Communications in Physical Sciences
Vol. 2. No. 1, 35-49. (2017)

AN INTEGRATED APPROACH TO PETROLEUM EXPLORATION IN THE EASTERN COASTAL SWAMP DEPOBELT OF THE NIGER DELTA BASIN, NIGERIA.

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ABSTRACT

Sequence stratigraphic, structural and reservoir analytical tools have been employed in interpreting the geology of the eastern Coastal Swamp Depobelt of the Niger Delta Basin. The aim was to understand the stratigraphic framework, structural styles and hydrocarbon reservoir distribution for improved regional hydrocarbon exploration across the onshore Niger Delta basin. This interpretative study made use of well logs, biostratigraphic (biofacies and bio-zonation) and petrophysical data obtained from twenty wellbores, integrated with recently merged and reprocessed 3D regional seismic volume spanning across eight fields. Results reveal the occurrence of nine key chronostratigraphic surfaces (five maximum flooding surfaces and four sequence boundaries) that were tied to well-established pollen and foram bio-zones for high resolution sequence stratigraphic interpretation. The sediment stacking patterns recognized from gamma ray log signatures were used in delineating the lowstand system tract (LST), transgressive system tract (TST) and highstand system tract (HST) genetic units. Well log sequence stratigraphic correlation reveals that stratal packages within the area were segmented into three depositional sequences occurring from middle to late Miocene age. Furthermore, there is thickening of stratal packages with corresponding decrease in net-to-gross thickness from north to south (basinwards). This is due possibly to the influence of syn-depositional structures on stratigraphy. The combination of reservoir sands (of LST and HST), source and seal shales (of TST and HST) and fault structures allows for good hydrocarbon accumulation and should be targeted during exploration. Reservoir evaluation studies using petrophysical parameters indicate the presence of good quality reservoir intervals, which are laterally continuous across several fields and partly compartmentalized within individual fields. Structural top maps of reservoirs show good amplitude response that are stratigraphically and structurally controlled. Structural analysis revealed the occurrence of back-to-back faulting, collapsed crest structures, simple/faulted rollovers, regional foot wall and hanging wall closures and sub-detachment structures. These structural styles constitute the major hydrocarbon entrapment mechanism in the area. Overall, the study has unraveled the existence of undrilled hydrocarbon leads at deeper depths that should be further revalidated for development.

Keywords: Sequence stratigraphic framework, Structural configuration, Reservoir distribution, Coastal Swamp Depobelt.

INTRODUCTION

A lot of the earlier hydrocarbon prospectivity studies carried out over the years in the onshore Niger Delta Basin, were focused mainly on individual fields or leases except where adjacent fields or leases belonged to the same operator or company (Balogun, 2003; Magbagbeola, and Willis, 2007; Ehinola et al., 2010). Hence were unable to provide information on stratigraphic intervals, structural features, and reservoir zones on a regional basis. This research work is aimed at utilizing a recently merged and reprocessed regional 3D (Pre-Stack Depth Migrated - PreSDM) seismic volume and data from several wells in furthering our understanding of the stratigraphic framework, structural styles and reservoir distribution using integrated exploration techniques. The target is to identify stratigraphic interval and delineate potential reservoirs and better define hydrocarbon leads and prospects within the paralic sequence of the Niger Delta Basin. The study area lies on the eastern part of the Coastal Swamp depo-belt of the Niger Delta Basin of Nigeria (Fig. 1).

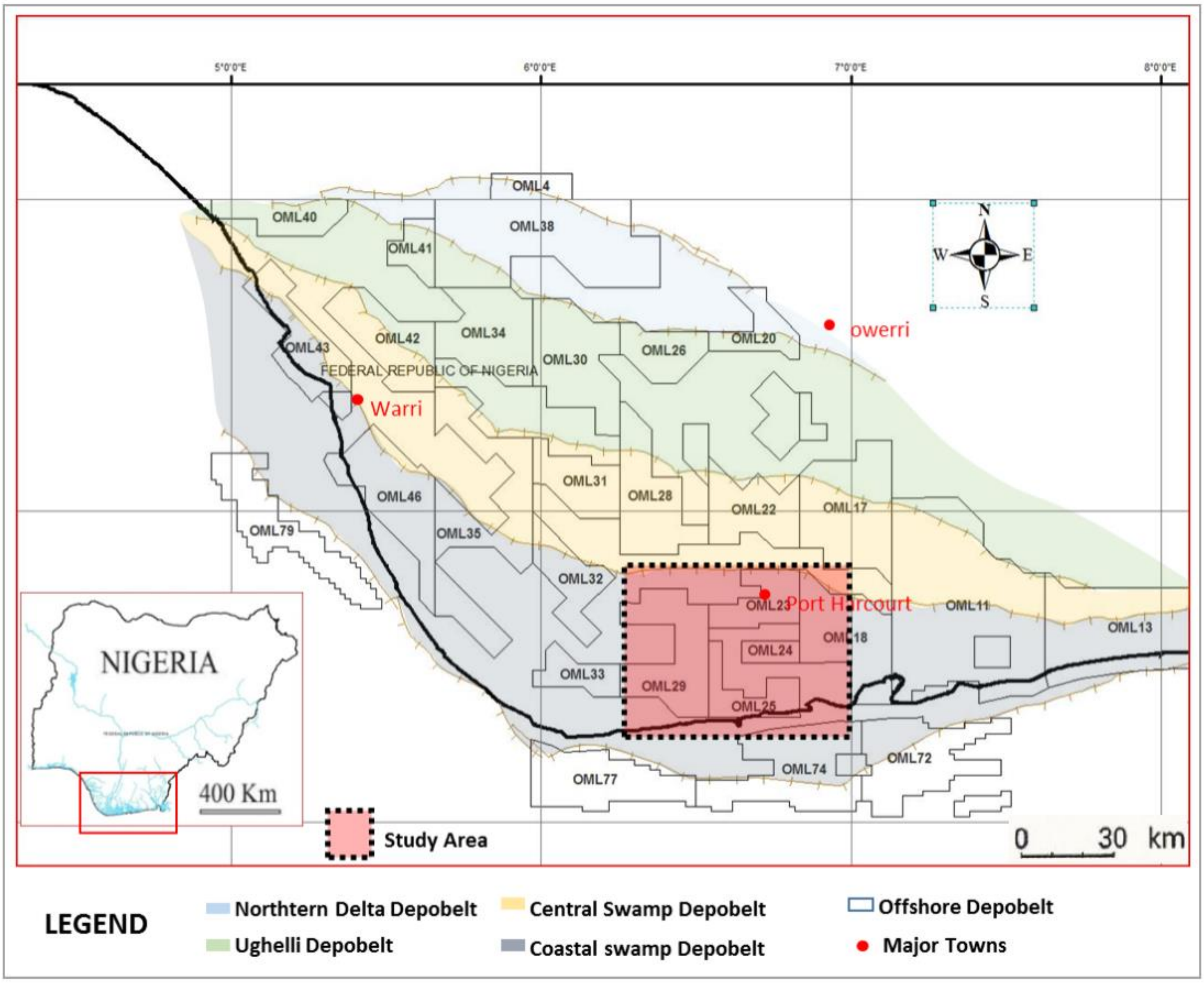

Fig. 1: Depobelt map with the oil and gas, onshore and offshore Niger Delta Basin showing the study area which lies on the eastern part of the Costal Swamp Depobelt.

GEOLOGIC FRAMEWORK

The evolution of the Niger delta was controlled by pre- and synsedimentary tectonics as described by Evamy et al. (1978), Ejedawe (1981) and Stacher (1995). The Niger Delta Basin is located in the Gulf of Guinea on the western coast of Africa (Fig. 1). The tectonic evolution and structural features in the Niger Delta basin has been widely documented in several works (Evamy et al., 1978; Lawrence et al., 2002). The stratigraphic succession comprises an upward-coarsening regressive association of Tertiary clastics up to 12 km thick (Weber and Daukoru 1975; Evamy et al. 1978). Three lithostratigraphic units have been recognized in the subsurface of the Niger Delta. These are the marine prodelta shales of Akata (claystones and shales), paralic intervals of Agbada (alternation of sandstones, siltstones and claystones) and continental sequence of Benin (alluvial sands) formations, all of which are strongly diachronous (Short and Stauble, 1967; Doust, 1990). These three sedimentary environments, typical of most deltaic environments, extend across the whole Niger delta and ranges in age from early Paleocene to Holocene/Recent (Reijers et al., 1997). The lithostratigraphic units are thick, complex sedimentary units deposited rapidly during high-frequency, fluvio-deltaic-eustatic sea level oscillations (Mitchum et al., 1994). The surface upon which they were deposited is underlain by thick, under-compacted unstable mobile shales of the Akata Formation, producing a complex series of gliding surfaces and depobelts. In these depobelts, deposition commonly is controlled by large contemporaneous glide-plane extensional faults and folds (Fig. 2). Regionally, sediment dispersal in the basin were controlled by marine transgressive/regressive cycles related to eustatic sea-level changes with varying duration. Differential subsidence locally influenced sediment accumulation. Collectively, these controls resulted in eleven chronostratigraphically confined delta-wide megasequences with considerable internal lithological variation (Reijers, 2011). The basin structures and stratigraphy have been controlled by the interplay between rates of sediment supply and subsidence (Doust and Omatsola, 1990).

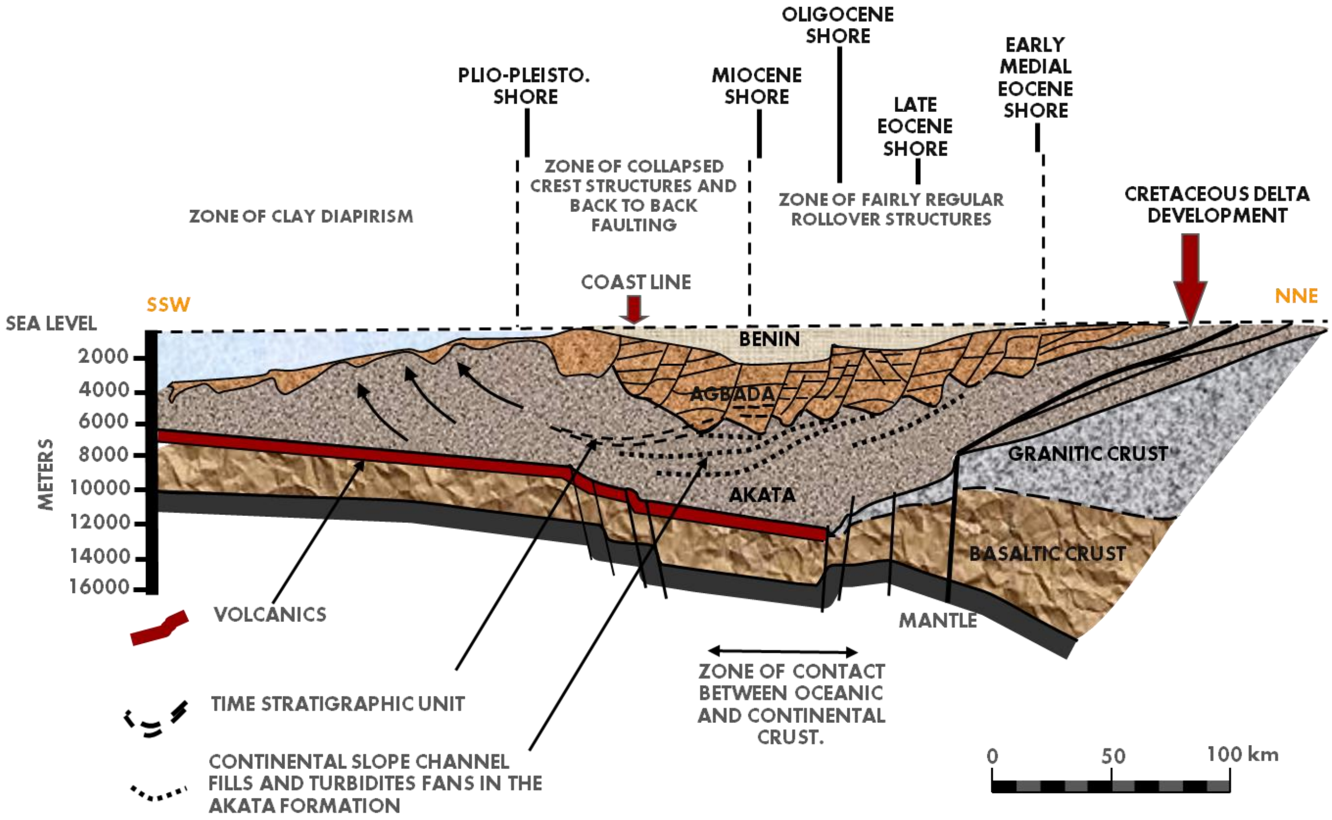

Fig. 2: Schematic Dip Section of the Niger Delta (Modified after Weber and Daukoru, 1975)

METHODOLOGY

The method of investigation employed in this study made use of regional merged 3D pre-stack time migrated (PreSTM) seismic data volume of nine fields and twenty-five wells with corresponding suites of wireline logs (Fig. 3). Key delineated stratigraphic bounding surfaces such as maximum flooding surfaces (MFSs) and sequence boundaries (SBs), were tied to well-defined palynological (P) and foraminiferal (F) zones. Maximum flooding surfaces were dated using biostratigraphic markers and were correlated with regional marker shales on the chronostraigraphic chart. In addition, paleobathymetric data (paleo-water depth) were used to constrain stratigraphic bounding surface interpretation (Fig. 4). These were calibrated using Shell Petroleum Development Company's 2010 Niger Delta Chronostratigraphic Chart (zonation schemes) (Fig. 5). These chrono-stratigraphic surfaces were also correlated on well logs and mapped across the seismic volume respectively. Stacking pattern, system tracts and sequence stratigraphic models (Van Wagoner et al., 1990; Kendall, 2008) aided well log sequence stratigraphic and depositional environment interpretations (Fig. 4). The fault stick picking and horizon mapping were done systematically at very close spacing in order to get as much detail as possible. Time – depth (T-Z) curves (polynomial) were generated from plots using check-shots data for depth-converting time structural maps (Fig. 6). Software used for this research includes; Petrel™ software, which aided in well log correlation, seismic interpretation and generation of structural top maps; Shell's nDI that was used in generating the semblance volume and Interactive Petrophysics™ that was used for reservoir delineation and petrophysical evaluation.

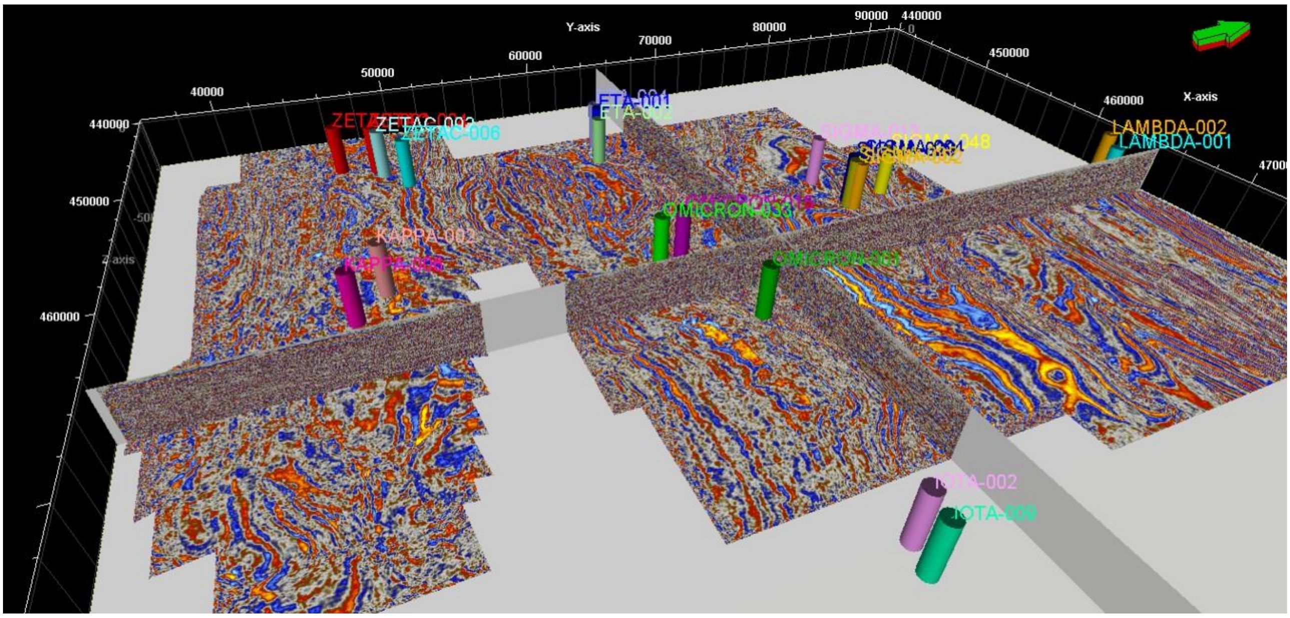

Fig. 3: 3D preSDM seismic volume showing time slice, in-line and cross-line intersections with well bores across the study area (NB: presence of amplitude enhanced stratigraphic and structural features in the time slice).

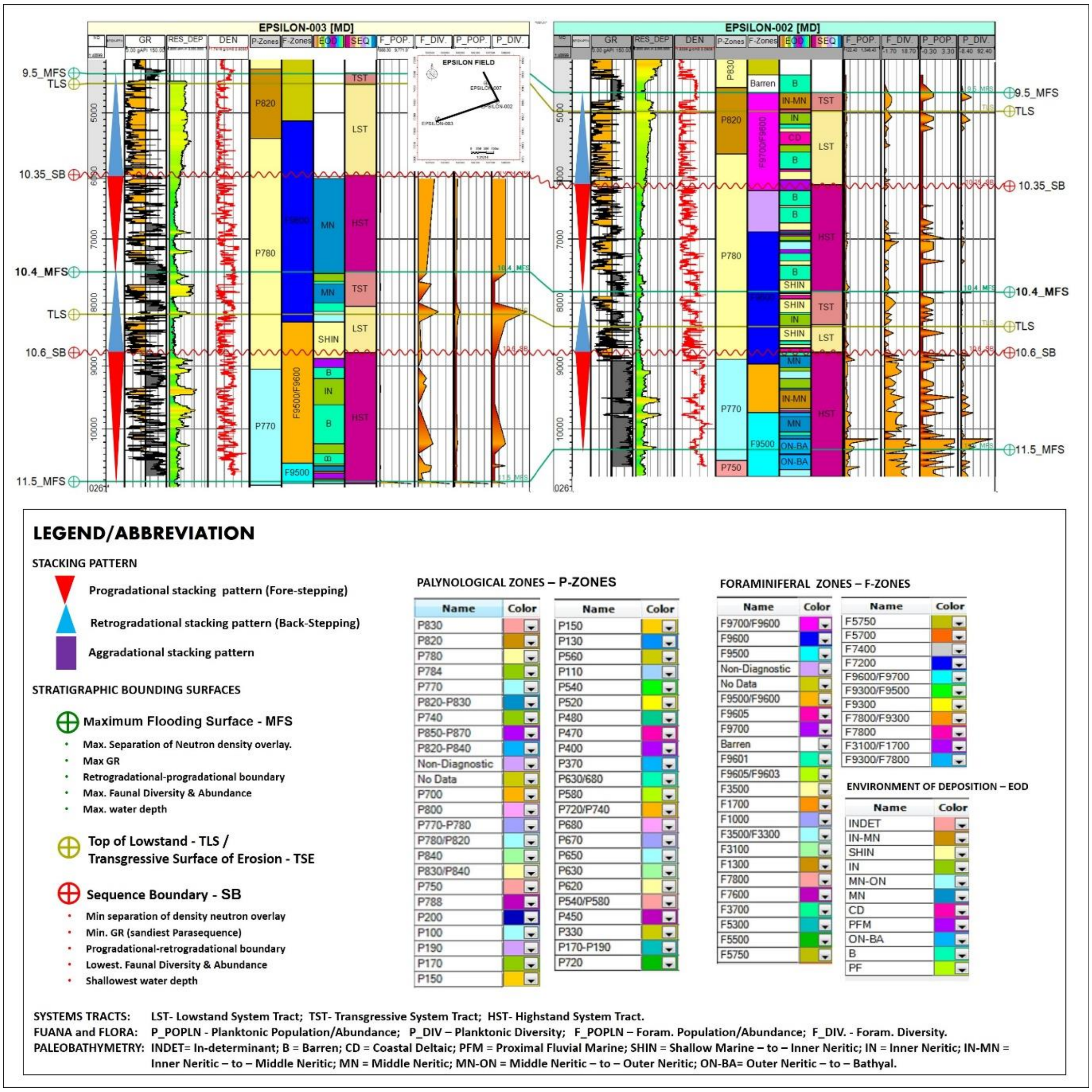

Fig. 4: Well log sequence stratigraphic correlation panel across one of the fields used in this study showing the template and representative data/tools.

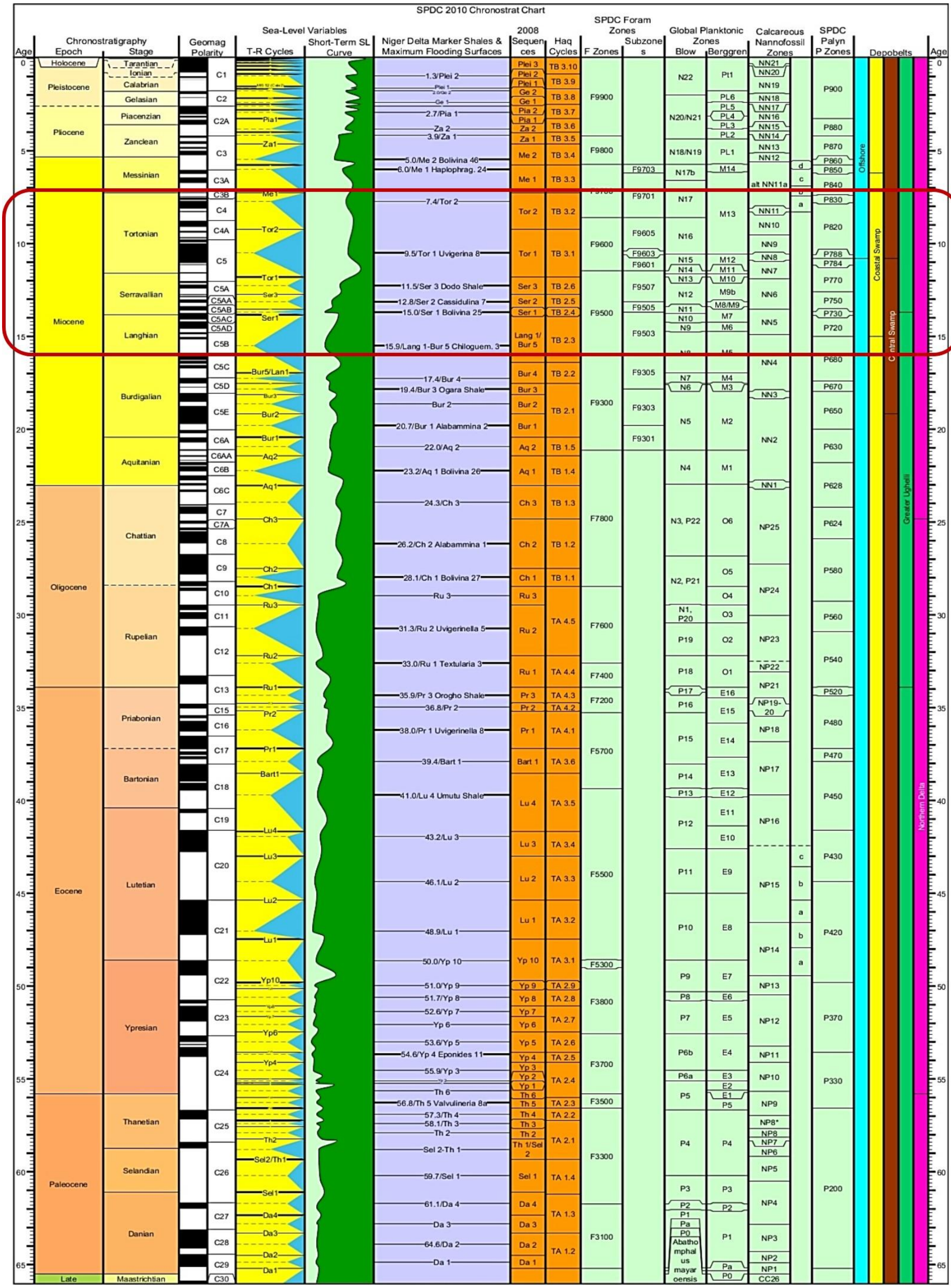

Fig. 5: SPDC 2010 Niger Delta Chronostratigraphic Chart showing geologic interval (Middle – Late Miocene) of interest in red box (Source: Shell, 2010).

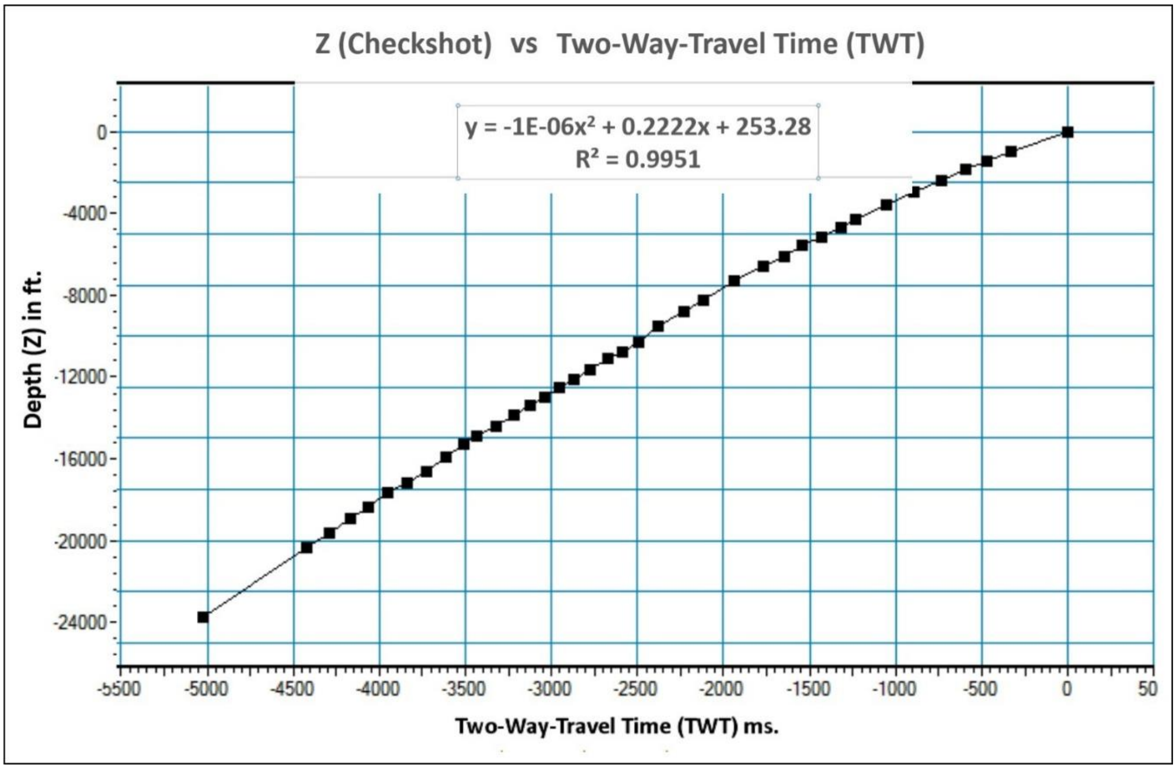

Fig. 6: Polynomial plot (T-Z) showing the time to depth relationship, a curve generated using checkshots from wells.

RESULTS AND DISCUSSION

Stratigraphic analysis reveals the occurrence of five sequence boundaries identified in the study area with the oldest identified sequence boundary being dated SB_13.1 Ma. Other Sequence Boundaries are dated 12.1 Ma, 10.6 Ma, 10.35 and 8.5 Ma respectively, based on their relative positions in the stratigraphic sections. In addition, five intervening maximum flooding surfaces were also identified. These surfaces, from the oldest to the youngest with their corresponding bio-zones have been described as follows: (i) 12.8 Ma Maximum Flooding Surface (*Ser-2-Cassidulina* regional marker).The surface occurrence of this event is within P680 and F9300/9500 bio-zones. (ii) 11.5 Ma Maximum Flooding Surface (*Ser-3-Dodo Shale* regional marker). This surface occurred within P770 and F9500/F9600 bio-zones. (iii) 10.4 Ma Maximum Flooding Surface (*Tor-Nonion-4* regional marker), which occurred within P780 and F9600 bio-zones. (iv) 9.5 Ma Maximum Flooding Surface (*Tor-1-Uvigerina-8* regional marker) that occurred within P820 and F9600 bio-zones. (v) 7.4 Ma Maximum Flooding Surface (*Tor-2* marker). This MFS occurred within P830 and F9700 bio-zones. Four depositional sequences (SEQ1, SEQ2, SEQ3, and SEQ4) and the component systems tracts were recognized. The three systems tracts observed in this study namely, lowstand system tracts (LST), transgressive system tract (TST) and highstand system tract (HST) are all characterized by variable thicknesses that appear to be structurally controlled. The average thickness distribution of these system tracts is such that there is a higher percentage of HST (57%) relative to LST (30%) and much lesser TST (13%) packages. In addition, interpretations reveal that the genetic units of LST (predominantly sand package), TST (predominantly shale package), and HST (sand and shale packages).

The correlation across the fields shows that the main reservoirs (the sand packages of the lowstand systems tract and highstand systems tract) are within the sequences from 8.5 to 12.1 Ma. (Fig. 7). The occurrence of the identified chronostratigraphic surfaces at different depths along dip and strike directions in the wells shows evidence of structural (faulting) influence on stratigraphy. Hence, the sediments are thinner in the up-dip (northeast) section and thicken down-dip (southwest). Generally, sediment package thickens on the down thrown section of the major listric / growth fault which characterizes the area in basin-ward directions (N–S). 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 (Mode, et al, 2015; Dim, 2017).

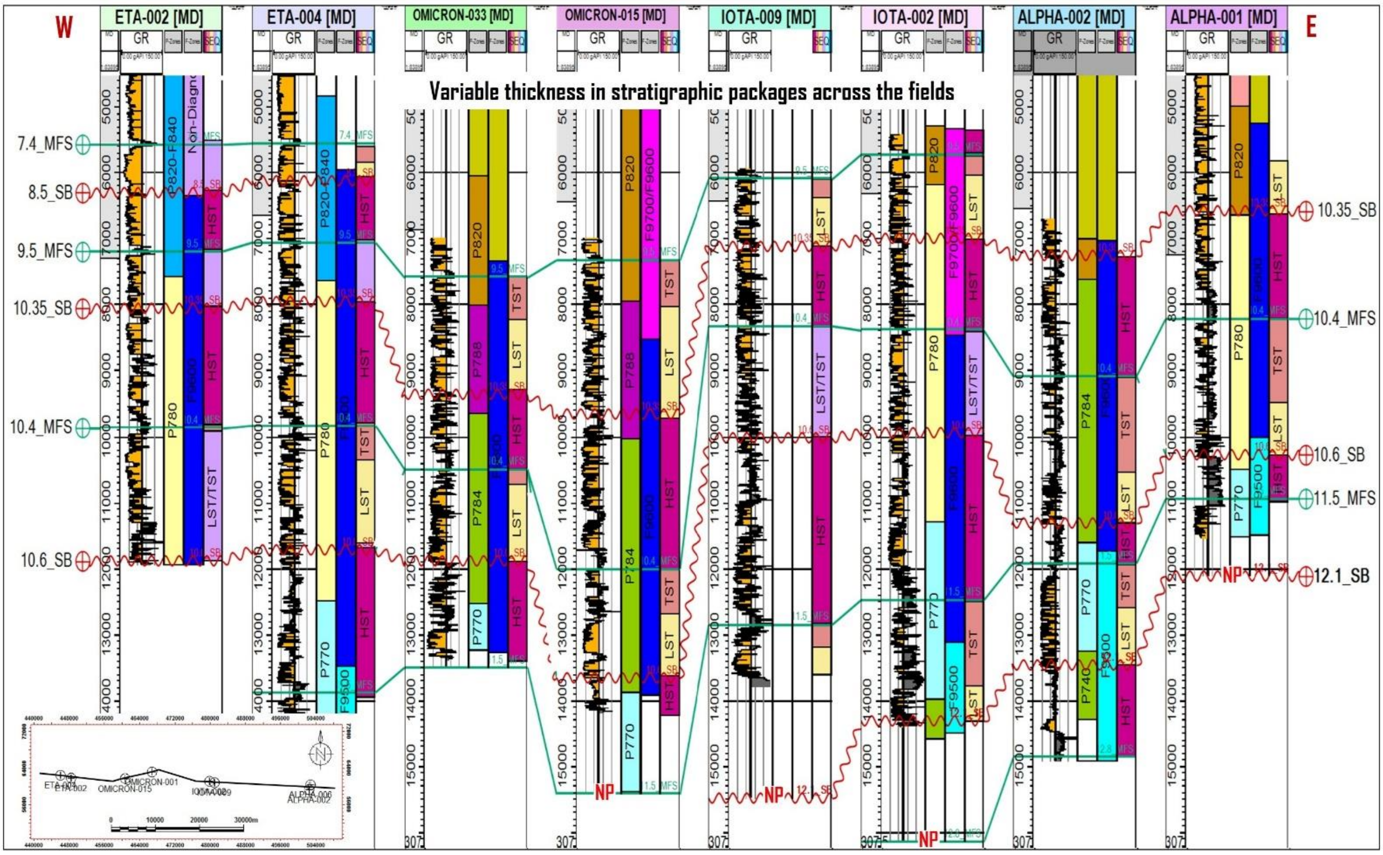

Fig. 7: Well log sequence stratigraphic correlation across representative well from various fields showing key chronostratigraphic surfaces – MFSs and SBs (Note: NP = Not Penetrated/Drilled).

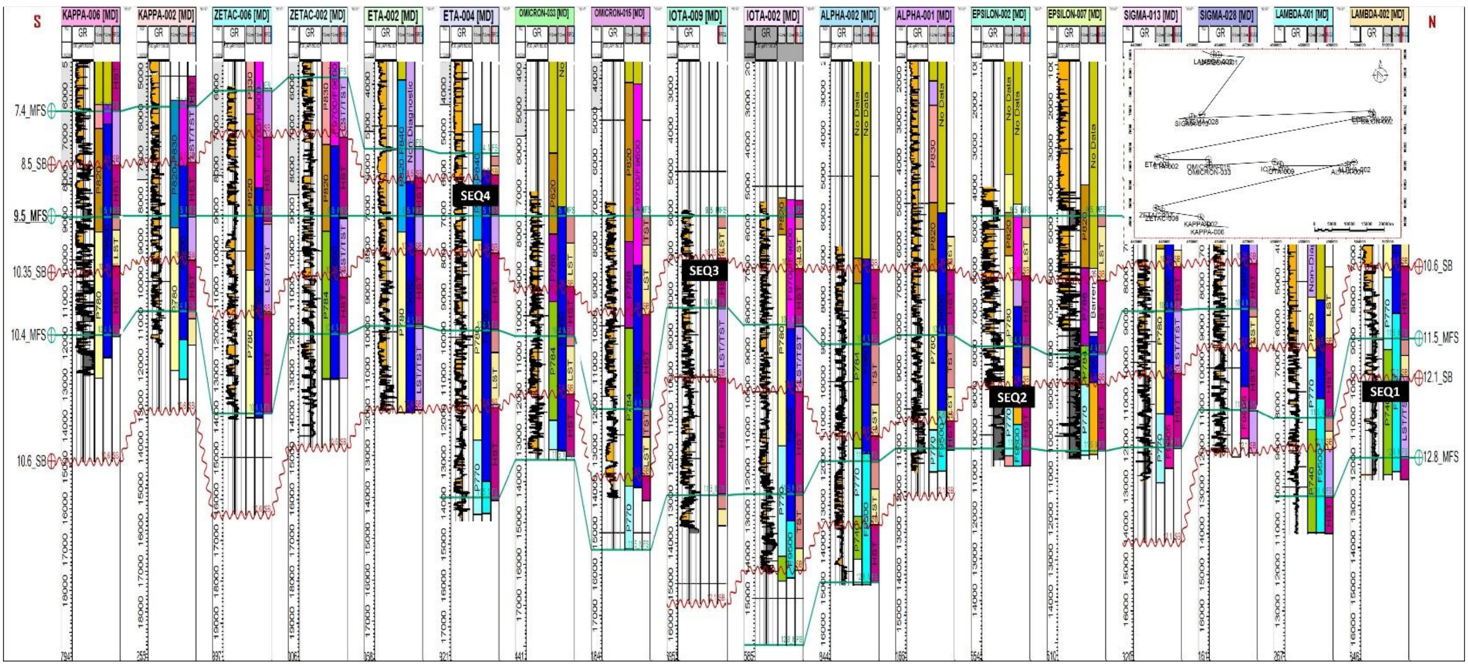

Fig. 8: Regional stratigraphic correlation panel flattened at 9.5 Ma. MFS showing a shift of depositional centers toward the southern section of the area.

Structural interpretation across the fields reveal down to basin listric faults that are large and regionally extensive. Majority of these faults dip in the same direction as the regional stratigraphy (synthetic faults), whereas few dip against the regional stratigraphic dip (counter regional faults). Generally the following structural configuration / styles were distinguished namely; simple/faulted rollovers, regional footwalls / hanging walls and associated fault dependent closures, back to back horst block (trapezoid zone), collapse crest structures, and sub-detachment structures (Fig. 9).

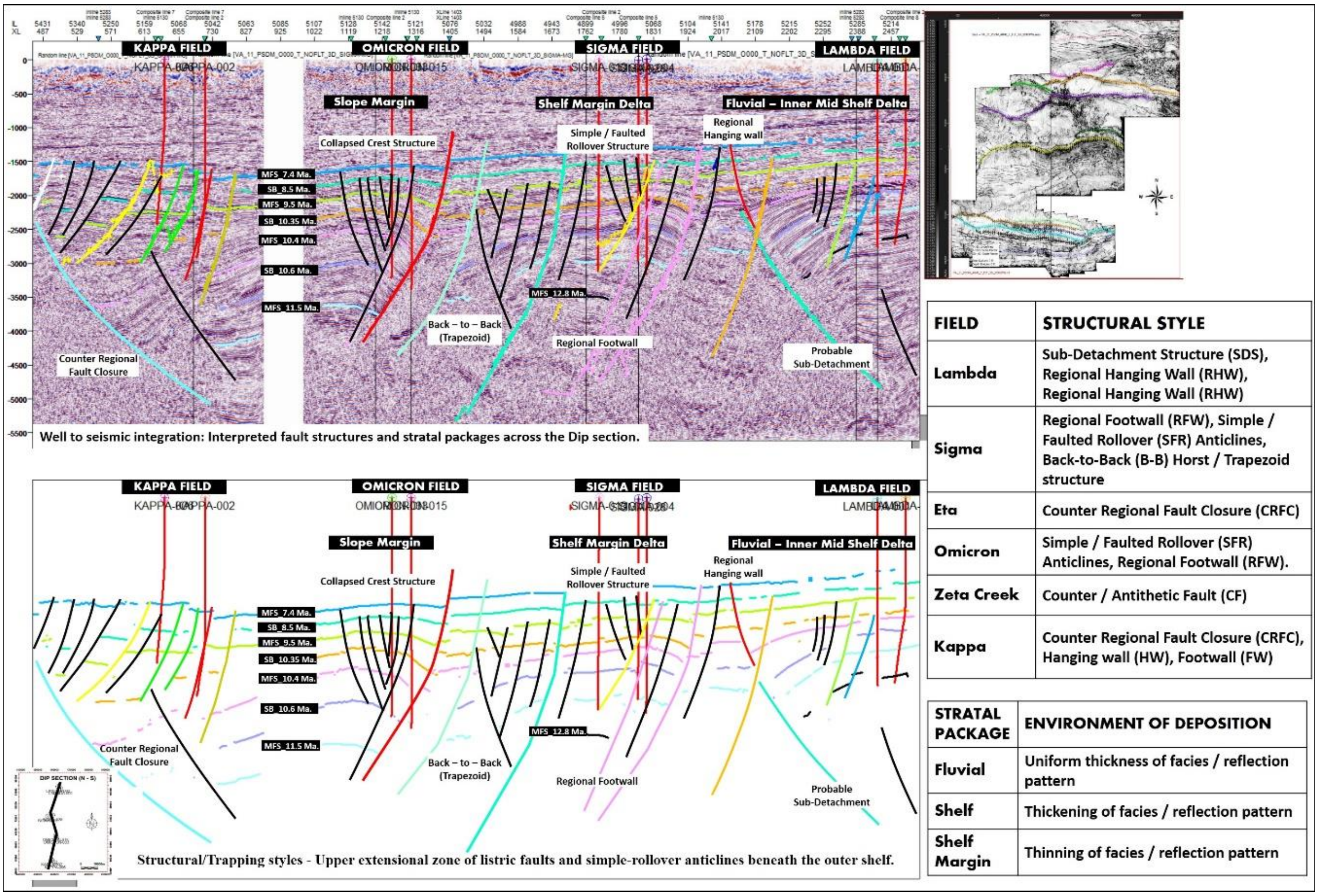

Fig. 9: Multiple dip line sections (using Petrel^{TM} software), showing interpreted stratigraphic surfaces and structural styles across various study area and inset structural semblance map (Adopted from Dim and Onuoha, 2017).

Reservoir formation evaluation studies indicate that the LST packages of the basin floor fans and channel, and HST packages of the shoreface constitute potential hydrocarbon reservoirs (Fig. 10). 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 (Mode, et al, 2015; Dim, 2017; Dim and Onuoha, 2017).

Studies show that these reservoir intervals are partly compartmentalized and laterally continuous extending regionally across several fields at intermediate and deeper zones (Fig. 11). There is also observable variation in reservoir thickness (with gross thickness of 30.5 – 239ft and a net thickness of 0.5 – 215ft). Reservoir properties such as net-to-gross (0.1 – 0.96 or 10 – 96%), porosity (0.13 – 0.28 or 13 – 28%), water saturation (0.1 – 0.95 or 10 – 95%) and hydrocarbon saturation (0.07 – 0.89 or 7 – 89%) indicate favourable condition for hydrocarbon accumulation and production (Fig. 12 and Table 1). Generated structural time and structural depth maps (Fig. 13a and Fig. 13b) with the seismic attribute attraction (amplitude) map (Fig. 13c) show evidence of booming amplitude, an indication of possible hydrocarbon leads. A closer examination reveals these hydrocarbon leads (potential accumulation but poorly defined and requires more data or evaluation in order to be classified as a prospect) to be predominantly structurally controlled. The leads with high amplitude suggests that the hydrocarbons, which due to their buoyant nature, have been trapped within structural closures (fault dependent closures).

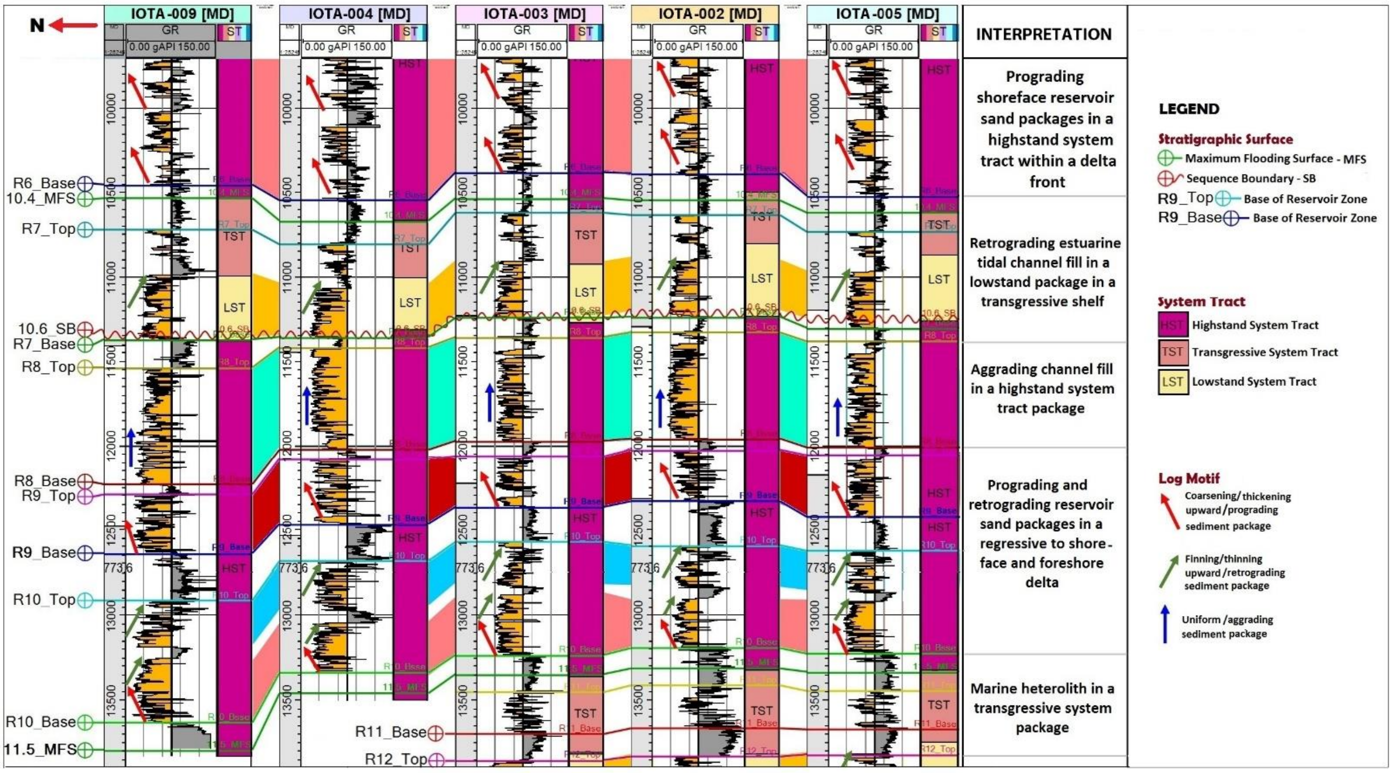

Fig. 10: Interpreted composite well correlation panel across the IOTA field showing the distribution of reservoirs packages (R_{TOPS} and R_{BASE}), continuity of sequence stratigraphic surfaces (MFSs and SBs), system tracts (LSTs, TSTs and HSTs) distribution and environments of deposition

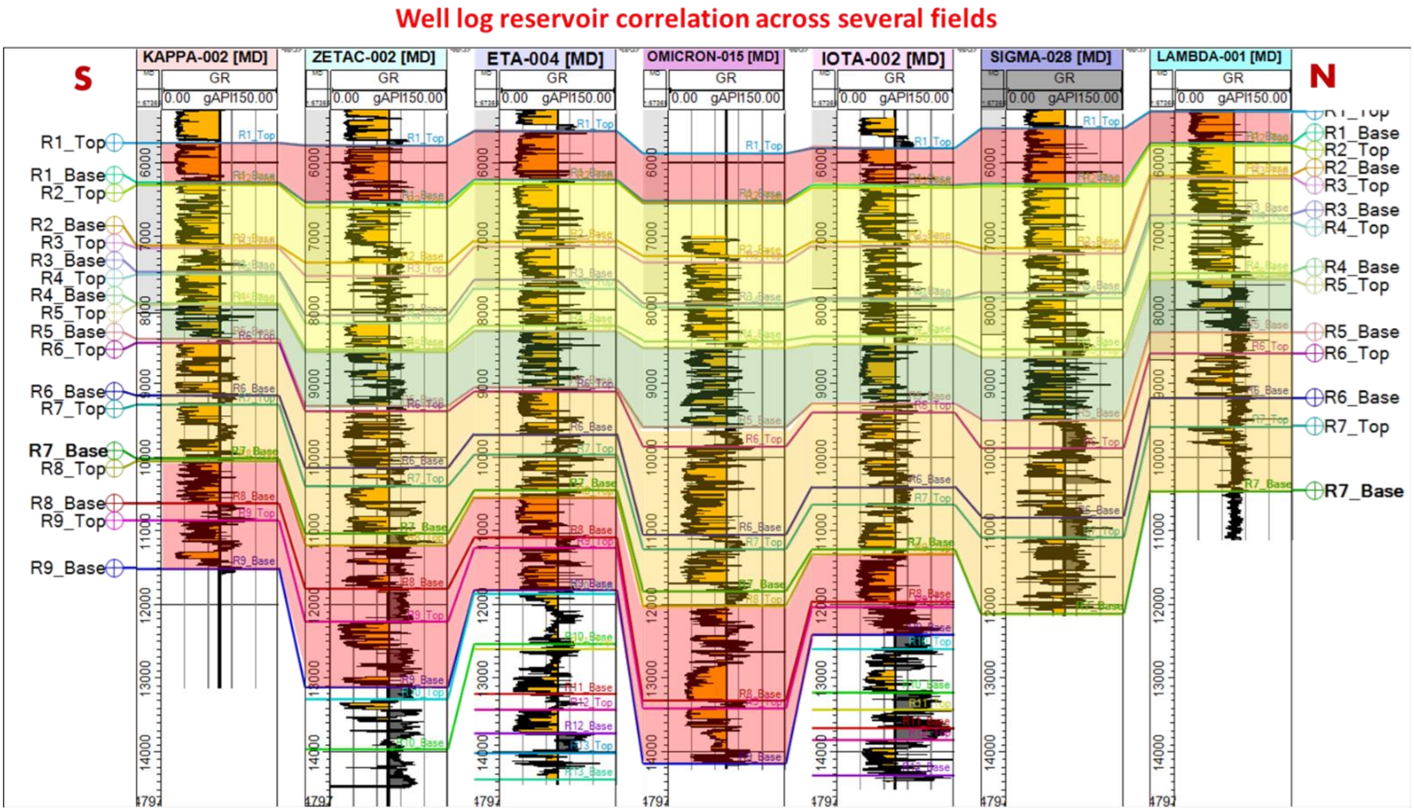

Fig. 11: Well log correlation panel showing spatial distribution of reservoir packages that are correlatable and continuous across several fields in the area (thickening of reservoir package at the central section and thinning at the flanks)

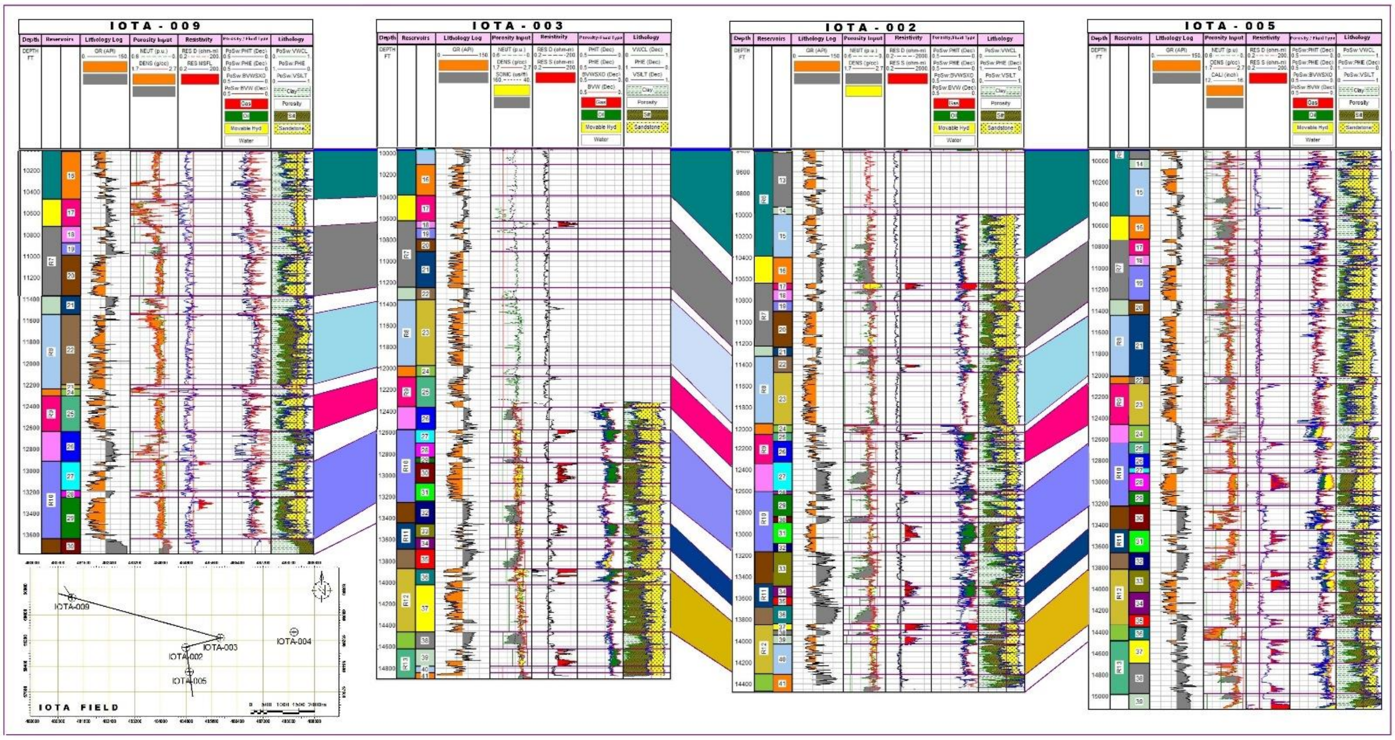

Fig. 12: Intra-well correlation panel on interactive petrophysics software interface showing delineated reservoir at intermediate and deeper zones in the Iota field (Iota-002, Iota-003, Iota-005 and Iota-009 wells). Note: Delineated reservoir zones show variable thicknesses and are laterally continuous across the field.

Table 1: Summary of some estimated petro-physical parameters from Iota 002

WELL: IOTA-002										
NET RESERVOIR ROCK SUMMARY										
Reservoir Zone	**Top Depth (ft)**	**Bottom Depth (ft)**	**Gross Thickness (ft)**	**Net Thickness (ft)**	**N/G**	**Av. Vcl**	**Av. Phi**	**Av. Sw**	**Av. Sh**	**Fluid Type**
R7	10399.5	10638.5	239	21.5	0.09	0.262	0.176	0.923	0.077	Gas
	10638.5	10699.5	61	60	0.984	0.123	0.189	0.176	0.824	
	10699.5	10807.5	108	72.5	0.671	0.145	0.206	0.804	0.196	
	10807.5	10906.5	99	29.5	0.298	0.256	0.139	0.953	0.047	
R8	11237	11399.5	162.5	39.75	0.245	0.195	0.156	0.894	0.106	Water
	11399.5	11475	75.5	59.25	0.785	0.136	0.158	0.365	0.635	
R9	11963.5	12033	69.5	25	0.36	0.212	0.285	0.688	0.312	Oil
	12033	12136	103	93.5	0.908	0.136	0.2	0.234	0.766	
R10	12331	12602.5	271.5	29.25	0.108	0.226	0.177	0.762	0.238	Oil
	12602.5	12633	30.5	29.5	0.967	0.147	0.184	0.129	0.871	
	12633	12841.5	208.5	129	0.619	0.16	0.187	0.791	0.209	
	12841.5	12897.5	56	0.5	0.009	0.264	0.146	0.782	0.218	
	12897.5	13090	192.5	178	0.925	0.124	0.176	0.207	0.793	
R11	13169.5	13486.5	317	64.75	0.204	0.216	0.164	0.516	0.484	Oil
	13486.5	13588	101.5	88.25	0.869	0.159	0.176	0.156	0.844	
R12	13669.5	13840.5	171	4.5	0.026	0.241	0.147	0.657	0.343	Gas/Oil
	13840.5	13901.5	61	51.25	0.84	0.114	0.148	0.103	0.897	
	13945	14030	85	62.5	0.735	0.128	0.133	0.249	0.751	
R13	14030	14312	282	215.25	0.763	0.129	0.149	0.869	0.131	Water
	14312	14479	167	13.75	0.082	0.136	0.135	0.616	0.384	

Note: N/G = net-to-gross, Av. Vcl = average volume of clay, Av. Phi = average effective porosity, Av Sw = average water saturation and Av Sh =average hydrocarbon saturation.

CONCLUSION

Regional geologic studies carried out across several fields in the eastern Coastal Swamp of the Niger Delta, provided a rare opportunity for a better understanding of the stratigraphic and structural framework and reservoir distribution across the eastern Coastal Swamp Depobelt of the Niger Delta. Maximum flooding surfaces mark regional seals and cap the major reservoir units across the various fields in the study area. Observed structural styles and associated entrapment mechanisms fault such as rollover anticlines, fault dependent closures, regional hanging wall and footwalls are typical of those found most giant oil fields of the world. These structural features have thrown light to several possible existing hydrocarbon leads identified at intermediate and deeper intervals at several zones that are yet to be drilled. In terms of hydrocarbon exploration, the alternation of sands of the LST and HST and the shale units of the TST offer good reservoir and seal / source rocks. Well stratigraphic correlation and event mapping on seismic sections have also helped in unravelling zones and intervals that have not been drilled, but were possibly by-passed. Petrophysical evaluation revealed the presence of hydrocarbon fluid such oil and gas occurring at several reservoir intervals.

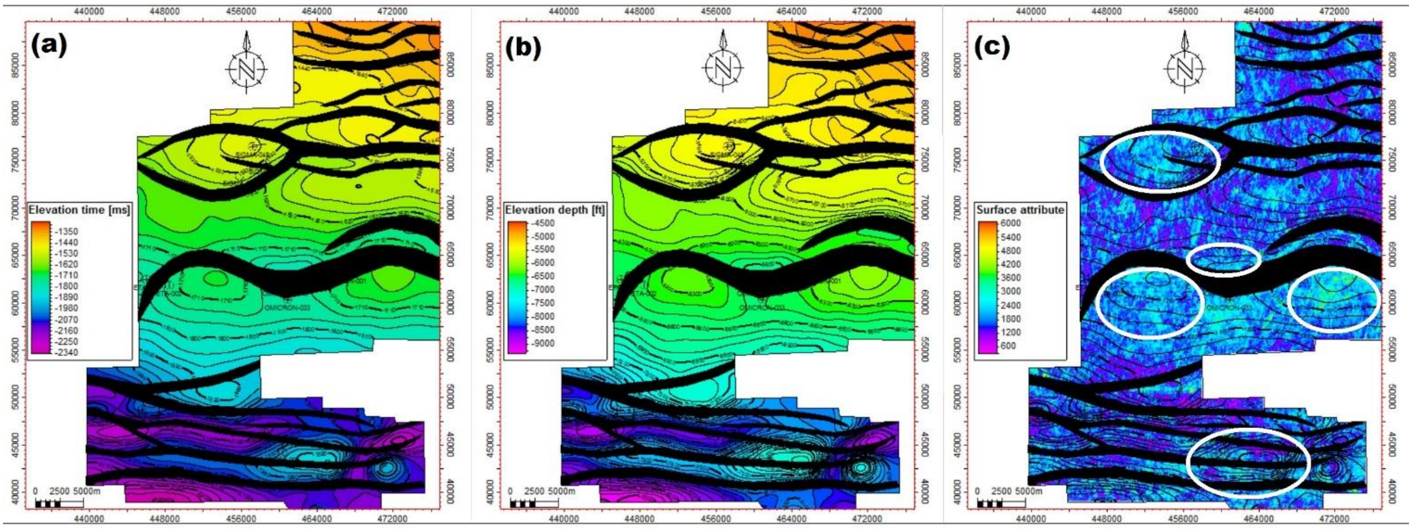

Figure 13. a) Structural time maps (STM), b) Structural depth maps (SDM) c). Amplitude Map with encircled (white ring) section with booming amplitude – hydrocarbon indicator.

The deepest well in the area is 16,000 feet, but beneath are possible leads that could hold great potential in deep and ultra-deep prospects, as seen from seismic sections and structural top maps. Hence, this points to the existence of prospectivity at intermediate and deeper horizons in the eastern Coastal Swamp Depobelt of the Niger Delta.

ACKNOWLEDGEMENT

The authors are grateful to the entire Geological Services, Geophysics, Exploration and IT-Help Desk teams of the Shell Petroleum Development Company of Nigeria Limited for provision of dataset and technical support which were instrumental to the success of this work.

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