Sequence Architecture and Depositional Model for the Tortonian Succession, in the Jeth Oilfield, Niger Delta.

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ABSTRACT

The Jeth oilfield forms part of a group of oil fields in the coastal swamp depo-belt of the Niger Delta province that holds abundant oil, and reserves of both associated and non-associated gas. Among the key risks associated with reservoir development in the oil field are those pertaining to uncertainties of reservoir characteristics, depositional environments of the reservoirs, and reservoir continuity/and connectivity. This study adopted a sequence stratigraphic approach based on biostratigraphic/palynological data, wireline logs, and core data, to identify and characterize the reservoirs in terms of lithofacies, depositional environments, and reservoir distribution, in order to provide a framework that ensures optimum hydrocarbon production from the oilfield. Results of the analyses of wireline logs, and lithofacies data revealed that the late Middle-Miocene (Tortonian) succession penetrated in the Jeth oilfield contains five reservoir lithofacies including (i) fine to coarse grained cm-scale cross bedded sandstone (*Sx*), (ii) Very fine-grained mm-scale laminated sandstone (*Sc*), (iii) very fine-grained mm-scale laminated sandstone with clay drapes/laminae (*Sl*), (iv) bioturbated sandstone (*Sb*), (v) wavy-bedded sandy heteroliths *(SMw)*, and (vi) bioturbated sandy heteroliths (*SMb*). These reservoir lithofacies cumulatively make up 60% of the succession. The non-reservoir lithofacies include (i) lens-bedded muddy heterolith (*Mst*), (ii) bioturbated muddy heterolith (*Msb*), (iii) bedded/ massive mudstone (*Mb/Mm*), and (iv) Sideritic-bedded mudstone (*Msd*). These reservoir and non-reservoir lithofacies are further grouped into five facies associations that are interpreted to have accumulated in either (i) distributary channel, (ii) tidal channel, (iii) tidal flat (iv) lagoon or (v) distributary mouth bar environments. Sequence stratigraphic analysis revealed that these deposits belong to two major 3rd-order depositional cycles dating 10.35 Ma -8.5 Ma and 8.5 Ma -6.7 Ma respectively. Each depositional cycle begins with a transgressive systems tract comprising distributary channel, tidal channel, tidal flat, and lagoon (fluvio-estuarine) deposits, and ends in a highstand systems tract (HST) composed of delta front deposit. The transgressive systems tracts (TST) contain high quality reservoir sands that hold the bulk of the total original oil in place in the Jeth oilfield, while the highstand systems tract (HST) reservoirs hold most of the less developed reserves in the field. The distribution and internal architecture of the sequences reflect the complex interplay between depositional style, sea level change and basin structures. Reservoir sands are better developed within incised valleys (TST) in the distal areas, and are less developed in the more proximal areas. These sand units grade laterally into more mud-dominated facies that possibly reflect basinward decline in clastic influx. This research thus provides a reliable framework for predicting the spatial distribution and continuity of reservoirs within the Tortonian succession in the Niger Delta, especially in areas where well coverage is poor. Production strategy in the Jeth oilfield should therefore be reviewed in line with the new knowledge of the sequence architecture and depositional environments of the reservoir sands.

Keywords: Tortonian succession, Niger Delta, sequence stratigraphy, reservoir characterization, depositional model

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INTRODUCTION

Study Background

The Jeth oilfield forms part of a group of oil fields in the coastal swamp depo-belt of the Niger Delta province (Fig. 1.1). The region is reported to hold abundant oil, and reserves of both associated and non-associated gas estimated to be in excess of 202 Trillion (standard) cubic feet (Tcf) (Ekweozor and Daukoru (1994). A field report reveals that the Jeth oilfield was discovered in 1972, and went into production in 1975. It has eight different reservoir levels out of which only one, provides the bulk of the reserves in nine completed wells.

The reports further established that the productive reservoir has a STOOIP of 247.3 MMStb and an ultimate recovery of 137.2 MMStb. Based on these production data, the Jeth oilfield is considered to be an ideal candidate for a comprehensive sedimentological and sequence stratigraphic investigation to evaluate the remaining field potentials in order to optimize the total oil recovery.

To enhance better understanding of the sedimentary characteristics, depositional processes, and sequence stratigraphic architecture of the Tortonian succession penetrated in the Jeth oilfield, there is need to adopt a study approach that integrates well data, biostratigraphic-, and core data. The result is expected to provide a sound basis for better reservoir management, optimization of processes and facilities and the development of new reserves.

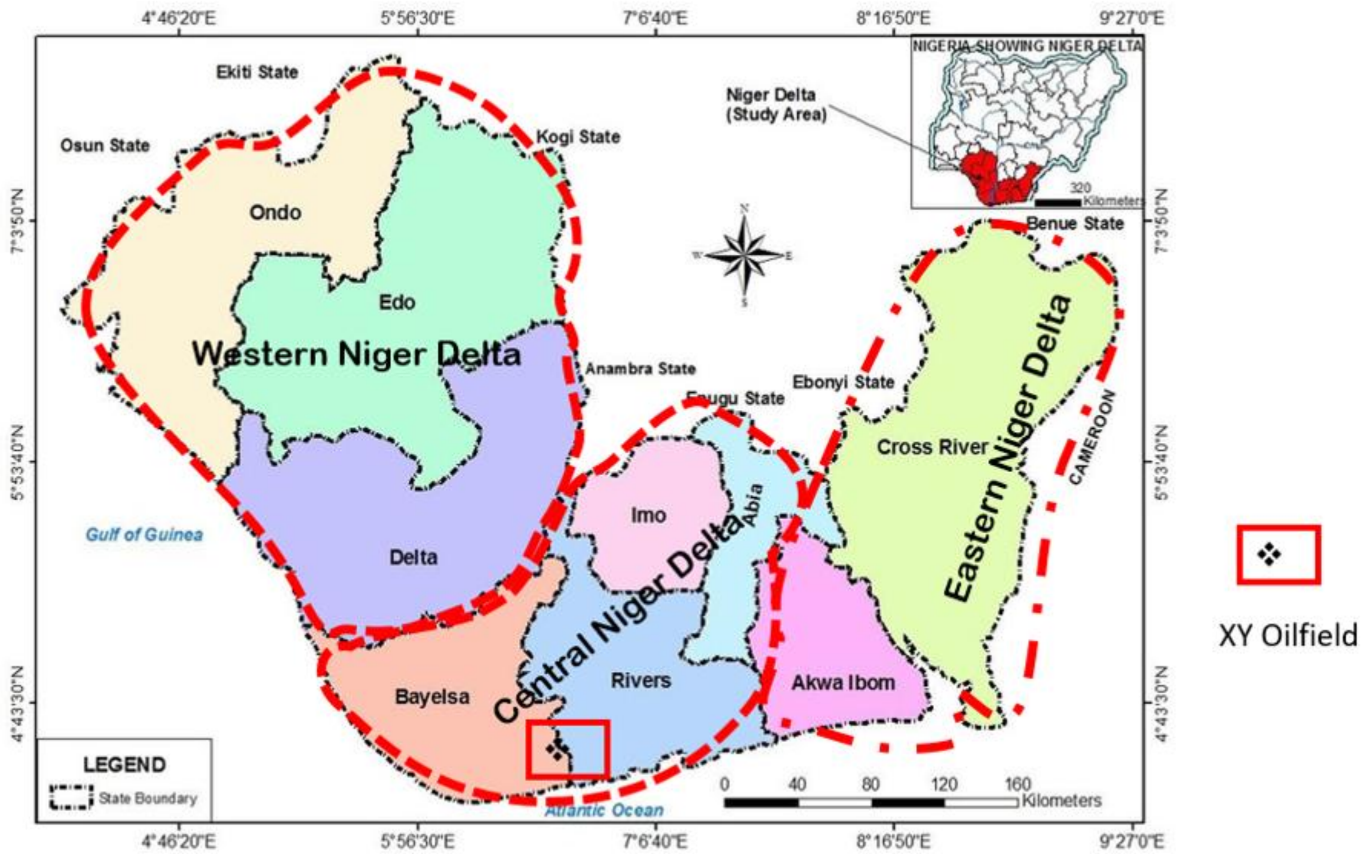

Fig. 1.1. Map of the Niger Delta showing States and the study area (Edegbene et al., 2022)

Statement of problem

Previous studies on the Jeth oilfield have focused essentially on formation evaluation. Three-dimensional geological modelling study which is basic for a realistic reserve estimation, field development, field management and economic assessment have not been carried out. There is therefore need for a sequence stratigraphic framework that will characterize the reservoirs in the field and provide a realistic geological model that will address the uncertainties associated with hydrocarbon production in the field and ensure optimum oil and gas recovery.

Aim and Objectives

Among the key risks associated with reservoir development in the Jeth oilfield are the uncertainties of reservoir characteristics, depositional environments, and reservoir continuity and connectivity. This project was therefore initiated to provide a framework for managing these subsurface uncertainties in the oil field. The study should also provide a geological framework that could be used in predicting source, seal and reservoir lithofacies, particularly in adjacent areas where well coverage is poor.

The key objectives of this research project are therefore to:

(i) Identify and characterize the sedimentary facies penetrated by oil wells,

(ii) Interpret their depositional environments,

(iii) Identify the sequence architectural elements, and

(iv) Present a depositional model that will support the development of the reservoirs in the oil field.

Study Area

The Niger Delta which separates the Bight of Benin from the Bight of Bonny within the larger Gulf of Guinea has been described under three sub-regional zones:

(i) The Western Niger Delta;

(ii) The Central Niger Delta, and

(iii) The Eastern Niger Delta (Edegbene *et al.*, 2022), (Fig. 1.1),

The Jeth oilfield is located in the coastal South-South portion of the Central Nigeria Niger Delta.

Regional Stratigraphic Setting

Previous studies (e.g. Ekweozor and Daukoru, 1994) have established that sedimentation in the Niger Delta started during the Paleocene following a major marine transgression that led to the accumulation of the Akata Shale over the late Cretaceous sediments of southern Nigeria. The Akata Formation ranges in thickness from 2000 m (6600 ft.) at the most distal part of the delta, to 7000 m (23,000 ft.) beneath the continental shelf. It is reported to contain the source rocks as well as turbidite sands that serve as potential reservoirs in deep-water environments (Doust and Omatsola, 1990). The overlying Agbada and the Benin Formations (Table 2.1) document the regressive event that followed the Akata sedimentation (Reijers *et al.*, 1997).

Table 2.1. Lithologic characteristics of the components of the Paleocene-Oligocene succession in the Niger Delta (Reijers *et al.*, 1997)

Age	Formations		Characteristics
	Surface	Subsurface	
Oligocene	Ogwashi	Benin Formation	Alternating coarse-grained sandstone, lignite seams and kaolinitic clays of continental origin
Eocene	Ameki	Agbada	Fossiliferous, green-grey sand-rich heteroliths, calcareous concretions, and sand-rich heteroliths, displays rapid lateral facies changes
Paleocene	Imo	Akata	Dark grey, fossiliferous, shale, sandstone and ironstone of marine origin

Avbovbo (1978) reported that the Agbada Formation is the dominant reservoir rock in the Niger Delta petroleum system, and that it consists of alternating sandstones and shales of delta-front, distributary channel, and deltaic-plain origin. The alternation of fine and coarse-grained clastics provides multiple reservoir-seal couplets that characterize all the Eocene to Pleistocene depobelts, of the Niger Delta (Doust and Omatsola, 1990).

The Benin Formation represents the top-most part of the Niger Delta stratigraphic sequence and is composed mainly of late Eocene to Holocene continental sand deposits, including alluvial and coastal plain deposits that are up to 2000 m in thickness (Avbovbo, 1978). According to Doust and Omatsola (1990) the Benin Formation provides the overburden needed for oil/gas maturation, and becomes thinner and disappears near the shelf edge.

DATA AND METHODOLOGY

Data Sets

The data sets available for this study include (i) wireline logs, and (ii) high quality core descriptions for Wells T-5, T-6, T-9, T-10 and T-13, all corrected to true vertical depth sub-sea (tvdss); (ii) CT-scanned photos of the cores, and (iv) a summary of the Tortonian Biostratigraphy of the Jeth Oilfield. These are summarized in Tables 3.1 and 3.2.

Table 3.1. Summary of data availability

Data		Available			
Wells	T-5	T-6	T-9	T-10	T-13
P-zones with markers	x	x	x	x	x
Core logs	x	x	x	x	x
Core photos	x	x	x	x	x
Gamma ray logs	x	x	x	x	x
Neutron-density logs	x	x	x	x	x
Tortonian Biostratigraphy			x		

Methods of Analyses

Sedimentology: The Tortonian stage in the drilled intervals was delineated based on the biostratigraphy data (Table 3.2). Lithostratigraphic and sedimentological interpretations were based on well-log (Gamma ray, Resistivity, Neutron and Density logs,) responses and lithological characteristics of the deposits cored in the selected wells.

Table 3.2. Summary of the Tortonian Biostratigraphy of the Study Area

Depth (m)	P-zone	Age
2150	P-830 & ? younger	Late Miocene
2920		
3190		
3590	P-820	
4035	P-780	Middle Miocene

The core slabs were described on a scale of 1: 50 onto pre-prepared standard Clastic Core Description sheets. Depositional interpretations relied heavily on the following among others:

(a) The Walther's Law of facies that governs the vertical and lateral relationship of sedimentary facies in an undisturbed succession,

(b) The presence of marker horizons (such as coal),

(c) The vertical trends in wireline log responses,

(d) The association of sedimentary structures,

(e) Trace fossil associations,

(f) Diagenetic fabrics (cementation and concretions), and on

(g) Comparison with deltaic/marginal marine-offshore facies models (e.g., Coleman and Prior (1982), Walker and James (1992).

Trace fossils identification was based on the criteria of Hettinger, (1995) as summarized in Table 3.3.

Table 3.3. Guide to identification of some common trace fossils (Hettinger, 1995)

Trace Fossils	Characteristics
Diplocraterion	U-shaped barrows with spreite, commonly vertical.
Monocraterion	Funnel-shaped, vertically repetitive burrows with concentric laminae.
Ophiomorpha	Horizontal-oblique burrows 5mm-2cm in diameter, sand-filled, and with pelletized exterior walls.
Paleophycus	Isolated, nearly horizontal burrows 5mm-1cm in diameter, sand-filled, with smooth lined walls.
Teichichnus	Burrows, about 1.5cm diameter, horizontal -oblique, sand-filled, may occur in stacks as much as 5cm high.
Skolithos	Tunnels of uniform diameter, commonly en masse and vertical, smooth-walled.
Thalassinoides	Irregular network of tunnels and shafts with variable diameter, typically branching, horizontal-oblique, sand-filled, and with smooth unlined walls.
Chondrites	Compressed, straight or curved, root-like equidimensional cylindrical, un-walled shafts that often branch at acute angle. Diameter in the range of less than 1 mm to a few millimeters

The lithofacies scheme of the SPDC Ltd was adopted for the description (Table 3.4).

Sequence Straigraphy: The sequence stratigraphy approach adopted in this work is based upon interpreting and integrating four (4) independent basic data sets and involves:

(a) Interpreting high resolution biostratigraphy and palaeoecology of wells penetrating the sequences (Wornadt and Vail, 1991; Armentout, 1991; Pacht *et. al.*, 1990) for determining

Table 3.4. Lithofacies Classification Scheme (After Flint *et al*., 1988)

Sediment Type		Lithofacies description	Code	Reservoir classification
Sandstone < 20% Clay		Pebbly sandstone	PS	Reservoir
		Fine to coarse grained cm-scale cross-bedded sandstone	Sx	
		Very fine-grained mm-scale laminated sandstone	Sl	
		Very fine to fine grained mm-scale laminated sandstone with clay drapes/laminae	Sc	
		Bioturbated sandstone	Sb	
Mixed sand and clay	Sandy-rich Heteroliths > 20% <5 0% clay	Wavy-bedded sandy heterolith	SMw	
		Bioturbated sandy heterolith	SMb	
		Glauconitic/shelly muddy sandstone	SMshg	

(Heteroliths)	Mud-rich Heteroliths > 50% <8 0% clay	Lens-bedded muddy heterolith	Mst	Non-reservoir
		Bioturbated muddy heterolith	Msb	
Mudstone > 80% clay		Bedded/massive mudstone	Mb/Mm	
		Sideritic-bedded mudstone	Msd	
Re-deposited/slumped sandstone/mudstone/ heteroliths		Re-deposited/slumped sandstone	RS	Depends on original sediment characteristics.
		Re-deposited/slumped mudstone/heteroliths	RM/MS	

paleowater depths, interpreting depositional environments, recognizing condensed sections from faunal abundance and diversity peaks and for dating the condensed sections.

To identify key sequence stratigraphic surfaces, each well was calibrated in terms of biostratigraphic zonations (i.e. P-zones and F-zones). Identification of maximum flooding surfaces (MFS) from the well logs and biostratigraphic spreadsheets, were then carried out independently as a first step, and results were subsequently compared. Maximum flooding surfaces (MFS) were located at points on the well log that show the highest relative neutron-porosity values, lowest resistivity values relative to the other surrounding flooding surfaces. Candidate sequence boundaries were identified at the base of the thickest and coarsest/shallowest sand between two adjacent maximum flooding surfaces. Absolute ages for the key surfaces were derived from the chronostratigraphic chart for the Niger Delta (Stacher *et al*., 1993), correlated with the eustatic sea level curves of Haq *et al*., (1987) (Table 3.5).

Table. 3.5. Tortonian Chronostratigraphic Chart of the Jet Oil Field, Niger Delta (Modified Stacher *et al*., 1993)

Depth	F- Zone	Marker	P- zone	Key event	Age
2150 2920	F 9600	.... 7.4 Ma	P830 & Younger		TORTONIAN
3190	F 9500		P 820	Quantitave base *Stereisporites sp*	
3590		Uvigerina-8 .... 9.5 Ma		Base continuous *Stereisporites sp*	
4035			P 780	Top regular occurrence of *Racemonocolpites hians*	

To bring out clearly the structural and stratigraphic relationships of the sequences drilled in the wells, a down-dip correlation panel for wells T-5, T-6, T-9, T-13 and T-10 was generated using the STRATLOG 2 v2.2 software package. Sequence stratigraphic correlation was guided by the identified key surfaces and by the parasequences stacking patterns.

Petrophysics: Petrophysical parameters evaluated include porosity, permeability, and net-to-gross. Porosity was computed from FLAME and calibrated with that from core data, while permeability was computed using a neural network trained from the available logs. *Net-to-gross* was estimated from the Density-Neutron separation/or gamma ray and spontaneous potential logs. Intervals that are hydrocarbon-bearing were identified from the scanned core images based on their fluorescence colours (Table 3.6).

Table 3.6. Hydrocarbon Fluorescence Colour Chart

Fluorescence Colour	Organic Maturity
Blue green	Immature
Greenish yellow	
Golden yellow	Mature main phase of liquid petroleum generation
Orange	
Red	
No fluorescence	Dry gas or barren

RESULTS AND INTERPRETATIONS

Summary of Lithofacies

The lithofacies present in the Tortonian succession are summarized in Tables 4.1-4.4, and consist of reservoirs and non-reservoirs.

They include reservoir lithofacies comprising: (i) fine to coarse grained cm-scale cross bedded sandstone (Sx), (ii) Very fine-grained mm-scale laminated sandstone (Sc), (iii) very fine-grained mm-scale laminated sandstone with clay drapes/laminae (Sl), (iv) bioturbated sandstone (Sb), (v) wavy-bedded sandy heteroliths (SMw), and (vi) bioturbated sandy heteroliths (SMb). These reservoir lithofacies cumulatively make up 60% of the succession.

The non-reservoir lithofacies include (vii) lens-bedded muddy heterolith (Mst), (viii) bioturbated muddy heterolith (Msb), (ix) bedded/ massive mudstone (Mb/Mm), and (x) Sideritic-bedded mudstone (Msd).

Depositional Environments

Lithofacies analysis assigned these lithofacies to five facies associations which are here interpreted to document sedimentation in either (i) distributary channel, (ii) tidal channel, (iii) tidal flat (iv) Prodelta or (v) distributary mouth bar environments (Tables 4.5-4.8).

Distributary Channel Facies Association: Distributary Channel Facies association ranges in thickness from 40-100m, and is generally composed of alternating poorly-moderately sorted, coarse-fine grained, cross-bedded sandstone (Sx), very fine-grained mm-scale laminated sandstone (Sl) and strongly bioturbated sandstones (Sb), arranged in a general fining-upward motif. It contains clay bands, *Ophiomorpha* and *Paleophycus* at various levels (Fig. 4.1).

Based on the overall coarse-fine grain size, poor sorting, fining upward grain size motif, presence of carbonaceous bands, unidirectional cross beds, and the presence of clay bands and *Paleophycus*, the facies association is interpreted, on the model of Coleman and Prior (1982), to have accumulated in a sandy, coastal plain high energy environment such as a distributary channel, under brackish water condition.

Tidal Channel Facies Association: The distributary channel facies passes upward into an interval comprising inter-bedding of thin mud layers (Mb), bioturbated sandy heteroliths (SMb) and lens-bedded muddy heteroliths (Mst). The units which range in thickness from 30 m-50 m, contain *Chondrites*, *Skolithos* (Fig. 4.2) and *Paleophycus*.

Table 4.1. P-zones and lithofacies depth listing for Well T-5

	Top	Bottom	Code	m	Description
P-830	2100	2190	SMb	90	Inter-bedding of thin carbonaceous mud layers (Mb), bioturbated fine grained sandstone (Sb), sandy heteroliths (SMb) and lens-bedded muddy heteroliths (Mst). The units which range in thickness from 30 m-50 m, contain *Chondrites, Skolithos* (Fig. 4.2) and *Paleophycus.*
	2190	2210	Sx	20	alternating, strongly bioturbated sandstone (Sb), laminated sandstone (Sl) and herringbone- cross-bedded sandstone (Sx). Sand is generally poorly sorted, carbonaceous, and occasionally burrowed. It contains clay flasers and *Paleophycus*
	2210	2235	SMb	25	Inter-bedded, grey, lenticular bedded, sandy heteroliths (SMb) and, clayey heteroliths (Msb). *Teichichnus, Thalassinoides* and *Skolithos Paleophycus*
	2235	2285	Msd	50	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	2285	2340	Sx	55	This unit is composed of alternating poorly-moderately sorted, coarse-fine grained cross-bedded sandstone (Sx), very fine-grained mm-scale laminated sandstone (Sl) and strongly bioturbated sandstones (Sb) arranged in a general fining-upward motif
	2340	2450	MSb	110	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	2450	2490	SMw	40	Inter-bedded fine-grained sandstone and thick-thin alternation of sand-rich and mud-rich heterolith, lenticular bedded, glauconitic, coarsening upward
	2490	2520	Mb	30	Dark grey, sideritic-bedded mudstone (Msd), bedded mudstone (Mb) and massive mudstone (Mm), interlaminated with light grey silty bands. Syn-sedimentary deformation features are present. Sandstone/mudstone ratios within the interval are less than 1:20. Shell fragments are commonly dispersed within the units. *Planolites, Chondrites, Thalassinoides and Paleophycus* dominate
	2520	2650	Sl	130	alternating, strongly bioturbated sandstone (Sb), laminated sandstone (Sl) and cross-bedded sandstone (Sx). Sand is generally poorly sorted, carbonaceous, and occasionally burrowed. It contains clay flasers and *Paleophycus*.
	2650	2680	SMb	28	Inter-bedded, grey, lenticular bedded, sandy heteroliths (SMb) and, clayey heteroliths (Msb). *Teichichnus*, *Thalassinoides*, *Skolithos* and *Paleophycus*
	2680	2747	SMw	67	Inter-bedded fine-grained sandstone and thick-thin alternation of sand-rich and mud-rich heterolith, lenticular bedded, glauconitic, coarsening upward

Table 4.2. P-zones and lithofacies depth listing for Well T-6

ZONE	Interval (m0		Code	m	Description
	Top	Bot			
P-830	3100	3140	Mst	40	bioturbated, carbonaceous, lens-bedded muddy heterolith (Mst), light brown, strongly bioturbated sandstone (Sb) and very fine-grained laminated sandstone (Sl). These are arranged in a general coarsening upward motif.
	3140	3200	Mm	60	Dark grey, sideritic-bedded mudstone (Msd), bedded mudstone (Mb) and massive mudstone (Mm), interlaminated with light grey silty bands. Synsedimentary deformation features are present. Sandstone/mudstone ratios within the interval are less than 1:20. Shell fragments are commonly dispersed within the units. *Planolites, Chondrites*,*Thalassinoides* and *Paleophycus* dominate
P-820	3200	3250	SMb	50	Inter-bedded, grey, lenticular bedded, sandy heteroliths (SMb) and, clayey heteroliths (Msb). *Teichichnus, Thalassinoides* and *Skolithos Paleophycus*.
	3250	3275	Sl	25	alternating, strongly bioturbated sandstone (Sb), laminated sandstone (Sl) and cross-bedded sandstone (Sx). Sand is generally poorly sorted, carbonaceous, and occasionally burrowed. It contains clay flasers and *Paleophycus*.
	3275	3325	SMb	50	Inter-bedded, grey, lenticular bedded, sandy heteroliths (SMb) and, clayey heteroliths (Msb). *Teichichnus, Thalassinoides* and *Skolithos Paleophycus*
	3325	3400	Sx	75	alternating, strongly bioturbated sandstone (Sb), laminated sandstone (Sl) and cross-bedded sandstone (Sx). Sand is generally poorly sorted, carbonaceous, and occasionally burrowed. It contains clay flasers and *Paleophycus*.
P-780	3400	3450	SMb	50	Inter-bedded, grey, lenticular bedded, sandy heteroliths (SMb) and, clayey heteroliths (Msb). *Teichichnus, Thalassinoides* and *Skolithos Paleophycus*
	3450	3500	Sb	50	alternating, strongly bioturbated sandstone (Sb), laminated sandstone (Sl) and cross-bedded sandstone (Sx). Sand is generally poorly sorted, carbonaceous, and occasionally burrowed. It contains clay flasers and *Paleophycus*.
	3500	3550	Sl	50	This unit is composed of alternating poorly-moderately sorted, coarse-fine grained cross-bedded sandstone (Sx), very fine-grained mm-scale laminated sandstone (Sl) and strongly bioturbated sandstones (Sb) arranged in a general fining-upward motif
	3550	3612	SMb	62	Inter-bedded, grey, lenticular bedded, sandy heteroliths (SMb) and, clayey heteroliths (Msb). *Teichichnus, Thalassinoides* and *Skolithos Paleophycus*.

Table 4.3. P-zones and lithofacies depth listing for Well T-10

ZONE	Top	Bottom	Code	m	Description
P-830	3000	3090	Msd	90	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	3090	3205	Mm	115	Dark grey, sideritic-bedded mudstone (Msd), bedded mudstone (Mb) and massive mudstone (Mm), interlaminated with light grey silty bands. Syn-sedimentary deformation features are present. Sandstone/mudstone ratios within the interval are less than 1:20. Shell fragments are commonly dispersed within the units. *Planolites, Chondrites,Thalassinoides and Paleophycus* dominate
P-820	3205	3325	Msd	20	Alternation of light grey, shale and calcareous, well-sorted sandstone
	3325	3350	Msb	25	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	3350	3390	Sx	40	This unit is composed of alternating poorly-moderately sorted, coarse-fine grained cross-bedded sandstone (Sx), very fine-grained mm-scale laminated sandstone (Sl) and strongly bioturbated sandstones (Sb) arranged in a general fining-upward motif. *Ophiomorpha & Paleophycus*
P-780	3390	3450	SMw	60	Inter-bedded fine-grained sandstone and thick-thin alternation of sand-rich and mud-rich heterolith, lenticular bedded, glauconitic, coarsening upward
	3450	3540	SMb	90	Sand-rich heterolith interbedded with thin units of mud-rich heterolith and very fine-grained sandstone, Sandying upward.
	3540	3600	Msd	60	Mud-rich heterolith, sandying upward, calcareous, carbonaceous

Table 4.4. P-zones and lithofacies depth listing for Well T-13

Zone	Top	Bottom	Code	m	Description
P-830	2800	2850	Msd	50	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	2850	2890	Sl	40	alternating, strongly bioturbated sandstone (Sb), laminated sandstone (Sl) and cross-bedded sandstone (Sx). Sand is generally poorly sorted, carbonaceous, and occasionally burrowed. It contains clay flasers and *Paleophycus*.
	2890	2920	Msd	30	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	2920	2950	Sb	30	alternating, strongly bioturbated sandstone (Sb), laminated sandstone (Sl) and cross-bedded sandstone (Sx). Sand is generally poorly sorted, carbonaceous, and occasionally burrowed. It contains clay flasers and *Paleophycus*.
	2950	3000	Sx	50	This unit is composed of alternating poorly-moderately sorted, coarse-fine grained cross-bedded sandstone (Sx), very fine-grained mm-scale laminated sandstone (Sl) and strongly bioturbated sandstones (Sb) arranged in a general fining-upward motif
	3000	3020	Msd	20	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	3020	3080	SMw	60	Sand-rich heterolith interbedded with thin units of mud-rich heterolith and very fine-grained sandstone, Sandying upward
	3080	3200	Msd	120	Dark grey, sideritic-bedded mudstone (Msd), bedded mudstone (Mb) and massive mudstone (Mm), interlaminated with light

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					grey silty bands. Synsedimentary deformation features are present. Sandstone/mudstone ratios within the interval are less than 1:20. Shell fragments are commonly dispersed within the units. *Planolites, Chondrites,Thalassinoides and Paleophycus* dominate
	3200	3240	SMw	40	Alternation of light grey, shale and calcareous, well-sorted sandstone
P-820	3240	3280	Msd	40	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone
	3280	3330	Msd	50	Alternation of light grey, calcareous mudstone and well-sorted fine-grained sandstone
P-780	3330	3430	Sx	100	This unit is composed of alternating poorly-moderately sorted, coarse-fine grained cross-bedded sandstone (Sx), very fine-grained mm-scale laminated sandstone (Sl) and strongly bioturbated sandstones (Sb) arranged in a general fining-upward motif
	3430	3456	Msd	26	Interbedded thick grey shale and very thin very fine-grained calcareous sandstone and siltstone

Table 4.5. Depositional interpretation for the lithofacies penetrated by Well T-5

ZONE	Top	Bottom	Code	m	Depositional Environments
P-830	2100	2190	SMb	90	Tidal Channel
	2190	2210	Sx	20	
	2210	2235	SMb	25	Tidal Flat
	2235	2285	Msd	50	
	2285	2340	Sx	55	Distributary Channel
	2340	2450	MSb	110	Mouth bar
	2450	2490	SMw	40	
	2490	2520	Mb	30	Lagoon
	2520	2650	Sl	130	Tidal channel
	2650	2680	SMb	28	Tidal flat
	2680	2747	SMw	67	

Table 4.6. Depositional interpretation for the lithofacies penetrated by Well T-6

	Interval (m)		Code	m	Depositional Environments
ZONE	Top	Bottom			
P-830	3100	3140	Mst	40	Lagoon
	3140	3200	Mm	60	
P-820	3200	3250	SMb	50	Tidal flat
	3250	3275	Sl	25	Tidal channel
	3275	3325	SMb	50	Tidal flat
	3325	3400	Sx	75	Tidal channel
P-780	3400	3450	SMb	50	Tidal flat
	3450	3500	Sb	50	Distributary channel
	3500	3550	Sl	50	
	3550	3612	SMb	62	Tidal channel

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Table 4.7. Depositional interpretation for the lithofacies penetrated by Well T-10

ZONE	**Top**	**Bottom**	**Code**	**m**	Environment
P-830	3000	3090	Msd	90	Lagoon
	3090	3205	Mm	115	
P-820	3205	3325	Msd	20	Tidal channel
	3325	3350	Msb	25	Tidal flat
	3350	3390	Sx	40	Distributary channel
P-780	3390	3450	SMw	60	Distributary mouth bar
	3450	3540	SMb	90	
	3540	3600	Msd	60	

Table 4.8. Depositional interpretation for the lithofacies penetrated by Well T-13

ZONE	**Top**	**Bottom**	**Code**	**m**	Depositional Environments
P-830	2800	2850	Msd	50	Tidal flat
	2850	2890	Sl	40	Tidal Channel
	2890	2920	Msd	30	Tidal flat
	2920	2950	Sb	30	Tidal Channel
	2950	3000	Sx	50	Distributary mouth bar
	3000	3020	Msd	20	
	3020	3080	SMw	60	Lagoon
P-820	3080	3200	Msd	120	Tidal Channel
	3200	3240	SMw	40	
	3240	3280	Msd	40	
	3280	3330	Msd	50	
	3330	3430	Sx	100	Distributary channel
P-780	3430	3456	Msd	26	Mouth bar

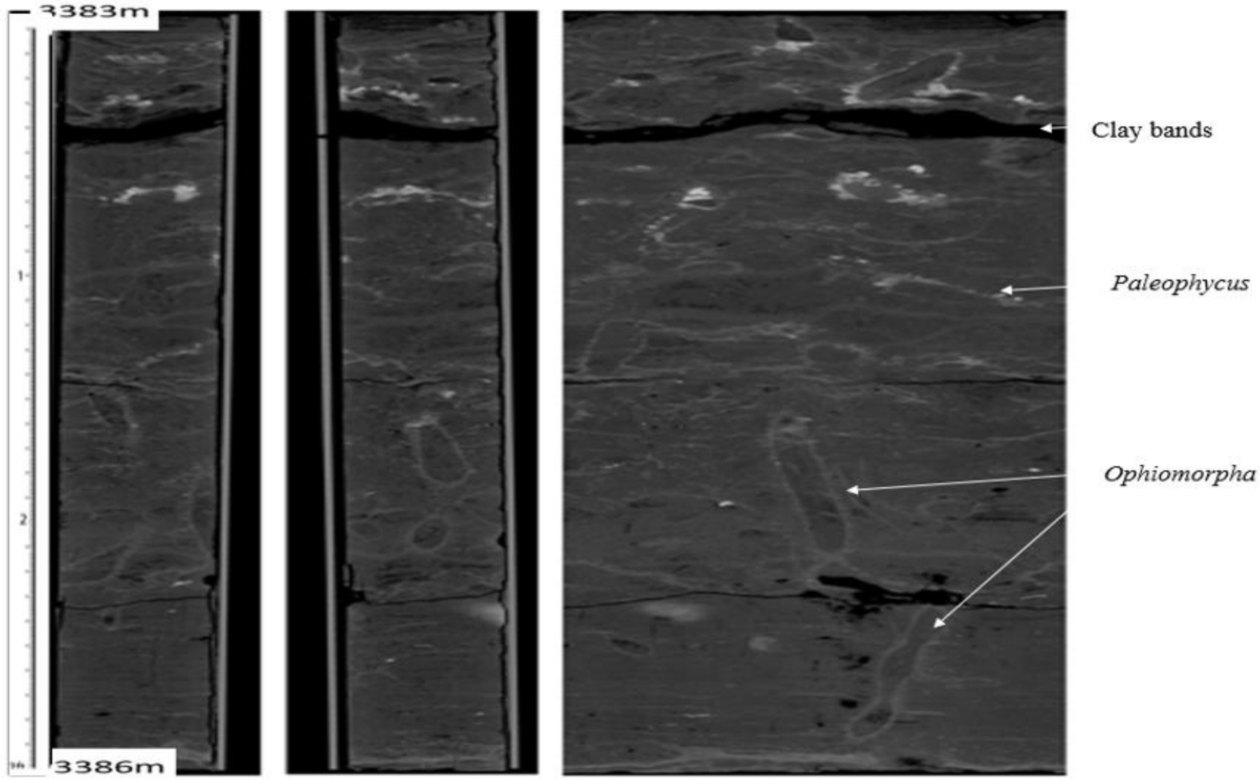

Fig. 4.1. Distributary channel facies (T-10, interval 3383m-3386) showing strongly bioturbated sandstone containing *Ophiomorpha* and *Paleophycus*

These rocks are recognized as delta plain deposits based on the stratigraphic relationship with the underlying distributary channel deposit and inter-bedding of thin mud layers (Mb), bioturbated sandy heteroliths (SMb) and lens-bedded muddy heteroliths (Mst).

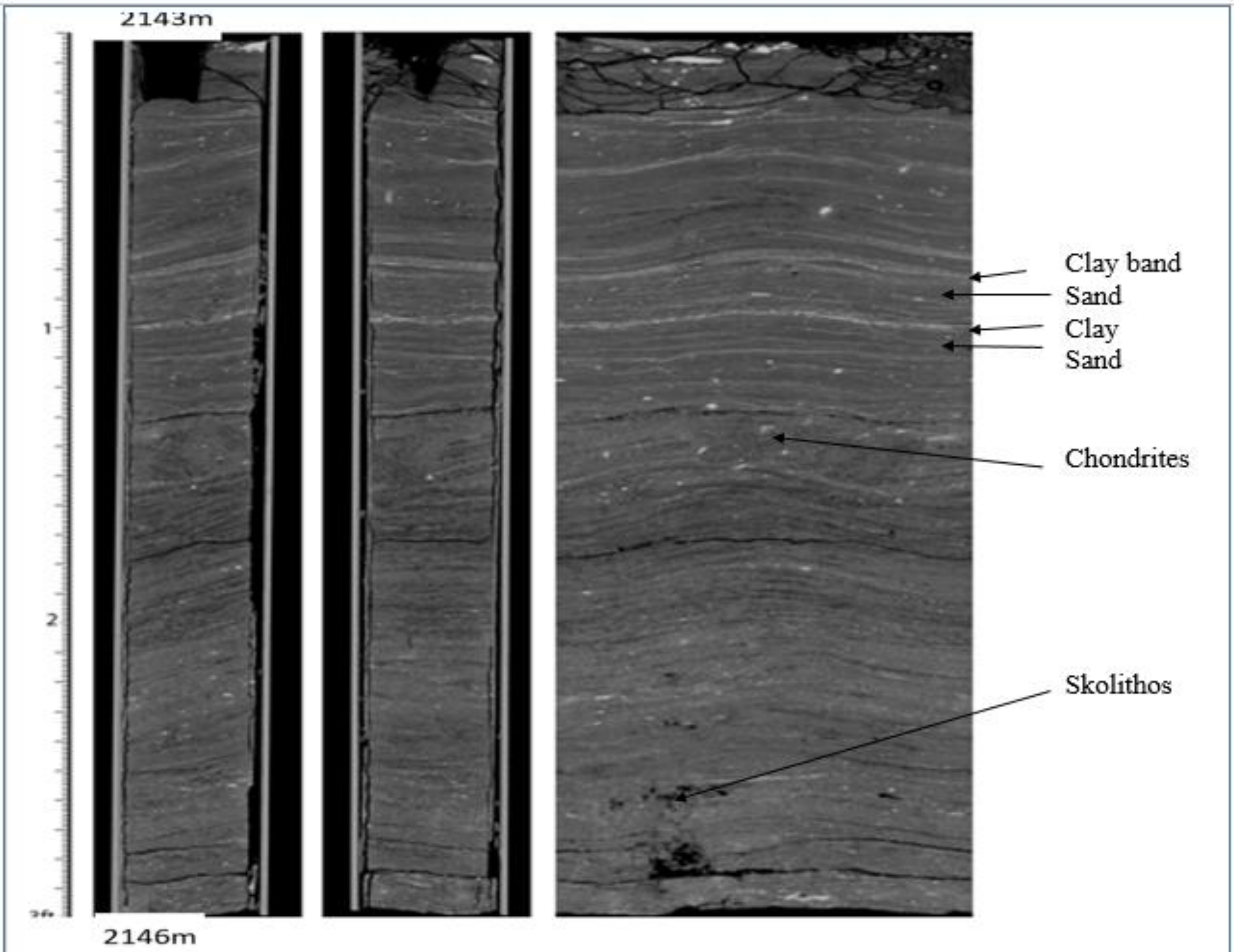

Fig. 4.2. Tidal channel facies (T-5, interval 2143m-2146m showing alternation of thick, ripple laminated sand and thin clay bands, containing *Chondrites*

These sediments are thus envisaged to have accumulated by overbank spilling of fine-grained material from the Niger River during a flood stage, based on the model of Weimer *et al*. (1982).

The observed rapid alternation of thick-thin, fine grained sand and clay layers (tidal bundles) is typical of tidally influenced channel deposits (Nilsen, 1982; and Miall, 1992). Tidal bundles and mud drapes probably relate to ebb-flood tidal cycles (Yang and Nio, 1985; Leckie and Singh, 1991; Shanley *et al.*, 1992).

Tidal Flat Facies Association: This association comprises inter-bedded, grey, lenticular bedded, sandy heteroliths (SMb) and, clayey heteroliths (Msb) containing abundant *Skolithos* (Fig. 4.3) *Thalassinoides*, and *Paleophycus.*

These heterolithic facies that overlie the tidal channel facies are recognized as a product of tidal flat sedimentation based on the model of Weimer et al. (1982), Kamola (1984); Allen (1993), and Allen and Posamentier (1993), and on the overall sedimentary characteristics and stratigraphic relationship with the underlying tidally influenced channel facies. The inter-bedding of thin, grey, fine-grained sandstone and sand-rich heteroliths is typical of deposits of sand flats/floodplain/overbank environments (Nilsen, 1982; Miall, 1992; Uduezue *et al*., 2021).

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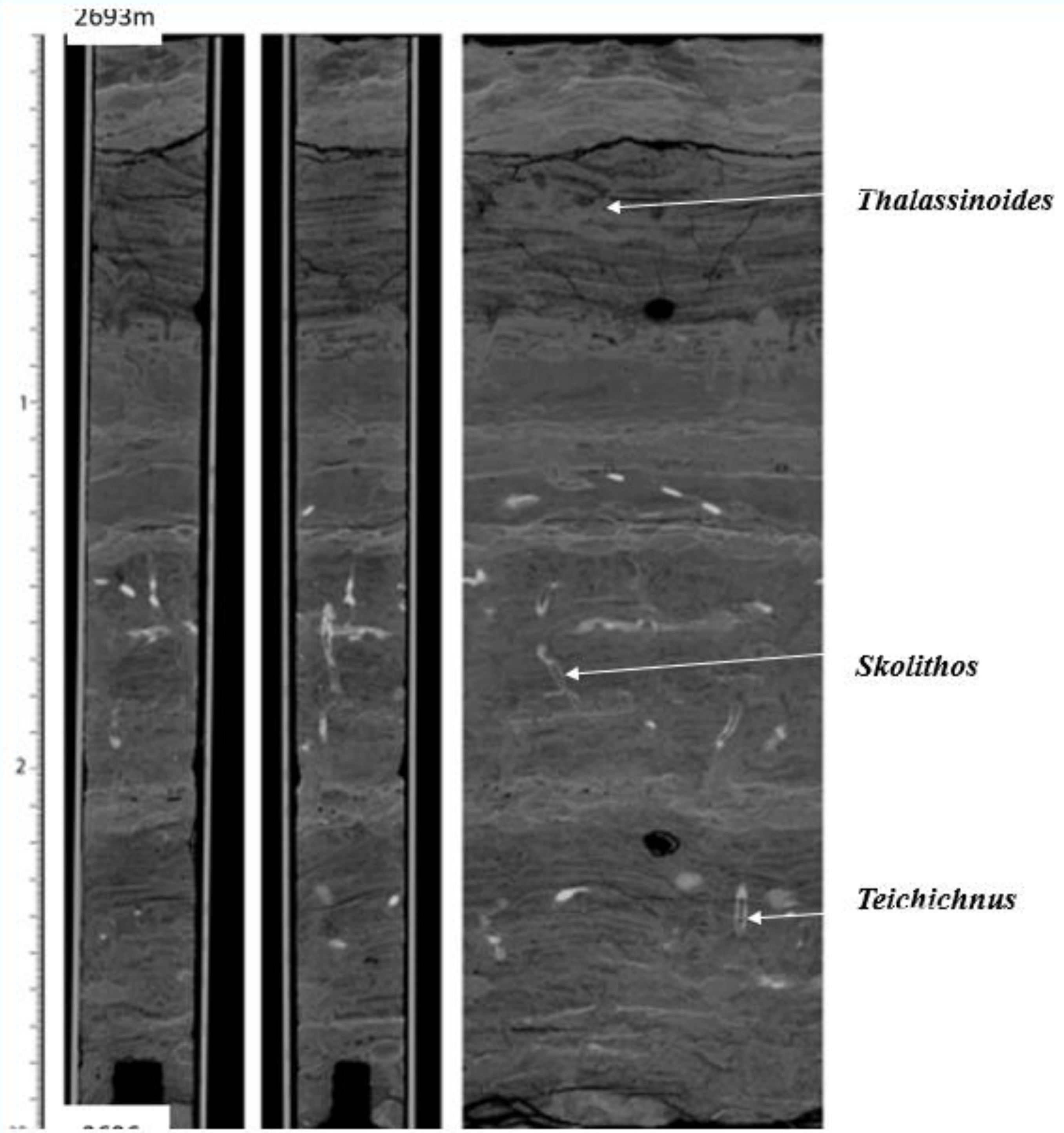

Fig. 4.3. Tidal flat facies (interval 2693-2696 (T-5) showing strongly bioturbated heteroliths containing *Skolithos* , *Teichichnus* and *Thalassinoides*

Lagoon/Prodelta Facies Association: The prodelta environment is indicated by the gross sedimentary characteristics of the lithofacies occurring between 2490-2520m in Well T-5, 3140-3200 in Well T-6, 3090-3205m in Well T-10, and 3080-3200m in Well T-13. (Tables 4.1, 4.2, 4.3 and 4.4). Lithofacies identified within the interval include dark grey, sideritic-bedded mudstone (Msd), bedded mudstone (Mb) and massive mudstone (Mm), interlaminated with light grey silty bands. Sandstone/mudstone ratios within the interval are less than 1:20. Shell fragments are commonly dispersed within the units. The *Cruziana* ichnofacies represented by *Planolites*, and P*aleophycus* dominate the ichnofossil assemblage (Fig. 4.4).

These characteristics are indicative of sand-starved, poorly oxygenated environments where low energy suspension fallout was the dominant process (Leckie *et al.*, 1989; Buatois, 2005). Poor oxygen conditions are indicated by the presence of the *Cruziana* ichnofacies (Buatois, 2005).

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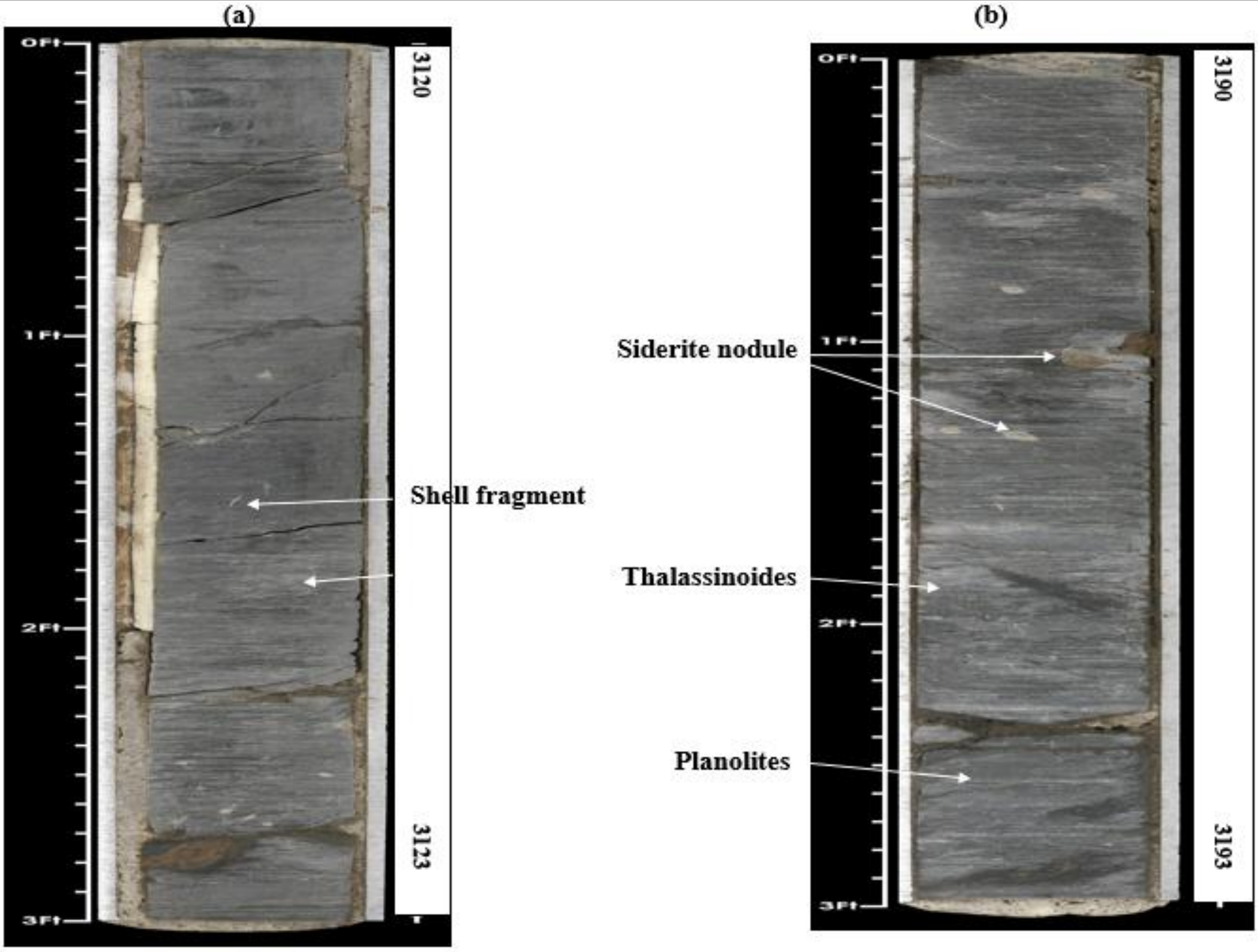

Fig. 4.4. Prodelta facies (a) (interval 3120-3123 (T-10) and (b) interval 3190-3193 (T-13) showing siderite nodule, shell fragment, *Thalassinoides and Planolites.*

Distributary Mouth bar Facies Association: Directly overlying the lagoon/prodelta succession is the distal bar lithofacies comprising interbedded thick to thin, dark brown, sharp-based, clayey, very fine grained bioturbated sandstone (Sb) and sandy heterolith (SMb). These facies occur at interval 2450 -2490m in T-5, interval 3100 -3140m in Well T-6, interval 3000 -3090m in Well T-10, and interval 3020 -3080m in Well T-13 (Tables 4.1-4.4). The transition is marked by a sudden increase in sediment influx of coarser clastics and remarkable decrease in the amount of clays and silty clays. This is indicative of an increase in sedimentation rates (Buatois, 2005). The sandy heteroliths contain relict wave-ripple-/sub horizontal lamination, starved current ripples, scour and fill occasional organic lenses and graded units. The sediments are associated with *Ophiomorpha*, *Thalassinoides, Teichichnus*, and occasional siderite nodules

Upward the sediments become less clayey (about 10-20%clay), better sorted and composed of bioturbated, carbonaceous, lens-bedded muddy heterolith (Mst), light brown, strongly bioturbated sandstone (Sb) and very fine-grained laminated sandstone (Sl). These are still arranged in a general coarsening upward motif. Based on these sedimentary characteristics and stratigraphic relationship with the underlying prodelta facies assemblage, the interval is interpreted as distributary mouth bar (delta front) deposit.

The depositional interpretations are summarized in Tables 4.6-4.9.

Sequence Architectural Elements

Sequence stratigraphic analysis reveals that the Tortonian succession of this study contains three depositional sequences, A, B, and C. The sequences are defined by three 3rd-order sequence boundaries (dating 10.5Ma, 8.5Ma, and 6.7Ma) related to relative sea level fall (Bhattacharya, 1993), and two intervening maximum flooding surfaces dated 9.5 Ma, and 7.4 Ma respectively (Figs. 4.5-4.7; Table 4.10). The sedimentary characteristics and lateral distribution of the sequences and the architectural elements are highlighted below.

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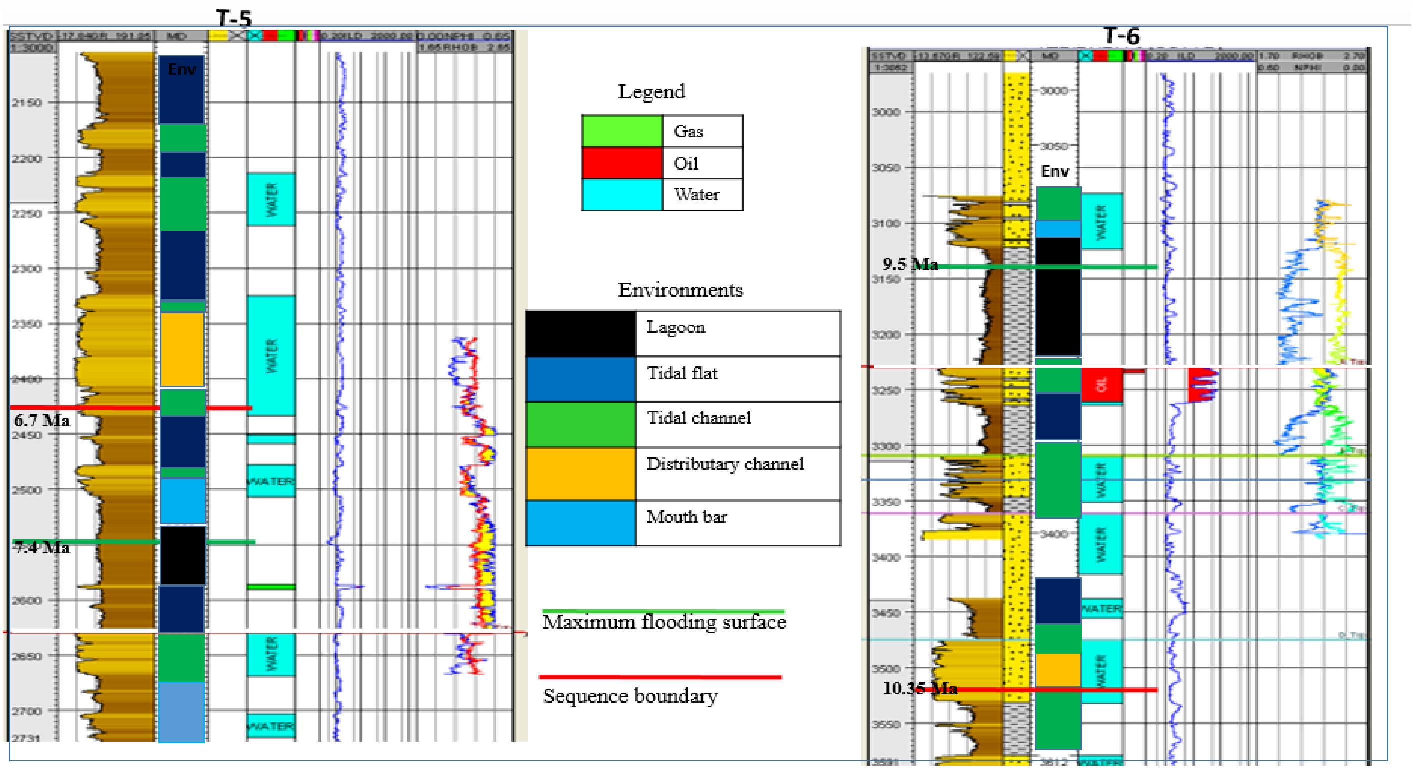

Fig .4.5. Core-derived lithostratigraphic profiles and wireline logs of the successions penetrated by the wells T-5.& T-6 showing the depositional environments, key surfaces and hydrocarbon-bearing intervals.

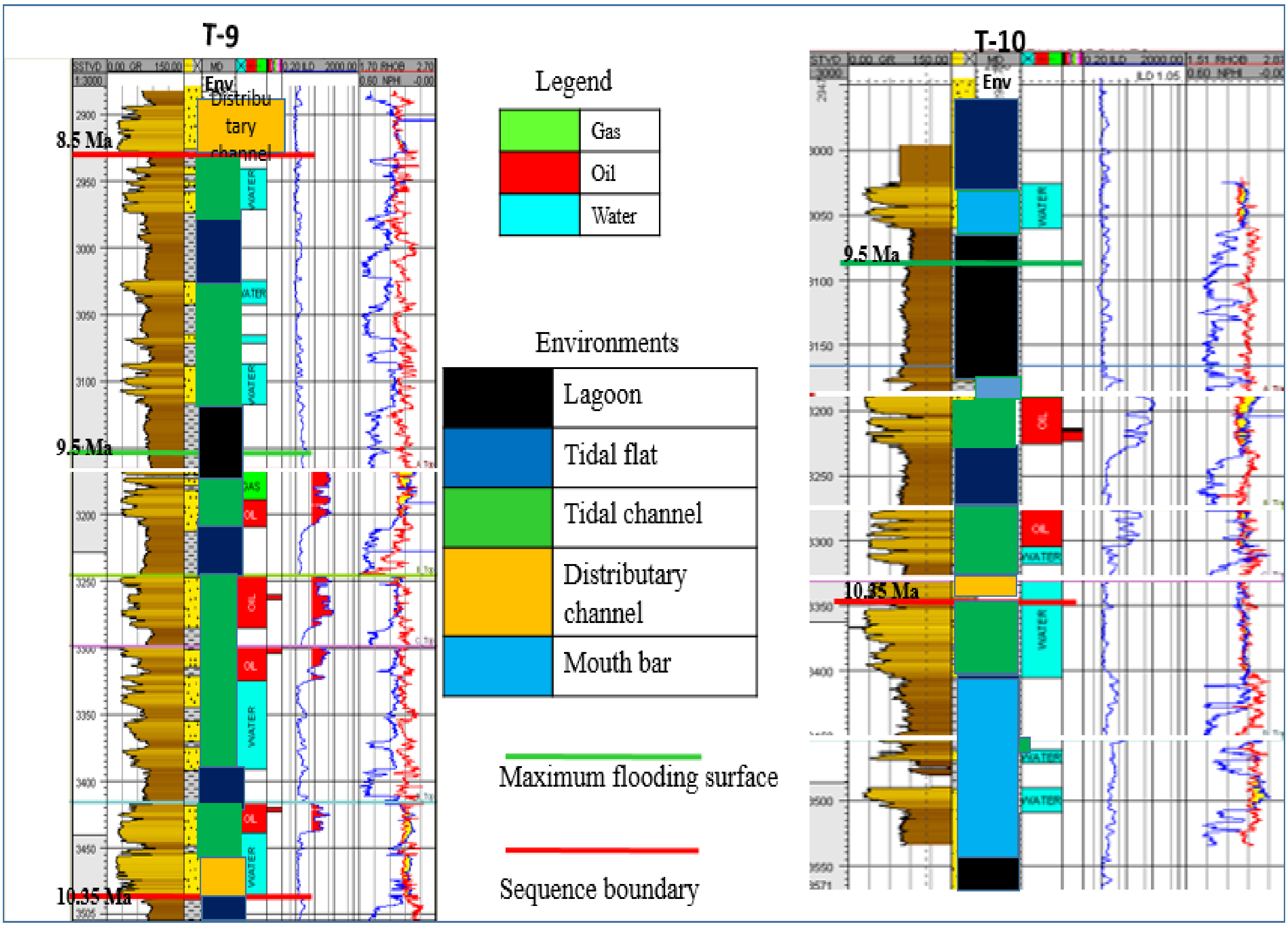

Fig .4.6. Core-derived lithostratigraphic profiles and wireline logs of the successions penetrated by the wells T-9.& T-10 showing the depositional environments, key surfaces and hydrocarbon-bearing intervals.

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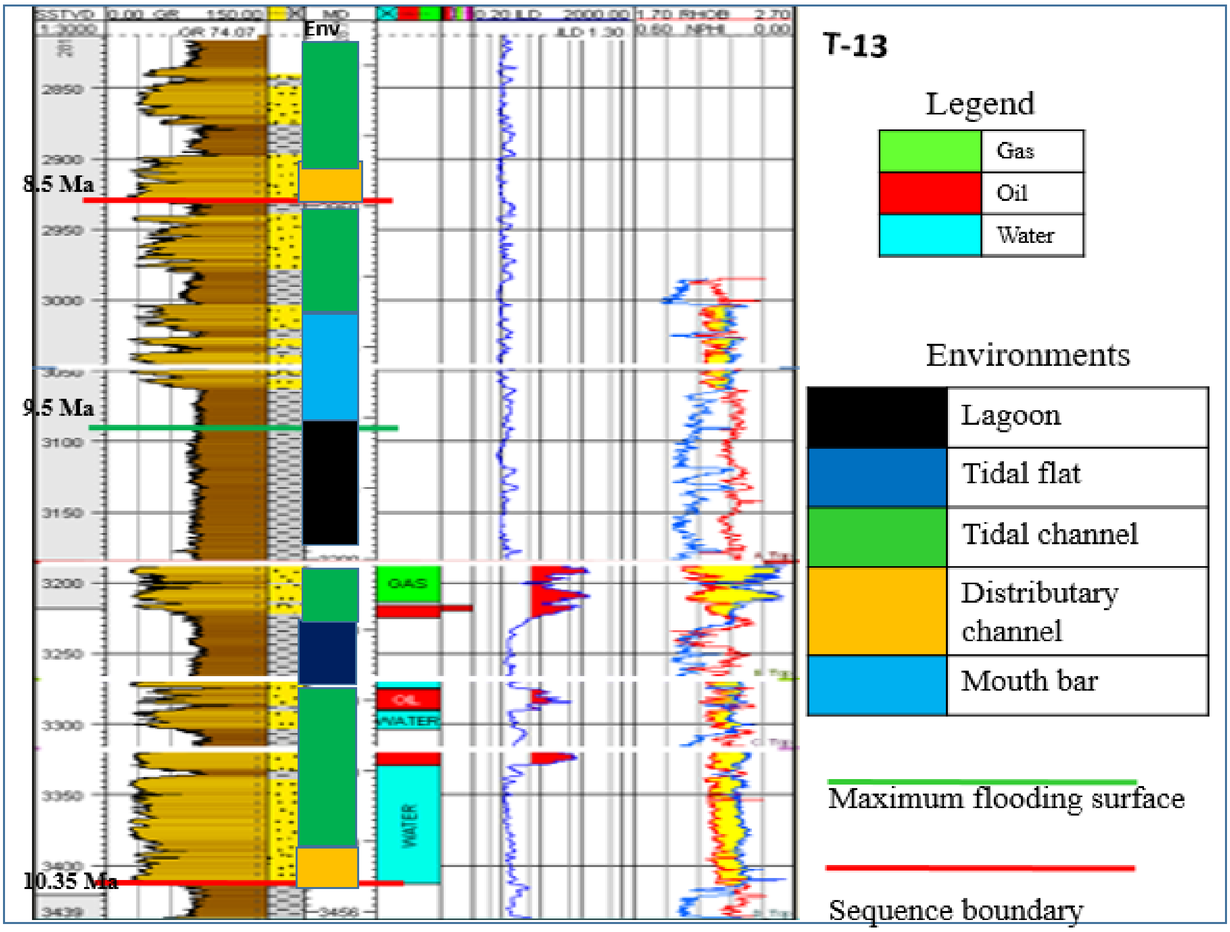

Fig. 4.7. Core-derived lithostratigraphic profiles and wireline logs of the successions penetrated by the well T-13 showing the depositional environments, key surfaces and hydrocarbon-bearing intervals.

Table 4.10. Summary of the key sequence stratigraphic surfaces identified in the study area.

P-Z	Sequences	Surfaces	Ages	T-6	T-10	T-13	T-9	T-5
830	C	Mxfs -3	7.4Ma	2561m	2460			2522
820		Sb-3	8.5			2950	2990	2653
	B	Mxfs 2	9.5	3153.5	3153.5	3150	3170	NOT PENETRATED
		Sb-2	10.35	3550	3325	3430	3510	
780	A	Mxfs-1	10.4	4182	Not penetrated			

Sequence A: (10.5my- 10.35my) Sequence-A was penetrated in Wells T-6, T-9 and T-10, (Fig. 4.8; Table 4.10.). In Well T-10 sequence-A begins with some 100m of subtidal channel sands and inter-tidal flat mud rocks belonging to the transgressive systems tract, (TST) (Fig. 4.6). The basal distributary channel facies that mark the sequence boundary was not penetrated. Facies of the transgressive systems tract is terminated by the 10.4my maximum flooding surface at a depth of about 3450m.

The succeeding HST facies consist of stacked, coarsening-upward and shallowing upward delta front/shoreface parasequences. In Wells T-9 and T-6 only the uppermost part of the highstand systems tract was encountered (Fig. 4.8). Thickness of HST facies varies from only 20 meters in Well T-9, to about 60m in Wells-T-6 and T-10 (Table 4.11).

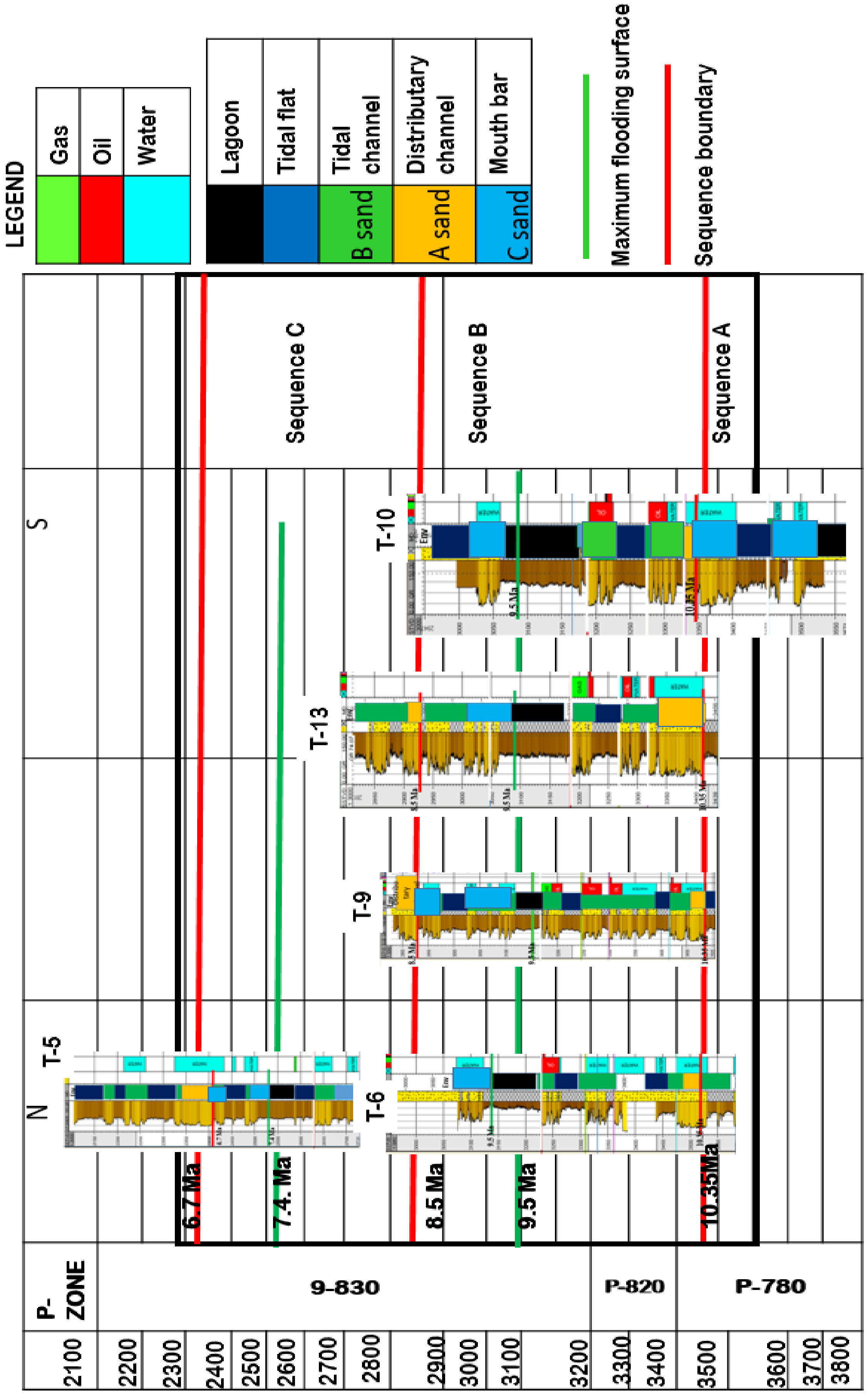

Fig. 4.8. Down-dip correlation panel for wells T-5, T-6, T-9, T-13 and T-10

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Table 4.11. Thicknesses of the systems tracts in the Tortonian sequences of the Niger Delta

Sequences	Systems Tract	Thickness (m)				
		T-5	T-10	T-9	T-6	T-13
C	HST	180	==	==	==	
	TST	150	==	45		
B	HST	67	105	208	90	
	TST	==	275	352	360	
A	HST	==	60	20	62	
	TST	==	100	==	==	

Sequence-A terminates at the 10.35Ma sequence boundary where tidally influenced fluvial-channel sandstone (B- sands) is juxtaposed over the tidal flat facies.

Sequence-B (SB)

In Wells T-6, T-9 and T-10, where **Sequence-B** is completely penetrated, the sequence begins with laterally correlative B sands that sharply overlie muddy inter-distributary bay facies (Fig. 4.8). These sand bodies are generally medium-coarse grained and exhibit blocky to fining-upward grain size trend on gamma-ray log. Results of facies analysis indicate that the sand accumulated in tidally influenced fluvial-channel within the delta plain depositional environment. The thickness varies from 275 meters in Well T-10, to a maximum of about 360m in Wells-T-6 (Table 4.11). The stratigraphic relationship with the underlying muddy coastal plain facies, regional extent and the depositional environment of this sand body is consistent with a drop in sea level.

Subsequent transgression led to establishment of an estuarine condition under which the overlying transgressive facies accumulated. A regional condensed shale marker that defines the 9.5.4My maximum flooding surface caps these transgressive /estuarine parasequences.

The mouth bar sands that overlie the 9.5Ma maximum flooding surface (Mxfs-2) consist of several coarsening upward parasequences arranged in a general aggradational to progradational stacking pattern. Based on the parasequence architecture, the sands are interpreted as delta front/shoreface facies belonging to the highstand systems tract (HST) of sequence-B.

Sequence-C

The third depositional sequence was only drilled in Well T-5. In this well sequence-C begins with a transgressive systems tract (TST) comprising the distributary channel sands (Figs. 4.5 and 4.8). The sand body makes an abrupt, erosional contact with the coastal plain HST sand facies of sequence-B. Biofacies indications suggest that sedimentation occurred in inner neritic water depths. The facies comprise upward-deepening, coarse-fine grained sandstone that displays an upward increase in proportion of interstratified mudstone. The shale lithofacies acts as seal to the sandstone reservoirs. The sand continues upward into an interval of interlayered grey shale lithofacies and very thin, fine-grained calcareous sandstone and siltstone characterized by irregular, serrated gamma ray log response. The estimated thickness of the Sequence-C transgressive facies penetrated in T-5 well is in the order of 150m (Table 4.11).

DISCUSSION

Conceptual Depositional Model

The deltaic succession penetrated in the Jeth oilfields represents three 3rd-order (Vail *et al.,* 1991) sedimentary cycles (Fig. 4.8). The cycles generally begin on a Type-1 sequence boundary, and contain a three-part vertical succession of facies consistent with the estuarine model of Leckie and Singh (1991). From base upward, the facies succession includes:

(i) a basal, coarse grained pebbly fluvial sandstone that accumulated directly over an erosional sequence boundary. This unit progressively grades upward into tidally influenced facies.

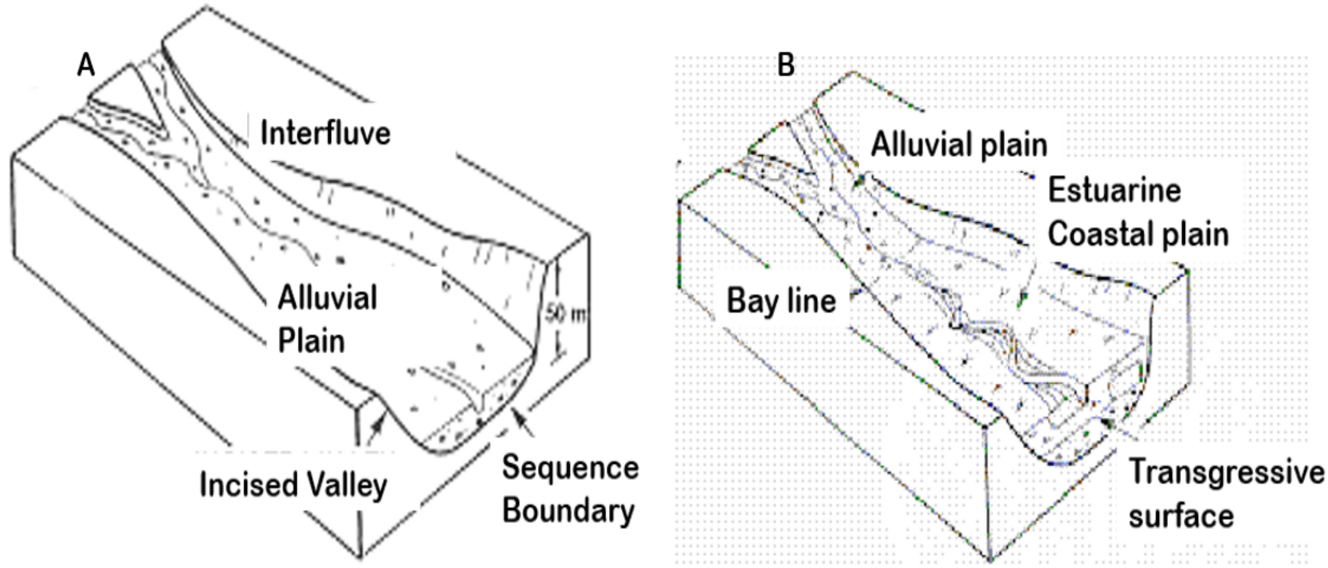
(ii) a central marine mudstone that contains symmetrical sandstone ripples, and

(iii) upper unit of wave-ripple laminated/or channelized facies that accumulated in shoreface-foreshore environment.

According to Leckie and Singh (1991), the basal unit represents the initial filling of a channel cut onto the shelf. The second unit accumulated in the central part (shallow shelf environment) of the estuary, while the upper wave-ripple laminated/or channelized shoreface-foreshore facies represents the progradational filling of the bay-head of the estuary.

Development of each of the estuarine cycles in the Jeth Oilfield can be explained as highlighted below (Fig. 4.9), in line with the model of Leckie and Singh (1991).

Stage-1: Valley incision and marine transgression: A relative sea level fall amplified by basin subsidence amplified by basin subsidence, at 10.35Ma, 8.5Ma, and 6.7Ma respectively, led to valley incision. Subsequently, coarse fluvial distributary channel sediments bypassed the incised valley and accumulated at the lowstand shoreline located at the continental shelf (Fig. 4.9 (a)). The presence of tidal channel facies above the distributary channel deposit suggests that the valley was rapidly flooded by marine waters and that the rate of increase in accommodation space was greater than the fluvial clastic influx. Consequently, these tidal facies onlap on the lowstand fluvial profile as the valley transformed from a fluvial valley into an estuary (Leckie and Singh, 1991).



Stage I: Valley incision and marine transgression

A: Lowstand: Coarse fluvial sediments bypassed the incised valley on route to the lowstand shoreline at the continental shelf

B: Initiation of marine transgression: incised valley was transgressed and became an estuary, with estuarine coastal plain deposits onlapping on to the alluvial plain as the bay line migrated up the valley.

Fig. 4.9 (a). Depositional model for the Jeth oil field (After Leckie and Singh, 1991).

Stage-2: Maximum marine flooding: As the valley became flooded to its maximum point at 9.5Ma, and 7.4Ma respectively, the estuary-mouth sands migrated up the estuary in the form of tidal inlet and flood-tidal delta complex (Fig. 4.9(b)). The base of the tidal inlet eroded deeply into the underlying tidal-estuarine sands and muds and formed a tidal ravinement surface. As explained by Leckie and Singh (1991), the valley flooded, and the adjacent open coast retreated landward because of drowning and wave-induced erosional shoreface retreat, forming a wave-ravinement surface.

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Stage II. Maximum marine flooding:

Estuary mouth sands in the form of the tidal inlet and flood-tidal delta complex migrate up the estuary

Stage III. Bay head filling:

Still-stand of relative sea level and progradation of a regressive tidal-estuarine bay head delta into the upper estuarine, gradually filling it with sediment.

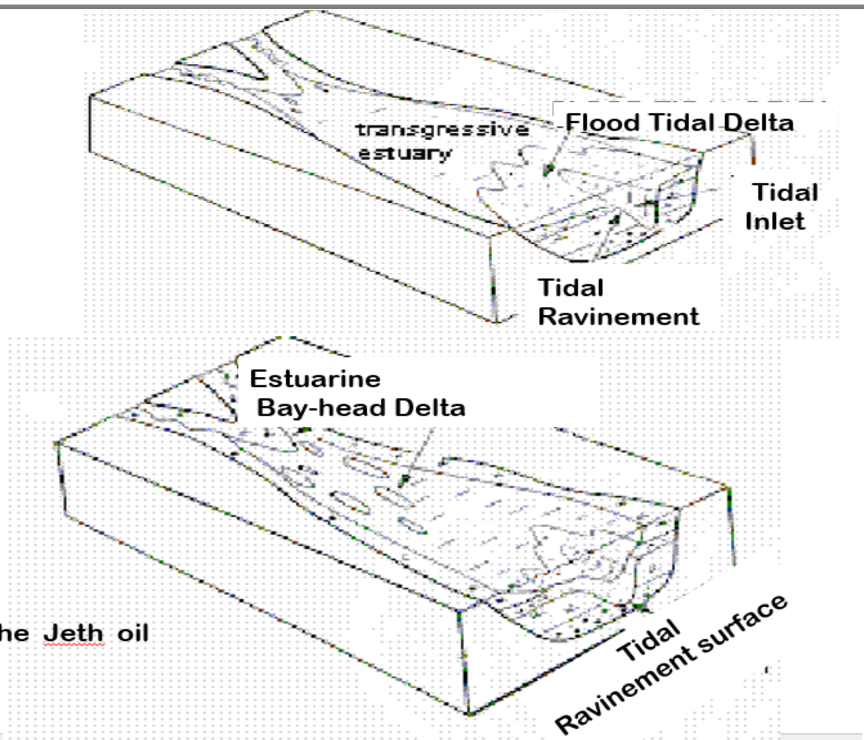

Fig. 4.9 (b). Depositional model for the Jeth oil field (After Leckie and Singh, 1991).

Stage-3: Bay-head filling: During this stage, infilling of the estuary started with fluvially scoured tidal-estuarine sand and mud, and a regressive bay-head prograded into the upper estuary, gradually filling it with sediment (Fig. 4.9(b)). These deposits prograded over the transgressive tidal estuarine sands and muds in the upper and middle estuary, and the estuary-mouth sands in the lower estuary. Another episode of basin subsidence and relative sea-level fall abruptly terminated the cycle at the next sequence boundary (Leckie and Singh (1991).

Sand Development

The Tortonian succession is important because it holds the bulk of the hydrocarbon reservoirs in the Jeth oilfield. Stratigraphic correlation (Fig.4.8) reveals the presence of several discrete, elongate and parallel HC-bearing sand bodies that are both stratigraphically and structurally isolated from one another. Effective separation is provided by intervening shale units and by growth faulting. The distribution and internal architecture of the sandy units reflect the complex interplay between depositional style, and sea level change. Throughout the Tortonian interval in the study area, reservoirs are developed within incised valleys. In the more proximal areas (e.g. Well-5), HC-bearing reservoirs are generally not well developed within the interval. Southward, the reservoirs occur as compartmentalized sands within the transgressive systems tract (Fig. 4.8). These sandy units grade laterally into more mud-dominated facies that possibly reflect basinward decline in clastic influx. Based on the stacking patterns, and gross sedimentological characteristic, these facies are recognized as sub-tidal channel sand deposits.

As the delta prograded southward the palaeoecology changed from coastal plain in the more northerly areas to shelf in the more southerly areas. Associated with this is a change in regional slope gradient that affected grain size and depositional environments of sediments. Accordingly, properties changed within reservoir units. In Well-9 (Fig. 4.8) for example, both associated and non-associated gas reservoirs occur directly above outer neritic mudstone, mainly within the incised valley that constitute the transgressive systems tracts.

The development of the distributary channel facies in the distal areas reflects the progressive southward shift of the Tortonian depocenter as the delta prograded basin-ward. The sands in the down-dip wells are thicker and possibly reflect the influence or growth faulting and associated increase in accommodation on the down-thrown block.

The distributary channel facies are essentially multi-storey, laterally less continuous, coarse-grained channelized sandstones that grade upwards into lower energy subtidal sands and intertidal mud rocks. They are separated by intervals of shallow marine mud rocks. These channel facies are vertically stratified as cyclic alternation of subtidal and intertidal facies preserved as shallowing-upward parasequences in which more sandy subtidal facies are gradationally overlain by more muddy intertidal facies.

Implications for Production

This study has provided new information on depositional environments and reservoir architecture in the Tortonian succession of the Niger Delta that can contribute to the geologic component of 3D-modelling of reservoirs within the study area. Down-dip the reservoirs (e.g. those penetrated by Wells T-10, T-9 and T-6), comprising discrete/amalgamated, proximal fluviatile-distal marine sand bodies encased in marine shales, are genetically related, but much older than the reservoirs up-dip (e.g. in T-5). Table 4.12 shows that these reservoirs contained within the productive 10.35Ma-9.5Ma transgressive estuarine valley fill of sequence B (Fig. 4.8)) have good porosity (18%-28%), good permeability (800-1700md) and net-to-gross ranging from 0.30-0.90.

These parameters progressively decrease down-dip, from the distributary channel reservoirs (A Sands) upwards to the distributary mouth bar reservoirs (C Sands; Fig. 4.8). Kv/kh ratios in these reservoirs are as high as 0.8. Thin shale baffles characteristic of tidal sands could constitute barriers to fluid flow, but interconnectivity (**kv/kh**) is likely to be improved by vertical burrows (e.g. *Ophiomorpha*) which are commonly associated with tidal environments. However, pressure decline commonly associated with reservoir heterogeneity in tidal settings (Obi and Ebong, 2003) should be expected in the oilfield.

Table 4.12. Petrophysical parameters for the productive reservoir sands within sequence B

Wells	Well T-6			Well T-9			Well T-10			Well T-13		
Sand	Por	Perm	NTG	Por	Perm	NTG	Por	Perm	NTG	Por	Perm	NTG
C	0.25	1200	0.57	0.19	1085	0.30	0.18	940	0.57	0.18	803	0.30
B	0.25	1340	0.68	0.26	1099	0.50	0.21	1050	0.65	0.20	960	0.30
B	0.26	1715	0.72	0.26	1099	0.89	0.23	1060	0.80	0.22	1028	0.50
A	0.28	1715	0..91	0.28	1403	0.89	0.28	1360	0.85	0.26	1715	0.81
Por = Porosity; Perm = permeability; NTG= Net-to-gross												
Sand A= Distributary channel sand; Sand B = Subtidal sands; Sand C= distributary mouth bar sands												

CONCLUSIONS

This report presents a lithostratigraphic and sequence stratigraphic perspectives of the Tortonian succession in the Jeth oilfield of the Niger delta. Sixty (60%) percent of the lithofacies are reservoir sand while the non-reservoir lithofacies make up about 40% of the succession. The lithofacies are grouped into five facies associations that are interpreted to have accumulated in either (i) distributary channel, (ii) tidal channel, (iii) tidal flat (iv) prodelta/lagoon or (v) distributary mouth bar environments.

The lithofacies belong to three 3rd order depositional sequences characterized by two sequence architectural elements namely, a basal transgressive systems tract represented by fluvio-estuarine deposits, and an overlying highstand systems tract represented by wave-tide dominated distributary mouth bar deposits.

The productive intervals are mainly the subtidal sand of the 10.35Ma - 9.5Ma transgressive systems tract. This interval which contains high quality reservoir sands that hold the bulk of the total original oil in place in the field should be the production target.

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