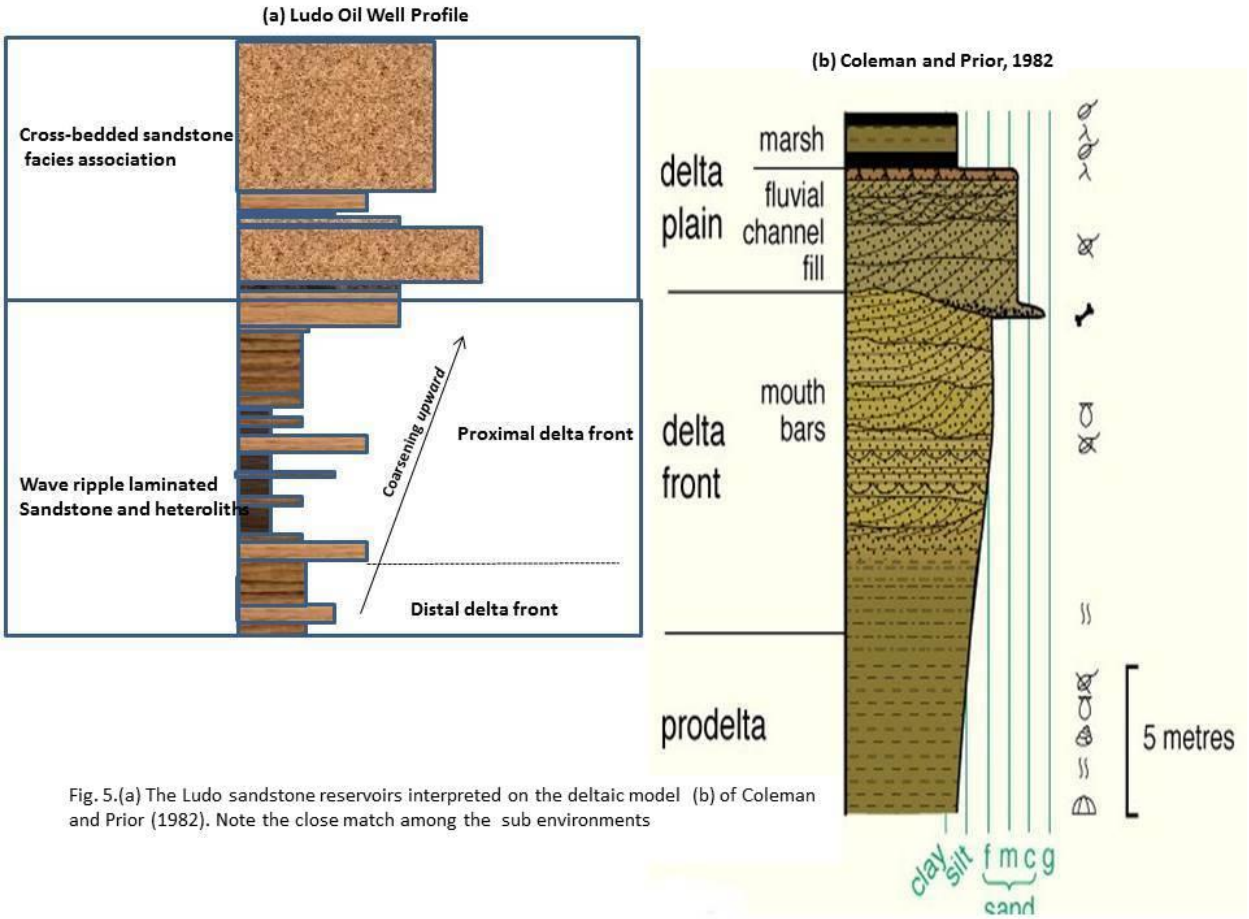

Fig. 5.(a) The Ludo sandstone reservoirs interpreted on the deltaic model (b) of Coleman and Prior (1982). Note the close match among the sub environments

Table 5. Summary of lithofacies depth listing and depositional environments of the Ludo reservoir

Driller's Depth(ft.)		Lithofacies	Thickness	Depositional Environment	
TOP	BOTTOM	CODE			
8765.80	8782.20	Sx	16.4	Tidally-influenced fluvial Channel (DELTA PLAIN)	DELTA PLAIN
8782.20	8783.00	Sl	0.8		
8783.00	8789.20	PS	6.20		
8789.20	8792.60	Sc	3.40	Proximal delta front	DELTA FRONT
8792.60	8793.40	Mst	0.80	Distal delta front	
8793.40	8795.00	Msb	0.50		
8795.00	8798.00	Mst	3.00		
8798.00	8801.00	Msb	3.00		
8801.00	8803.00	Mst	2.00		

Table 5 (continued) . Summary of lithofacies depth listing and depositional environments of the Ludo reservoir

Driller's Depth(ft.)		Lithofacies	Thickness	Depositional Environment	
TOP	BOTTOM	CODE			
8803.00	8805.00	SMb	2.00	Distal Delta front	DELTA FRONT
8805.00	8806.50	Mb	1.50		
88.6.50	8807.00	Mst	0.50		
8807.00	8809.00	Mb	2.00		
8809.00	8810.00	Msb	1.00		
8810.00	8813.00	Mb	3.00		
8813.00	8815.50	Sb	2.50		
8815.50	8816.00	Mst	0.50		
8816.00	8819.00	Msb	3.00		
8819.00	8821.00	SMw	2.00		
8821.00	8821.92	Mst	0.92		

Delta front facies association (interval 8821.92-8789.20ft)

This facies association was recognized based on the overall coarsening-upward grain-size motif , presence of wave- generated sedimentary structures and the association of the Cruziana ichnofacies (Pemberton et al., 1992). The basal part (interval 8821.92-8792.0ft) comprising inter-bedded mudstone (Msd), bioturbated muddy heterolith (Msb) and lens-bedded muddy heterolith (Mst), that displays an upward transition from muddier- to sandier facies, represents the distal delta front. The distal delta front facies gives way upward to proximal delta front facies comprising erosive-based, grey to yellow, well-sorted, thin-bedded lenticular-bedded/wave ripple laminated sandstone that displays an upwards transition from very fine grained silty facies to fine grained sandstone beds (Sc). The sandy interval is strongly ferruginized and truncated at the top by an ironstone layer. The thin-bedded, lenticular-/wave-ripple laminated sandstone is consistent with lower and middle shoreface sedimentation (Swift and Niedoroda, 1985).

Delta Plain Facies Association (8789.20-8765.80ft)

The cross-bedded sandstone facies association is represented by 2-storeyed, channelized sandstones that display an overall fining-upward grain-size motif (Figure 2). The basal channelized unit rests directly on an ironstone layer that marks the top of the delta front facies and begins with about 5.0ft of brown, loose, pebbly sandstone (PS) that is heavily HC-stained. The interval gives way upward to coarse to fine grained, poorly-sorted sandstone, containing by planar cross-beds with mud-draped fore-sets (Fig. 6).

These rocks are recognized as tidally influenced fluvial channel deposits based on (i) the grain size range and motif, (ii) degree of sorting, (iii) presence of planar cross-bed and (iv) the stratigraphic relationship with the underlying delta front facies. The observed fining-upward motif is a common signature of meandering fluvial channel facies. The basal erosional surface of the sandstone units is interpreted to be a record of channel thalweg eroding laterally as the channel evolves. Tidal influence is reflected in the presence of mud-draped cross-beds.

The overall arrangement of the depositional facies within the cored interval reflects deltaic progradation.

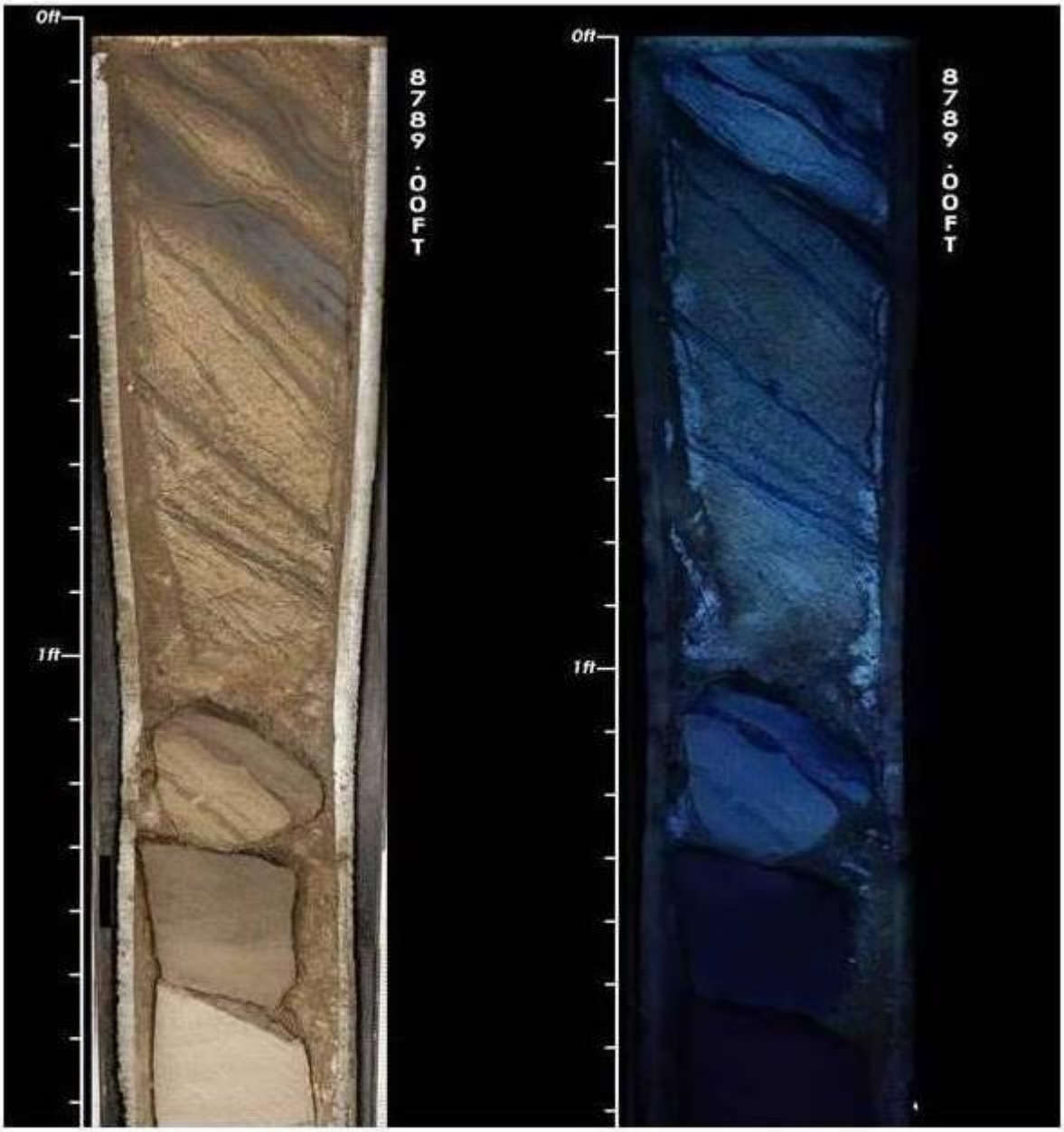

Fig. 6. Interval 8790-8799 showing cross-bedded sandstone with mud draped and ferruginized foresets planes. The mud drapes are ascribed to tidal processes

Summary

Ten lithofacies are identified within the cored interval of the LUDO Oil well. These include seven reservoir lithofacies comprising (i) pebbly sandstone (PS), (ii) fine to coarse grained cm- scale cross-bedded sandstone Sx, (iii) very fine grained mm-scale laminated sandstone (Sl), (iv) very fine to fine grained mm-scale laminated sandstone with clay drapes/laminae (Sc), (v) bioturbated sandstone (Sb), (vi) wavy-bedded sandy heteroliths *(SMw), and (vi)* bioturbated sandy heterolith (SMb). Non-reservoir lithofacies include (i) lens-bedded muddy

heteroliths (Mst), (ii) bedded (Mb) and (iii) bioturbated muddy heteroliths. Reservoir lithofacies makes up 59.28% of the cored interval, while the non-reservoirs constitute the remaining 39.74%.

The gross sedimentary characteristics and the overall vertical arrangement of the lithofacies suggest that the sediments accumulated in environments that ranged from the distal delta front to the delta plain. The reservoir lithofacies accumulated in environments that ranged between proximal delta front and tidally-influenced fluvial channel (delta plain) environments, while the non-reservoir lithofacies accumulated in distal delta front environments. The overall coarsening upward motif of the lithofacies suggests that sedimentation occurred during the progradation phase of the delta building episode.

REFERENCES

Arua, I., 1980. Palaeocene Macrofossils from the Imo Shale in Anambra State, Nigeria. Journal of Mining and Geology 17, 81–84.

Coleman, J.M., and Prior, D.B.K., 1982. Deltaic environments of deposition: In: P.A. Scholle and Spearing, D. (Eds) Sandstone depositional environment. AAPG Publication, Tulsa, 139-178.

Ekweozor, C.M. and E.M. Daukoru, 1992. The Northern depobelt portion of the Akata-Agbada petroleum system, Niger delta, Nigeria. NAPE Bull., 10, 102-120.

Nwajide, C. S. 2013. Geology of Nigeria's sedimentary basins. CSS Bookshops Limited,

Obi, G. C. and Ebong U. 2003. , Sequence Architecture of the Gbaran Node: Impact on Production. SPDC Project, 17p.

Oboh-Ikuenobe, F.E., Obi, C.G., Jaramillo C.A., 2005. Lithofacies, palynofacies and sequence stratigraphy of Paleogene strata in Southeastern Nigeria. Journal of African Earth Sciences 41, 79-102.

Pemberton, S.G., Maceachern, J.A., and Frey, R. W., 1992. Trace fossil facies models: environmental and allostratigraphic significance. In: Walker R.G. and James, N.P.(eds.), Facies Models, pp. 47-72. Geology Association of Canada.

Reyment, R.A., 1965. Aspects of the Geology of Nigeria: The stratigraphy of the Cretaceous and Cenozoic deposits, Ibadan University Press, Ibadan, 145 pp.

Swift, D.J.P. and Niedoroda, A.W. (1985). Fluid and sediment dynamics on continental ` shelves, in: Tillman, R.W., Swift, D.J.P. and Walker, R.G., eds. Shelf sands and sandstone reservoirs. SEPM Short Course 13, Notes, 47-133.

LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS OF HYDROCARBON RESERVOIR OF THE LUDO OIL FIELD IN THE COASTAL SWAMP II DEPO-BELT, NIGER DELTA, NIGERIA

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Introduction

The Paleocene marine transgression marked an important stage in the evolution of the Niger Delta. The transgressive event resulted in the southward progradation of the Niger Delta sediments into the Equatorial Atlantic Ocean (Arua, 1980, Obi *et. al.*, 2003, Oboh-Ikuenobe *et. al* 2005). The sediment build-up was accompanied by growth fault tectonics normal to the direction of the progradation, resulting to the formation of parallel, fault-bound Northern, Ugheli, Central Swamp I, Central Swamp II Coastal Swamp I, Coastal Swamp II and the offshore depo-belts that are successively younger from north to south (Ekweozor and Daukoru, 1992; Fig. 1). Each depo-belt contains three thick rock units, which from shallowest to the deepest include (i) fluviatile sand belonging to the Benin Formation, (ii) interbedded sand and shale of the marginal marine-shallow marine Agbada Formation and (iii) marine shale representing the Akata Formation (Reyment, 1965 and Nwajide, 2013). The present study focused on the LUDO Oil field that is located within the Coastal Swamp II depo-belt. The oil field forms part of a north-south trending group of oil fields in the eastern part of the Niger Delta. It contains a single oil reservoir that is buried to a depth of over 8,500 ft. below the surface. There is currently an on-going development activity in the field that involves the updating of information on the reservoir distribution, reservoir heterogeneity and the depositional model.

To contribute to the above initiative, the present study (i) provides detailed record of the lithologic variations, sedimentary structures, textural characteristics and diagenetic aspects of the reservoir; (ii) provides a written summary of each lithofacies interval and lithofacies depth listing, (iii) characterizes and

classifies the reservoir interval using a standard lithofacies scheme and (iv) iinterprets the depositional environments of the reservoir.

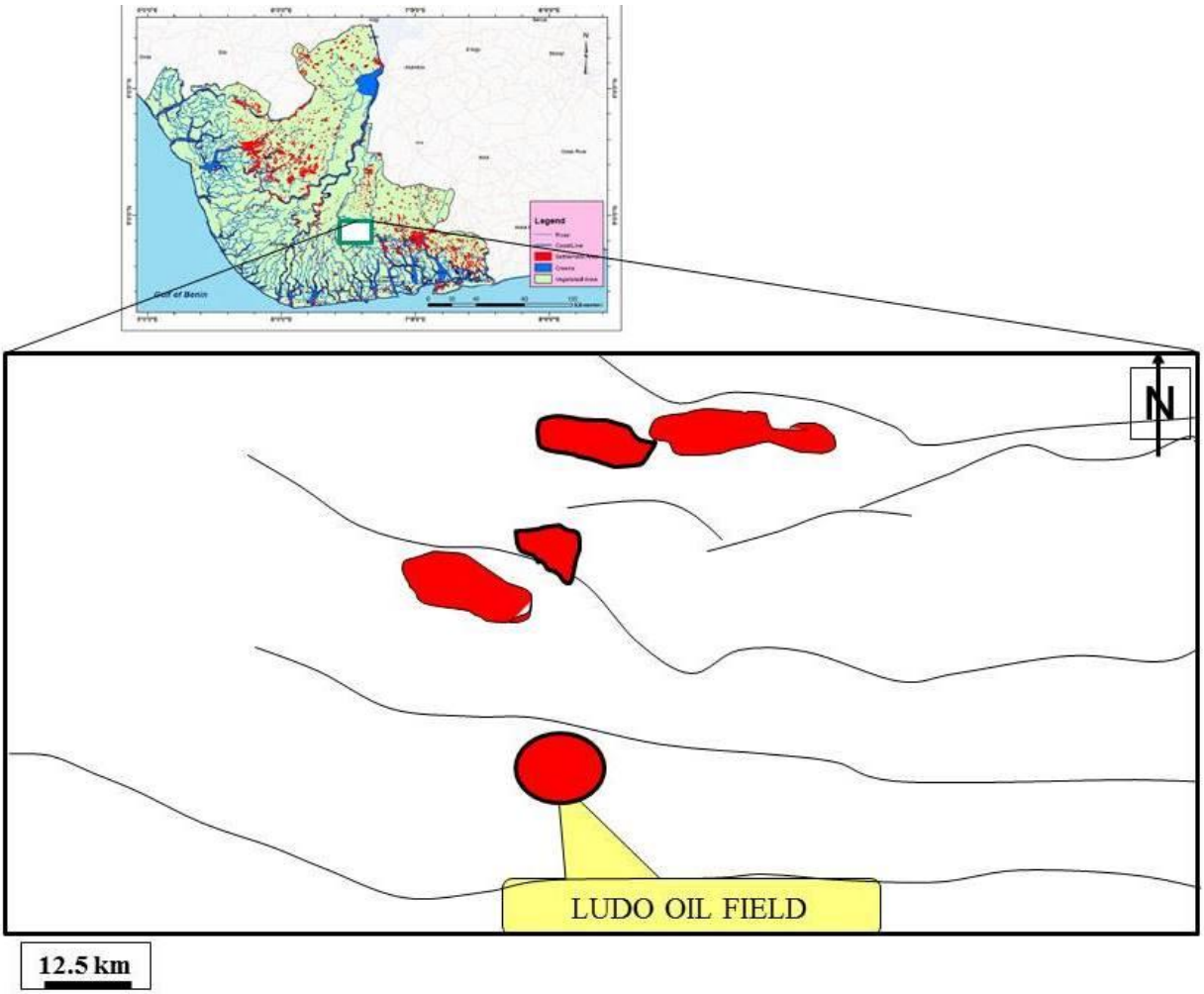

Fig. 1. Play Map Showing the location of the Ludo Oil Field Area

DATA SETS

The sedimentological interpretations presented hereunder are based on the study of 56.16 feet of core slabs taken from depth interval of 8765.80ft to 8821.96ft and arranged in nineteen 3-ft trays. The cores are backed up with the following:

v. Depth manifest for the cored interval,

vi. Spectral core gamma log of the cored interval,

vii. Core photographs on both white light and ultraviolet light, and

viii. Computerized tomography scan images of the core.

METHODS OF STUDY

Textural, compositional and lithological aspects of the cores were estimated by visual examination using the hand lens, dilute acid and standard colour and textural charts. Close-up examination of the cores was then carried out on the core photographs and on the CT-scan images. Sedimentary facies were identified and characterized based on lithology, colour, grain size trend, physical sedimentary structures, types of bed contacts, degree of bioturbation, and faunal content. The slabs were described at a scale of 1: 40 onto Clastic Core Description sheet, using the lithofacies scheme of the SPDC Ltd (Table 1). The schematic lithological log of the cored interval was then matched with the core gamma log signatures and the observed trends were compared with standard deltaic/marginal marine-offshore facies models.

Table 1. Lithofacies scheme used in this study (After Obi and Ebong, 2003)

SEDIMENT TYPE		LITHOFACIES DESCRIPTION	CODE	CLASSIFICATIO N	% Abundance
Sandstone < 20% clay		Pebbly sandstone	PS 1/4	RESERVOIR	
		Fine to coarse grained Cm- scale cross-bedded sandstone	S 2/4x		
		Very fine grained mm-scale Laminated sandstone	S 1/21		
		Very fine to fine grained mm-scale laminated Sandstone with clay drapes/laminae	S 1/2c		
		Bioturbated sandstone	S 1/3b		
Mixed sand and clay (Heteroliths) 20%-80% clay	Sand-rich heteroliths < 20-50% clay	Wavy-bedded sandy heterolith	S 1/2Mw		
		Bioturbated sandy heterolith	S 1/2Mb		
		Glauconitic/shelly muddy sandstone	S 1/4Mshg		
	Mud-rich heteroliths 50-80% clay & silt	Lens-bedded muddy heterolith	Mst	NON-RESERVOIR	
		Bioturbated muddy heterolith	Msb		
Mudstone >80% clay		Bedded or massive mudstone	Mb/Mm		
		Sideritic-bedded mudstone	Msd		
Re-deposited/slumped Sandstone/mudstone & heteroliths		Re-deposited/slumped sandstone	RS 1/4	DEPENDENT ON ORIGINAL SEDIMENT CHARACTERISTICS	
		Re-deposited/slumped mudstone & heteroliths	RM/MS		

Sedimentological Descriptions

The 56.16ft-core extends from a depth of 8765.80ft to 8821.96ft (Table 2). Figure 2 shows that the cored interval is sub-divisible into two major lithologic intervals:

Table 2. Summary of lithofacies depth listing for Ludo oil well

DRILLER'S DEPTH (FT)			LITHOFACIES	DESCRIPTION
TUBE	TOP	BOTTOM	CODE	
1-6	8765.80	8782.20	Sx	Sandstone, dark brown/ferruginized, loose, fine to coarse grained , < 20% clayey, poorly sorted, cm- scale planar & herringbone cross-bedded, clay-draped fore-sets, occasional bioturbation, Thalassinoides, HC stained
6-	8782.20	8783.00	Sl	Dark-brown interval of alternating ,HC-stained, very fine grained, well-sorted sandstone, and clayey siltstone, Thalassinoides along bedding planes,
7-8	8783.00	8788.00	PS	Sand, brown, very coarse grained, pebbly, loose, HC-stained, rests sharply on Fe-stone,
8-9	8788.00	8789.20	PS	Sandstone, strongly ferruginized, coarse, poorly-sorted, iron-bands, HC-stained,
9-10	8789.20	8792.60	Sl	Sandstone, grey-yellow, very fine to fine grained, well-sortd, wave-ripple lamination, H.C-stained,
10	8792.60	8793.40	Mst	Heterolith, mud-rich, grey, lens-bedded,
	8793.40	8795.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic
11	8795.00	8796.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
	8796.00	8798.00	Mb	Heterolith, mud-rich, grey-brown, lens-bedded,
12	8798.00	8800.20	Msb	Heterolith, muddy, grey, strongly bioturbated , crudely laminated, pyritic
12-13	8800.20	8801.50	Mb	Heterolith, mud-rich, light-brown, lens-bedded, , Planolites
13	8801.50	8803.00	Mst	Heterolith, mud-rich, grey, strongly bioturbated, lens-bedded, , Planolites, Thalassinoides, Fe- concretions,
13-16	8803.00	8813.00	Mb	Heterolith, mud-rich, dark-brown, lens-bedded, bioturbated, ferruginized, Psilonichnus,
17	8813.00	8813.9	SMb	Heterolith, sandy, bioturbated , lens-bedded, carbonaceous bands,
	8813.9	8815.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic, Planolites
18	8815.00	8816.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
19	8816.00	8821.96	Mb	Heterolith, mud-rich, dark-brown, lens-bedded,

(c) Iinterval 8821.92-8789.20ft (Tubes 19-9; Fig. 2) is arranged in thickening-and

shallowing upward parasequences (intervals 8821.92-8813.0ft; 8813.0-8803ft and 8803.0-8792.0ft). Each parasequence is capped by a wave-ripple-laminated/bioturbated sandy lithofacies and composed of alternation of dark brown, thinly bedded mud stone (Mb), and lens-bedded (Mst)/bioturbated mud-rich heteroliths (Msb). The interval is generally characterized by members of Cruziana trace suite including the *Arenicolites, Planolites, Thalassinoides, Psilonichnus, Teichichnus, Skolithos and Paleophycus* (Figs. 3 and 4); and

(d) a monotonously sandy and oil-stained interval (8792.6-8765.8ft; Tubes 8-1) that sharply overlies interval-1 and composed of two sub-units: (i) A coarse/pebbly, loose, brown, poorly sorted sandstone (interval 8789.2-8783.0ft) that rests sharply on the ironstone layer; and (ii) A dark brown/ferruginized, loose, fine to coarse grained, < 20%

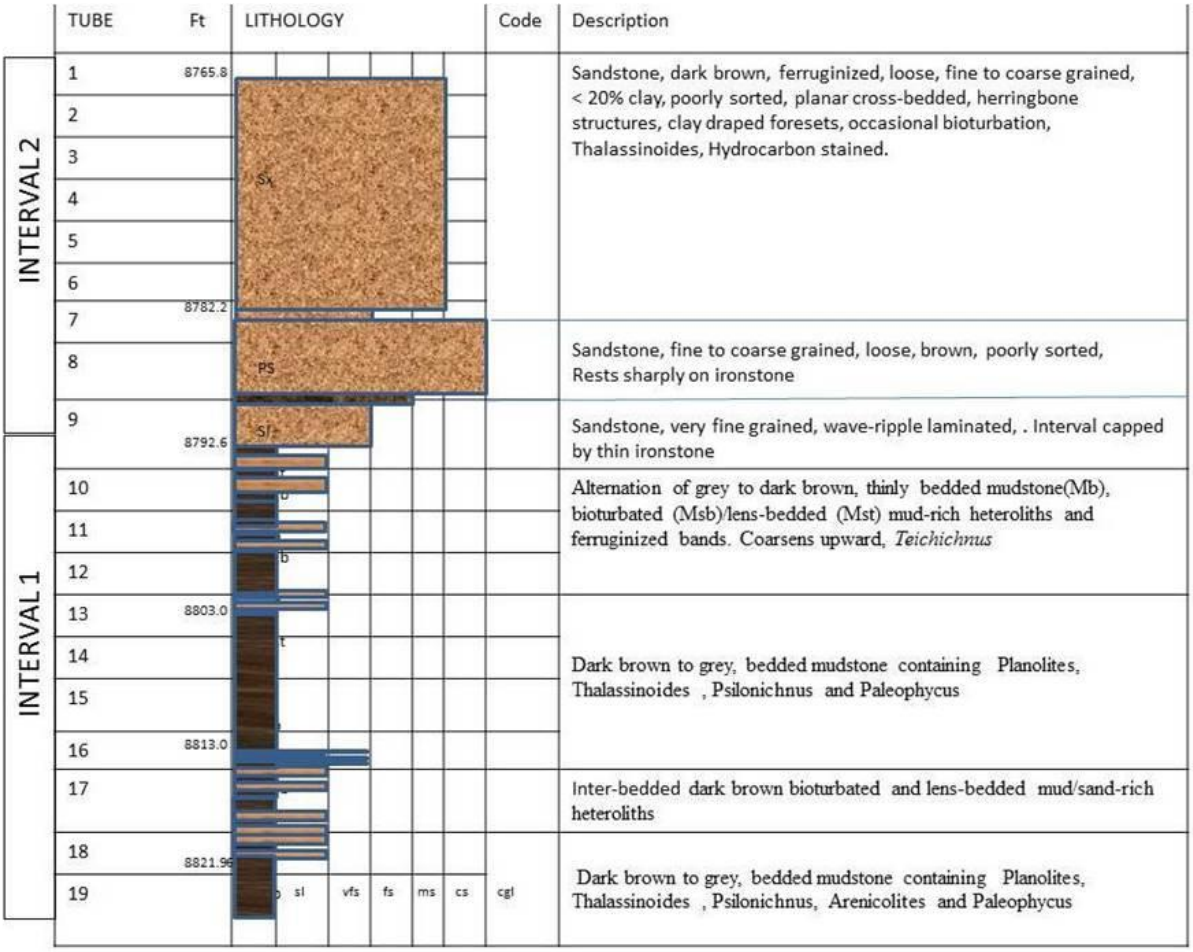

Fig. 2. Vertical facies profile of the cored interval of Ludo oil Well

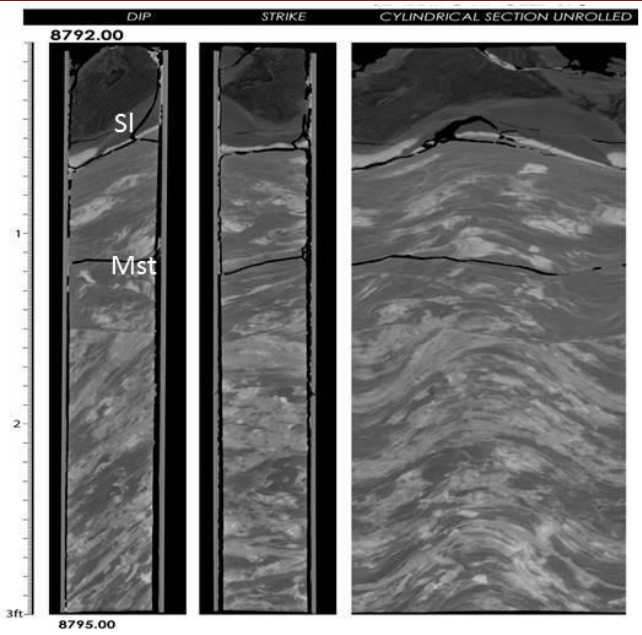

Fig. 3 CT-scan image of strongly bioturbated mud-rich heterolith, Mst (interval 8795-8792.60ft) sharply overlain by fine-grained, well-sorted, wave ripple laminated sandstone, *Sl, (interval 8792.6ft-8792.ft)*

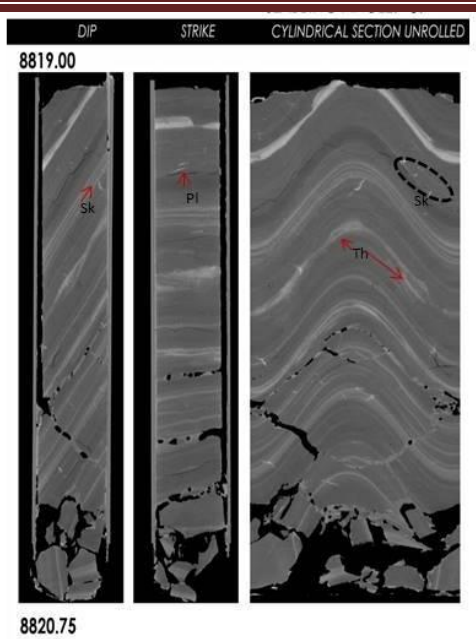

Fig. 4. Tube 19 showing bedded mudstone containing Thalassinoides *(Th)*, aligned horizontal to bedding, Sub-vertical U-tubes of the Skolithos (Sk*)*

clayey, poorly sorted, cm- scale planar & herringbone cross-bedded sandstone (interval 8783.0-8765.9ft), containing strongly ferruginized, clay-draped cross-bed fore-set planes (Fig. 6) and occasionally bioturbated. The two sub-units display a general fining-upward grain-size motif (Fig. 2).

Table 2. Summary of lithofacies depth listing for Ludo oil well

DRILLER'S DEPTH (FT)			LITHOFACIES	DESCRIPTION
TUBE	TOP	BOTTOM	CODE	
1-6	8765.80	8782.20	Sx	Sandstone, dark brown/ferruginized, loose, fine to coarse grained , < 20% clayey, poorly sorted, cm- scale planar & herringbone cross-bedded, clay-draped fore-sets, occasional bioturbation, Thalassinoides, HC stained
6-	8782.20	8783.00	Sl	Dark-brown interval of alternating ,HC-stained, very fine grained, well-sorted sandstone, and clayey siltstone, Thalassinoides along bedding planes,
7-8	8783.00	8788.00	PS	Sand, brown, very coarse grained, pebbly, loose, HC-stained, rests sharply on Fe-stone,
8-9	8788.00	8789.20	PS	Sandstone, strongly ferruginized, coarse, poorly-sorted, iron-bands, HC-stained,
9-10	8789.20	8792.60	Sl	Sandstone, grey-yellow, very fine to fine grained, well-sortd, wave-ripple lamination, H.C-stained,
10	8792.60	8793.40	Mst	Heterolith, mud-rich, grey, lens-bedded,
	8793.40	8795.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic
11	8795.00	8796.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
	8796.00	8798.00	Mb	Heterolith, mud-rich, grey-brown, lens-bedded,
12	8798.00	8800.20	Msb	Heterolith, muddy, grey, strongly bioturbated , crudely laminated, pyritic
12-13	8800.20	8801.50	Mb	Heterolith, mud-rich, light-brown, lens-bedded, , Planolites
13	8801.50	8803.00	Mst	Heterolith, mud-rich, grey, strongly bioturbated, lens-bedded, , Planolites, Thalassinoides, Fe- concretions,
13-16	8803.00	8813.00	Mb	Heterolith, mud-rich, dark-brown, lens-bedded, bioturbated, ferruginized, Psilonichnus,
17	8813.00	8813.9	SMb	Heterolith, sandy, bioturbated , lens-bedded, carbonaceous bands,
	8813.9	8815.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic, Planolites
18	8815.00	8816.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
19	8816.00	8821.96	Mb	Heterolith, mud-rich, dark-brown, lens-bedded,

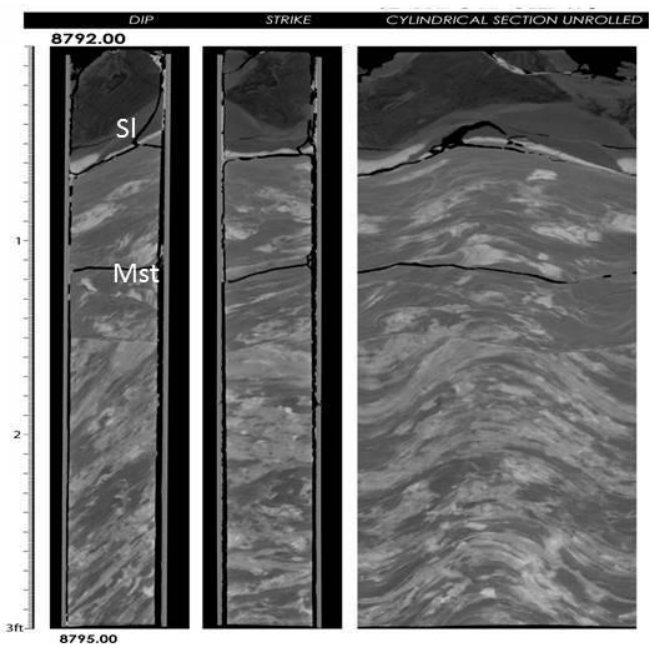

Fig. 3 CT-scan image of strongly bioturbated mud-rich heterolith, Mst (interval 8795-8792.60ft) sharply overlain by fine-grained, well-sorted, wave ripple laminated sandstone, *Sl, (interval 8792.6ft-8792.ft)*

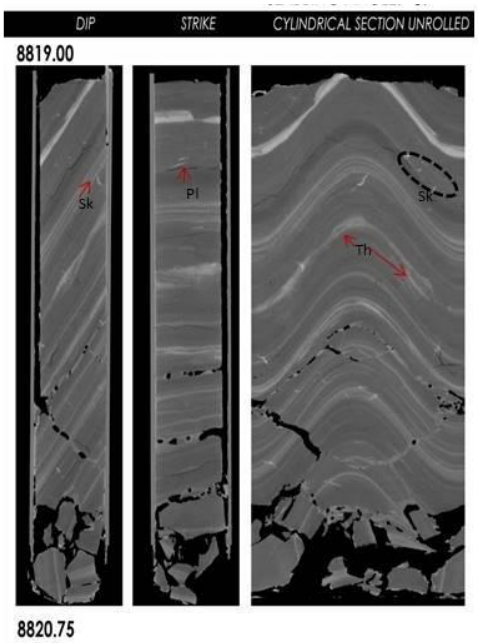

Fig. 4. Tube 19 showing bedded mudstone containing Thalassinoides *(Th)*, aligned horizontal to bedding, Sub-vertical U-tubes of the Skolithos (Sk*)*

Facies Analysis and Classification

Facies analysis and classification reveal that the lithofacies occurring within the cored interval include seven reservoir- and three non-reservoir varieties (Table 3). The reservoir lithofacies include (i) pebbly sandstone (PS), (ii) fine to coarse grained cm-scale cross-bedded sandstone (Sx), (iii) very fine to fine grained mm-laminated sandstone (Sl) , (iv) Very fine to fine grained mm-scale laminated sandstone with clay drapes/laminae (Sc), (v) bioturbated sandy heterolith (SMb) , (vi) bioturbated sandstone (Sb) and (vii) wavy-bedded sand-rich heterolith (SMw) . Non-reservoir lithofacies include: (i) the lens-bedded muddy heteroliths (Mst), (ii) bedded mudstone (Mb), and (iii) bioturbated muddy heterolith (Msb). Reservoir lithofacies makes up 59.32% of the cored interval, while the non-reservoirs constitute the remaining 40.68% (Table 3.). The detailed lithofacies depth listings for the cores are shown in Table 4.

Table 3. Lithofacies Classification Scheme for the Ludo Oil well

SEDIMENT TYPE		LITHOFACIES DESCRIPTION	CODE	CLASSIFICATIO N	% Abundance
Sandstone < 20% clay		Pebbly sandstone	PS 1/4	RESERVOIR	11.04
		Fine to coarse grained Cm- scale cross-bedded sandstone	S 2/4x		29.20
		Very fine grained mm-scale Laminated sandstone	S 1/2l		1.42
		Very fine to fine grained mm-scale laminated Sandstone with clay drapes/laminae	S 1/2c		6.05
		Bioturbated sandstone	S 1/3b		4.45
Mixed sand and clay (Heteroliths) 20%-80% clay	Sand-rich heteroliths < 20-50% clay	Wavy-bedded sandy heterolith	S 1/2Mw		3.56
		Bioturbated sandy heterolith	S 1/2Mb		3.56
		Glauconitic/shelly muddy sandstone	S 1/4Mshg		--
	Mud-rich heteroliths 50-80% clay & silt	Lens-bedded muddy heterolith	Mst	NON-RESERVOIR	10.19
		Bioturbated muddy heterolith	Msb		15.31
Mudstone >80% clay		Bedded or massive mudstone	Mb/Mm		14.249
		Sideritic-bedded mudstone	Msd		--
Re-deposited/slumped Sandstone/mudstone & heteroliths		Re-deposited/slumped sandstone	RS 1/4	DEPENDENT ON ORIGINAL SEDIMENT CHARACTERISTICS	--
		Re-deposited/slumped mudstone & heteroliths	RM/MS		--

Table 4. Summary of lithofacies depth listing for Ludo oil well

DRILLER'S DEPTH (FT)			LITHOFACIES	DESCRIPTION
TUBE	TOP	BOTTOM	CODE	
1-6	8765.80	8782.20	Sx	Sandstone, dark brown/ferruginized, loose, fine to coarse grained , < 20% clayey, poorly sorted, cm- scale planar & herringbone cross-bedded, clay-draped fore-sets, occasional bioturbation, Thalassinoides, HC stained
6-	8782.20	8783.00	Sl	Dark-brown interval of alternating ,HC-stained, very fine grained, well-sorted sandstone, and clayey siltstone, Thalassinoides along bedding planes,
7-8	8783.00	8788.00	PS	Sand, brown, very coarse grained, pebbly, loose, HC-stained, rests sharply on Fe-stone,
8-9	8788.00	8789.20	PS	Sandstone, strongly ferruginized, coarse, poorly-sorted, iron-bands, HC-stained,
9-10	8789.20	8792.60	Sl	Sandstone, grey-yellow, very fine to fine grained, well-sortd, wave-ripple lamination, H.C-stained,
10	8792.60	8793.40	Mst	Heterolith, mud-rich, grey, lens-bedded,
	8793.40	8795.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic
11	8795.00	8796.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
	8796.00	8798.00	Mb	Heterolith, mud-rich, grey-brown, lens-bedded,
12	8798.00	8800.20	Msb	Heterolith, muddy, grey, strongly bioturbated , crudely laminated, pyritic
12-13	8800.20	8801.50	Mb	Heterolith, mud-rich, light-brown, lens-bedded, , Planolites
13	8801.50	8803.00	Mst	Heterolith, mud-rich, grey, strongly bioturbated, lens-bedded, , Planolites, Thalassinoides, Fe- concretions,
13-16	8803.00	8813.00	Mb	Heterolith, mud-rich, dark-brown, lens-bedded, bioturbated, ferruginized, Psilonichnus,
17	8813.00	8813.9	SMb	Heterolith, sandy, bioturbated , lens-bedded, carbonaceous bands,
	8813.9	8815.00	Msb	Heterolith, muddy, strongly bioturbated , crudely laminated, pyritic, Planolites
18	8815.00	8816.00	Mst	Heterolith, mud-rich, grey, lens-bedded, laminated/lens-bedded
19	8816.00	8821.96	Mb	Heterolith, mud-rich, dark-brown, lens-bedded,

Depositional Interpretation

The ten lithofacies are further grouped into two facies associations based on the gross lithology, association of physical/biogenic sedimentary structures, and vertical arrangement of the facies. These include the wave ripple laminated sandstone and heteroliths at the base, and the cross-bedded, pebbly sandstone at the top. The overall sedimentary characteristics and close similarity to the deltaic model of Coleman and Prior (1982) provide basis for the recognition of the two facies associations as deposits of the delta front and delta plain environments respectively (Fig. 5). The lithofacies depth listing and the depositional interpretations are shown in Table 5.

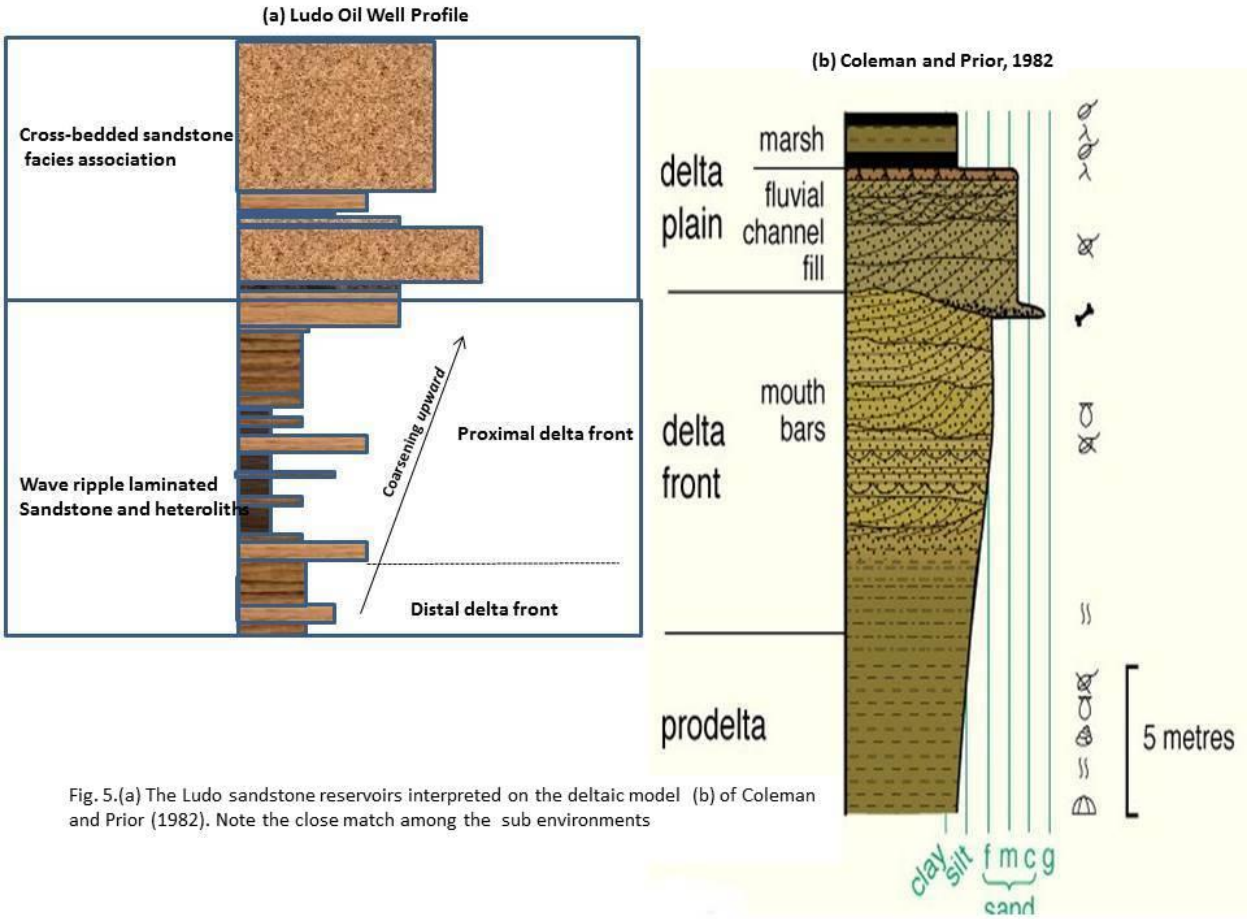

Fig. 5.(a) The Ludo sandstone reservoirs interpreted on the deltaic model (b) of Coleman and Prior (1982). Note the close match among the sub environments

Table 5. Summary of lithofacies depth listing and depositional environments of the Ludo reservoir

Driller's Depth(ft.)		Lithofacies	Thickness	Depositional Environment	
TOP	BOTTOM	CODE			
8765.80	8782.20	Sx	16.4	Tidally-influenced fluvial Channel (DELTA PLAIN)	DELTA PLAIN
8782.20	8783.00	Sl	0.8		
8783.00	8789.20	PS	6.20		
8789.20	8792.60	Sc	3.40	Proximal delta front	DELTA FRONT
8792.60	8793.40	Mst	0.80	Distal delta front	
8793.40	8795.00	Msb	0.50		
8795.00	8798.00	Mst	3.00		
8798.00	8801.00	Msb	3.00		
8801.00	8803.00	Mst	2.00		

Table 5 (continued) . Summary of lithofacies depth listing and depositional environments of the Ludo reservoir

Driller's Depth(ft.)		Lithofacies	Thickness	Depositional Environment	
TOP	BOTTOM	CODE			
8803.00	8805.00	SMb	2.00	Distal Delta front	DELTA FRONT
8805.00	8806.50	Mb	1.50		
88.6.50	8807.00	Mst	0.50		
8807.00	8809.00	Mb	2.00		
8809.00	8810.00	Msb	1.00		
8810.00	8813.00	Mb	3.00		
8813.00	8815.50	Sb	2.50		
8815.50	8816.00	Mst	0.50		
8816.00	8819.00	Msb	3.00		
8819.00	8821.00	SMw	2.00		
8821.00	8821.92	Mst	0.92		

Delta front facies association (interval 8821.92-8789.20ft)

This facies association was recognized based on the overall coarsening-upward grain-size motif , presence of wave- generated sedimentary structures and the association of the Cruziana ichnofacies (Pemberton et al., 1992). The basal part (interval 8821.92-8792.0ft) comprising inter-bedded mudstone (Msd), bioturbated muddy heterolith (Msb) and lens-bedded muddy heterolith (Mst), that displays an upward transition from muddier- to sandier facies, represents the distal delta front. The distal delta front facies gives way upward to proximal delta front facies comprising erosive-based, grey to yellow, well-sorted, thin-bedded lenticular-bedded/wave ripple laminated sandstone that displays an upwards transition from very fine grained silty facies to fine grained sandstone beds (Sc). The sandy interval is strongly ferruginized and truncated at the top by an ironstone layer. The thin-bedded, lenticular-/wave-ripple laminated sandstone is consistent with lower and middle shoreface sedimentation (Swift and Niedoroda, 1985).

Delta Plain Facies Association (8789.20-8765.80ft)

The cross-bedded sandstone facies association is represented by 2-storeyed, channelized sandstones that display an overall fining-upward grain-size motif (Figure 2). The basal channelized unit rests directly on an ironstone layer that marks the top of the delta front facies and begins with about 5.0ft of brown, loose, pebbly sandstone (PS) that is heavily HC-stained. The interval gives way upward to coarse to fine grained, poorly-sorted sandstone, containing by planar cross-beds with mud-draped fore-sets (Fig. 6).

These rocks are recognized as tidally influenced fluvial channel deposits based on (i) the grain size range and motif, (ii) degree of sorting, (iii) presence of planar cross-bed and (iv) the stratigraphic relationship with the underlying delta front facies. The observed fining-upward motif is a common signature of meandering fluvial channel facies. The basal erosional surface of the sandstone units is interpreted to be a record of channel thalweg eroding laterally as the channel evolves. Tidal influence is reflected in the presence of mud-draped cross-beds.

The overall arrangement of the depositional facies within the cored interval reflects deltaic progradation.

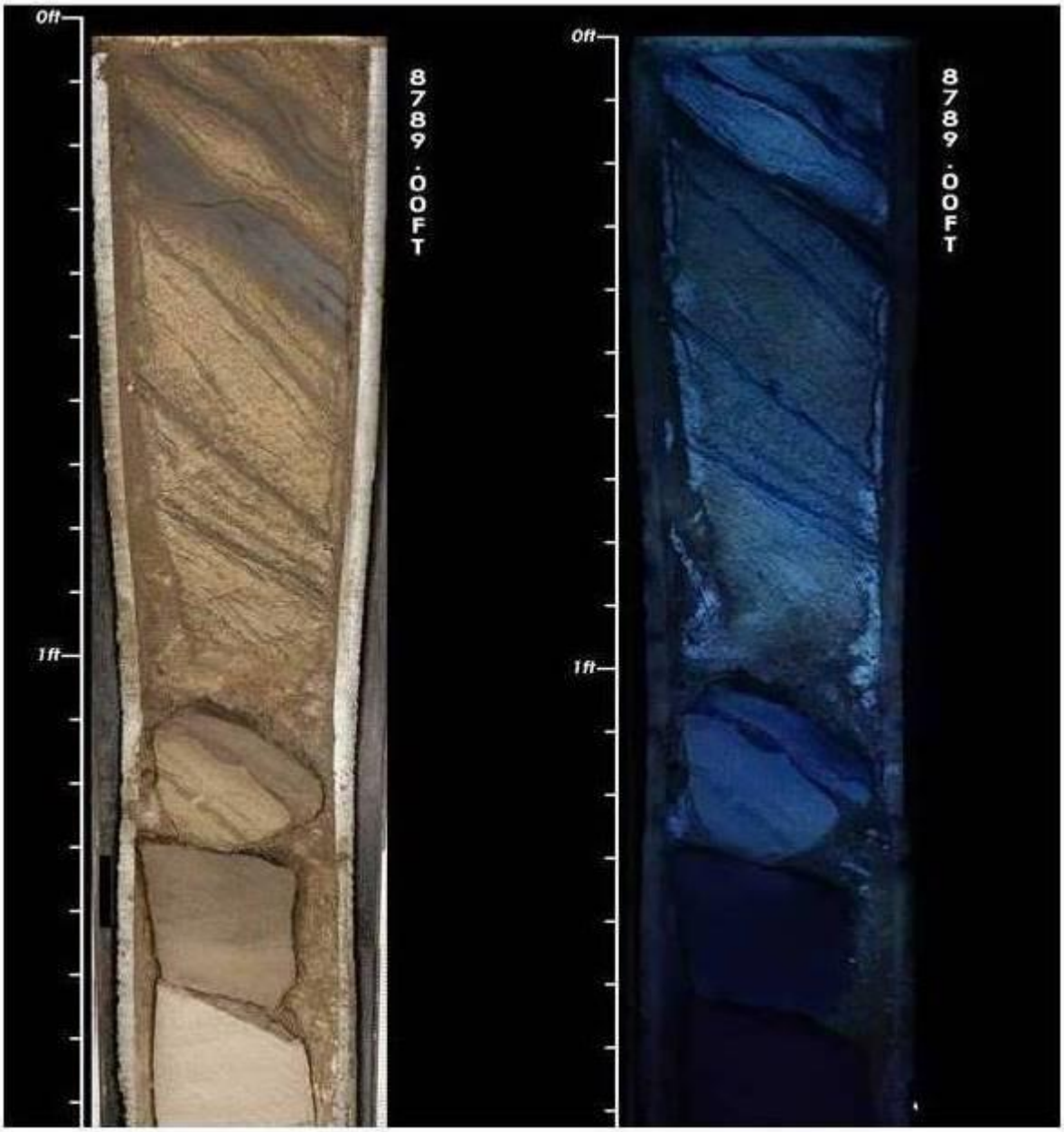

Fig. 6. Interval 8790-8799 showing cross-bedded sandstone with mud draped and ferruginized foresets planes. The mud drapes are ascribed to tidal processes

Summary

Ten lithofacies are identified within the cored interval of the LUDO Oil well. These include seven reservoir lithofacies comprising (i) pebbly sandstone (PS), (ii) fine to coarse grained cm- scale cross-bedded sandstone Sx, (iii) very fine grained mm-scale laminated sandstone (Sl), (iv) very fine to fine grained mm-scale laminated sandstone with clay drapes/laminae (Sc), (v) bioturbated sandstone (Sb), (vi) wavy-bedded sandy heteroliths *(SMw), and (vi)* bioturbated sandy heterolith (SMb). Non-reservoir lithofacies include (i) lens-bedded muddy

heteroliths (Mst), (ii) bedded (Mb) and (iii) bioturbated muddy heteroliths. Reservoir lithofacies makes up 59.28% of the cored interval, while the non-reservoirs constitute the remaining 39.74%.

The gross sedimentary characteristics and the overall vertical arrangement of the lithofacies suggest that the sediments accumulated in environments that ranged from the distal delta front to the delta plain. The reservoir lithofacies accumulated in environments that ranged between proximal delta front and tidally-influenced fluvial channel (delta plain) environments, while the non-reservoir lithofacies accumulated in distal delta front environments. The overall coarsening upward motif of the lithofacies suggests that sedimentation occurred during the progradation phase of the delta building episode.

REFERENCES

Arua, I., 1980. Palaeocene Macrofossils from the Imo Shale in Anambra State, Nigeria. Journal of Mining and Geology 17, 81–84.

Coleman, J.M., and Prior, D.B.K., 1982. Deltaic environments of deposition: In: P.A. Scholle and Spearing, D. (Eds) Sandstone depositional environment. AAPG Publication, Tulsa, 139-178.

Ekweozor, C.M. and E.M. Daukoru, 1992. The Northern depobelt portion of the Akata-Agbada petroleum system, Niger delta, Nigeria. NAPE Bull., 10, 102-120.

Nwajide, C. S. 2013. Geology of Nigeria's sedimentary basins. CSS Bookshops Limited,

Obi, G. C. and Ebong U. 2003. , Sequence Architecture of the Gbaran Node: Impact on Production. SPDC Project, 17p.

Oboh-Ikuenobe, F.E., Obi, C.G., Jaramillo C.A., 2005. Lithofacies, palynofacies and sequence stratigraphy of Paleogene strata in Southeastern Nigeria. Journal of African Earth Sciences 41, 79-102.

Pemberton, S.G., Maceachern, J.A., and Frey, R. W., 1992. Trace fossil facies models: environmental and allostratigraphic significance. In: Walker R.G. and James, N.P.(eds.), Facies Models, pp. 47-72. Geology Association of Canada.

Reyment, R.A., 1965. Aspects of the Geology of Nigeria: The stratigraphy of the Cretaceous and Cenozoic deposits, Ibadan University Press, Ibadan, 145 pp.

Swift, D.J.P. and Niedoroda, A.W. (1985). Fluid and sediment dynamics on continental ` shelves, in: Tillman, R.W., Swift, D.J.P. and Walker, R.G., eds. Shelf sands and sandstone reservoirs. SEPM Short Course 13, Notes, 47-133.