

Sequence stratigraphy and depositional environments of Middle-Late Miocene sediments in the eastern part of the Coastal Swamp depobelt, Niger Delta Basin, Nigeria

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Abstract Detailed studies on depositional sequence, genetic facies, and depositional environment were done using sequence stratigraphic tool in the paralic sequence of Middle to Late Miocene age in the Coastal Swamp depobelt of the Niger Delta Basin. This was aimed at increasing the resolution for prediction of reservoir, seal, and source rocks in the eastern part of the basin. Integration of well logs and biofacies data with paleobathymetric control allowed regional correlation of major transgressive-regressive events between wells, resulting in the generation of a sequence stratigraphic framework and environment of deposition (EOD). Dominant genetic facies include the following: marine shale, lower shoreface, upper shoreface, channel sands, and channel heterolithics. Three major stacking patterns were delineated and interpreted as Lowstand Systems Tract (LST), Highstand Systems Tract (HST), and Transgressive Systems Tract (TST). Correlation reveals ten major stratigraphic bounding surfaces of various ages (five sequence boundaries and five maximum flooding surfaces) and four depositional sequences. Stratigraphic flattening of events at various ages indicates a shift of the depositional center from north to south, aligning with the progradational pattern of deposition of the Niger Delta. The stratal package also thickens towards the south (basinwards). Generated paleobathymetric maps show generally that sediments were deposited within neritic through bathyal environments at different times. The EOD spans through incised canyons, channels, inner- mid shelf, shelf margin, and slope margin. A combination of the reservoir sands of the LST and HST and the shale units of the TST offers good stratigraphic traps for hydrocarbons and hence should be targeted during exploration.

Keywords Sequence stratigraphy · Systems tract · Genetic facies · Environment of deposition (EOD)

Introduction

The Middle to Late Miocene strata of the Niger Delta Basin are among the most challenging targets for stratigraphic and environment of deposition (EOD) interpretation because of the tectono-sedimentological factors inherent in their evolution and deposition. Successful exploration and production strategies are becoming increasingly dependent on the proper application of the concepts of sequence stratigraphy and depositional environment. Recent developments in sequence stratigraphy (Van Wagoner et al. 1990; Posamentier and Allen 1999; Catuneanu 2002; Kendall 2008) offer a more definitive approach to stratigraphic interpretation of these strata. Sequence stratigraphic studies by Stacher (1995) and Reijers et al. (1997) revealed the combined influence of eustatic cyclicity and local tectonics on the Tertiary stratigraphic succession of the Niger Delta. Ozumba (1999) developed a sequence stratigraphic framework for the western Niger Delta, using foraminifera and wireline log data obtained from four wells drilled in the Coastal and Central Swamp depobelts. Magbegbeola and Willis (2007) studied the Robertkiri field in the proximal side of the Coastal Swamp depobelt and divided the upper 2,700 m of the Agbada Formation into six, fourth-order depositional sequences. These sequences were formed during episodic progradation and retrogradation of the delta shoreline.

The Niger Delta evolved as distinct subbasins (depobelts) which succeeded each other in time and space. Sequence stratigraphic study of the basin is therefore best approached on the basis of depobelts. The objective of the present study is to establish a sequence stratigraphic framework for correlation

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and prediction of reservoir, seal, and source rocks in the eastern part of the Coastal Swamp depobelt (Fig. 1).

Geologic setting

The study area is located in the eastern part of the Coastal Swamp depobelt of the Niger Delta basin (Fig. 1). The Tertiary Niger Delta covers an area of about 75,000 km² and is composed of an overall regressive clastic sequence which reaches a maximum thickness of 9,000 to 12,000 m (Weber and Daukoru 1975; Evamy et al. 1978) at the center of the basin. The evolution of the Niger Delta, which lies in the continental margin along the West Coast of equatorial Africa, is controlled by pre- and synsedimentary tectonics as described by Allen (1965), Evamy et al. (1978) and Knox and Omatsola (1989). The tectonic framework is controlled by Cretaceous fracture zones expressed as trenches and ridges in the deep Atlantic (Lehner and De Ruiter 1977). The subsurface Niger Delta stratigraphic succession comprises of three lithostratigraphic units (Akata, Agbada, and Benin formations) which are strongly diachronous (Short and Stauble 1967; Frankl and Cordry 1967; Avbovbo 1978). These units are thick, complex sedimentary units deposited rapidly during high-frequency, fluvio-deltaic-eustatic sea level oscillations. The Akata Formation which occurs at the base of succession is of marine origin and is composed of thick shale sequences, turbidite sand, and minor amounts of clay and silt. The shales are characteristically under-compacted and overpressured. Beginning in the Paleocene and through the Recent, the Akata Formation formed during lowstands when terrestrial organic matter and clays were transported to deep water areas characterized by low energy conditions and oxygen deficiency

(Stacher 1995). The Akata Formation is estimated to be up to 7,000 m thick in the zone of maximum subsidence overlying the transition zone between oceanic and continental crust below the delta (Doust and Omatsola 1990; Nwajide 2013). The overlying Agbada Formation (Eocene–Recent) is a paralic sequence characterized by interbedded sandstone and shale units and was deposited in a number of delta-front, delta-topset, and fluvio-deltaic environments (Reijers 1996). Shale and sandstone beds were deposited in equal proportions in the lower Agbada Formation; however, the upper portion is mostly sand with only minor shale interbeds (Tuttle et al. 1999). The Agbada Formation is the hydrocarbon-prospective sequence in the Niger Delta. It is widely variable in thickness across the delta with estimates ranging from 3,700 to 4,500 m (Merki 1972; Weber and Daukoru 1975; Tuttle et al. 1999; Nwajide 2013). The Benin Formation (Eocene–Recent) is the topmost lithostratigraphic unit and consist of continental sands and sandstones (>90 %) with few shale intercalations; it is up to 2,000 m in thickness (Avbovbo 1978). The stratigraphic column showing the three formations of the Niger Delta is shown in Fig. 2.

The Niger Delta clastic wedge comprises a series of discrete depocenters or depobelts which were the main belts of deposition that succeeded each other progressively as the delta shifted its loci downdip through time. These depobelts which are 30–60 km wide prograde southwestward 250 km over the oceanic crust into the Gulf of Guinea (Stacher 1995) and are defined by synsedimentary faulting that occurred in response to variable rates of subsidence and sediment supply (Doust and Omatsola 1990). The depobelts are characterized as self-contained entities with respect to stratigraphy, structure building, and hydrocarbons distribution

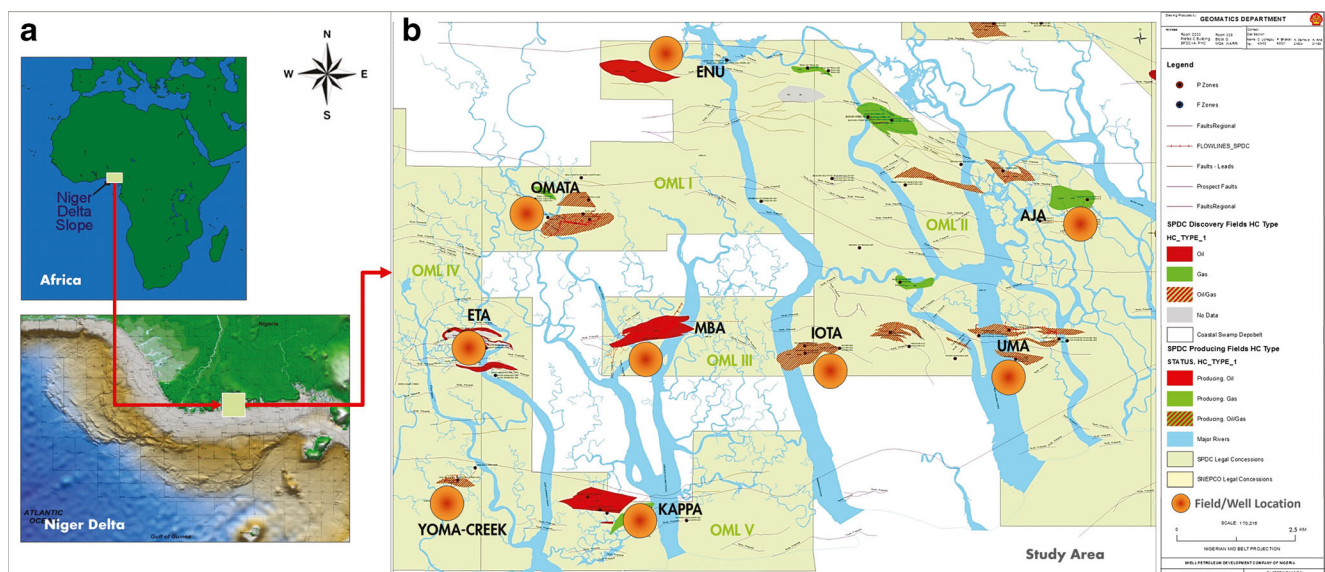
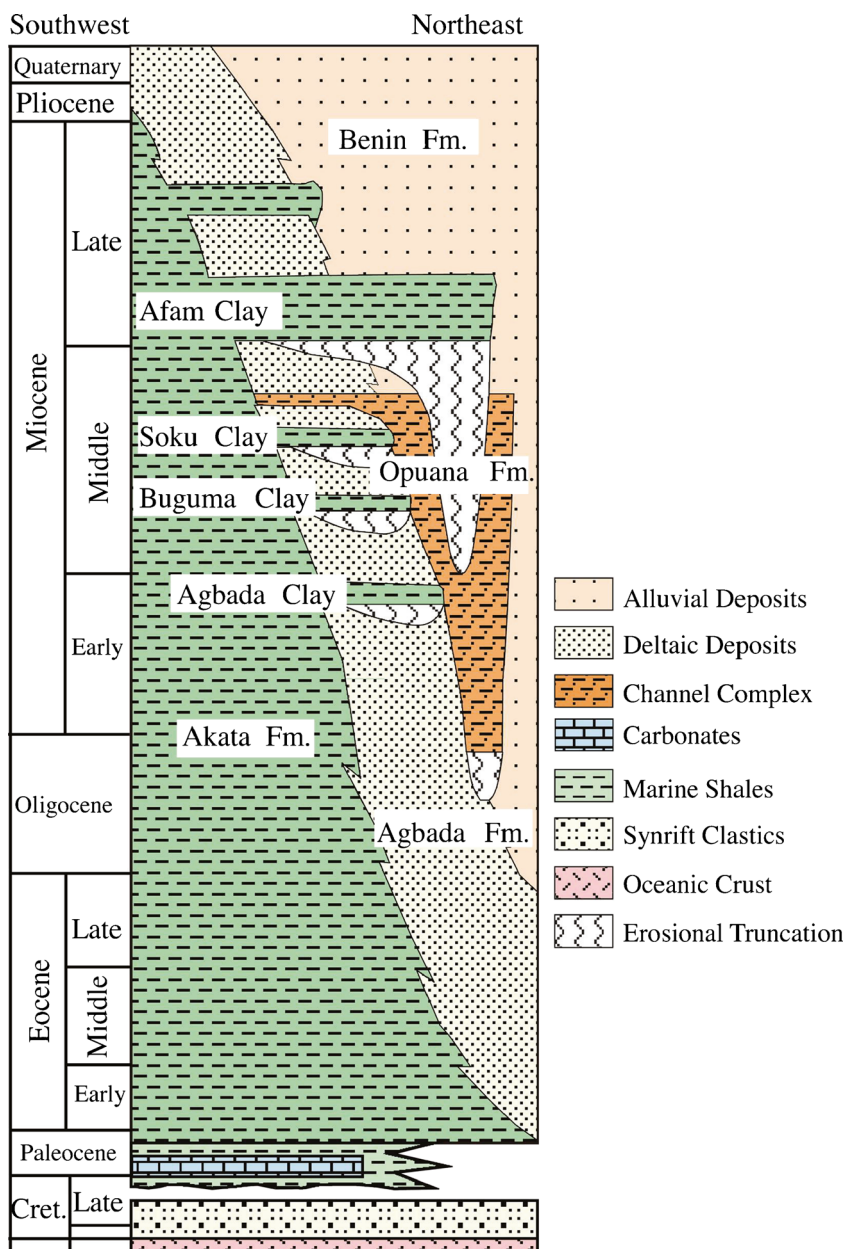


Fig. 1 Location map of the study area. **a** Location of the study area (*inset*) in Niger Delta along the west coast of Africa. **b** Map of the study area showing oil and gas concession (blocks/fields) in the Eastern Coastal Swamp depobelt of the Niger Delta

Fig. 2 Stratigraphic column showing the three formations of the Niger Delta (After, Lawrence et al. 2002)



(Evamy et al. 1978; Tuttle et al. 1999; Nwajide 2013). The depobelts from the oldest to the youngest include Northern Delta, Greater Ughelli, Central Swamp, Coastal Swamp, and Offshore depobelts. The Northern Delta, and Greater Ughelli depobelts which are characterized by moderate subsidence rates (not greater than 700 m/My), formed before mid-Miocene and are situated over seaward dipping basement. The younger depobelts—Central Swamp, Coastal Swamp, and Offshore depobelts formed after the Middle Miocene, are situated over the landward dipping oceanic lithosphere. They are characterized by relatively high subsidence rates ranging from 1,200 to 2,000 m/My (Nwajide 2013).

Methodology

The study area spans across nine fields which are named in this study as Enu, Omata, Mba, Aja, Uma, Iota, Eta, Yoma, and Kappa (Fig. 1b). Conventional suites of well log data (Gamma Ray (GR), Neutron, Density, and Resistivity) from 24 wells were used for this study. Lithology (rock types such as sand, silt, or shale), system tracts, stratigraphic surfaces, and genetic facies (belonging to distinct depositional environments) were defined using Petrel software tool. This tool used interactive-based syntaxes containing wireline log values and stratigraphic data as key inputs in defining rock types and stratigraphic correlation. Also, ArcGIS and ArcMap 10 software tools were used in generating the base and

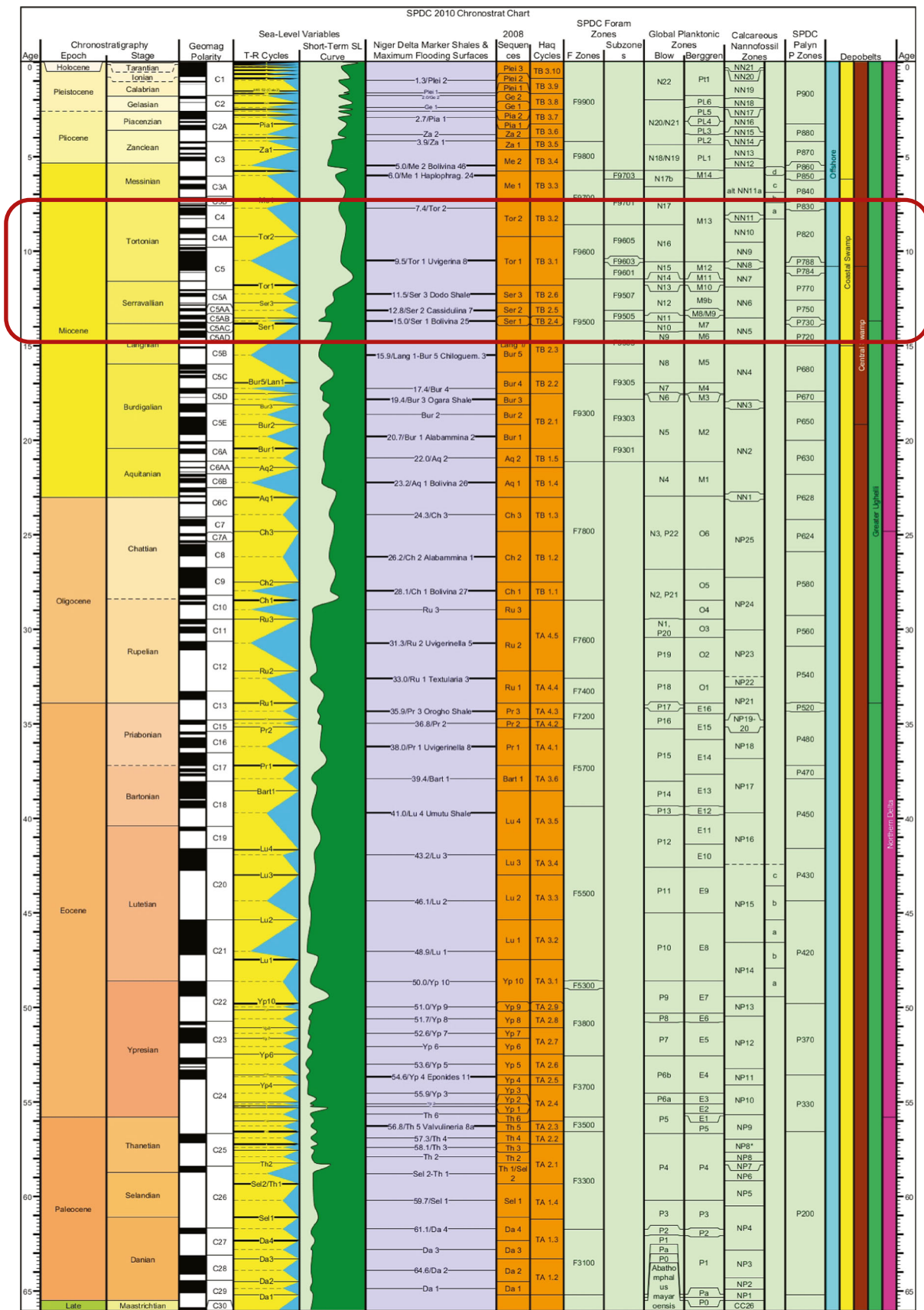
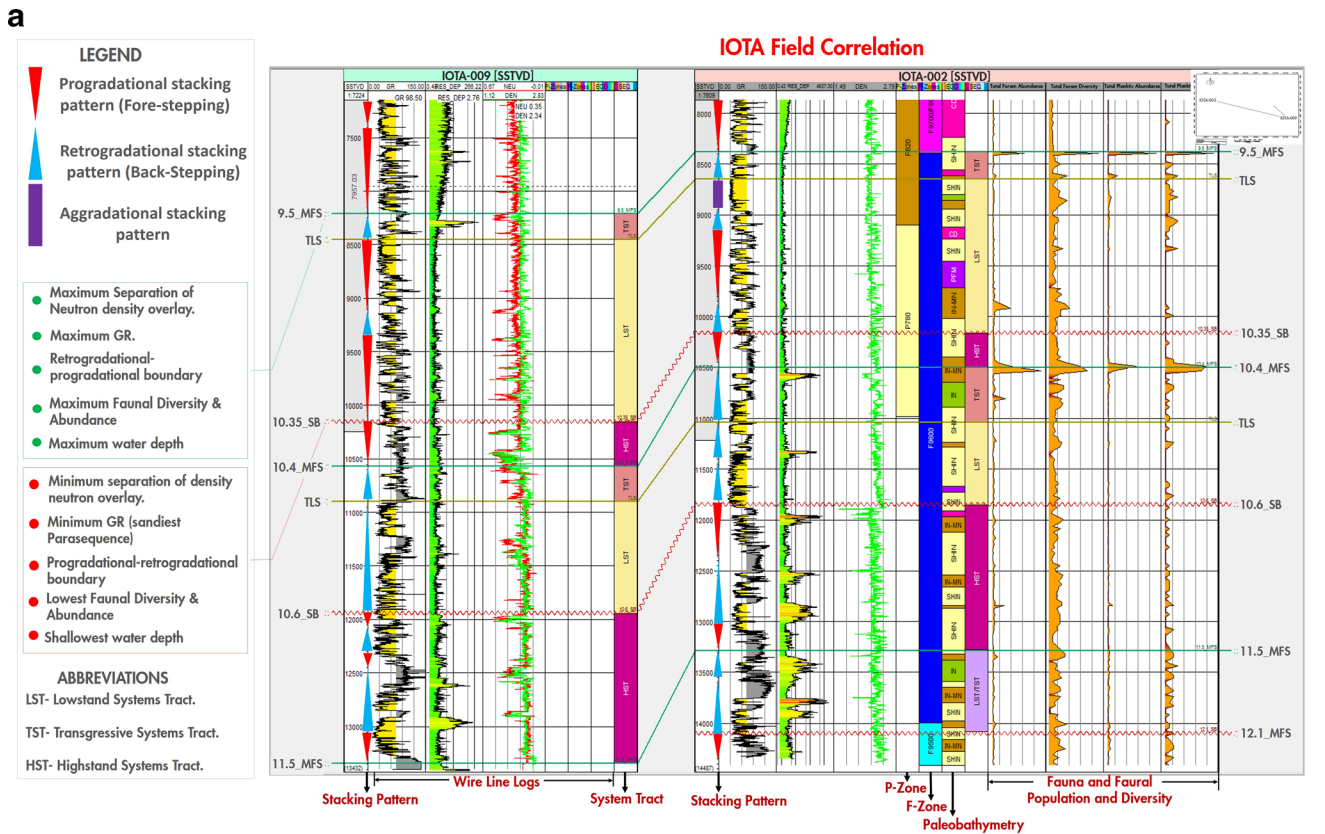


Fig. 3 Niger Delta chronostratigraphic chart showing the geologic interval of the study area (Source: Shell 2010)



APPLIED COLOUR CODIFICATION LEGEND

SYSTEMS TRACT			PALYNOLOGICAL ZONE (P-ZONE)			FORAMINIFERAL ZONE (F-ZONE)																																												
Code	Name	Color	Code	Name	Color	Code	Name	Color																																										
0	HST	[Pink]	0	P830	[Red]	23	P150	[Yellow]																																										
1	TST	[Purple]	1	P820	[Orange]	24	P130	[Blue]																																										
2	LST	[Green]	2	P780	[Cyan]	25	P560	[Magenta]																																										
3	LST/TST	[Purple]	3	P784	[Light Blue]	26	P110	[Light Green]																																										
<p>PALEOBATHMETRY</p> <table border="1"> <thead> <tr> <th>Code</th> <th>Name</th> <th>Color</th> </tr> </thead> <tbody> <tr><td>0</td><td>INDET</td><td>[Red]</td></tr> <tr><td>1</td><td>IN-MN</td><td>[Orange]</td></tr> <tr><td>2</td><td>SHIN</td><td>[Yellow]</td></tr> <tr><td>3</td><td>IN</td><td>[Light Green]</td></tr> <tr><td>4</td><td>MN-ON</td><td>[Cyan]</td></tr> <tr><td>5</td><td>MN</td><td>[Light Blue]</td></tr> <tr><td>6</td><td>CD</td><td>[Blue]</td></tr> <tr><td>7</td><td>PFM</td><td>[Magenta]</td></tr> <tr><td>8</td><td>ON-BA</td><td>[Purple]</td></tr> <tr><td>9</td><td>B</td><td>[Green]</td></tr> <tr><td>10</td><td>PF</td><td>[Light Green]</td></tr> </tbody> </table>			Code	Name	Color	0	INDET	[Red]	1	IN-MN	[Orange]	2	SHIN	[Yellow]	3	IN	[Light Green]	4	MN-ON	[Cyan]	5	MN	[Light Blue]	6	CD	[Blue]	7	PFM	[Magenta]	8	ON-BA	[Purple]	9	B	[Green]	10	PF	[Light Green]	4	P770	[Light Blue]	27	P540	[Light Green]	0	F9700/F9600	[Magenta]	20	F5300	[Cyan]
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10	PF	[Light Green]																																																
5	P820-P830	[Light Blue]	28	P520	[Light Green]	1	F9600	[Blue]	21	F5500	[Green]																																							
6	P740	[Light Green]	29	P480	[Light Blue]	2	F9500	[Cyan]	22	F5750	[Yellow]																																							
7	P850-P870	[Light Blue]	30	P470	[Light Green]	3	Non-Diagnostic	[Purple]	23	F5700	[Orange]																																							
8	P820-P840	[Light Blue]	31	P400	[Light Green]	4	No Data	[White]	24	F7400	[White]																																							
9	Non-Diagnostic	[Purple]	32	P370	[Light Blue]	5	F9500/F9600	[Yellow]	25	F7200	[Blue]																																							
10	No Data	[White]	33	P630/680	[Light Green]	6	F9605	[Magenta]	26	F9600/F9700	[Cyan]																																							
11	P700	[Light Green]	34	P580	[Light Blue]	7	F9700	[Yellow]	27	F9300/F9500	[Light Green]																																							
12	P800	[Light Blue]	35	P720/P740	[Light Green]	8	Barren	[White]	28	F9300	[Yellow]																																							
13	P770-P780	[Light Blue]	36	P680	[Light Green]	9	F9601	[Cyan]	29	F7800/F9300	[Orange]																																							
14	P780/P820	[Light Blue]	37	P670	[Light Green]	10	F9605/F9603	[Light Green]	30	F7800	[Magenta]																																							
15	P840	[Light Green]	38	P650	[Light Blue]	11	F3500	[Light Green]	31	F3100/F1700	[Purple]																																							
16	P830/P840	[Light Green]	39	P630	[Light Green]	12	F1700	[Light Blue]	32	F9300/F7800	[Blue]																																							
17	P750	[Light Blue]	40	P620	[Light Green]	13	F1000	[Light Blue]																																										
18	P788	[Magenta]	41	P540/P580	[Light Green]	14	F3500/F3300	[Light Green]																																										
19	P200	[Blue]	42	P450	[Magenta]	15	F3100	[Light Green]																																										
20	P100	[Light Blue]	43	P330	[Yellow]	16	F1300	[Light Green]																																										
21	P190	[Light Green]	44	P170-P190	[Light Green]	17	F7800	[Light Green]																																										
22	P170	[Light Green]	45	P720	[Light Green]	18	F7600	[Magenta]																																										
						19	F3700	[Light Green]																																										

Fig. 4 a Well log sequence stratigraphic correlation panel across Iota wells showing the representative data/tools provided for the study. (abbreviations: Paleobathymetry: *INDET* = In-determinant; *B* = Barren; *CD* = Coastal Deltaic; *PFM* = Proximal Fluvial Marine; *SHIN* = Shallow Marine-to-Inner Neritic; *IN* = Inner Neritic; *IN-MN* = Inner Neritic-to-Middle Neritic; *MN* = Middle Neritic; *MN-ON* = Middle Neritic-to-Outer Neritic. System Tract: *LST* = Lowstand System Tract; *TST* = Transgressive System Tract; *HST* = Highstand System Tract. Stratigraphic Surface: *MFS* = Maximum Flooding Surface; *SB* = Sequence Boundary; *TLS/TSE* = Top of Lowstand/Transgressive Surface Erosion. Zonation Scheme: *P-*

Zone = Palynological Zone; *F-Zone* = Foraminiferal Zone. **b** Genetic facies in some selected wells across the study area. (The lithologic (sand, silt, and mudrocks) profiles are derived from gamma ray log values and signatures). Bell-shaped log patterns on gamma ray logs indicating fining upward trends or an upward increase in gamma ray value is a typical feature of fluvial channel deposits. Funnel-shaped log patterns indicating coarsening upward trend, clearly showed deltaic progradation. Cylindrical (blocky or boxcar) log motif are on thick uniformly graded coarse grained sandstone unit, probably deposits of braided channel, tidal channel deposits (Emery and Myers 1996 for details))

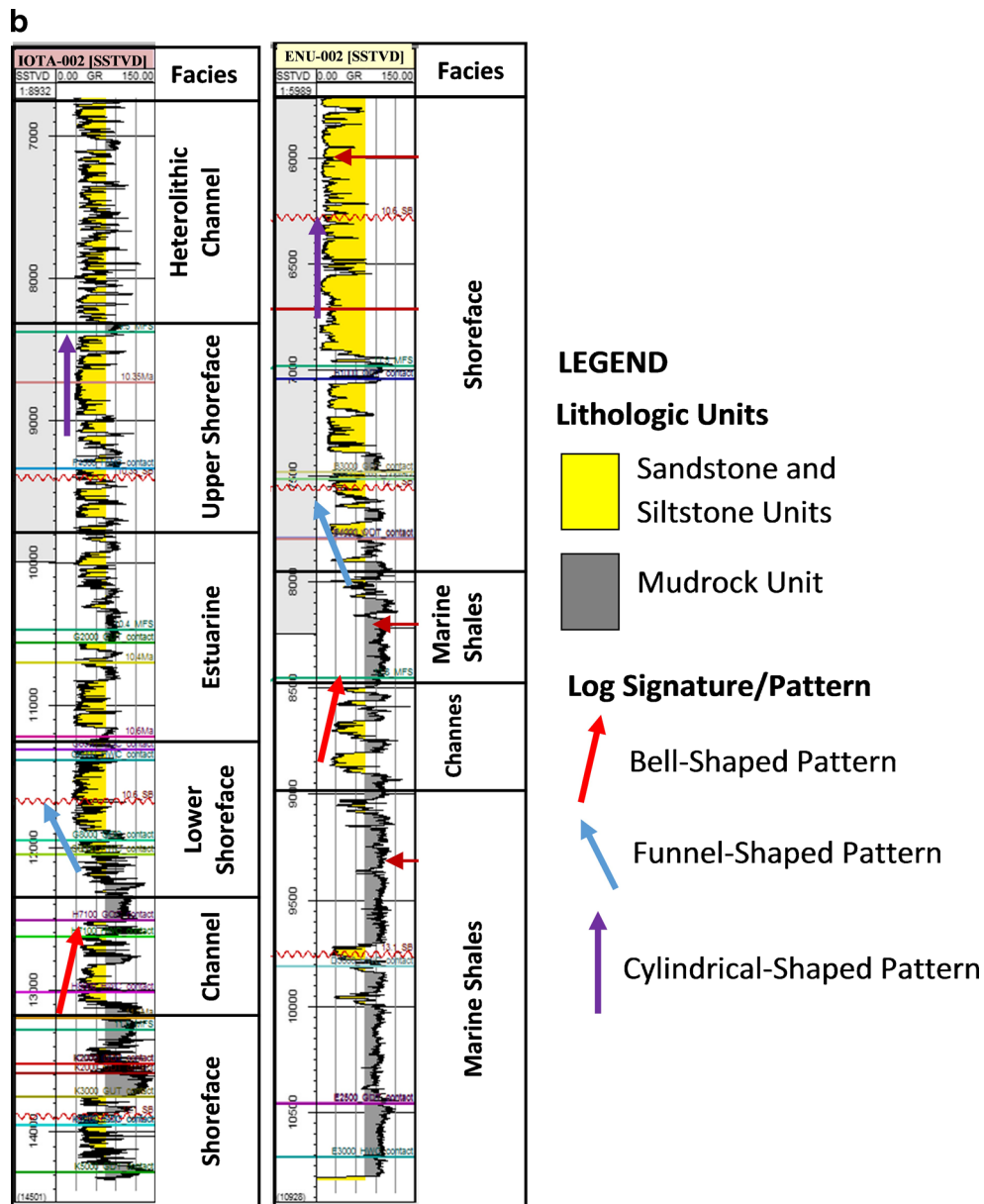


Fig. 4 (continued)

paleobathymetric maps in this study. Biostratigraphic data comprising of interpreted Palynological (P) zone, Foraminifera (F) zone, and paleobathymetric data were calibrated and depth matched with corresponding wireline logs using the Niger Delta chronostratigraphic chart (Fig. 3). The population and diversity of the benthic and planktonic foraminifera were used for stratigraphic surfaces (maximum flooding surfaces (MFSs) and sequence boundaries (SBs)) interpretation. The delineated surfaces (MFSs and SBs) were dated with markers in P and F zones. The well logs were then displayed at consistent scales to enhance log motifs/trends and also to aid recognition of genetic facies, stratal stacking patterns (progradation, retrogradation, and aggradation), and sequences (Emery and Myers 1996; Kendall 2003) (Fig. 4a).

The stacking patterns encountered gave insight to systems tract (Lowstand Systems Tracts (LST), Transgressive Systems Tract (TST), and Highstand System Tracts (HST)) interpretation (Van Wagoner et al. 1990).

Results and interpretations

Genetic facies Six main genetic facies were identified: marine shale, lower shoreface, upper shoreface, tidal channel, channel, and channel heterolithics (Fig. 4b). The marine shales are highly correlatable, varying in thickness from a few feet to over hundreds of feet. The lower shoreface units are generally laterally extensive with good continuity and transition to

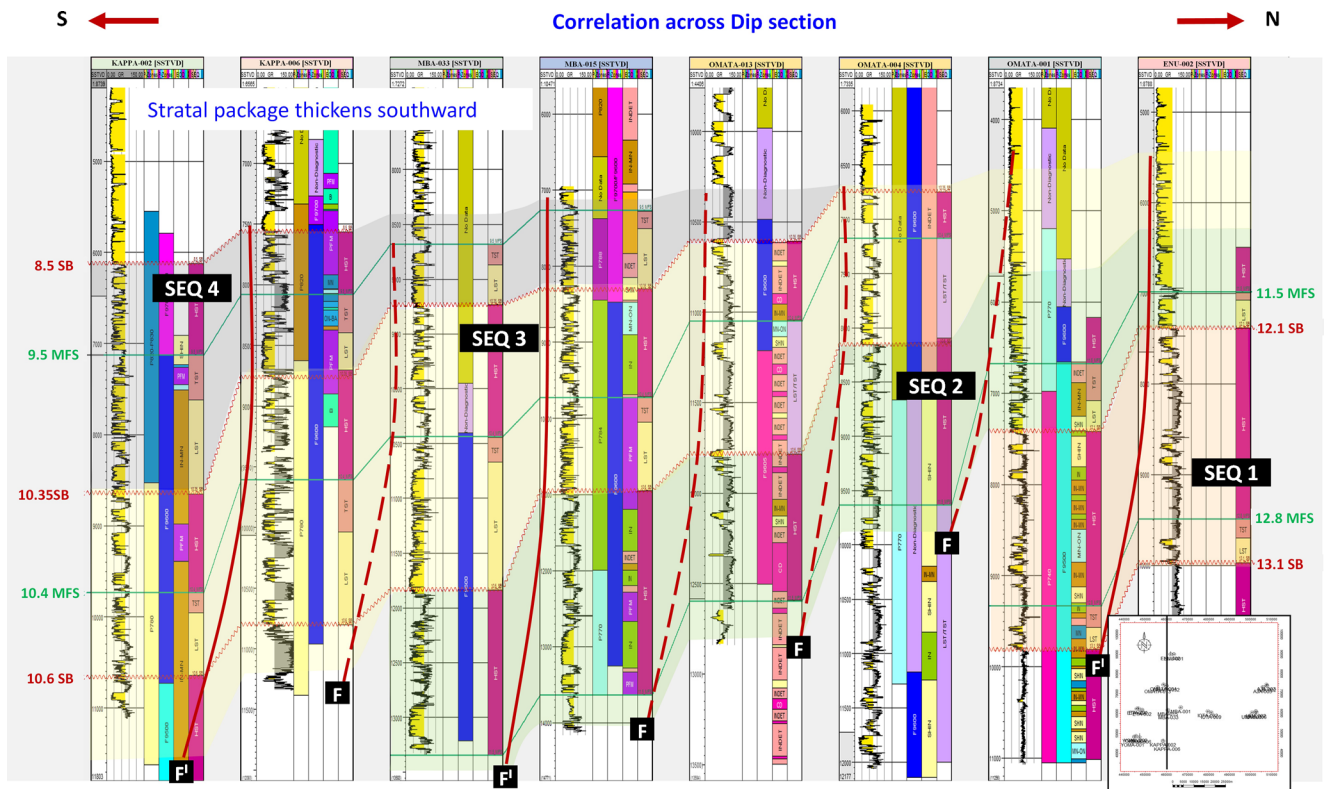


Fig. 5 Well log sequence stratigraphic interpretation and correlation showing major depositional sequences (SEQ1–SEQ4) across the studied wells (indicated by shades of colors). *F'* and *F* (major bounding

faults and minor faults structures, respectively) represent possible faulting during sedimentation, which shows downthrow of sediment package to the southern part

marine shale basinward and upper shoreface units landward. Upper shoreface deposits are clean sand facies; they show a gradational change from lower shoreface to clean sand facies. The upper shoreface units also have good lateral continuity (except where channel incision has occurred) with transition

to lower shoreface basinward. Channel fills are characterized by log signatures similar to that of upper shoreface facies; the key difference being that channel facies has a blocky or fining up signature whereas upper shoreface deposits have a coarsening up signature. Channels are often positioned on top of

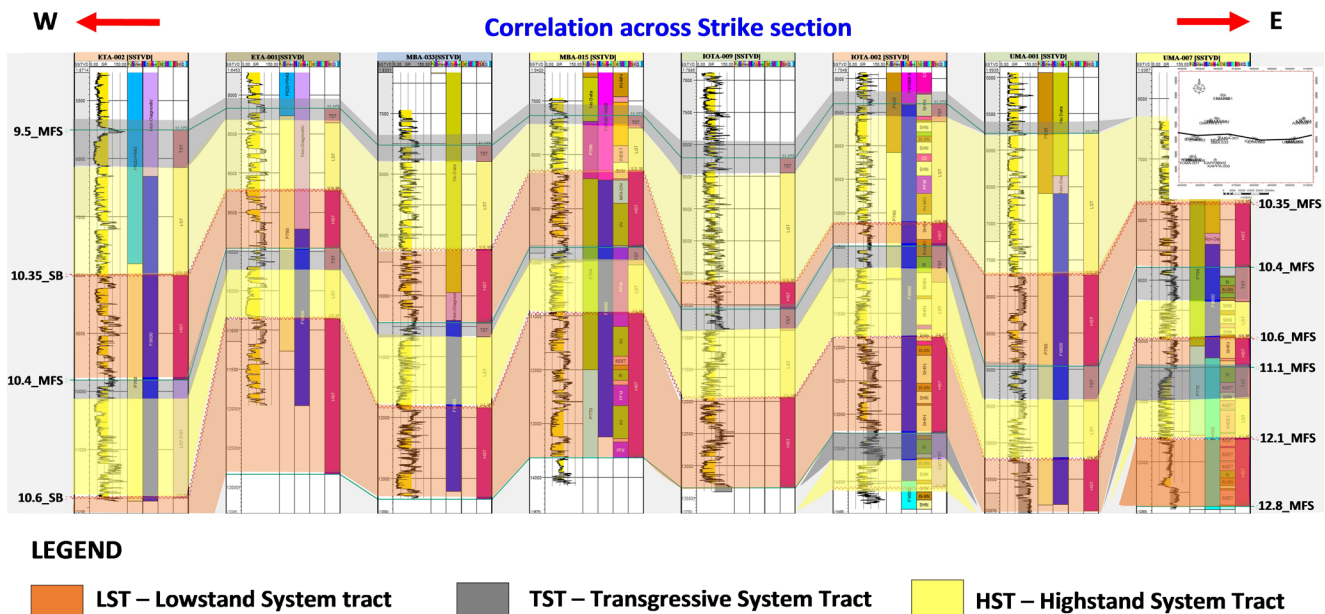


Fig. 6 Well log sequence stratigraphic interpretation and correlation showing major systems tract (LST, TST, and HST) across the studied wells

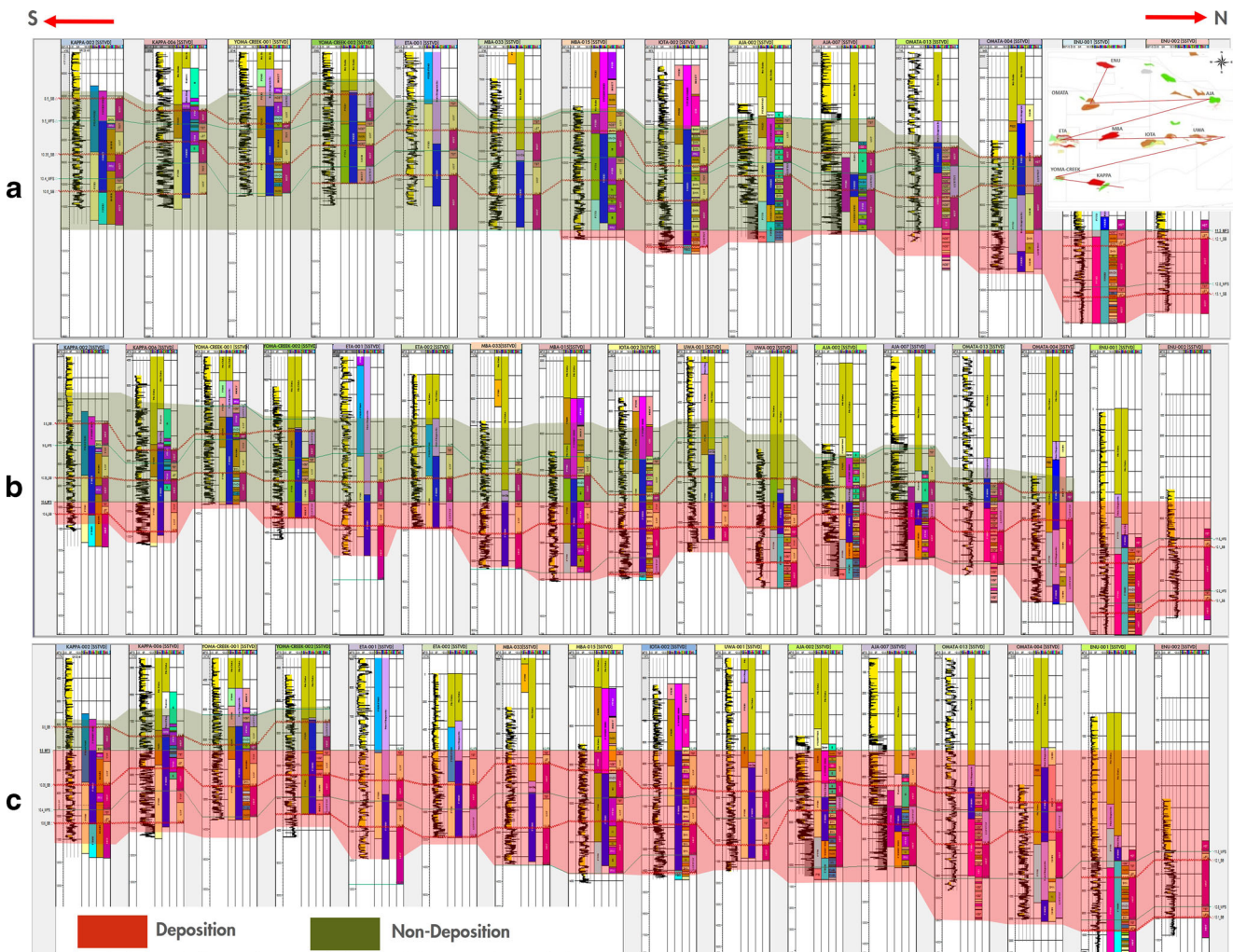


Fig. 7 a 11.5 Ma_MFS: Depocenter mainly in the northern part, with incipient deposition in the central part during 11.5 Ma. b 10.4Ma_MFS Depocenter within central part and incipient deposition during 10.4 Ma

after 10.4 Ma in the southern part. c 9.5Ma_MFS Depocenter shift from northern part before 9.5 Ma to southern after 9.5 Ma

shoreface facies but can completely erode the shoreface and even the underlying shale. With prolonged channelization, multi-story channels build up where the lateral migration of channels forms a channel sheet. Channel heterolithics can only be interpreted within channel fill as no distinct log signature characterizes this facies on its own. Facies defined as channel heterolithics generally represent intervals 5–10 ft thick that are often towards the top of a channel sequence and are limited in lateral extent.

Well log sequence stratigraphic correlation Well log sequence stratigraphic correlation was done to determine lateral continuity or discontinuity of facies and system tracts, hence aiding reservoir seal studies. The correlation across the fields shows that the main reservoirs (the sand package of the lowstand systems tract and highstand systems tract) are within the sequences from 8.5 to 12.1 Ma. In addition, the

stratigraphic column is generally dipping in a north-south/northeast-southwest direction and striking in the east-west direction. The occurrence of the identified chronostratigraphic surfaces at different depths along dip and strike directions in the wells shows evidence of tectonics (faulting) in the fields. Hence, the sediments are thinner in the up-dip (northeast) section and thicken down-dip (southwest) with a corresponding decrease in net-to gross (Fig. 5). This thickening of sediment package down-dip could be attributed to the high rate of subsidence and deposition that is influenced by structures on stratigraphy. Generally, sediment package thickens on the down thrown section of the major listric/growth fault which characterizes the area in basinward directions (N–S).

There seem to be an anomaly to the observed trend of basinwards net-to-gross decrease of sediment package within the central part (Omata-Mba area). This is probably due to infilling of exposed channels and incised valleys with marine

Table 1 Summary sheet of delineated MFS, marker fauna, and biozone of the studied wells

Wells	Depth (ft)	MFS age (Ma)	Marker fauna	Biozones	
				P-zone	F-zone
ENU-001	6,680	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
	9,350	12.8	<i>Ser-2-Cassidulina</i>	P680	F9300/9500
ENU-002	7,000	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
	9,500	12.8	<i>Ser-2-Cassidulina</i>	P680	F9300/9500
OMATA-002	8,050	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	10,700	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
OMATA-004	7,200	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	10,200	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
OMATA-013	11,050	10.4	<i>Tor-Nonion-4</i>	P780	F9600
OMATA-048	12,575	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
	8,440	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	9,450	10.4	<i>Tor-Nonion-4</i>	P780	F9600
AJA-002	4,650	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	6,850	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	10,100	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
AJA-003	4,320	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	7,600	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	10,800	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
AJA-007	4,750	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	7,450	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	10,300	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
UMA-001	5,775	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	8,850	10.4	<i>Tor-Nonion-4</i>	P780	F9600
UMA-002	8,800	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	10,450	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
UMA-006	5,350	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	8,400	10.4	<i>Tor-Nonion-4</i>	P780	F9600
IOTA-002	8,375	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	10,500	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	13,300	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
IOTA-009	8,200	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	10,550	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	13,350	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
MBA-001	7,150	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	10,050	10.4	<i>Tor-Nonion-4</i>	P780	F9600
MBA-015	7,300	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	9,700	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	13,650	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
MBA-033	8,700	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	10,450	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	13,350	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
ETA-001	8,200	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	9,850	10.4	<i>Tor-Nonion-4</i>	P780	F9600
ETA-002	5,500	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	9,800	10.4	<i>Tor-Nonion-4</i>	P780	F9600
ETA-004	8,200	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	11,150	10.4	<i>Tor-Nonion-4</i>	P780	F9600

Table 1 (continued)

Wells	Depth (ft)	MFS age (Ma)	Marker fauna	Biozones	
				P-zone	F-zone
YOMA CREEK-001	13,900	11.5	<i>Ser-3-Dodo Shale</i>	P770	F9500/9600
	6,400	7.4	<i>Tor-2</i>	P830	F9700
	8,700	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
YOMA CREEK-002	13,100	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	6,550	7.4	<i>Tor-2</i>	P830	F9700
	9,100	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
YOMA CREEK-006	11,950	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	7,300	7.4	<i>Tor-2</i>	P830	F9700
	9,200	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
KAPPA-002	11,600	10.4	<i>Tor-Nonion-4</i>	P780	F9600
	7,150	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	9,720	10.4	<i>Tor-Nonion-4</i>	P780	F9600
KAPPA-006	8,080	9.5	<i>Tor-1-Uvigerina-8</i>	P820	F9600
	9,600	10.4	<i>Tor-Nonion-4</i>	P780	F9600

muds (mud-filled channel complex) at the shelf edge, accompanying major transgressive events (Fig. 6). Sedimentary packages also thicken from the northern section to the southern section. The flattening at various MFS(s) reveals a shift of depocenter from northern section towards the southern which is a typical scenario of the progradational pattern in the Niger Delta (Fig. 7a–c). The well correlation across various fields and delineated bounding surfaces (Surface of Erosion-SB and flooding surfaces-MFS) and the depth at which they occur in the wells are summarized in Tables 1 and 2. Generally, five SBs and five intervening MFSs were delineated.

Maximum flooding surfaces The maximum flooding surfaces identified in the study area include the following: 12.8 Ma MFS (*Ser-2-Cassidulina-7* marker), 11.5 Ma MFS (*Ser-3-Dodo Shale-7* marker), 10.4 Ma MFS (*Tor-Nonion-4* marker), 9.5 Ma MFS (*Tor-1-Uvigerina-8* marker), and 7.4 Ma MFS (*Tor-2* marker). The five MFSs beginning from the oldest to the youngest occur within the following biozones: P680 and F9300/9500 (12.8 Ma MFS), P780 and F9600 (11.5 Ma and 10.4 Ma MFSs), P820 and F9600 (9.5 Ma MFs), and P830 and F9700 (7.4 Ma MFS) (Figs. 5, 6, 7 and Table 1).

Sequence boundary The oldest sequence boundary identified in the fields was dated 13.1 Ma. The surface represents a substantial erosional surface defined before the 12.8 Ma MFS. The 13.1 Ma SB is overlain in the down dip section by a relatively thick and sharp-based sand unit identified as incised valley fill and in the up dip areas by sharp-top facies of the uppermost prograding highstand parasequence. Other sequence boundaries are dated 12.1, 10.6, 10.35, and 8.5 Ma, respectively,

based on their relative positions in the stratigraphic sections (Figs. 5, 6, 7 and Table 2). Identified transgressive surfaces of erosion lie close to the sequence boundaries marking abrupt changes from progradational facies to retrogradational facies and substantially causing diminution of sand thickness deposited during relative sea level fall.

Depositional sequence Four depositional sequences (SEQ1, SEQ2, SEQ3, and SEQ4) and the component systems tracts were interpreted and correlated across the fields based on log-motifs of the various wells and the spatial distribution of the recognized constrained stratigraphic surfaces (MFSs and SBs) (Fig. 5). The first sequence (SEQ1) is an incomplete sequence, which is about 2,600 ft thick and is bounded top and bottom by 12.1 and 13.1 Ma sequence boundaries, respectively. The 12.1 Ma SB bounding the top is seen only in wells Enu-001 and Enu-002 (Table 2) that penetrated deeper stratigraphic sections across the field. The LST sands are interpreted as shoreface sands deposited in the shelf region during rising sea levels. The TST unit of this sequence is capped by the 12.8 Ma MFS marker (*Ser-2-Cassidulina 7*). The HST is deposited in the inner-middle neritic (IN-MN) setting depicting mainly progradational-retrogradational stacking patterns.

The second sequence (SEQ2) is approximately 2,800 ft thick and is bounded top and bottom by 10.6 and 12.1 Ma Sequence Boundaries, respectively. The LST and TST of this sequence formed thick sand deposits interpreted as upper shoreface deposited in the shallow marine to inner neritic (SHIN) depositional settings. The LST is barren in faunal contents in most wells and overlies the 12.1 Ma SB. This is capped by 11.5 Ma MFS marker (*Ser-3-Dodo Shale 7*).

Table 2 Summary sheet of delineated SBs within the studied wells

Wells	Depth (ft)	SB age (Ma)	Depositional sequences
ENU-001	7,400	12.1	SEQ1
	9,800	13.1	
ENU-002	7,400	12.1	SEQ3
	9,950	13.1	
OMATA-002	7,525	10.35	SEQ3
	9,025	10.6	
OMATA-004	6,750	10.35	SEQ3
	8,100	10.6	
OMATA-013	10,600	10.35	SEQ4
	11,775	10.6	
OMATA-048	8,900	10.35	SEQ4
AJA-002	6,100	10.35	SEQ3
	7,450	10.6	
AJA-003	6,000	10.35	SEQ3
	8,750	10.6	
AJA-007	6,450	10.35	SEQ3
	8,300	10.6	
UMA-001	7,700	10.35	SEQ2
	10,250	10.6	
UMA-002	7,750	10.35	SEQ2
	9,950	10.6	SEQ3
	11,600	12.1	SEQ3
UMA-006	7,000	10.35	SEQ2
	9,800	10.6	SEQ3
IOTA-002	10,150	10.35	SEQ3
	11,850	10.6	
	14,100	12.1	
IOTA-009	10,150	10.35	SEQ3
	11,950	10.6	
MBA-001	8,700	10.35	SEQ4
MBA-015	8,300	10.35	SEQ3
	10,950	10.6	
MBA-033	9,250	10.35	SEQ3
	11,850	10.6	
ETA-001	9,250	10.35	SEQ3
	10,850	10.6	
ETA-002	8,000	10.35	SEQ3
	11,850	10.6	
ETA-004	9,400	10.35	SEQ3
	12,600	10.6	
YOMA CREEK-001	8,350	8.5	SEQ4
	11,150	10.35	
YOMA CREEK-002	7,350	8.5	SEQ3
	10,600	10.35	SEQ4
	13,000	10.6	SEQ4
YOMA CREEK-006	8,500	10.35	SEQ3
	10,500	10.6	
KAPPA-002	8,500	8.5	SEQ3
	8,650	10.35	SEQ4
	10,300	10.6	SEQ4

Table 2 (continued)

Wells	Depth (ft)	SB age (Ma)	Depositional sequences
KAPPA-006	7,600	8.5	SEQ3
	8,750	10.35	SEQ
	10,800	10.6	SEQ

The third sequence (SEQ3) is approximately 2,500 ft thick and it is bounded top and bottom by the 10.35 Ma SB and the 10.6-Ma SB, respectively. The sequence displayed predominantly fluvial and tidal processes (progradational stacking pattern) as shown in the parasequence stacking pattern of the wells in the western part of the study area (Omata, Aja, Uma, Iota, Mba fields). The LST of this sequence contains reworked channel sand deposits which are more pronounced in the down dip wells and some predominantly mud fill channels. The TST of this sequence is capped by the 10.4 Ma MFS (*Tor-Nonion-4*) marker.

Sequence Four (SEQ4), which is approximately 2,000 ft thick, is an incomplete sequence. It is the topmost/youngest sequence in the study area. It is bounded by the 8.5 and 10.35 Ma SB, respectively. The sequence was deposited within the inner to middle neritic paleo-depositional environment. The TST of this sequence is capped by 9.5 Ma MFS (*Tor-I-Uvigerina-8*) marker.

Depositional environment Paleobathymetric maps for the four regional and time significant horizons were generated with information from biostratigraphic data and interpretation of well log signatures, which are indicative of depositional environment. Generally, sediments are deposited within neritic to bathyal environments at different times, aligning with the progradational pattern of deposition of the Niger Delta. Some biofacies are diagnostic of different depositional environments. These were studied and their spatial distributions on these horizon surfaces were used to subdivide the area into different depositional environments (Fig. 8a–c). The observed depositional environments appear to have been consistently fluvial to shallow marine (shallow-inner neritic, inner neritic-middle, and outer neritic) environments (mainly pro-delta) with isolated coastal deltaic and proximal fluvial influence. The environment of deposition spans through incised canyons, channels, inner mid shelf, shelf margin, and slope margin. Generally, the depositional environment and paleobathymetric maps show basinwards deepening which is suggestive of progradation, in conformity with the geology of the Niger Delta.

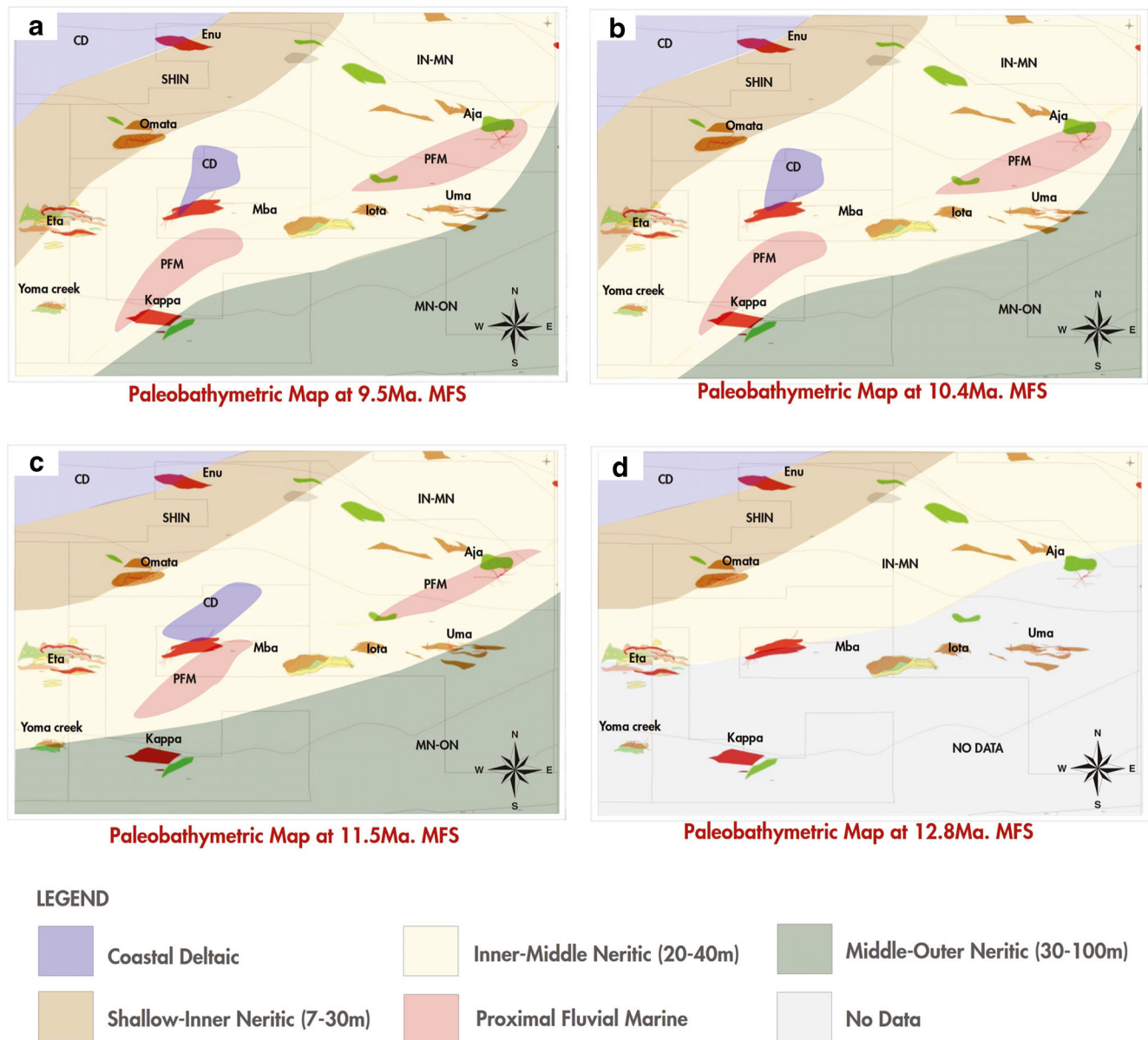


Fig. 8 The paleobathymetric maps at various ages showing the depositional environments across the study area. **a** Paleobathymetric maps at 9.5 Ma MFS; **b** paleobathymetric maps at 10.4 Ma MFS; **c** paleobathymetric maps at 11.5 Ma MFS and **d** paleobathymetric maps at 12.8 Ma MFS

Discussion and conclusion

In the study area, four third-order depositional sequences (SEQ1, SEQ2, SEQ3, and SEQ4) of mid-Miocene age bounded chronologically by 13.1, 12.1, 10.6, 10.35, and 8.5 Ma SB—type 1 sequence boundaries (Van Wagoner et al. 1990) were recognized. Five MFSs including 12.8, 11.5, 10.4, 9.5, and 7.4 Ma MFS occur within the stratal package. The SBs are characterized by sizeable sand unit defined in well log by abrupt and sharp bases of thick low gamma ray value intervals usually separating coarsening-upwards intervals from fining-upwards intervals (Fig. 4a). The MFSs are characterized by thick and extensive shale units defined by thick high gamma

ray value intervals that separates overall fining-upward interval from coarsening-upwards intervals, and high abundances and diversity of microfossils (see Fig. 4a.). Successively younger systems tracts and depositional sequences are on the average thinner vertically, but laterally, the stratal package thickens basinwards (Figs. 5 and 6). Other workers have also documented upward thinning of sequences and basinwards thickening of the stratal package in the Niger Delta (Ozumba 1999; Magbagbeola and Willis 2007). Studies also revealed that depocenter has shifted from the northern section towards the southern in time (Ma) and space. This is a typical scenario of the progradational pattern in the Niger Delta (Fig. 7a–c).

Six main genetic facies were identified namely marine shale, lower shoreface, upper shoreface, tidal channel, channel, and channel heterolithics. The depositional environments spans through incised canyons, channels, inner mid shelf, shelf margin, and slope margin. The generated paleobathymetric maps show generally that sediments were deposited within neritic through bathyal environments at different times, aligning with the progradational pattern of deposition of the Niger Delta. Similarly, correlation across the fields shows a decreasing net-to-gross (NTG) from north to south, with an anomaly at Omata-Mba area due to the presence of mud-filled channels. The maximum flooding surfaces mark regional seals and caps the major reservoir units across the various fields in the study area. The LST and HST sand units of the basin floor fans, channel, and shoreface are potential good hydrocarbon reservoirs (Fig. 6). The shale unit (marine shales) of the TST, which is capped by MFS, also provides regional seals to the reservoir units. A combination of the reservoir sands of the LST and HST with the shale units of the TST offers good stratigraphic hydrocarbon traps with associated numerous fault structures, associated with rapidly subsiding delta, hence should be targeted during hydrocarbon exploration and production.

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