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Hydrocarbon Prospectivity in the Eastern Coastal Swamp Depo-belt of the Niger Delta Basin

Stratigraphic Framework and Structural Styles

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Contents

Abstract

Detailed studies have been carried out within the Middle to Late Miocene sequence of the Niger Delta basin using well logs, biostratigraphic, paleobathymetric, hydrocarbon type/occurrence and seismic data integrated with sequence stratigraphic tool. This involved interpretation aimed at understanding the sequence stratigraphic framework and structural styles to better unravel possible hydrocarbon leads and prospects at the intermediate and deeper intervals of the Eastern Coastal Swamp depobelt of the onshore Niger Delta basin. Facies interpretations reveal the occurrence of four lithofacies units; namely (a) sandstones facies, (b) shaly sandstone facies, (c) mud-rock facies, and (d) heterolithic facies. Well log sequence stratigraphic interpretation and correlation across these fields indicates that ten major stratigraphic bounding surfaces, five each of sequence boundaries (SB) with ages ranging from 13.1 Ma through 8.5 Ma and maximum flooding surfaces (MFS) with ages between 12.8 Ma and 7.4 Ma respectively, were identified and correlated. Four depositional sequences were delineated and stratigraphic flattening at various ages (MFSs) indicates that there is a shift of the depo-center from north to south. Stacking patterns (progradational, retrogradational and aggradational) were delineated and interpreted as lowstand systems tract (LST), highstand systems tract (HST) and transgressive systems tract (TST) using their bounding surfaces. The alternation of the LST, HST and TST offers good reservoir sands and source/seal shales for hydrocarbon accumulation. 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. The environment of deposition spans through inner mid-shelf, shelf margin and slope margin constituting incised valley and channel-filled deposits. Horizon and faults that were mapped and interpreted in seismic volume shows that the stratigraphy of the area were greatly influenced by structures as sediment deposits thicken down-dip of the down-thrown section of the bounding faults. Structural interpretations reveal the occurrence of back to back (horst block-trapezoid zone), collapse crest structures, simple/faulted rollovers, regional foot walls/hanging walls and sub-detachment structures dominating within the mainly extensional zone and these constitute the major hydrocarbon traps in the area. The distribution of hydrocarbon types is such that gas is concentrated at the proximal end (northern section), oil and gas at the central part while oil predominates at the distal end (towards the southern part). Generally, structural and stratigraphic framework has shown that indeed there exist zones at intermediate and deeper intervals with booming amplitudes and well-developed trapping mechanisms that have not been drilled. These form possible hydrocarbon leads that should be subjected to further revalidation. Hence, an evaluation of lithofacies, depositional environment, stratigraphy, structures, reservoirs, seals, hydrocarbon types and distribution is critical in hydrocarbon prospectivity at intermediate and deeper depths across the eastern Coastal Swamp depobelt of the Niger Delta.

Keywords Hydrocarbon prospectivity · Sequence stratigraphic framework · Structural styles · Coastal swamp depobelt · Niger delta basin

Chapter 1
General Introduction

1.1 Introduction

The Middle to Late Miocene sequence of the Niger Delta Basin can be said to be among the most challenging targets for both stratigraphic and structural interpretation in petroleum exploration because of the tectono-sedimentological factors involved in their deposition. The lithostratigraphic units (mainly the Akata, Agbada and Benin Formations) of this basin are thick, complex sedimentary units deposited rapidly during high-frequency, fluvio-deltaic-eustatic sea level oscillations. The surface upon which they were deposited is underlain by thick, under-compacted unstable mobile shales of the Akata Formation; this loading has produced a complex series of gliding surfaces and depobelts. In these depobelts, deposition commonly is controlled by large contemporaneous glide-plane extensional faults and folds. The basin structure and stratigraphy have been controlled by the interplay between rates of sediment supply and subsidence (Doust and Omatsola 1990). Many of the sediments were deposited within neritic to bathyal water depths and are highly variable in their patterns of deposition. Because of this complexity, the Niger Delta Basin remains highly attractive, but truly challenging in today's expensive deeper interval drilling.

The understanding of facies units, stratigraphic framework, structural configuration/style, hydrocarbon type and distribution within the paralic sequence of Middle to Late Miocene age across several fields in the Tertiary Niger Delta basin fills, is expected to improve immensely with the application of the concept of sequence stratigraphy. Recent developments in sequence stratigraphy (Posamentier and Allen 1999; Posamentier 2000; Catuneanu 2002; Catuneanu et al. 2005) offer a more definitive approach to stratigraphic interpretation of these strata. Greater emphasis on interpretation of well-log, biostratigraphic and paleobathymetric information, closely integrated with seismic data, increases the resolution for

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prediction of environment of deposition. This work presents the results of a regional geological mapping, correlation and interpretation, in which the aspects related to the stratigraphic and structural framework of the siliciclastic sequences, and the system tracts, depositional sequences, reservoirs, seals, structural styles and trapping mechanisms are discussed, with the view of unravelling possible hydrocarbon leads and the existence of prospectivity within deeper depths across the study area.

1.2 Location of the Basin and the Study Area

The Niger Delta Basin, situated at the apex of the Gulf of Guinea on the west coast of Africa, is one of the most prolific deltaic hydrocarbon provinces in the world (Fig. 1.1). The sedimentary basin occupies a total area of about 75,000 km^2 and is at least 11 km deep in its deepest parts. The study area spans through five major acreage/blocks/OMLs (oil mining lease), which for proprietary reasons are named OMLs I, II, III, IV and V. These acreages/blocks lie on the onshore part of the Eastern Coastal Swamp of the Niger Delta Basin. The field is between Latitudes 4° 20′ 00″ N and 4° 50′ 00″ N and Longitudes 6° 30′ 00″ E and 7° 10′ 00″ E and covers an area of approximately 3610 km^2 (Fig. 1.2).

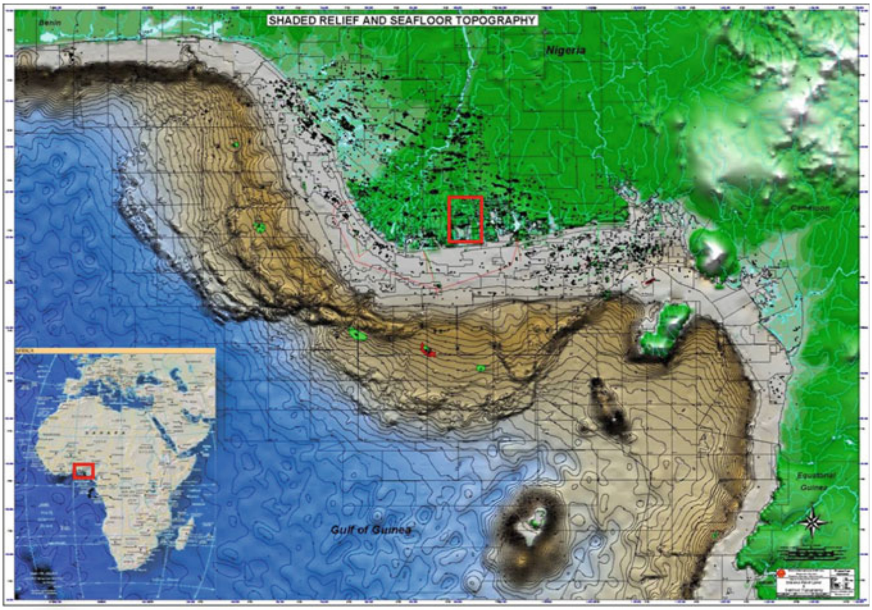

Fig. 1.1 Inset map of the Niger Delta basin in Africa and location map of the study area (*red rectangle*) showing relief and oil and gas concessions. *Source* Shell (2007)

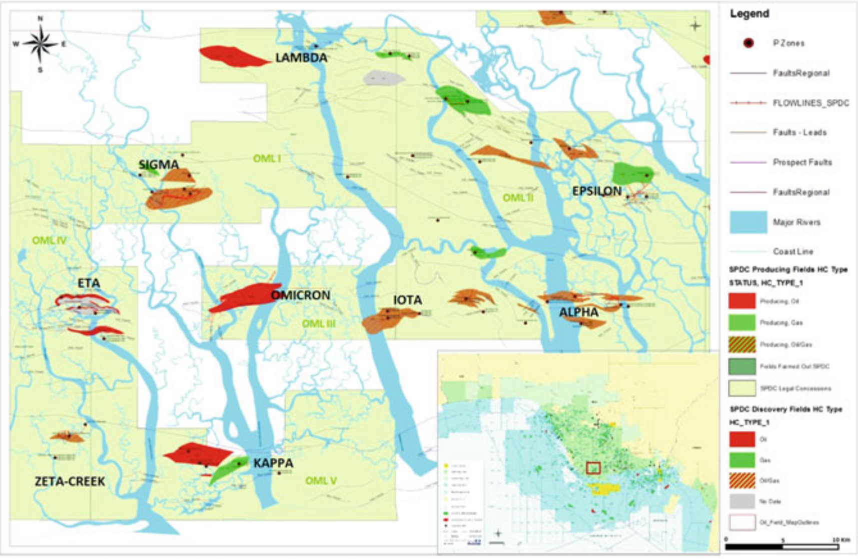

Fig. 1.2 Map of the study area showing the various fields and blocks (oil mining leases). NB: renamed for proprietary reasons. *Source* Shell (2012)

1.3 Literature Review

Detailed discussion on the history, evolution, and structural features of the Niger Delta can be found in the works of Allen (1964), Hospers (1971), Burke et al. (1971) and Whiteman (1982). Stoneley (1966) and Burke et al. (1972) analyzed and discussed the mega tectonic setting of the Niger Delta. The syn-sedimentary tectonics of the Tertiary delta was extensively described by Evamy et al. (1978). Previous studies reveal that the tectonic framework of the continental margin in the Niger Delta is controlled by Cretaceous fracture zones expressed as trenches and ridges in the deep Atlantic. The fracture zone ridges subdivide the margin into individual basins, and, in Nigeria, form the boundary faults of the Cretaceous Benue-Abakaliki trough, which cuts far into the West African shield. The trough represents a failed arm of a rift triple junction associated with the opening of the South Atlantic. In this region, rifting started in the Late Jurassic and persisted into the Middle Cretaceous (Lehner and De Ruiter 1977).

Detailed studies on tectonics, stratigraphy, depositional environment, petrophysics, sedimentology and hydrocarbon potential are well documented in the literature (Weber and Daukoru 1975; Doust and Omatsola 1990; Reijers and Nwajide 1996; Nton and Adebambo 2009; Nton and Adesina 2009, among others). The Niger Delta, on the passive western margin of Africa, has long been recognized as a classic example of continental-margin structural collapse under sediment loading (Daily 1976; Khalivov and Kerimov 1983; Morley 1992; Morley et al. 1998;

Rensbergen et al. 1999; Edwards 2000; Rensbergen and Morley 2000). The modern Niger Delta has distinctive basinward variations in structural style that define; (1) an inner extensional zone of listric growth faults beneath the outer shelf; (2) a translational zone of diapirs and shale ridges beneath the upper slope; and (3) an outer compressional zone of imbricate toe-thrust structures beneath the lower slope (Hooper et al. 2002). These areas of contrasting structural style are linked on a regional scale by slow gravity collapse of this thick deltaic prism (Damuth 1994).

Although broad regional relationships between patterns of deposition and deformation caused by structural collapse within the inner extensional zone of the Niger Delta have been proposed (Knox and Omatsola 1989), details of high-frequency sequence development within this setting are less well documented. Most recent stratigraphic studies of the Niger Delta deposits based on modern three-dimensional (3-D) seismic records have focused on relationships between depositional patterns within the compressional toe of this clastic wedge along the base of the continental slope (Morgan 2004; Adeogba et al. 2005; Corredor et al. 2005). Short and Stauble (1967) defined three formations within the 13,000 ft thick Niger Delta clastic wedge based on sand/shale ratios estimated from subsurface well logs: (i) basal, offshore-marine, and pro-delta shale of the Akata Formation; (ii) interbedded sandstone and shale of the dominantly deltaic Agbada Formation; and (iii) the capping sandy fluvial Benin Formation.

Previous sedimentological, biostratigraphical and sequence-stratigraphic studies (Ladipo et al. 1992; Stacher 1995; Reijers et al. 1997) revealed the combined influence of eustatic cyclicity and local tectonics. Recent studies on the offshore Niger Delta (Owajemi and Willis 2006; Magbagbeoloa and Willis 2007) demonstrate that these concepts are still valid but perhaps could benefit from the stratigraphic information and the new approaches presented here. Depositional sequences as defined by Vail (1987) and consisting of strata bounded by unconformities and their lateral equivalents are only recognised in specific sectors of the delta. In contrast, delta-wide genetic sequences as defined by Galloway (1989) and consisting of strata bounded by maximum flooding surfaces within transgressive shales are more readily identifiable in the Niger Delta. Individual sea-level cycles are reflected in the Niger Delta in various sedimentary sequences. Interferences of cycles with different periods result in megasequences that are chronostratigraphically confined and sedimentologically characterised.

Sequence stratigraphic concepts are increasingly finding new and unique applications in the regressive siliciclastic deposits of the Niger Delta. Haq et al. (1988) found that the most useful criteria for the recognition of sequence boundaries in the acreage in the Niger Delta include truncation of underlying reflections, drape, dip discordance, or onlap of younger reflection over topography on sequence boundary, contrasts in seismic attributes across the sequence boundary and the sequence termination of faults at the sequence boundary. Pacht and Hall (1993) applied the sequence stratigraphic concept to exploration in the offshore of the Niger Delta. Stacher (1994) revised the earlier SPDC Bio and Time-Stratigraphic Scheme and put the scheme in a sequence stratigraphic framework allowing correlation with Haq et al. (1988) sea level curve using the Harland et al. (1992) global time scheme. Bowen et al. (1994) established an integrated geologic framework of the Niger Delta slope, by applying established sequence stratigraphic concepts, on the newly acquired seismic data sets of the Niger Delta, coupled with biostartigraphic data, from twenty-six (26) key wells.

Over the years, delta wide framework of Cretaceous chronostratigraphic surfaces, and a sequence stratigraphic chart for the Niger Delta has been produced, using biostratigraphic data, obtained from several wells. Ozumba (1999) developed a sequence stratigraphic framework of the western Niger Delta, using foraminifera and wire line log data obtained from four wells drilled in the coastal and central swamp depobelts. He concluded that the late Miocene sequences were thicker than the middle Miocene sequences. Asseez (1976) reviewed the stratigraphy, sedimentation and structures of the Niger Delta. Merki (1972), described the structural geology of the Tertiary Niger Delta, which is on the overlap sequence that is deformed by syn-sedimentary faulting and folding. Ekweozor and Daukoru (1984, 1994) presented a detailed report on the petroleum geology and stratigraphy of the Niger Delta showing the relationship between depositional patterns, structures and stratigraphy and their influence on the oil generation in the Niger Delta basin (Knox and Omatsola 1989).

This current work focuses on understanding the distribution of lithofacies, systems tracts, hydrocarbon type and establishing the stratigraphic framework and structural configuration or styles within the paralic sequence of Middle to Late Miocene age across several fields in the Eastern Coastal Swamp of the Tertiary Niger Delta.

1.4 Aim and Objectives of Study

This research is aimed at integrating well logs, biostratigraphic, paleobathymetric, hydrocarbon type/occurrence and seismic data with sequence stratigraphic tools to better understand the structural and stratigraphic framework and hence unravel possible hydrocarbon leads and the existence of prospectivity within intermediate and deeper intervals in the Eastern Coastal Swamp depobelt of the Niger Delta basin.

The objectives of this research work involve:

(i) delineating and correlating of the lithofacies, key stratigraphic bounding surfaces, systems tracts, depositional sequences across wells, to understand the environment of deposition and the distribution of source, seal and reservoir rock presence in the study area,

(ii) mapping of the delineated stratigraphic surfaces (events/horizons) and structures (faults) on seismic data to better establish the stratigraphic and structural framework and understand the influence of structures on stratigraphy, which will help in identifying possible hydrocarbon leads (especially at intermediate and deeper leads),

(iii) using available data on hydrocarbon occurrence at different intervals to establish trends/distribution of hydrocarbon types (gas and/or oil) across the study area which are useful in influencing exploration and production decisions.

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Chapter 2
Geologic Framework

2.1 Regional Tectonic Setting

The Niger Delta basin is located at the southernmost extremity of the elongated intracontinental Benue Trough. To the west, it is separated from the Dahomey (or Benin) basin by the Okitipupa basement high, and to the east it is bounded by the Cameroun volcanic line. Its northern margin transects several older (Cretaceous) tectonic elements—the Anambra basin, Abakaliki basin, Afikpo syncline, and the Calabar Flank (Fig. 2.1a).

The evolution of the Niger delta is controlled by pre- and synsedimentary tectonics described by Evamy et al. (1978), Ejedawe (1981), Knox and Omatsola (1989) and Stacher (1995). The tectonic framework of the continental margin along the West Coast of equatorial Africa is controlled by Cretaceous fracture zones expressed as trenches and ridges in the deep Atlantic. The fracture zone ridges (Fig. 2.1b) subdivide the margin into individual basins, and, in Nigeria, form the boundary faults of the Cretaceous Benue-Abakaliki trough, which cuts far into the West African shield. The trough represents a failed arm of a rift triple junction associated with the opening of the South Atlantic. Rifting started in the Late Jurassic and persisted into the Middle Cretaceous (Lehner and De Ruiter 1977). In the Niger Delta region, rifting diminished altogether in the Late Cretaceous. Figure 2.2a, b show the gross paleogeography of the region as well as the relative position of the African and South American plates since rifting began.

After rifting ceased, gravity tectonics became the primary deformational process. For any given depobelt, gravity tectonics were completed before deposition of the Benin Formation and are expressed in complex structures, including shale diapirs, roll-over anticlines, collapsed growth fault crests, back-to-back features, and steeply dipping, closely spaced flank faults (Evamy et al. 1978; Xiao and Suppe 1992). These faults mostly offset different parts of the Agbada Formation and flatten into detachment planes near the top of the Akata Formation.

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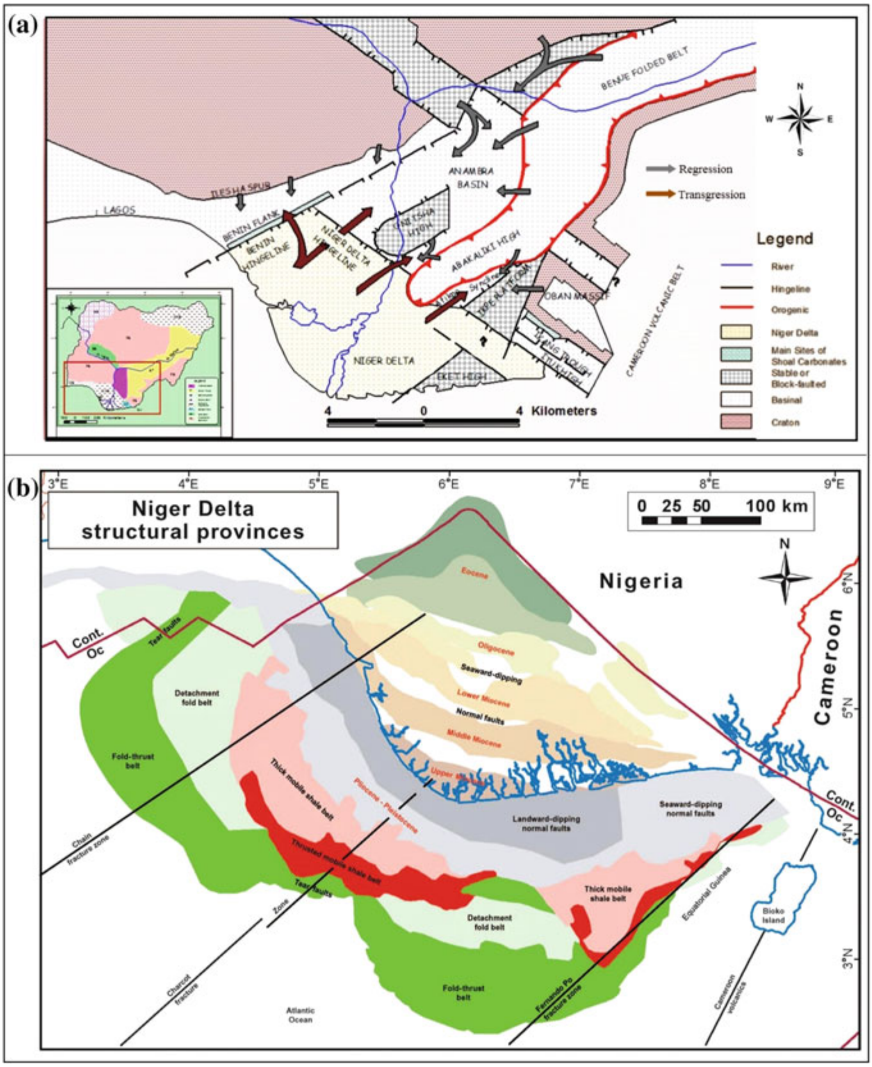

Fig. 2.1 Tectonic setting and structural elements of the Niger Delta Basin. **a** Tectonic Map showing the Niger Delta (After Kogbe 1989). **b** Regional structural provinces map of the Niger Delta showing the Fracture Zones (Wiener et al. 2010)

The Niger Delta stratigraphic sequence comprises an upward-coarsening regressive association of Tertiary clastics up to 12 km thick (Weber and Daukoru 1975; Evamy et al. 1978). It is informally divided into three gross lithofacies: (i) marine claystones and shales of unknown thickness, at the base; (ii) alternation of sandstones, siltstones and claystones, in which the sand percentage increases upwards; (iii) alluvial sands, at the top (Doust 1990). Three lithostratigraphic units

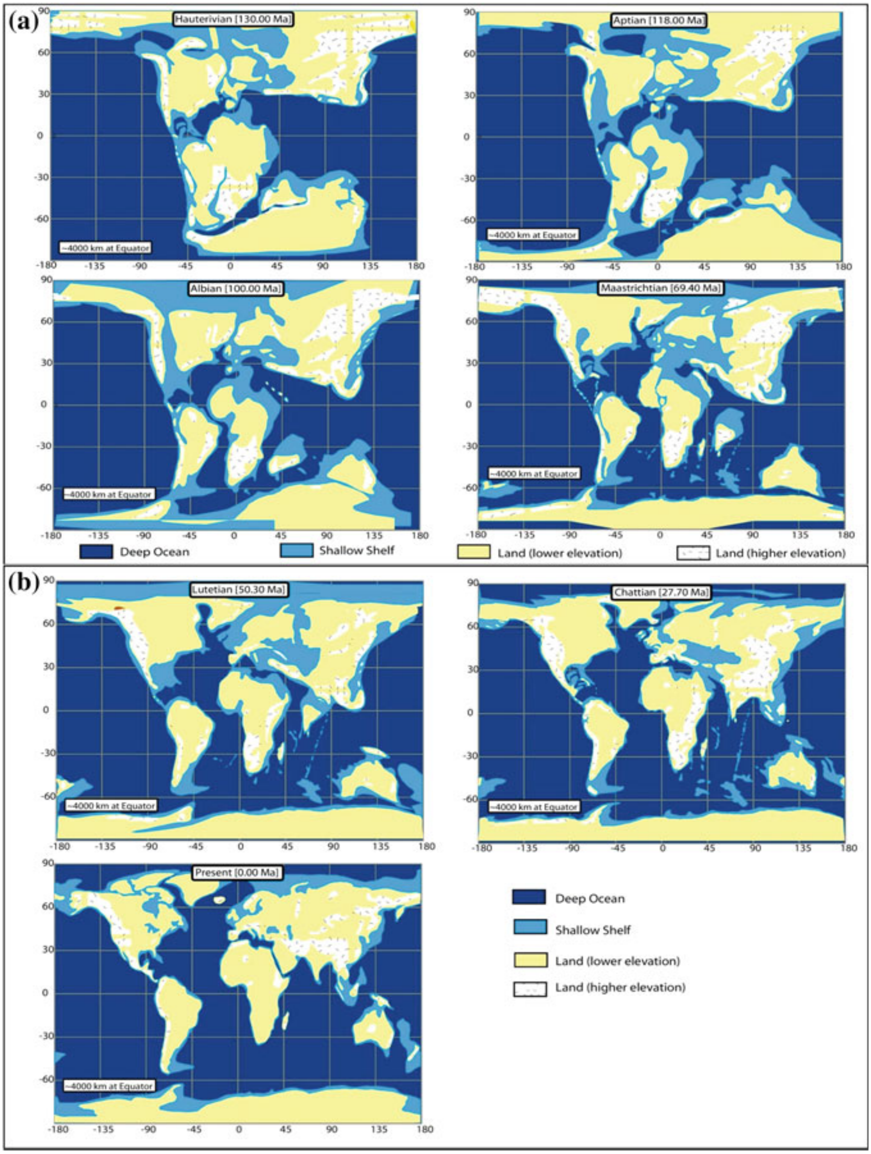

Fig. 2.2 Paleogeography showing the opening of the South Atlantic, and development of the region around Niger Delta. **a** Cretaceous paleogeography (130.0–69.4 Ma). **b** Cenozoic paleogeography (50.3 Ma to present). Plots generated with PGIS software (Tuttle et al. 1999)

have been recognized in the subsurface of the Niger Delta (Short and Stauble 1967; Frankl and Cordy 1967; Avbovbo 1978). These are from the oldest to the youngest, the Akata, Agbada and Benin Formations all of which are strongly diachronous (Fig. 2.3a, b).

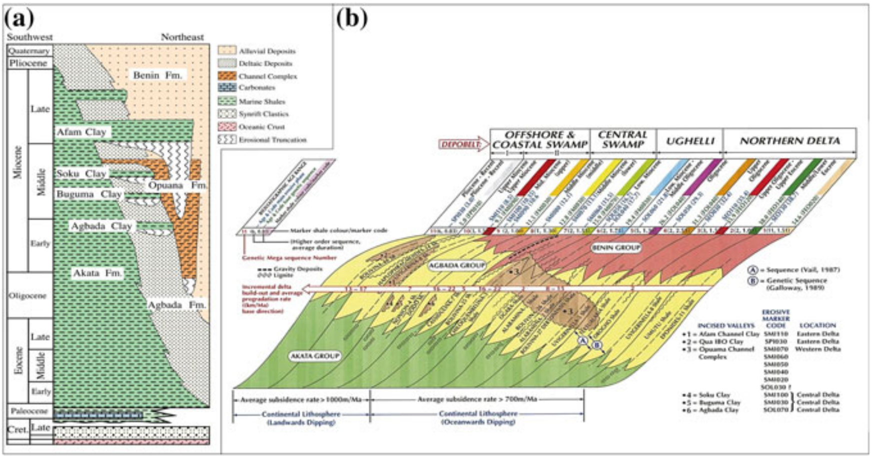

Fig. 2.3 Stratigraphy of Niger Delta Basin. **a** Stratigraphic column showing the three formations of the Niger Delta (modified from Lawrence et al. 2002). **b** Diagrammatic representation of the stratigraphic evolution of the Niger Delta (After Reijers 2011)

2.2 Regional Stratigraphic Setting

2.2.1 Akata Formation (Marine Shales)

The Akata Formation (Eocene–Recent) is the oldest lithostratigraphic unit in the Niger Delta. It is a marine sedimentary succession that is laid in front of the advancing delta and ranges from 1,968 to 19,680 ft in thickness. It consists of mainly uniform under-compacted shales, clays, and silts at the base of the known delta sequence with lenses of sandstone of abnormally high pressure at the top (Avbovbo 1978). These streaks of sand are possibly of turbidite origin, and were deposited in holomarine (delta-front to deeper marine) environments. The shales are rich in both planktonic and benthonic foraminifera and were deposited in shallow to deep marine environments (Short and Stauble 1967). Marine shales form the base of the sequence in each depobelt and range from Paleocene to Holocene in age. They outcrop offshore as diapirs along the continental slope, and onshore in the northeastern part of the delta, where they are known as the Imo Shale.

2.2.2 Agbada Formation (Paralic Clastics)

The Agbada Formation (Eocene–Recent) is characterized by paralic interbedded sandstone and shale with a thickness of over 3000 m (Reijers 1996). These paralic clastics are the truly deltaic portion of the sequence and were deposited in a number of delta-front, delta-topset, and fluvio-deltaic environments. The top of Agbada Formation is defined as the first occurrence of shale with marine fauna that coincides with the base of the continental-transitional lithofacies (Adesida and Ehirim 1988). The base is a significant sandstone body that coincides with the top of the Akata Formation (Short and Stauble 1967). Some shales of the Agbada Formation were thought to be the source rocks, however; Ejedawe et al. (1984) deduced that the main source rocks of the Niger Delta are the shales of the Akata Formation. The Agbada Formation forms the hydrocarbon-prospective sequence in the Niger Delta. As with the marine shales, the paralic sequence is present in all depobelts, and ranges in age from Eocene to Pleistocene. Most exploration wells in the Niger delta have bottomed in this lithofacies.

2.2.3 Benin Formation (Continental Sands)

The Benin Formation is the youngest lithostratigraphic unit in the Niger Delta. It is Miocene—Recent in age with a minimum thickness of more than 6000 ft and made up of continental sands and sandstones (>90 %) with few shale intercalations. The shallowest part of the sequence is composed almost entirely of nonmarine sand. The sands and sandstones are coarse-grained, sub-angular to well-rounded and are very poorly sorted. It was deposited in alluvial or upper coastal plain environments following a southward shift of deltaic deposition into a new depobelt. The oldest continental sands are probably Oligocene, although they lack fauna required to date them directly. Offshore, they become thinner and disappear near the shelf edge.

2.3 Depobelts

Deposition of the three formations occurred in each of five offlapping siliciclastic sedimentation cycles that comprise the Niger Delta (Fig. 2.4a, b). These cycles (depobelts) are 30–60 km wide, prograde southwestward 250 km over oceanic crust into the Gulf of Guinea, and are defined by synsedimentary faulting that occurred in response to variable interplay of subsidence and sediment supply rates (Doust and Omatsola 1990; Stacher 1995). Depobelts become successively younger basinward, ranging in age from Eocene in the north to Pliocene offshore of the present shoreline. These depobelts are separate unit that corresponds to a break in regional dip of the delta and is bounded landward by growth faults and seaward by large counter-regional faults or the growth fault of the next seaward belt. Each depobelt contains a distinct shallowing-upward depositional cycle with its own tripartite assemblage of marine, paralic, and continental deposits.

Depobelts define a series of punctuations in the progradation of this deltaic system. As deltaic sediment loads increase, underlying delta front and prodelta marine shale begin to move upward and basin-ward. Mobilization of basal shale caused

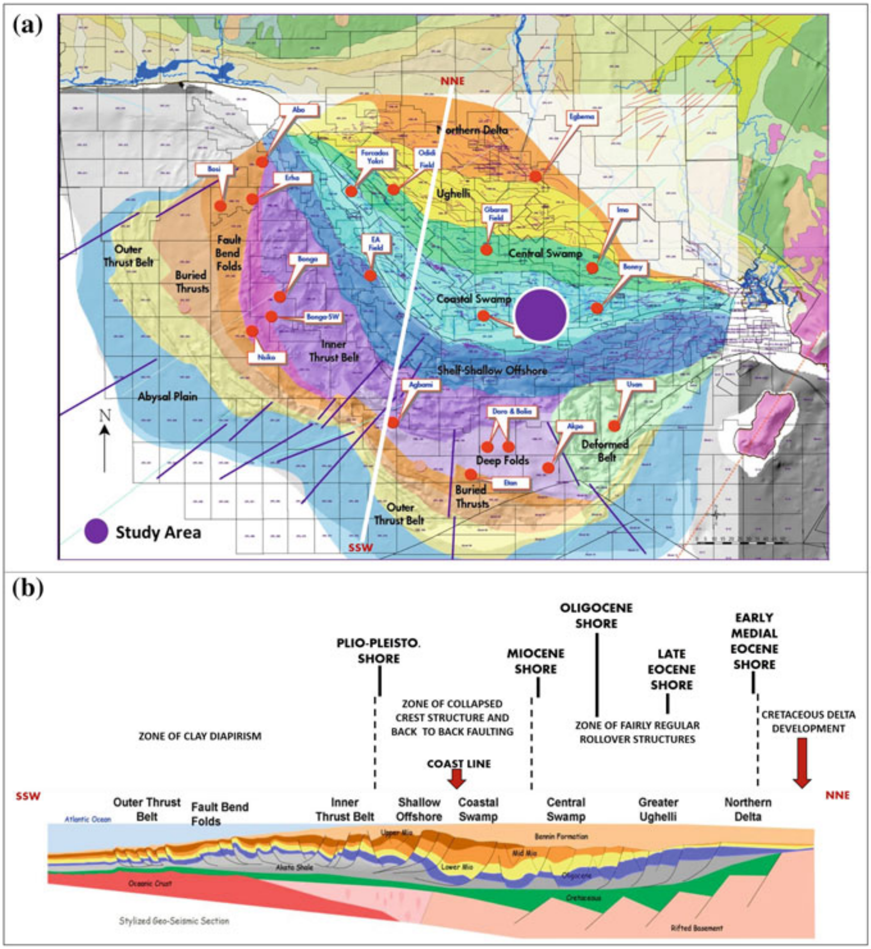

Fig. 2.4 Depositional belts showing the study area and Dip section of the Niger Delta Basin. **a** Depobelt map with the structural play segments, onshore and offshore Niger Delta Basin showing the study area. *Source* Shell (2007). **b** Schematic Dip section of the Niger Delta (After Shell 2007; Weber and Daukoru 1975)

structural collapse along normal faults, and created accommodation for additional deltaic sediment accumulation. As shale withdrawal nears completion, subsidence slows dramatically, leaving little room for further sedimentation. As declining accommodation forces a basinward progradation of sediment, a new depocenter develops basin-ward. The northern delta province, which overlies relatively shallow basement, has the oldest growth faults that are generally rotational, evenly spaced, and increase in steepness seaward. The central delta province has depobelts with well-defined structures such as successively deeper rollover crests that shift seaward for any given growth fault. The distal delta province is the most structurally complex due to internal gravity tectonics on the modern continental slope. The study area lies within the coastal swamp depobelt (Fig. 2.4a). It is described as shelf contained entities with respect to stratigraphy, structure building, and hydrocarbon distribution (Unukogbon et al. 2008).

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Chapter 3
Methodology

3.1 Dataset and Workflow

A total of nine (9) fields and twenty-four (24) wells were used in this study (Fig. 3.1). The oil/gas fields used in this study, for proprietary reasons, were renamed; Lambda, Sigma, Omicron, Epsilon, Alpha, Iota, Eta, Zeta-Creek and Kappa. The 3D seismic Post-Stack Depth Migrated (PosSDM) volume used comprises of a merge of various fields that include both Post-Stack Migrated (PosSTM) and Pre-Stack Time Migrated (PreSTM) data of several vintages (acquired and processed/reprocessed in the early 1990s and early 2000s). The summary of the workflow employed in this research is given in Fig. 3.2. This approach is effective in thick, complex strata, such as the late Cenozoic deposits of the Niger Delta Basin.

Well log suites used in this study are gamma ray (GR) logs, porosity logs (density and neutron) and resistivity logs. Interpreted biostratigraphic data (palynological (P) zone and foraminiferal (F) zones) and biofacies data comprising planktonic and benthic foraminiferal abundance/population and diversity were used for delineating stratigraphic bounding surfaces. Paleobathymetric data for various depth intervals of the wellbore were used to generate paleobathymetric maps. These information were calibrated and depth matched with corresponding well logs. Well log suites were displayed at consistent scales to enhance log trends and also aid lithofacies delineation and stacking pattern recognition. A combination of paleobathymetric information and depositional environment models (Allen 1964, 1965), were used in interpreting the various environments of deposition (Fig. 3.3). Key stratigraphic bounding surfaces such as Maximum Flooding Surfaces—MFSs (dated with marker shales) and Sequence Boundaries—SBs were delineated and matched with their corresponding P-Zones and F-Zones. They were calibrated using an established zonation schemes contained in the SPDC 2010 Niger Delta Chronostratigraphic Chart (Figs. 3.4 and 3.5). These surfaces were also correlated

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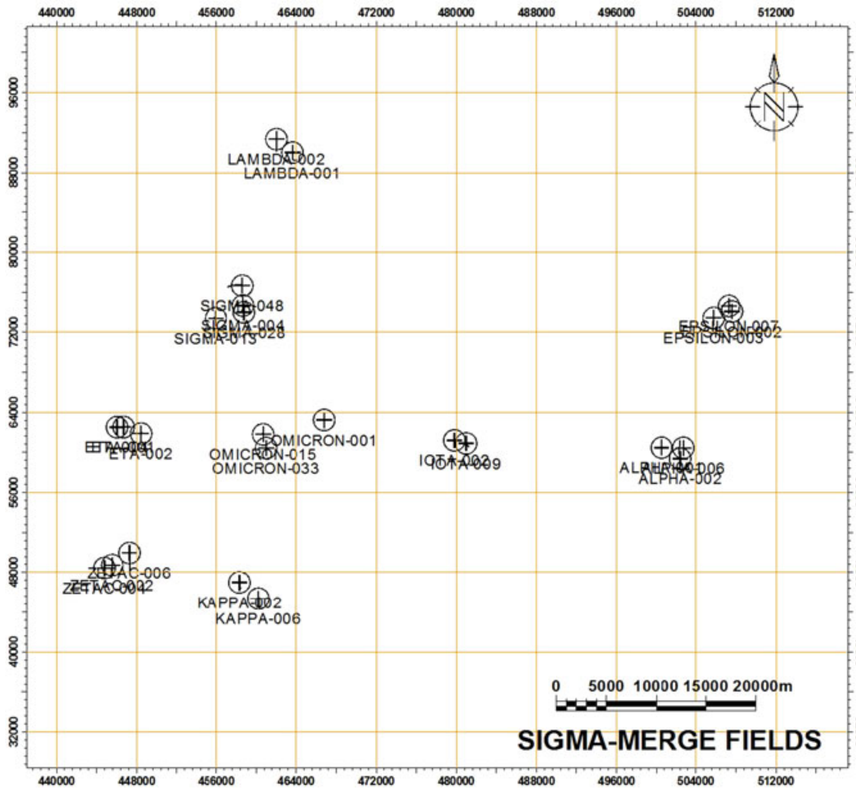


Fig. 3.1 Well bore location and distribution across fields in the study area

on well logs and mapped across the seismic volume respectively. Sequence stratigraphic models (Van Wagoner et al. 1990; Kendall 2008) aided well log sequence stratigraphic correlation/mapping and were applied in deciphering system tracts and depositional sequences.

3.1.1 Data Quality and Software Resources

In some wells the suites of logs used were completely logged throughout the wellbore while in some others only a small portion, the productive zone, were logged. The quality of the logs are quite good especially where the whole length of the wellbore is logged. Biostratigraphic data were not available for some well intervals, while some sections were represented as indeterminate. The seismic volume is characterized by data quality that generally deteriorates with increasing time/depth. The basal part (below 3.5 s TWT) is disrupted by several zones with

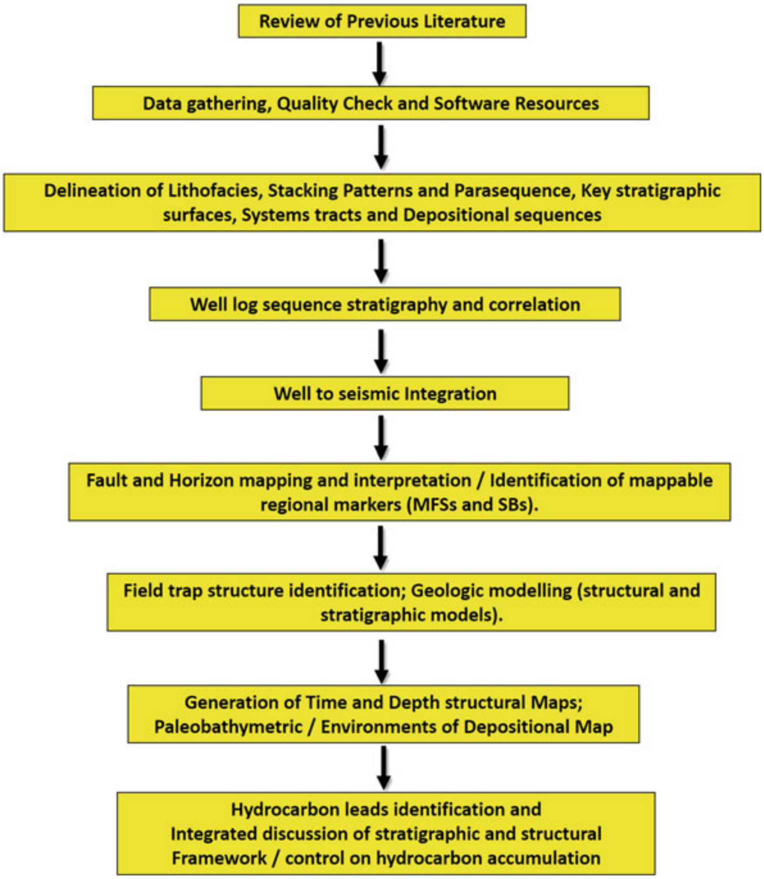


Fig. 3.2 Workflow chart

low to highly discontinuous reflection patterns, while the reflections between 3.5 and 1.5 TWT have moderate to good continuity and high amplitude variations. This aided the mapping and interpretation of faults and stratigraphic surfaces/horizons (MFS) on seismic sections. Time–depth (T-Z) curves (polynomial) were generated from plots using imported checkshots. This was used in depth-conversion of time structural maps to depth structural maps. Correlation panels 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 paleobathymetric maps in this study. Shell's nDI software and Petrel™ were both used to generate semblance volume, carry out fault and horizon interpretations and also generate top structural maps in this study.

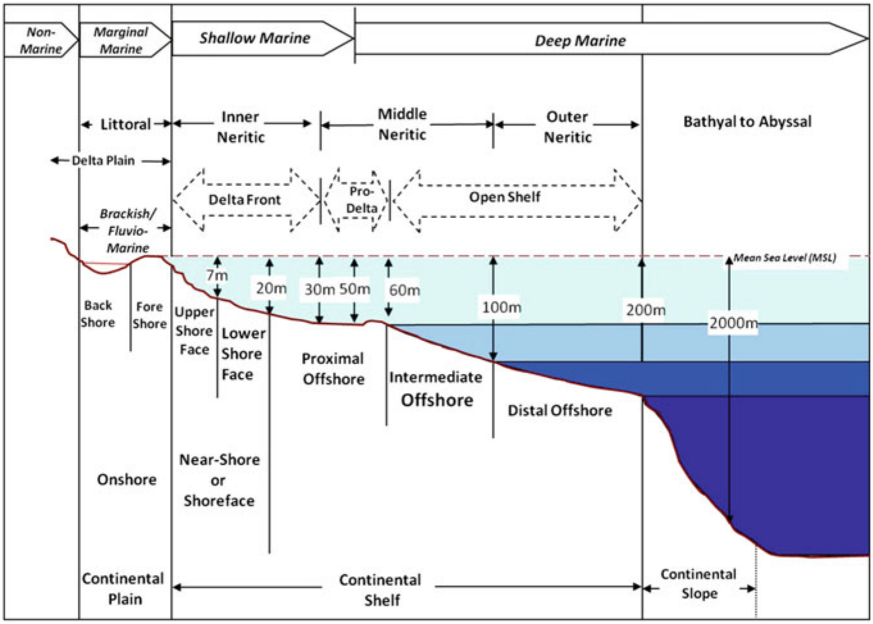


Fig. 3.3 Paleobathymetry and depositional environment chart (After Allen 1965)

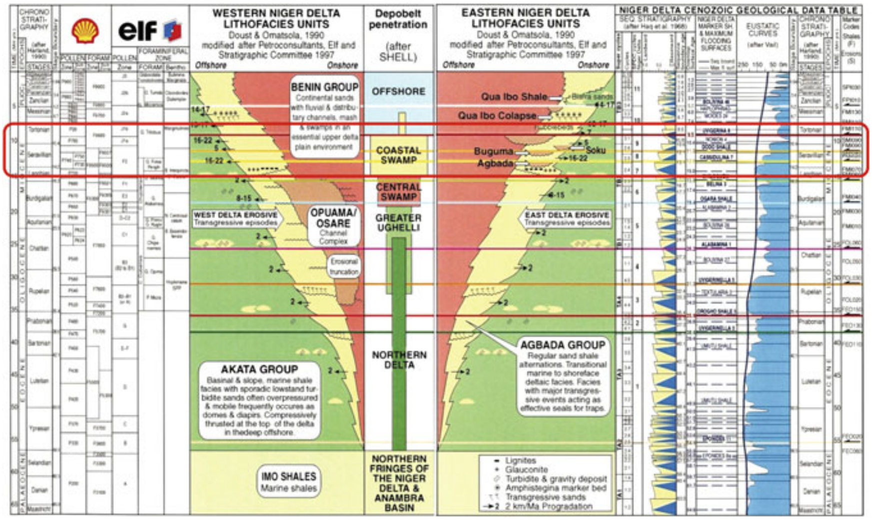


Fig. 3.4 Stratigraphic data sheet (west and east halves combined) of the Niger Delta Basin showing geologic interval (Middle–Late Miocene) of interest in red box (Reijers 2011)

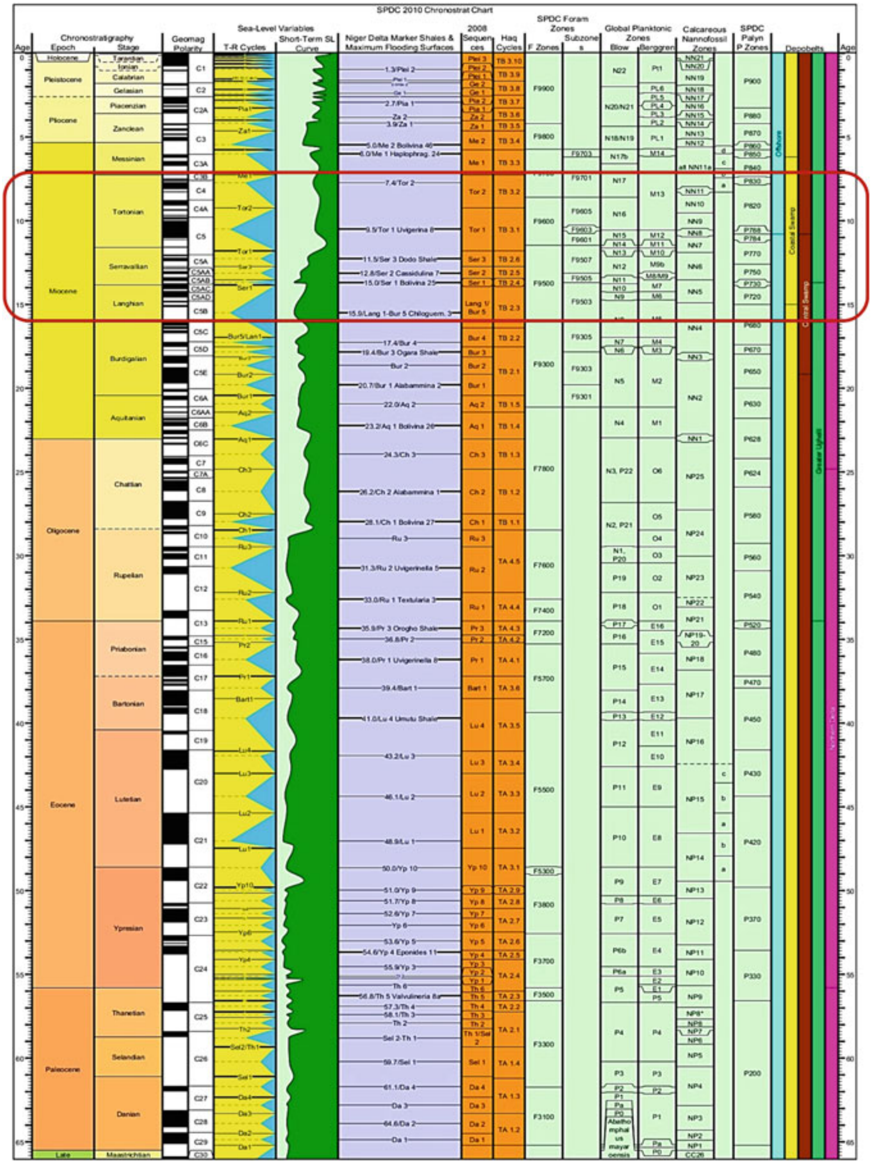


Fig. 3.5 SPDC 2010 Niger Delta Chronostratigraphic Chart showing geologic interval (Middle–Late Miocene) of interest in red box. *Source* Shell (2010)

3.2 Delineation of Lithofacies and Depositional Environments

Well log information obtained from gamma ray log values and signatures/patterns integrated with paleobathymeric data were used to delineate various rock units and lithofacies belonging to various environments of depositional. Bell shaped log patterns indicating increasing clay content up section or fining upward trends or an upward increase in gamma ray value, a typical feature of fluvial channel deposits. Funnel-shaped log patterns indicating decreasing clay content up section or a coarsening upward trend, clearly showed deltaic progradation. Cylindrical (blocky or boxcar) log motif was delineated as thick uniformly graded coarse grained sandstone unit, probably deposits of a braided channel, tidal channel or subaqueous slump deposits. Serrated log motif suggested intercalation of thin shales in a sandstone body, typical of fluvial, marine and tidal processes (Fig. 3.6a).

3.3 Stacking Patterns and Parasequences

The well log suites provided for the study were displayed at consistent scales to enhance log trends and also to aid recognition of facies stacking patterns and parasequences. Parasequence sets usually consist of succession of genetically related parasequences that have the same stacking pattern which consists of vertical occurrences of repeated cycles of coarsening or fining upwards sequences (aggradational, progradational or retrogradational), and typically bounded by major marine flooding surfaces and their correlative surfaces. Parasequence set boundaries may coincide with sequence boundaries in some cases (Fig. 3.6b).

Progradational Stacking (**Fore-stepping**): Progradational geometries occur when sediment supply exceeds the rate of creation of topset accommodation space, and facies belts migrate basinwards. In other words accommodation space is filled more rapidly than it is created, water depth becomes shallower, and facies increasingly move farther seaward over time. This results when the long-term rate of accommodation is exceeded by the long-term rate of sedimentation. Progradational stacked parasequence sets, builds out or advances somewhat farther seaward than the parasequence before. Each parasequence contains a somewhat shallower set of facies than the parasequence before. This produces an overall shallowing-upward trend within the entire parasequence set and the set is referred to as a progradational parasequence set or is said to display progradational stacking (Fig. 3.6b).

Retrogradational Stacking (**Back-stepping**): Retrogradational geometries occur when the rate of sediment supply is less than the rate of creation of topset accommodation space and facies belts migrate landward. In other words accommodation space is created more rapidly than it is filled, water depth becomes deeper, and facies increasingly move further landward. This results when the

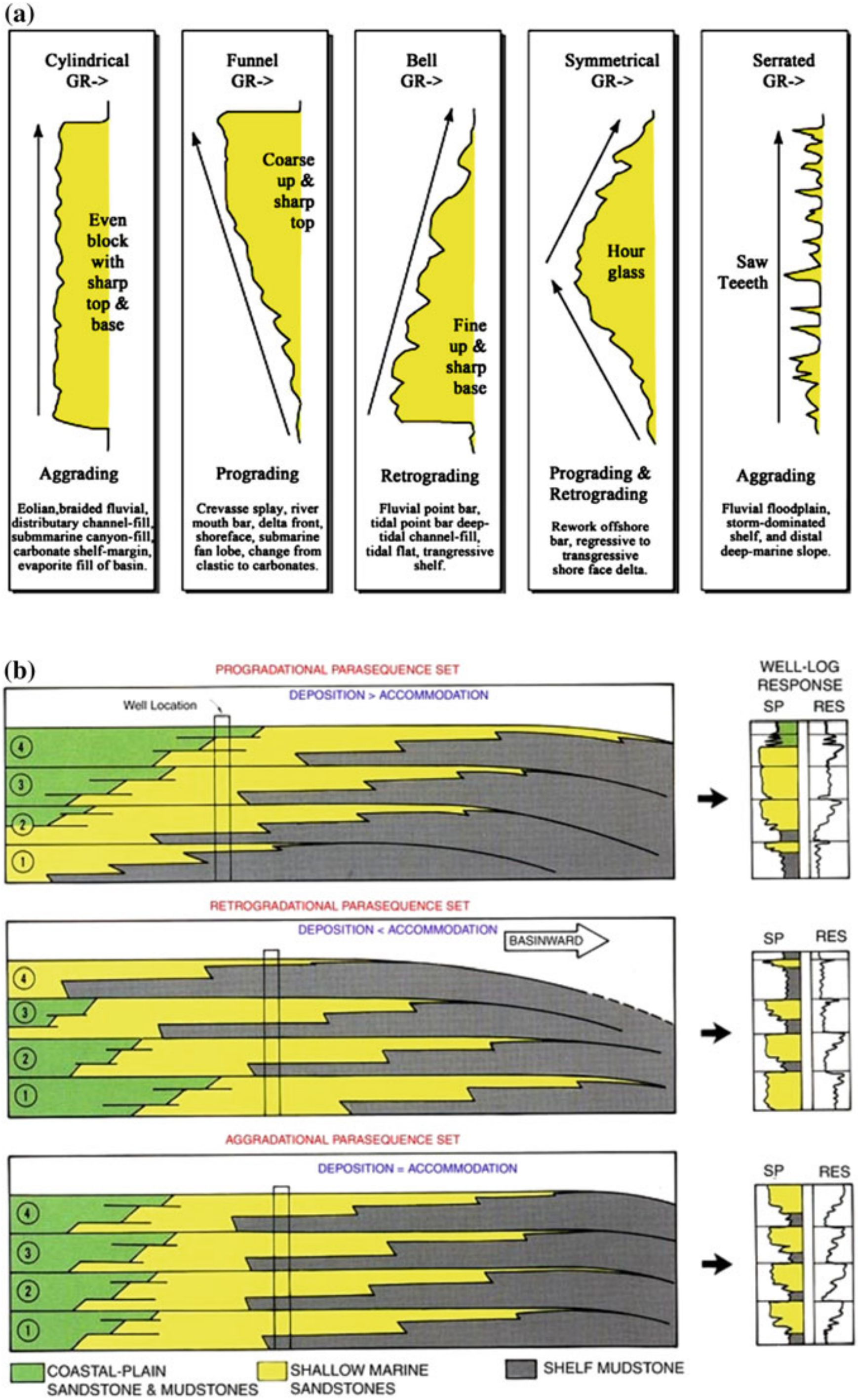


Fig. 3.6 Models for well log response to sediment packages and various stacking pattern. **a** Gamma ray response to stacking pattern/grain size variation model (After Emery and Myers 1996). **b** Parasequence stacking pattern model and well log response (After Van Wagoner et al. 1990)

long-term rate of accommodation exceeds the long-term rate of sedimentation. Retrogradational stacked parasequence sets, progrades less than the preceding parasequence. Each parasequence contains a deeper set of facies than the parasequence below. This net facies shift produces an overall deepening upward trend within the entire parasequence set and the set is referred to as retrogradational parasequence set or is said to display retrogradational stacking (Fig. 3.6b).

Aggradational Stacking: Aggradational geometries occur when the rate of sediment supply is about equal to the rate of creation of topset accommodation space and facies belts stack vertically. In other words accommodation space is filled about as rapidly as it is created, water depth remains constant from one parasequence to the next, and facies show no net landward or seaward movement. This results when long-term rate of accommodation closely matches the long-term rate of sedimentation. Aggradational stacked parasequence sets, prograde to roughly the same position as the previous parasequence. Each parasequence contains essentially the same suite of facies as the parasequences above and below. Hence, the lack of overall facies change results in no net vertical trend in water depth. This set is known as an aggradational parasequence set or is said to display aggradational stacking (Fig. 3.6b).

3.4 Key Stratigraphic Surfaces, Systems Tracts and Depositional Sequences

The Maximum Flooding Surface (**MFS**): This surface was delineated using well logs and biostratigraphic data as: the surface that caps the transgressive systems tract and marks the turnaround from retrogradational stacking in the transgressive systems tract to aggradational or progradational stacking in the early highstand systems tract; units with maximum positive neutron-density separation, high gamma response, minimum shale resistivity and high faunal diversity and abundance and maximum water depth. Plots in Petrel correlation panel of faunal abundance and diversity curves alongside well logs enhanced the delineation of the maximum flooding surfaces (Fig. 3.8a).

The Transgressive Surface of Erosion (**TSE**)/**Top of Lowstand** (**TLS**): A prominent flooding surface that caps the lowstand systems tract, is the first significant flooding surface to follow the sequence boundary and forms the base of the retrogradational parasequence stacking patterns of the transgressive systems tract. This was delineated and inferred from the presence of nick or neck on resistivity logs caused by presence of carbonate cements probably derived from the carbonate fauna eroded during ravinement of already deposited sediments. It usually occurs at the base of the retrogradational parasequence stacks of the transgressive systems tracts (Fig. 3.8a).

Sequence Boundaries (**SBs**): These were recognized in areas of low faunal abundance and diversity or absence of known bio-events, which corresponded to low gamma ray and high resistivity, responses within the shallowing section. Sequence boundaries were identified at the base of thickest and coarsest sand units between two adjacent maximum flooding surfaces, which naturally coincided with the shallowest environments associated with the least foraminiferal abundance and diversity or complete absence of foraminifera. The base of a progradational stacking pattern was also used to define a sequence boundary.

Systems Tracts: These are linkage of contemporaneous depositional systems, which are three-dimensional assemblages of lithofacies. A system tract might consist of fluvial and deltaic depositional systems. Sytems tracts are defined by their position within sequences and by the stacking pattern of successive parasequences. The three main systems tracts namely; the lowstand systems tracts (LST), transgressive systems tracts (TST), and highstand systems tracts (HST) were recognized, correlated and mapped with the aid of the depositional sequence model (Figs. 3.7a–c and 3.8a, b).

Depositional Sequences: These are relatively conformable (containing no major unconformities), genetically related succession of strata. Sequences are bounded by sequence boundaries (unconformities or their correlative conformities). These are also composed of successions of genetically linked deposition systems (systems tracts—LST, TST and HST) and are interpreted to be deposited between eustatic-rise and fall inflection points (Fig. 3.8a).

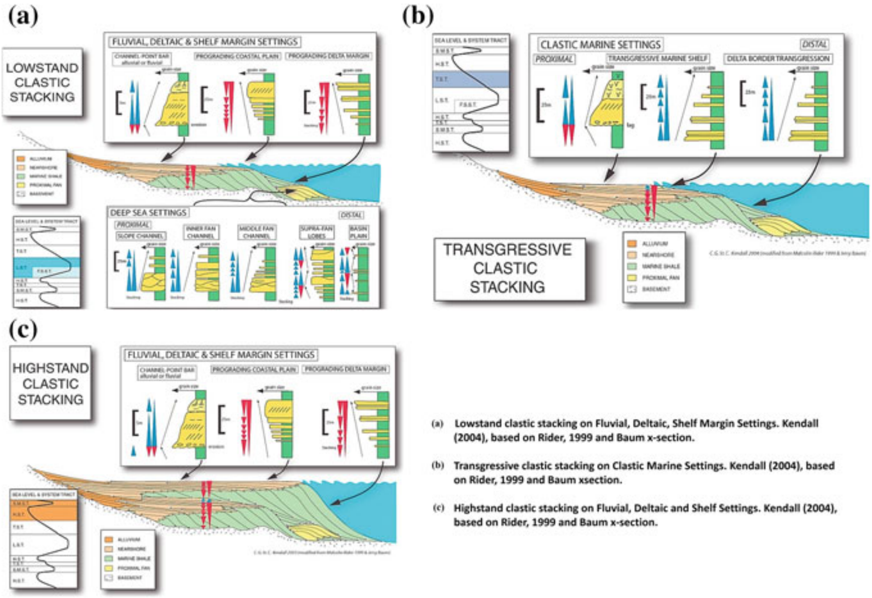
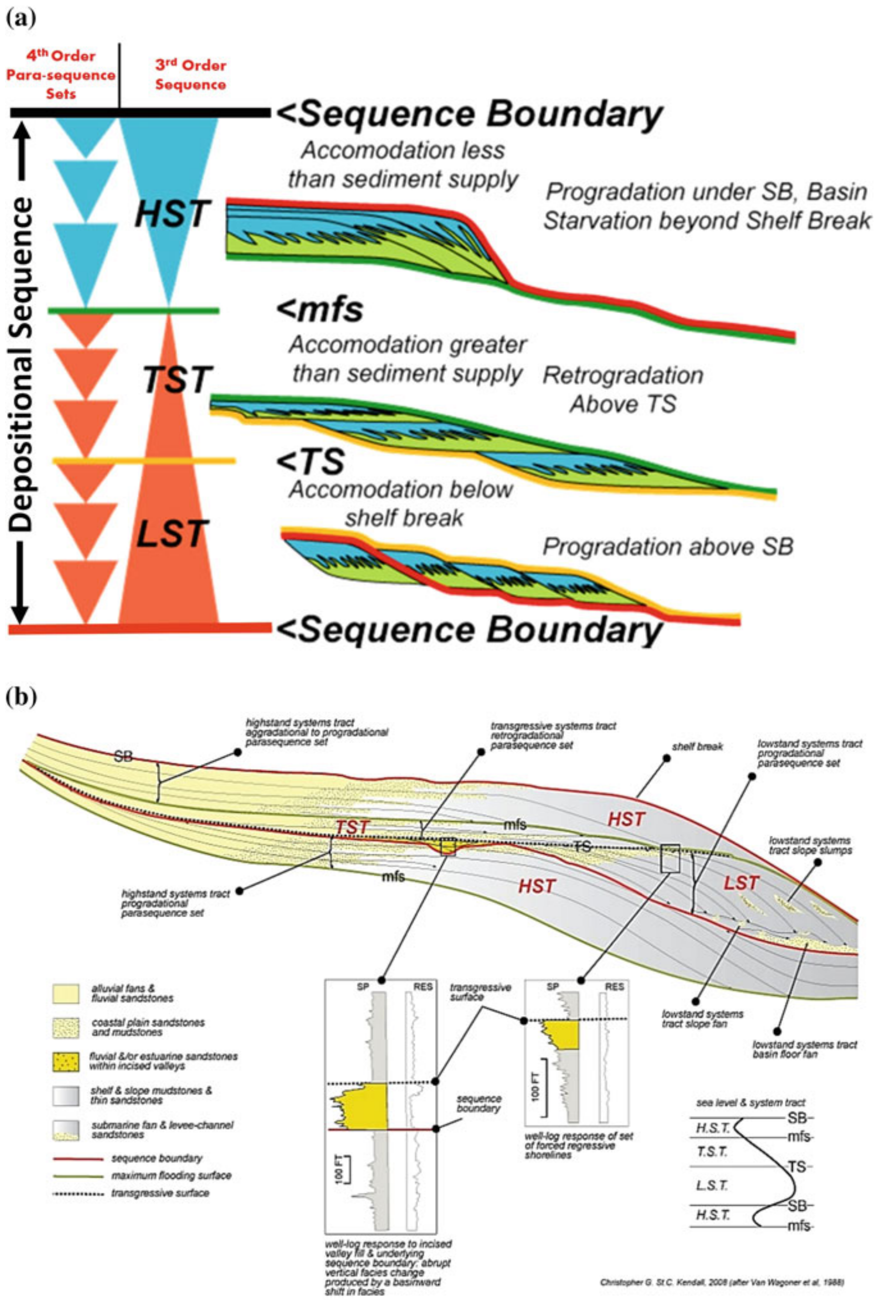


Fig. 3.7 Models for systems tracts clastic stacking for various depositional settings. **a** Lowstand clastic stacking on Fluvial, Deltaic, Shelf Margin Settings. Kendall (2004), based on Rider (1999) and Baum x-section. **b** Transgressive clastic stacking on Clastic Marine Settings. Kendall (2004), based on Rider (1999) and Baum x-section. **c** Highstand clastic stacking on Fluvial, Deltaic and Shelf Settings. Kendall (2004), based on Rider (1999) and Baum x-section



Christopher G. St.C. Kendall, 2008 (after Van Wagoner et al, 1988)

Fig. 3.8 Models showing various sequence stratigraphic surfaces and systems tracts. **a** Ideal clastic sequence Staking pattern (Kendall 2004). **b** Sequence stratigraphic model showing key stratigraphic surfaces and various systems tracts (Kendall 2008, After Van Wagoner et al. 1988)

3.5 Well Correlation

Well correlation was achieved using stratigraphic bounding surfaces (such as sequence boundaries and maximum flooding surfaces) of same geologic age defined in the study area. Marine flooding surfaces were the best markers or datum on which the correlation across sections were hung. Correlation was done to determine lateral continuity or discontinuity of facies, hence aiding source, seal and reservoir studies in the area. The delineated MFSs and SBs were dated with marker shales (P and F zones) and calibrated using the SPDC Niger Delta Chronostratigraphic Chart (Fig. 3.5). Relative ages of the surfaces mapped across the fields were determined using the provided biostratigraphic report and correlated with the established works on the study area. A template of well log sequence stratigraphic correlation in the Epsilon field which shows the main well datasets and interpretation tools used in this study is displayed in Fig. 3.9.

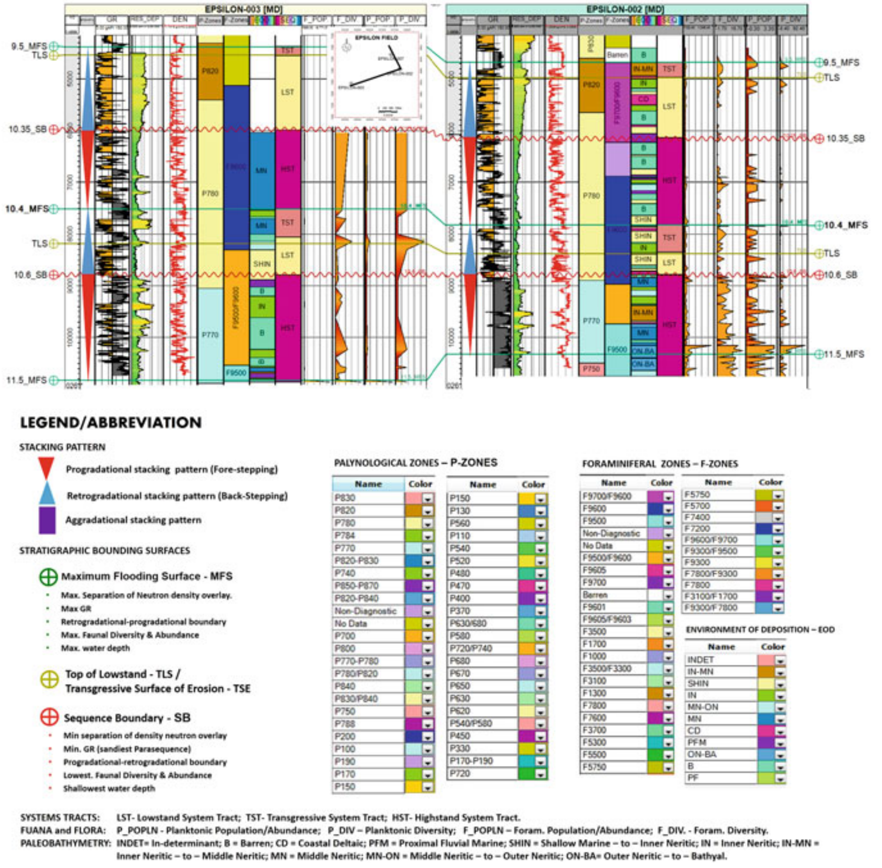


Fig. 3.9 Well log sequence stratigraphic correlation panel across one of the fields of study showing the template and representative data/tools used the study

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Chapter 4
Data Interpretations and Results

4.1 Lithofacies and Implication for Environments of Deposition

Lithofacies is an aspect of sedimentary facies that treats the total textural, compositional and structural characteristics of a sedimentary deposit (grain-size, composition, and dominant sedimentary structures only) resulting from accumulation and modification in a particular setting (Miall 1978). The stratigraphic sequence in the study area were generally divided into four (4) lithofacies, namely; (i) Sandstones Facies, (ii) Shaly Sandstone Facies, (iii) Mud-rock Facies, and (iv) Heterolithic Facies.

4.1.1 Sandstone Facies

Sandstone Facies are coarse-grained basal sandstone units that consists of amalgamated and isolated sharp-based fining upward sand bodies characterized by blocky to bell-shaped gamma ray log motif (Fig. 4.1). The sand units are partly separated by thin bands of shale/mudstone and lack marine fauna. This facies is interpreted as fluvial channel deposits based on these characteristics. These channel deposits represent deposition in a coastal plain setting landward of the tidal zone. The blocky log pattern is common in incised valley fills. The lack of serration in the gamma ray log signature and absence of marine fauna suggest minimal or complete absence of tidal influence.

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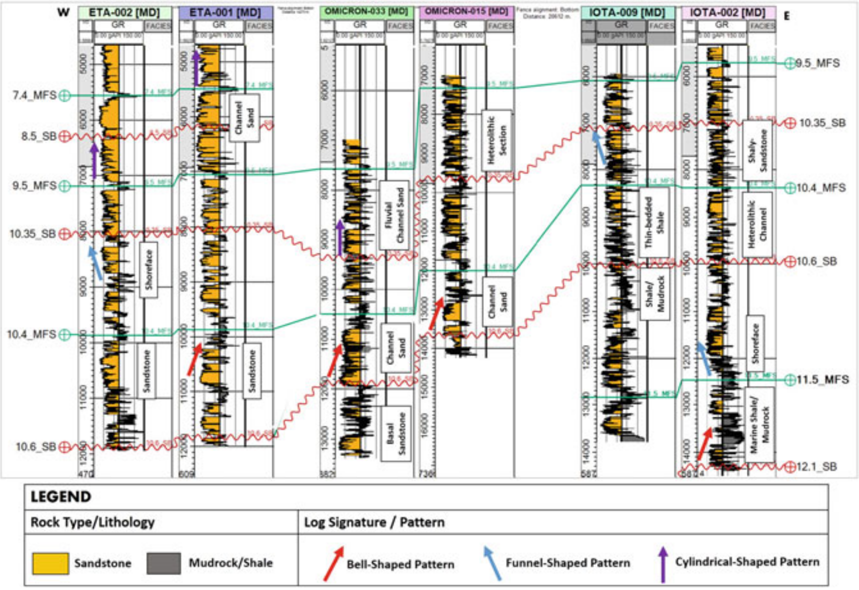


Fig. 4.1 Lithofacies across Iota, Lambda, Omicron and Sigma Field

4.1.2 *Shaly-Sandstone Facies*

Shaly-Sandstone Facies are characterised by the predominance of fine to medium-grained sandstones and mudstone/shale interbeds (Fig. 4.1). It consists predominantly of serrated funnel shaped gamma ray log pattern and sometimes serrated bell to blocky shaped patterns at certain intervals. These intervals are also characterised by little intervals exhibiting low frequency and low diversity of foraminifera belonging to the inner-outer neritic (IN-ON) depositional environment. This facies is interpreted as tide dominated estuarine deposits based on the presence of cyclic alternation of sandstones and mudstones. Each funnel shape represented a succession of coarsening–upward from mud to shallow/marginal marine sandstones. Rhythmic alternation of high gamma ray log response and serrated funnel, bell and blocky gamma ray log motif resulted from frequent fluctuations in current strength which is common in tidal processes. The successions are interpreted to have been deposited in a prograding, estuarine environment. The biofacies data showed increase in foraminiferal assemblages indicating progressive deeper water bathymetry within the mudstone units and low diversity forms at shallow water depths within the sandstone units.

4.1.3 Mudrock Facies

This facies is predominantly composed of shale units with thin siltstone intercalations displaying a retrogradational parasequence pattern. The facies also exhibited high frequency and diversity of foraminifera particularly those of outer neritic (ON) to bathyal (BA) depositional environments (Fig. 4.1).

4.1.4 Heterolithic Facies

This facies is comprised of sandstone and mudstone heteroliths. The sandstone unit is recognised as upward–cleaning units on the gamma ray log (Fig. 4.1). Crescent or bow trend in the gamma ray log shows a cleaning–up trend overlain by a dirtying up trend without any sharp break. Available biofacies data indicate that facies accumulated in proximal-fluvial marine (PFM) and inner-middle neritic (IN-MN) depositional environments (i.e. the facies is interpreted a shoreface deposits). Crescent log pattern is generally the result of waxing and waning clastic sedimentation rate. The serrated nature of the gamma ray log signature is indicative of tide/wave activity and the heteroliths probably reflect deposition from waning storm generated flows. The muddy portion characterised by high gamma ray values with paleobathymetry in the neritic environment indicates storm emplacement or inter-storm pelagic sedimentation.

4.2 Sequence Stratigraphic Interpretation

4.2.1 Maximum Flooding Surface (MFS)

MFSs were characterized by thick and extensive shale unit intervals in well log, that separate overall fining or thinning-upward intervals from coarsening or thickening-upward intervals. In seismic section they (MFS) are characterized by extensive and continuous, conformable events that can be correlated from fault block to fault block. Five (5) maximum flooding surfaces were identified in the study area. These surfaces, from the oldest to the youngest with their corresponding biozones have been described as follows; (i) 12.8 Ma Maximum Flooding Surface (MFS_12.8) was correlated across Lambda, Iota and Alpha wells and was dated 12.8 Ma using a regional marker, *Ser-2-Cassidulina.* This surface occurs within

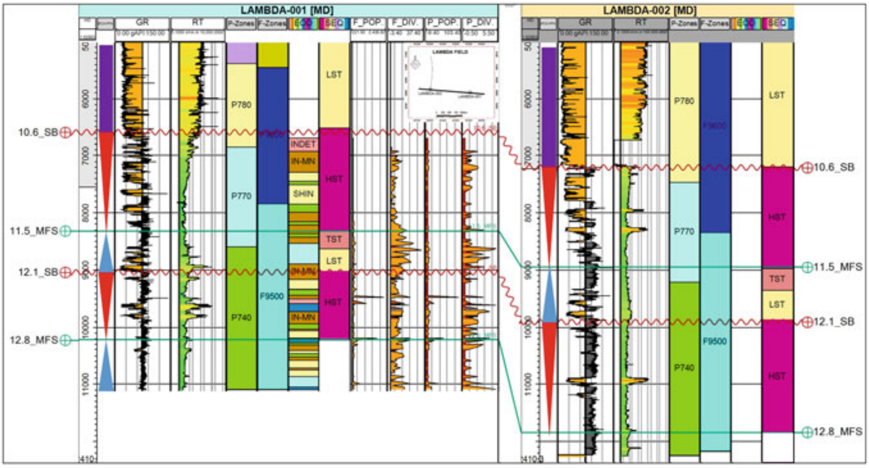


Fig. 4.2 Lambda field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

P680 and F9300/9500 biozones. (ii) 11.5 Ma Maximum Flooding Surface (MFS_11.5) was correlated across Lambda, Sigma, Epsilon, Alpha, Omicron, and Eta wells and was dated 11.5 Ma. using *Ser-3-Dodo Shale* regional marker. This surface occurred within P770 and F9500/F9600 biozones. (iii) 10.4 Ma Maximum Flooding Surface (MFS_10.4) was correlated through the entire field used in this study. In other words the record of this surface/event was seen across Lambda, Sigma, Epsilon, Alpha, Iota, Omicron, Eta, Zeta Creek and Kappa wells and was dated 10.4 Ma. using *Tor-Nonion-4* regional marker. This MFS occurred within P780 and F9600 biozones. (iv) 9.5 Ma Maximum Flooding Surface (MFS_9.5) was not seen in the Lambda field, however this was identified and correlated across the Sigma, Epsilon, Alpha, Iota, Omicron, Eta, Zeta Creek and Kappa wells. This surface was dated 9.5 Ma. using the *Tor-1-Uvigerina-8* regional marker. The MFS occurred within P820 and F9600 biozones. (v) 7.4 Ma Maximum Flooding Surface (MFS_7.4) was correlated across three (3) fields. These restricted correlation only to the Eta, Zeta Creek and Kappa wells. This surface was dated 7.4 Ma using the *Tor-2* marker. This MFS occurred within P830 and F9700 biozones. The well log sequence stratigraphic correlation using the MFS, for each field is seen in Figs. 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 and 4.10. The depth at which the MFS occurred in various wells is summarized in Table 4.1.

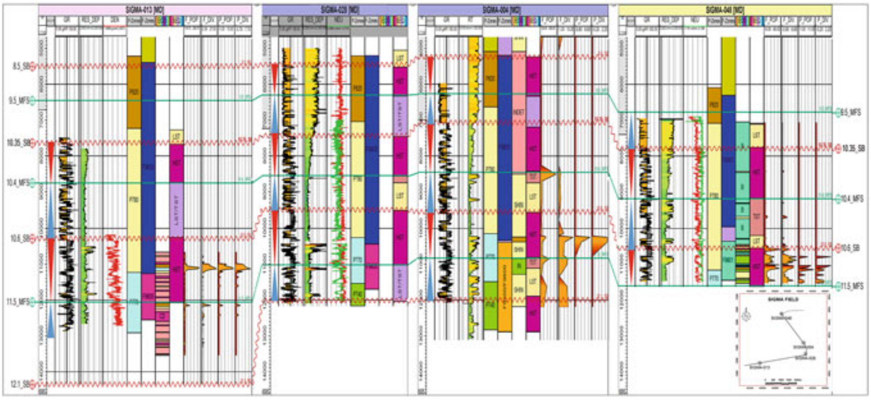


Fig. 4.3 Sigma field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

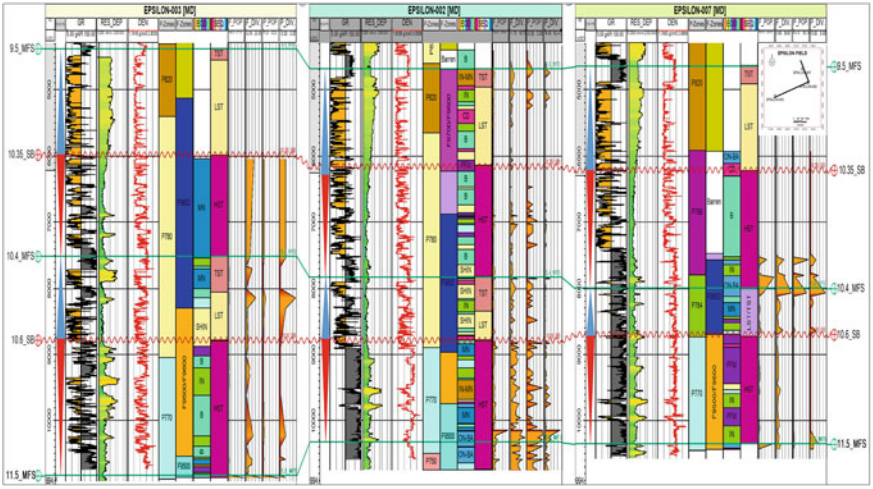


Fig. 4.4 Epsilon field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

4.2.2 Sequence Boundary (SB) and Transgressive Surface of Erosion (TSE)/Top of Lowstant (TLS)

Five (5) sequence boundaries were identified in the study area. The SBs are characterized in well log by sizeable abrupt and sharp bases of thick sand units separating coarsening or thickening-upward intervals from fining-upward intervals. Also in seismic, SBs are somewhere marked by evidences of erosional activity and other truncations. The oldest sequence boundary identified was dated SB_13.1 Ma.

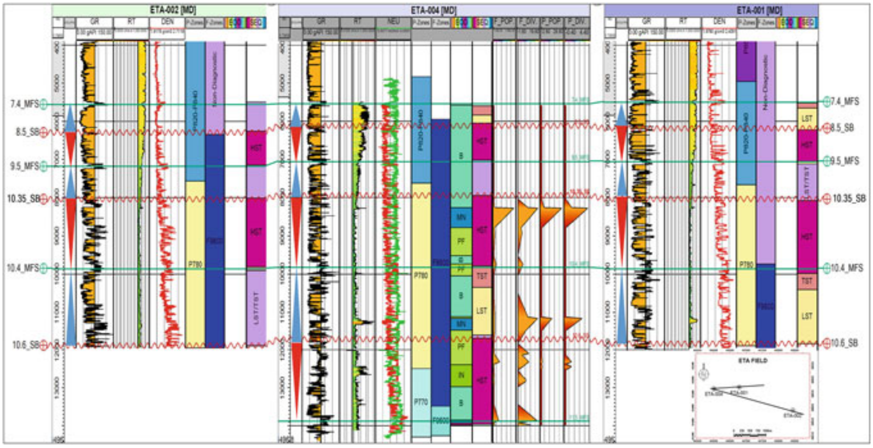


Fig. 4.5 Eta field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

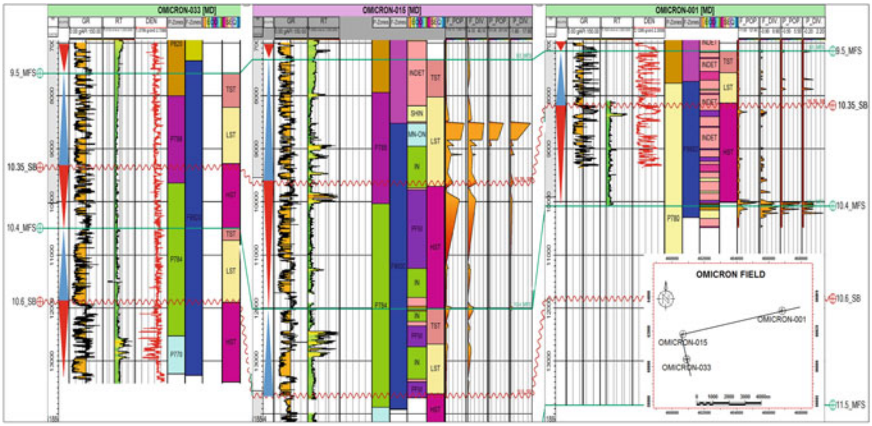


Fig. 4.6 Omicron field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

This was not correlated across the across the fields due to non-penetration of well at deeper interval. The onset of this event is partly seen in northern part (Lambda field) in which only one (1) well bottomed (Fig. 4.7). The surface represents a substantial erosional surface defined before the MFS_12.8 Ma. 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. Identified Transgressive Surfaces of Erosion, lie close to the SBs marking abrupt changes from progradational to retrogradational facies and substantially causing diminution of sand thickness deposited during relative sea

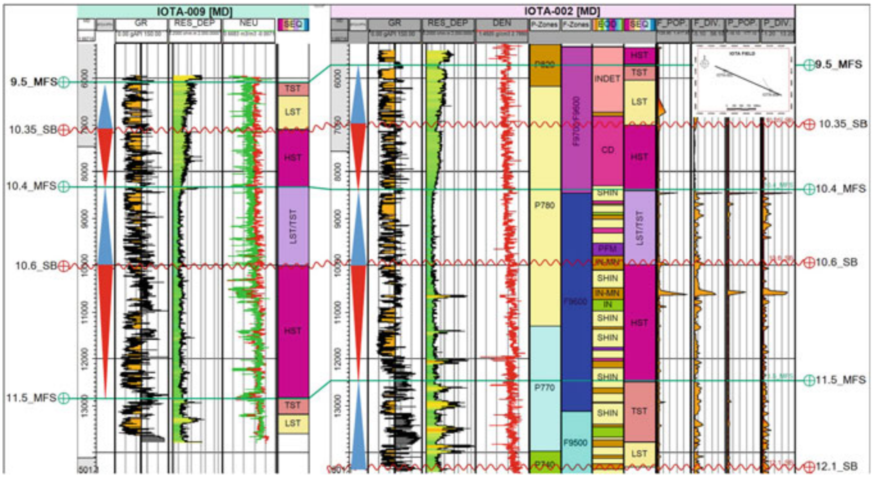


Fig. 4.7 Iota field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

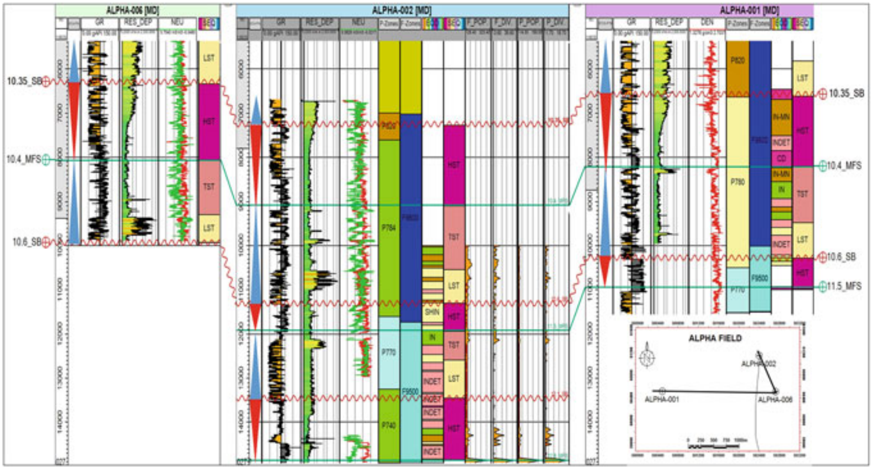


Fig. 4.8 Alpha field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

level fall (Fig. 3.9). The well log sequence stratigraphic correlation using the sequence boundaries (SB), for each field is seen in Figs. 4.2, 4.3, 4.4, 4.5, 4.6, 4.7, 4.8, 4.9 and 4.10. The depth at which the MFS occurred in various wells is summarized in Table 4.2.

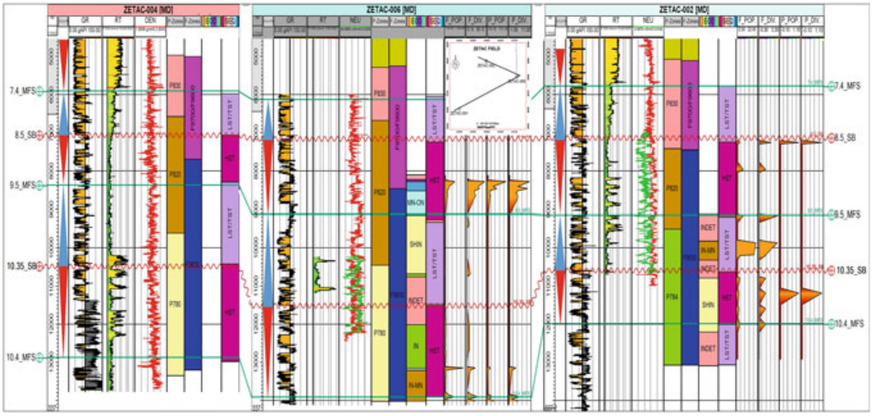


Fig. 4.9 Zeta-Creek field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

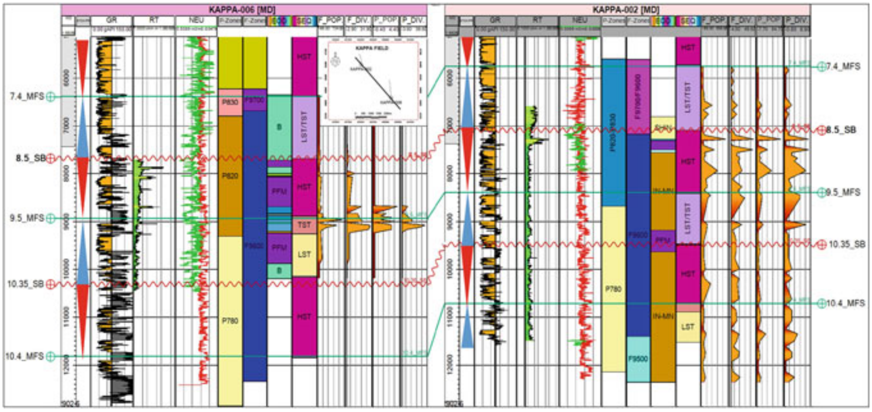


Fig. 4.10 Kappa field well log sequence stratigraphic correlation showing the key stratigraphic surfaces, stacking pattern and systems tracts

4.2.3 Well Log Sequence Stratigraphic Correlation

Ten stratigraphic bounding surfaces (five SBs and five intervening MFSs) recognized in this study were used for well log sequence stratigraphic correlations. Figure 4.11, depicts that correlations were carried out across several dip lines [north-south (N–S), northeast-southwest (NNE–SSW and NE–SW)] and strike [East-West (E–W)]. These correlation aided in determining the lateral continuity or discontinuity of stratal packages and facies geometry. The occurrence of the identified chronostratigraphic surfaces at different depths in dip direction (N–S, NNE–SSW and NE–SW) shows evidence of stratigraphic thickening down dip

Table 4.1 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
Lambda-001	8312.91	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	10219.46	12.8	*Ser-2-Cassidulina*	P680	F9300/9500
Lambda-002	8947.14	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	11836.82	12.8	*Ser-2-Cassidulina*	P680	F9300/9500
Sigma-004	6271.67	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	8463.67	10.4	*Tor-Nonion-4*	P780	F9600
	10830.96	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Sigma-013	6455.37	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	8749.02	10.4	*Tor-Nonion-4*	P780	F9600
	12054.77	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Sigma-028	6296.39	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	8557.11	10.4	*Tor-Nonion-4*	P780	F9600
	11015.63	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Sigma-048	6783.31	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	9193.79	10.4	*Tor-Nonion-4*	P780	F9600
	11616.45	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Epsilon-002	4680.29	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	7829.28	10.4	*Tor-Nonion-4*	P780	F9600
	10322.02	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Epsilon-003	4376.25	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	7514.06	10.4	*Tor-Nonion-4*	P780	F9600
	10825.17	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Epsilon-007	4645.61	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	7996.87	10.4	*Tor-Nonion-4*	P780	F9600
	10349.45	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Alpha-001	8205.78	10.4	*Tor-Nonion-4*	P780	F9600
	10939.22	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Alpha-002	9081.95	10.4	*Tor-Nonion-4*	P780	F9600
	11921.74	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	14858.03	12.8	*Ser-2-Cassidulina*	P680	F9300/9500
Alpha-006	8064.64	10.4	*Tor-Nonion-4*	P780	F9600
	10500 (NP)	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Iota-002	5720.74	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	8377.87	10.4	*Tor-Nonion-4*	P780	F9600
	12464.05	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	14310.07 (NP)	12.8	*Ser-2-Cassidulina*	P680	F9300/9500
Iota-009	6088.28	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	8321.16	10.4	*Tor-Nonion-4*	P780	F9600

(continued)

Table 4.1 (continued)

Wells	Depth (ft)	MFS age (Ma)	Marker fauna	Biozones	
				P-Zone	F-Zone
	12843.44	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Omicron-001	7157.09	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	10078.66	10.4	*Tor-Nonion-4*	P780	F9600
	13829.9 (NP)	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Omicron-015	7320.22	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	12006.49	10.4	*Tor-Nonion-4*	P780	F9600
	15500 (NP)	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Omicron-033	7576.77	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	10490.29	10.4	*Tor-Nonion-4*	P780	F9600
	13500 (NP)	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Eta-001	5497.25	7.4	*Tor-2*	P830	F9700
	7056.78	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	9860.03	10.4	*Tor-Nonion-4*	P780	F9600
Eta-002	5564.24	7.4	*Tor-2*	P830	F9700
	7193.86	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	9860.41	10.4	*Tor-Nonion-4*	P780	F9600
Eta-004	5541.91	7.4	*Tor-2*	P830	F9700
	7056.78	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	9833.46	10.4	*Tor-Nonion-4*	P780	F9600
	13876.23	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Zeta Creek-002	5776.05	7.4	*Tor-2*	P830	F9700
	9141.46	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	11993.76	10.4	*Tor-Nonion-4*	P780	F9600
Zeta Creek-004	5906.52	7.4	*Tor-2*	P830	F9700
	8375.27	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	12880.8	10.4	*Tor-Nonion-4*	P780	F9600
Zeta Creek-006	6121.32	7.4	*Tor-2*	P830	F9700
	9132.4	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	13922.91	10.4	*Tor-Nonion-4*	P780	F9600
Kappa-002	5757.53	7.4	*Tor-2*	P830	F9700
	8390.51	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	10707.44	10.4	*Tor-Nonion-4*	P780	F9600
Kappa-006	6383.84	7.4	*Tor-2*	P830	F9700
	8929.51	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	11816.94	10.4	*Tor-Nonion-4*	P780	F9600

NP Not Penetrated Interval

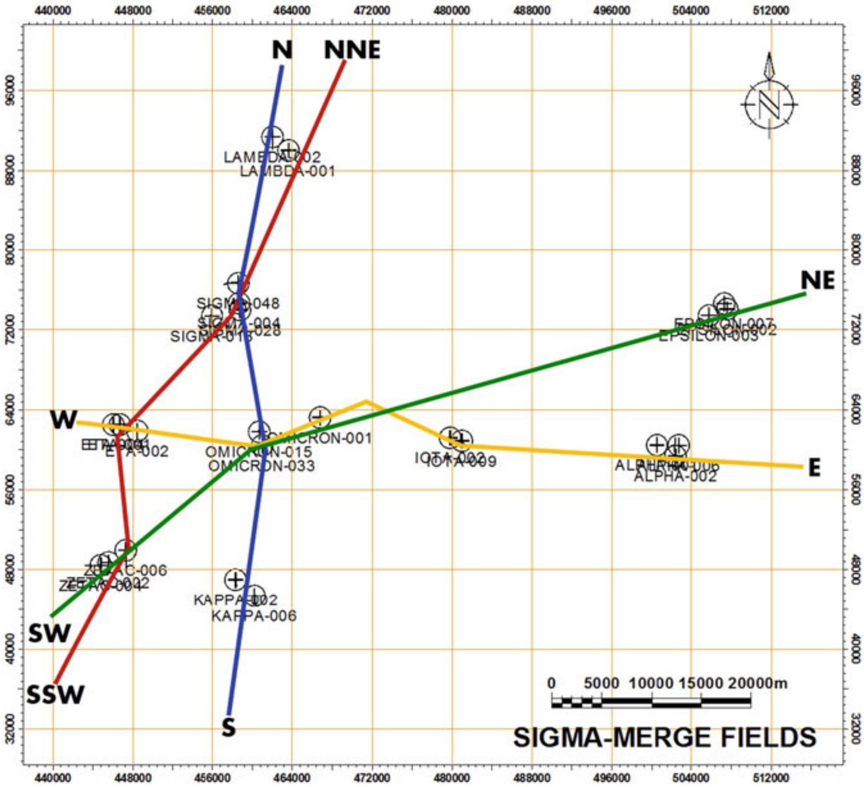


Fig. 4.11 Dip and Strike lines across various wells and fields in the study area

(southwards) and thinning, up-dip (northwards) (Figs. 4.12, 4.13 and 4.14). In the correlation along strike (E–W), there appear to be variable thickness in stratigraphic packages across the fields (Fig. 4.15). The flattening at various stratigraphic bounding MFS(s) indicates a shift of depositional center from the northern to the southern section of the study area (Figs. 4.17, 4.18, 4.19 and 4.20).

4.2.4 Systems Tracts and Depositional Sequences

The three (3) systems tracts observed in this study were correlated (N–S) across the entire area. This aided the recognition of reservoirs rocks (sand packages in LST and HST) and seal and source rocks (TST and HST). These systems tracts are characterized by variable thickness that appears to be structurally controlled. The thickness and percentage of systems tracts vary across wells such that the average

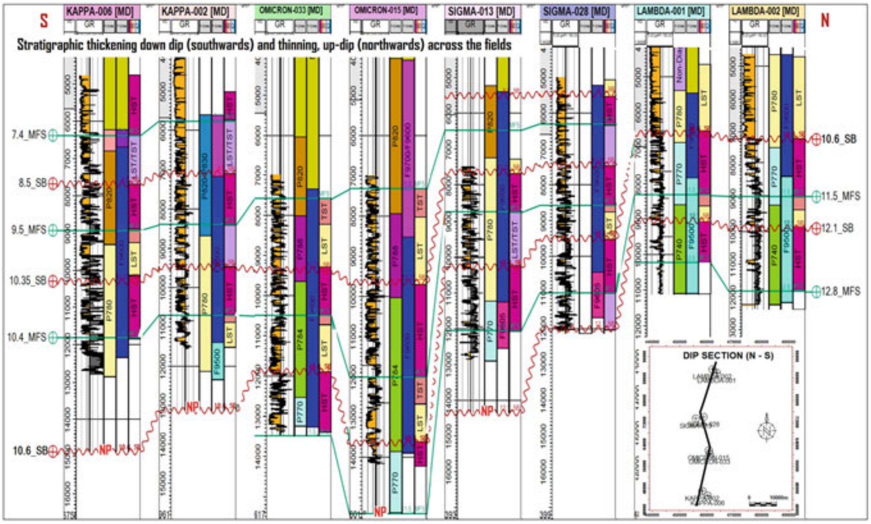


Fig. 4.12 Well log sequence stratigraphic correlation and interpretation across dip (N–S) within various fields and wells

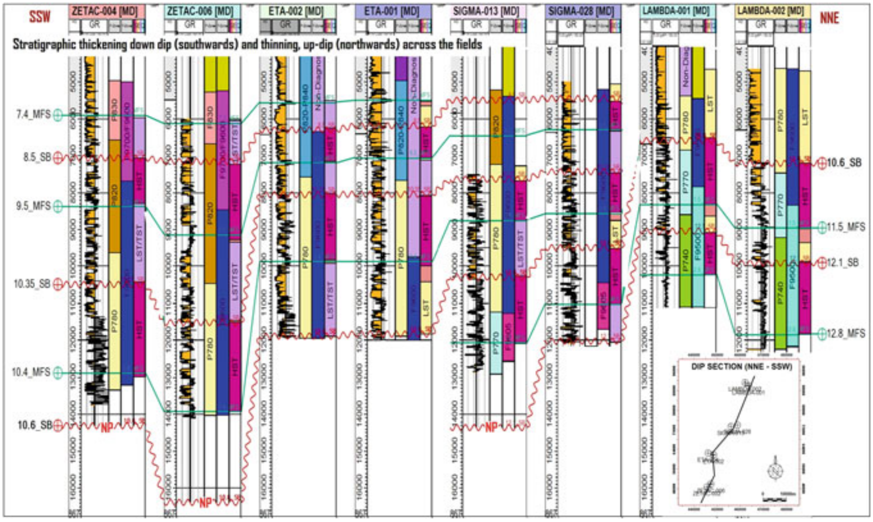


Fig. 4.13 Well log sequence stratigraphic correlation and interpretation across dip (NNE–SSW) within various fields and wells

distribution consists of 30 % of the Lowstand System Tract (LST), 13 % of the Transgressive System Tract (TST) and 57 % of the Highstand System tract (HST) (Fig. 4.16). Four (4) depositional sequences (SEQ1, SEQ2, SEQ3 and SEQ4) were also recognized within the study area. The component systems tracts

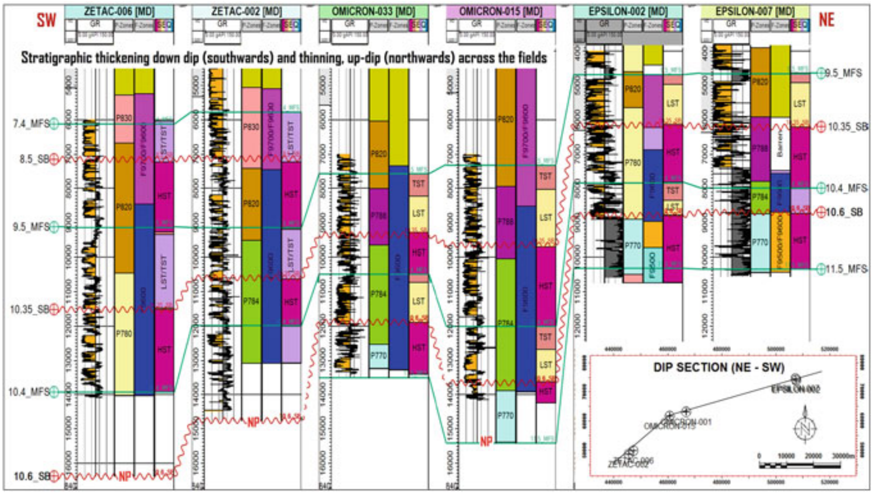


Fig. 4.14 Well log sequence stratigraphic correlation and interpretation across dip direction (NE–SW) within various fields and wells

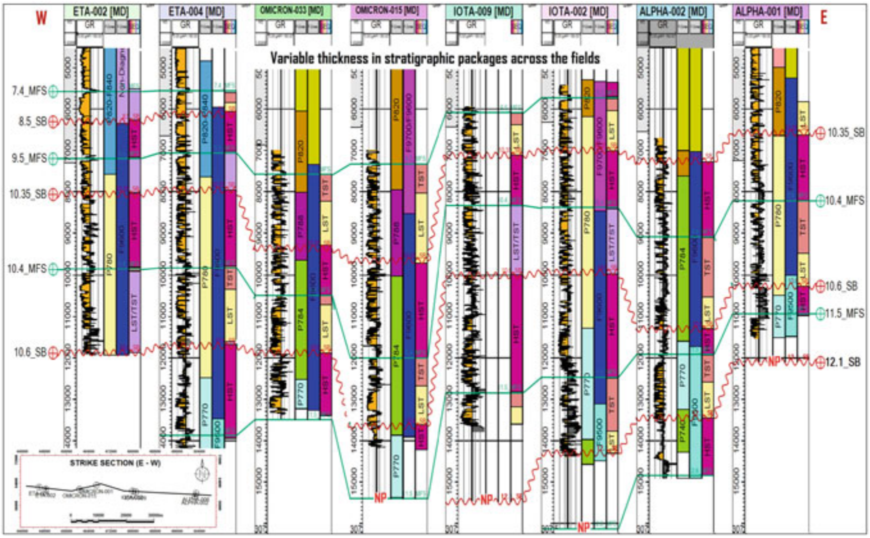


Fig. 4.15 Well log sequence stratigraphic correlation and interpretation across strike (E–W) within various fields and wells

which were correlated and interpreted across the fields based on stacking pattern and log–motifs in various wells and the spatial distribution of the recognized constrained stratigraphic surfaces (MFSs and SBs) gave more insight on these depositional sequences. Details of these sequences have been explained below.

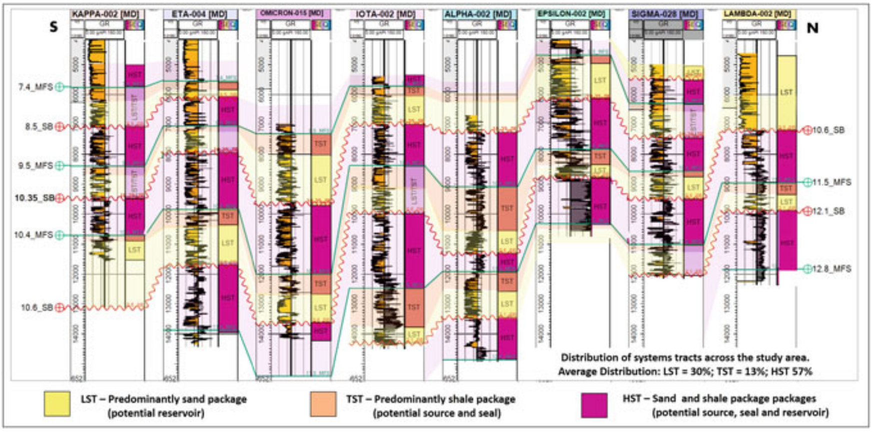


Fig. 4.16 Well log sequence stratigraphic correlation and interpretation showing key systems tracts (LST, TST, and HST) and their distribution across the study area

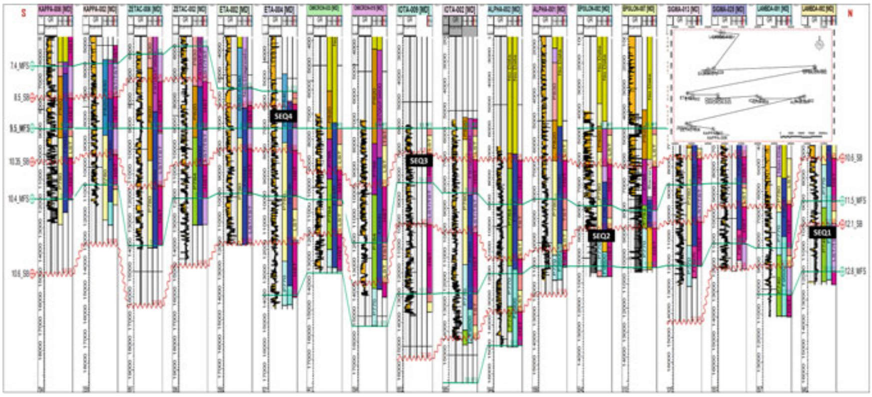


Fig. 4.17 Stratigraphic correlation panel flattened at 9.5 Ma MFS with the major depositional sequences

The first sequence (**SEQ1**) is an incomplete sequence is approximately about 2600 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 Lambda-001 and 002 wells (Table 4.2) that penetrated deeper stratigraphic sections across the field. The lowstand system tract (LST) sands are interpreted as shoreface sands deposited in the shelf region during rising sea levels. The Transgressive System Tract (TST) unit of this sequence, is capped by the 12.8 Ma MFS marker (*Ser-2-Cassidulina 7*). The Highstand Systems Tract (HST) is deposited

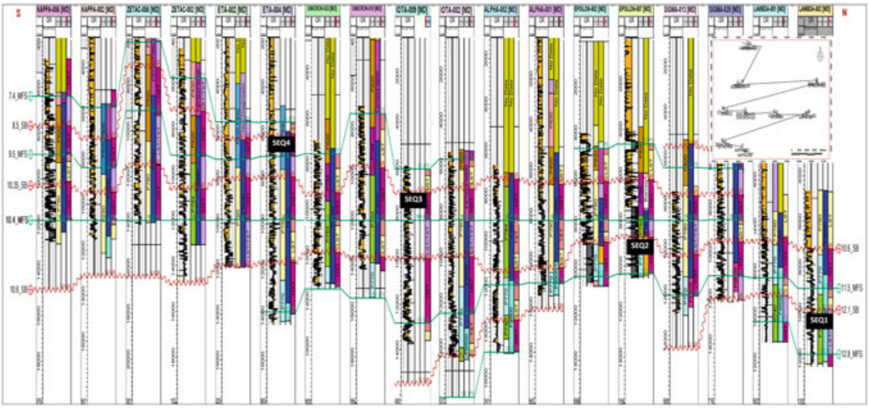


Fig. 4.18 Stratigraphic correlation panel flattened at 10.4 Ma MFS with the major depositional sequences

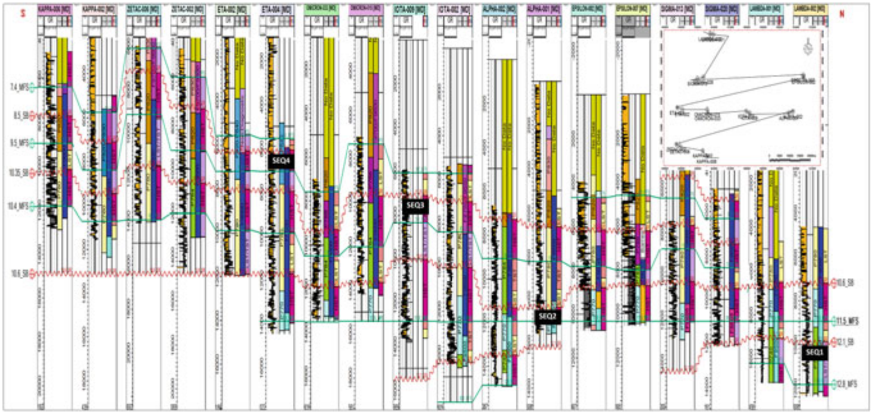


Fig. 4.19 Stratigraphic correlation panel flattened at 11.5 Ma MFS with the major depositional sequences

in the Inner-Middle Neritic (IN-MN) setting depicting mainly progradational-retrogradational stacking patterns.

The second sequence (**SEQ2**) is approximately 2800 ft thick and is bounded top and bottom by 10.6 Ma and 12.1 Ma Sequence Boundaries, respectively. The lowstand system tract (LST) and transgresssive system tract (TST) of this sequence formed thick sand deposits interpreted as upper shoreface deposited in the Shallow to Inner Neritic (SHIN) depositional settings. The LST is found to be barren in faunal contents in most wells and unconformably overlying the 12.1 Ma SB. This is capped by 11.5 Ma MFS marker (*Ser-3-Dodo Shale 7*).

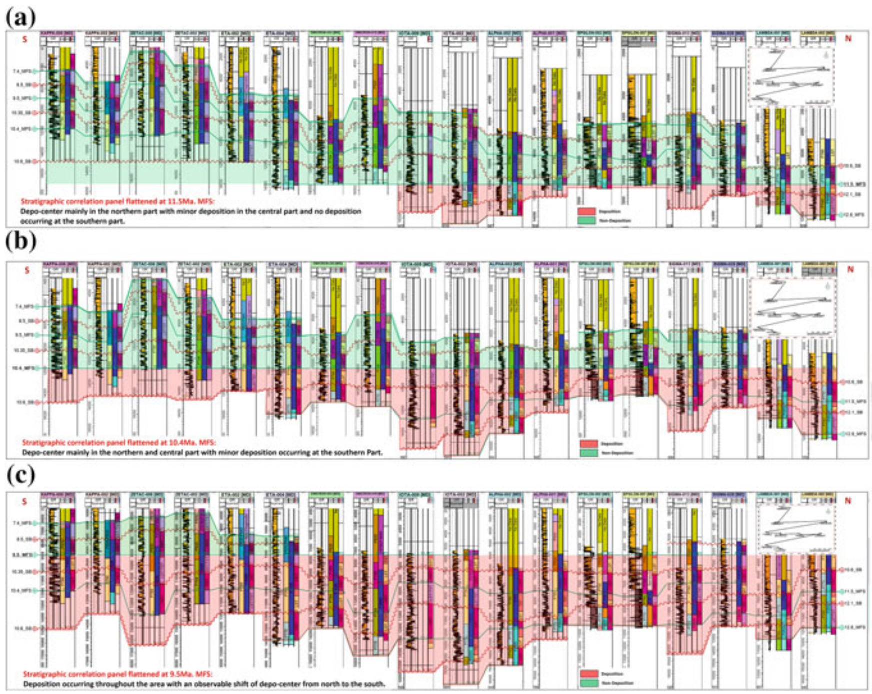


Fig. 4.20 Stratigraphic correlation panel flattened at various MFSs showing the behaviour of depositional centers at various ages (Ma)

The third sequence (**SEQ3**) is approximately 2500 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 eastern part of the study area (Sigma, Epsilon, Alpha, Iota, Omicron fields). The LST of this sequence contains reworked channel sand deposits which were more pronounced in the down dip wells and some predominantly mud fill channels. The transgresssive systems tract (TST) unit of this sequence, is capped by the 10.4 Ma MFS (*Tor-Nonion-4*) marker.

Sequence Four (**SEQ 4**), which is approximately 2000 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 transgressive systems tract (TST) unit of this sequence, is capped by 9.5 Ma MFS (*Tor-1-Uvigerina-8*) marker.

Table 4.2 Summary sheet of delineated SBs within the studied wells (NP—Not Penetrated Interval)

Wells	Depth (Ft)	SB age (Ma)	Depositional sequences
LAMBDA-001	6590.47	10.6	SEQ2
	9035.33	12.1	
LAMBDA-002	8947.14	10.6	
	9906.25	12.1	
SIGMA-004	5239.82	8.5	SEQ4
	7067.1	10.35	SEQ3
	9541.36	10.6	SEQ2
	11997.52	12.1	
SIGMA-013	5498.67	8.5	SEQ4
	7634.13	10.35	SEQ3
	10284.28	10.6	SEQ2
	14353.8 (NP)	12.1	
SIGMA-028	5455.7	8.5	SEQ4
	7432.06	10.35	SEQ3
	9484.35	10.6	SEQ2
	12016.99	12.1	
SIGMA-048	7790.92	10.35	SEQ3
	10550.51	10.6	
EPSILON-002	6156.8	10.35	
	8784.52	10.6	
EPSILON-003	5978.79	10.35	
	8782.04	10.6	
EPSILON-007	6210.89	10.35	
	8697.2	10.6	
ALPHA-001	6574.58	10.35	
	10275.25	10.6	
	12000 (NP)	12.1	
ALPHA-002	7252.32	10.35	SEQ3
	11309.09	10.6	SEQ2
	13457.04	12.1	
ALPHA-006	6294.27	10.35	SEQ3
	9933.73	10.6	
IOTA-002	6993.49	10.35	
	9940.89	10.6	SEQ2
	14310.07	12.1	
IOTA-009	7115.41	10.35	SEQ3
	10018.16	10.6	SEQ2
	15076.32	12.1	

(continued)

Table 4.2 (continued)

Wells	Depth (Ft)	SB age (Ma)	Depositional sequences
OMICRON-001	8186.72	10.35	SEQ3
	11820.3	10.6	
OMICRON-015	9652.02	10.35	
	13651.27	10.6	
OMICRON-033	9352.37	10.35	
	11881.37	10.6	
ETA-001	6189.45	8.5	SEQ4
	8043.93	10.35	SEQ3
	11827.59	10.6	
ETA-002	6301.09	8.5	SEQ4
	8052.02	10.35	SEQ3
	11880.83	10.6	
ETA-004	6122.46	8.5	SEQ4
	7950.16	10.35	SEQ3
	11714.32	10.6	
ZETA CREEK-002	7131.57	8.5	SEQ4
	10595.63	10.35	
	14900 (NP)	10.6	
ZETA CREEK-004	7061.26	8.5	
	10487.02	10.35	
ZETA CREEK-006	7156.61	8.5	
	11516.74	10.35	
	16500 (NP)	10.6	
KAPPA-002	7090.97	8.5	
	9475.01	10.35	SEQ3
	13131.89 (NP)	10.6	
KAPPA-006	7676.88	8.5	SEQ4
	10303.37	10.35	SEQ3
	14900 (NP)	10.6	

NP Not Penetrated Interval

4.3 Seismic, Semblance Cube/Time Slice Generation

The seismic volume used for this study extends to 5.0 s two way travel time (TWT). Time slices generated semblance cube at 1500, 2000, 2500 ms and 3000 m reveals significant regional structural and stratigraphic features are evident at shallow to intermediate intervals (1–3.5 s) (Fig. 4.21). However these features becomes quit difficult to identify at deeper interval (below 3.5 s), due to poor seismic quality at such depth.

Time Slice at various interval shows complexity of structural features with increasing time. Structures are easily identifiable within 1.5 – 3.0 seconds but becomes much difficult to identify from 3.5 seconds and below.

Fig. 4.21 Time slice map generation from semblance volume on study area

4.3.1 Seismic Stratigraphic/Facies Interpretation

This involves determination of depositional environments of sediments from seismic reflection characteristics. These characteristics include reflection configuration, amplitude and continuity among others. Based on seismic reflection frequency and amplitude continuity (Weimer et al. 1988) the seismic volume were divided into

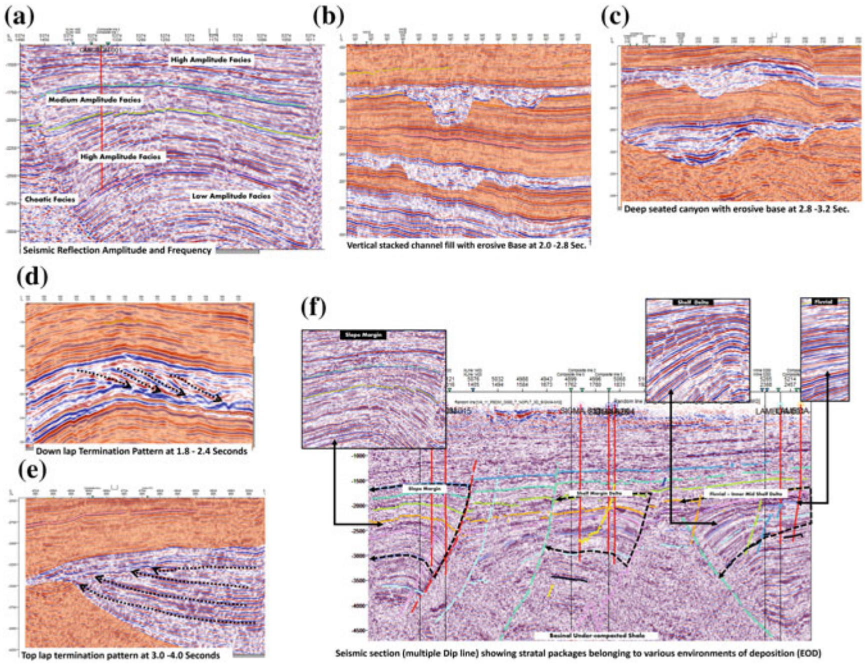


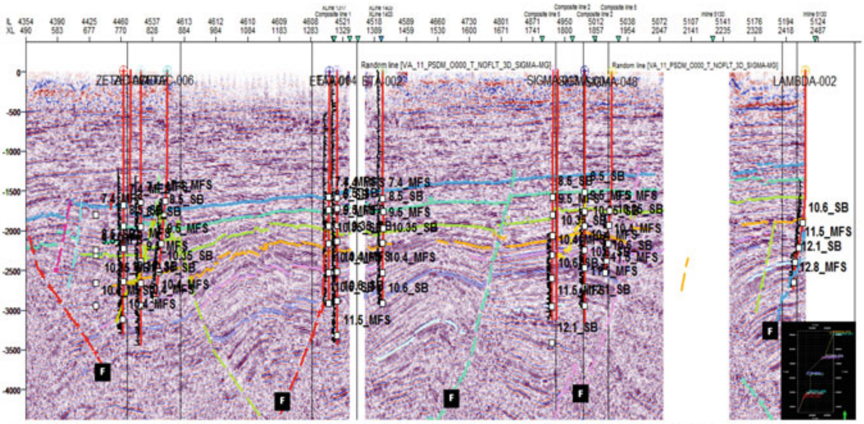
Fig. 4.22 **a** Seismic reflection amplitude and frequency. **b**–**c** Vertically stacked channels with erosional base. **d**–**e** Reflection termination of showing baselaps (downlap and onlap). **f** Seismic showing reflection patterns signifying various environments of deposition (with inset of close-up)

various facies. These includes; (i) facies with high frequency, continuous, parallel/divergent reflection, (ii) facies with lower amplitude parallel/divergent reflection, (iii) facies comprising of chaotic, discontinuous/inclined internal reflection (Fig. 4.22a–f).

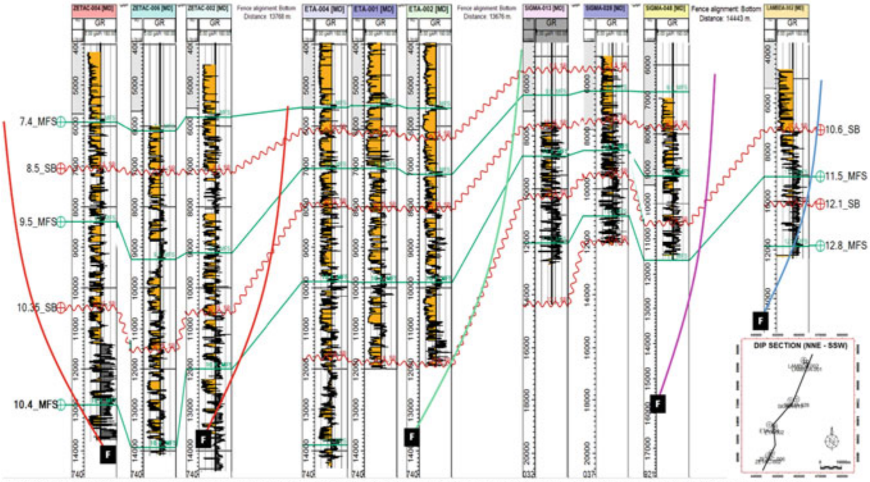
High continuity and high amplitude reflection: This reflection pattern occurs within 1.8–2.4 s in cross-lines (XLs) 1049–2525 with parallel/divergent reflection patterns and grades into a low continuity, variable amplitude facies in the eastern section (Fig. 4.22a and f). High continuity of the reflection facies suggests continuous beds deposited in a relatively widespread and uniform environment. The high amplitude reflections are interpreted as inter-bedding of shale with relatively thick sands. This indicates inter-bedding high and low energy deposits which indicates a shelf environment. This corroborates the findings of Sangree and Widmier (1979) and Posamentier and Kolla (2003).

Low amplitude reflection: This is seen between 1.0 and 1.8 s on cross-line (XL) 1049 and 2525. Low amplitude facies is an indication of zone of one predominant lithologic type and this interval corresponds to massive sand facies on the well log. According to Sangree and Widmier (1979), this massive sand associated with low amplitude reflections tend to be near shore to fluvial sands that are transported and deposited by high energy fluvial and wave processes. An intermediate facies also exist which falls between the low and high amplitude reflections. This is known as the medium amplitude reflection (Fig. 4.22a).

Chaotic configuration: This is appears as a discontinuous discordant reflections at the base of the section. The chaotic configuration gradually develops within XL 443, 1394, 1805–2284, and also within 3.5–6.0 s (Fig. 4.22a). Chaotic configuration suggests a disordered arrangement of reflection surfaces which shows a relative high energy and variability of deposition or disruption of beds after deposition (Sangree and Widmier 1979). This configuration has variably abrupt to diffuse gradational boundaries which are interpreted to be reflection deposits that have been



Multiple line of section across Dip (NNE - SSW) showing well bore, mapped bounding faults (F) and horizons/events (MFS s and SBs). NB: seismic in time – milliseconds.



Well log sequence stratigraphic correlation across dip (NNE - SSW) section showing major bounding fault (F). (NB: wellbore in feet and well spacing distance in meter.

Fig. 4.23 Multiple dip lines on seismic and well sections across the study area showing stratigraphic and structural interpretation. Insect map show traverse line fractures by overpressures and moved upward under the weight of overlying strata during fault displacement (Fig. 4.22a).

The various reflection patterns with associated reflection configuration and terminations gave insight into the definition of marine unconformity and flooding surfaces. Maximum flooding surfaces and sequence boundaries are also known as downlap and onlap surfaces respectively (Haq et al. 1988). These were recognized on seismic section as show in Fig. 4.22d and e. Erosional surfaces marking significant unconformities and channel base were also observed (Fig. 4.22b and c). These unconformities also coincided with sequence boundaries mapped across the seismic section (Figs. 4.23, 4.24 and 4.25).

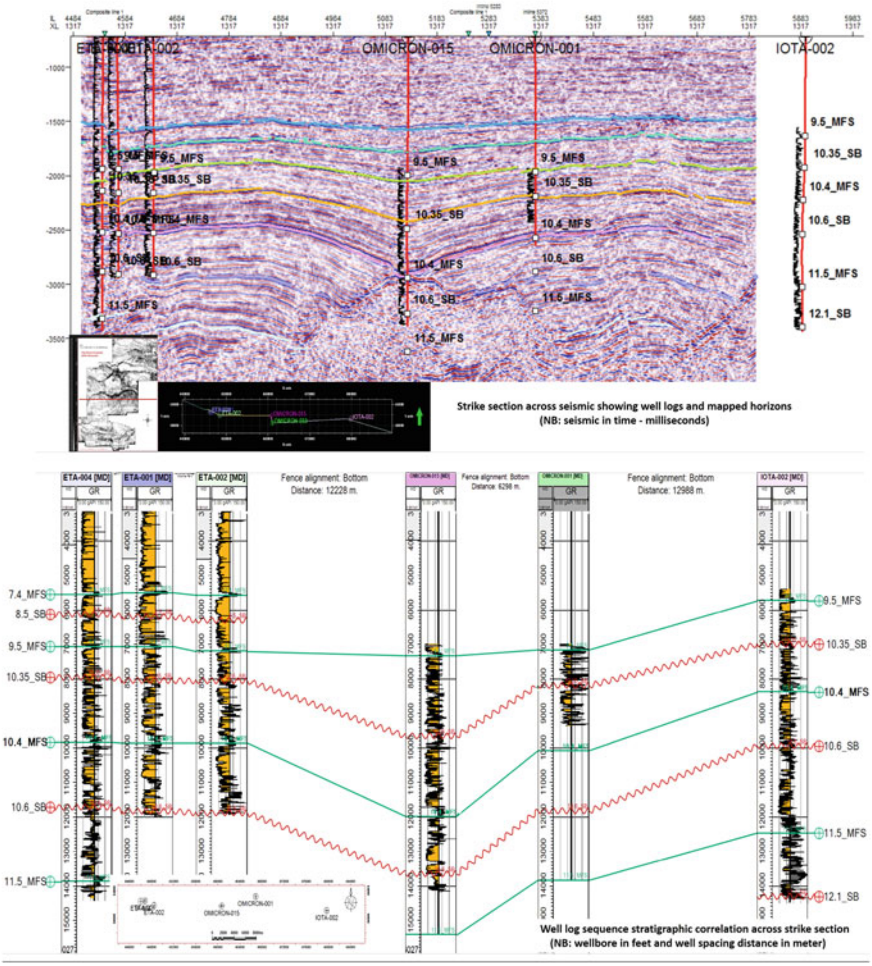
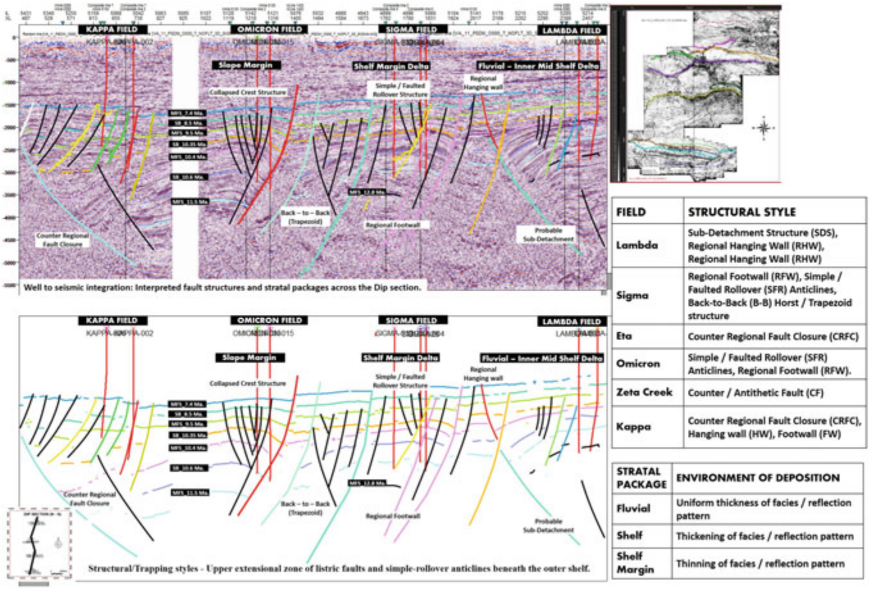


Fig. 4.24 Multiple strike lines on seismic and well sections across the study area showing stratigraphic and structural interpretation. Insect maps show traverse line



FIELD	STRUCTURAL STYLE
Lambda	Sub-Detachment Structure (SDS), Regional Hanging Wall (RHW), Regional Hanging Wall (RHW)
Sigma	Regional Footwall (RFW), Simple / Faulted Rollover (SFR) Anticlines, Back-to-Back (B-B) Horst / Trapezoid structure
Eta	Counter Regional Fault Closure (CRFC)
Omicron	Simple / Faulted Rollover (SFR) Anticlines, Regional Footwall (RFW).
Zeta Creek	Counter / Antithetic Fault (CF)
Kappa	Counter Regional Fault Closure (CRFC), Hanging wall (HW), Footwall (FW)

STRATAL PACKAGE	ENVIRONMENT OF DEPOSITION
Fluvial	Uniform thickness of facies / reflection pattern
Shelf	Thickening of facies / reflection pattern
Shelf Margin	Thinning of facies / reflection pattern

Fig. 4.25 Multiple dip line (seismic section, N–S), showing interpreted stratigraphic surfaces and structural styles across various fields in the study area

The footwall thicknesses of reflection pattern indicates the occurrence of various environments of deposition. Uniform thickness observed at the onset of lambda field area represents fluvial package, thickening (divergence dip) package also at lambda field indicates shelf delta, while thinning (convergence dip) package seen at Sigma and Omicron fields suggest shelf margin delta and slope margin environments of deposition (Fig. 4.22f).

4.4 Well to Seismic Integration

Regional stratigraphic markers (MFSs and SBs) identified from well log sequence stratigraphy were calibrated as well-tops along well-track and displayed against seismic. This made it possible to tie these markers/surfaces to seismic events (Figs. 4.23 and 4.24). Evidences in seismic such as reflection terminations and geometry were interpreted and used to constrain their picks. However, not all picks in the well-log sequence stratigraphic panel were adequately tied to seismic all through the area of interest. Some very old MFS and SB were not picked in all the wells especially in wells located to the distal part of the study area where they did not penetrate older units, and hence it was difficult to tie and map these older markers across faults. Similarly, very young MFS and SB which lie within the chaotic and discontinuous reflections of the Benin Formation were also difficult to map across the whole study area. Pattern recognition and basic stratigraphic and structural geology principles were used to extrapolate and map these markers across the study area.

4.4.1 Fault Interpretation

Seismic volume and semblance map revealed reflection discontinuities and patterns which are identified and interpreted as faults (Figs. 4.21, 4.24 and 4.25). These fault sticks were interpreted manually using interactive 2D and 3-D windows. The fault stick picking was done systematically at very close spacing in order to get as much detail as possible. This was particularly important and quite helpful at the very deep sections of the seismic section where tracing of fault continuity becomes more challenging due to data quality deterioration with increasing depth (Fig. 4.25). Although some of the faults were linear especially the shorter ones, most of the interpreted sticks were large listrics faults. The bounding regional (down-to-basin) faults are mainly listric in nature and concave basinwards. They are mainly synthetic (Lambda, Sigma and Omicron fields), having the same dip direction with regional stratigraphic package, although few antithetic (counter) faults that dip against the direction of regional stratigraphic package were observed in the Kappa field.

4.4.2 Horizon Interpretation

Key stratigraphic surfaces such as MFSs and SBs (horizons/events) already delineated and correlated across wells and fields all through the study area. Horizon picks were done iteratively in in-line and cross-line directions, and corrected for mis-ties. In areas where reflection quality and characteristics are of good quality, lines are picked at larger intervals while at areas where reflection quality is relatively poor and characterized by discontinuities and chaotic, lines were picked at closer intervals in order to reduce mis-ties to acceptable minimum. Seven (7) horizons were mapped across dip and strike sections, namely; MFS_11.5 Ma, SB_10.6 Ma, MFS_10.4 Ma, SB_10.35 Ma, MFS_9.5 Ma, SB_8.5 Ma and MFS_7.4 Ma respectively (Figs. 4.23, 4.24 and 4.25). Interpretation indicates that these stratigraphic surfaces, generally thickens from north to south (basinward).

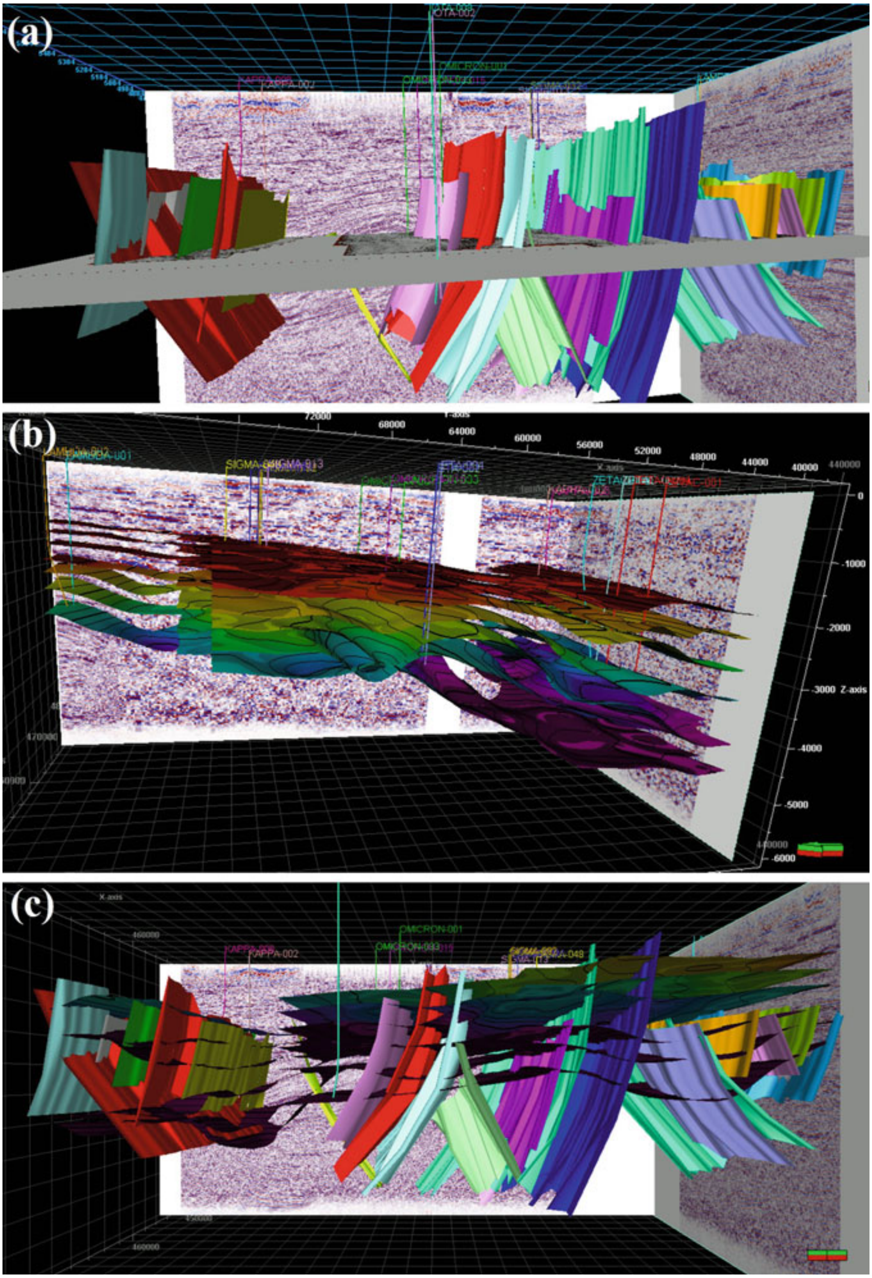


Fig. 4.26 Geologic model showing structural and stratigraphic framework of the study area. **a** 3D view of fault model. **b** 3D view of horizon model. **c** 3D view of fault and horizon models

4.4.3 Geologic Modelling

This step entails modeling of the interpreted fault horizons to generate a three dimensional framework of the faults and horizons. Seed grids were generated across mapped/picked faults (fault-sticks) and horizon lines. This was gridded using the appropriate module in software interface to produce structural and stratigraphic framework and also generate horizon maps of selected regional markers. Furthermore boundary polygon were created on these fault sticks and horizon lines to generate structural top maps. Figure 4.26a, b, c shows the fault and horizon framework in a 3-D window.

4.4.4 Time–Depth (T–Z) Conversion

Time–depth conversion was done using the checkshots data from wells across the field. The 1D polynomial function plot (from T-Z relationships) generated was based on Petrels depth conversion and Microsoft Excel workflows. The polynomial equation indicates that R^2 coefficient is high (approximately = 1.0) thus giving a high confidence that the time–depth relationship is correlatable (Fig. 4.27). The time and depth generated maps have been placed side-by-side (by way of comparison). This shows that the same structures (faults and general geometry) are present for both time and depth surfaces (Fig. 4.28a–c, d–f).

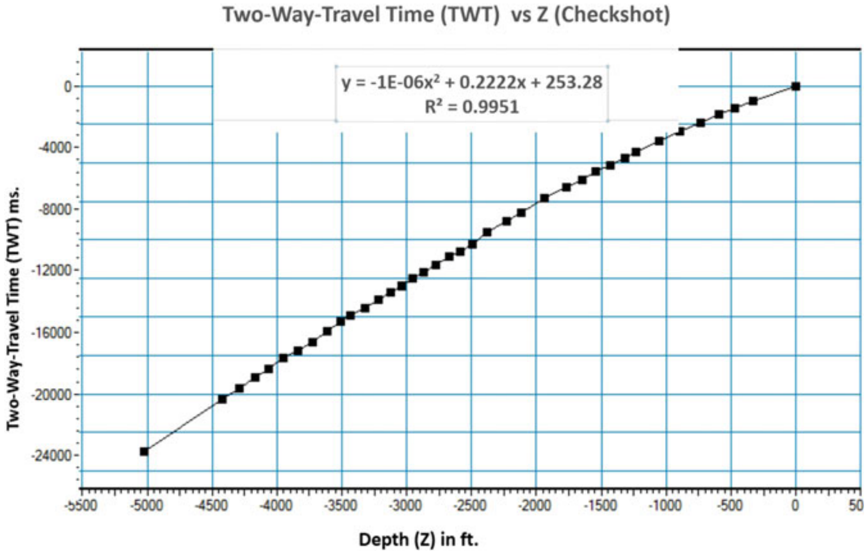
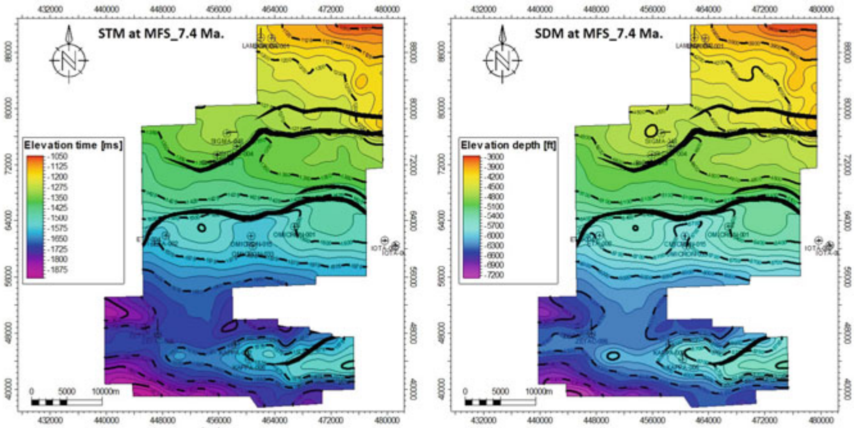
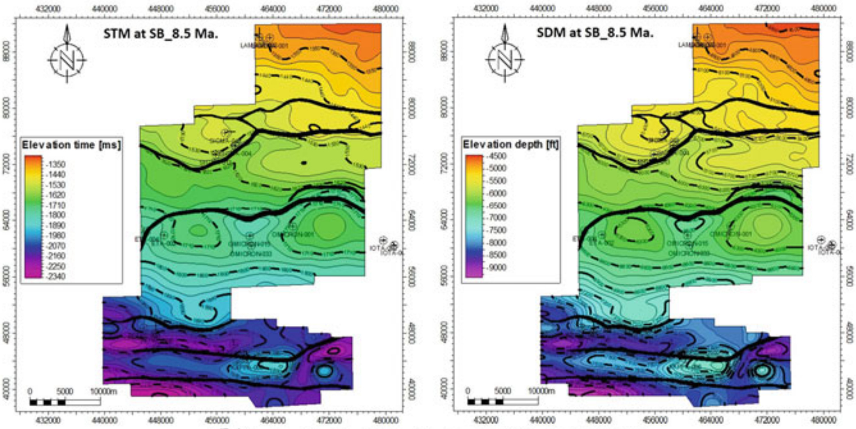


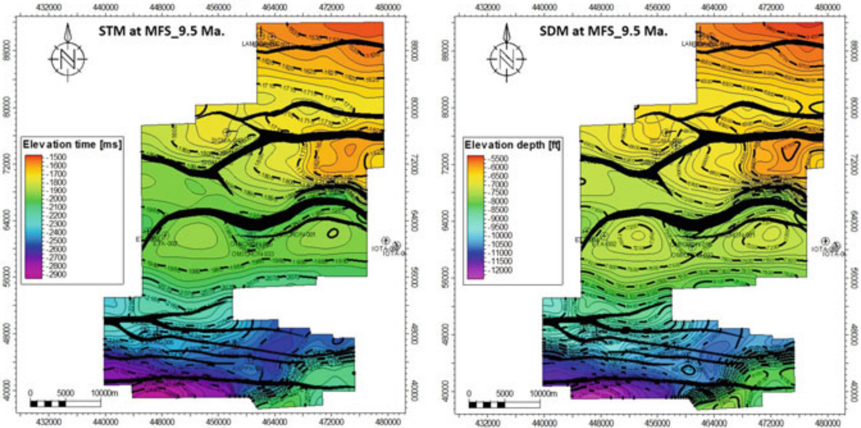
Fig. 4.27 Time-Depth (T-Z) curve generated using checkshots from wells



(a) Structural Time Map (STM) and Structural Depth Map (SDM) at MFS_7.4 Ma.

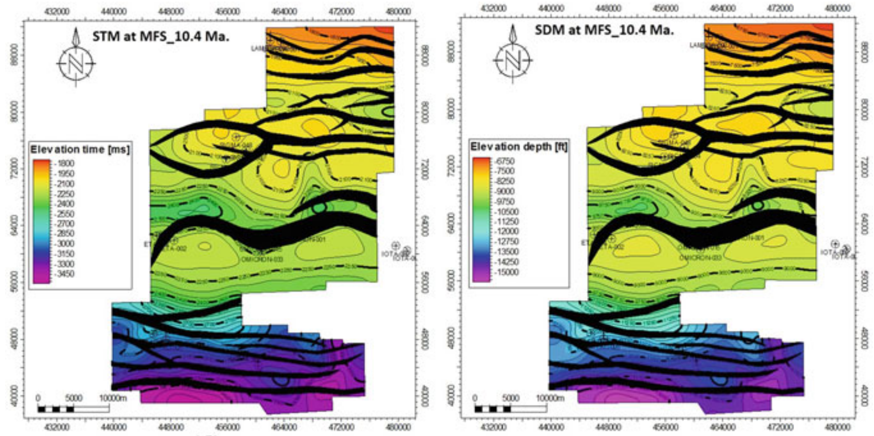


(b) Structural Time Map (STM) and Structural Depth Map (SDM) at SB_8.5 Ma.

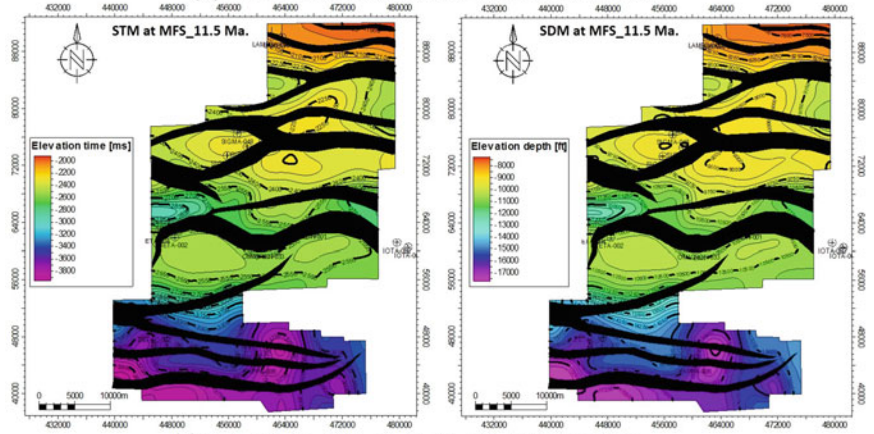


(c) Structural Time Map (STM) and Structural Depth Map (SDM) at MFS_9.5 Ma.

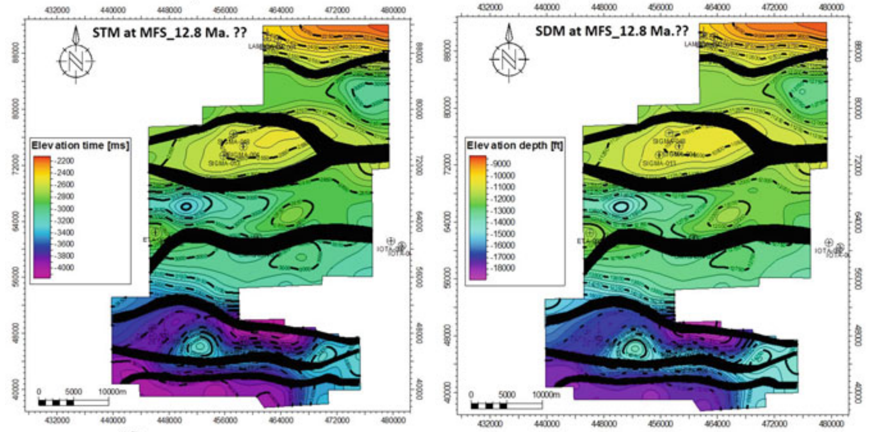
Fig. 4.28 Structural time (STM) and depth (SDM) maps at stratigraphic intervals. **a** STM and SDM at MFS_7.4 Ma. **b** STM and SDM at SB_8.5 Ma. **c** STM and SDM at MFS_9.5 Ma. **d** STM and SDM at MFS_10.4 Ma. **e** STM and SDM at SB_11.5 Ma. **f** STM and SDM at MFS_12.5 Ma



(d) Structural Time Map (STM) and Structural Depth Map (SDM) at MFS_10.4 Ma.



(e) Structural Time Map (STM) and Structural Depth Map (SDM) at MFS_11.5 Ma.



(f) Structural Time Map (STM) and Structural Depth Map (SDM) at Deep Seated Interval MFS_12.8 Ma.??

Fig. 4.28 (continued)

4.5 Field Entrapment Structure Identification

Fault and horizon interpretations in the area, aided identification of entrapment structures (trapping styles) and their classification (Fig. 4.25). From assessments carried out on the fault network and key horizons, the field has more of E-W trending regional faults, rollover anticlines and collapsed crest structures. The closures are fault dependent (Figs. 4.25 and 4.28a–c, d–f). Also present are regional hanging wall closure (RHW), simple/faulted rollover (SFR) and back—to—back (B-B) structures. The seismic interpretations show that at deeper levels (below MFS_11.5 Ma.) the fault structures dies out. However, the shallow and intermediate intervals (MFS 7.4–10.4 Ma.) are more intensely faulted by E-W trending with dominance of collapsed crest structures (Fig. 4.28a–c, d–f).

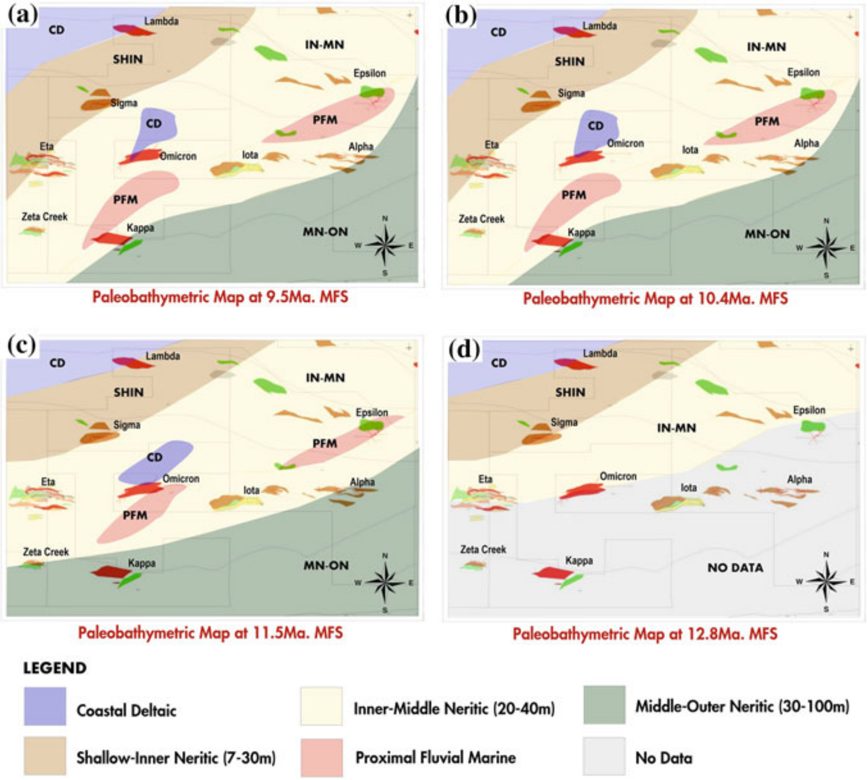


Fig. 4.29 The Paleobathymetric maps at various ages showing environments of deposition. **a** Paleobathymetric maps at MFS_9.5 Ma. **b** Paleobathymetric maps at MFS_10.4 Ma. **c** Paleobathymetric maps at MFS_11.5 Ma and **d** Paleobathymetric maps at MFS_12.8 Ma

4.6 Environments of Deposition (EOD) Interpretation

Paleobathymetric maps for four regional and time significant horizons were generated with information from paleobathymetric data and interpretation. These were integrated with log motifs which are indicative of depositional environment. Generally, sediments were deposited within neritic to bathyal environments at different times. Depositional environments appear to have been consistently fluvial to shallow marine environments (mainly pro-delta) with isolated coastal deltaic and proximal fluvial influence. 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 such as inner neritic, middle neritic, outer neritc and bathyal (Fig. 4.29).

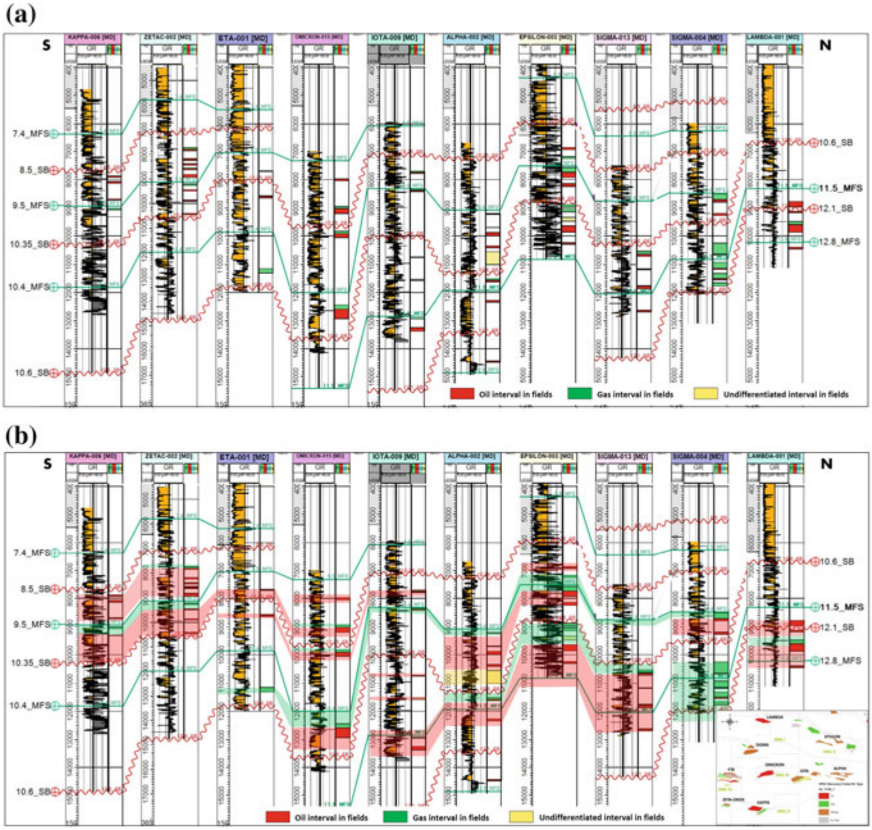


Fig. 4.30 Well log stratigraphic correlation showing hydrocarbon interval occurrence and distribution across the study area. **a** Hydrocarbon occurrence at various stratigraphic intervals across wells. **b** Hydrocarbon distribution by zones across various wells in the study area

4.7 Hydrocarbon Data Integration

Hydrocarbon fluid types and occurrence data at various interval across the fields were obtained and plotted alongside the wells.). These includes information on oil-up-to (OUT), oil-down-to (ODT), gas-up-to (GUT), gas-down-to (GDT), gas-oil contact (GOC) and undifferentiated fluids. These were also textured against the sequence stratigraphic correlation panel, in order to study and understand the hydrocarbon distribution trend (Fig. 4.30a). Interpretations show that generally gas is more concentrated at the proximal end (northern section), oil and gas at the central part while there is predominance of oil at the distal south, within the sequence stratigraphic intervals of 12.8 through 7.4 Ma (Fig. 4.30b).

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Chapter 5
Discussion

5.1 Stratigraphic Framework

Sequence stratigraphic interpretation indicates that the study area is characterised by numerous episodes of transgressive and regressive events which are reflected by global chronostratigraphic surfaces such as the maximum flooding surfaces (partly through condensation) and or sequence boundaries (erosional surfaces). Well log sequence stratigraphic correlation constrained by seismic stratigraphy and biostratigraphic reveals the occurrence of ten key stratigraphic bounding surfaces (five sequence boundaries (SBs) with ages ranging from 13.1 to 8.5 Ma, and five maximum flooding surfaces (MFS) with ages between 12.8 and 7.4 Ma respectively). These stratigraphic surfaces were better constrained to the northern/proximal part of the study area where wells were deep enough to penetrate them, thereby providing data for calibration and correlation. Stratigraphic correlation using bounding surfaces (MFS and SB) shows that the genetic units of LST, TST and HST are seen throughout the entire section. Further studies reveal that the genetic units of LST (predominantly sand package), TST (predominantly shale package) and HST (sand and shale packages) which constitute the reservoir and source/seal rock package are laterally continuous. Average percentage distribution these systems tracts across the study area, indicates that there is a predominance of HST package relative to LST and TST packages. The stratigraphic column generally strikes east–west and dips southerly. The occurrence of the identified chronostratigraphic surfaces at different depths along dip and strike directions in the wells shows reveals that stratal package thickens from the northern to the southern section (basinward directions, N–S). Sediment influx is from the north. Hence, the sediments are thinner in the up-dip (northeast) section and thicken down-dip (southwest). This shows structural influence on stratigraphy as there are clear evidence of faulting across the study area. Sediment packages thicken on the down

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thrown section of major faults. These could be attributed are high rate of subsidence and deposition that is influenced by syn-sedimentary and depositional activities (that forms growth faults) associated with the Niger delta basin. 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. 4.22f).

5.2 Depositional Sequence and Environments of Deposition

Depositional sequence in the study area comprises of lowstand system tract, transgressive systems tract and highstand system tract. Lowstand systems tracts (LST) are represented by coeval facies dominated by deposition basinward of the shelf-edge during maximum regression and are characterized by possibly deep-water deposition from gravity flows and/or traction processes within shelf-edge or canyon-head delta. The sediments package recognized in the study area, belonging to LSTs are the fluvial channel sands (associated with erosion of canyons into slopes and incision of fluvial valleys into the shelf) and slope fans (characterized by crescent log motif in individual levee channel units, thickening and thinning of individual overbank sands and fining upwards of individual channel sands from a sharp base). Transgressive system tract (TST) develops in response to sea level rise and when sedimentation rate cannot keep pace with the rate of sea level rise, thus marine facies retrograde landward to flood the shelf; deltaic progradation ceases and much of the sand is trapped up-dip in estuaries. TSTs (relatively thick and contained mainly marine shales with minor transgressive sands) were observed to be capping the LST units and characterized by transition from upward shallowing to upward deepening in deposition environments and transgressive erosional surfaces (TSE) on the shelf. The rate of sea level rise decreased during the development of highstand systems tracts (HSTs) (Van Wagoner et al. 1990). These are characterized by intervals of coarsening and shallowing upwards, with both fluvial and deltaic sands near the top of the unit, prograding laterally into neritic shales. In the studied wells, the HST intervals are very thick. This may be attributed to very high rates of subsidence, high sediment input and instability similar to sediment pattern in the Gulf Coast (Winker 1982). Generally these deposition sequence were bounded by erosional surfaces (SBs). The majority of sequences reflects a third order cycle (0.3–5 Ma Time slices) composed of transgressive and regressive sequences, reflecting relative sea level fluctuation (Reijers 1996; Kendall 2004). Paleobathymetric maps at various ages reveal a deposition settings within the incised canyons, channels, inner mid shelf, shelf margin and slope margin environments. This indicates an environment of deposition that spans from fluvio-marine, upper shoreface through lower shoreface, proximal, intermediate and distal offshore (Allen 1965). The environment of deposition and paleobathymetric maps show basinward deepening which is suggestive of progradation and in conformity with the geology of the Niger Delta (Fig. 4.22f).

5.3 Structural Framework

Structural interpretation across the fields reveal that the severity and complexity of structural deformation increases from the proximal north to distal south of the study. These structures are mainly listric faults that are large and regional. In addition they extend down the basin. Majority of these faults dip in the same direction as the regional stratigraphy (synthetic faults). Few of which dip against the regional stratigraphic dip (counter 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. These structural styles are in agreement with the findings of Doust and Omatsola (1990), which revealed the occurrences of un-faulted simple dip rollover; dip closures faults, faulted anticlinal dip closures, up-thrown fault or footwall closures, downthrown fault or hanging-wall closures within the extensional belt of the Niger Basin. These is an indication that the majority of the entrapment styles in the Niger Delta basin are structural.

5.4 Hydrocarbon Occurrence and Distribution/Trend

The Niger Delta basin is known for its hydrocarbon potentials. Several oil and gas fields have been discovered in the study area with appreciable production history. Interpretation of hydrocarbon interval occurrences in the study area was undertaken with respect to their spatial and depth locations, as well as age and sequence stratigraphic position (Fig. 4.30). Results show that generally gas is more concentrated at the proximal end (northern section) within the sequence stratigraphic interval MFS 12.8 and MFS 11.5 Ma, oil and gas at the central part while there is predominance of oil at the distal south, within the interval MFS 10.4 and MFS 9. 5 Ma. This observed trend is a consequence of the distribution of organic matter types in deltaic settings, such as that of the Niger Delta basin (Barker 1979). This also follows for the spatial distribution of hydrocarbon based on vitrinite reflectance (VR_E) and source rock evaluation which show the occurrence of gas in the proximal, oil and gas in the central and the predominance of oil in the distal section of the Niger Delta basin (Fig. 5.1).

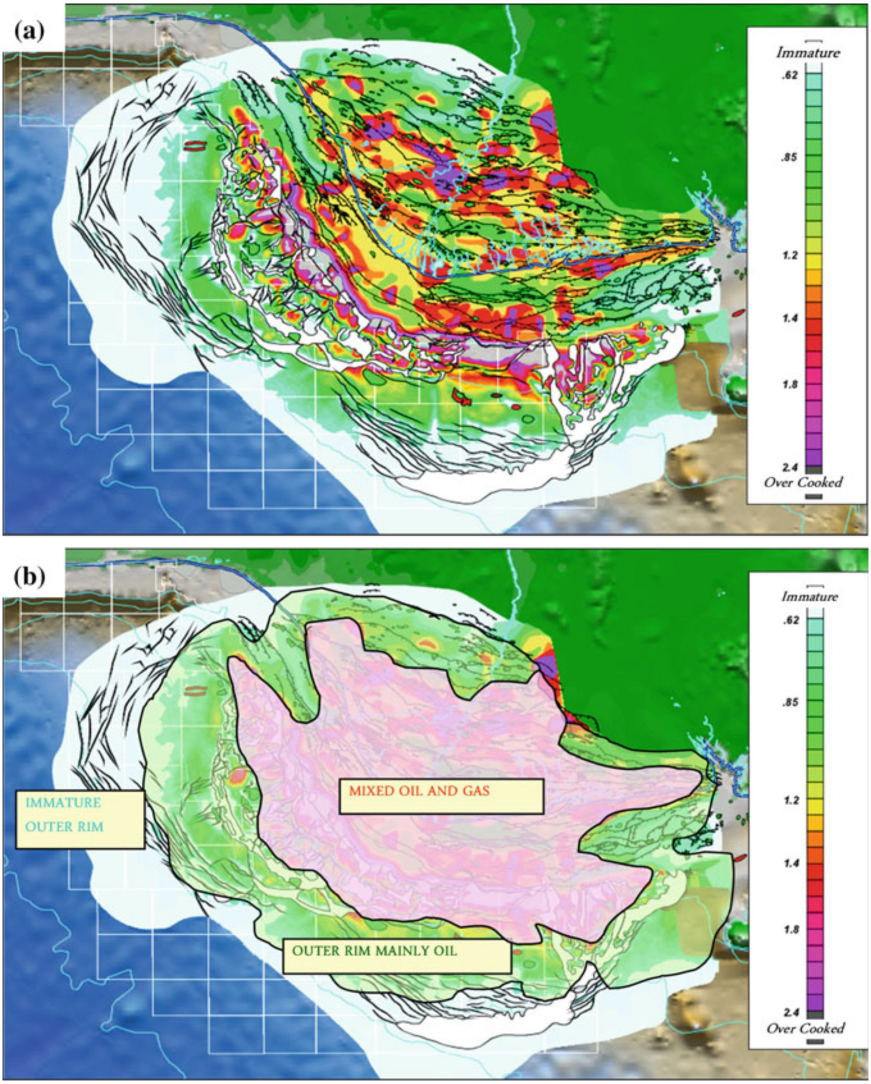
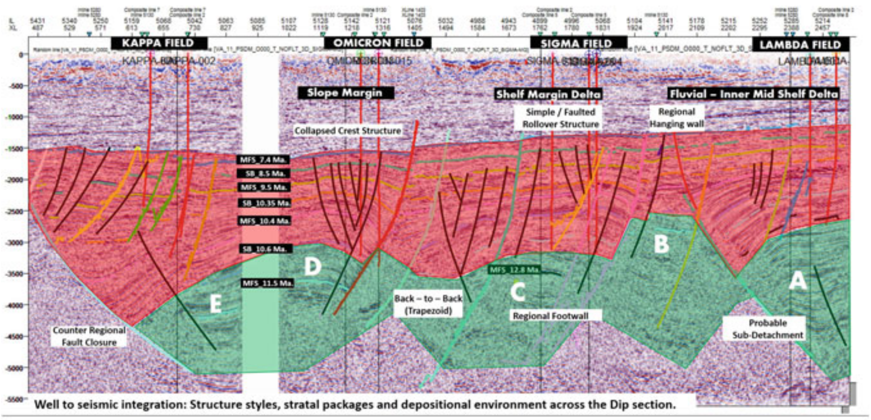


Fig. 5.1 Niger delta top source Rock VR$_E$ Maturity and hydrocarbon distribution. *Source* Shell (2008)

5.5 Hydrocarbon Leads and Implication for Exploration and Production

Structural interpretation reveals that the study area has fairly high fault density (down-to-basin faults). These characteristics of Niger Delta fault trend with appreciable throw, which can serve as potential path ways for hydrocarbon



HYDROCARBON PRODUCING ZONES

🟥 Drilled/ Penetrated Zone

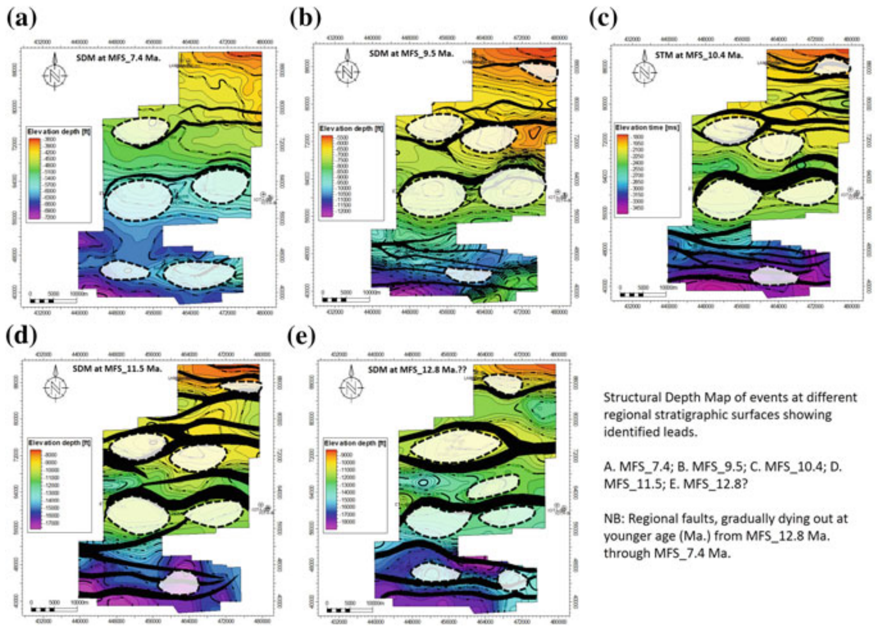
🟩 Not Drilled/ Penetrated Zone

LEAD	REMARK
A, B	Down thrown hanging wall rollover anticlinal structure with high reflection amplitude at deeper interval
C	Fault dependent closure (Fault bounded rollover anticline with high reflection amplitude)
E, D	Fault dependent closure (Fault bounded rollover anticline with high reflection amplitude)

Fig. 5.2 Seismic transects (N–S) showing penetrated and non-penetrated zones with identified hydrocarbon leads. NB: Observed the major (down—to—basin) faults and key structural styles with associated stratigraphic intervals in this study

migration and accumulation. Typical structural styles are those of the anticlines, which also have possibility of possessing multiple pay horizons, and they are major parts of most giant oil fields. Most of the field found in a given locality and stratigraphic interval in a particular fault block have ‘equivalent’ stratigraphic units within good trapping structures in adjacent block which can accommodate hydrocarbon. Promising hydrocarbon leads were identified in the study area by interpreting the seismic volume both in cross-section and in horizon maps (Figs. 5.2 and 5.3). These leads were identified based on a combination of criteria such as structural closure, relatively high amplitude interval and spatial location within proven hydrocarbon bearing intervals/horizons in adjacent fields.

The morphology and importance of reservoir and seal vary greatly between the system tracts. The highstand system tract contain fluvial-deltaic and shore face sands, while the highstand system tract are characterized by upward coarsening sands with shale intercalations, thus serving as the potential reservoir in the field. The transgressive system tracts are sand deficient and contain abundant fine grained sediments, rich in organic matter. They have potential for hydrocarbon source, seal and reservoir, however source and seal are mainly the dominant facies in transgressive system tract. The shale of the TST therefore forms the seal for the potential traps in the study area. The alternation of the LST, HST and TST sands and shale with associate structural styles therefore provide a combination of reservoir and seal rocks that are essential for hydrocarbon accumulation and entrapment (Bassey and Fagbola 2002). In the fields across the study, which consist of a complex crestal zones of largely synthetic fault traps, most of the hydrocarbons is trapped in fault



Structural Depth Map of events at different regional stratigraphic surfaces showing identified leads.

A. MFS_7.4; B. MFS_9.5; C. MFS_10.4; D. MFS_11.5; E. MFS_12.8?

NB: Regional faults, gradually dying out at younger age (Ma.) from MFS_12.8 Ma. through MFS_7.4 Ma.

Fig. 5.3 Identified leads highlighted as structural culmination on SDM of various stratigraphic surface. NB: lead are associated with faulted dependent closures

closures below a regional seals of the transgressive marine *Ser-2-Cassidulina*, *Tor-Nonion-4*, Ser-3-*Dodo Shale*, *Tor-1-Uvigerina-8* and *Tor-2* shale markers. Structural top maps of reservoirs show good amplitude response that are stratigraphically and structurally controlled. These constitute the deep, ultra-deep plays and hydrocarbon leads at intermediate and deeper horizons across the study area (Figs. 5.2 and 5.3).

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Summary

Regional stratigraphic and structural framework studies in some parts of the eastern Coastal Swamp of the Niger Delta (Blocks/OMLs I, II, III, IV and V), were carried out using well logs, biostratigraphic and seismic data integrated with sequence stratigraphic tool. This provided a rare opportunity to the understanding of lithofacies, stacking patterns, depositional sequences and systems tracts distribution across the study area. Chronostratigraphic surfaces such as MFSs and SBs matched with palynological and foraminiferal zones encountered, indicate that the studied section was deposited through Middle Miocene to Upper Miocene times. The following Maximum Flooding Surfaces were mapped; MFS_12.8/Ser.2.*Cassidulina 7*, 11.5/Ser.3. *Dodo Shale*, 10.4/*Nonion 4*, 9.5/Tor.1.*Uvigerina 8 and* 7.4/T or.2 Markers. Sequence Boundaries; SB_13.1, 12.1, 10.6 were correlated across wells of various fields. The stacking patterns (progradation, retrogradation and aggradation) encountered gave insight into systems tracts (LST, TST and HST) interpretation. These systems tracts constitutes a depositional sequence. Analysis of the vertical succession of depositional facies revealed four third order depositional sequences of mid-Miocene age bounded chronologically by 12.1 Ma SB, 10.6 Ma SB and 10.35 Ma SB (Type 1 Sequence Boundaries).

Sequence stratigraphic correlation across fields shows a thickening of sediment package from northeast to the southwest. This reveals evidence of structural influence on stratigraphy, which have been attributed to syn-sedimentary and deposition activities within the Niger Delta basin. Also, flattening at various MFS(s) reveals a shift of depositional centres from the north to the south (typical scenario of the progradational pattern in the Niger Delta). Four depositional sequence recognized were made up of genetic units of LST, TST and HST. The sands of LST and HST constitute the reservoir packages whereas, the shales of the TST in which most of the MFS were delineated serves as seal/cap rocks for the reservoir units. The alternation of reservoir units of the LST and HST and the seal units of the TST offer good stratigraphic configuration for entrapment, hence should be targeted during hydrocarbon exploration. Hydrocarbon occurrence at various intervals (shallow and intermediate zones) reveals that indicate distribution across the fields is such that there are concentration of gas at the proximal end (northern section), oil and gas at

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the central and oil at the distal end (towards the southern part). This trend has been attributed to source rock maturation from vitrinite reflection studies.

Environments of deposition as deduced from paleobathymetric maps show generally, that sediments were deposited within neritic to bathyal environments at different times, aligning with the progradational pattern of deposition of the Niger Delta. Depositional environment spans through incised canyons, channels, inner mid shelf, shelf margin and slope margin. Structural styles observed in the field include those of simple/faulted rollovers, regional footwalls/hanging walls and fault dependent closures, back-to-back horst block (trapezoid zone), collapse structures, and sub-detachment structures. These are world class entrapment structures that are good for hydrocarbon accumulation. These structural features gave insight to several possible existing hydrocarbon leads identified at intermediate and deeper intervals at several zones which has not yet been drilled.

Generally, this research work has given more insight into the understanding of stratigraphic framework and structural configuration of the eastern Coastal Swamp depo-belt. Well stratigraphic correlation and event mapping on seismic have also helped in unravelling zone that have not been drilled and possible by-passed intervals. The deepest well in the area is 16,000 ft, but beneath are possible leads that could hold great potential in deep and ultra-deep prospects, as seen from structural top maps and structural configuration. Hence, this points to the existence of prospectivity at intermediate and deeper horizons of the eastern Coastal Swamp depo-belt of the Niger Delta.

By way of recommendation, this exercise should be extended to the western part of the Coastal Swamp depo-belt and further to the offshore. Furthermore, revalidation studies should be carried out on identified hydrocarbon leads, so as to further evaluate and classify these as prospects. Finally, detailed petrophysical and reservoir evaluation studies should be done to better understand the reservoir property and hydrocarbon occurrence distribution in this area.

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