TITLE PAGE

REGIONAL STRATIGRAPHIC AND STRUCTURAL FRAMEWORK OF PARTS OF THE EASTERN COASTAL SWAMP DEPO-BELT OF THE NIGER DELTA.

BY

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CERTIFICATION

This is to certify that **Dim, Chidozie Izuchukwu Princeton** a post postgraduate student of the Department of Geology, University of Nigeria, Nsukka with Registration Number PG/M.Sc/09/51430 has satisfactorily completed the requirements for research work for the degree of Master of Sciences (M.Sc.) in Petroleum Geology.

The research work embodied in this Project Report is original and has not been submitted in part or full for any other degree or diploma of this or any other university.

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DEDICATION

This piece of work is dedicated to the Lord God Almighty, who is forever faithful. Unto His Name be all praise, blessing, glory, honour and power even now and forever more Amen!

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My profound gratitude goes to the management of the Shell Petroleum Development Company of Nigeria Limited, Port-Harcourt, most especially the Geo-solutions Manager, Nedo, Osayande, and the Geological Services, Geophysics, Exploration, Petrel/nDI Geo-Sign-IT Help Desk and University Liaison Teams, for the support provided throughout the period of this research.

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ABSTRACT

Facies geometry, stratigraphic configuration, structural style, hydrocarbon type and distribution within the paralic Agbada Formation of Middle to Late Miocene age across several fields in the Eastern part of the Coastal Swamp depo-belt were studied using regional 3D seismic, wire-line well logs and biostratigraphic data. The study involved analyses of sequence stratigraphic framework across nine fields using information obtained from twenty- four wells. 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, correlated and mapped across several wells and seismic sections. Four depositional sequences were delineated and stratigraphic flattening at various MFS(s) indicates that there is a shift of the depositional center from north to south. Three major stacking patterns (progradational, retrogradational and aggreadational) were delineated and interpreted as Lowstand Systems Tract (LST), Highstand Systems Tract (HST) and Trangressive Systems Tract (TST) using their bounding surfaces. The alternation of the reservoir sands of the LST and HST and the shale units of the TST offers good stratigraphic traps for hydrocarbon. The Gross Depositional Environment spans through incised Canyons, Channels, Inner Mid Shelf, Shelf Margin and Slope Margin. 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. Structural analyses 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. Revalidated and newly identified leads at intermediate and deeper horizons indicate that detailed mapping of stratigraphy and structures are critical in hydrocarbon evaluation of deeper prospects in the Niger Delta.

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CHAPTER ONE

General Introduction

1.1 INTRODUCTION

The Late Cenozoic strata of the Niger Delta Basin are among the most challenging targets for both stratigraphic and structural interpretation in petroleum exploration because of the several factors involved in their deposition. They 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, unstable mobile clay; this loading has produced a complex series of gliding surfaces and sub-basins. In these sub-basins, deposition commonly is controlled by large contemporaneous glide-plane extensional faults and folds related to diapirism, shale sills, and underlying structures. 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 deep-water drilling environments.

The understanding of facies geometry, stratigraphic configuration, structural trend, 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 and biostratigraphic information, closely integrated with seismic data, increases the resolution for prediction of reservoir, seal and source rocks.

This work presents the results of a regional geological analysis of the Niger Delta basin. Aspects related to the structural framework, stratigraphy of the siliciclastic sequences, and the tectonic-sedimentary evolutions are discussed. In this study, a generalized description, regional correlation, synchronization, and interpretation of genetic relationship of the most significant structural features are given. The following main features constitute the structural framework of the Niger Delta basin: antithetic tilted step-fault blocks, synthetic untilted step-fault blocks, structural inversion axes, hinges with compensation grabens, homoclinal structures, growth faults with rollovers, shale diapirs, and structural features related to igneous activity. The hypothesized contemporaneous development of the two faulted block systems mentioned above constitutes a new viewpoint regarding to the evolution of the structural framework of the Niger Delta basin.

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 (Figure 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. Current daily oil production is 2.1 million bbl, and daily condensate production is 85,000 bbl (Haack et al., 2000). The study area spans through five Blocks (which for proprietary reasons are named OMLs I, II, III, IV and V) on the onshore part of the Eastern Coastal Swamp of the Niger Delta Basin. The field lies between Latitudes 4° 20^{1} 00^{11} N and 4° 50^{1} 00^{11} N and Longitudes 6° 30^{1} 00^{11} E and 7° 10^{1} 00^{11} E and covers an area of 3610.656 km^2 (Figure 1.2).

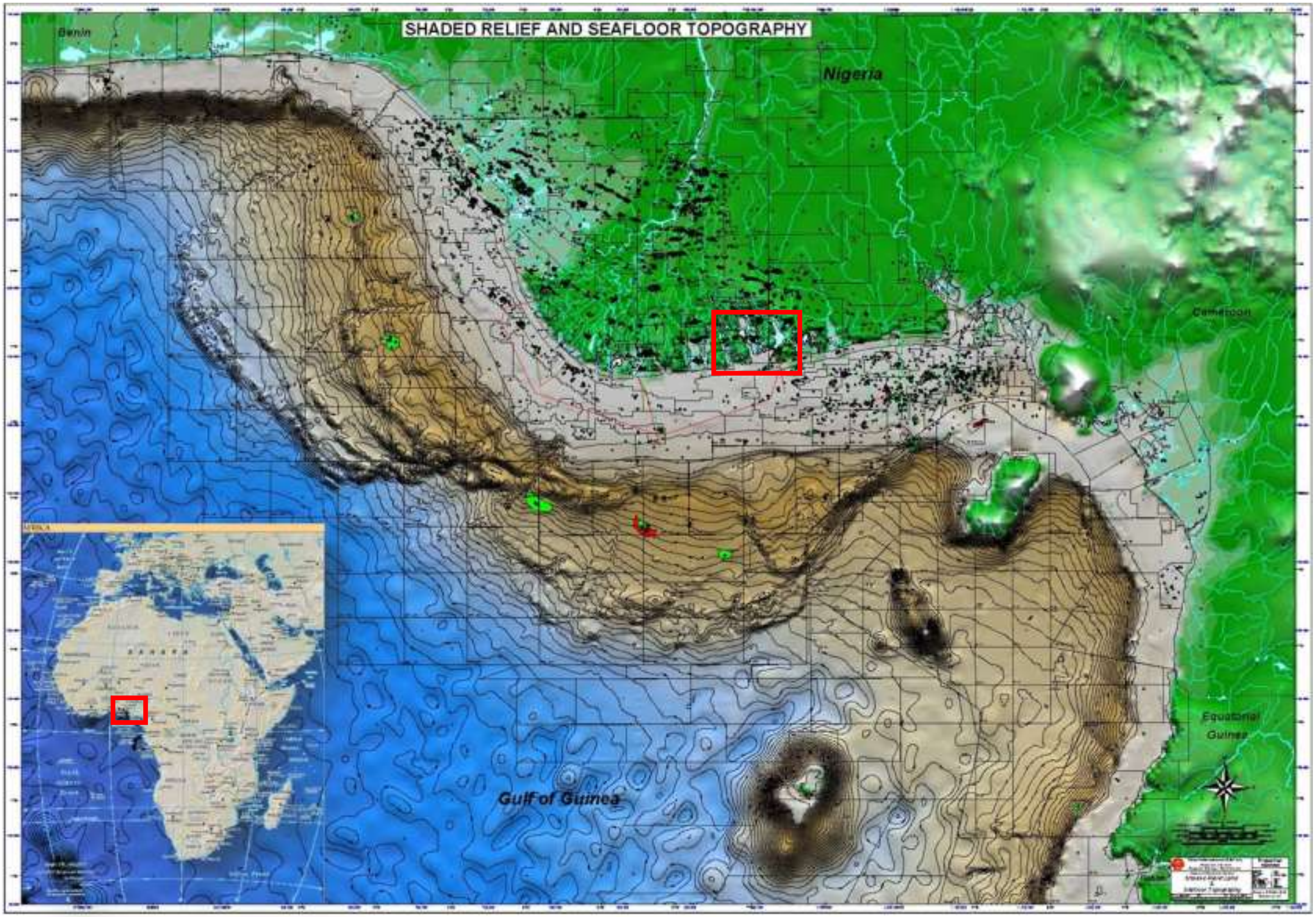


Figure 1.1: Niger Delta: Location Map of Study area showing Topographic and Oil and Gas Fields (Courtesy: Shell)

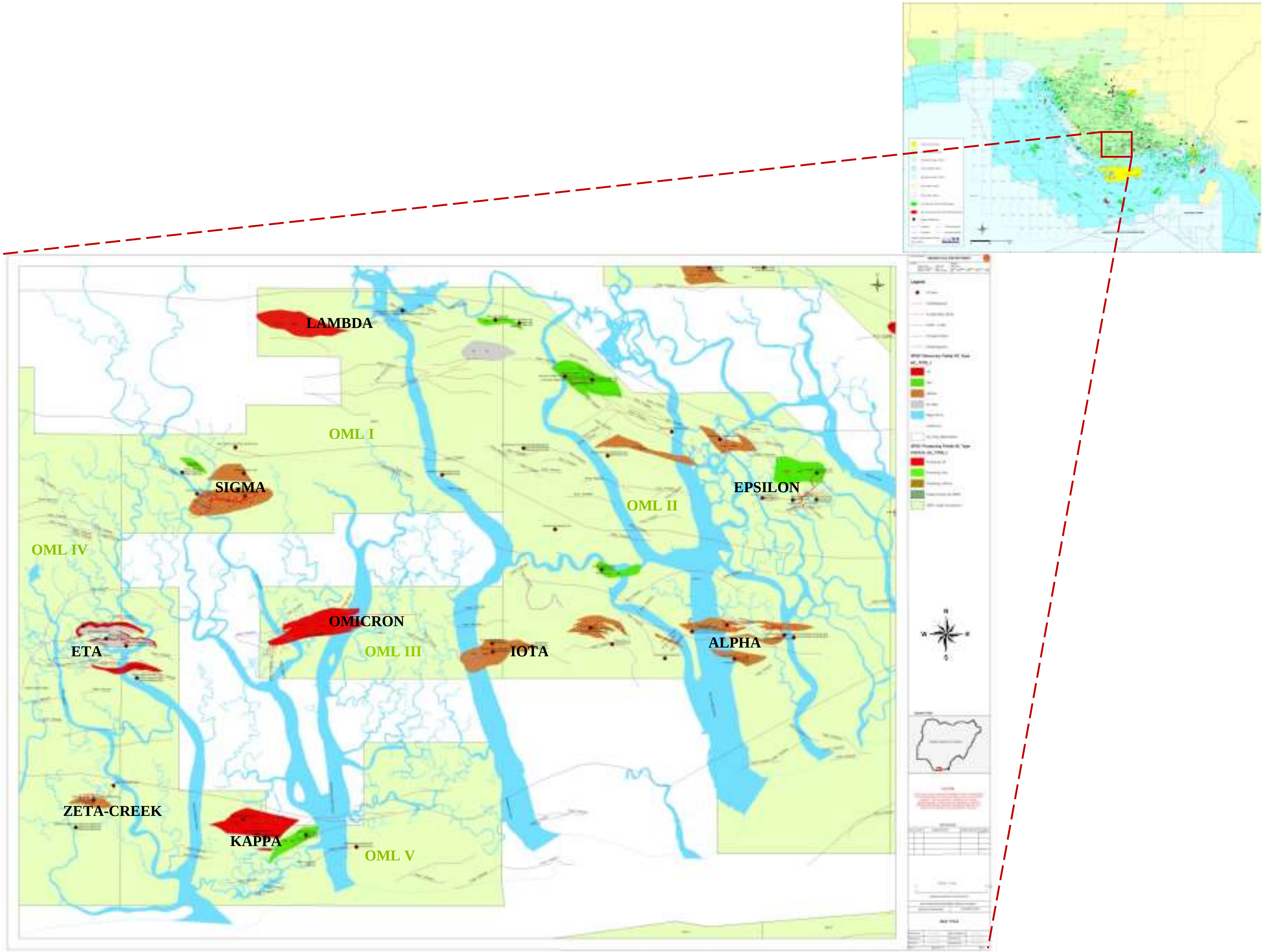


Figure 1.2: Map of the Study area showing the various Fields and Blocks (OMLs). (Fields and Blocks: Renamed for proprietary reasons reseons)

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: (1) basal, offshore-marine, and pro-delta shale of the Akata Formation; (2) interbedded sandstone and shale of the dominantly deltaic Agbada Formation; and (3) 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 and 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) used escalator regression model and impact on hydrocarbon distribution and its development.

This current work focuses on understanding the facies geometry, stratigraphic configuration, structural trend, hydrocarbon type and distribution 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 AIMS/SCOPE OF STUDY

This research aims at:

i. Building a high-resolution structural and stratigraphic framework for parts of the eastern Niger Delta by using biostratigraphy and suites of geophysical well logs, along with seismic and sequence stratigraphy. This will offer an integrated sequence/seismic stratigraphic interpretation for predicting reservoir, seal and source rocks of petroleum.

ii. Determining the influence of structural evolution and stratigraphy on the hydrocarbon system in the fields in the study area. This structural and stratigraphic framework will provide better understanding of stratigraphic and structural evolution on retention or non-retention of hydrocarbons; hydrocarbon trends; Hydrocarbon types (gas and/or oil) and distribution, useful in influencing exploration and exploitation decisions.

iii. Identifying new and/or revalidate leads (especially deeper leads) in the study area, using cutting-edge computer tools such as Petrel, nDI-Geosign and ArcGIS..

CHAPTER TWO

Geologic Framework

2.1 REGIONAL TECTONIC SETTING

The Niger Delta basin is located within the perioceanic section of the Abakaliki-Benue suture zone of the much larger southern Nigerian basin. On the west, it is separated from the Dahomey (or Benin) basin by the Okitipupa basement high, and on the east it is bounded by the Cameroun volcanic line. Its northern margin transects several older (Cretaceous) tectonic elements—the Anambra basin, Abakaliki uplift, Afikpo syncline, and Calabar Flank (Figure 2.1).

The evolution of the delta is controlled by pre- and synsedimentary tectonics as described by Evamy et al. (1978), Ejedawe (1981), Knox & Omatsola (1987) 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 (Figure 2.2) 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). In the region of the Niger Delta, rifting diminished altogether in the Late Cretaceous. Figure 2.3 shows the gross paleogeography of the region as well as the relative position of the African and South American plates since rifting began.

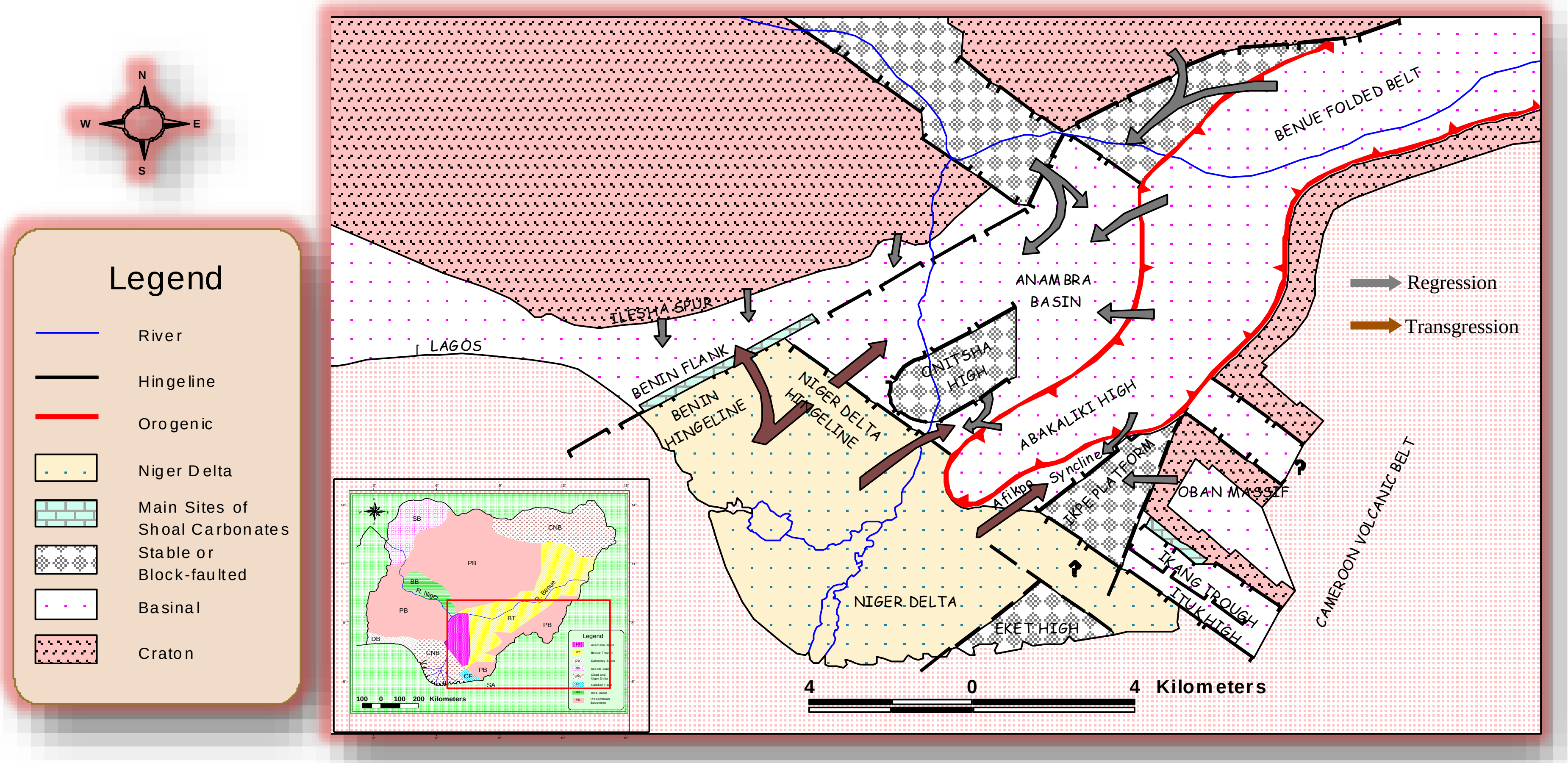


Figure 2.1: Tectonic Map showing the Niger Delta (Modified after Kogbe, 1989).

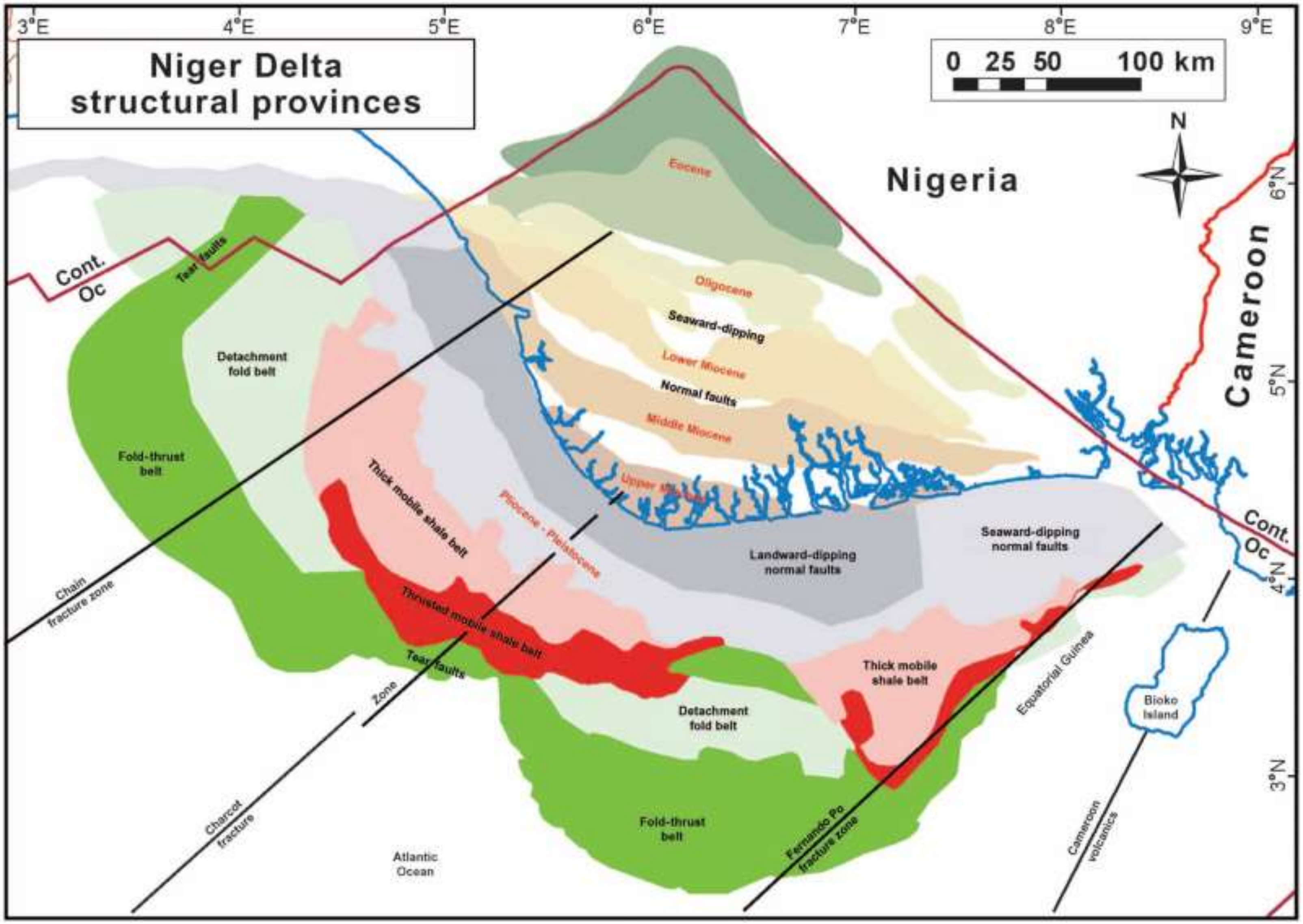


Figure 2.2: Regional structural provinces map of the Niger Delta showing the Fracture Zones. (Wiener et al., 2010)

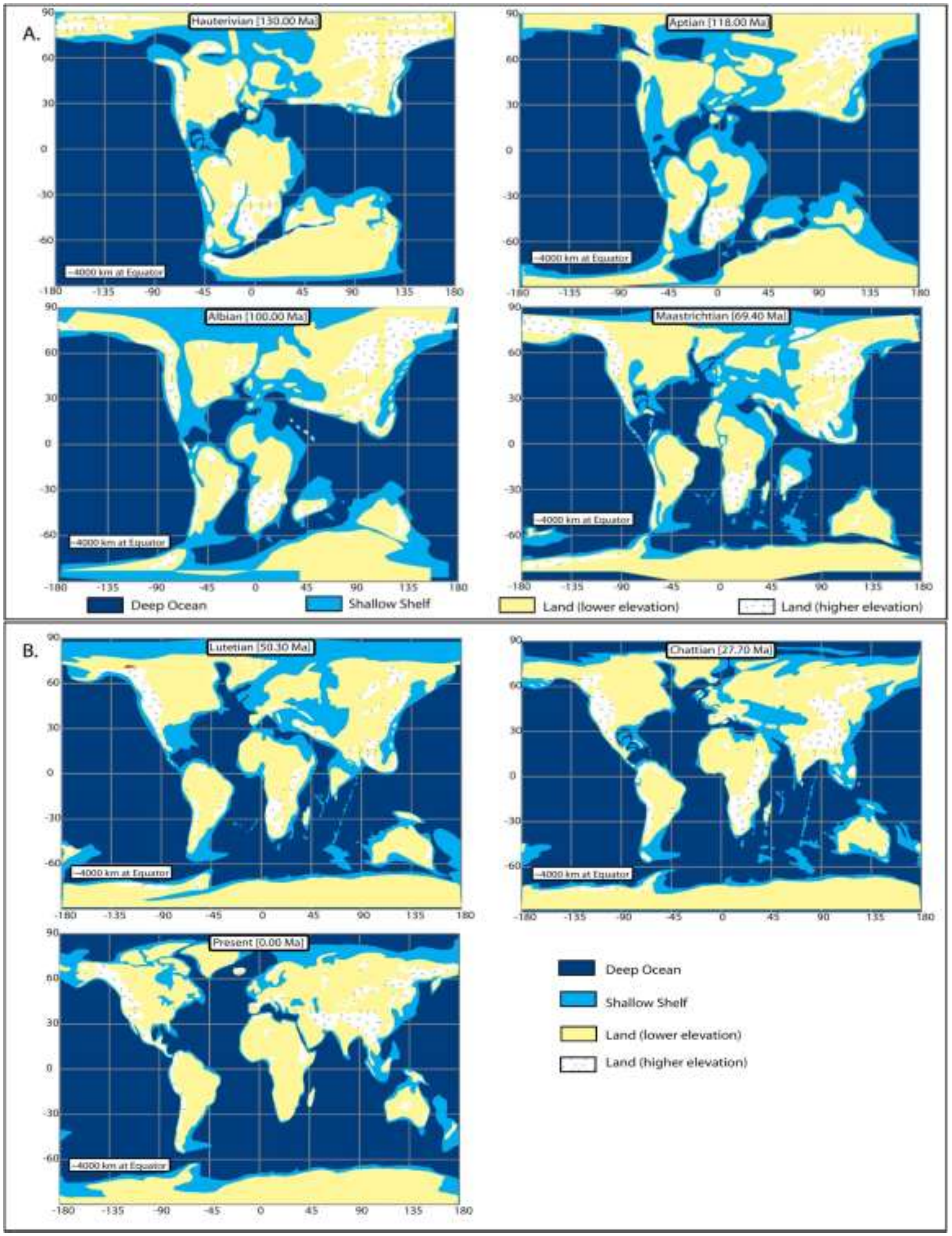


Figure 2.3: Palegeography showing the opening of the South Atlantic, and development of the region around Niger Delta. A. Cretaceous palegeography (130.0 to 69.4 Ma). B. Cenozoic paleogeography (50.3Ma to present). Plots generated with PGIS software. (Tuttle et al., 1999)

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.

2.2 REGIONAL STRATIGRAPHIC SETTING

The Niger Delta stratigraphic sequence comprises an upward-coarsening regressive association of Tertiary clastics up to 12 km thick (Figure 2.4). 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 have been recognized in the subsurface of the Niger Delta (Short and Stauble, 1967; Frankl and Cordy, 1967 and Avbovbo, 1978). These are from the oldest to the youngest, the Akata, Agbada and Benin Formations all of which are strongly diachronous (Figures 2.5 and 2.6).

2.2.1 AKATA FORMATION (MARINE SHALES)

The Akata Formation is the oldest lithostratigraphic unit in the Niger Delta. The Akata Formation (Eocene – Recent) is a marine sedimentary succession that is laid in front of the advancing delta and ranges from 1,968 ft 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 crop out offshore in 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 3,000m (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.

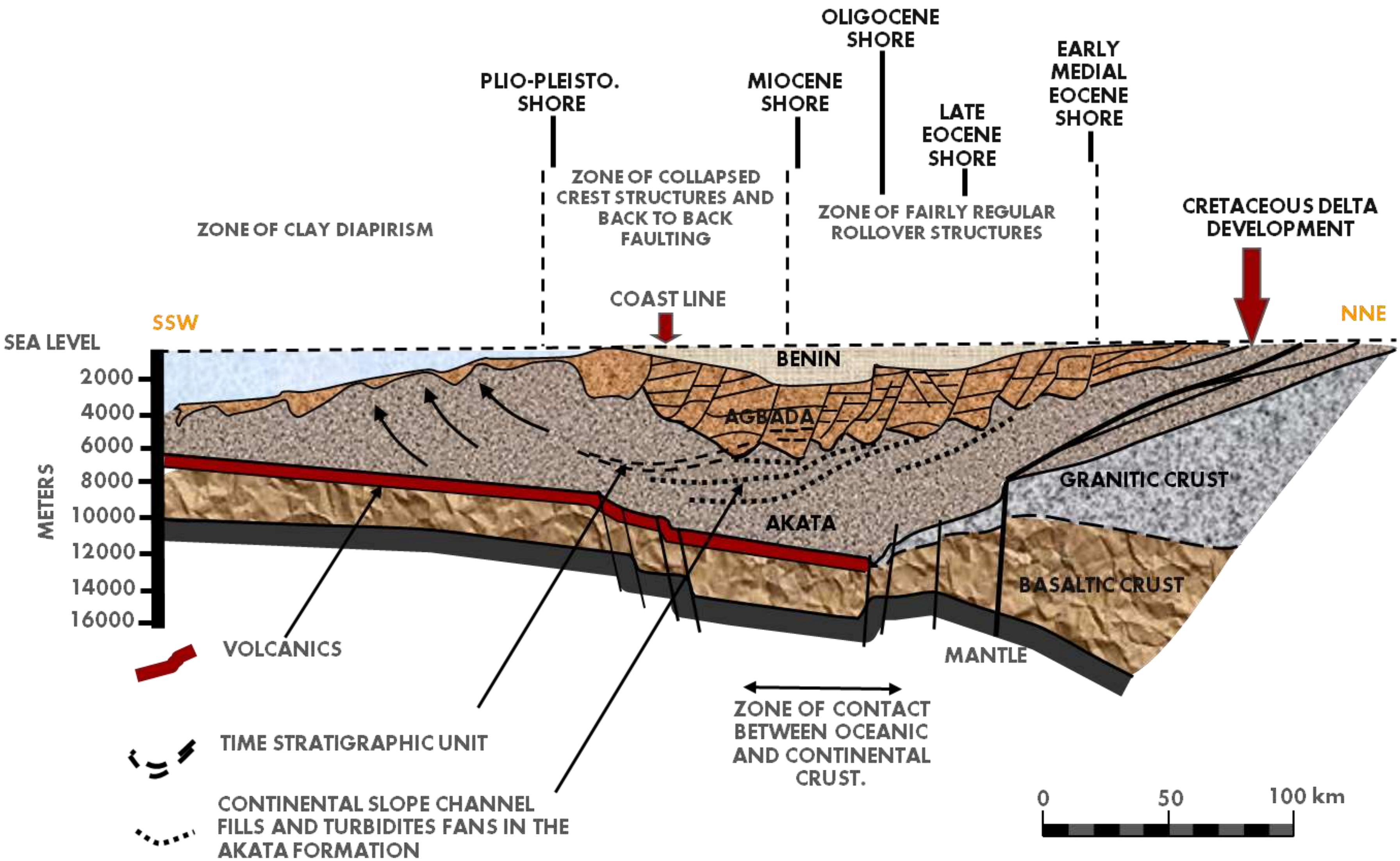


Figure 2.4: **Schematic Dip Section of the Niger Delta (Modified after P. Kamerling, from Weber and Daukoru, 1975)**

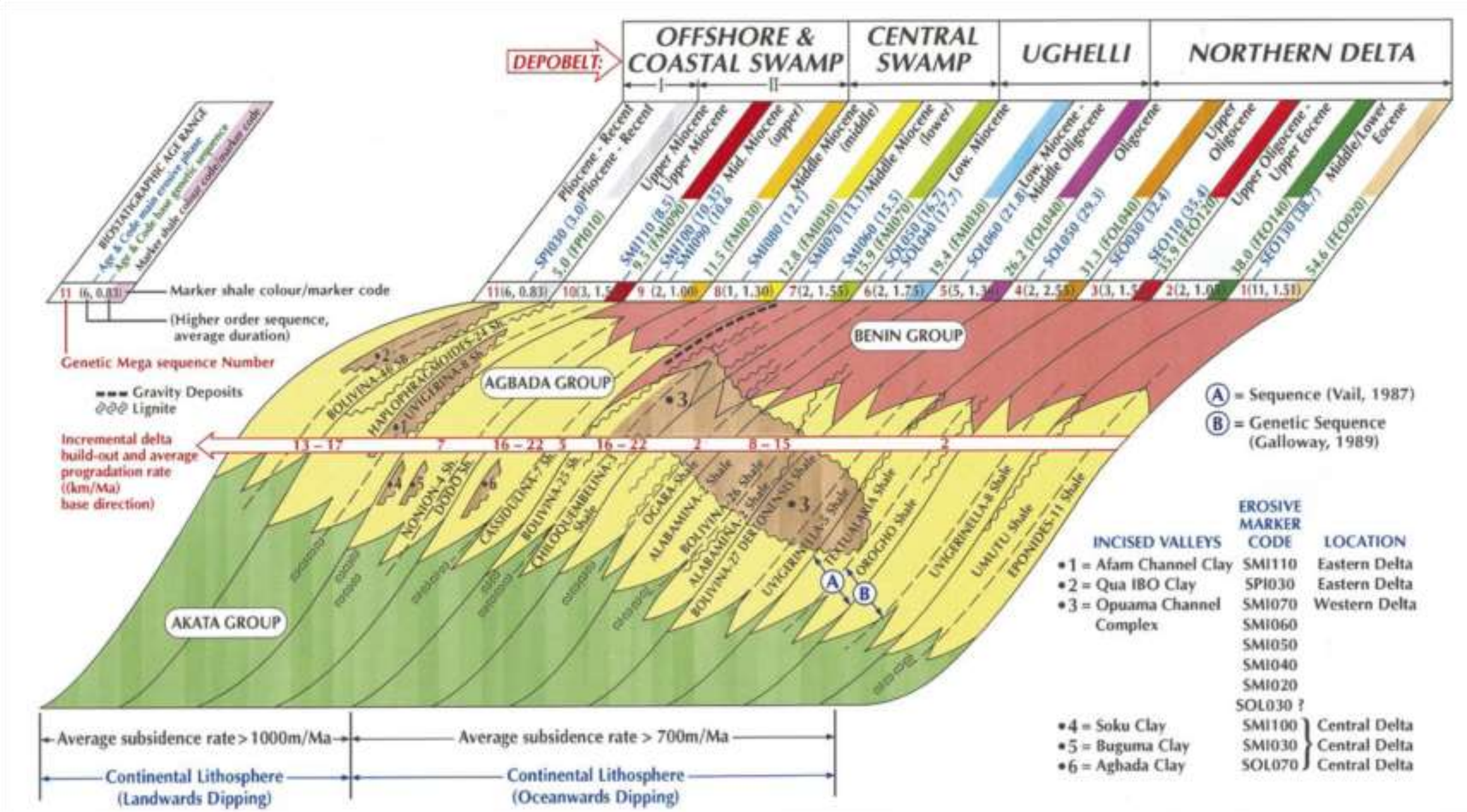


Figure 2.5: Diagrammatic representation of the stratigraphic evolution of the Niger Delta (After Reijers, 2011).

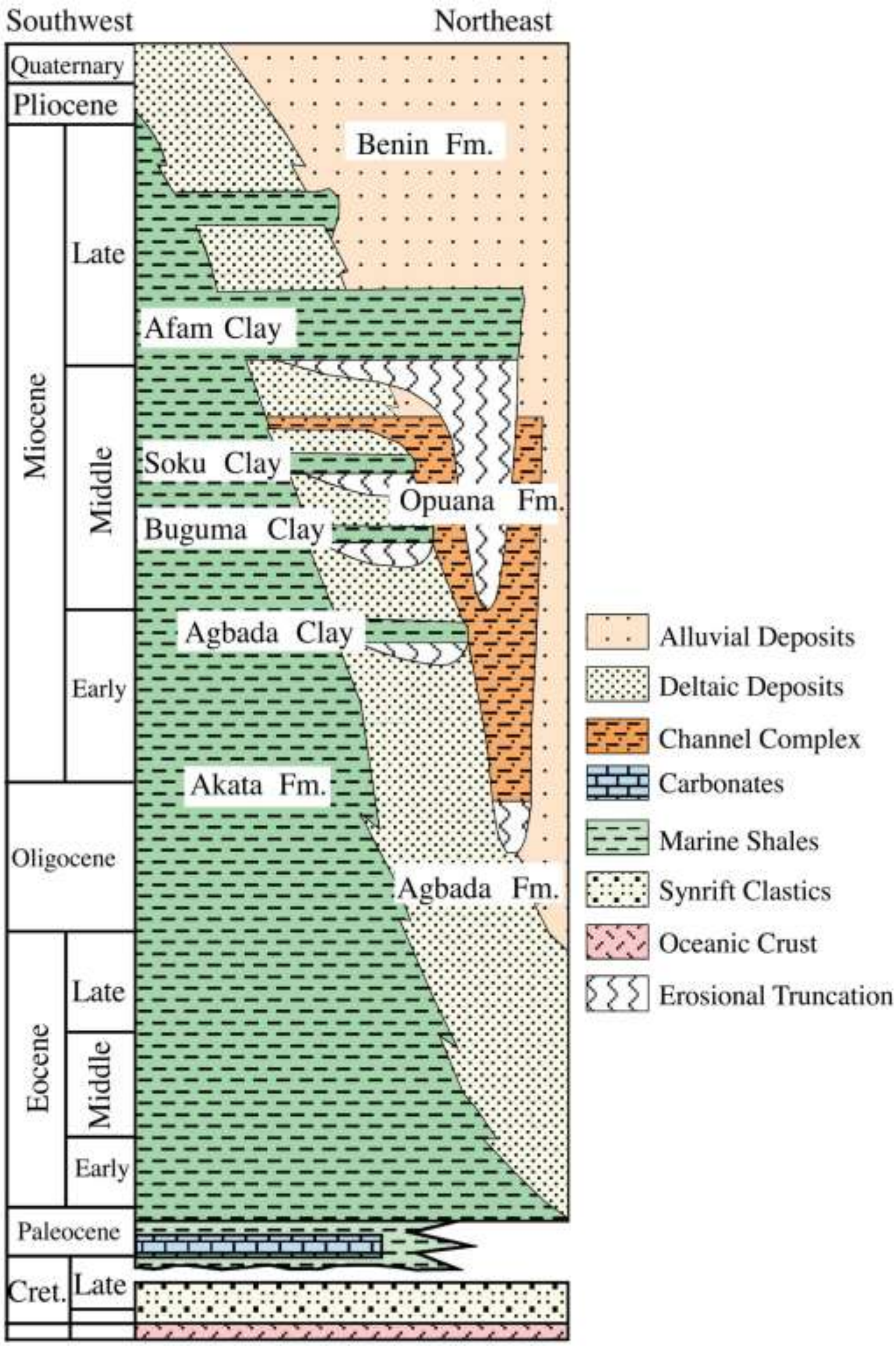


Figure 2.6: Stratigraphic column showing the three formations of the Niger Delta (modified from Lawrence et al, 2002).

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 6,000 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 and are impossible to date directly. Offshore, they become thinner and disappear near the shelf edge.

2.3 DEPOBELTS

Deposition of the three formations occurred in each of the five offlapping siliciclastic sedimentation cycles that comprise the Niger Delta**.** These cycles (depobelts) are 30-60 kilometers wide, prograde southwestward 250 kilometers over oceanic crust into the Gulf of Guinea (Stacher, 1995), and are defined by synsedimentary faulting that occurred in response to variable rates of subsidence and sediment supply (Doust and Omatsola, 1990). Depobelts become successively younger basinward, ranging in age from Eocene in the north to Pliocene offshore of the present shoreline. The interplay of subsidence and supply rates resulted in deposition of discrete depobelts when, further crustal subsidence of the basin could no longer be accommodated, the focus of sediment deposition shifted seaward, forming a new depobelt (Doust and Omatsola, 1990).

Each depobelt is a 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 (Evamy et al., 1978; Doust and Omatsola, 1990). Each sub-basin 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 basinward. Mobilization of basal shale caused 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 basinward.

Five major depobelts are generally recognized, each with its own sedimentation, deformation, and petroleum history (Figures 2.7). Doust and Omatsola (1990) described three depobelt provinces based on structure. The northern delta province, which overlies relatively shallow basement, has the oldest growth faults that are generally rotational, evenly spaced, and increases their 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. Last, the distal delta province which is the most structurally complex due to internal gravity tectonics on the modern continental slope. The study area lies within the coastal swamp depobelts (Figures 2.7a and b). It is described as shelf contained entities with respect to stratigraphy, structure building, and hydrocarbon distribution (Unukogbon, 2008).

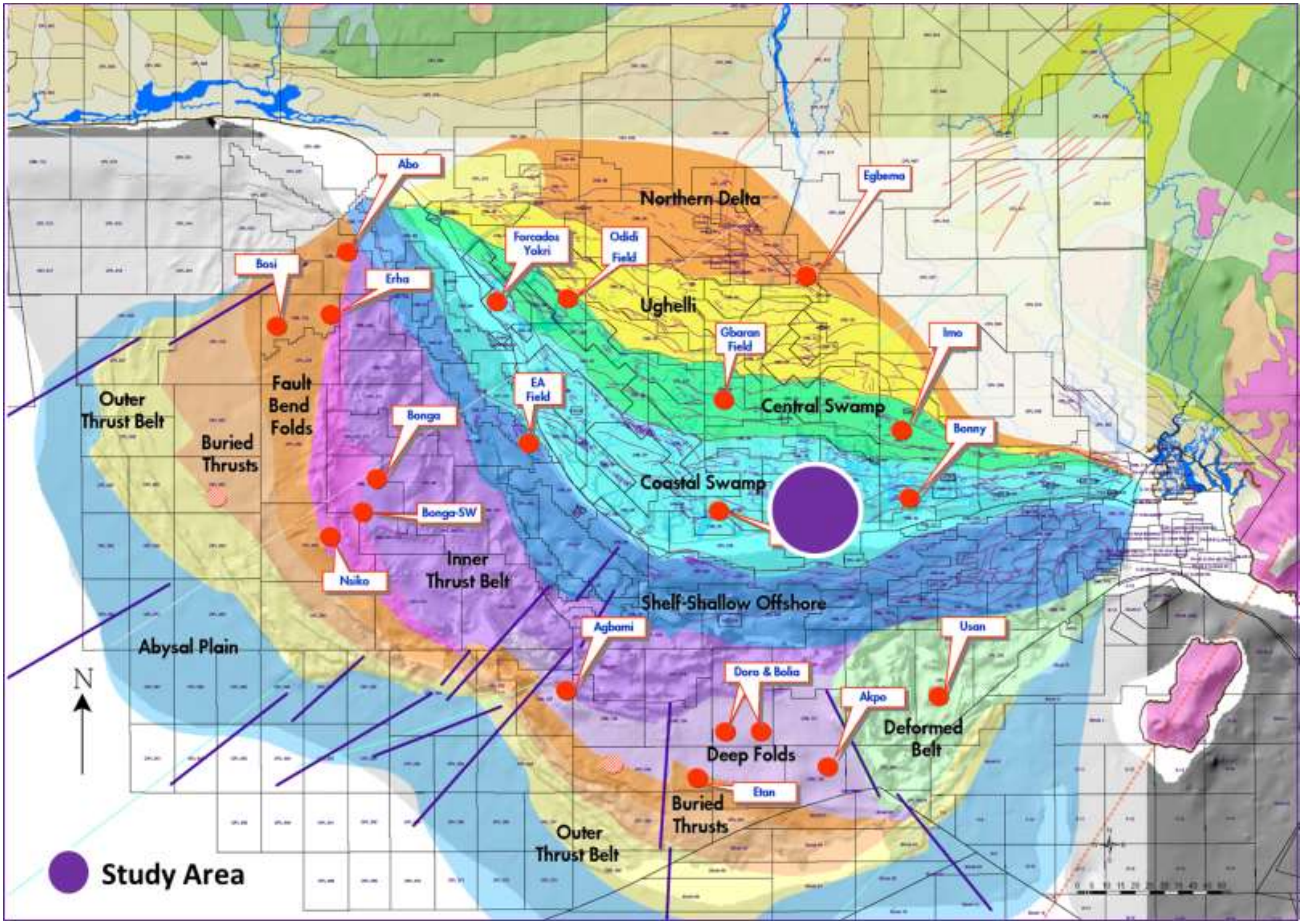


Figure 2.7: Depobelt map with the structural play segments, onshore and offshore Niger Delta Basin showing the study area (Courtesy: Shell).

CHAPTER THREE

Methodology

The study focuses on integrating sequence stratigraphy with biofacies, well logs and seismic tools in interpreting the structural and stratigraphic framework within the Coastal Swamp Depo-belt. The summary of the workflow employed in this research is given in Figure 3.1. This approach is effective in thick, complex strata, such as the late Cenozoic deposits of the Niger Delta Basin.

3.1 DATA SET

The fields for proprietary reasons are renamed in this study as; Lambda, Sigma, Omicron, Epsilon, Alpha, Iota, Eta, Zeta-Creek and Kappa. Conventional suites of well log data provided for the study included Gamma Ray (GR) Logs, Spontaneous Potential (SP) Logs, Porosity Logs and Resistivity Logs. The biofacies data extracted from core samples, side-wall samples and ditch-cuttings were calibrated and depth matched with corresponding wireline logs. The population and diversity of the benthic and planktonic foraminifera were used for environmental and paleobathymetric interpretation (Figure 3.2).

The seismic (pre and post stack time/depth migrated (PreSTM, PreSDM, PosSTM an PosSDM) datasei) data volume comprises a merge of some vintages Sigma_Merge PSDM, Zeta-Creek_PreSDM, Kappa_PreSDM, Eta_PosSTM, Sigma_PreSDM, Lambda_PreSDM, Epsilon_PreSDM, Omicron_PSI, Iota-PosSTM, Lambda_PreSDM, Alpha. They were all acquired and processed/reprocessed in the early 1990s and early 2000s respectively.

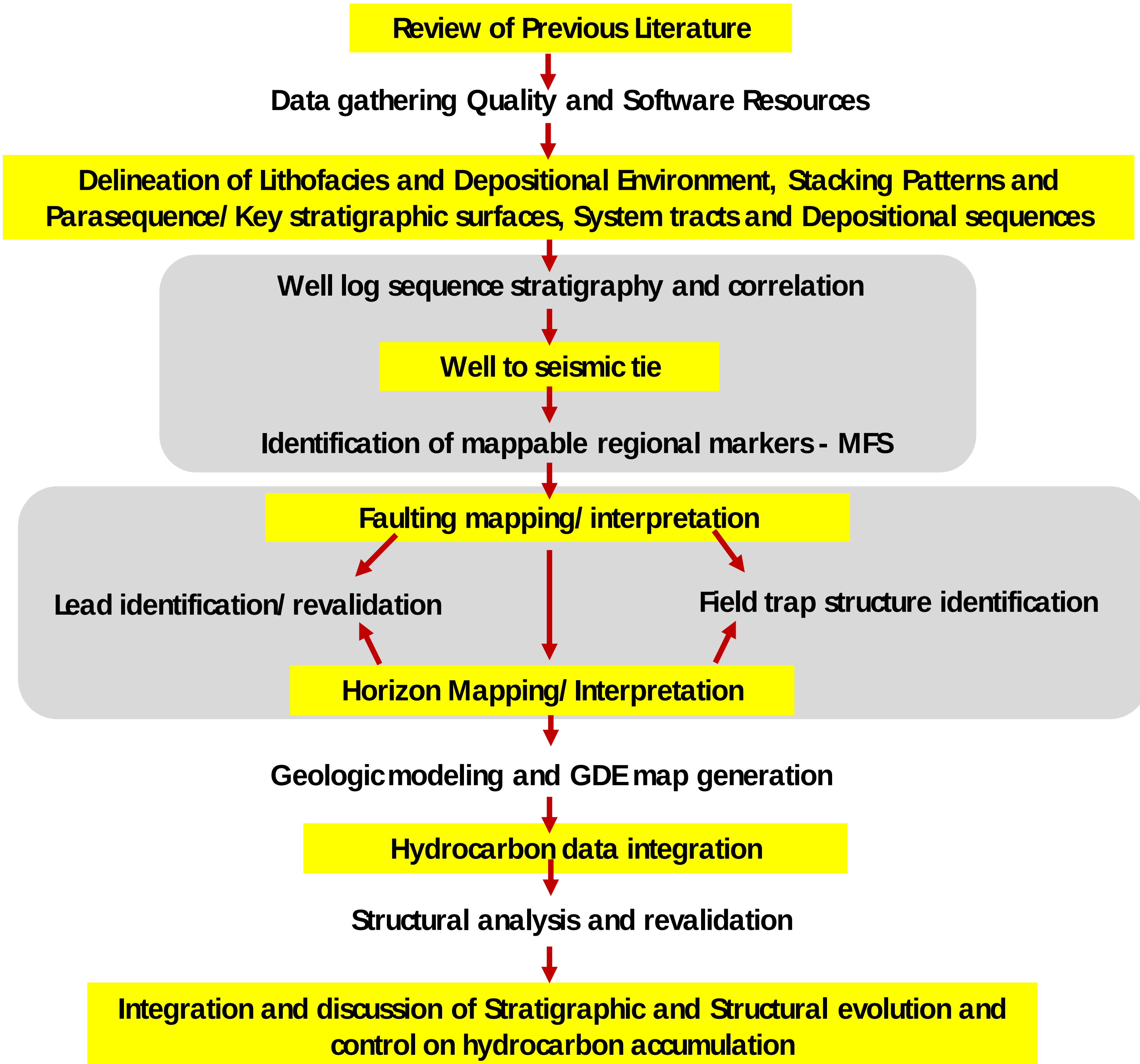


Figure 3.1: Workflow chart.

3.1.1 DATA QUALITY AND SOFTWARE RESOURCES

The seismic volume is characterized by a series of nearly parallel reflections that are quite chaotic close to and behind faults and continuous at zones away from faults. Reflections within the upper one second two-way-travel time are slightly discontinuous and of relatively low amplitude. At intervals between one and four second two-way-travel time, the reflections are generally continuous and of relatively high amplitude. Data quality generally deteriorates at depth below four second two-way-travel time characterized by zones of discontinues and chaotic low amplitude reflection; and zones of continuous and high amplitude reflections.

Well log suites comprise Gamma Ray logs and Spontaneous Potential SP logs. In some wells the whole length of the bore were logged while in some others only a small portion, mainly in the productive zone, were logged. The quality of the logs is quite good especially where the whole length of the well bore is logged.

Biostratigraphic data comprises Biofacies data, Palynological zone (P-Zone) and foraminifera zone (F-Zone). These were calibrated using an established Niger Delta basin zonation schemes (Figure 3.3, 3.4 and 3.5). The biofacies data contain information on total foraminifera abundance and diversity, total planktonic facies abundance and diversity, total benthic calcareous facies abundance and diversity, total benthic arenaceous facies abundance and diversity, paleobathymetry and environment of deposition for various depth intervals of the well bore. In some wells these are available for the whole length while in others it covers only some intervals of interest. The main computer softwares used for this research include Shell's nDI and Petrel run on high definition Linux workstations and 64bits Windows Vista workstation respectively.

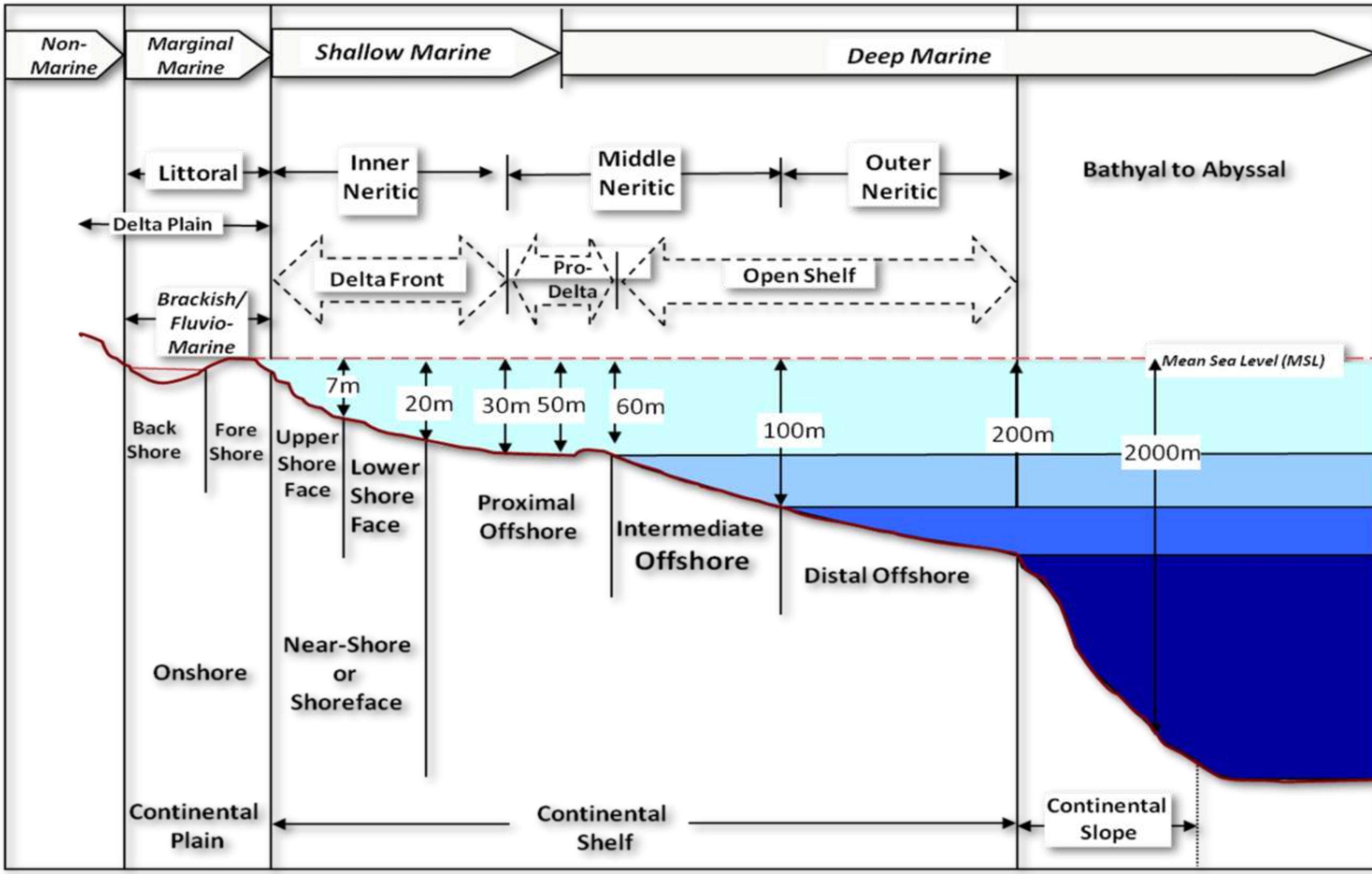


Figure 3.2: Paleobathymmetry and Depositional Environment Chart (Modified After Allen, 1965)

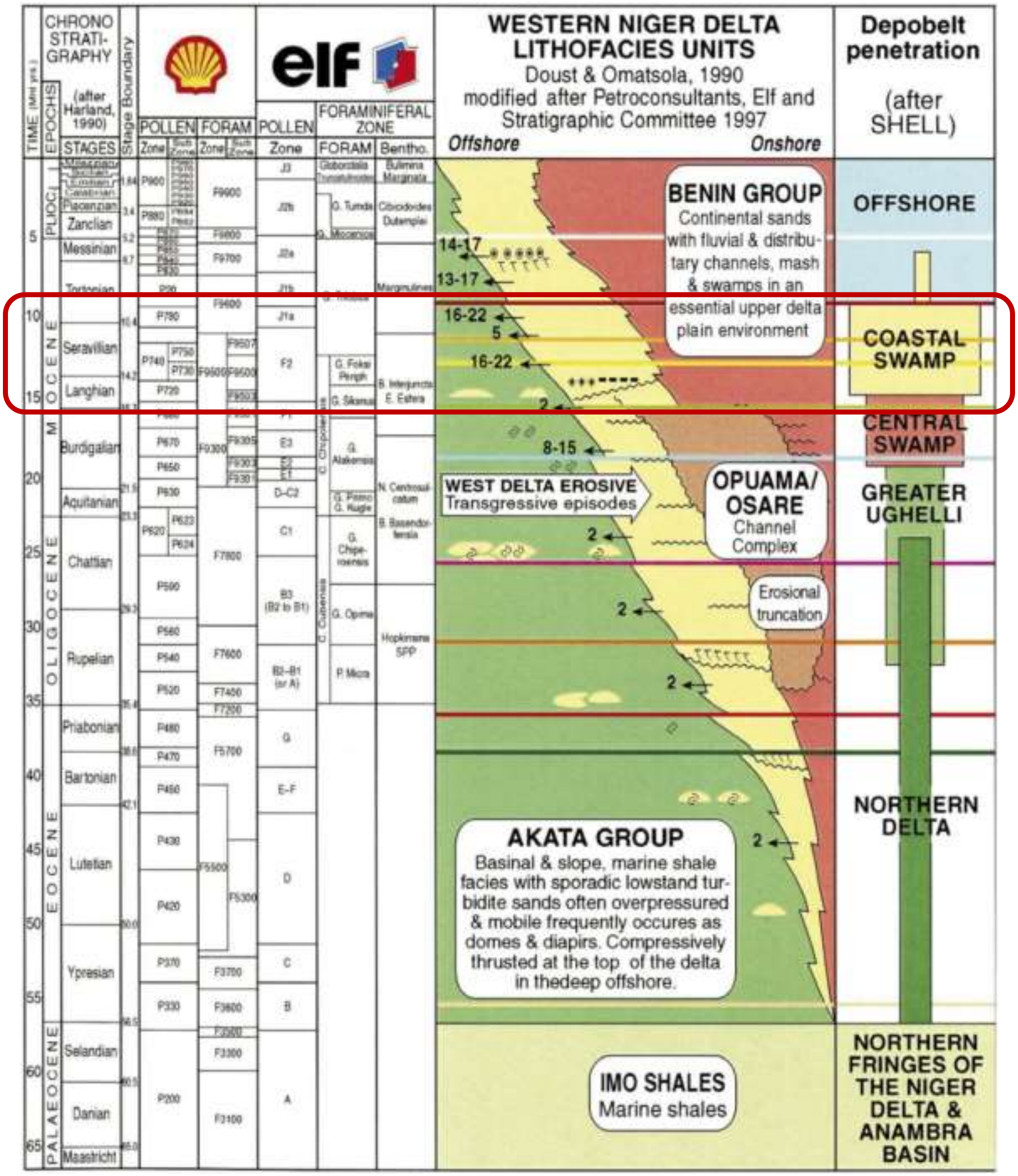


Figure 3.3: Stratigraphic data sheet (west and east halves combined) of the Niger Delta (Reijers, 2011).

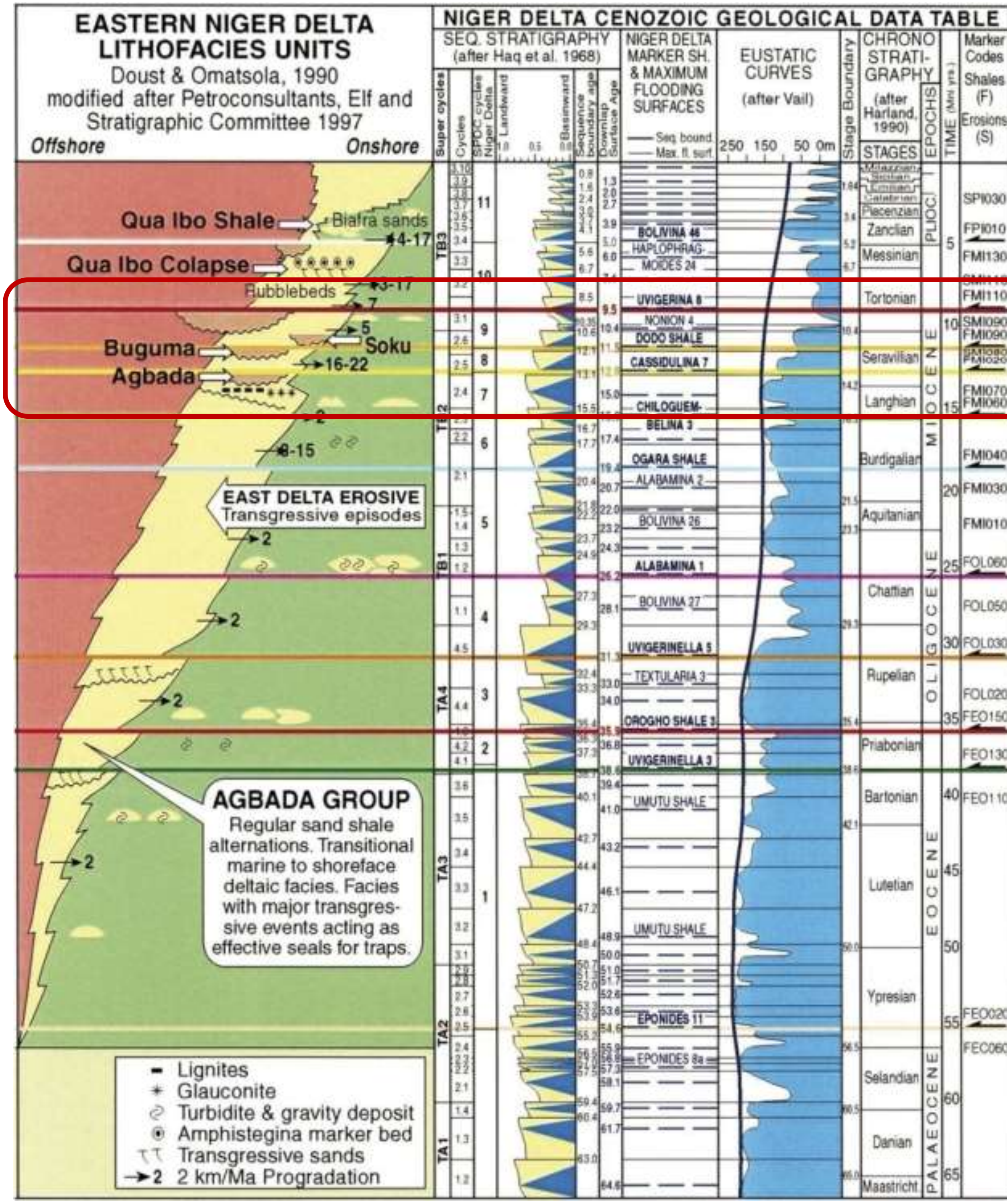


Figure 3.4: Stratigraphic data sheet (west and east halves combined) of the Niger Delta cont'd (Reijers, 2011).

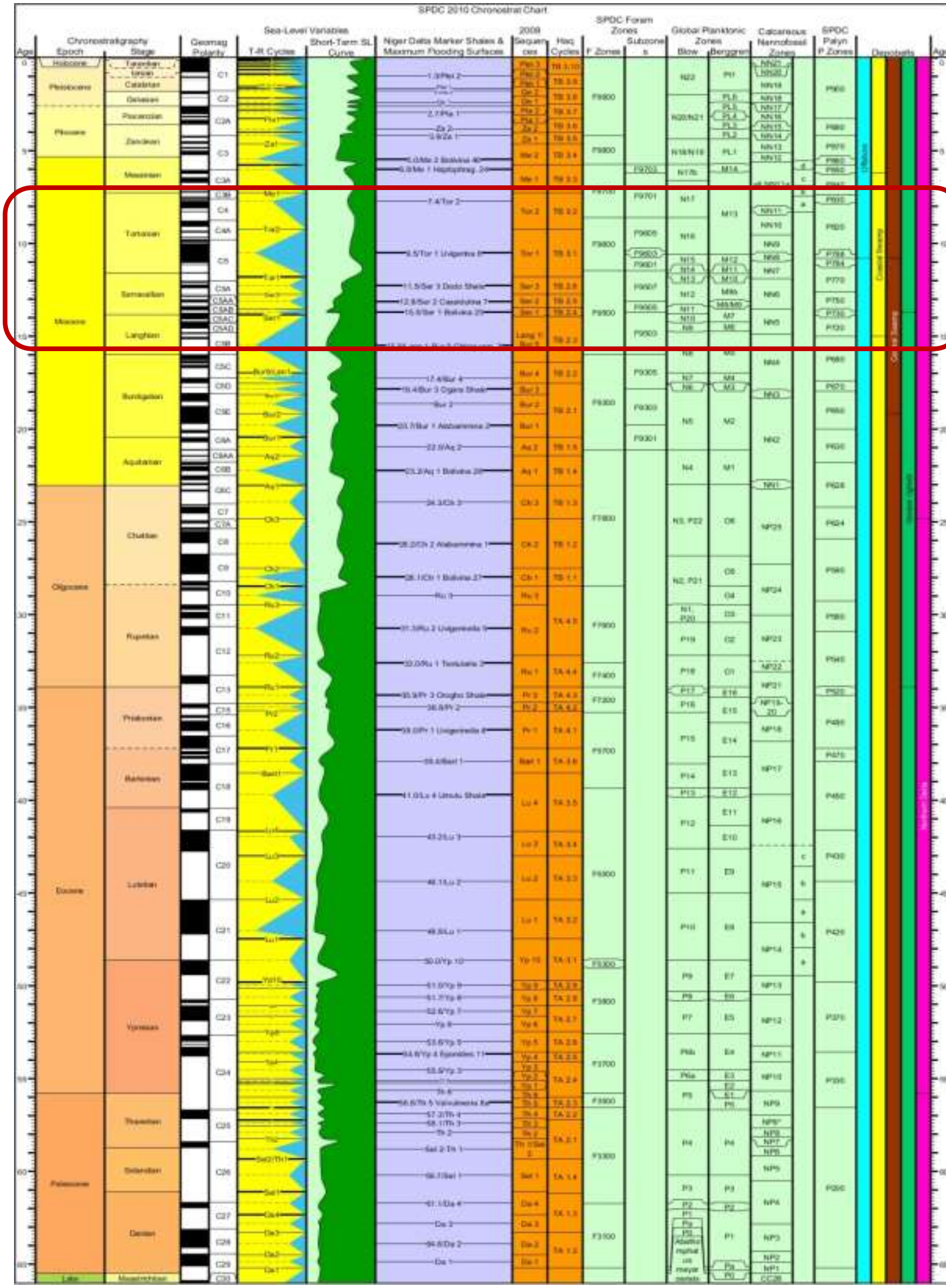


Figure 3.5: SPDC 2010 Niger Delta Chronostratigraphic Chart

3.2 DELINEATION OF LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

The lithofacies profiles were derived from Gamma Ray Log values and signatures (fining and coarsening upward signatures) and the biofacies data helped in determining lithofacies and depositional environments of the different rock units in the study fields. Bell shaped log patterns on Gamma Ray Logs indicating increasing clay contents up section or fining upward trends or an upward increase in gamma ray value is a typical feature of fluvial channel deposits (Figure 3.6a). Funnel-shaped log patterns indicating decreasing clay contents 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 braided channel, tidal channel or subaqueous slump deposits. Serrated log motif suggested intercalation of thin shales in a sandstone body, typically of fluvial, marine and tidal processes (Figure 3.6b).

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 stacks (vertical occurrences of repeated cycles of coarsening or fining upwards sequences), gave rise to progradational, retrogradational, or aggradational parasequence sets (see Figure 3.7a and 3.7b)

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. Progradational parasequence set can be recognized by the seaward movement of a particular facies contact at an equivalent position in a parasequence.

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 farther landward. This results when the 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. Retrogradational parasequence set can be recognized by the landward movement of a particular facies contact at an equivalent position in a parasequence.

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.

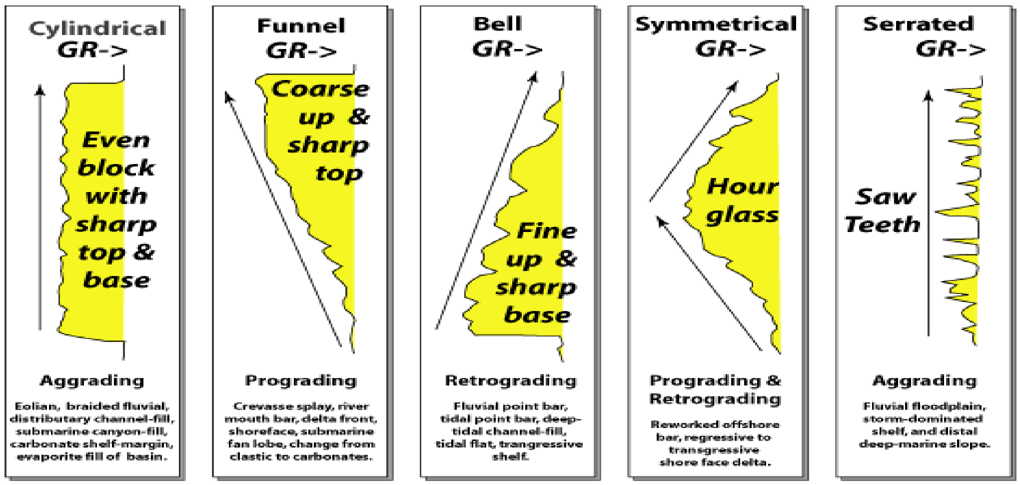


Figure 3.6a: Gamma ray response to grain size variation model (After Emery and Myers, 1996)

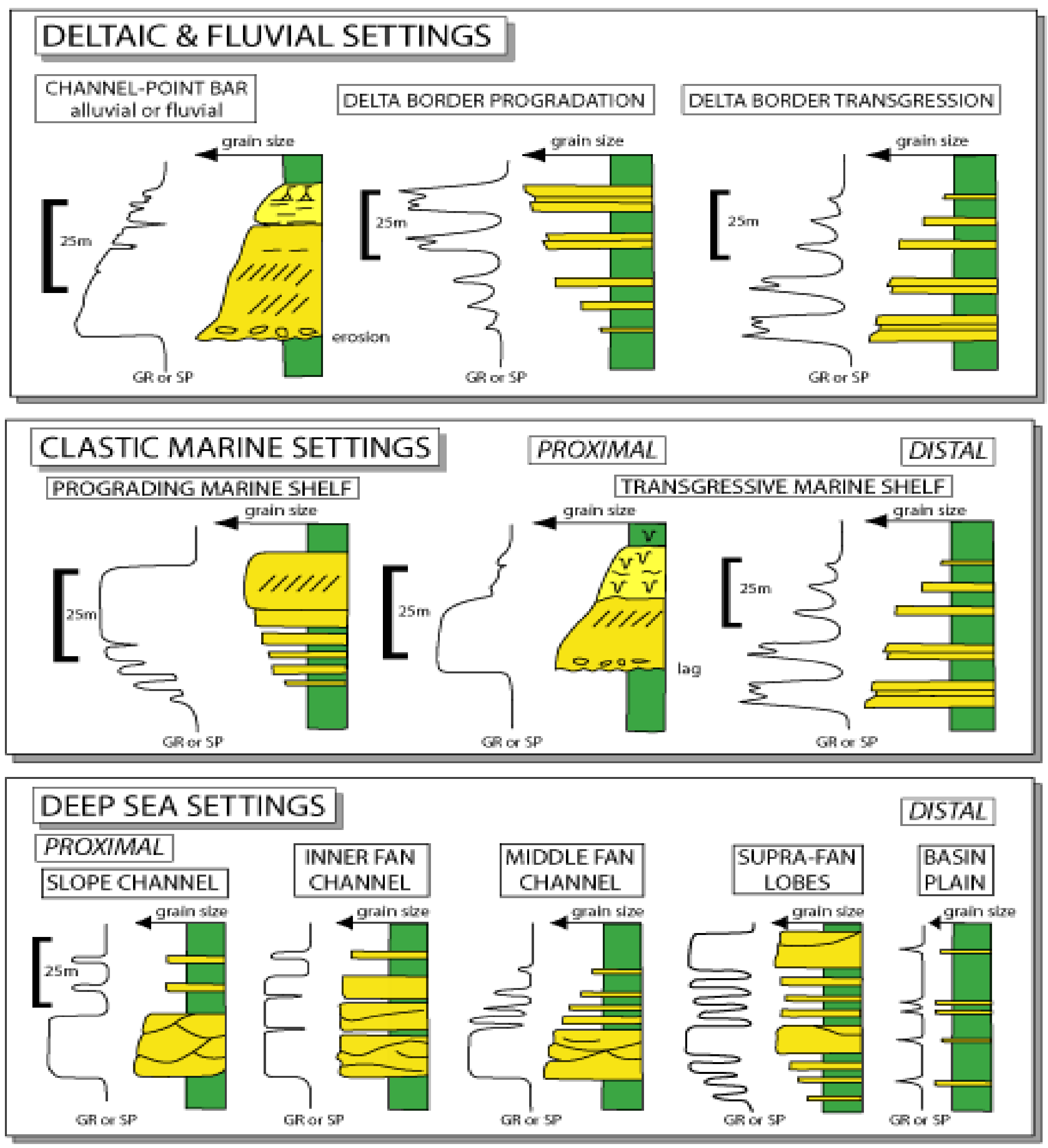


Figure 3.6b: Gamma Ray Log Response and Depositional on Deltaic and Fluvial, Clastic Marine, and Deep Sea Setting. Kendall (2003), modified from Rider, 1999.

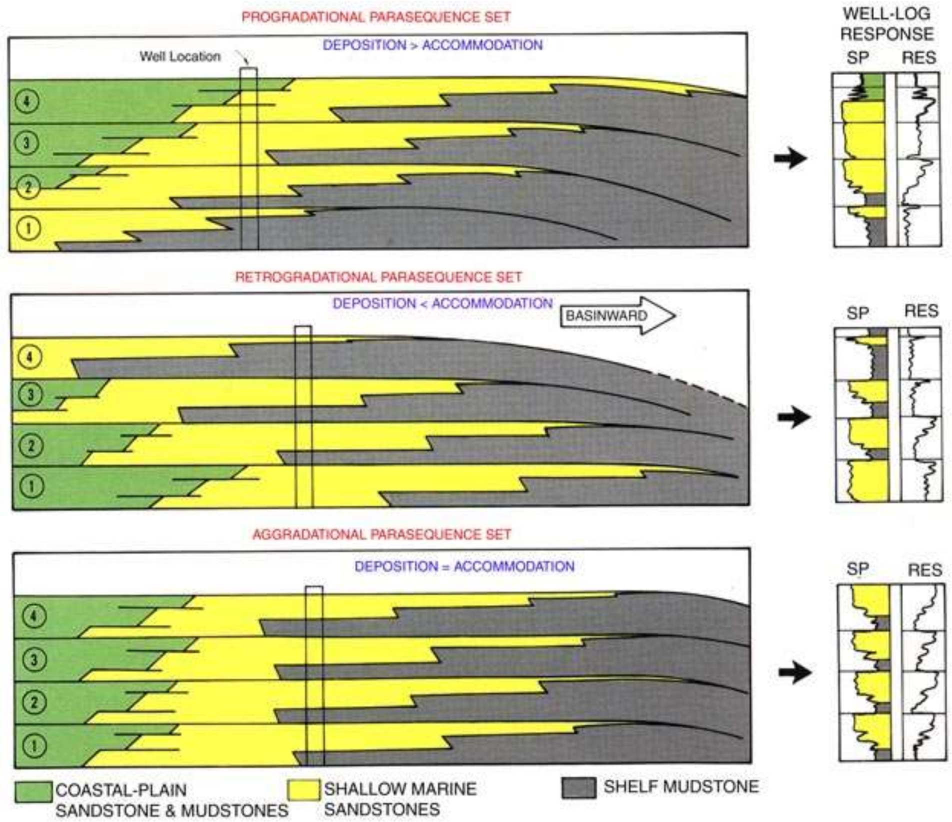


Figure 3.7a: Parasequence stacking pattern model *(after Van Wagoner et al., 1990)*

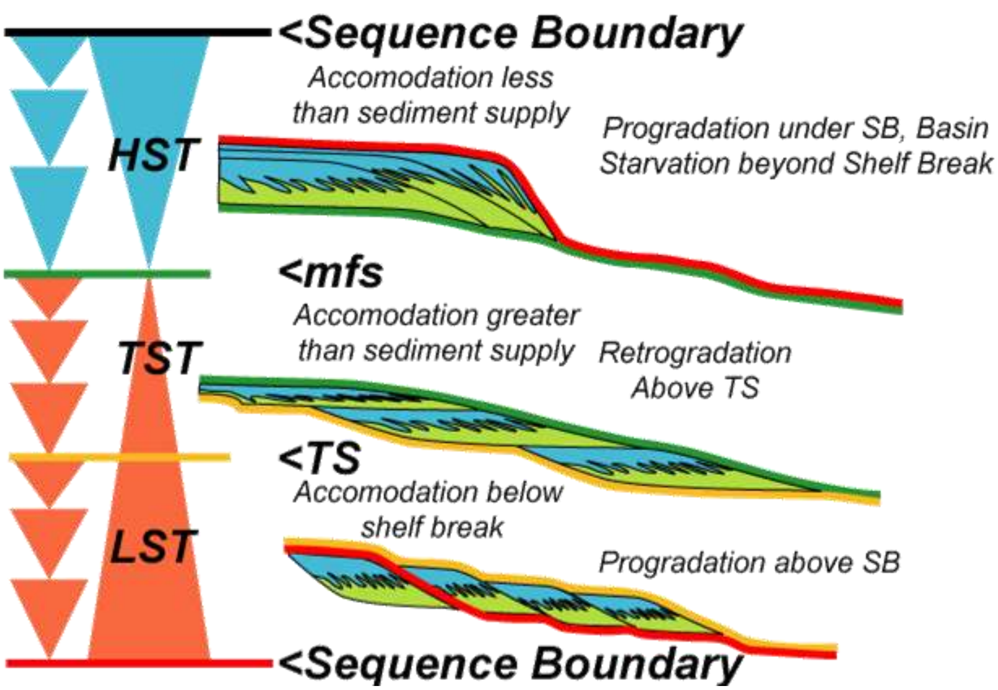


Figure 3.7b: Ideal clastic sequence Staking pattern (Kendall, 2004)

3.4 KEY STRATIGRAPHIC SURFACES, SYSTEMS TRACTS AND DEPOSITIONAL SEQUENCES

The Maximum Flooding Surface (MFS) was delineated using wireline 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 density 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 Maximum Flooding Surfaces (MFSs) (see Figure 3.8).

The Transgressive Surface of Erosion (TSE), 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

Sequence Boundaries (SBs) were recognized in areas of low faunal abundance and diversity or absence of known bio-events, which corresponded to low Gamma Ray, high Resistivity, SP and sonic logs responses within the shallowing section. Candidate 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 (SB).

Systems Tracts (Lowstand Systems Tract, Transgressive Systems Tract, and Highstand Systems Tract) were recognized and mapped with the aid of the depositional sequence model (Figure 3.9a, 3.9b, 3.9c and 3.10).

3.5 WELL CORRELATION

Well correlation was achieved in Petrel window with surfaces (SBs and MFSs) of same geologic age defined in the study area. Marine Flooding surfaces were the best markers or datum on which the correlation cross sections were hung. Correlation was done to determine lateral continuity or discontinuity of facies, hence aiding reservoir studies in the fields. The delineated MFSs and SBs were dated with marker shales (P and F zones) and by correlation with the Niger Delta Chronostratigraphic Chart (see Figure 3.3, 3.4 and 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. The biozone records obtained from the wells were the palynological and foraminiferal zones popularly referred to as the P-Zones and F-Zones. Various pollen zones (P-Zones) and fauna zones (F-Zones) were recognized.

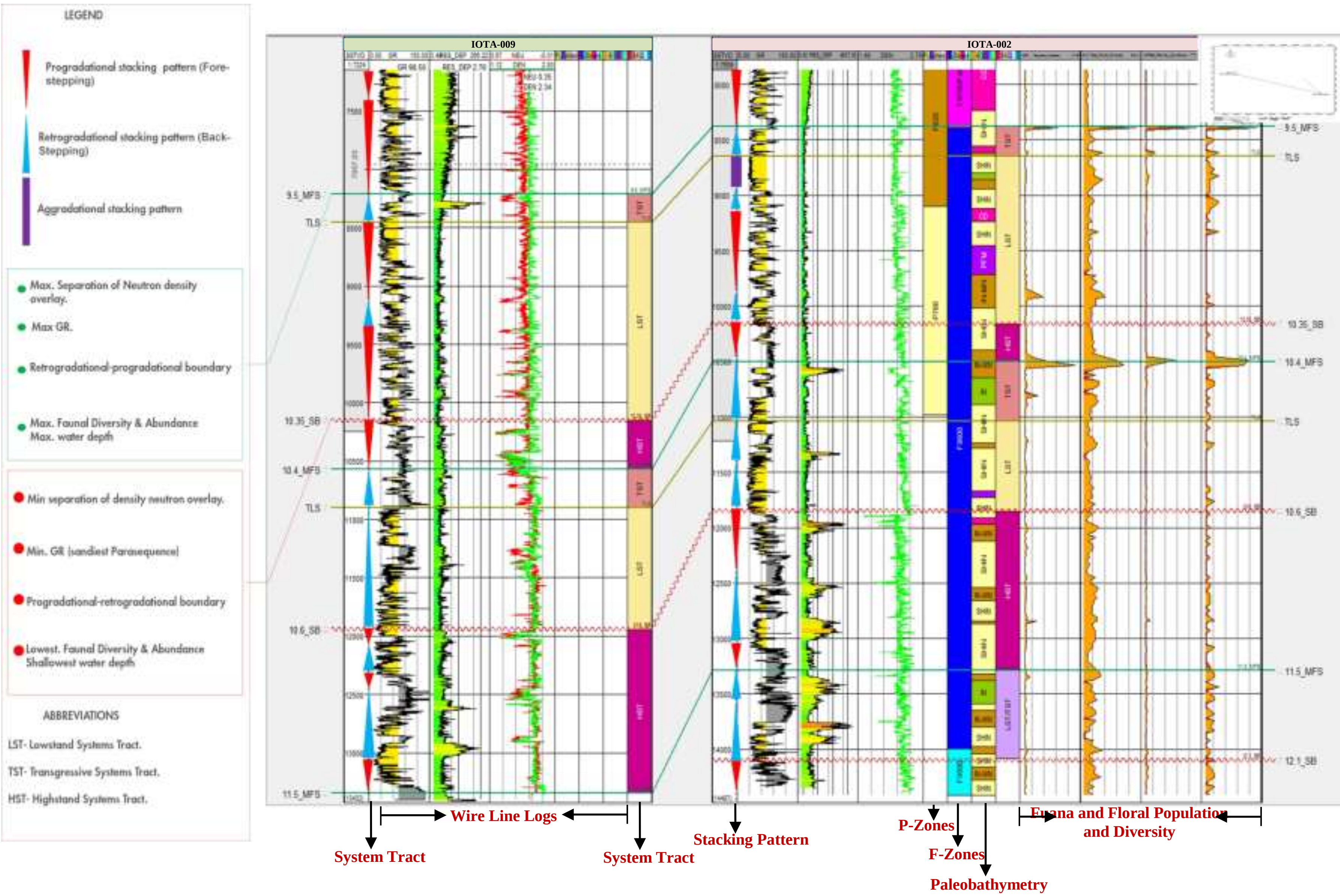


Figure 3.8: Representative Data provided for the study

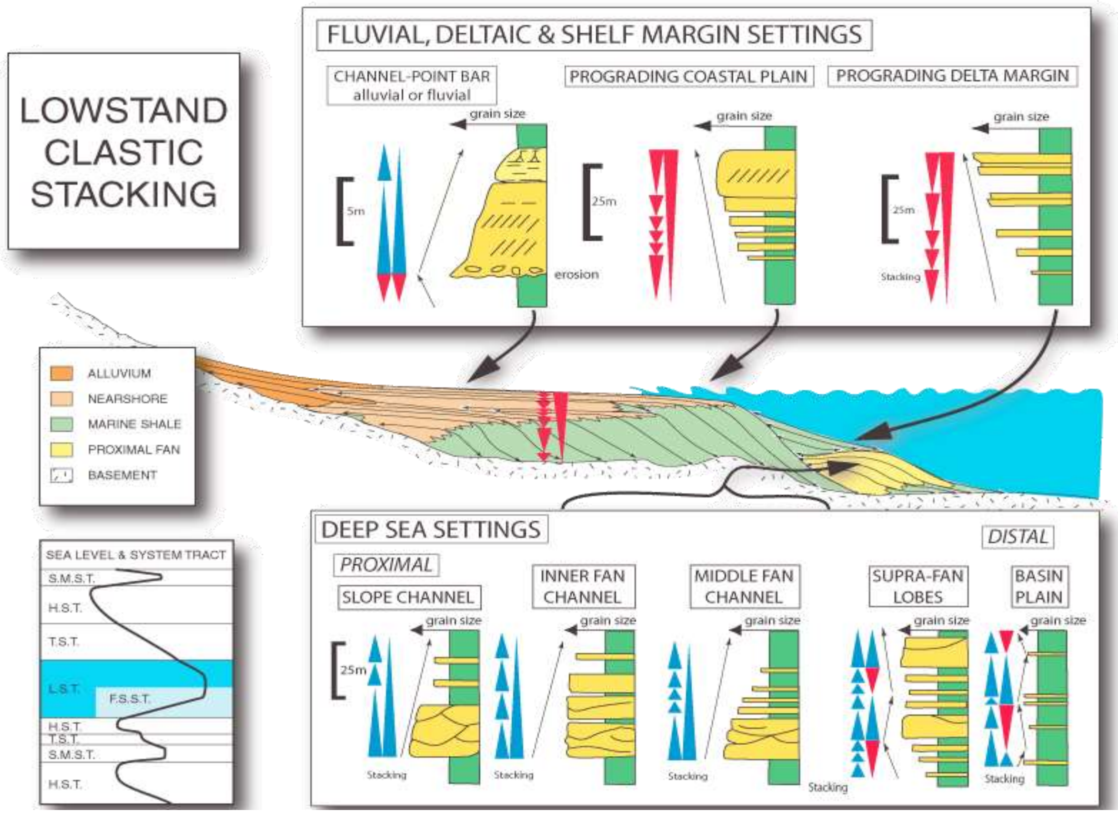


Figure 3.9a: Lowstand clastic stacking on Fluvial, Deltaic, Shelf Margin Settings. Kendall (2004), based on Rider, 1999 and Baum x-section.

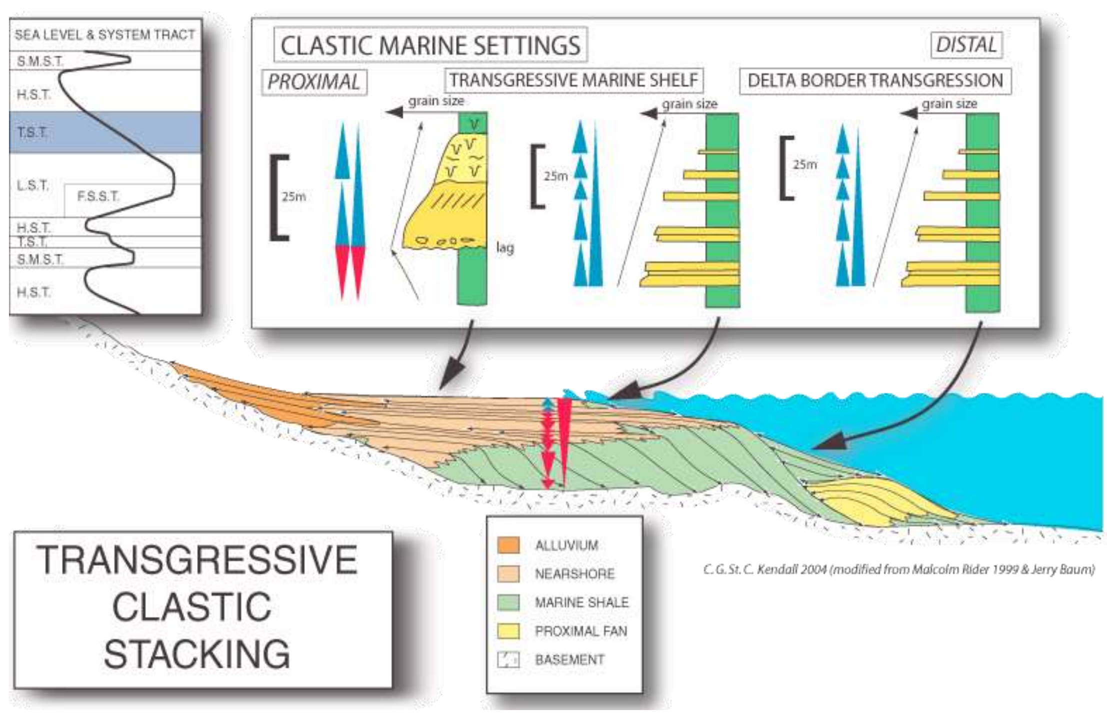


Figure 3.9b: Transgressive clastic stacking on Clastic Marine Settings. Kendall (2004), based on Rider, 1999 and Baum x-section.

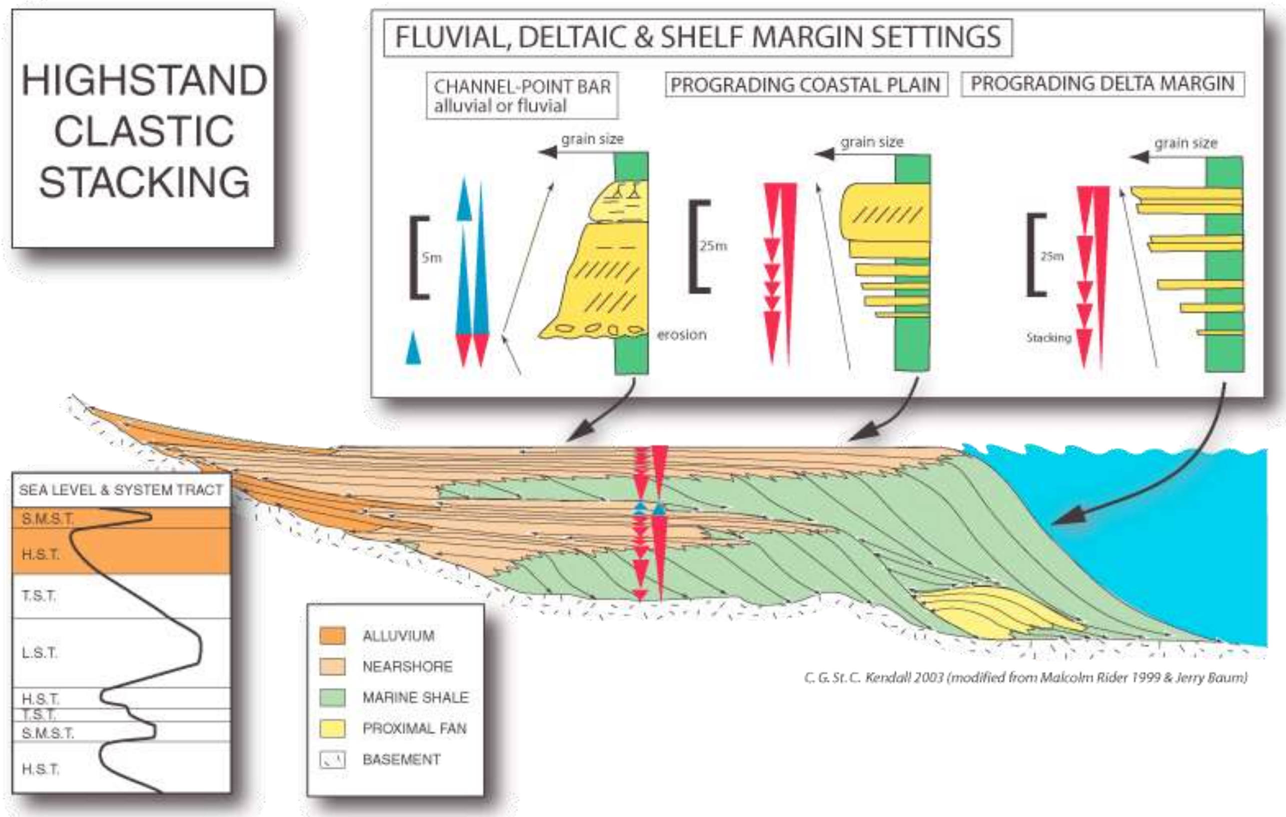


Figure 3.9c: Highstand clastic stacking on Fluvial, Deltaic and Shelf Settings. Kendall (2004), based on Rider,1999 and Baum x-section.

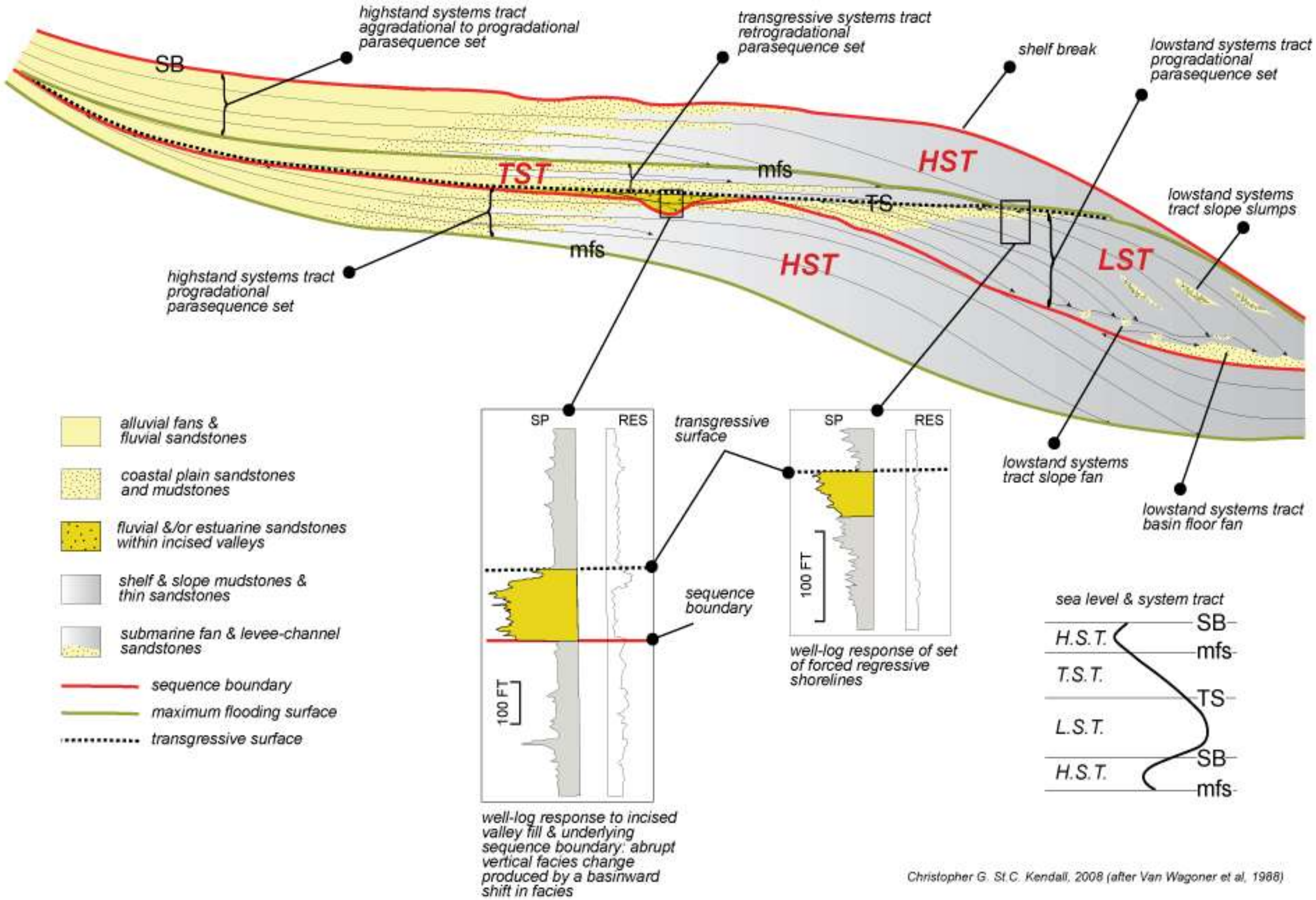


Figure 3.10: Sequence stratigraphic model showing key stratigraphic surfaces and various systems tracts. (Kandall, 2008, After Van Wagoner et al, 1988)

Results, Data Analysis and Interpretations

4.1 LITHOFACIES AND DEPOSITIONAL ENVIRONMENTS

The stratigraphic column in the study area was generally divided into four (4) lithofacies, namely: a) Coarse-Grained Basal Sandstones Facies; b) Shaly Sandstone Facies; c) Mud-rock Facies; and d) Heterolithic Facies (Figure 4.1a and b).

4.1.1 COARSE-GRAINED BASAL SANDSTONE FACIES

The Coarse-Grained Basal Sandstone Facies consists of amalgamated and isolated sharp-based fining upward sand bodies characterized by blocky to bell-shaped Gamma Ray Log motif with little or no separation on the Neutron-Density Logs (Figure 4.1b). The sand units are locally 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.

4.1.2 SHALY-SANDSTONE FACIES

The Shaly-Sandstone Facies (Figure 4.1a) is characterised by the predominance of fine to medium-grained sandstones and mudstone/shale interbeds. 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 high Neutron and Density Porosity

Log values with 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.

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 and upward increasing porosity values on the Density Log. 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 indicated storm emplacement or inter-storm pelagic sedimentation.

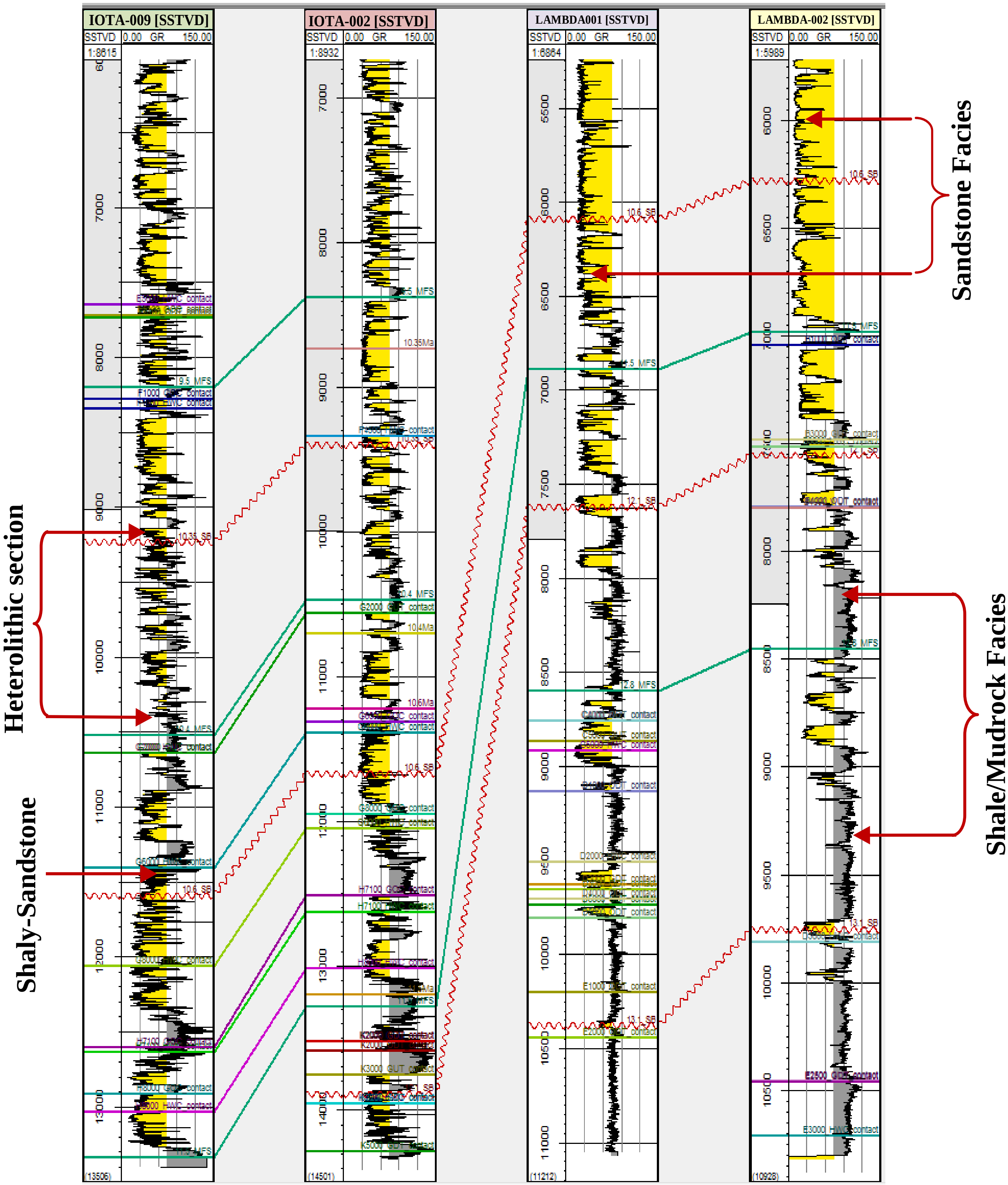


Figure 4.1a: Lithofacies across Iota and Lambda Fields

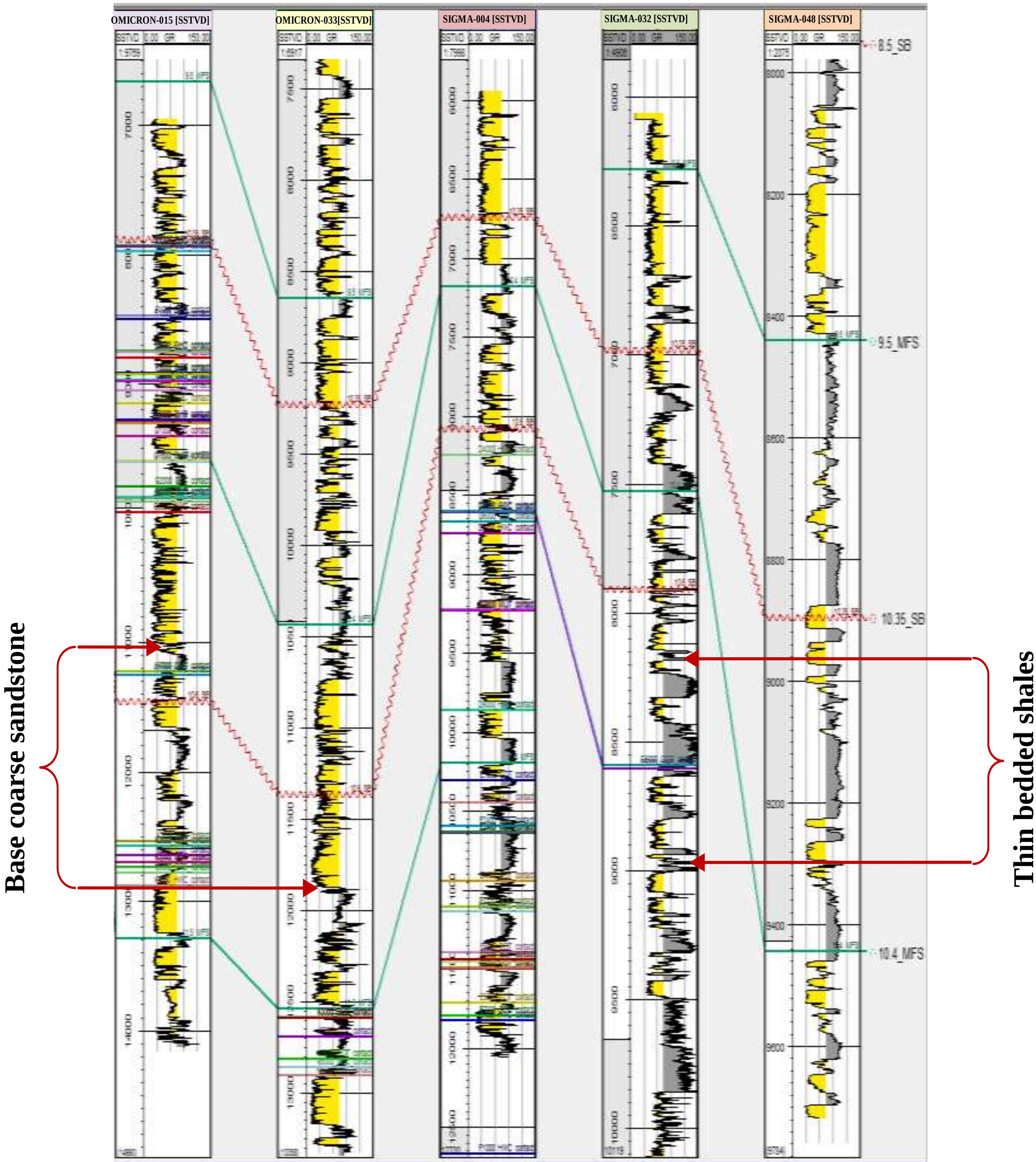


Figure 4.1b: Coarse grained basal sandstone Facies represented by Blocky Gamma Ray Logs across Omicron and Sigma Fields.

4. 2. SEQUENCE STRATIGRAPHIC ANALYSIS

4.2.1 MAXIMUM FLOODING SURFACE (MFS)

Maximum Flooding Surface (MFS_12.8) was correlated across Lambda-001 and Lambda-002 wells and was dated 12.8Ma using a regional marker, *Ser-2-Cassidulina.* The surface occurrence of the event is within P680 and F9300/9500 biozones.

Maximum Flooding Surface (MFS_11.5) was correlated across Lambda-001and 002; Sigma-002, 004 and 013; Epsilon-002, 003 and 007; Alpha-001 and 002; Iota-002 and 009; Omicron-015 and 033, Eta-004; wells and was dated 11.5 Ma. The surface occurred within P770 and F9500/F9600 biozone characterised by Ser-3-*Dodo Shale* marker.

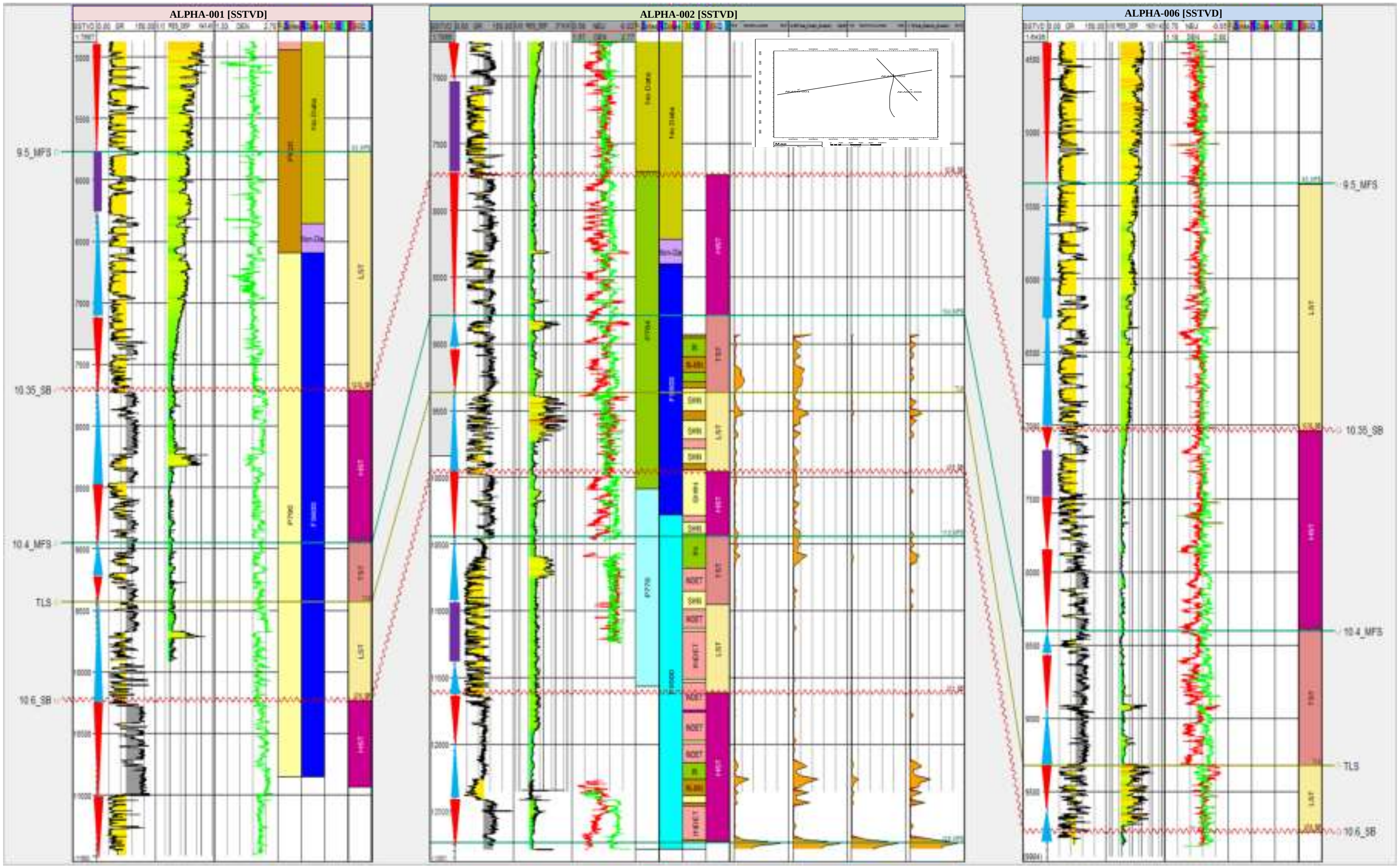
Maximum Flooding Surface (MFS_10.4) was correlated across Lambda-001and 002; Sigma-002, 004, 013 and 048; Epsilon-002, 003 and 007; Alpha-001, 002 and 006; Iota-002 and 009; Omicron-001, 015 and 033, Eta-001, 002 and 004, Zeta Creek-001, 002 and 006; Kappa-002 and 006 wells and was dated 10.4 Ma. The MFS occurred within P780 and F9600 biozone and characterized by *Tor-Nonion-4* marker.

Maximum Flooding Surface (MFS_9.5) was correlated across Sigma- 048; Epsilon-002, 003 and 007; Alpha- 006; Iota-002 and 009; Omicron-001, 015 and 033, Eta-001, 002 and 004, Zeta Creek-001, 002 and 006; Kappa-002 and 006 wells and was dated 9.5Ma. The MFS occurred within P820 and F9600 biozone and characterized by *Tor-1-Uvigerina-8* marker.

Maximum Flooding Surface (MFS_7.4) was correlated across Zeta Creek-001, 002 and 006 wells and was dated 7.4Ma. The MFS occurred within P830 and F9700 biozone and characterized by *Tor-2* marker. The well correlation across various and delineated bounding surfaces (Surface of Erosion - Sequence Boundaries and flooding surfaces - Maximum Flooding Surfaces) and the depth at which they occur in the wells are shown in Figures 4.2 - 4.10 and Table 1.0.

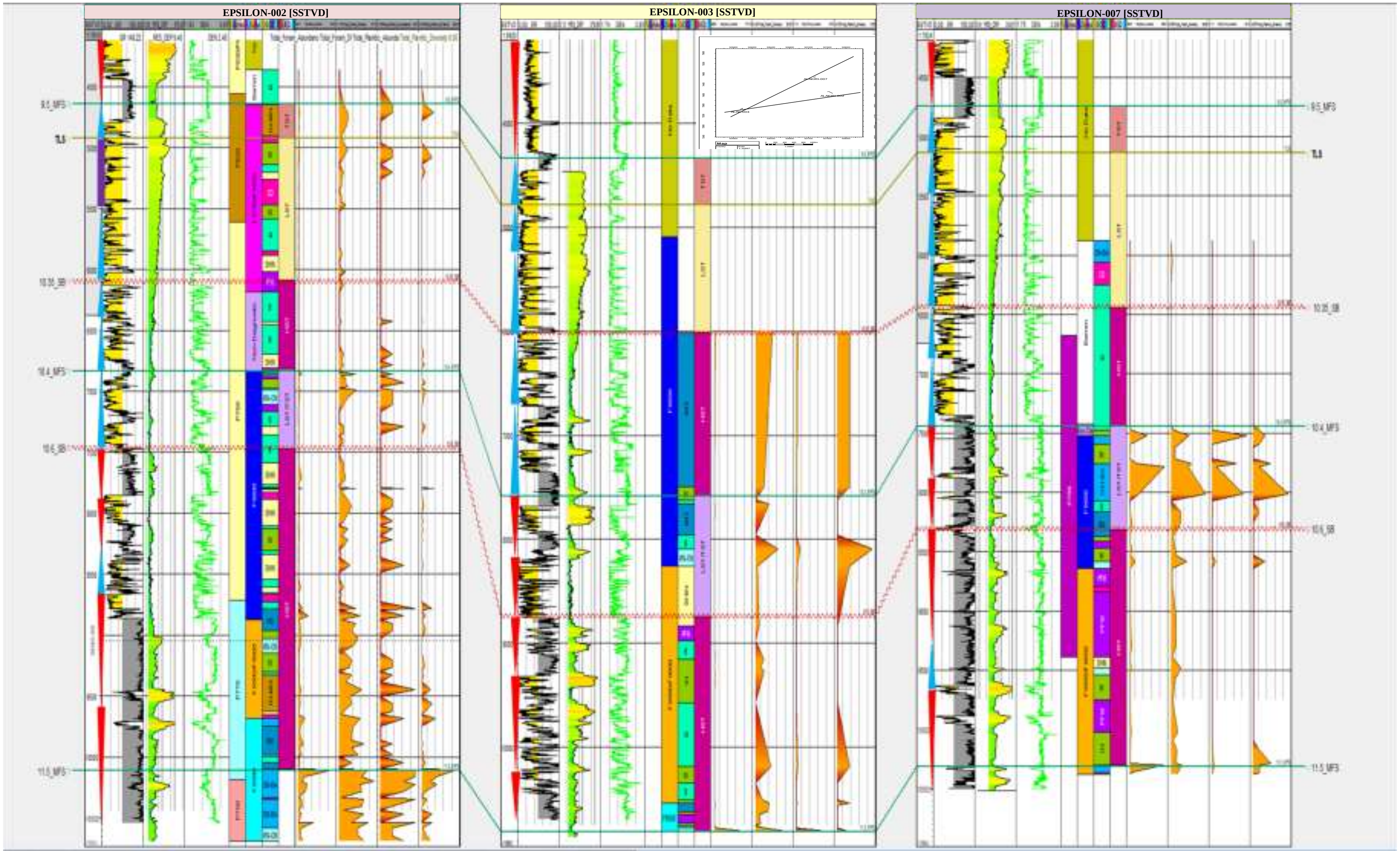
4.2.2 SEQUENCE BOUNDARY (SB) AND TRANSGRESSIVE SURFACE OF EROSION (TSE)

The oldest Sequence Boundary (SB) identified within the study fields were dated 13.1 Ma. The surface represents a substantial erosional surface defined before the MFS of 12.8Ma (Figure 4.2-4.10). The SB_13.1 Ma is overlain in the down dip section by a relatively thick and sharp-based sand unit identified as incised valley fill (Basin Floor Fan) and in the up dip areas by sharp-top facies of the uppermost prograding Highstand parasequence. The thickness of the sand units overlying SB_13.1 in the down dip section, however, varied from well to well due to local erosion of the sands (ravinement) at the onset of rising sea level and beginning of a retrogradational facies that starts with initial substrate erosion: the Transgressive Surface of Erosion (TSE). Other Sequence Boubdaries are dated 12.1 Ma, 10.6 Ma, 10.35 and 8.5 Ma respectively, based on their relative positions in the stratigraphic sections and with reference to the Niger Delta Chronostratigraphic Chart. Identified Transgressive Surfaces of Erosion, lie close to the SBs marking abrupt changes from progradational facies to retrogradational facies and substantially caused diminution of sand thickness deposited during sea level fall (Figures 4.2 – 4.10, 4.12 and 4.13 and Table 2.0).



LST-Lowstand systems tracts | LST/TST-Lowstand systems tracts/Transgresive systems tracts | TST- Transgresive systems tracts | HST- High systems tracts

Figure 4.2: Alpha Field Well log Sequence Stratigraphic Interpretation and Correlation



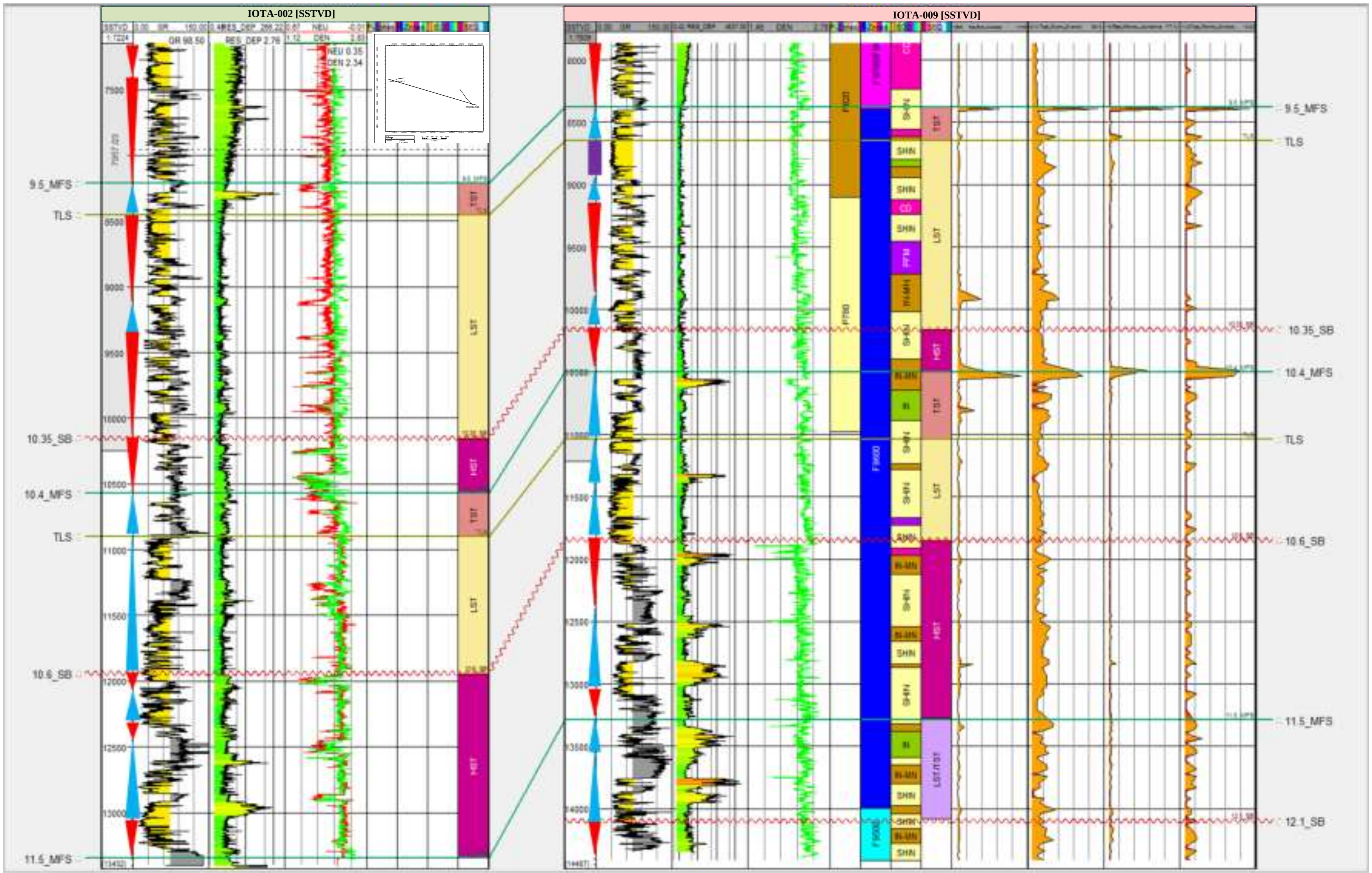
LST-Lowstand systems tracts

LST/TST-Lowstand systems tracts/Transgresive systems tracts

TST- Transgresive systems tracts

HST- High systems tracts

Figure 4.3: Epsilon Field Well log Sequence Stratigraphic Interpretation and Correlation



LST-Lowstand systems tracts

LST/TST-Lowstand systems tracts/Transgresive systems tracts

TST- Transgresive systems tracts

HST- High systems tracts

Figure 4.4: Iota Field Well log Sequence Stratigraphic Interpretation and Correlation

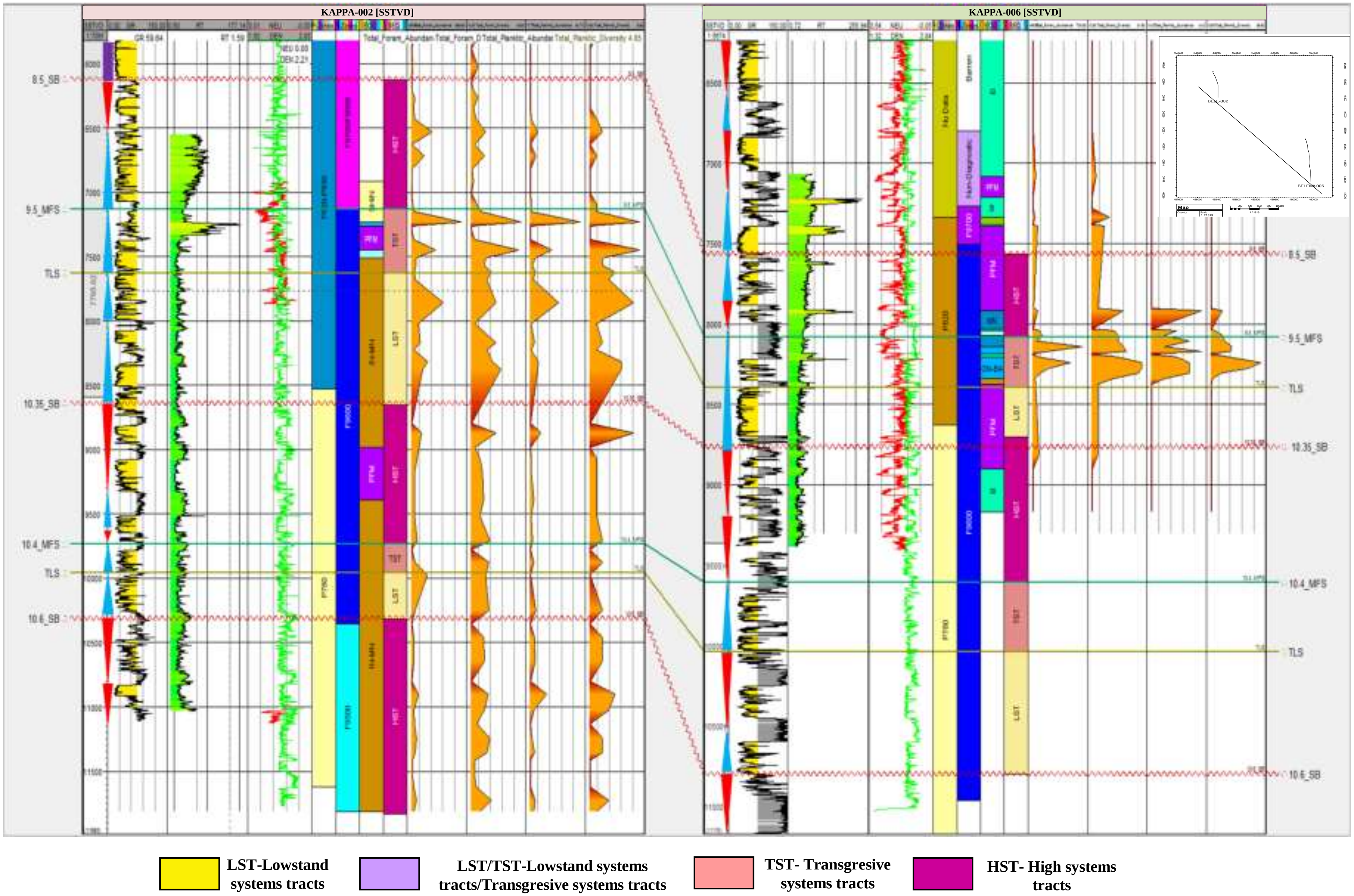


Figure 4.5: Kappa Field Well log Sequence Stratigraphic Interpretation and Correlation

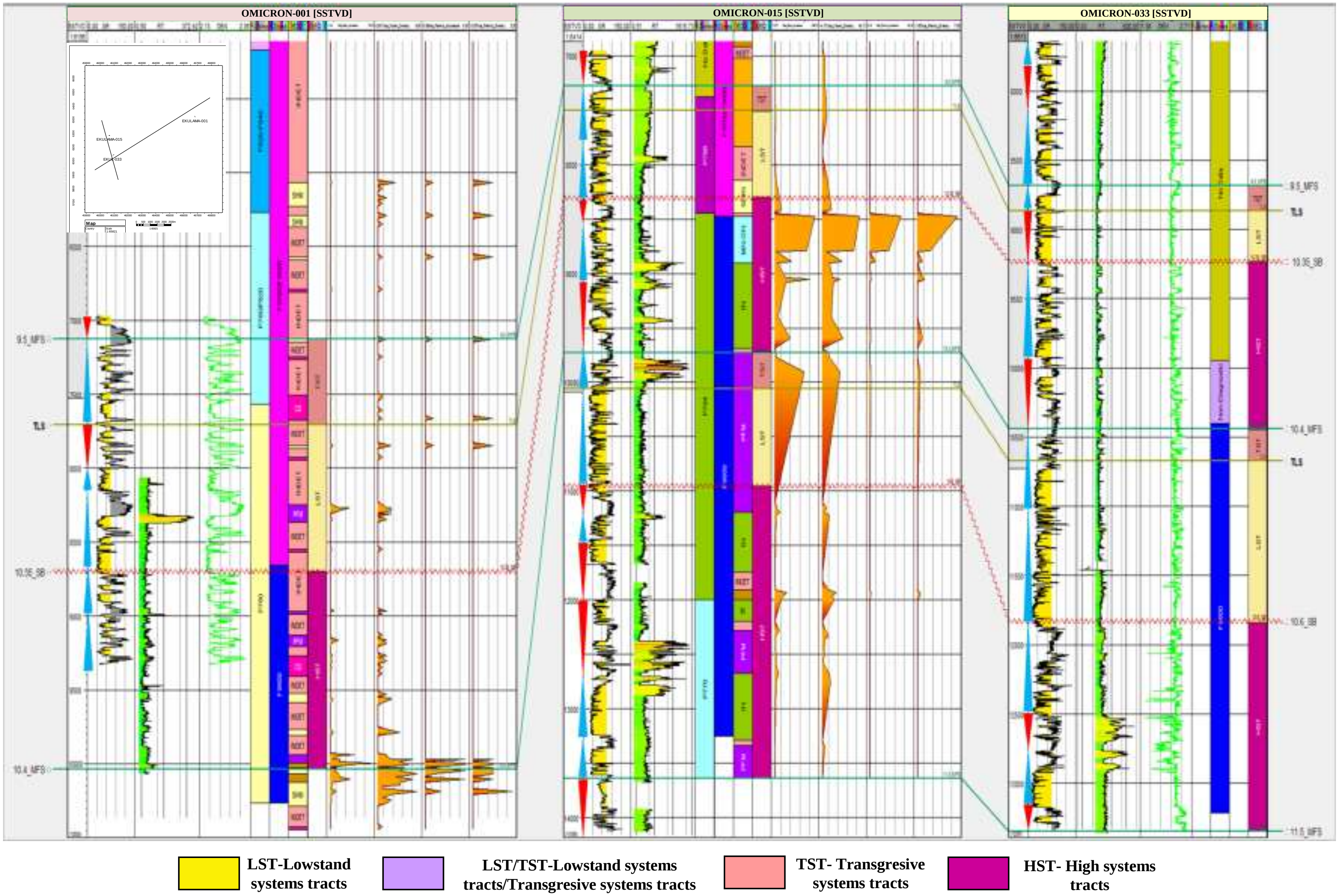


Figure 4.6: Omicron Field Well log Sequence Stratigraphic Interpretation and Correlation

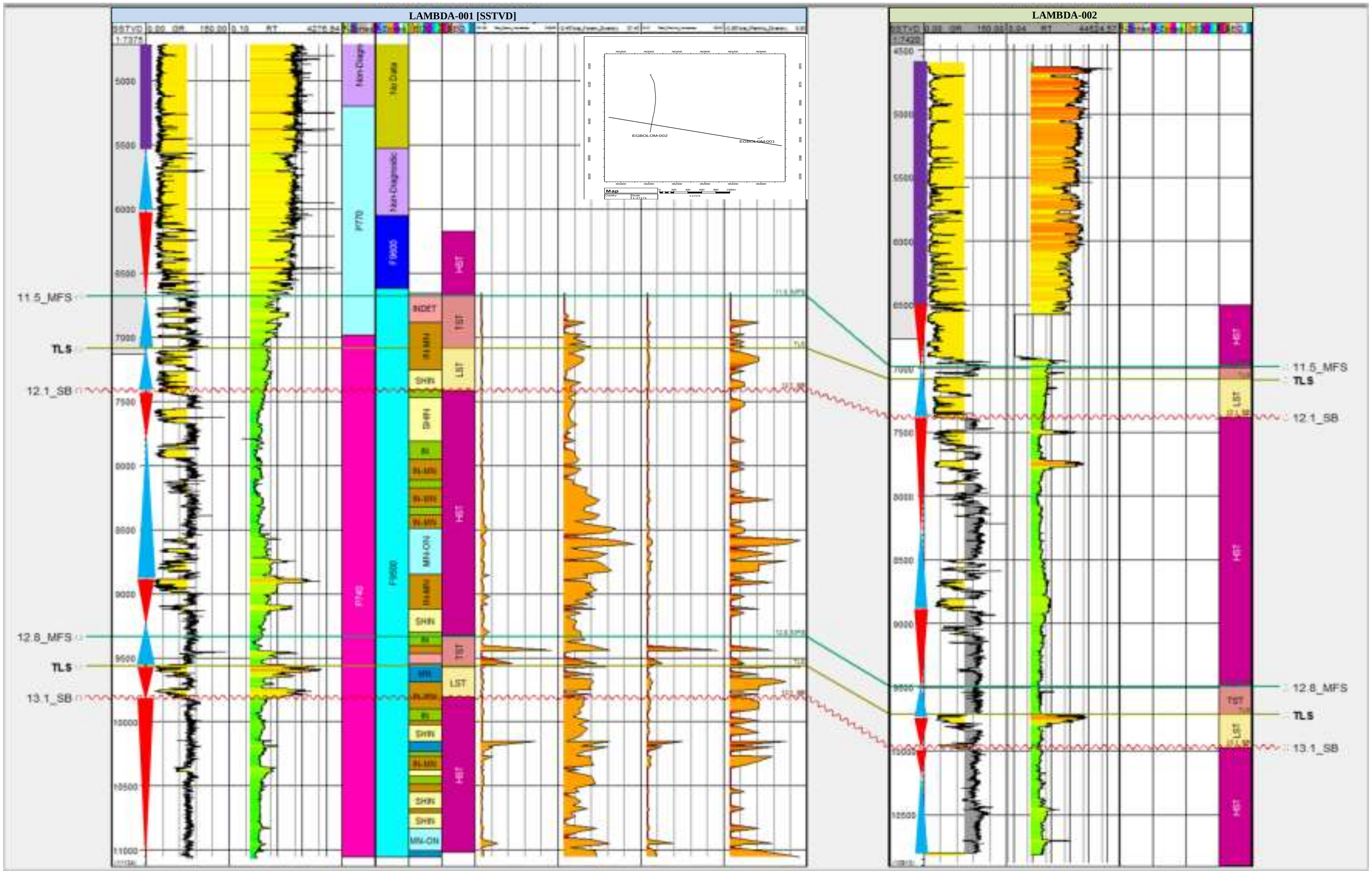
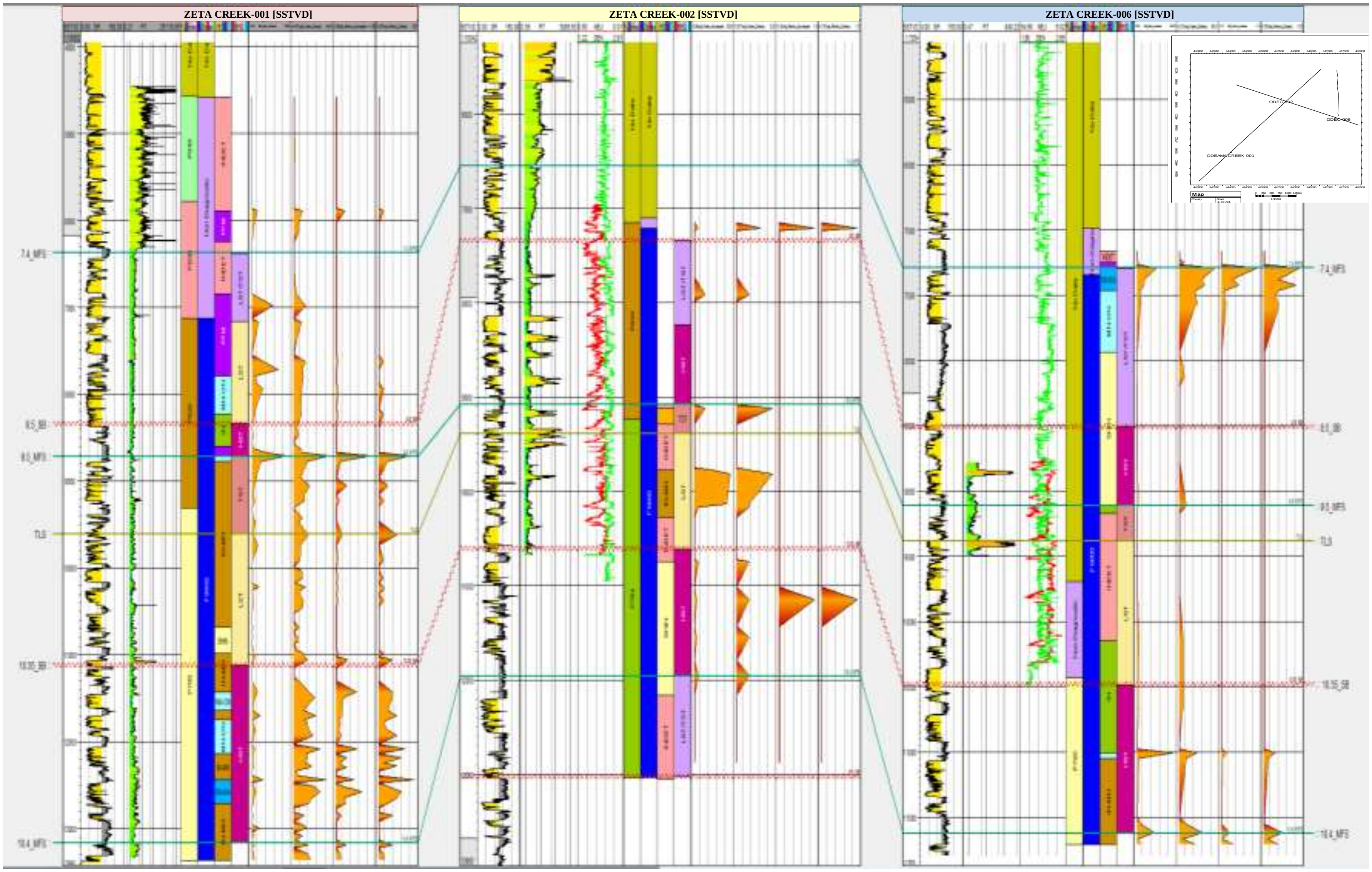


Figure 4.7: Lambda Field Well log Sequence Stratigraphic Interpretation and Correlation



LST-Lowstand systems tracts | LST/TST-Lowstand systems tracts/Transgresive systems tracts | TST- Transgresive systems tracts | HST- High systems tracts

Figure 4.8: Zeta-Creek Field Well log Sequence Stratigraphic Interpretation and Correlation

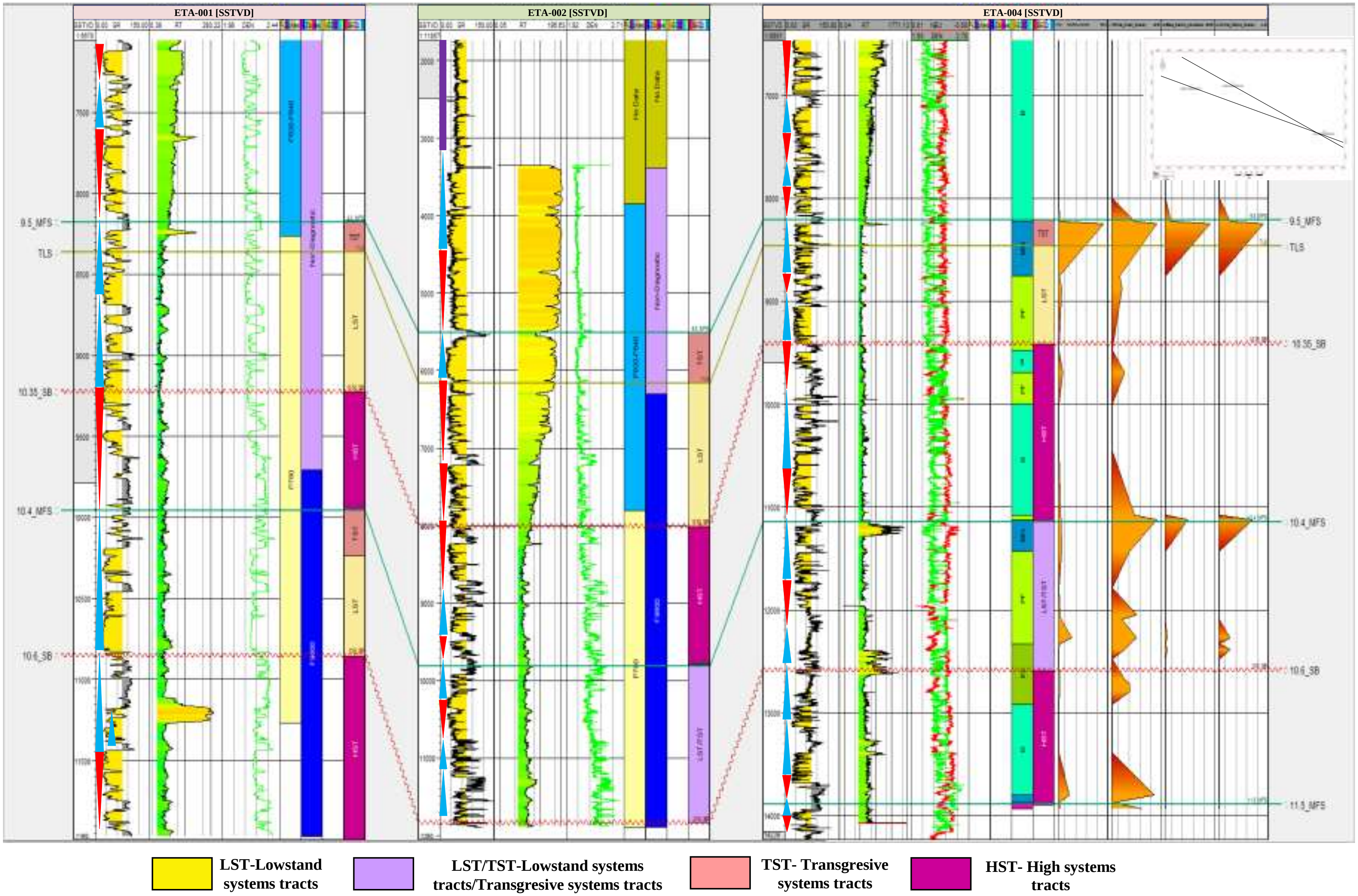


Figure 4.9: Eta Field well log Sequence Stratigraphic Interpretation and Correlation

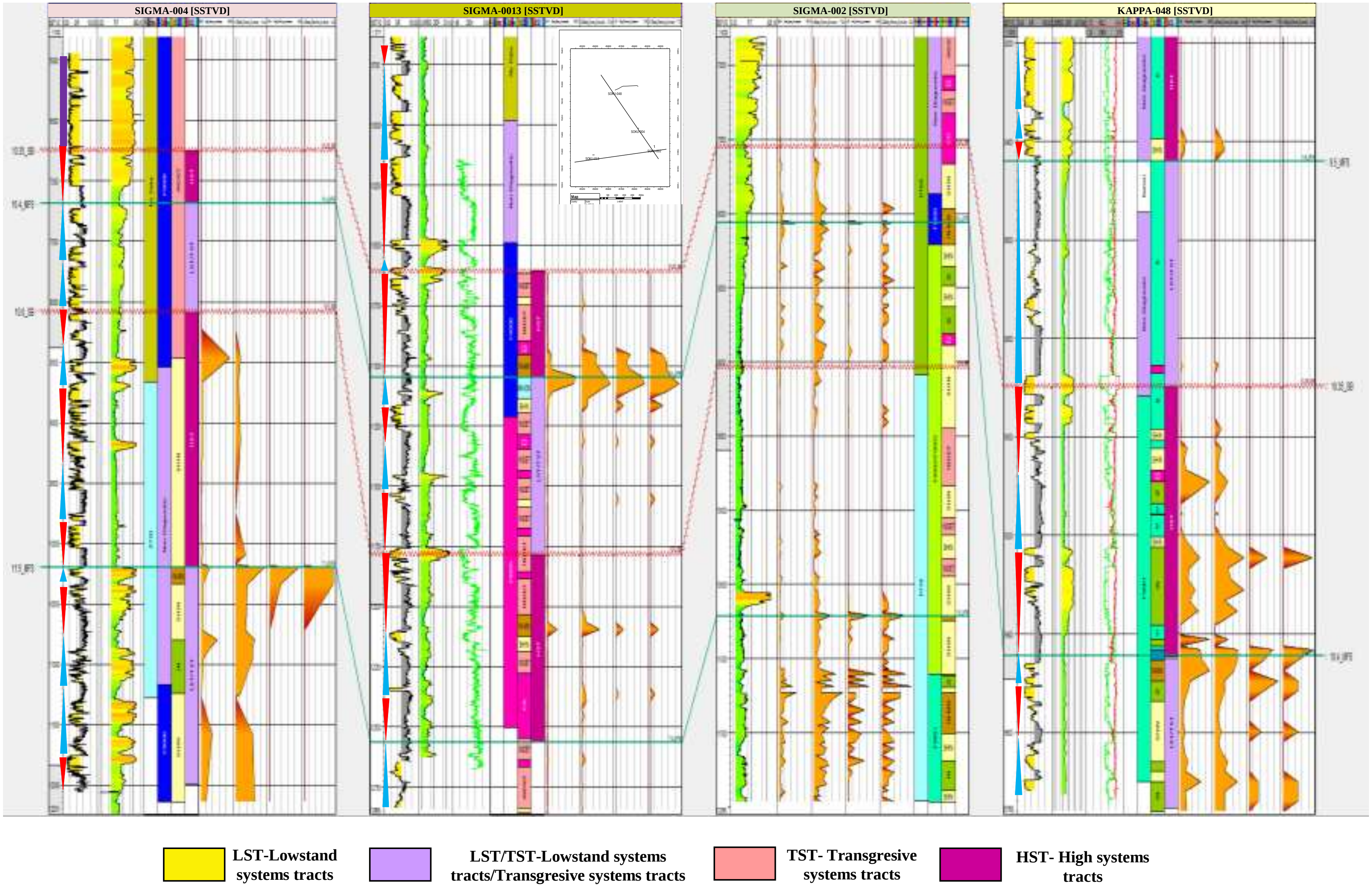


Figure 4.10: Sigma Field Well log Sequence Stratigraphic Interpretation and Correlation

Table 1.0: 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	9350	12.8	*Ser-2-Cassidulina*	P680	F9300/9500
	6680	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Lambda-002	9500	12.8	*Ser-2-Cassidulina*	P680	F9300/9500
	7000	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
Sigma-002	10700	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	8050	10.4	*Tor-Nonion-4*	P780	F9600
Sigma-004	10200	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	7200	10.4	*Tor-Nonion-4*	P780	F9600
Sigma-013	12575	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	11050	10.4	*Tor-Nonion-4*	P780	F9600
Sigma-048	9450	10.4	*Tor-Nonion-4*	P780	F9600
	8440	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Epsilon-002	10100	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	6850	10.4	*Tor-Nonion-4*	P780	F9600
	4650	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Epsilon-003	10800	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	7600	10.4	*Tor-Nonion-4*	P780	F9600
	4320	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Epsilon-007	10300	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	7450	10.4	*Tor-Nonion-4*	P780	F9600
	4750	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Alpha-001	8850	10.4	*Tor-Nonion-4*	P780	F9600
	5775	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Alpha-002	10450	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	8800	10.4	*Tor-Nonion-4*	P780	F9600
Alpha-006	8400	10.4	*Tor-Nonion-4*	P780	F9600
	5350	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Iota-002	13300	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	10500	10.4	*Tor-Nonion-4*	P780	F9600
	8375	9.5	*Tor-1-Uvigerina-8*	P820	F9600

Table 1.0 cont'd: Summary sheet of delineated MFS, marker fauna and biozone of the studied wells

Iota-009	13350	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	10550	10.4	*Tor-Nonion-4*	P780	F9600
	8200	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Omicron-001	10050	10.4	*Tor-Nonion-4*	P780	F9600
	7150	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Omicron-015	13650	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	9700	10.4	*Tor-Nonion-4*	P780	F9600
	7300	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Omicron-033	13350	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	10450	10.4	*Tor-Nonion-4*	P780	F9600
	8700	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Eta-001	9850	10.4	*Tor-Nonion-4*	P780	F9600
	8200	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Eta-002	9800	10.4	*Tor-Nonion-4*	P780	F9600
	5500	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Eta-004	13900	11.5	Ser-3-*Dodo Shale*	P770	F9500/9600
	11150	10.4	*Tor-Nonion-4*	P780	F9600
	8200	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Zeta Creek-001		10.4	*Tor-Nonion-4*	P780	F9600
	8700	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	6400	7.4	*Tor-2*	P830	F9700
Zeta Creek-002	11950	10.4	*Tor-Nonion-4*	P780	F9600
	9100	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	6550	7.4	*Tor-2*	P830	F9700
Zeta Creek-006	11600	10.4	*Tor-Nonion-4*	P780	F9600
	9200	9.5	*Tor-1-Uvigerina-8*	P820	F9600
	7300	7.4	*Tor-2*	P830	F9700
Kappa-002	9720	10.4	*Tor-Nonion-4*	P780	F9600
	7150	9.5	*Tor-1-Uvigerina-8*	P820	F9600
Kappa-006	9600	10.4	*Tor-Nonion-4*	P780	F9600
	8080	9.5	*Tor-1-Uvigerina-8*	P820	F9600

4.2.3 DEPOSITIONAL SEQUENCES AND SYSTEMS TRACTS

Four (4) depositional sequences (First/SEQ1, Second/SEQ2, Third/SEQ3 and Fourth/SEQ4) and the accompanying systems tracts were interpreted and mapped within Lambda, Sigma, Omicron, Epsilon, Iota, Alpha, Eta, Zeta-Creek, Kappa Fields (see Figures 4.18 – 4.20), based on log–motifs of the various reference wells (Lambda-001, 002; Sigma-004, 013, 048; Epsilon-007, 002; Alpha-001, 002; Iota-002, 009; Omicron-001, 015, 033; Eta-001, 002, 004; Zeta-Creek 001, 002; Kappa-002, 006) and the spatial distribution of the recognized constrained surfaces (MFSs and SBs).

The First (SEQ1) and Second (SEQ2) formed the deepest (oldest) and topmost (youngest) depositional sequences respectively. First sequence is an incomplete sequence and approximately about 2600 ft and is bounded top and bottom by 12.1 Ma and 13.1 Ma Sequence Boundaries, respectively. It is enveloped on top by the 12.1 Ma SB, which was revealed only in wells Lambda-001 and 002 (Table 2.0) that probed deeper stratigraphic sections across the field. Accompanying Transgressive Systems Tract (TST) contained marine shales rich in fauna with minor sand unit enveloped by the 11.5Ma MFS. The transgresssive sand units have been interpreted as shoreface sands deposited in the shelf region during rising sea levels. Highstand Systems Tract (HST) of the sequence, estimated to be about 2000 ft was deposited in the Innne-Middle Neritic (IN-MN) setting depicting mainly progradational-retrogradational stacking patterns.

Second sequence (SEQ2) is approximately 3000 ft thick and is bounded top and bottom by 10.6 Ma and 12.1 Ma Sequence Boundaries, respectively. The Lowstand Systems Tract (LST) of this sequence formed thick sand deposits interpreted as upper shore face deposited in the Shallow to Inner Neritic (SHIN) depositional settings. The LST was observed to be barren in faunal contents in most wells and unconformably overlying the 12.1 Ma SB and underlies a TST of about 1000ft thick.

Third sequence (SEQ3) overlies the 10.6 Ma SB and is capped by the 10.35 Ma SB. The sequence was identified at the depth range of 10800 - 13000 ft in the down dip wells (Eta-004; Zeta-Creek 002; Kappa-002, 006) and from a depth range of 6750 - 10300 ft in the up dip wells (Sigma-004, 013, 048; Epsilon-007, 002; Alpha-001, 002; Iota-002, 009; Omicron-001, 015, 033). The sequence displayed predominantly fluvial and tidal processes (progradational stacking pattern) as shown in the parasequence stacking pattern of the western wells (Sigma-004, 013, 048; Epsilon-007, 002; Alpha-001, 002; Iota-002, 009; Omicron-001, 015, 033). LST of this sequence contains reworked channel sand deposits which were more pronounced in the down dip wells and some predominantly mud fill channel.

SEQ4 is the topmost (youngest) sequence in the study area. It rests unconformably on the 10.35 Ma SB. The sequence consists of thick sand units at its base, deposited during relative sea level lows. The sequence was deposited within the Inner to Middle Neritic paleodepositional environment. The 9.5 Ma MFS was mapped in this Sequence and it is capped by 7.5 Ma MFS.

Table 2.0: Summary sheet of delineated SB within the studied wells

WELLS	DEPTH (Ft)	SB AGE (Ma)	SEQUENCES
Lambda-001	9800	13.1	SEQ1
	7400	12.1	
Lambda-002	9950	13.1	
	7400	12.1	
Sigma-002	9025	10.6	SEQ3
	7525	10.35	
Sigma-004	8100	10.6	
	6750	10.35	
Sigma-013	11775	10.6	
	10600	10.35	
Sigma-048	8900	10.35	SEQ4
Epsilon-002	7450	10.6	SEQ3
	6100	10.35	
Epsilon-003	8750	10.6	
	6000	10.35	
Epsilon-007	8300	10.6	
	6450	10.35	
Alpha-001	10250	10.6	
	7700	10.35	
Alpha-002	11600	12.1	SEQ 2
	9950	10.6	SEQ3
	7750	10.35	
Alpha-006	9800	10.6	SEQ3
	7000	10.35	
Iota-002	14100	12.1	SEQ2
	11850	10.6	SEQ3
	10150	10.35	
Iota-009	11950	10.6	
	10150	10.35	

WELLS	DEPTH (Ft)	SB AGE (Ma)	SEQUENCES
Omicron-001	8700	10.35	SEQ4
Omicron-015	10950	10.6	SEQ3
	8300	10.35	
Omicron-033	11850	10.6	
	9250	10.35	
Eta-001	10850	10.6	
	9250	10.35	
Eta-002	11850	10.6	
	8000	10.35	
Eta-004	12600	10.6	
	9400	10.35	
Zeta Creek-001	11150	10.35	SEQ4
	8350	8.5	
Zeta Creek-001	13000	10.6	SEQ3
	10600	10.35	
	7350	8.5	SEQ4
Zeta Creek-001	10500	10.35	
	8500	8.5	
Kappa-002	10300	10.6	SEQ3
	8650	10.35	SEQ4
	6100	8.5	
Kappa-006	10800	10.6	SEQ3
	8750	10.35	SEQ4
	7600	8.5	

4.2.4 WELL CORRELATION

Correlation across the various fields of study (Figure 4.11) was done using the recognized and identified constrained chronostratigraphic surfaces typified by Maximum Flooding Surfaces (MFSs) and Sequence Boundaries (SBs). Correlation helped to compartmentalize the stratigraphic section and showed how the surfaces correlated along dip and strike at certain depths within the depositional basin, thus depicting basin geometry and depositional sequences across the fields of study.

The displayed correlation panels (Figures 4.12 - 4.15) indicates that the stratigraphic column appears to be dipping in a North-South/Northeast-Southwest direction and striking in the East–West direction. Deposition tends to be thicker in wells Eta-004; Zeta-Creek 002; Kappa-002, 006, which were located down dip. The occurrence of the identified chronostratigraphic surfaces at different depths along dip and strike lines in the studied wells (see Figure 4.11) shows evidence of faulting within the fields. The main reservoirs are within the sequences from 9.5. to 12.8 Ma, hence a decreasing net-to gross. Generally, there is a thickening of reservoir sand up-dip (Northeast) and thinning-out down-dip (southwest). There appears to be an anomaly within the central part (Sigma-Omicron section), probably due to the channel sand Complex at shelf edge (Figure 4.16**)**. Flattening at various MFS(s) reveals a shift of Depositional Center from Northern section towards the southern which is a typical scenario of the progradational pattern in the Niger Delta (Figures 4.17 - 4.19 and 4.20).

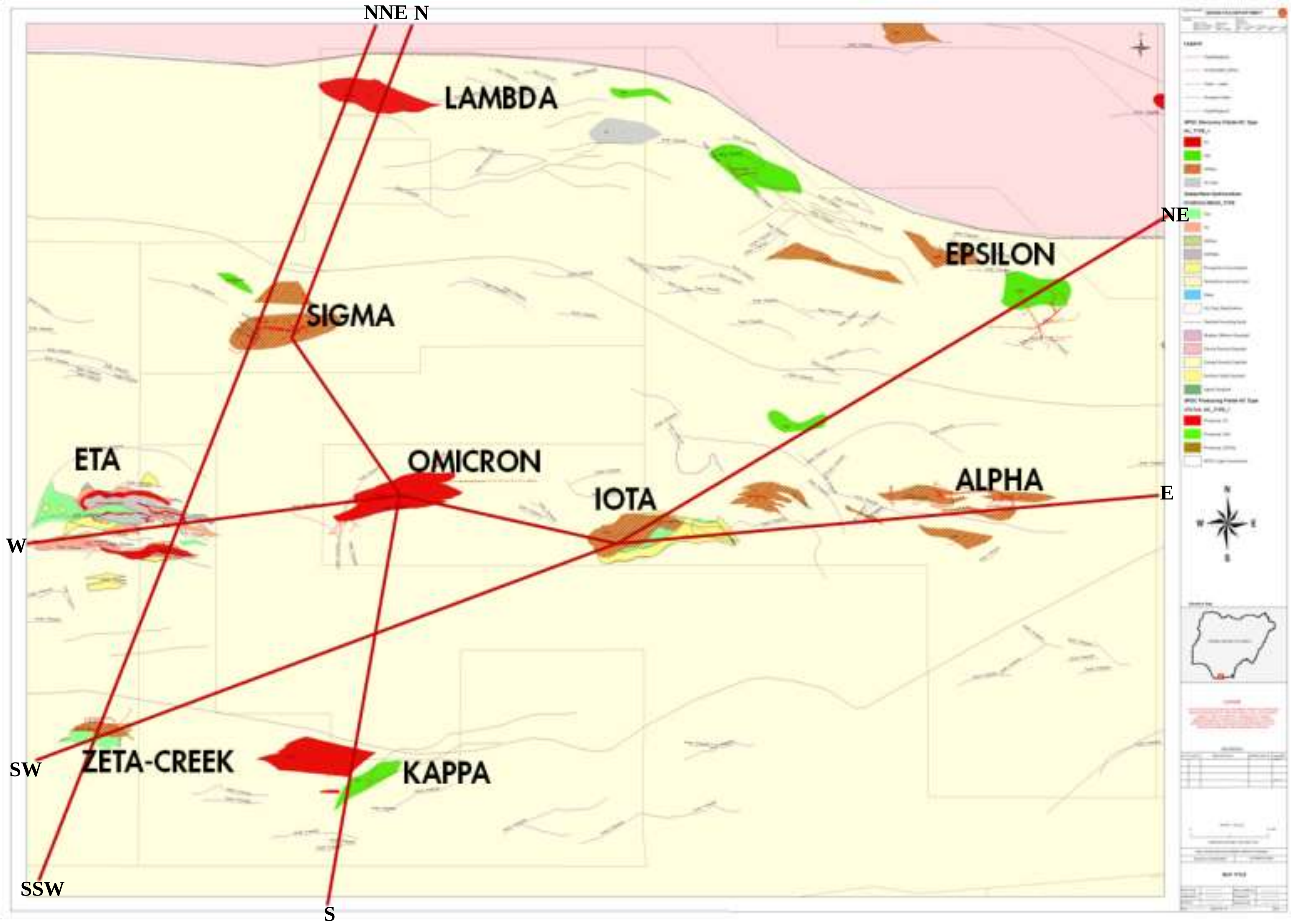


Figure 4.11: Dip and strike Lines of Section across Fields and Wells in the study area

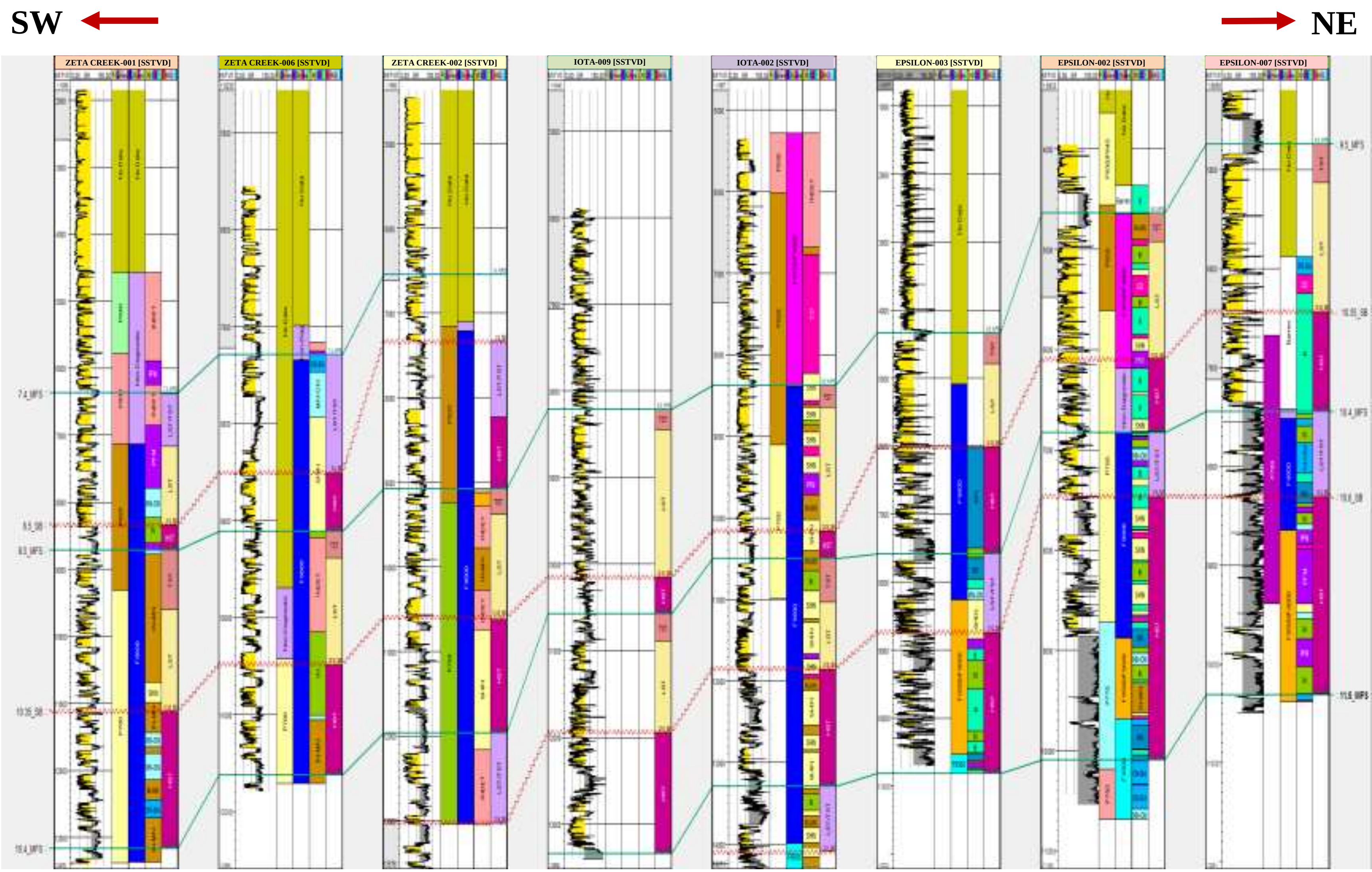


Figure 4.12: Well Log Sequence Stratigraphic Interpretation and Correlation across Dip within various Fields and Wells

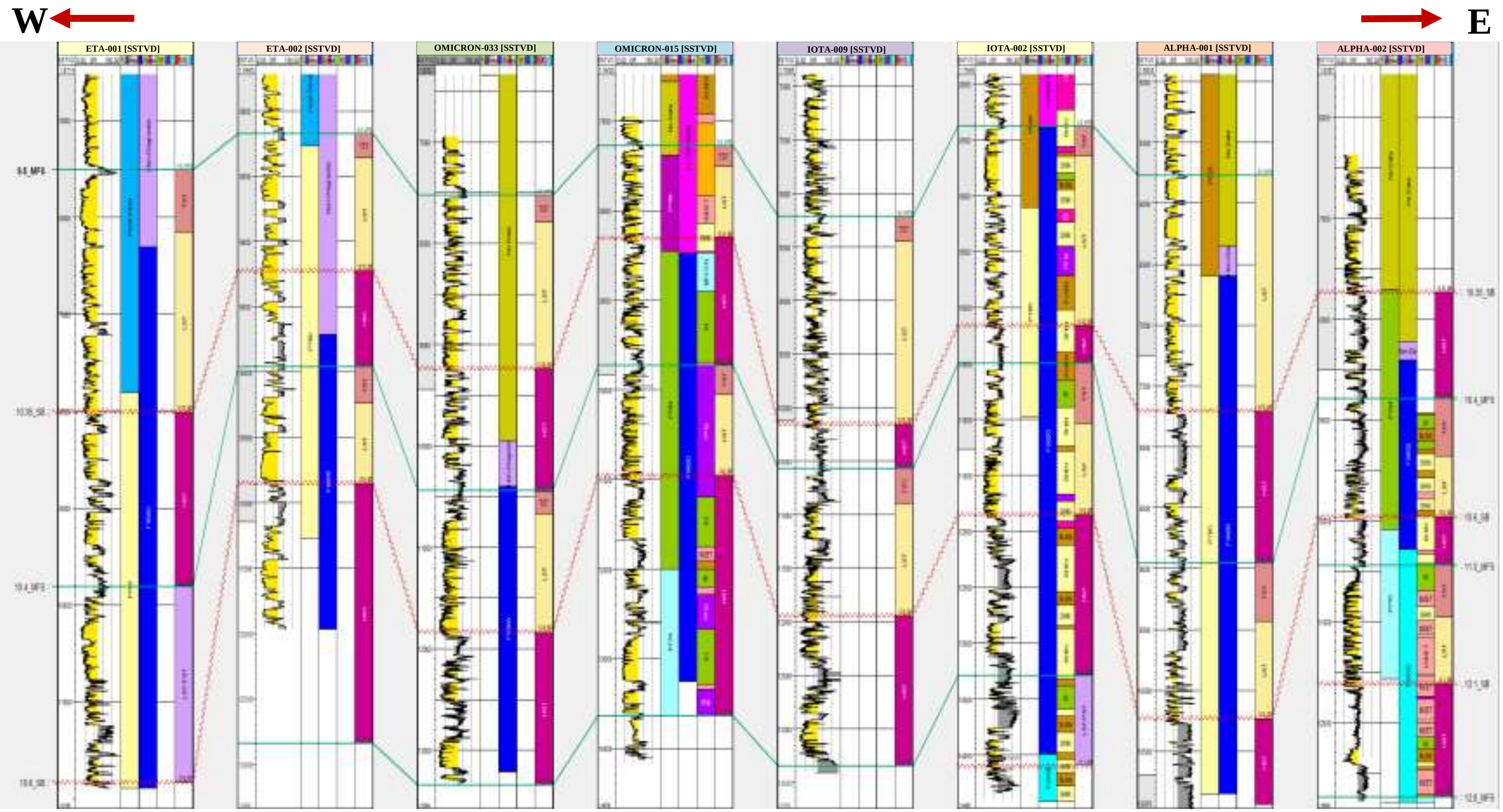


Figure 4.13: **Well Log Sequence Stratigraphic Interpretation and Correlation across Strike witin various Fields and Wells**

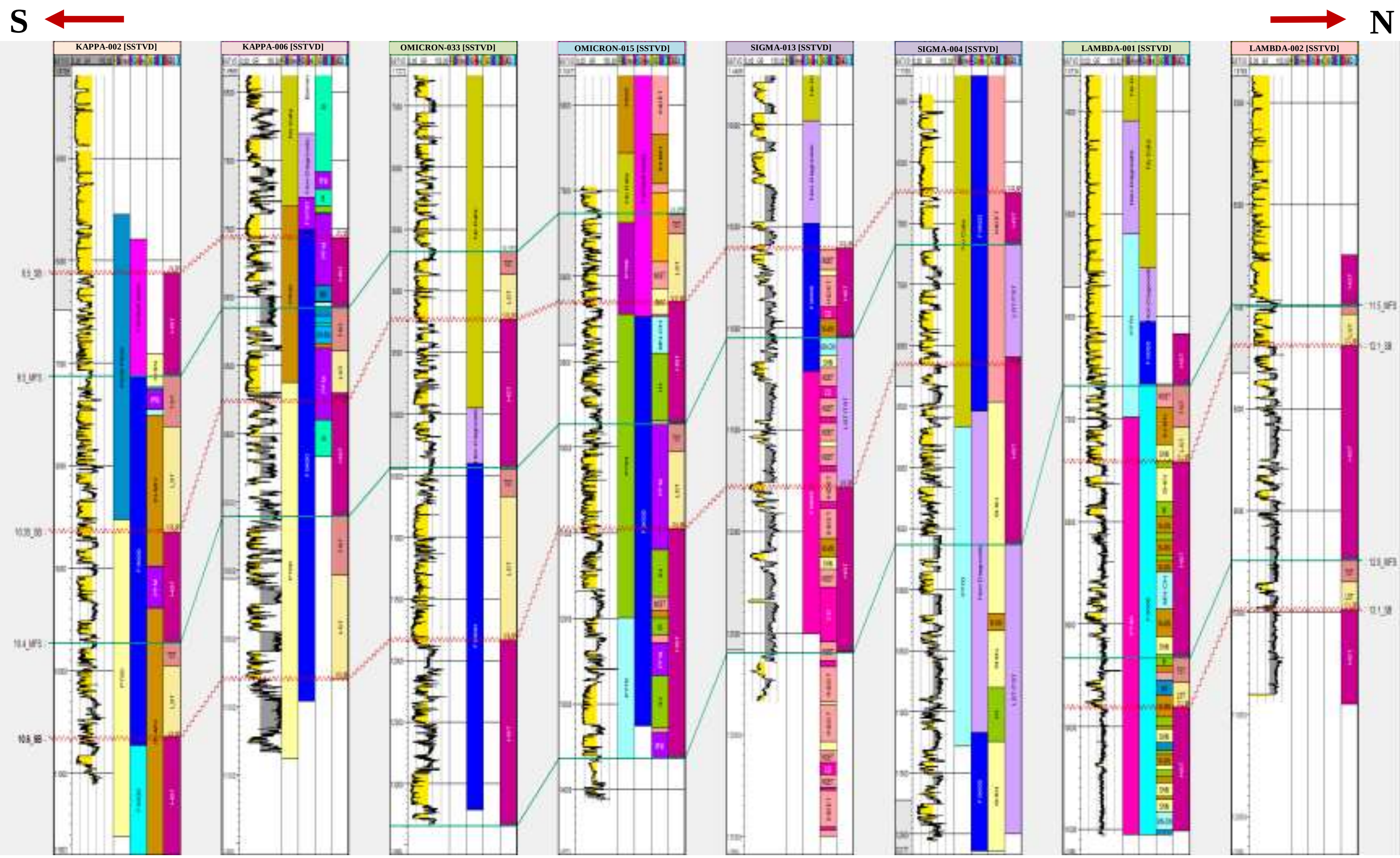


Figure 4.14: **Well Log Sequence Stratigraphic Interpretation and Correlation across Dip within various Fields and Wells**

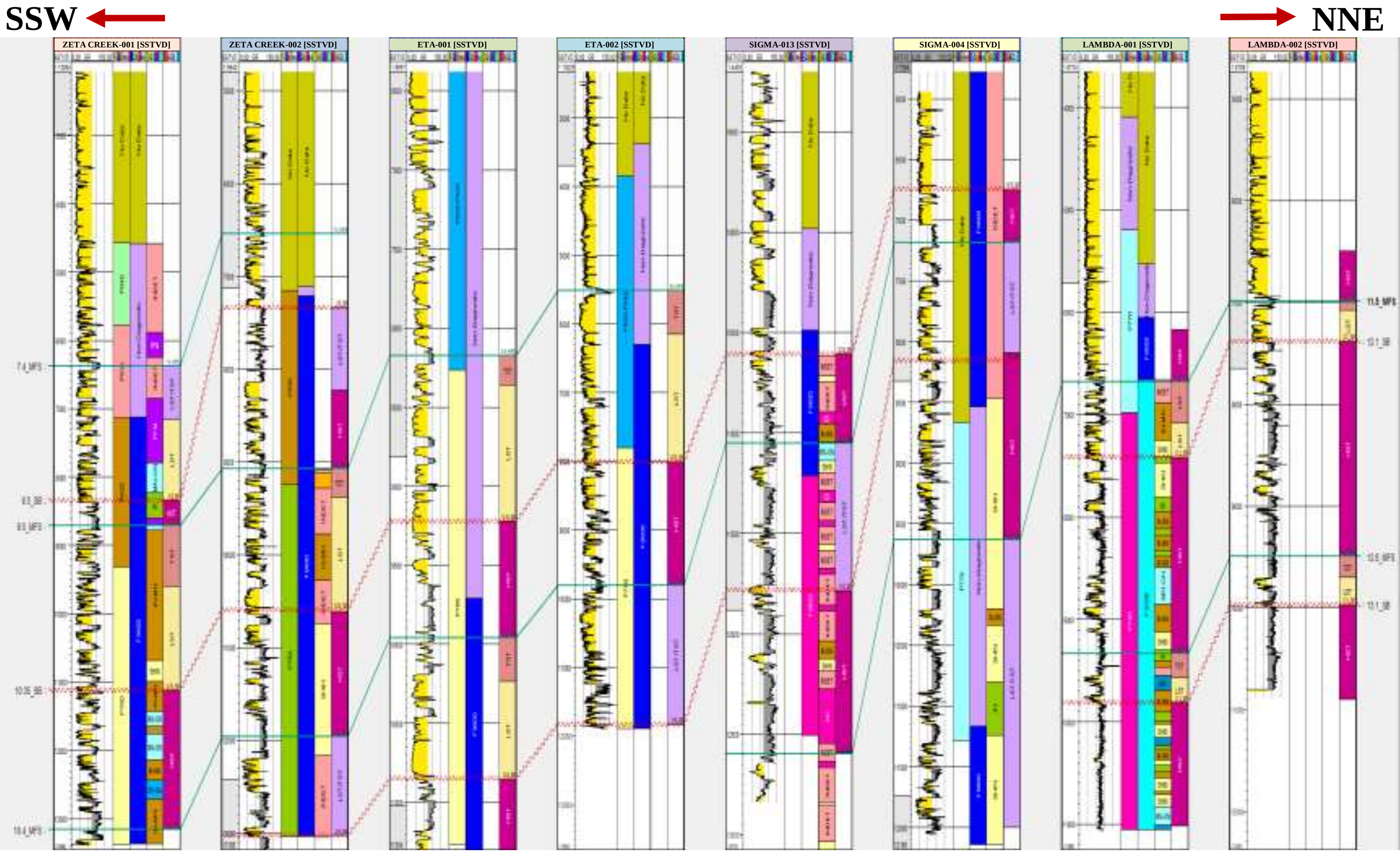


Figure 4.15: **Well Log Sequence Stratigraphic Interpretation and Correlation across Dip within various Fields and Wells**

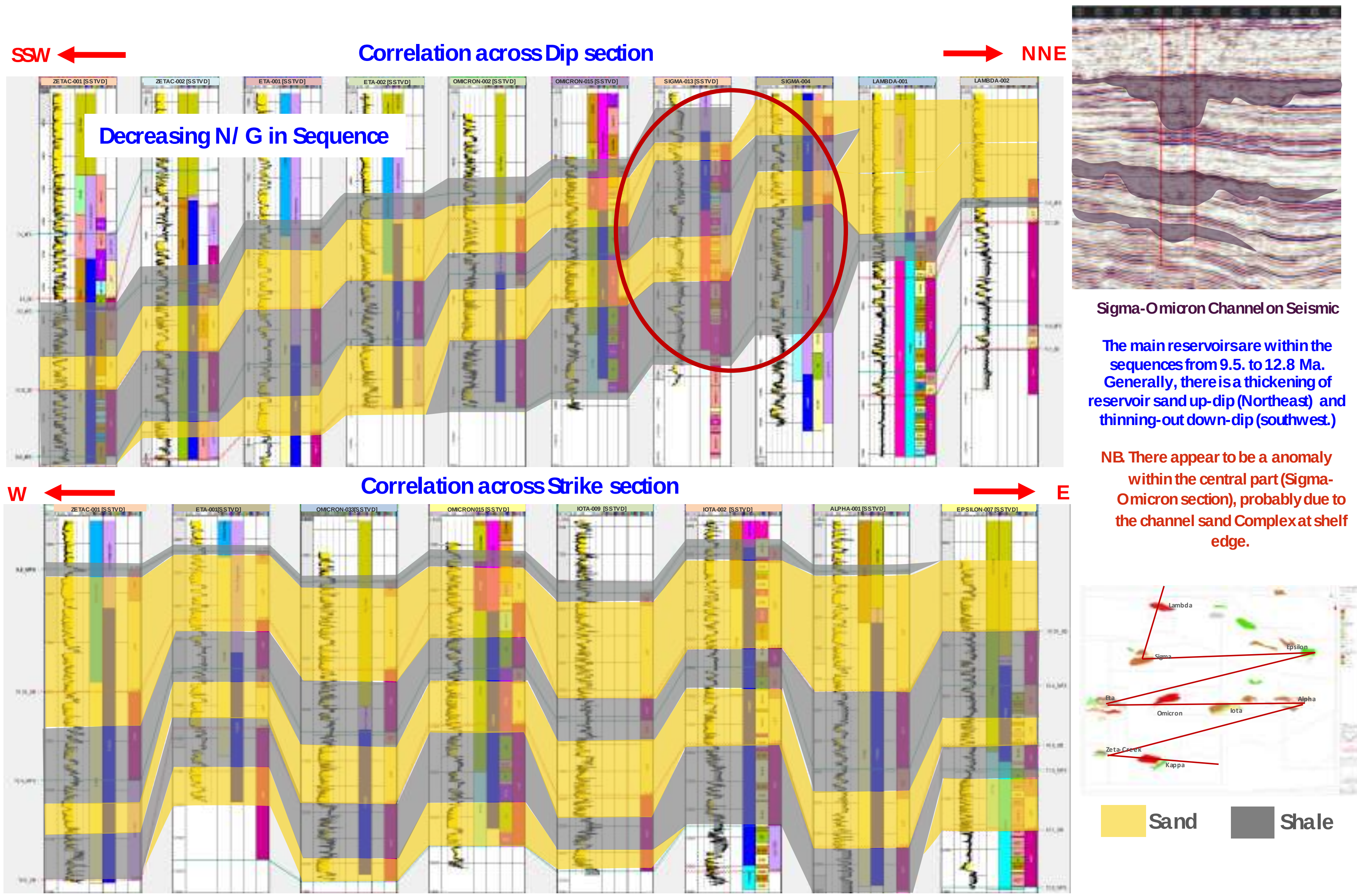


Figure 4.16: Well Log Sequence Stratigraphic Interpretation and Correlation across Dips and Strikes within various Fields and Wells

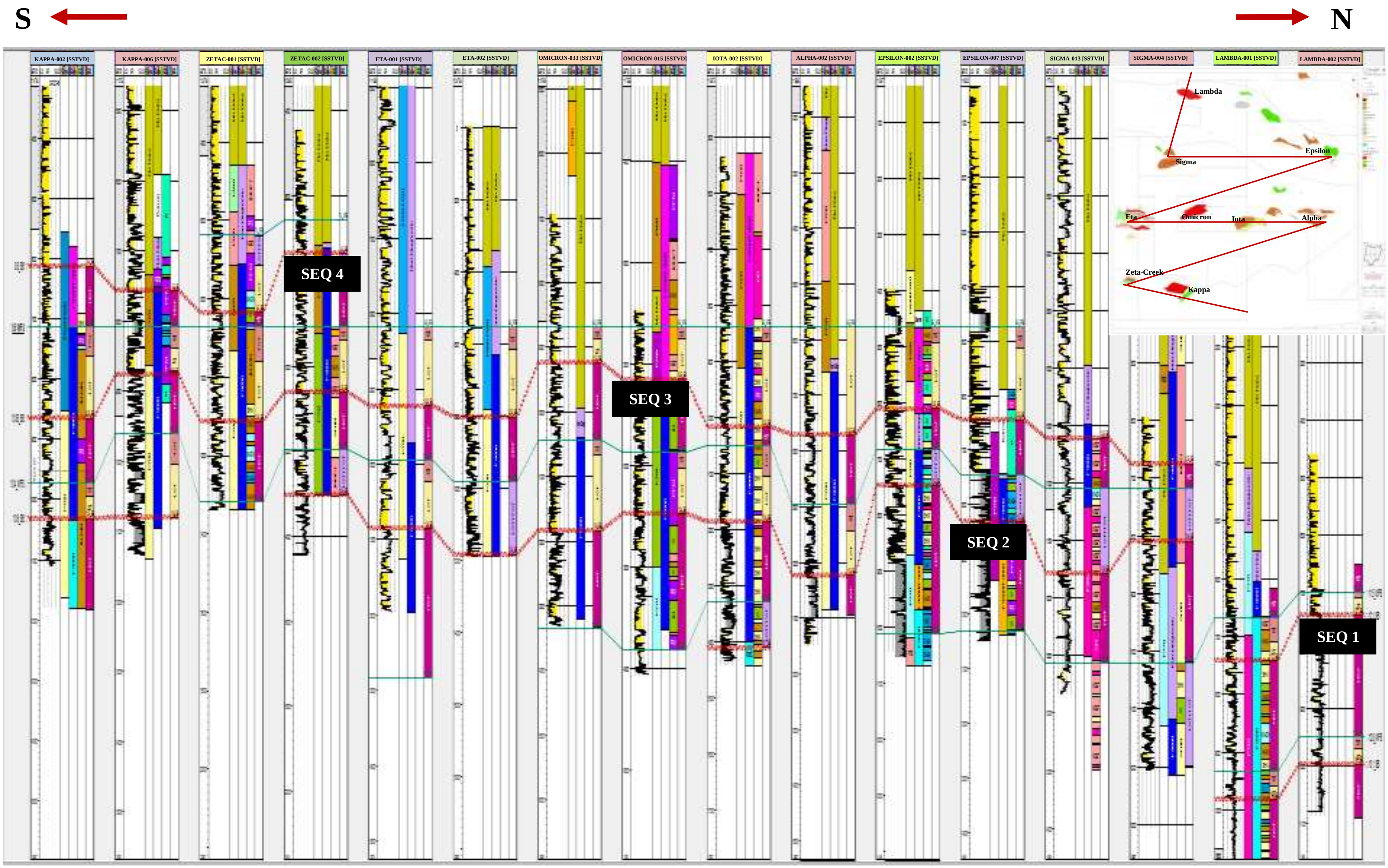


Figure 4.17: Stratigraphic correlation panel flattened at 9.5_MFS

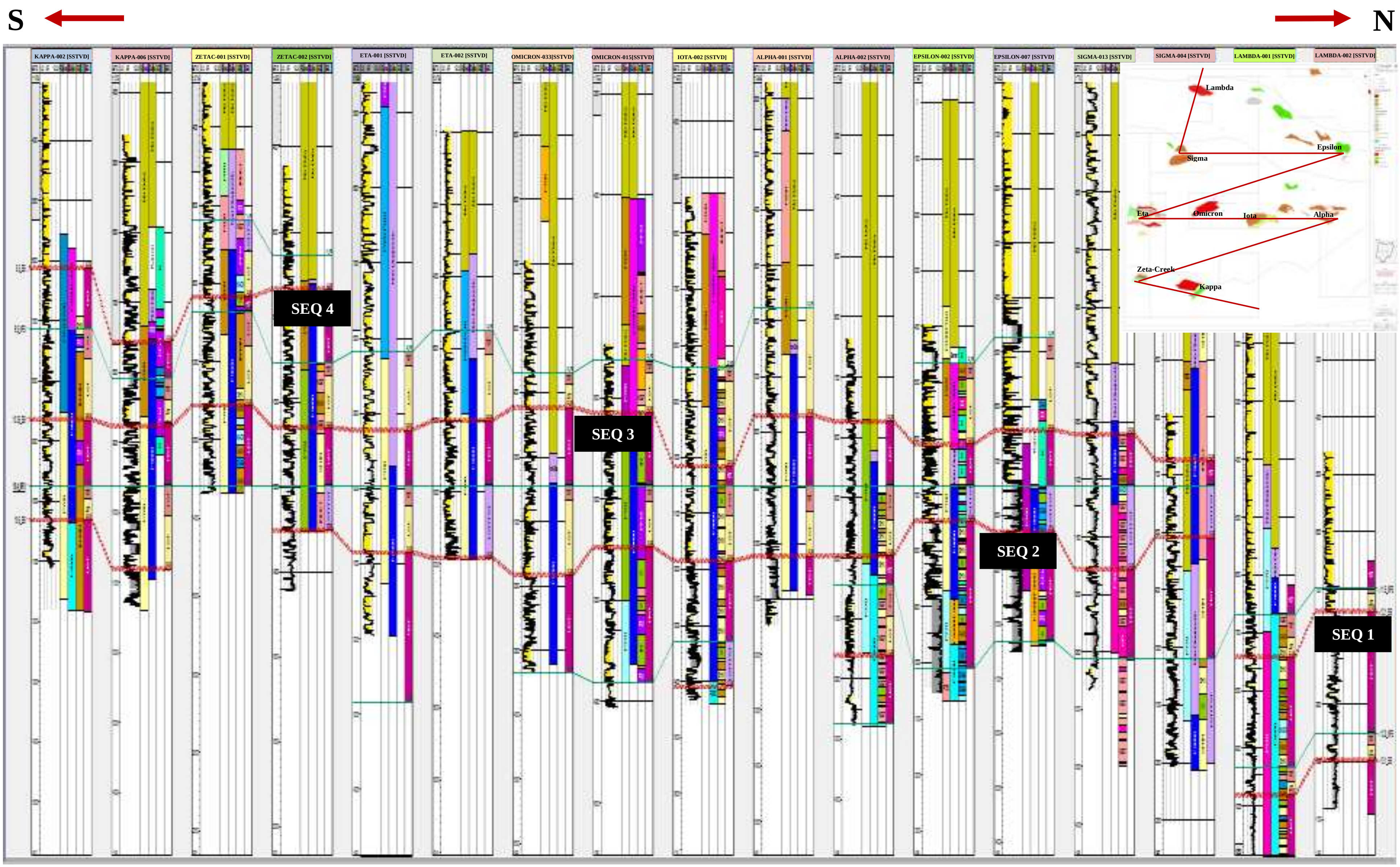


Figure 4.18: **Stratigraphic correlation panel flattened at 10.4_MFS**

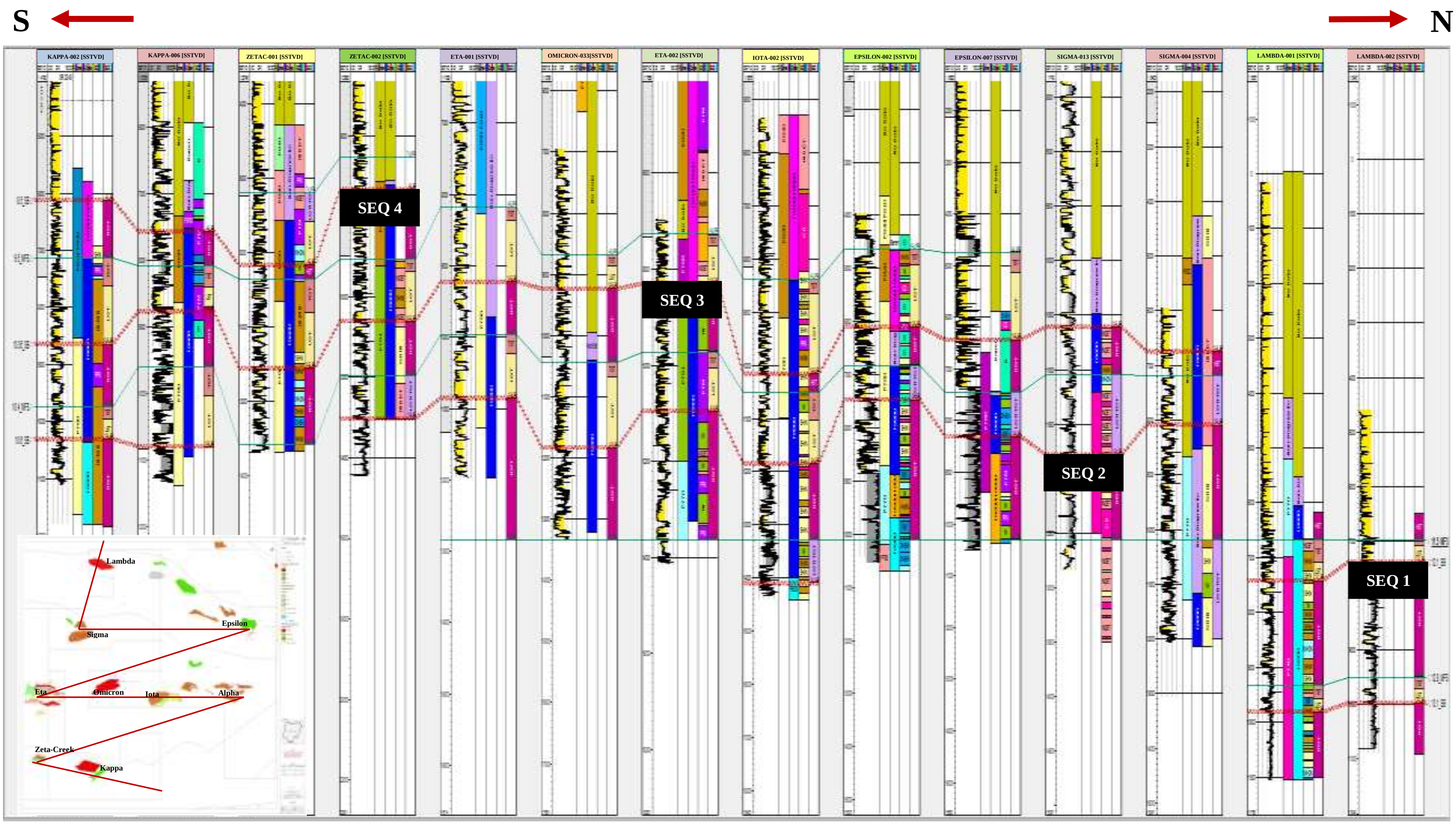


Figure 4.19: **Stratigraphic correlation panel flattened at 11.5_MFS**

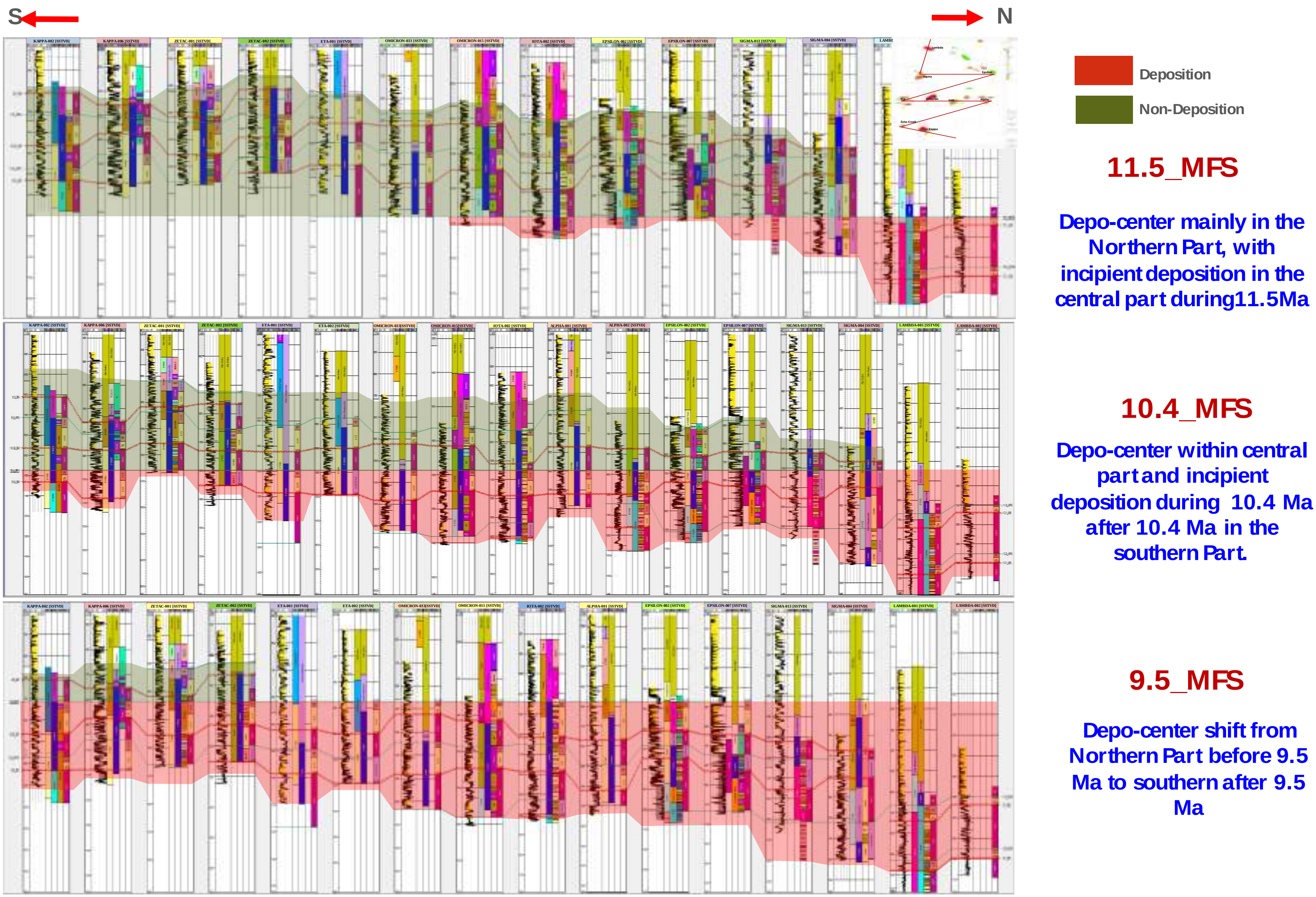


Figure 4.20: Depositional Centers at various age (Ma) - Stratigraphic correlation panel flattened at various MFSs.

4.3. SEISMIC

The seismic volume used for this study extends to 3.5 seconds two way travel time (TWT), below which reflection continuity is generally poor (Figure 4.21). Time slice at 2.0 seconds shows the best structural display (Figure 4.22a and b). The seismic volume is characterized by series of parallel/divergent reflection offset and formed by major listric growth faults, the character of the seismic volume changes with depth (see Figure 4.24). The basal part of record (below 3.5s TWT) is disrupted by several zones with low to highly discontinuous reflection patterns, while the reflections between 3.5 to 1.5 TWT have moderate to good continuity and high amplitude variations.

4.3.1 SEMBLANCE CUBE / TIME SLICE GENERATION

Structurally and stratigraphically significant features and insights can be deduced from time-slice semblance cube generated at appropriate time intervals. Time slices were generated at 1100ms, 1500ms, 2000ms, 2500ms and 3000ms (Figure 4.21). Slices at deeper and shallower horizons are chaotic and of poor image quality, and hence discarded. These slices were able to image some regional structures and their evolution (Figures 4.22a and 4.22b).

4.3.2 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 is divided into two different facies. Facies one comprises high frequency, continuous, parallel/divergent reflections while facies two comprises lower amplitude, chaotic, discontinuous/inclined internal reflection (Figures 4.23a – 4.23e). The various reflection patterns, observed on seismic sections are described below which indicates the reflection configuration and the nature of cycle termination at seismic facies boundary.

High continuity and high amplitude reflection: This reflection pattern occurs within the section of about 1.8 to 2.4 seconds in trace 1049 to trace 2525, from the East towards the western part of the section within the parallel/divergent reflection pattern (Figure 4.23a). To the north east, it grades into a low continuity, variable amplitude facies (Fig. 4.9). The 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, which 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 observed between 1.0 to 1.8 seconds on traces 1049 and 2525 which also corresponds to a depth of 11350 – 55830 ft on the well log. 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.

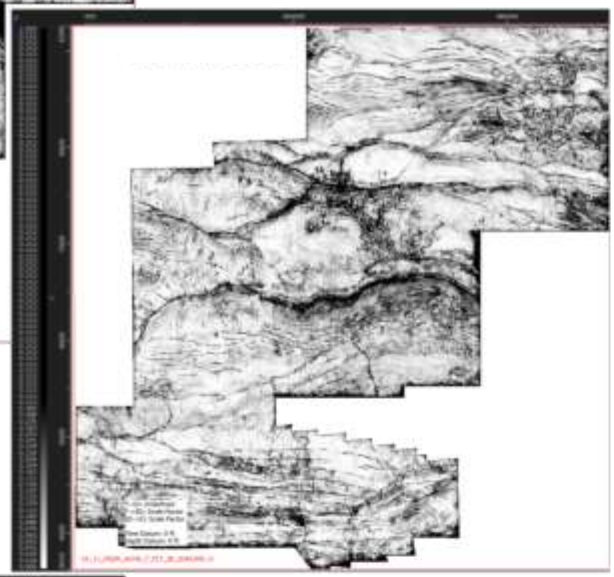
Choatic configuration: This is seen on the section as a discontinuous discordant reflections at the base of the section. This chaotic configuration gradually develops as one moves from traces

443, 1394, 1805 to 2284, within the section of about 3.5 to 6.0 seconds where it is more developed (Figure 4.23a) The 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 fractures by overpressures and moved upward under the weight of overlying strata during fault displacement.

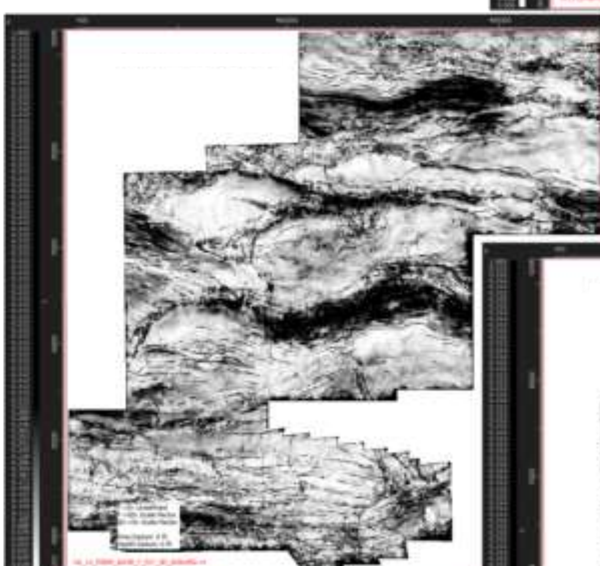
4.4 WELL TO SEISMIC TIE / INTEGRATION

Regional stratigraphic markers (MFS and SB) identified from well log sequence stratigraphy were calibrated as well-tops along well-track in nDi Geo-sign software interface and displayed against seismic. This made it possible to tie these markers or surfaces to seismic events (Figure 4.16). Evidences in seismic such as reflection terminations and geometry were also analyzed and used to constrain the 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 correlate 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 correlate across the whole study area. Pattern recognition and basic stratigraphic and structural geology principles were used to extrapolate and correlate these markers across the study area.

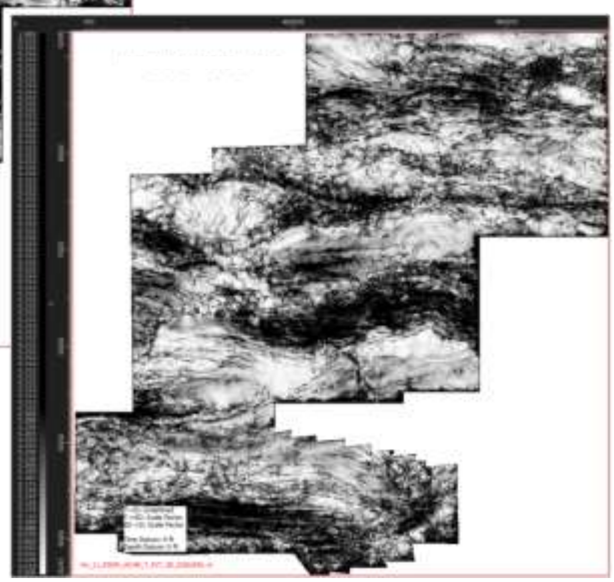
Time Slice at 1.5 seconds (1500 millisecond) Sigma Merge Amp. File/Map



Time Slice at 2.0 seconds (2000 millisecond) Sigma Merge Amp. File/Map



Time Slice at 2.5 seconds (2500 millisecond) Sigma Merge Amp. File/Map



Time Slice at 3.0 seconds (3000 millisecond) Sigma Merge Amp. File/Map

Figure 4.21: Semblance Cube / Time Slice Generation on study area map/semblance

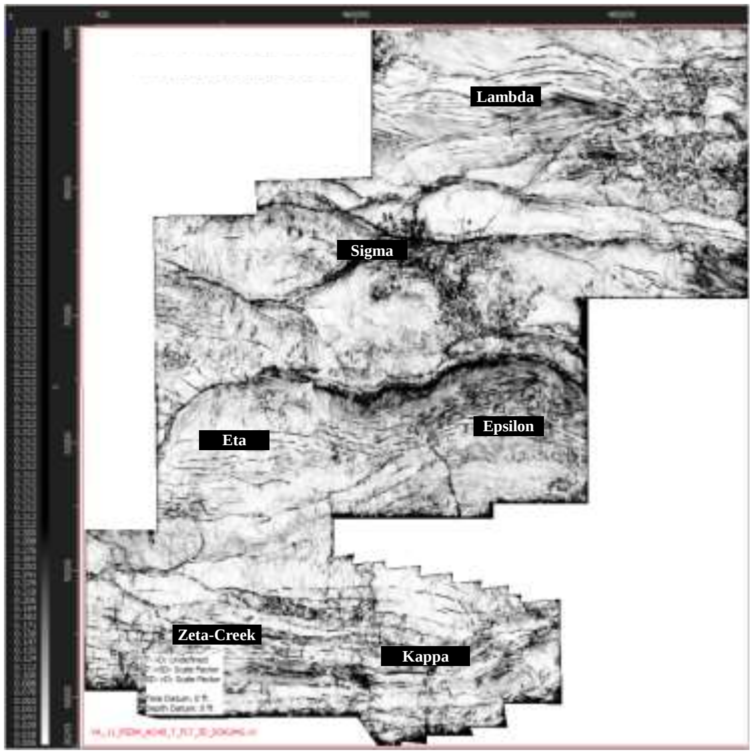


Figure 4.22a: **A close-Up on Sigma Merge Time slice at 2.0 Seconds.**

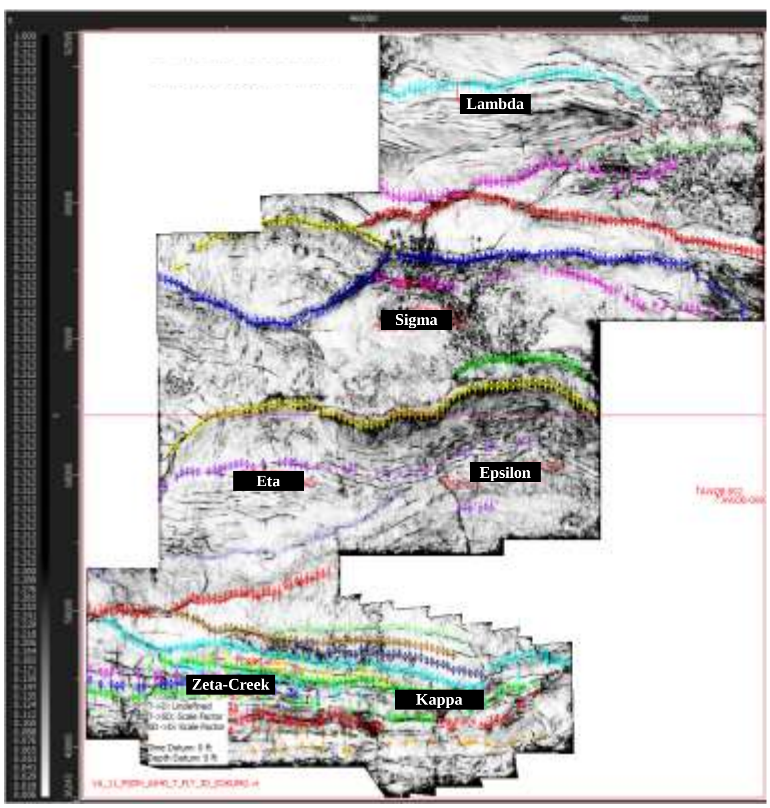


Figure 4.22b: **Time Slice Fields and bounding Regional Faults Sigma Merge Map/Semblance view.at 2.0 seconds (2000 millisecond) Sigma Merge Amp. File/Map**

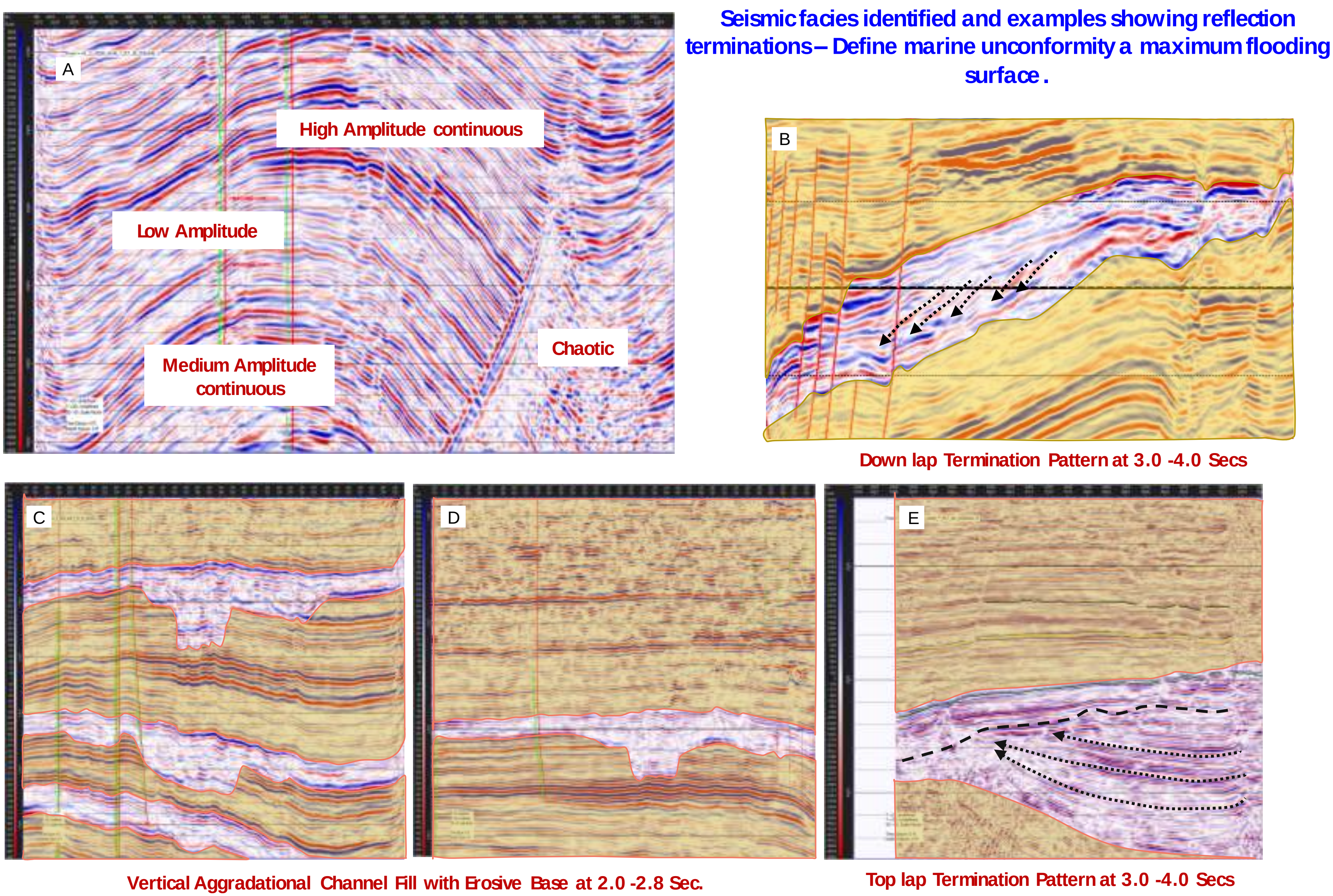


Figure 4.23a: Seismic Reflection Amplitude and Frequency
Figure 4.23b, c, d and e: Seismic Facies interpretation across time in Traaverse showing reflection Termination.

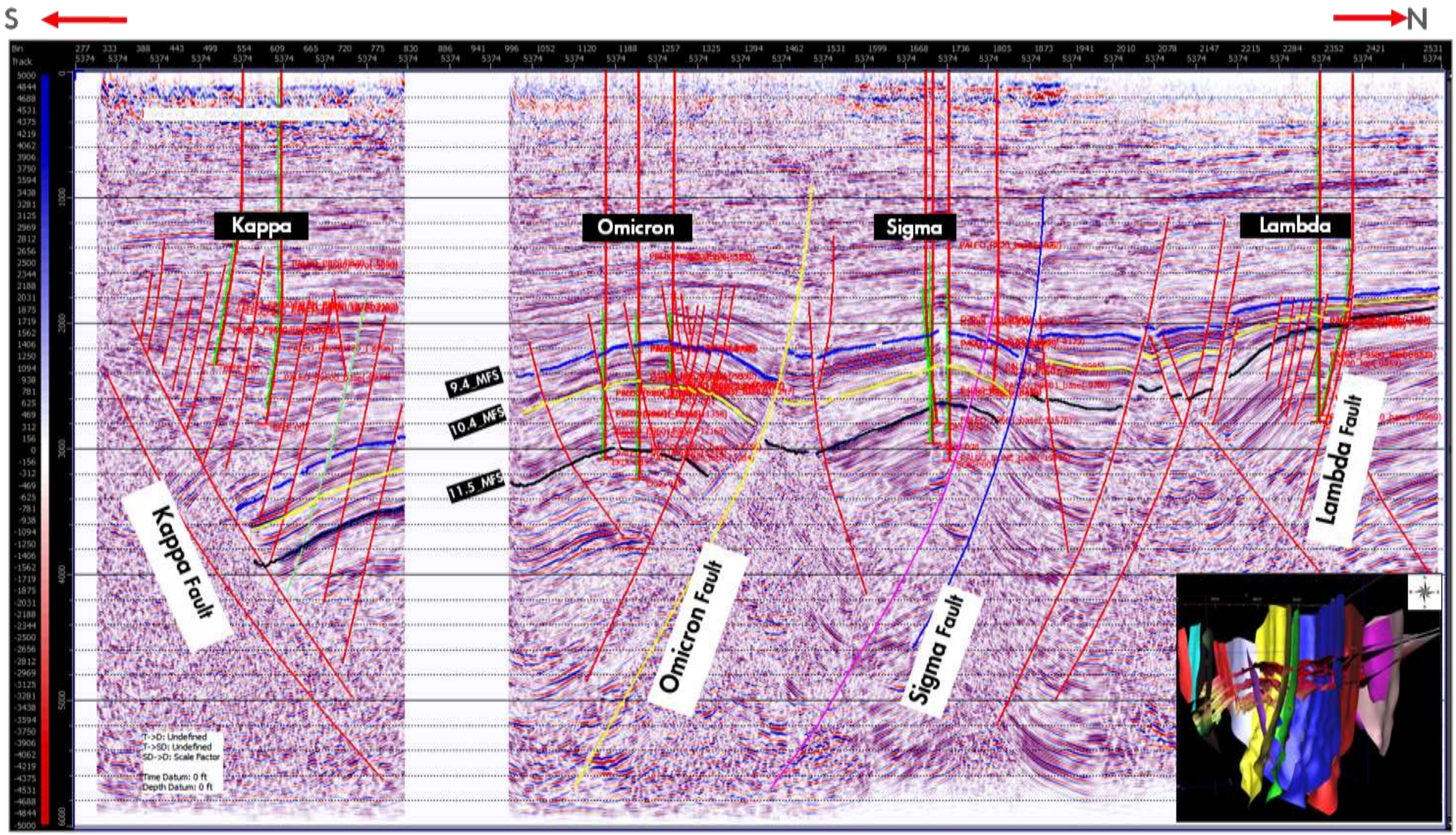


Figure 4.24: Interpretation – well to seismic integration Interpreted seismic section N-S (See the location), showing major faults (listric) and stratigraphic intervals in this study.

4.4.1 FAULT MAPPING/INTERPRETATION

Seismic volume reveals the presence of patterned reflection discontinuities which are identified and interpreted as faults (Figures 4.25 - 4.26). The regional faults are mainly listric in nature and concave basinwards. They are mainly synthetic (Lambda, Sigma and Omicron), dipping in the same direction as the main fault with a few antithetic faults that dip in opposite direction to the main fault (Kappa). Interpreting fault plane geometry was quite difficult in most areas due to poor reflection characteristics around fault – a seismic acquisition and processing artefact. Also mapping faults detachments at depth was difficult and sometimes impossible as data quality deteriorates greatly with depth. However simple extrapolations were made to constrain interpretation picks.

4.4.2 HORIZON MAPPING/INTERPRETATION

Horizon/events were mapped, interpreted and correlated 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. Three major Horizons were mapped namely; MFS_11.5, MFS_10.4 and MFS_9.5 respectively (see Figure 4.27). Seed grids were generated across mapped/picked faults (Fault-sticks) and horizon line. This was gridded using the appropriate module in nDi Geo-sign interface to produce structural and stratigraphic framework and also generate horizon maps of selected regional markers (Figure 4.28).

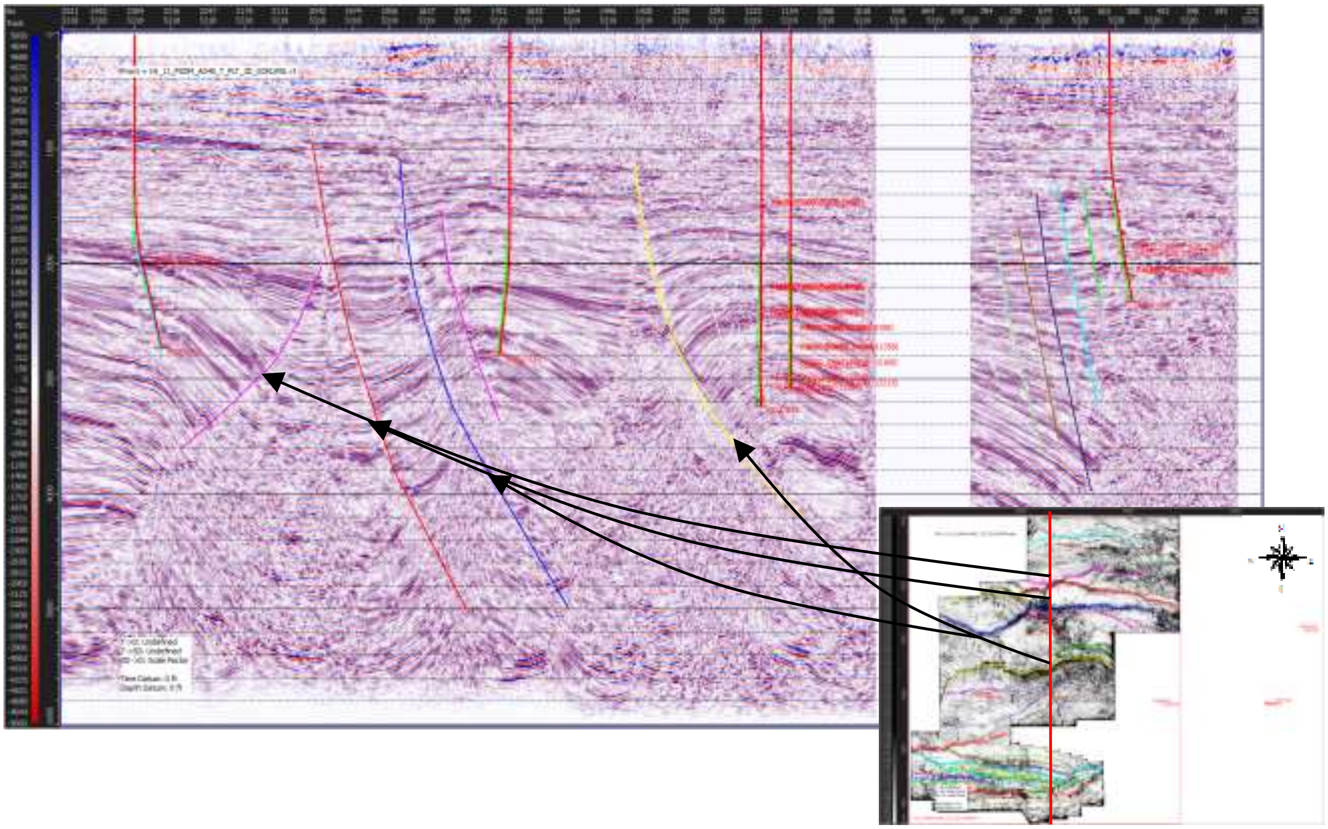


Figure 4.25a: Dip line through the middle of the study area showing structural interpretation and Well bores. Inset shows position of seismic line on the map. Sigma Merge Traverse

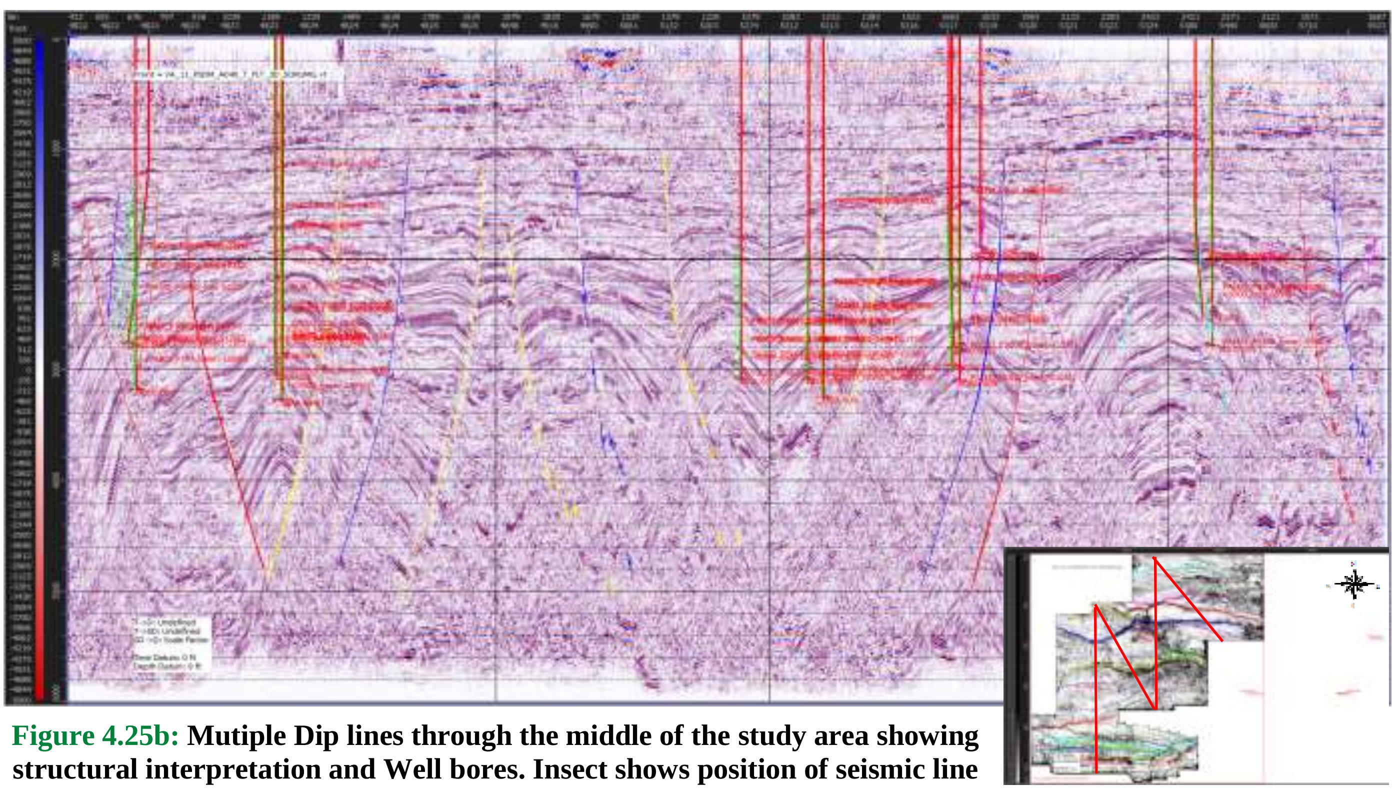


Figure 4.25b: Mutiple Dip lines through the middle of the study area showing structural interpretation and Well bores. Insect shows position of seismic line on the map. Sigma Merge Traverse

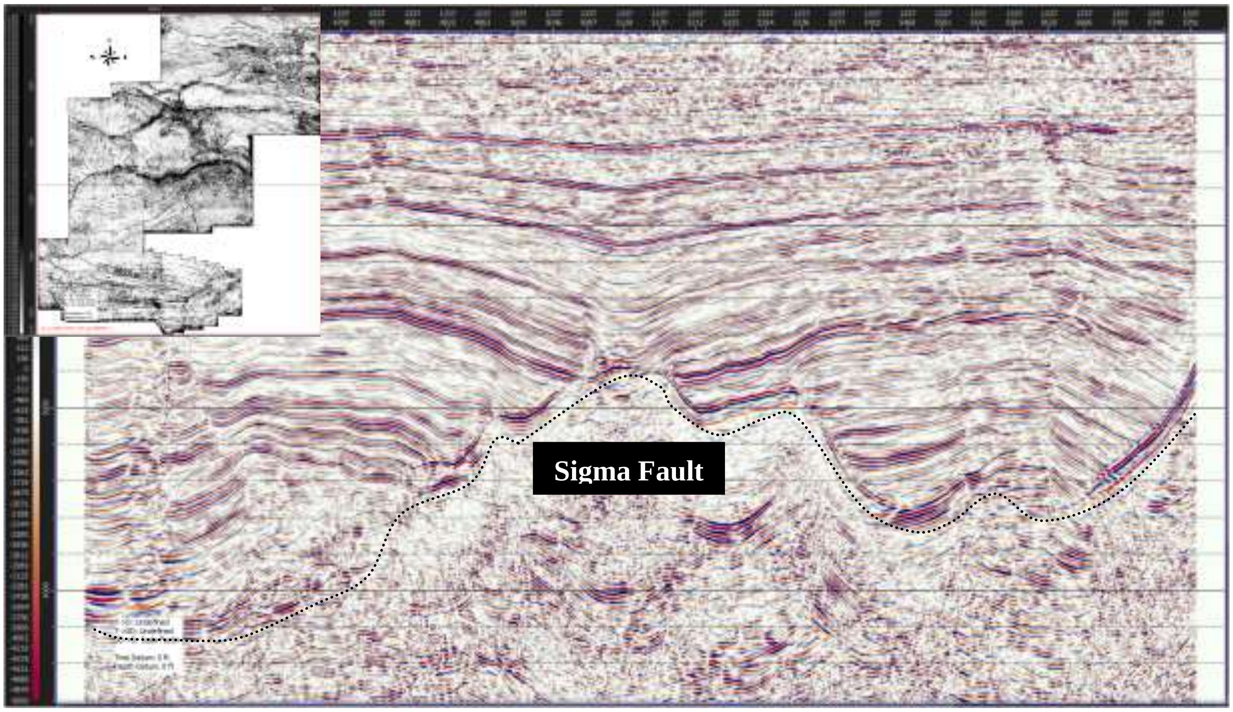


Figure 4.26: **Strike section across the major sigma fault.**

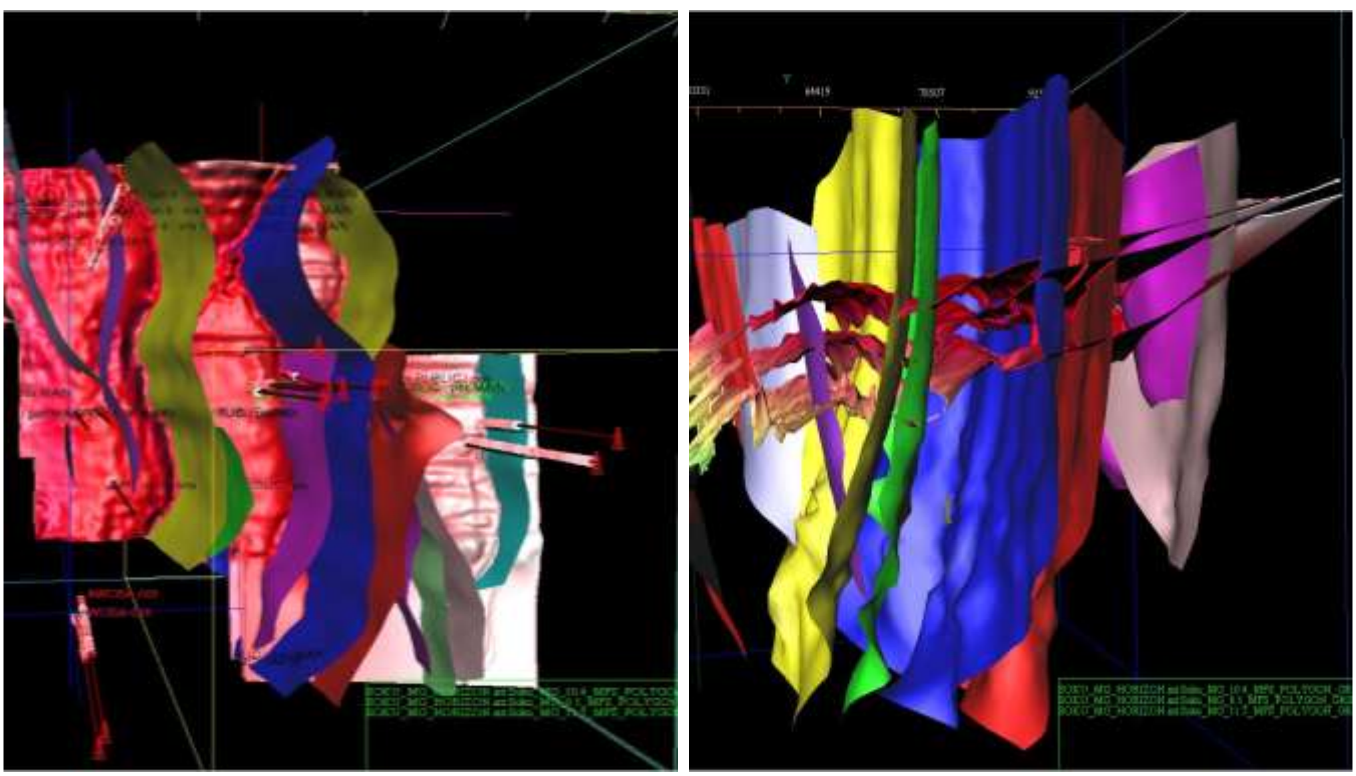
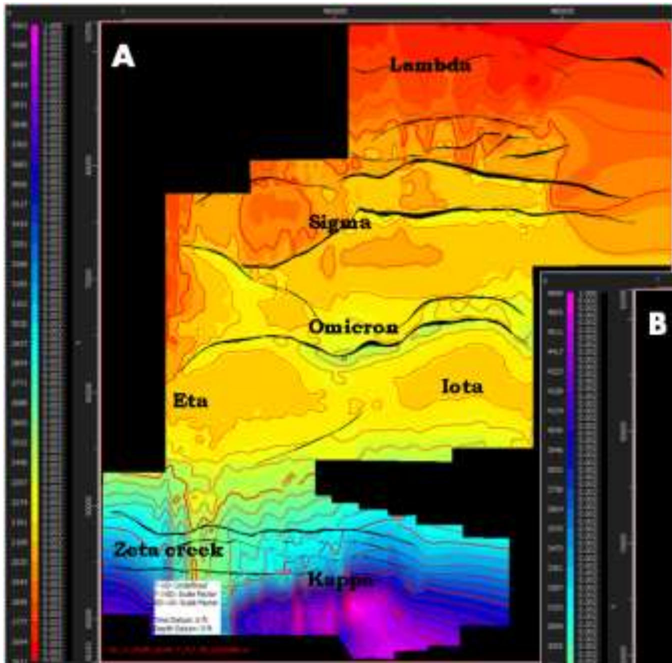
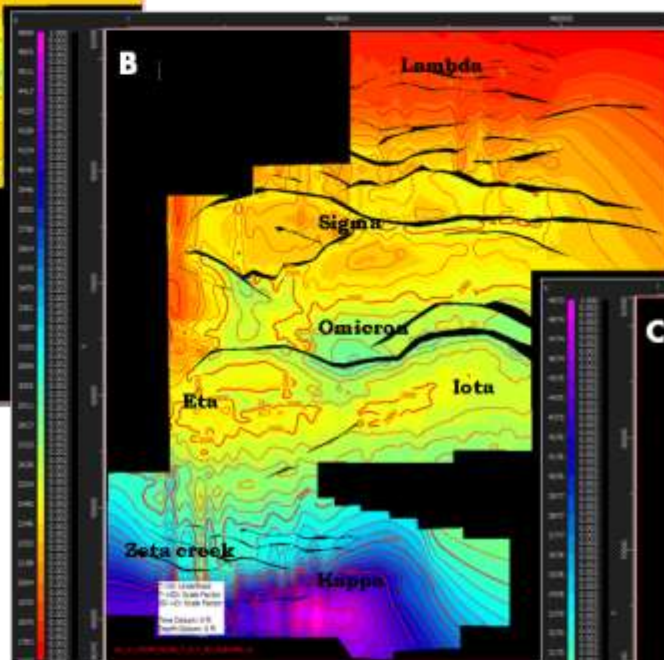


Figure 4.27: **Gridded Fault and Event on nDIVolume view showing Structural and stratigraphic Framework of study area on Plan and Dip section.**

Horizon/Event map at MFS_9.5



Horizon/Event map at MFS_10.4



Horizon/Event map at MFS_11.5

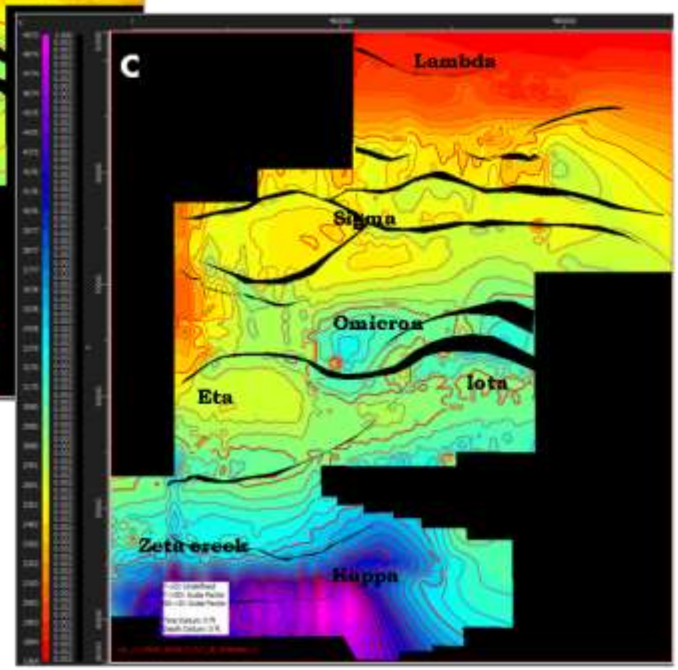


Figure 4.28: Gridded Horizon/Event map of (A). MFS_9.5 (B). MFS_10.4 and (C) MFS_11.5. Display at depth/time of the event at the data points.

4.5 FIELD TRAPPING STRUCTURE IDENTIFICATION

The major traps in the Niger Delta are structural traps. A number of fields have been discovered in the study area. Some of them include Lambda, Sigma, Omicron, Eta, Zeta-Creek, and Kappa (Figure 4.29). Faults and horizon mapping/interpreting in the area, aided identification of trapping structures and their classification. The major trapping structures include Regional Hanging Wall closure RHW, Simple/Faulted Rollover SFR and Back – to – Back Structure B2B. These are summarized in Figure 4.30 and Table 3.0.

4.6 LEAD IDENTIFICATION / REVALIDATION

Promising hydrocarbon leads were identified in the study area by interpreting the seismic volume both in cross-section and in plan view (i.e. horizon maps). 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. Some of these leads are captured in cross-section in Figure 4.31 and Table 4.0.

4.7 GROSS DEPOSITIONAL ENVIRONMENT AND PALEOBATHYMETRY

Paleobathymetric maps for four regional and time significant horizons were generated with information from biostratigraphic data and analysis of well log signatures. These were used to constrain these subdivisions as some log signature patterns are indicative of depositional environment. Generally, sediments were deposited within Neritic to Bathyal environments at different times, aligning with the progradational pattern of deposition of the Niger Delta. Some bio-facies 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) spaning from upper shoreface through lower shoreface to distal offshore (see Figures 4.32). The Gross Depositional Environment spans through incised Canyons, Channels, Inner Mid Shelf, Shelf Margin and Slope Margin. The GDE and paleobathymetric maps show basinward deepening which is suggestive of progradation and in conformity with the geology of the Niger Delta.

4.8 HYDROCARBON DATA INTEGRATION

Hydrocarbon pools are contained in reservoirs. Their spatial location and distribution are greatly influenced by factors such as structure, lithology and stratigraphy amongst others. Hydrocarbon and volumetric data in fields within the study area were obtained and plotted in the wells in the fields, and textured against the sequence stratigraphic correlation panel, in order to study and understand the hydrocarbon distribution trend (Figure 4.33).

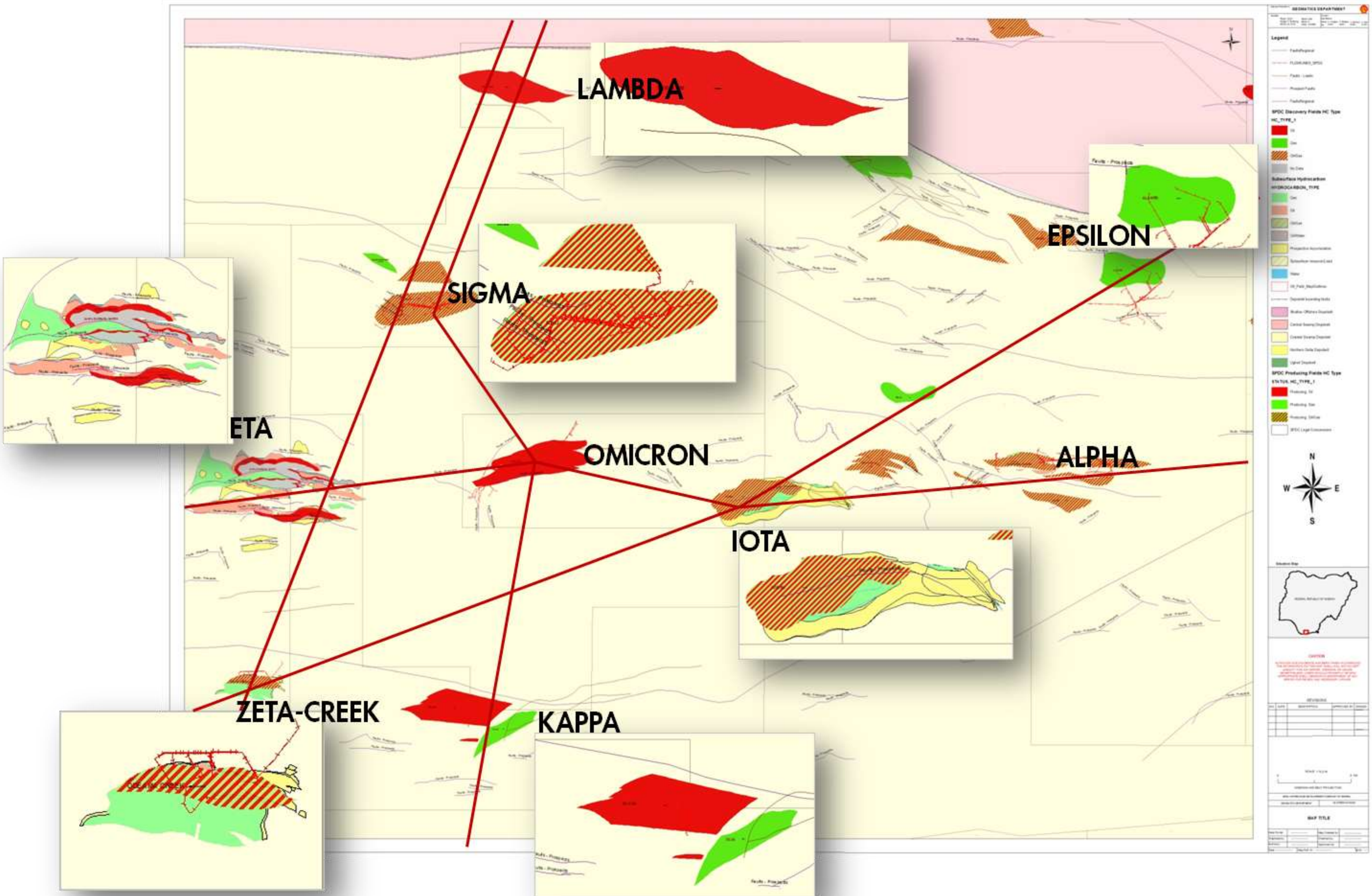


Figure 4.29: **Prospects and lead maps within study area.**

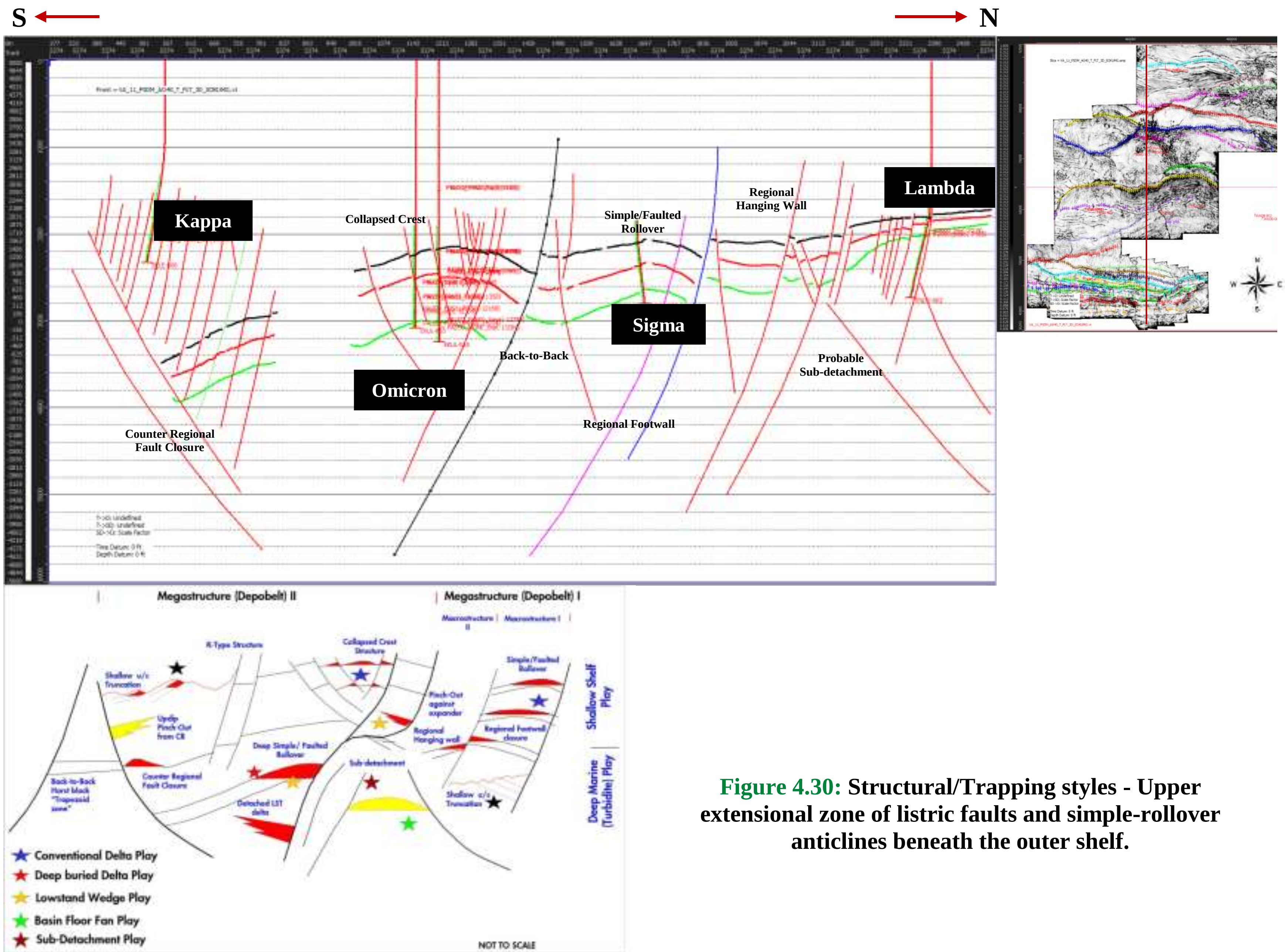


Figure 4.30: **Structural/Trapping styles - Upper extensional zone of listric faults and simple-rollover anticlines beneath the outer shelf.**

Table 3: **Fields trapping structure identification and classification.**

FIELD	STRUCTURAL STYLES
OMICRON	**Collapse Crested Structure (CCS)**
SIGMA	**Simple / Faulted Rollover (SFR)**
OMICRON	**Simple / Faulted Rollover (SFR)**
EPSILON	**Simple / Faulted Rollover (SFR)**
LAMBDA	**Sub-detachment**
KAPPA	**Counter Regional Fault Closure (CRFC)**
ETA	**Counter Regional Fault Closure (CRFC)**
OMICRON	**Back to Back Structure (B2B)**
SIGMA	**Back to Back Structure (B2B)**
LAMBDA	**Regional Hanging and Foot Wall (RHW/RFW)**
SIGMA	**Regional Hanging and Foot Wall (RHW/RFW)**

Table 4: Lead identification and classification template.

LEAD	REMARK
A	Down thrown hanging wall roll-over anticlinal structure with high amplitude deeper
B	Down thrown hanging wall roll-over anticlinal structure with high amplitude deeper
C	Fault bounded and tilted block with high amplitude
E	Fault bounded and tilted block with high amplitude
D	Fault bounded and tilted block with high amplitude

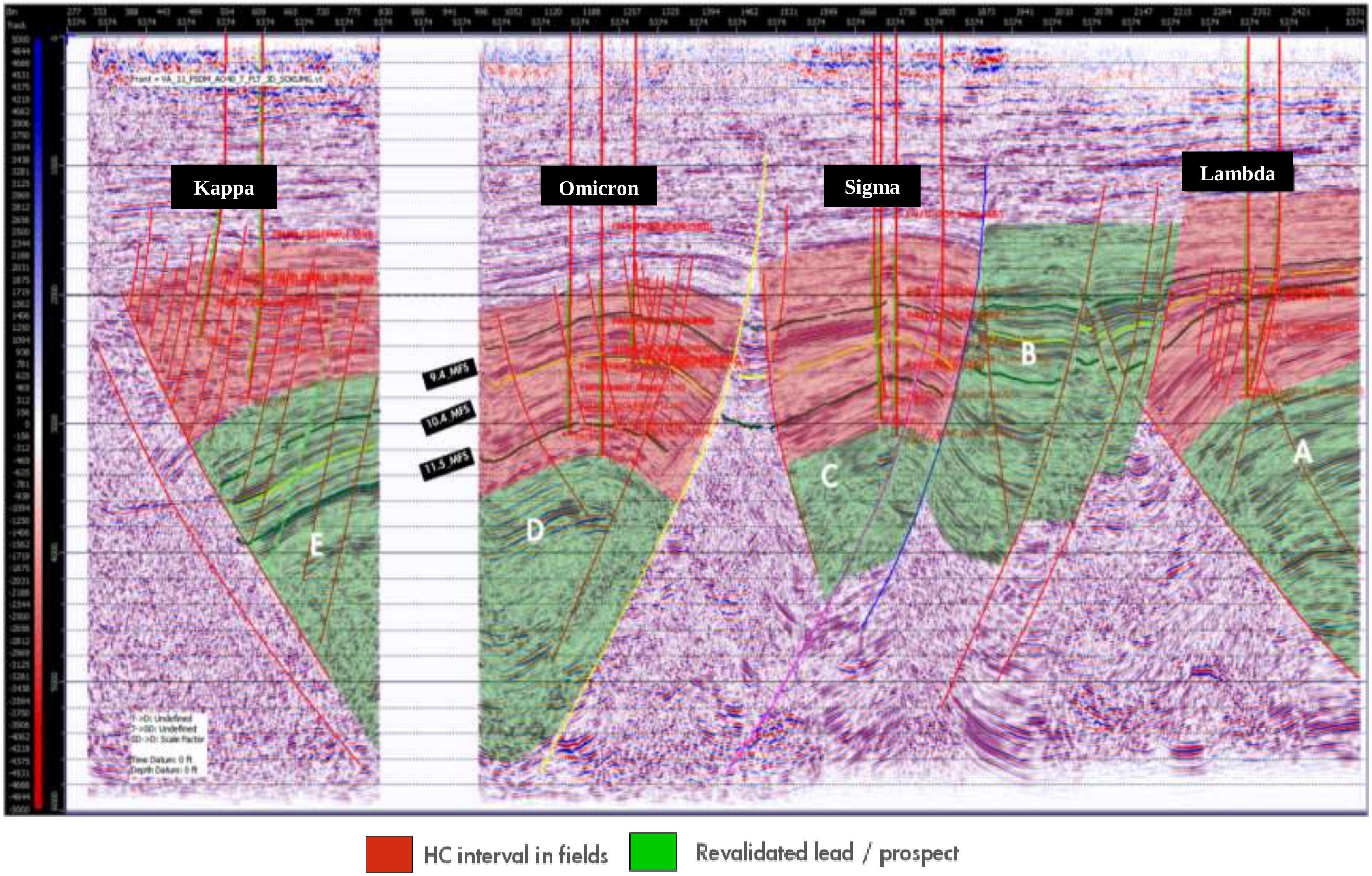


Figure 4.31: Seismic transects showing some hydrocarbon bearing fields and interval, and leads.

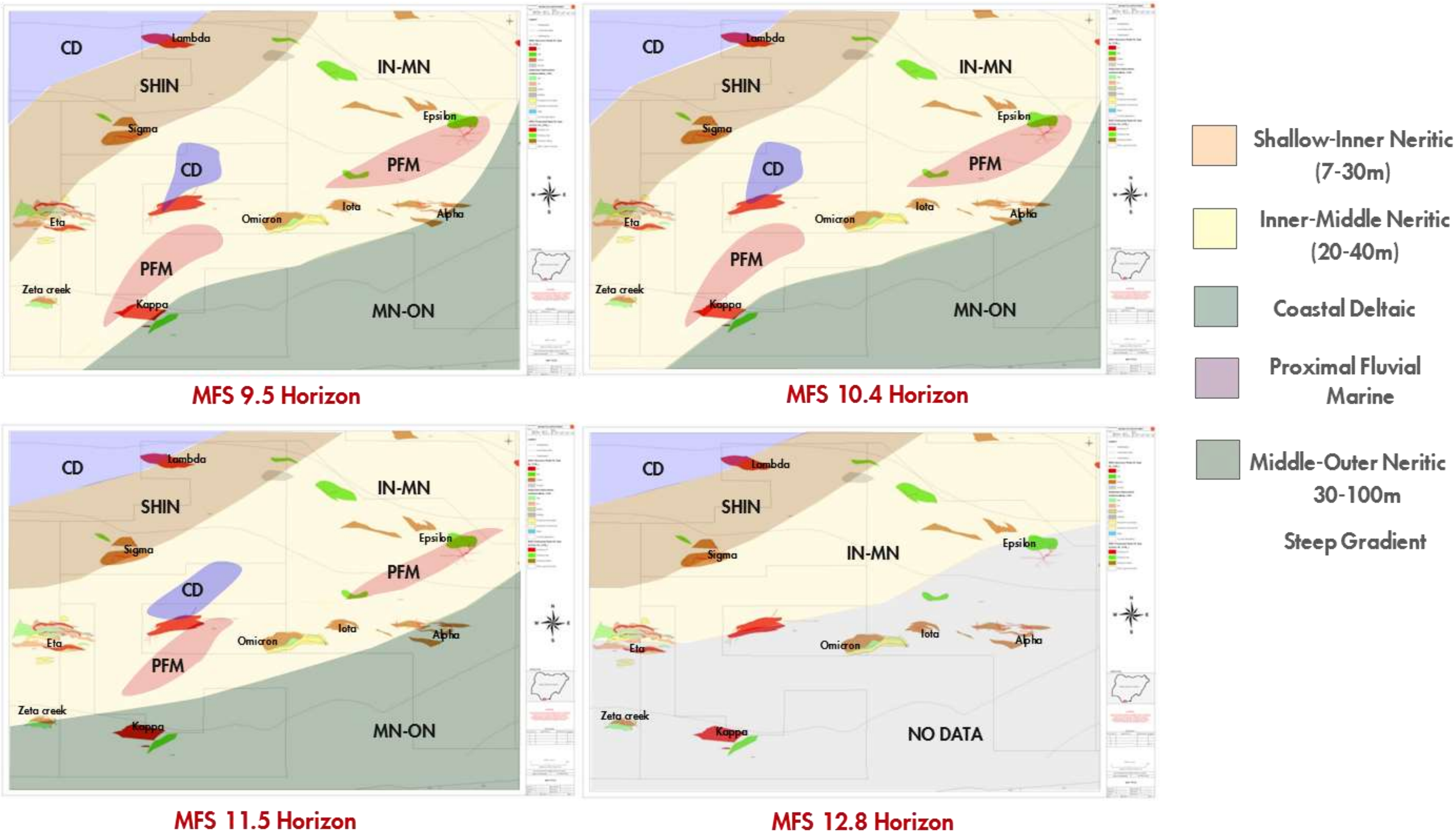


Figure 4.32: The Paleobathymetric maps. Shallowing gradient is seen in12.8-11.5 Ma. and a Steep gradient is seen in10.4-9.5 Ma. Depositional environments appear to have been consistently fluvial to shallow marine (Shallow-Inner Neritic, Inner Neritic-Middle and Outer Neritic) environments (mainly pro-delta) with isolated Coastal Deltaic and Proximal Fluvial influence.

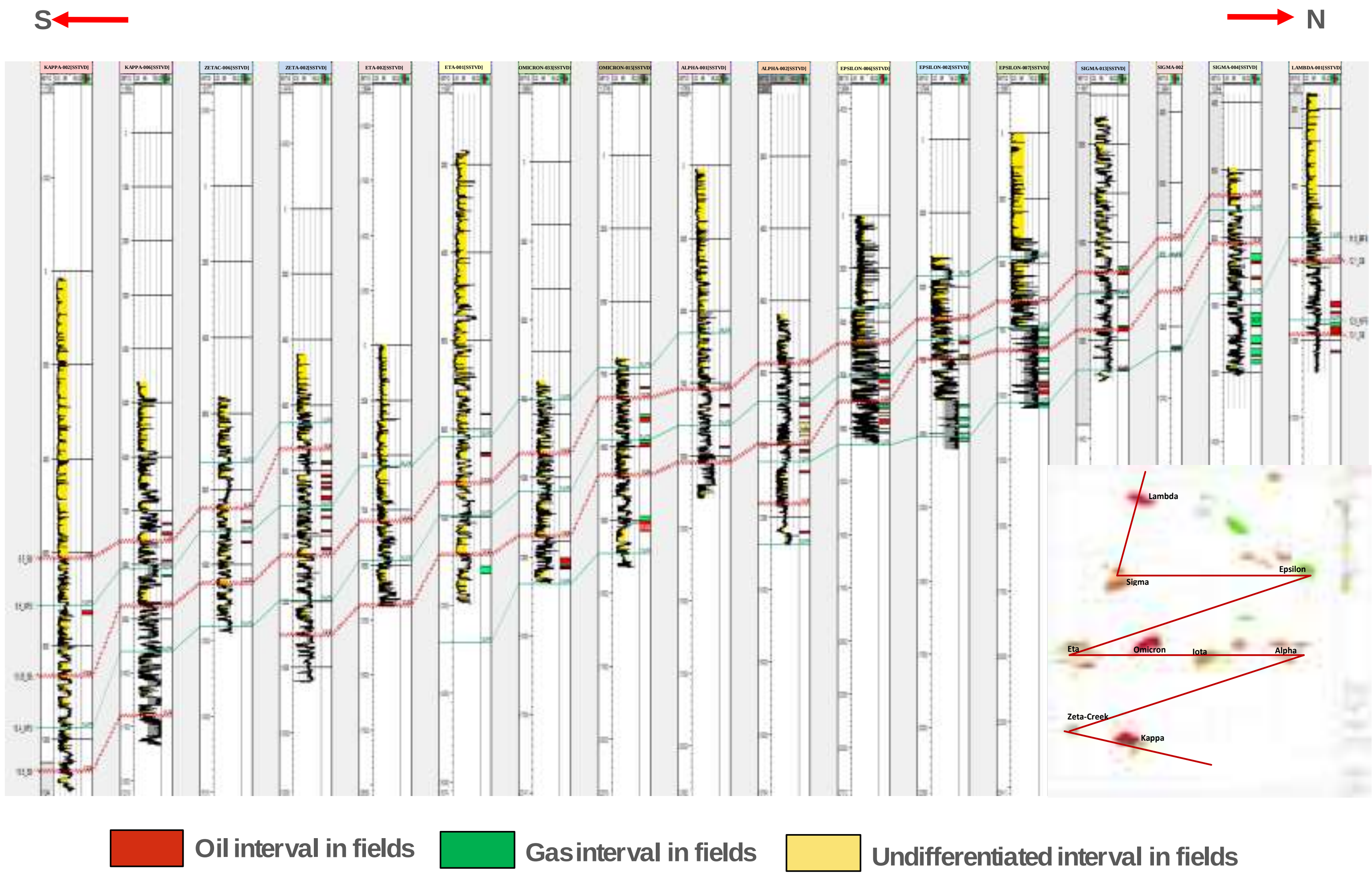


Figure 4.33: Template showing the plotting of hydrocarbon volumetric on Well log sequence stratigraphic correlation panel

CHAPTER FIVE

Results and Discussion

5.1 SEQUENCE STRATIGRAPHIC FRAMEWORK

Well-log sequence stratigraphy constrained by seismic stratigraphy and biostratigraphic data was carried out. 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, correlated and mapped across several wells and seismic sections. These were calibrated using the standard Niger Delta Chronostratigraphic Chart as follows: from oldest to youngest: 12.8Ma MFS, 12.1Ma SB, 11.5Ma MFS, 10.6Ma SB, 10.4 Ma MFS, 10.35Ma SB, 9.5Ma MFS, 8.5Ma SB and 7.4Ma MFS.

The MFS 12.8Ma, SB 12.1Ma, MFS 11.5Ma and SB 10.6Ma picks 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. Maximum Flooding Surfaces were characterized by thick and extensive shale units defined by thick high gamma-ray intervals that separate overall fining or shallowing upward intervals from coarsening or thickening upward intervals, and high abundance and diversity of microfossils. This can be seen for most of the MFSs in the entire well studied (see Figures 4.17 - 4.19). In seismic section they (MFS) are characterized by extensive and continuous, conformable events that can be correlated from fault block to fault block (Figure 4.24). The SBs are characterized by sizeable sand units defined in well log by abrupt and sharp bases of thick, low gamma ray intervals usually separating coarsening-upward intervals from fining-upward intervals (Figure 4.17 - 4.19). Also in seismic, SBs are somewhere marked by evidences of erosional activity and other truncations. Successively younger MFS and SB stratigraphic intervals are, on the average thinner and show more lateral strata thickening basinwards. Such up-section changes in sequence geology are particularly pronounced to the proximal northeast of the study area and indicative of structural induced accommodation space creation and large scale deltaic progradation into the basin as can be seen from the generated Paleobathymetry Maps (Figure 4.32). These maps show deepening basinwards which is suggestive of progradation and in conformity with the geology of the Niger Delta.

5.1.1 DEPOSITIONAL SEQUENCE ARCHITECTURE

Depositional systems in the study area across fields comprise Lowstand Systems Tracts (LSTs), Transgressive Systems Tracts (TSTs) and Highstand Systems Tracts (HSTs). The LSTs are represented by coeval facies dominated by deposition basinward of the shelf-edge during maximum regression and are characterized by deep-water deposition from gravity flows and/or traction processes within shelf-edge or canyon-head delta. The sediments associated with LSTs recognized in the study area are the Fluvial Channel Sands and Slope Fans (SF).

Fluvial Channel Sands are associated with erosion of canyons into slopes and incision of fluvial valleys into the shelf. The Slope Fan system is commonly 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. Slope fans are formed as the rate of eustatic sea level fall becomes less than the rate of rise associated with subsidence.

The Transgressive Systems Tract (TST) developed in response to sea level rise and when sedimentation rate was not able to 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 updip in estuaries. The upper boundary of the TST defines the MFS. Condensed sections, characterized by faunal abundance and diversity peaks are developed near this surface. Transgressive Systems Tracts were characterized by transition from upward shallowing to upward deepening and transgressive erosional surfaces (TSE) on the shelf.

The TSTs capping the LST Facies in the studied wells, across the fields were observed to be very thick and contained mainly marine shales with minor transgressive sands.

The rate of sea level rise decreased during the development of Highstand Systems Tracts (HSTs). 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 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).

5.2 STRUCTURAL FRAMEWORK

Structural interpretation of the Sigma Fields reveals the presence of growth fault and associated rollover anticlines and crestal faults which can serve as path ways, for upward migration of hydrocarbon generated within the shale below. The identified faults are characteristic of Niger Delta, and have appreciable throw which can serve as potential pathway for hydrocarbon. The anticlines also have possibility of possessing multiple pay horizons, and they are major parts of most giant oil fields.

The morphology and importance of reservoir and seal vary greatly between the system tracts. The highstand system tracts contain fluvial-deltaic and shore face sands, while the highstand system tracts are characterized by upward coarsening sands with shale intercalations, thus serving as the potential reservoir in the field. The trangressive system tracts are sand deficient and contain abundant fine grained sediments, rich in organic matter. They have potential for source, seal and reservoir of hydrocarbon; however source and seal are mainly the dominant facies in trangressive system tracts. The shale of the TST therefore forms the seal for the potential traps in the study area. The alternation of the HST and TST sands and shale therefore provide a combination of reservoir and seal rocks that are essential for hydrocarbon accumulation and stratigraphic trapping (Bassey and Fagbola, 2002).

5.3 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. The major traps are fault juxtaposition traps and rollover anticlines sealed by thick shale units, though the possibilities for stratigraphic traps exists. Analysis of the discovered hydrocarbons in the study area was undertaken with respect to their spatial and depth locations, as well as age and sequence stratigraphic position (Figure 5.1). Results show that generally gas is more concentrated at the proximal end (northern section) within the sequence stratigraphic interval MFS 12.8Ma and MFS 11.5Ma, oil and gas at the central part while there is predominance of oil at the distal south, within the interval MFS 10.4Ma and MFS 9.5Ma. 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).

5.4 HYDROCARBON LEADS AND POTENTIALS

The study area has fairly high fault density which makes trapping structures available for hydrocarbon accumulation. 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. Also there abound several high amplitude units (bright spots) in deeper and intermediate horizons below and around existing fields (Figure 4.34 and 5.2).

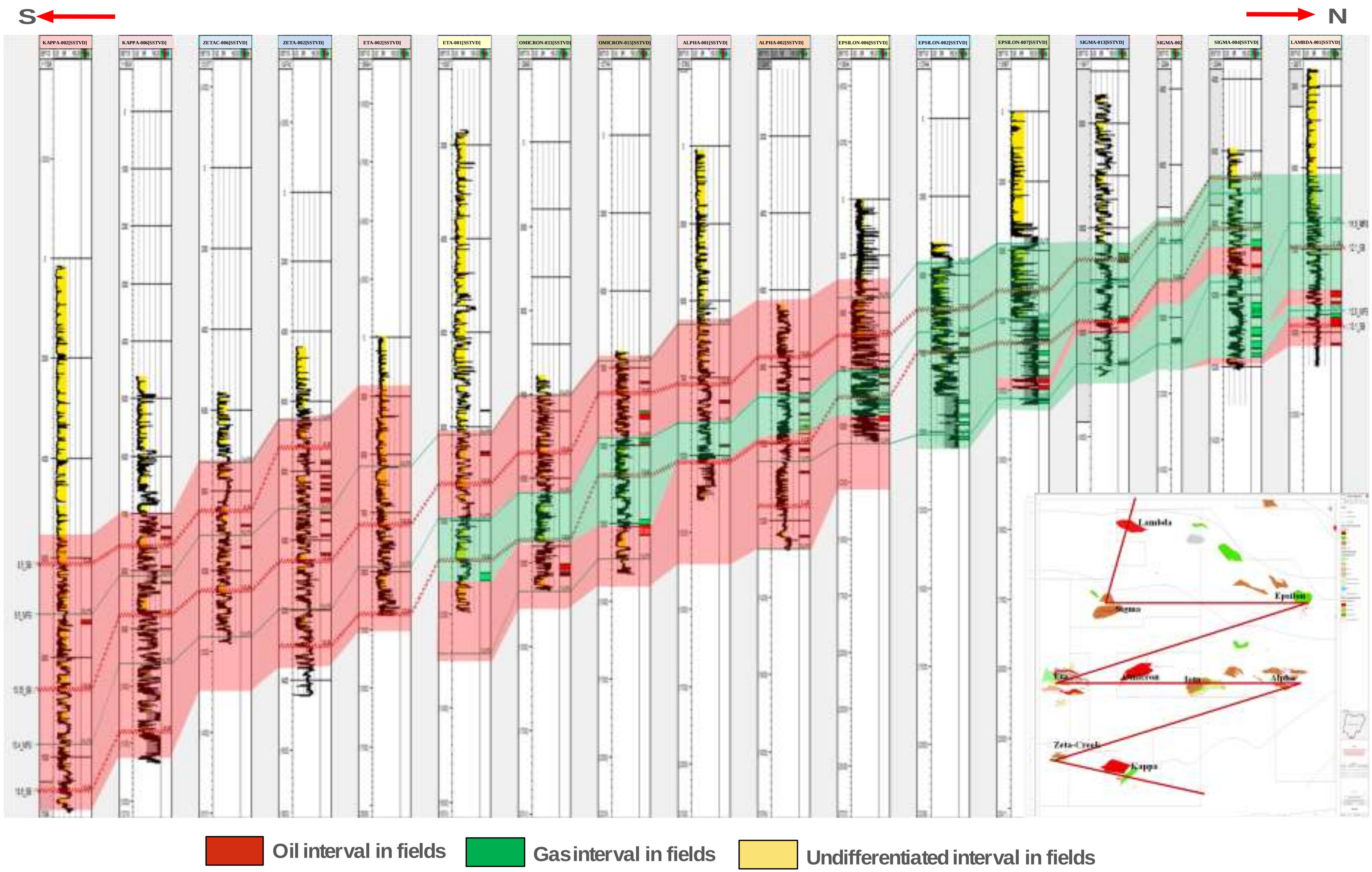


Figure 5.1: Hydrocarbon trends and interval distribution across the fields

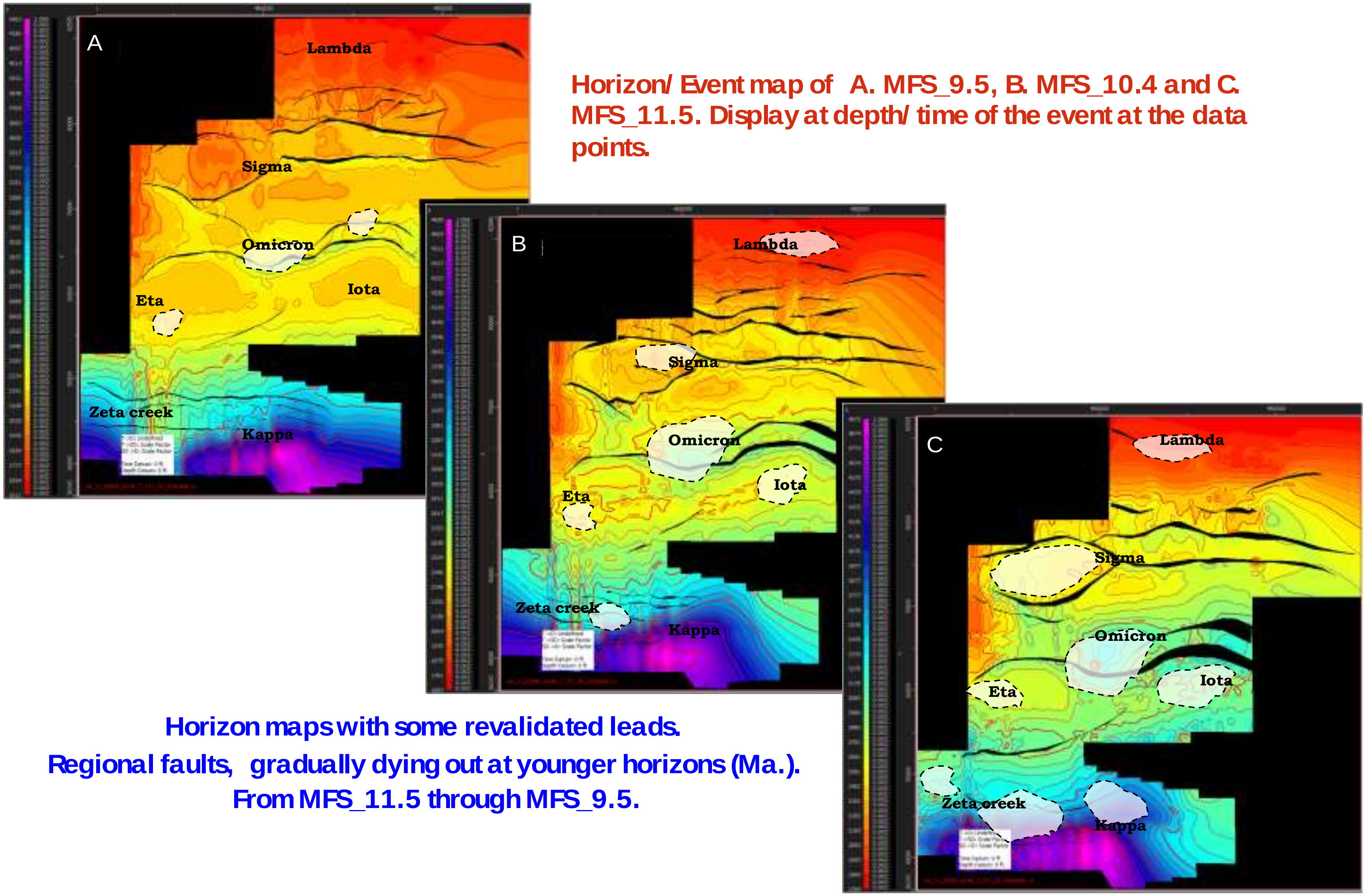


Figure 5.2: **Identified leads highlighted as structural culmination on horizon maps of different regional stratigraphic surface (A) MFS 9.5, (B) MFS 10.4 and (C) MFS 11.5.**

Summary and Conclusion

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 lithofacies, stacking patterns, depositional sequences and systems tracts interpretation and mapping of faults and horizons (stratigraphic surfaces/events) across Lambda, Sigma, Omicron, Epsilon, Iota, Alpha, Eta, Zeta-Creek and Kappa Fields located within the coastal Swamp depobelt, Niger Delta basin.

Palynologicl and foraminiferal zones encountered indicates that the study is of Middle Miocene through Upper Miocene age. 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 Sequence Tract (LST, TST and HST) Interpretation. Analysis of the vertical succession of depositional facies revealed four third order depositional sequences of mid-Miocene age bounded chronologically by 12.1Ma SB, 10.6 Ma SB and 10.35 Ma SB (Type 1 Sequence Boundaries).

The depositional sequences experienced major flooding episodes characterized by high faunal population and diversity. In each sequence, the lowermost sections were marked by deposits arising from relatively low sea level, forming channels and slope complexes. The middle sections were deposited during a generally high relative sea level, while the uppermost sections were deposited during gradual drops in relative sea level lowering (Highstand). These inferred variations in relative sea level defined third order depositional systems that comprised Lowstand Systems Tract (LST) at the base of the section, Transgressive Systems Tract (TST) in the middle of the section and the Highstand Systems Tract (HST) at the top of each section.

Correlation across fields shows a decreasing net-to-gross from northeast to southwest with an anomaly at Sigma-Omicron area. Also flattening at various MFS(s) reveals a shift of Depo-Center from Northern section towards the southern (typical scenario of the progradational pattern in the Niger Delta).

In terms of hydrocarbon exploration, the sand units of the LST and HST formed the basin floor fans, channel and shoreface sands of the delta. The high resistivity log values revealed that they are potential hydrocarbon reservoirs. The shales of the TST in which most of the MFS were delineated could form seals to the reservoir units. A combination of the reservoir sands of the LST and HST and the shale units of the TST can form good stratigraphic traps for hydrocarbon and hence should also be targeted during hydrocarbon exploration.

A quick reservoir evaluation as revealed from the petrophysical interpretation indicates the occurrence of hydrocarbon at intermediate/deeper horizons. Hydrocarbon trends and interval distribution across the fields reveals the concentration of gas at the proximal end (northern section), oil and gas at the central part while predominance of oil at the distal end (towards the southern part). Also delineated reservoirs were mainly the channel sands and shoreface sands of LSTs and HSTs, respectively, which displayed low Gamma Ray and high Resistivity values

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. Gross Depositional Environment spans through incised Canyons, Channels, Inner Mid Shelf, Shelf Margin and Slope Margin. 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.

Mapped faults aided field trap structure identification – Back to Back Horst Block (Trapezoid Zone), collapse Structures, Simple/Faulted Rollovers, Regional Foot Walls/Hanging Walls and Sub-detachment structures. Structural framework analysis showed that structural deformation greatly influenced stratigraphy. Event map reveals that faults die out at younger age (Ma.)/ Shallower depth.

Revalidated leads suggested possibility for hydrocarbon pools in the area at different intermediate and deeper horizons; and with the presence of infrastructure in-place, these can be exploited profitably.

Recommendation

The challenges encountered in the interpretation and mapping of surfaces and structures at deeper horizons using the available dataset indicate that some of the seismic datasets used are characterized by poor imaging with increasing depth. Hence reacquisition and/or processing should be done to improve seismic data quality for better imaging and interpretation/mapping especially at deeper horizon and behind faults in the central and southern parts of the area of study.

Sparse well control and deep penetrating wells across some areas also constrained mapping. Deeper exploration wells should be drilled to provide data for analyzing and constraining deeper interpretations. In addition, studies should be carried out to better understand the structural and stratigraphic/sedimentological controls on hydrocarbon distribution and trend in the area

References

Adeogba, A. A., McHargue, T. R., and Graham, S. A., 2005. Transient fan architecture and depositional controls from near-surface 3-D seismic data, Niger Delta continental slope: American Association of Petroleum Geologists Bulletin, Vol. 89, p. 627–638.

Adesida, A. and Ehirim, B.O., 1988. Cenozoic Niger Delta: A guide to its lithosedimentary analysis. SPDC Exploration note 88.002 (Ref: on-shore wells) p. 1-10.

Allen, J. R. L., 1964. The Nigerian Continental Margin; bottom sediments, submarine morphology and geological evolution, *Marine Geology* 1, 289-332.

Allen, J.R.L., 1965. Late Quaternary Niger Delta, and adjacent areas-sedimentary environments and lithofacies. American Association of Petroleum Geologists Bulletin, Vol.49, p. 547-600.

Asseez, L.O., 1976. Review of stratigraphic sedimentation and structure of the Niger Delta. Geology of Nigeria. pp 259-272.

Avbovbo, A. A., 1978. Tertiary lithostratigraphy of Niger Delta. American Association of Petroleum Geologists Bulletin, Tulsa, Oklahoma, p. 96-200.

Barker, C., 1979. Organic Geochemistry in Petroleum Exploration. American Association of Petroleum Geologists Continuing Education Course Note, Series 10, 159pp.

Bassey, C.E. and Fagbola, O., 2002. Sequence stratigraphy of Iso Field, Western onshore Niger delta, Nigeria: Journal of Mining and Geology, Vol.38 (1). pp 43-47.

Bowen, B.E., Hall, D.J., Rosen, R.N., and Shaffer, B.L., 1994. Sequence stratigraphic and structural framework, southeast Niger delta shelf: Nigerian Association of Petroleum Explorationist Bulletin, Vol.9/01, p.51-58.

Burke, K., 1972, Longshore drift, submarine canyons, and submarine fans in development of Niger delta: American Association of Petroleum Geologists Bulletin, Vol. 56, p. 1975-1983.

Burke, K., Dessauvagie, T. E., and Whiteman, A. J., 1971. Opening of the Gulf of Guinea and geological history of the Benue depression and Niger Delta. *Nature, Phys. Sci.* 233, 51-55.

Burke, K., Dessauvagie, T. F. J. and Whiteman, A. J., 1972. Geological history of the Benue Valley and adjacent areas, in 1st Conference on African geology, Ibadan, 1970, Proceedings: Ibadan, Nigeria, Ibadan Univ. Press, p. 287-305.

Catuneanu, O., 2002. Sequence stratigraphy of clastic systems: concepts, merits and pitfalls. Journal of African Earth Sciences 35, 1–43.

Catuneanu, O., Wopfner, H., Eriksson, P.G., Cairncross, B., Rubidge, B.S., Smith, R.M.H., and Hancox, P.J., 2005. The Karoo basins of south-central Africa. *Journal of African Earth Sciences* 43.211-253.

Corredor, F., Shaw, J. H. and Billoti, F., 2005. Structural styles in the deep-water fold and thrust belts of the Niger Delta: American Association of Petroleum Geologists Bulletin, Vol. 89, p. 753–780.

Daily, G. C., 1976. A possible mechanism relating progradation, growth faulting, clay diapirism and overthrusting in a regressive sequence of sediments: Bulletin of Canadian Petroleum Geology, Vol. 24, p. 92–116.

Damuth, J. E., 1994, Neogene gravity tectonics and depositional processes on the deep Niger Delta continental margin: Marine and Petroleum Geology, Vol. 11, p. 320–346.

Doust, H., 1990. Petroleum Geology of the Niger Delta. Geochemical Society, London, Special Publications. 50: 365

Doust, H. and Omatsola, E., 1990. Niger Delta: in Edwards, J. D., and Santogrossi, P.A., (Eds.), Divergent/passive margin basins: American Association of Petroleum Geologists Bulletin Memoir 48, p. 239-248.

Edwards, M. B., 2000, Origin and significance of retrograde failed shelf margins; Tertiary northern Gulf Coast Basin: Transactions of the Gulf Coast Association, v. 50, p. 81–93.

Ejedawe, J. E., 1981. Patterns of incidence of oil reserves in Niger delta basin: American Association of Petroleum Geologists Bulletin, Vol. 65, p. 1574-1585.

Ejedawe, J.E., Coker, S.J.L., Lambert-Aikhionbare, D.O., Alofe, K.B., and Adoh, F.O., 1984. Evolution of oil-generative window and oil and gas occurrence in Tertiary Niger Delta Basin: American Association of Petroleum Geologists, Vol. 68, p.1744 -1751.

Ekweozor, C. M., and Daukoru, E. M., 1984. Petroleum source-bed evaluation of Tertiary Niger Delta; discussion and reply, American Association of Petroleum Geologists Bulletin, Vol. 68, pp.387–394.

Ekweozor, C. M., and Daukoru, E. M., 1994. Northern delta depobelt portion of the Akata–Agbada(!) petroleum system, Niger Delta, Nigeria, *in* L. B. Magoon and W. G. Dow, eds, The petroleum system—from source to trap: AAPG Memoir 60, p. 599–613.

Emery, D. and Myers, K. 1996. Sequence Stratigraphy. Blackwell, London, 297 p.

Evamy, B.D., Haremboure, J., Kamerling, P., Knaap, W.A., Molloy, F.A., and Rowlands, P.H., 1978. Hydrocarbon habitat of Tertiary Niger Delta: American Association of Petroleum Geologists Bulletin, Vol. 62, p. 1-39.

Frankl, E. J. and Cordy, E. A., 1967. The Niger Delta oil province: Recent developments onshore and offshore. Seventh world petroleum congress proceedings, Mexico, 2: pp 195-209.

Galloway, W.E., 1989. Genetic stratigraphic sequences in basin analysis; I, Architecture and genesis of flooding-surface bounded depositional units: American Association of Petroleum Geologists Bulletin, 73, p. 125–142.

Haack, R.C., Sundararaman, P., Diedjomahor, J.O., Xiao, H., Gant, N.J., May, E.D., and Kelsch, K., 2000. Niger Delta petroleum systems, Nigeria: in Mello, M.R., and Katz, B.J., eds., Petroleum systems of South Atlantic margins. American Association of Petroleum Geologists Memoir 73, p. 213–231.

Haq, B.U., Hardenbol, J., and Vail, P.R., 1988. Mesozoic and Cenozoic Chronostratigraphy and Cycles of Sea-level Change, in C.K. Wilgus et al. (eds), Sea-Level changes: an integrated approach: Society of Economic Paleontologists and Mineralogists, Special Publication Vol. 42, p. 71-108.

Harding, T.P., and Lowell, J.D., 1979. Structural Styles, Their Plate-Tectonic Habitats and Hydrocarbon Traps in Petroleum Province: American Association of Petroleum Geologists Bulletin, Vol. 63. p. 1016-1058.

Harland, W.B., Scott, R.A., Aukland, K.A., and Snape, I., 1992. The Ny Friesland Orogen, Spitsbergen. Geol. Mag. 129, 679-707.

Hooper, R. J., R. J. Fitzsimmons, N. Grant, and Vendeville, B. C., 2002. The role of deformation in controlling depositional patterns in the south-central Niger Delta, west Africa: Journal of Structural Geology, Vol. 24, p. 847–859.

Hospers, J., 1971. The geology of the Niger Delta area, in the Geology of the East Atlantic continental margin. Great Britain, Institute of Geological Science, Report, 70(16): 121-141.

Kogbe, C. A. 1989. The Cretaceous Paleocene Sediments of Southern Nigeria. In C. A. Kogbe (Ed.), Geology of Nigeria (pp. 320–325). Jos: Rock View Ltd.

Khalivov, N. Y., and Kerimov, A. A., 1983, Origin of mud volcanism and diapirism: International Geological Review, Vol. 25, p. 877–881.

Kendall, C., 2003. Use of well logs for sequence stratigraphic interpretation of the subsurface. USC Sequence Stratigraphy Web. http://strata.geol.sc.edu/index.html, University of South Carolina.

Kendall, C.G. St. C., 2004. Critical accidents in paleo-geography and oceanography induced by abrupt changes in base level, signaled by hard or firm grounds in shallow water clastics and carbonates: American Association of Petroleum Geologists Bulletin, Vol. 13, p. 75.

Kendall, C. G., 2008. Template for “conceptual models” used to interpret depositional systems USC Sequence Stratigraphy Web. http://strata.geol.sc.edu/index.html, University of South Carolina.

Knox, G. J., and E. M. Omatsola, 1989. Development of the Cenozoic Niger delta in terms of the "Escalator Regression" model and impact on hydrocarbon distribution: Proceedings KNGMG Symposium "Coastal Lowlands, Geology and Geotechnology," 1987: Dordrecht, Kluwer, p. 181-202.

Ladipo, K.O., Nwajide, C.S., and Akande, S.O., 1992. Cretaceous and Paleogene sequences in the Abakaliki and Anambra basins, south eastern Nigeria: a field guide. International Symposium on Geology of Deltas, Port Harcourt.

Lawrence, S.R., Munday S., and Bray, R., 2002. Regional geology and geophysics of the eastern Gulf of Guinea (Niger Delta to Rio Muni): The Leading Edge, 21:1112– 1117.

Lehner, P., and De Ruiter, P. A. C., 1977. Structural history of Atlantic margin of Africa. American Association of Petroleum Geologists Bulletin, 61:961-981.

Magbagbeola, O.A. and Willis, B.J., 2007. Sequence stratigraphy and syndepositional deformation of the Agbada formation, Robertkiri field, Niger Delta, Nigeria. American Association of Petroleum Geologists Bulletin 91 (7), 945–958.

Merki, P. J., 1972. Structural geology of the Cenozoic Niger delta, *in* 1st Conference on African Geology Proceedings: Ibadan University Press, p. 635-646.

Mitchum, R. M., Vail, P. R., and Sangree, J. B., 1977. Stratigraphic interpretation of seismic reflection patterns in depositional sequences: American Association of Petroleum Geologists Bulletin Memoir, 26, p. 117-133.

Morgan, R., 2004. Structural controls on the positioning of submarine channels on the lower slopes of the Niger Delta: Geological Society (London) Memoir 29, p. 45–51.

Morley, C. K., 1992. Notes on Neogene basin history of the western Alboran Sea and its implications for the tectonic evolution of the Rif-Betic orogenic belt: Journal of African Earth Sciences, v. 14, p. 57–65.

Morley, C. K., Crevello, P. and Ahmad, Z. H., 1998. Shale tectonics and deformation associated with active diapirism: The Jerudong anticline, Brunei Darussalam: Journal of the Geological Society (London), Vol. 155, p. 475–490.

Nton, M.E. and Adebambo, B.A., 2009. Petrophysical evaluation and depositional environments of reservoir sands of X- field, offshore Niger delta. Mineral Wealth, Vol. 150, pp 1-12.

Nton, M.E. and Adesina, A. D., 2009. Aspects of structures and depositional environment of sand bodies within Tomboy field, offshore western Niger Delta, Nigeria. RMZ – Materials and Geoenvironment, Vol. 56, No. 3, pp. 284–303

Nwajide, C.S. and Reijers, T.J.A., 1996. Geology of the Southern Anambra Basin. In: Reijers, T.J.A. (Ed), selected chapters on Geology, SPDC, Warri, pp. 133-148.

Owoyemi, A.O., and Willis, B.J., 2006. Depositional patterns across syndepositional normal faults, Niger Delta, Nigeria. Journal of Sedimentary Research 76 (1–2), 346–363.

Ozumba, B.M., 1999. Middle to Late Miocene sequence stratigraphy of the Western Niger Delta. NAPE Bulletin, 13 & 14(2), pp. 176-192.

Pacht, J. A., and D. J. Hall, 1993. Sequence stratigraphic approach to exploration in offshore Nigeria: Offshore Technology Conference, v. 1, p. 241-248.

Posamentier, H.W., 2000. Seismic stratigraphy into the next millennium; a focus on 3D seismic data, American Association of Petroleum Geologists Annual Convention, New Orleans, Abstracts Vol. 9 (2000), p. A118.

Posamentier, H.W. and Allen, G.P., 1999. Siliciclastic sequence stratigraphy: concepts and applications. Society of Economic Paleontologists and Mineralogists (SEPM), Concepts in Sedimentology and Paleontology no. 7, 210 pp.

Posamentier, H.W., Jervey, M.T., and Vail, P.R., 1988. Eustatic controls on clastic deposition. I. Conceptual framework: in Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van Wagoner, J.C., eds., Sea Level Changes—An Integrated Approach, vol. 42. Society of Economic Paleontologists and Mineralogist, Special Publication, p. 110– 124.

Posamentier, H.W., and Kolla, V., 2003. Seismic geomorphology and stratigraphy of depositional elements in deep-water settings. Journal of Sedimentary Research 73, 367–388.

Reijers, T.J.A. 1996. Selected Chapters on Geology: with notes on Sedimentary Geology, Sequence Stratigraphy and three case studies and a field guide. S.P.D.C. Corporate Reprographic Services, Warri, Nigeria. 197p.

Reijers, T. J. A., Petters, S. W. and Nwajide,C. S., 1997. The Niger Delta basin. In: Selley, R. C. (Ed), African basins, Amsterdam, Elsivier science, sedimentary basins of the world; Vol. 3, p. 151–172.

Reijers, T. R. A., 2011. Stratigraphy and sedimentology of the Niger Delta. *Geologos*, *17*(3), 133-162. http://dx.doi.org/10.2478/v10118-011-0008-3

Rensbergen, P. V., and Morley, C. K., 2000. 3D seismic study of a shale expulsion syncline at the base of the Champion delta, offshore Brunei and its implications for the early structural evolution of large delta systems: Marine and Petroleum Geology, Vol. 17, p. 861–872.

Rensbergen, P. V., Morley, C. K., Ang, D. W., Hoan, T. Q. and Lam, N. T., 1999. Structural evolution of shale diapirs from reactive rise to mud volcanism: 3D seismic data from the Baram delta, offshore Brunei Darussalam: Journal of the Geological Society (London), Vol. 156, p. 633–650.

Rider, M.H. 1999. The geological interpretation of well logs. Whittles Publishing Services, Dunbeath. 288pp.

Sangree, J.B and J.M. Widmier, 1979. Seismic stratigraphy and global changes in sea level Part 9: seismic interpretation of clastic depositional facies. In: Payton (Ed.), Seismic

Stratigraphy: Application to Hydrocarbon Exploration, AAPG-Memoir No. 26, AAPG, Tulsa, p. 165–184.

Short, K. C., and Stauble, A. J., 1967. Outline of geology of Niger Delta. American Association of Petroleum Geologists Bulletin, Vol. 51, p. 761-779.

Stacher, P. 1994. Niger Delta Hydrocarbon Habitat. Nigerian Association of Petroleum Explorationists Bull. 9(10):67-75.

Stacher, P., 1995**.** Present understanding of the Niger Delta hydrocarbon habitat; In: M.N. Oti and G.Postma (Eds.), Geology of deltas; A. A. Balkema, Rotterdam; pp.257– 267.

Stoneley, R., 1966. The Niger delta region in the light of the theory of continental drift: Geol. Mag., Vol. 105, p. 385-397.

Tuttle, W.L.M, Brownfield, E.M. and Charpentier, R.R. 1999. The Niger Delta Petroleum System. Chapter A: Tertiary Niger Delta (Akata-Agbada) Petroleum System, Niger Delta Province, Nigeria, Cameroon and Equatorial Guinea, Africa. U.S. Geolgical Survey, Open File Report. 99-50-H

Unukogbon, N.O, Asuen, G.O, and Emofurieta, W.O., 2008. Sequence Stratigraphic Appraisal: Coastal Swamp Depobelt in the Niger Delta Basin Nigeria Global Journal of Geological Sciences Vol. 6 (2), pp. 129-137

Vail, P.R.**,** 1987. Seismic stratigraphy interpretation using sequence stratigraphy, part 1: Seismic stratigraphy interpretarion procedure: in Bally, A.W. (Ed.), American Association of Petroleum Geologists, Atlas of Seismic Stratigraphy.

Van Wagoner, J.C., Posamentier, H.W., Mitchum, R.M., Vail, P.R., Sarg, J.F., Loutit, T.S., and Hardenbol, J., 1988. An overview of sequence stratigraphy and key definitions: in Wilgus, C.K., Hastings, B.S., Kendall, C.G.St.C., Posamentier, H.W., Ross, C.A., Van

Wagoner, J.C. (Eds.), Sea Level Changes—An Integrated Approach, Vol. 42. Society of Economic Paleontologists and Mineralogist, Special Publication, p. 39–45.

Van Wagoner, J.C., Mitchum, R.M., Campion, K.M., and Rahmanian, V.D., 1990. Siliciclastic Sequence Stratigraphy in Well Logs, Cores, and Outcrops. American Association of Petroleum Geologists, Tulsa, p. 55.

Weber, K. J., and Daukoru, E. M., 1975. Petroleum geology of the Niger Delta: Proceedings of the 9th World Petroleum Congress, Vol. 2, Geology: London, Applied Science Publishers, Ltd., p. 210–221.

Weimer, R. J., Rebne, C. A., and Davis, T. L., 1988, Geologic and seismic models, Muddy Sandstone, Lower Cretaceous, Bell Creek--Rocky Point area, Powder River basin, Montana and Wyoming, in Diedrich, R,, Dyka, M., and Miller, W. (Eds.), Eastern Powder River basin--Black Hills: Wyoming Geological Association 39th Field Conference Guidebook, p. 147-160.

Whiteman, A., 1982. Nigeria—its petroleum geology, resources and potential: London, Graham and Trotman, p. 394.

Wiener, Richard W., Michael G. Mann, Michael Terry Angelich, and Joseph B. Molyneux, 2010. Mobile shale in the Niger Delta: Characteristics, structure, and evolution, in L. Wood, ed., Shale tectonics: AAPG Memoir 93, p. 145 – 161.

Winker, C.D., 1982. Cenozoic Shelf Margins, Northwestern Gulf of Mexico," Gulf Coast Association of Geological Societies, Vol. 32, pp. 427-448.

Xiao, H., and Suppe, J., 1992. Origin of rollover: American Association of Petroleum Geologists Bulletin, Vol. 76, p. 509-229.

SEQUENCE STRATIGRAPHIC DATA

WELL NAME: IOTA – 002 STD

Well Name: Iota-2									*Date updated:*	*10.20.2011*	*by :*	*SPDC*
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeo-Environment**	**Chronostrat.**	**Sequence**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0.0	5300.0		Not studied									23.1.2008
0.0	5320.0					No data						9.29.2011
0.0	14495.0			No Data								
5330.0			Indeterminate									
5330.0	5780.0				P820-P830							
5330.0							Indeterminate					
5350.0	8450.0	F9700/F9600										
5350.0							Inner-middle neritic					
5380.0	6427.0						Indeterminate					
5780.0	6344.0				P788	q.b. Multiareolites formosus					4	
6344	13955				P784	top reg. Racemonocolpites hians					3	
6728.0	6814.0						Fluvio-marine					
7093.0	8270.0						Coastal deltaic					
8300	8600						Shallow Inner neritic					
8460.0	14060.0	F9600	Top Cristellaria 16								2	
8630	8660						Coastal deltaic					
8690	8720						Inner - middle neritic					
8750	8840						Shallow Inner neritic					
8870	8990						Inner - middle neritic					
9020	9180						Shallow Inner neritic					
9200	9260						Coastal deltaic					
9315.0	9500						Shallow Inner neritic					
9530	9740						Proximal fluvio-marine					
9796.0	10070						Inner-middle neritic (fluvio-marine)					
10100	10450.0						Shallow Inner neritic					
10480.0	10535.0						Inner-middle neritic (fluvio-marine)					
10570.0			F9620 (*Nonion* 4 = Tortonian 1 / 10.4 Ma. Fs)								1	
10570.0	10618.0						Middle-outer neritic					
10640	10700						Inner - middle neritic					
10730.0	10940						Inner neritic (fluvio-marine)					
10970	11301.0						Shallow Inner neritic					
11317.0							Inner - middle neritic					
11360	11720						Shallow Inner neritic					
11750	11780						Proximal fluvio-marine					
11810	11960						Shallow Inner neritic					
11990	12020						Coastal deltaic					
12050	12170						Inner - middle neritic					
12200	12590						Shallow Inner neritic					
12620	12710						Inner-middle neritic (fluvio-marine)					
12740	12890						Shallow Inner neritic					
12920	12924.0						Inner-middle neritic (fluvio-marine)					
12950	13280						Shallow Inner neritic					
13400	13430						Inner - middle neritic					
13460	13640						Inner neritic					
13670	13700						Shallow Inner neritic					
13730	13819.0						Inner - middle neritic					
13880	14030						Shallow Inner neritic					
14060	14090						Inner - middle neritic					
14090.0	14495.0	F9500	Top Nonion 6								2	
14120	14210						Shallow Inner neritic					
14240	14330						Inner - middle neritic					
14360	14495						Shallow Inner neritic					

Cristelleria 16 = Lenticulina inornata; Nonion 4 = Florilus ex gr. costiferum
Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

WELL NAME: ETA - 001 STD

Well Name:	*Eta-1*							*Date updated:*	*04 May 2009*	*by :*	*SPDC*
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeo-Environment**	**Chronostrat.**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0.0	**150.0**	**Not Studied**									**05/05/2008**
0.0	**2400.0**				**Not Studied**						**24/08/1989**
0.0	**12000**			**Not Studied**							**04/05/2009**
200	**1700**	**Non-diagnostic**	**Practically Barren**							**3**	**05/05/2008**
1800	**9740.0**	**Non-diagnostic**								**3**	**05/05/2008**
2413.0	**4860**				**?P870-P850**	**Insufficient Data**				**2**	**24/08/1989**
4960	**7600**				**?P840-P820**	**No evidence cited**				**2**	**24/08/1989**
7450.0									**9.5 MFS**	**1**	**14/02/2009**
7780	**11300**				**P780**	**No evidence cited**				**1**	**24/08/1989**
9276.0									**10.35 SB**	**1**	**14/02/2009**
9741.0	**12000**	**F9600**	**Top *Nonion* 4**							**1**	**05/05/2008**
9920			***F9620 (*Nonion* 4 fs = 10.4 m.a. fs)**							**1**	**05/05/2008**
9920.0									**10.4 MFS**	**1**	**14/02/2009**
10800.0									**10.6 SB**	**1**	**14/02/2009**
11400	**12000**				**Non-diag.**	**Very poor microflora**				**3**	**24/08/1989**
12843.0									**11.5 MFS**	**1**	**14/02/2009**

Nonion 4 = Florilus ex. gr. Costiferum; *Alabammina 1 = Epistominella virea; *Cristallaria 16 = Lenticulina inornata
Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

	MICROFAUNAL ZONATION OF ETA -002				
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	3400			No Data	8/4/1988
3425	6174			Undiagnostic	
6348	11944	F9600	4		

MICROFLORAL ZONATION ETA-002			**4/20/1988**		
P.ZONE	**TOP DEPTH**	**BOTTOM DEPTH**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
	0	3400		No data	
P800	3425	4776	1		
P820-P840	5212	7734	1	q.t. 399 & q.b. 200 & 292	
P780	7851	11890	1		
P770-P780	11943	11944	1		

WELL NAME: ALPHA - 002 STD

Well Name: Alpha-2								*Date updated: 13 Aug 2009*		*by :*	*SPDC*
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeo-Environment**	**Chronostrat.**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0.0	**9900**	**Not Studied**									**15/06/2009**
0.0	**9900**				**Not Studied**						**12/08/2009**
0.0	**14916**			**Not Studied**							**12/08/2009**
10000	**10750**	**Non-diagnostic**								**3**	**15/06/2009**
10000	**10300**				**P784**	**No event cited**				**1**	**12/08/2009**
10360	**14916**				**P770**	**Top reg. 250**				**1**	**12/08/2009**
10780	**14830**	**F9600**	**Top *Nonion* 4**							**1**	**15/06/2009**
14860	**14916**	**F9500**	**Top *Uvigerina* 5**							**3**	**19/01/2009**
									10.35 SB	**1**	**14/02/2009**
									10.4 MFS	**1**	**14/02/2009**
									10.6 SB	**1**	**14/02/2009**
									11.5 MFS	**1**	**14/02/2009**

Nonion 4 = Florilus ex. gr. Costiferum; Uvigerina 5 = Uvigerina sparsicostata
Palyn Remark: 250 = Racemonocolpites hians. Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

MICROFAUNAL ZONATION OF ALPHA-001					
Top Depth	Bottom Depth	F-Zones	Reliability Gradient	Remarks	Date Revised
0	6400			Not studied	6/18/2009
	6416.0			Non-diagnostic	
6640.0	11320.0	F9600	2	FDO Nonion 4	
MICROFAUNAL MARKER					
11035.0		F9620	2	Non. 4 & Alaba-1	

ALPHA -001 Study Interval: 2040-10150					
Top Depth	**Bottom Depth**	**P-Zones**	**Rel. Grad.**	**Remarks**	**Date Revised**
0	2000		3	Not studied	8/10/2010
2040	2280		3	Indeterminate	8/10/2010
2640	4870	?P830	2	Qb Cyperus type (118)	8/10/2010
4990	6970	?P820	2	Interval below quant. base Echiperiporite estelae (200)	8/10/2010
7090	10150	?P780	2	Absence of Echiperiporite estelae (200)	8/10/2010

WELL NAME: KAPPA – 001 STD

Well Name: Kappa-1								*Date updated:*	*06 Apr 2009*	*by :*	*SPDC*
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeo-Environment**	**Chronostrat.**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0.0	5950.0	Not Studied									19/03/2009
0.0	5800.0				Not Studied						02/04/2009
0.0	13800			Not Studied							19/03/2009
5840	6480				?P850	Negative evidence / Stratigraphic position				2	02/04/2009
5996.0	6504.0	Indet.								3	19/03/2009
6504.0	7190.0				P840-P830	No event cited				1	02/04/2009
6620.0									7.4 MFS	1	05/03/2009
6870	7650	Non-diag.								3	19/03/2009
7260	7930.0				P820	Below quant. base 292				1	02/04/2009
7690.0	7920	?F9700/F9600	No event cited							2	19/03/2009
7740.0									8.5 SB	1	05/03/2009
7930.0			*F9650 (Faunal Association)							1	19/03/2009
7930.0	13800	F9600	Top *Cristallaria* 16							1	19/03/2009
7930.0									9.5 MFS	1	05/03/2009
7960.0	10605				?P780	Stratigraphic position				2	02/04/2009

Cristallaria 16 = Lenticulina inornata; * The Uvigerina 8 MFS initially not delineated as the characteristic foram was not seen in this well but this MFS has been placed at 7930ft based on the associated fossils which usually co-occur with Uvig 8, i.e. Bolivina 34, Angulogerina 2, Sigmoilina 1, Bulimina 17B, etc
292 = Multiareolites formosus
Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

WELL NAME: KAPPA – 002 STD

Well Name: Kappa-2										*Date updated: 06 Apr 2009 by : SPDC*	
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeo-Environment**	**Chronostrat.**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0.0	5700.0	Not Studied									19/03/2009
0.0	5500.0				Not Studied						02/04/2009
0.0	12350			Not Studied							19/03/2009
5600	6311.0				P840	Questionable quant. base 118				2	02/04/2009
5736.0		Indet.								3	19/03/2009
5840	7200.0	?F9700/F9600	No event cited							2	19/03/2009
6405	7605				P830	Quant. base 45				1	02/04/2009
7280.0	12350	F9600	Top *Bolivina* 34							1	19/03/2009
7280.0			*F9650 (Faunal Association)							1	19/03/2009
7725	8974.0				P820	Below quant. base 292				1	02/04/2009
9180.0	12140.0				?P780	Stratigraphic position				2	02/04/2009

Bolivina 34 = Bolivina scalprata retiformis
118 = Cyperus type; 45 = cf. Matonisporites equiexinus; 292 = Multiareolites formosus
Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

MICROFAUNAL ZONATION OF KAPPA -006					
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	6300			No Data	12/21/2006
6350	7380			Barren	
7720	8050			Undiagnostic	
8065	9015	F9700	1	Rich Vern 4/4A	
9040	9768	F9600	3	Rich Bol 29A	
9870	10350			Barren	
MICROFAUNAL MARKER					
	8960	F9760		Haplo 24 mfs	

MICROFLORAL ZONATION KAPPA-006					
P.ZONE	**TOP DEPTH**	**BOTTOM DEPTH**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
	0	7999		No data	
P820	8000	11480	3		
P780	11540	12855	2		

WELL NAME: LAMBDA - 001 STD

									Date updated:	*11/04/2011*	*by :*	*SPDC*
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeoenvironment**	**Chronostrat.**	**Sequence**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0	6690	Not Studied										26/06/2009
0	11095			Not Studied								26/06/2009
0	4000				Not Studied							18/11/1987
4130	5930					Undiag. extre. poor in Microflora					3	18/11/1987
6050	6875				P770	t. 440 on cuttings					2	18/11/1987
6695	6845		Indeterminate								3	26/06/2009
6695	6905						Indeterminate					26/06/2009
6875	8588.0		Non-diagnostic								3	26/06/2009
6924	11095				P740		t. r. 320				3	18/11/1987
6924.0	7225						Inner - Middle Neritic					26/06/2009
7292.0	7420						Shallow Inner Neritic					26/06/2009
7450	7480.0						Inner Neritic					26/06/2009
7510	7810						Shallow Inner Neritic					26/06/2009
7846.0	7960						Inner Neritic					26/06/2009
7990	8134.0						Inner - Middle Neritic					26/06/2009
8155	8185						Inner Neritic					26/06/2009
8215	8335						Inner - Middle Neritic					26/06/2009
8365	8395						Inner Neritic					26/06/2009
8425	8500						Inner - Middle Neritic					26/06/2009
8530	8860						Middle - Outer Neritic					26/06/2009
8620	9040	F9600	Top *Bolivina* 29a								1	26/06/2009
8890	9160						Inner - Middle Neritic					26/06/2009
9060.0	11095	F9500	Top *Nonion* 6								3	26/06/2009
9162.0	9336.0						Shallow Inner Neritic					26/06/2009
9370	9414.0						Inner Neritic					26/06/2009
9445	9488.0						Inner - Middle Neritic					26/06/2009
??9480			??F9580 (*Cassidulina* 7 fs = Ser 2 / 12.8 Ma. fs)							12.8 MFS (Ser 2)	1	26/06/2009
9502.0	9532.0						Indeterminate					26/06/2009
9586.0	9700						Middle Neritic					26/06/2009
9730	9910						Inner - Middle Neritic					26/06/2009
9940	10000						Inner Neritic					26/06/2009
10030							Inner - Middle Neritic					26/06/2009
10060	10188.0						Shallow Inner Neritic					26/06/2009
10192.0	10232.0						Middle Neritic					26/06/2009
10270	10300						Inner Neritic					26/06/2009
10308.0	10402.0						Inner - Middle Neritic					26/06/2009
10412.0	10422.0						Shallow Inner Neritic					26/06/2009
10465	10495						Inner Neritic					26/06/2009
10525	10555						Inner - Middle Neritic					26/06/2009
10585	10690						Shallow Inner Neritic					26/06/2009
10720							Inner - Middle Neritic					26/06/2009
10750	10840						Shallow Inner Neritic					26/06/2009
10870	11023.0						Middle - Outer Neritic					26/06/2009
11050	11095						Middle Neritic					26/06/2009

Bolivina 29a = No scientific name;; Nonion 6 = Florilus ex. gr. Costiferum

Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

WELL NAME: OMICRON – 001 STD

Well Name: Omicron-1									*Date updated:*	*4.5.2011*	*by :*	*SPDC*
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeo-Environment**	**Chronostrat.**	**Sequence**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0	280		Not studied									7.7.2011
0	10480.0			No Data								
300	500		Indeterminate									
300	500						Indeterminate					
600	10000	F9700/F9600										
600							CD					
700	1500						Indeterminate					
1600	2200						SHIN					
2300.0	3500						Indeterminate					
2480	6000.0				P820 - P830							
3520.0							CD					
3600	3900						Indeterminate					
4000	4800						SHIN					
4900	6080						Indeterminate					
6000	6600.0				P788						4	
6100	6240						SHIN					
6260	6300						Indeterminate					
6320	6380						SHIN					
6400	6580						Indeterminate					
6600	9000.0				P784						4	
6600							SHIN					
6620	6800						Indeterminate					
6820							CD					
6840	7140						Indeterminate					
7160							SHIN					
7180	7260						Indeterminate					
7280							CD					
7300	7520						Indeterminate					
7540	7700						CD					
7710	7860						Indeterminate					
7880							SHIN					
7900	7940						Indeterminate					
7960							CD					
7980	8260						Indeterminate					
8280	8380						PFM					
8400	8560						Indeterminate					
8580							CD					
8600	8980						Indeterminate					
9000	9020						PFM					
9022	9140						Indeterminate					
9160	9220						PFM					
9240	9280						Indeterminate					
9300	9420						CD					
9440	9540						Indeterminate					
9555	9600						SHIN					
9620	9780						Indeterminate					
9800	9820						SHIN					
9840	9960						Indeterminate					
9974.0	10020						PFM					
10001	10300	F9600	Top Cristelleria 16								2	
10030.0		F9620	F9620 (*Nonion* 4 = Tor 1 / 10.4Ma fs)								2	
10030.0	10040						IN-MN					
10060.0							Indeterminate					
10061	10080						SHIN					
10100	10140						IN-MN					
10160	10300						SHIN					
10320	10480.0		Indeterminate									
10320	10440						Indeterminate					
10460							CD					
10480							Indeterminate					

Nonion 6 = Florilus ex gr. Costiferum; Bolivina 25 = Brizalina interjuncta; Chiloguembelina 3 = Chiloguembelina Victoriana; Bolivina 25a = Brizalina mandoroveensis
320 = Belskipollis elegans; 17 = Crassoretitriletes vanraadshooveni

WELL NAME: OMICRON - 015 STD

Well Name: Omicron-15								*Date updated:*	*11 Mar 2009*	*by :*	*SPDC*
Depth top	**Depth base**	**For. Zone**	**Foram Remarks**	**Nannpl.**	**Palyn Zones**	**Palyn Remarks**	**Palaeo-Environment**	**Chronostrat.**	**Seq. Elem.**	**Reliab.**	**Bio Reviewed**
0.0	**4100.0**	**Not Studied**									**29/01/2008**
0.0	**4100.0**				**Not Studied**						**15/12/1987**
0.0	**13694.0**			**Not Studied**							**11/03/2009**
4120.0	**6356.0**				**P800**	**No event cited**				**1**	**15/12/1987**
4120.0		**Indet.**								**3**	**29/01/2008**
5228.0	**8498.0**	**?F9700/F9600**								**2**	**29/01/2008**
6967.0	**8458.0**				**?P788**	**Negative evidence**				**2**	**15/12/1987**
7333.0									**9.5 MFS**	**1**	**14/02/2009**
8498.0	**12018.0**				**F784**	**Top regular 250**				**1**	**15/12/1987**
8525.0	**12814.0**	**F9600**	**Reg occ. *Nonion* 4**							**1**	**29/01/2008**
8525.0			**F9620 (*Nonion* 4 fs = 10.4 Ma. fs)**							**1**	**29/01/2008**
9268.0									**10.35 SB**	**1**	**14/02/2009**
9784.0									**10.4 MFS**	**1**	**14/02/2009**
10941.0									**10.6 SB**	**1**	**14/02/2009**
12051.0	**13694.0**				**P770**	**Top consistent 440**				**1**	**15/12/1987**
13340.0	**13694.0**	**Non-diag.**	**Practically Barren**							**3**	**29/01/2008**

Nonion 4 = Florilus ex. gr. Costiferum; *Alabammina 1 = Epistominella virea; *Cristallaria 16 = Lenticulina inornata
Palyn Remark: 250 = Racemonocolpites hians; 440 = Verrutricolporites rotundiporis
Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

	MICROFAUNAL ZONATION OF OMICRON -033				
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	9900			Not studied	9/3/2010
10000	10420			Non-diagnostic	9/3/2010
10450	13270	F9600		Top Nonion 4	9/3/2010

MICROFLORAL ZONATION OMICROM-O33					
P.ZONE	**TOP DEPTH**	**BOTTOM DEPTH**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
	0	9999		No data	
P700	5228	6390	4		

WELL NAME: ZETA CREEK - 001 STD

Depth top	Depth base	For. Zone	Foram Remarks	Nannpl.	Palyn Zones	Palyn Remarks	Palaeo-Environment	Chronostrat.	Seq. Elem.	Reliab.	Bio Reviewed
Well Name: Zeta Creek-1								*Date updated: 06 Apr 2009*		*by :*	*SPDC*
0.0	4600.0	Not Studied									06/03/2009
0.0	4600.0				Not Studied						02/04/2009
0.0	13425			Not Studied							06/03/2009
4626.0	5592.0				P840	Questionable base 118				1	02/04/2009
4626.0	5910	Indeterminate								3	06/03/2009
5823.0	6898.0				P830	Quant. base 45; quant. base 200				1	02/04/2009
5940.0	6898.0	?F9700/F9600	No event cited							2	06/03/2009
6393.0									7.4 MFS	1	05/03/2009
7035	13425	F9600	Top *Bolivina* 29A							1	06/03/2009
7130.0	8806.0				P820	Quant. base 292				1	02/04/2009
8353.0									8.5 SB	1	05/03/2009
8679.0									9.5 MFS	1	05/03/2009
8766.0			F9650 (*Uvigerina* 8 fs = 9.5 ma. fs)							1	06/03/2009
8826.0	13280.0				?P780	Presence 250				2	02/04/2009

Bolivina 29A = Not Named, Uvigerina 8 = Uvigerina subperegrina

118 = Cyperus type; 45 = cf. Matonisporites equiexinus; 200 = Echiperiporites estalae; 292 = Multiareolites formosus; 250 = Racemonocolpites hians

Reliability Indicator: 1 = Zone top is well defined; 2 = Zone is questionable defined; 3 = Non-diagnostic or Indeterminate; 3 = Flooding surface poorly constrained.

WELL NAME: ZETA CREEK-002

Depth top	Depth base	For. Zone	Foram Remarks	Nannpl.	Palyn Zones	Palyn Remarks	Palaeo-Environment	Chronostrat.	Seq. Elem.	Reliab.	Bio Reviewed
Well Name: Zeta Creek-2								*Date updated:*	*06 Apr 2009*	*by :*	*SPDC*
0.0	7150.0	Not Studied									19/03/2009
0.0	7000.0				Not Studied						02/04/2009
0.0	12930.0			Not Studied							19/03/2009
7200.0	7960.0				P830	Quant. base 45				1	02/04/2009
7200.0		Indet.								3	19/03/2009
7258.0	12000.0	F9600	Top *Bolivina* 29*							1	19/03/2009
8038.0	9504.0				P820	Quant. base 292				1	02/04/2009
8160.0									9.5 MFS	1	05/03/2009
9520.0	10213.0				P788	No event cited				1	02/04/2009
10322.0	12210.0				P784	Top regular 250				1	02/04/2009
12210.0	12930.0	Indeterminate								1	19/03/2009
12240.0	12930.0				P770	Top 440				1	02/04/2009

Bolivina 29 = Bolivina scalprata miocenica; *Single occurrence at 7258.0ft (SWC)

45 = cf. Matonisporites equiexinus; 292 = Multiareolites formosus; 250 = Racemonocolpites hians; 440 = Verrutricolporites rotundiporis

MICROFAUNAL ZONATION OF ZETA CREEK_006					
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	8090			Not Studied	3/7/2011
8100	8195			Indeterminate	3/7/2011
8220	8245			Non-diagnostic	3/7/2011
8280	14022	F9600	2	Top Bolivina 34	3/7/2011
MICROFAUNAL MARKER					
	8280	F9650	4	Uvig. 8 & Asso.Fauna	3/7/2011

MICROFLORAL ZONATION ZETA CREEK - 006					
P.ZONE	**TOP DEPTH**	**BOTTOM DEPTH**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
	0	12740		No data	
	12745			Poor in microflora	
P780	13068	13216			
	13220	13770		No data	
	13772	14022		Undiag, poor in microflora	

MICROFAUNAL ZONATION OF SIGMA -048					
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	7030'			No Data	11/20/2000
7050	8400'			Barren	
8430	9700			Undiagnostic(Pract. Barren)	
9730	10420'			Barren	
10450	10710			Undiagnostic	
10740	11450	F9601	3	Top Nonion 4	

MICROFAUNAL ZONATION OF SIGMA -013					
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	10600			Not studied	10/12/2011
10670	10980			Indeterminate	10/12/2011
11010	11070	F9600	1	Top Nonion 4	10/12/2011
11100	11220	F9605	1	Nonion 4 & (Influx of calcareous forms)	10/12/2011
11250	12893			Non-diagnostic	10/12/2011
12908	13073			Indedterminate	10/12/2011
13088	13313			Non-diagnostic	10/12/2011
13328	13553			Indedterminate	10/12/2011
MICROFAUNAL MARKER					
	11100	F9620	1	Nonion 4	10/12/2011

MICROFAUNAL ZONATION OF SIGMA -004					
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	4300			No Data	4/7/2011
4308	5520			Non-diagnostic	4/7/2011
10241	12185	F9600	2	Top Nonion 4	4/7/2011

MICROFLORAL ZONATION SIGMA - 004					
P.ZONE	**TOP DEPTH**	**BOTTOM DEPTH**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
	0	5080		No data	
P820	5083	5083		Probably P820	
	5090	8500		No data	
P770	8510	11325	1	T. 440	
	11330	12185		No data	

MICROFAUNAL ZONATION OF SIGMA -002					
TOP DEPTH	**BOTTOM DEPTH**	**F.ZONE**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
0	1400			Not Studied	4/7/2011
1500	6600			Non-diagnostic	4/7/2011
6720	7300			Indeterminate	4/7/2011
7355	7860			Non-diagnostic	4/7/2011
7900	8200	F9600		Top Nonion 4	4/7/2011
8240	11103	F9605/F9603			4/7/2011
11140	12000	F9601		Top quant. / reg occ. Of Non. 4	4/7/2011
MICROFAUNAL MARKER					
	8090	F9620	1	Nonion 4, Alab1, Bol 29	4/7/2011

MICROFLORAL ZONATION OF SIGMA - 002					
P.ZONE	**TOP DEPTH**	**BOTTOM DEPTH**	**RELIABILITY GRADIENT**	**REMARKS**	**DATE REVISED**
	0	3860		No data	
P820	3870	3900	2	q. b. 292	
P788	4000	4898		Negative	
P784	5000	7300	2	t. reg. 250	
P770	7400	8300	3	t. reg. 440	
	8660	12002		Not analysed	

Palynological Zones (F-Zones) Colour Codes

Code	Name	Parent	Color
0	P830		
1	P820		
2	P780		
3	P784		
4	P770		
5	P820-P830		
6	P740		
7	P850-P870		
8	P820-P840		
9	Non-Diagnostic		
10	No Data		
11	P700		
12	P800		
13	P770-P780		
14	P780/P820		
15	P840		
16	P830/P840		
17	P750		
18	P788		
19	P200		
20	P100		
21	P190		
22	P170		
23	P150		
24	P130		
25	P560		
26	P110		
27	P540		
28	P520		
29	P480		
30	P470		
31	P400		
32	P370		
33	P630/680		
34	P580		
35	P720/P740		
36	P680		
37	P670		
38	P650		
39	P630		
40	P620		
41	P540/P580		
42	P450		
43	P330		
44	P170-P190		
45	P720		

Foramineferal Zones (F-Zones) Colour Codes

Code	Name	Parent	Color
0	F9700/F9600		
1	F9600		
2	F9500		
3	Non-Diagnostic		
4	No Data		
5	F9500/F9600		
6	F9605		
7	F9700		
8	Barren		
9	F9601		
10	F9605/F9603		
11	F3500		
12	F1700		
13	F1000		
14	F3500/F3300		
15	F3100		
16	F1300		
17	F7800		
18	F7600		
19	F3700		
20	F5300		
21	F5500		
22	F5750		
23	F5700		
24	F7400		
25	F7200		
26	F9600/F9700		
27	F9300/F9500		
28	F9300		
29	F7800/F9300		
30	F7800		
31	F3100/F1700		
32	F9300/F7800		

Paleobathymetric Data Colour Code EOD

Code	Name	Parent	Color
0	INDET		
1	IN-MN		
2	SHIN		
3	IN		
4	MN-ON		
5	MN		
6	CD		
7	PFM		
8	ON-BA		
9	B		
10	PF		

System Tract Colour Codes

Code	Name	Parent	Color
0	HST		
1	TST		
2	LST		
3	LST/TST		
4			
5			

Hydrocarbon Types Colour Codes

Code	Name	Parent	Color
0	Gas zone		
1	Oil zone		
2	Water zone		
3	Undifferentiated		