Reconstruction of the Subsurface Depositional History of Onshore Niger Delta Basin*

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Search and Discovery Article #30497 (2017)**
Posted April 3, 2017

*Adapted from oral presentation given at AAPG International Conference & Exhibition, Barcelona Spain, April 3-6, 2016

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Abstract

Improvement in seismic data acquisition, processing and interpretation, as well as improved borehole-geophysical techniques, has made the geophysical approach highly effective in Basin Analysis in the absence of geological data. This work concentrated on the geological framework of sediment accumulation and facies distribution in the context of time and space through electro-sequence and seismo-sequence analysis. The study aimed at establishing the sedimentary facies, their succession and environments of deposition with a view to reconstruct the subsurface depositional history of the onshore Niger Delta Basin.

The study concluded that the Onshore Niger Delta is characterized by a typical prograding delta architecture with a shallowing-up pattern in which a series of strata consistently showed evidence of the younger beds being deposited in shallower water than the older beds they overlay. The younger beds tend to be of finer sediments (of delta slope region) than the older beds (of river mouth bars). The depositional systems revealed information, which was simulated from the start of deposition to the present day, and was used to carefully reconstruct the paleo-depositional history of the study area.

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INTRODUCTION

- Siliciclastic Depositional Systems owe most of their diversity and heterogeneity to the many different geologic processes that control their formation and give rise to the characteristics of the resultant sedimentary environments.

- Niger Delta is a regressive sequence of clastic sediments developed in a series of off-lap cycles. The base of the sequence consists of massive and monotonous marine shale. This grade upward into inter-bedded shallow-marine and fluvial sands, silts, and clays, and capped by a massive non-marine sand (Figure 1.0).

- The basin architecture of the Niger Delta can be divided into a series of depobelts, separated by major syn-sedimentary fault zones. These depobelts can be thought of as transient basinal areas succeeding one another in space and time as the delta prograded southward (Doust and Omatsola, 1990). This study covers the Northern Depobelt only.

-INTRODUCTION-

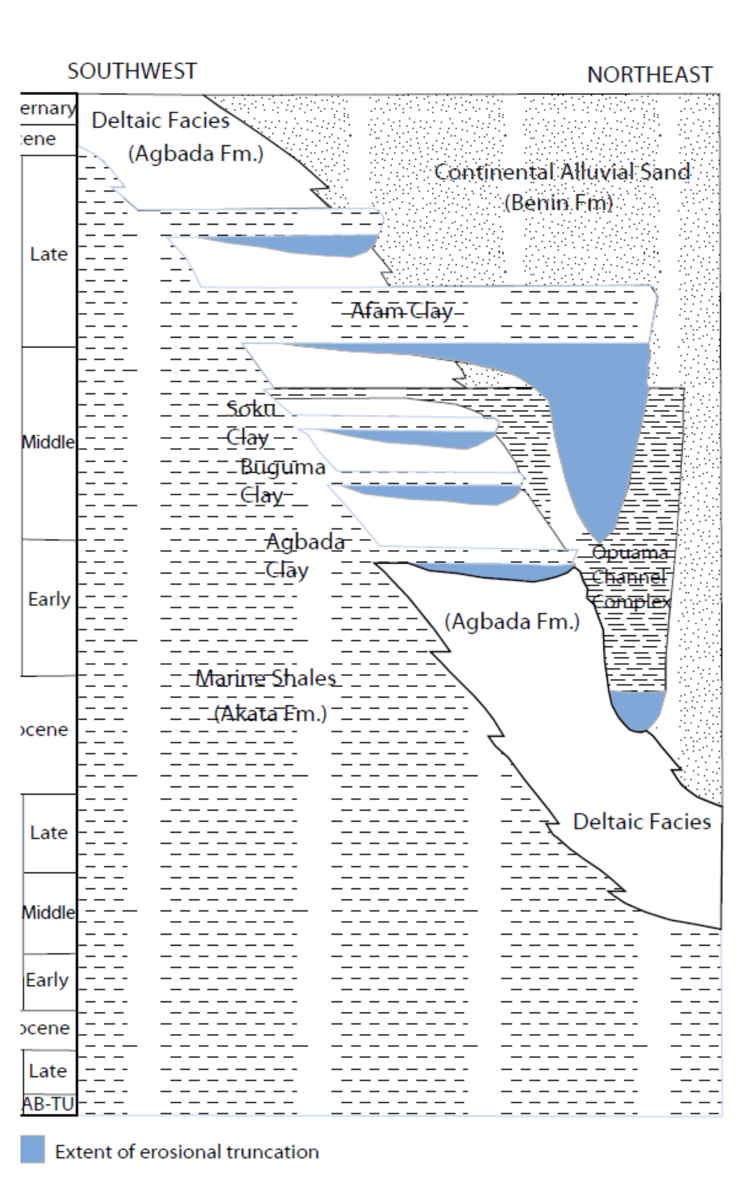


Figure 1.0: Stratigraphic column of the Niger Delta Basin (Doust and Omatsola 1990)

The figure shows three major stratigraphy of the Niger Delta Basin. The marine shale which is believed to be the oldest (Late Eocene to Early Oligocene) makes up the Akata Formation. The Akata shale is succeeded by Agbada Formation which forms the parallic sequence of sand-shale-silt inter-beds. The youngest bed (Late Miocene) is called Benin Formation. It is made up of purely continental sand.

-INTRODUCTION-

- The geology, stratigraphy and structure of the Niger Delta Basin have been extensively discussed in several publications, including Short and Stauble, 1967; Merki, 1971; Weber and Daukoru, 1975; Whiteman, 1976; Avbovbo, 1978; Evamy et al., 1978; Doust and Omatsola, 1990, among several others.

- Onshore Niger Delta is highly prolific with simple structural architecture, and formed the first focus of hydrocarbon exploration and production in the basin. However, large portion of the onshore delta has not been fully explored, while some fields have been abandoned, chiefly due to lack of adequate understanding of the subsurface depositional environment of facies in the onshore delta.

- This work is focused on reviewing the ‘RAY’ field located in the northeastern portion of the onshore Niger Delta Basin, as a case study, with the aim of reconstructing the subsurface geological processes as preserved in geological records, using the integrated electro-sequence and seismo-sequence approach.

MATERIALS AND METHODOLOGY

- ‘RAY’ field is located in the distal part of the Northern Depobelt, onshore Niger Delta. The field covers an area of 74, 100 acres (300Km^2) on the northeastern edge of the Depobelt.

- The dataset available for the study comprise of wireline log data from six vertical wells within the field and 3D seismic data. The wells include: RAY-1, RAY-2, RAY-3, RAY-4, RAY-5, and RAY-6 as shown in Figure 2.1. The principal well logs used included; Gamma Ray log, Resistivity log, sonic log, Neutron log and Density log.

- The seismic survey covered a wide area along OML-124 with 1400 seismic lines: 545 in-lines and 864 cross-lines (Figure 2.0).

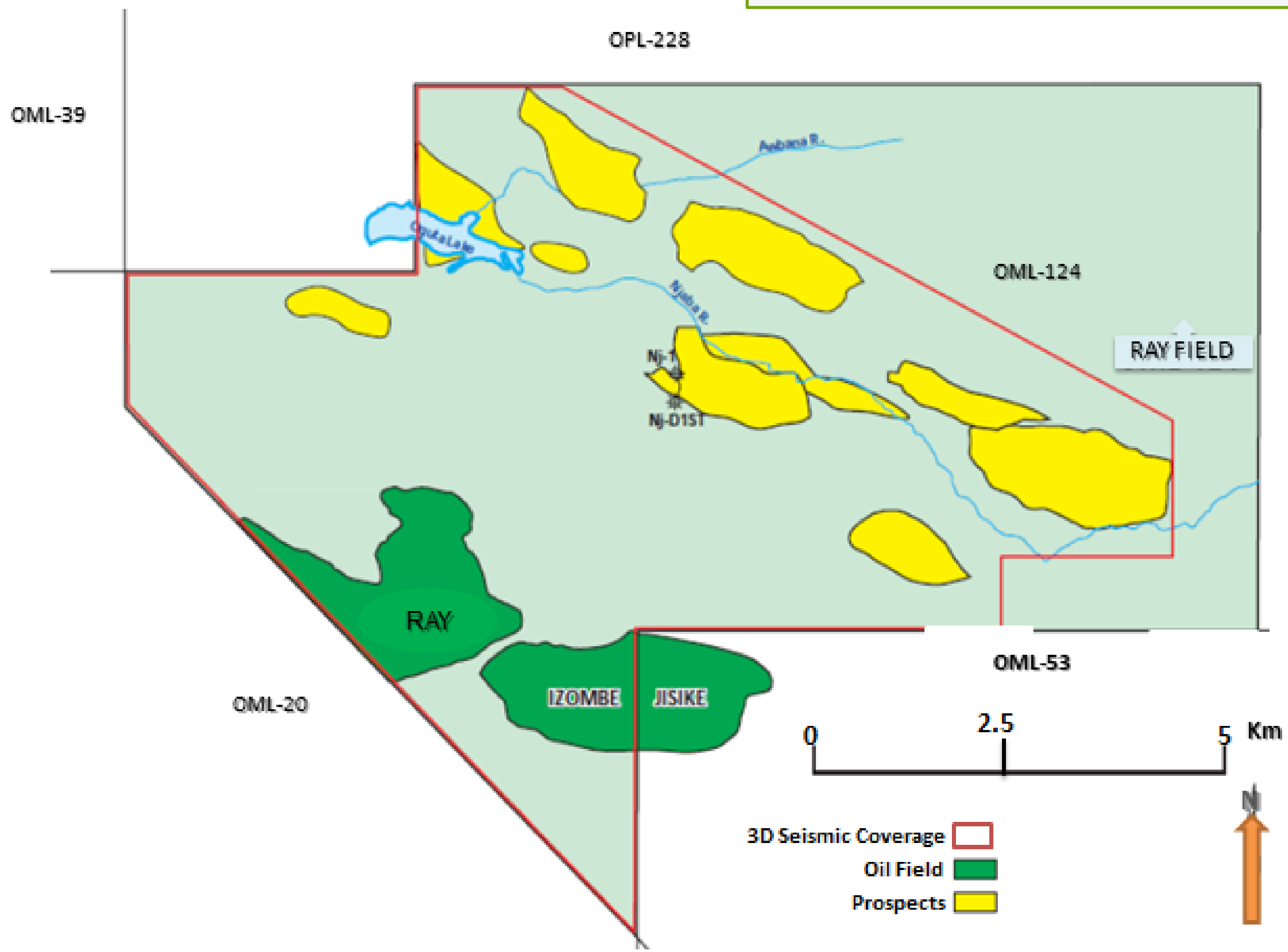


Figure 2.0: Map of RAY Field showing the 3-D Seismic Survey Coverage.

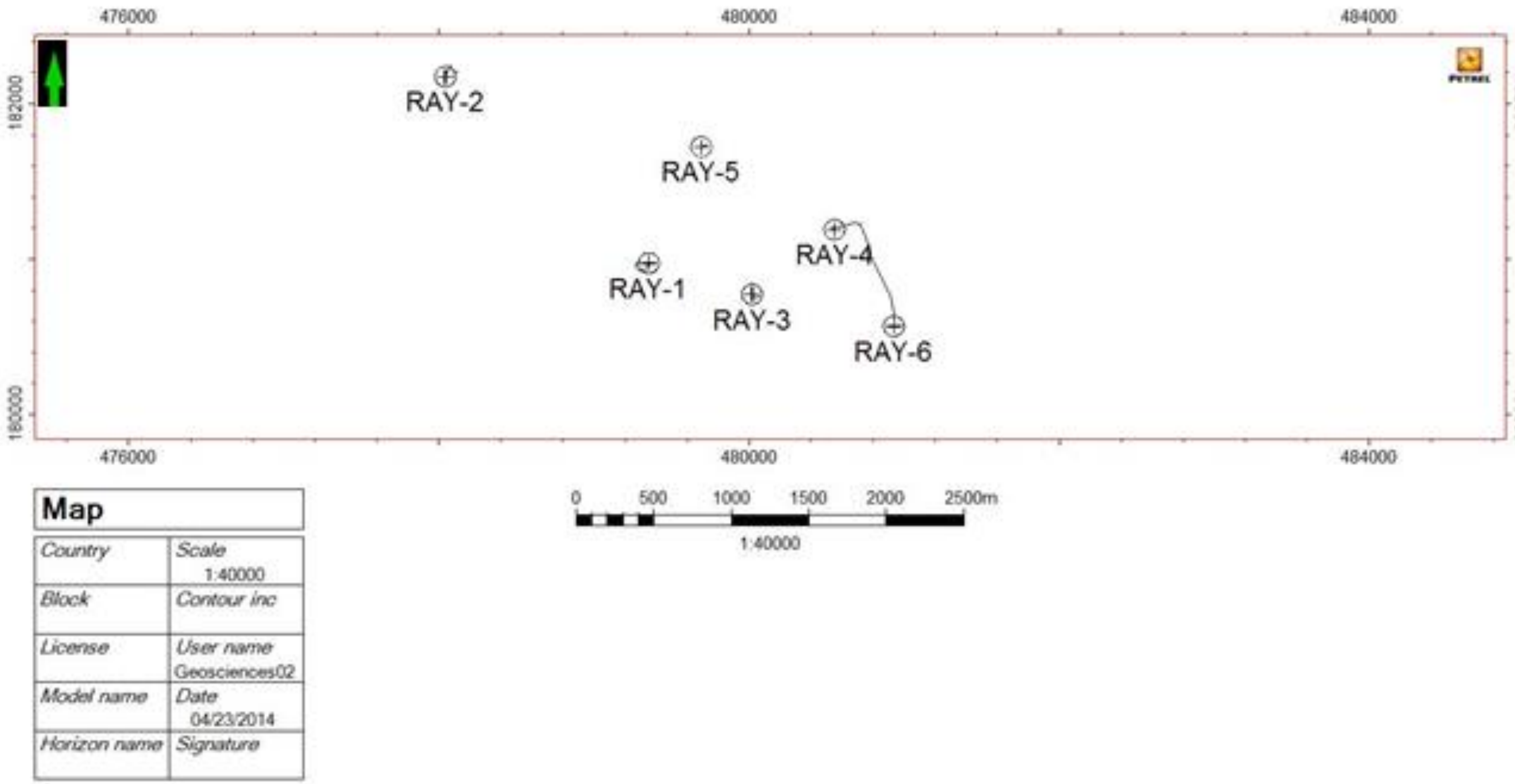


Figure 2.1: Base map of “RAY” field showing spatial distribution of studied wells

- The methodology adopted in this works consists of the interpretation of the set of available well logs and 3-D seismic lines using Schlumberger's PETREL 2012 version software.

- Prior to the interpretation, the data were subjected to series of quality check to reduce uncertainties. Surface seismic data was compared to synthetic seismic traces generated from wells to check for unwanted abnormalities.

- Once the data was properly checked to achieve sufficient resolution, a systematic workflow was constructed to interpret the dataset for optimum subsurface characterization (Figure 2.2).

-MATERIALS AND METHODOLOGY-

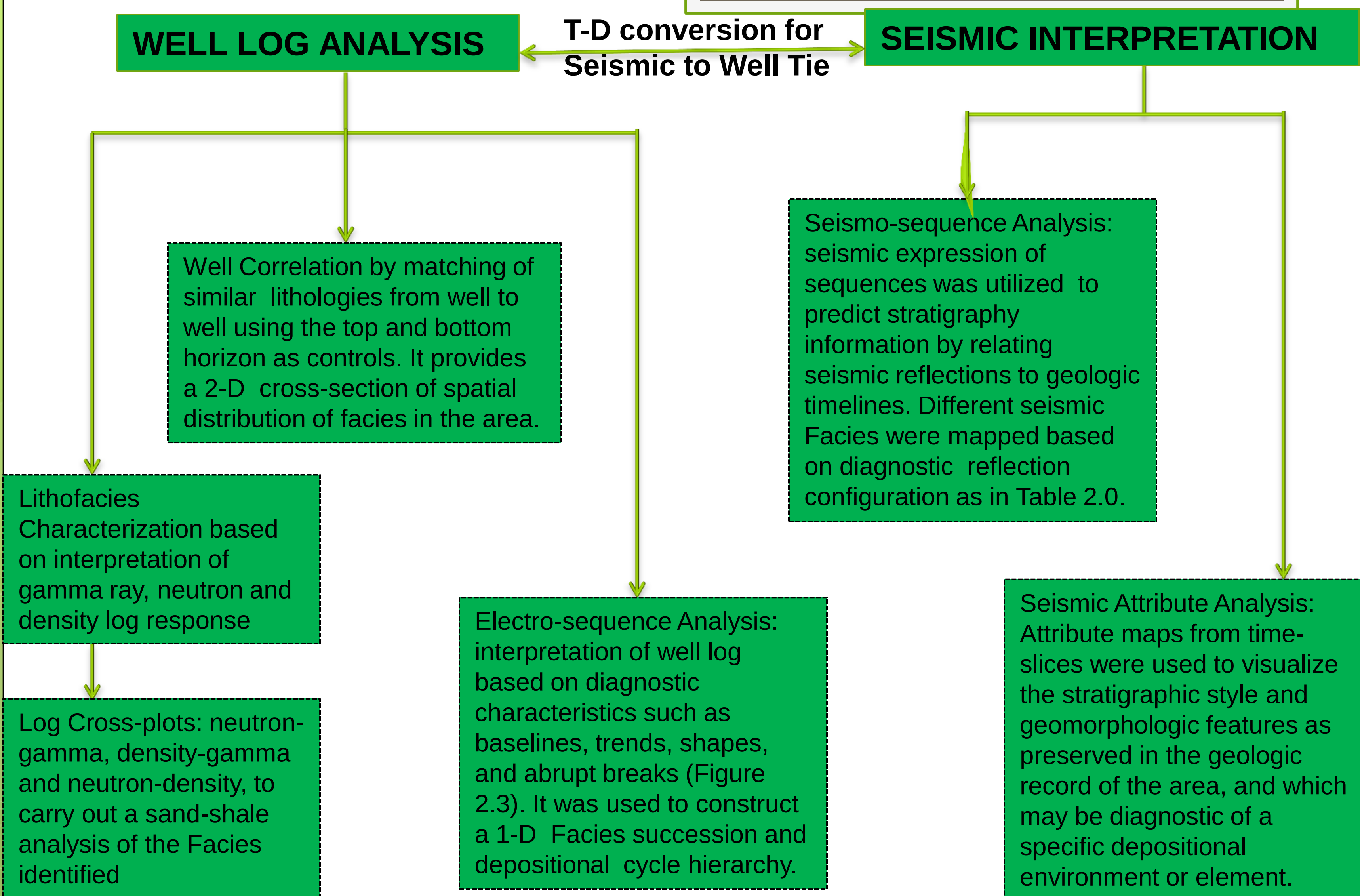


Figure 2.2: Framework of the methodology adopted for data interpretation

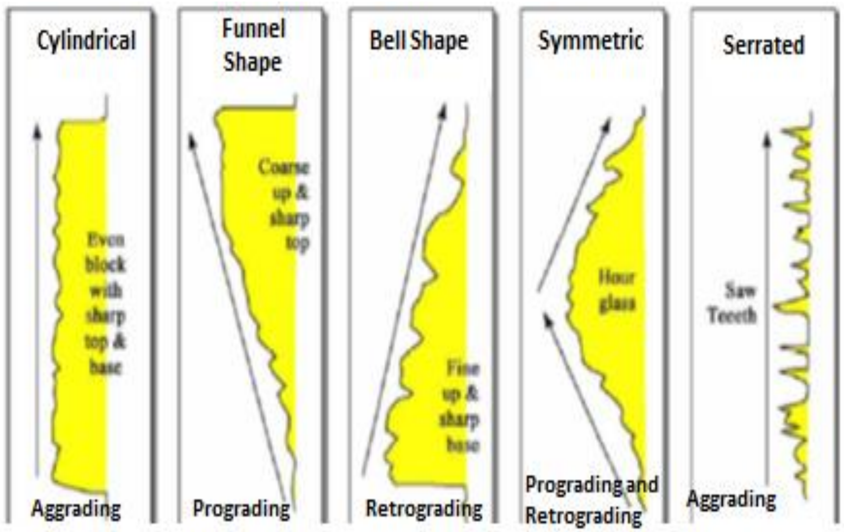


Figure 2.3: Log response character for different environments

Log signature with a blocky shape (cylindrical or serrated) shows evidence of aggradation ; accumulation of sand or inter-bedded Facies. This is a typical example of depositional features common in fluvial or river channel environment. Serration is an evidence of energy fluctuation during build up of sediment. A funnel shaped signature reflect a coarsening up sequence developed during progradation where continental sand facies are placed above marine shale. A bell shaped signature reflects progradation during landward shift of facies. Symmetric log signature reflect progradation and retrogradation occurring simultaneously.

Reflection Configuration	Interpretation
Parallel/subparallel	Uniformly deposited strata on a uniformly subsiding or stable setting
Chaotic	Disordered arrangement of reflection surfaces due to soft sediment deformation or deposition of strata in variable high-energy environment
Divergent	Wedge-shaped unit caused by thickening of individual reflection subunit within the main unit. Signifies lateral variations in rates of deposition or progressive tilting of the sedimentary surface during deposition.

Table 2.0: Summary of seismic reflection configuration and the geological interpretation

PRESENTATION OF RESULTS

- The stratigraphic column in the study area was divided into four lithofacies based on sand-shale ratio and gamma ray log signatures from the base of the wells to the top (Figures 3.0a, 3.0b, 3.0c and 3.0d). The gamma ray log interpretation was justified through the response from Neutron-Density combination log and SP log.

- The Gamma ray log cut-off fell on 75API, the value which formed the basis of the log facies interpretation (Sand: < 75API and Shale: > 75API). The lithofacies are: 1) Shale Facies; 2) Heterolithic Facies; 3) Shaly-Sandstone Facies; and 4) Sandstone Facies represented in Figure 3.0 as a, b, c and d respectively. This facies are diagnostics for the four super-environments in the Niger Delta Basin.

- Results of the lithofacies interpretation was further verified by and buttressed through log cross-plot (Figure 3.1), seismic attribute analysis (Figure 3.2), well-correlation (3.3b) and seismic facies analysis (3.4).

-PRESENTATION OF RESULTS-

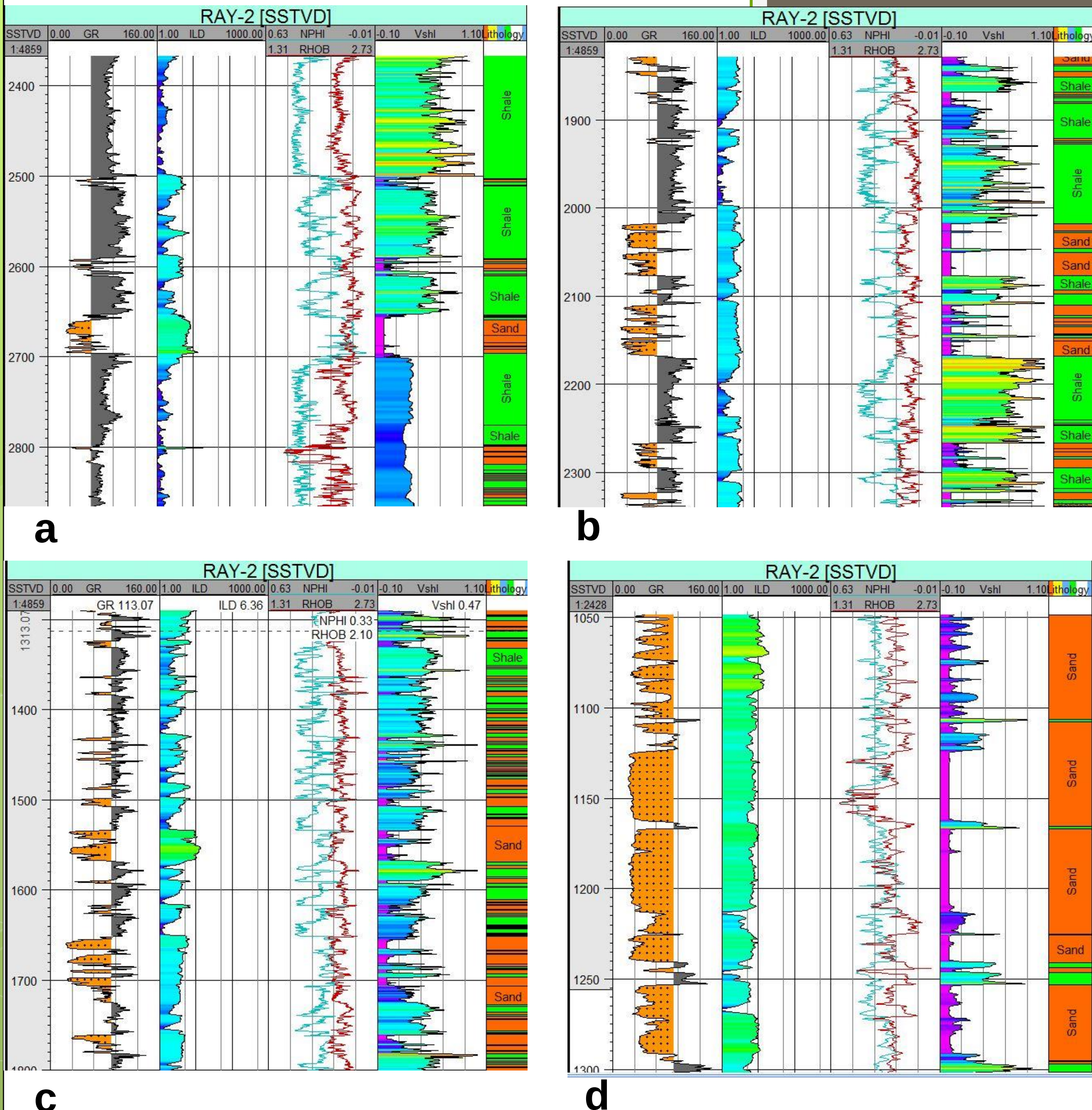


Figure 3.0: Four lithofacies mapped from the base of the well to the top

*The Shale Facies, **a**, is composed of predominantly shale lithology with few streaks of sand. This section on the gamma ray log shows high gamma ray signature above the cut-off. Heterolithic and Shaly-sandstone Facies sections of the gamma ray log; **b** and **c** respectively show highly serrated signature. This is a reflection of intercalation of materials (I.e. sand and shale) with varying radioactive content. **b** shows nearly equal distribution of sand and shale, while **c** shows predominance of sandstone over shale. The Sandstone Facies section of the log, **d**, reflect a block-shape signature with low gamma ray response. This indicates aggradation of continental sand with minimal marine influence.*

- Shale Facies; F1
- Heterolithic Facies; F2
- Shaly-sandstone Facies; F3
- Sandstone Facies; F4

N

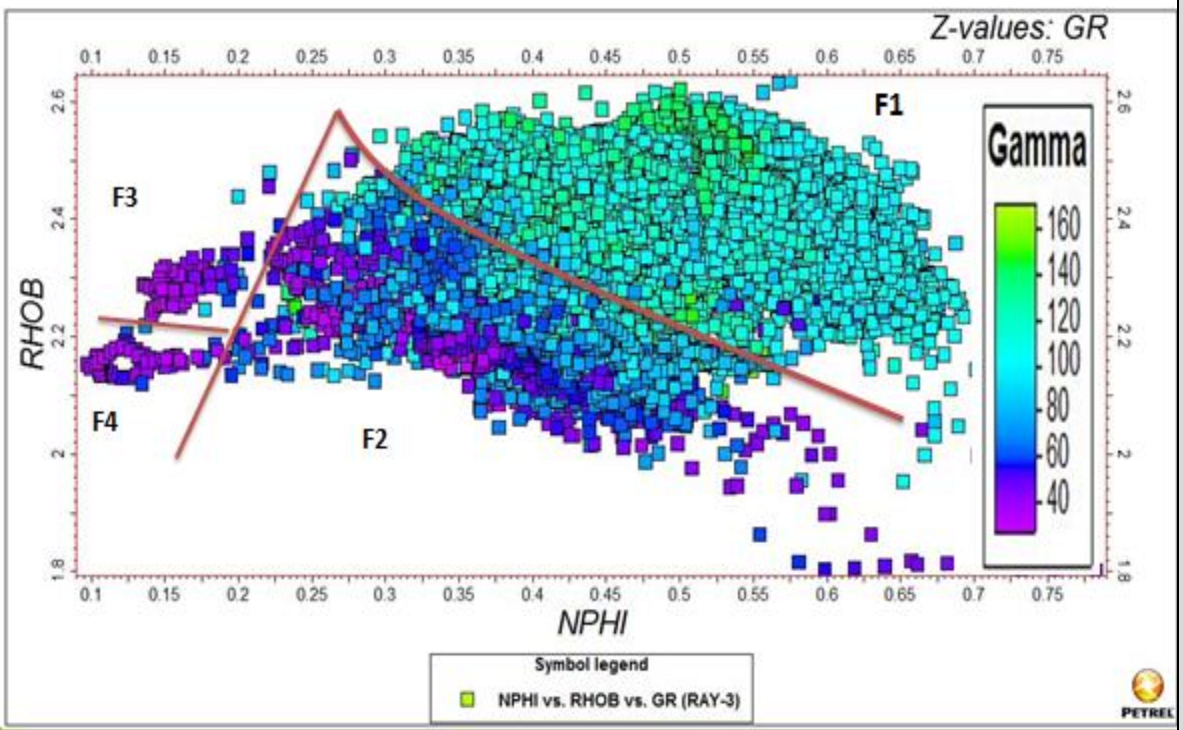


Figure 3.1: Cross-Plot of combination of gamma ray, neutron and density logs

Figure 3.1 shows an interesting result obtained by cross-plotting a combination of neutron and density log against gamma ray log, to buttress the lithofacies interpretation in Figure 3.0. By following the neutron-density data trend with a gamma ray cut-off of 75 API, it can be observed that the plots separate into two general trends; high and low gamma ray. The North-eastern portion of the plot shows high gamma, density and neutron values, which decrease progressively across the major boundary (MB) towards the South-west. The lithofacies can be identified across the boundaries based on sand-shale ratio. The shale facies, F1 follows a trend of data to the N-E of the major boundary with high gamma, density and neutron. Heterolithic facies, F2, is found just below the major boundary. F3 and F4 are found towards the west with relatively low gamma, neutron and density. F4 has the lowest gamma ray count; a typical property of sandstone facies.

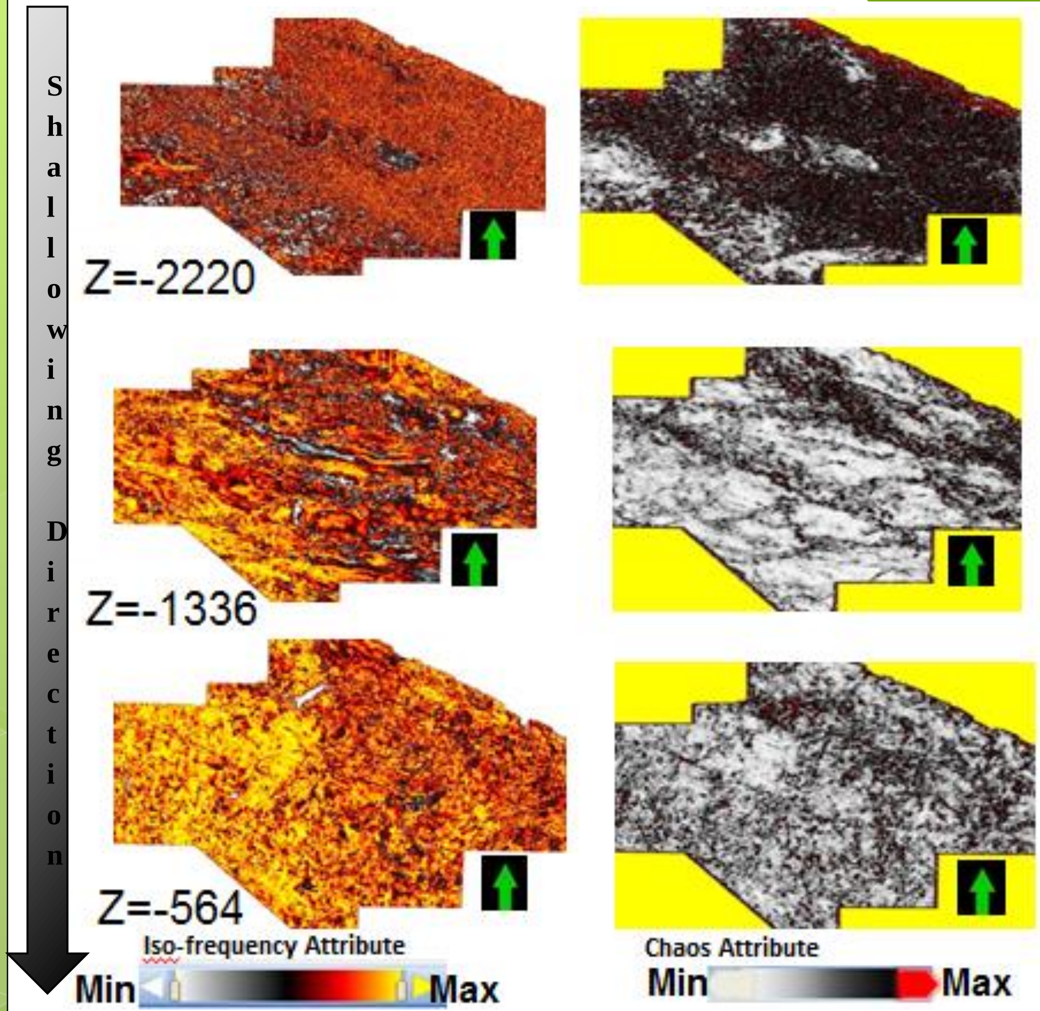


Figure 3.2: Attribute maps showing vertical and lateral variation of facies based on sand-shale distribution across the field

The stratigraphy attribute maps in Figure 3.2 reveal vertical and lateral changes in lithology and facies distribution within the seismic coverage. The variation is a reflection of spatial distribution of sand, silt and shale lithologies and change in deposition environment (i.e. Chaos attribute maps). The iso-frequency attribute maps (left) show vertical and lateral variation in frequency component as the lithology changes in composition (i.e. from sand to shale). Frequency increases laterally from northeast to south west, and vertically from the base of the sequence (at -2200mS) to the top (at -564). This response is typical of Onshore Niger Delta where the sequence is based by fine particles of low frequency (shale) and capped by high frequency lithology (sand). Lateral variation also reflect retrogradational and progradation activities during base level changes. Chaos attribute maps (right), which explain lack or organization within seismic volume, typically reflect a gradual shift from marine (highly chaotic site due to tide and wave influence) to continental environment with minimal tidal influence.

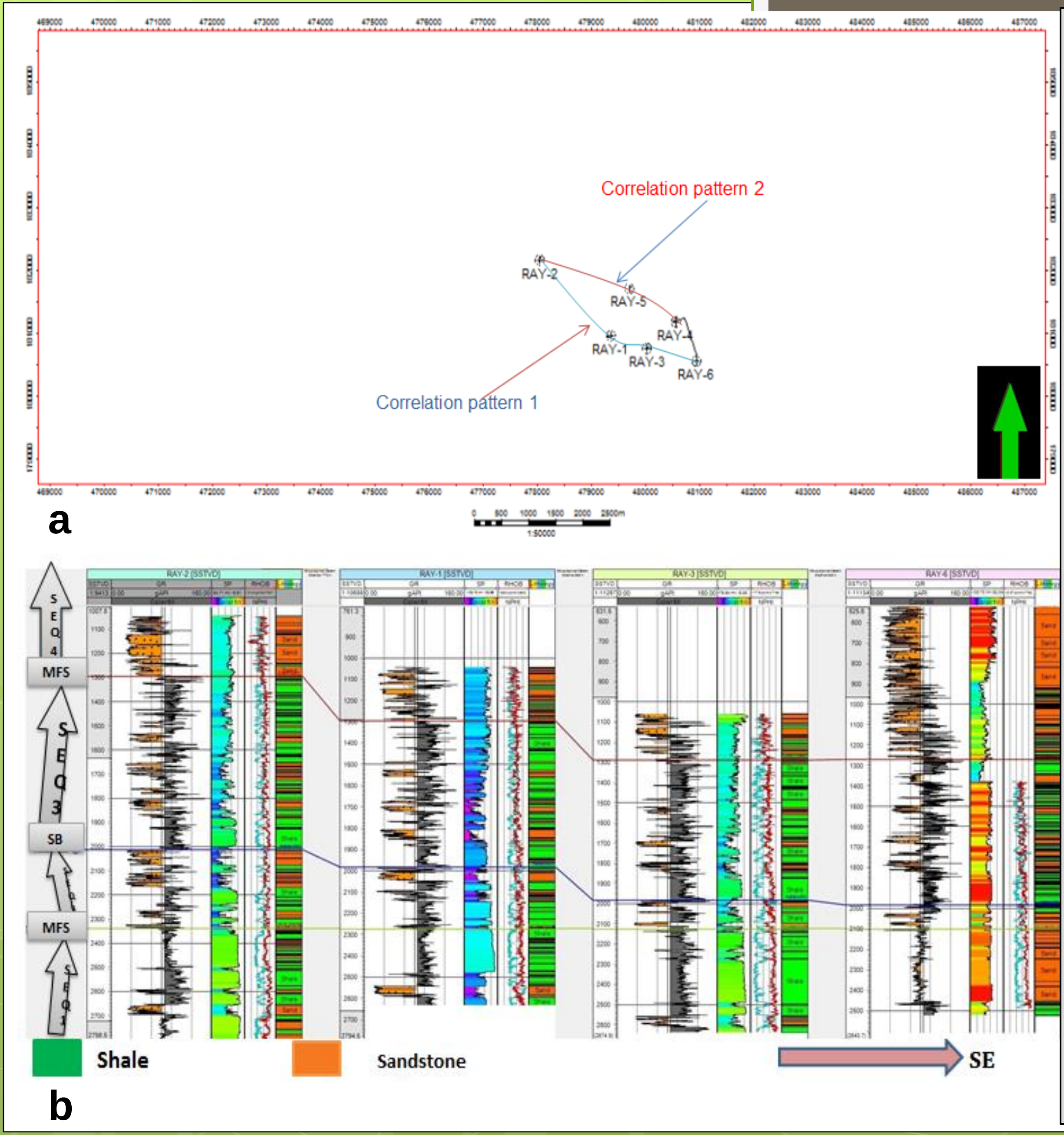


Figure 3.3: Depositional Sequence Hierarchy

Figure 3.3a shows correlation patterns achieved for two dimensional analysis of depositional facies mapped across the wells. Figure 3.3b is the Cross-section of the studied wells, RAY-2, RAY-1, RAY3 and RAY-6. It reveals vertical shifts in depositional environment and lateral facies distribution, giving rise to different and distinctive depositional sequences bounded by stratigraphic surfaces. The marked tops of the depositional environments led to the candidate for potential sequence boundary, SB and maximum flooding surfaces, MFS. The facies are observed to be dipping towards the southeast; an evidence of southeast progradation. This interpretation is further verified by the seismic facies analysis in Figure 3.4

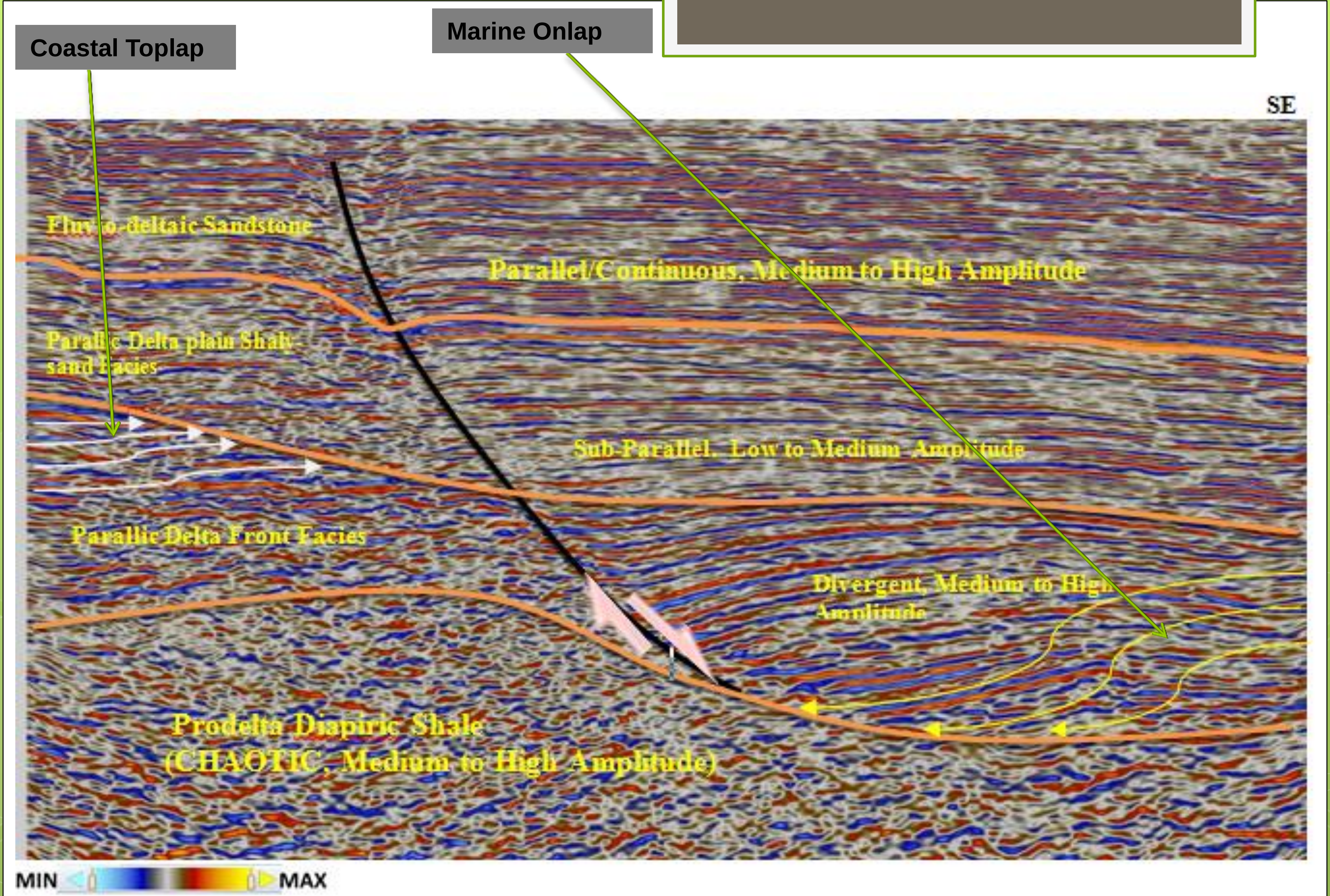
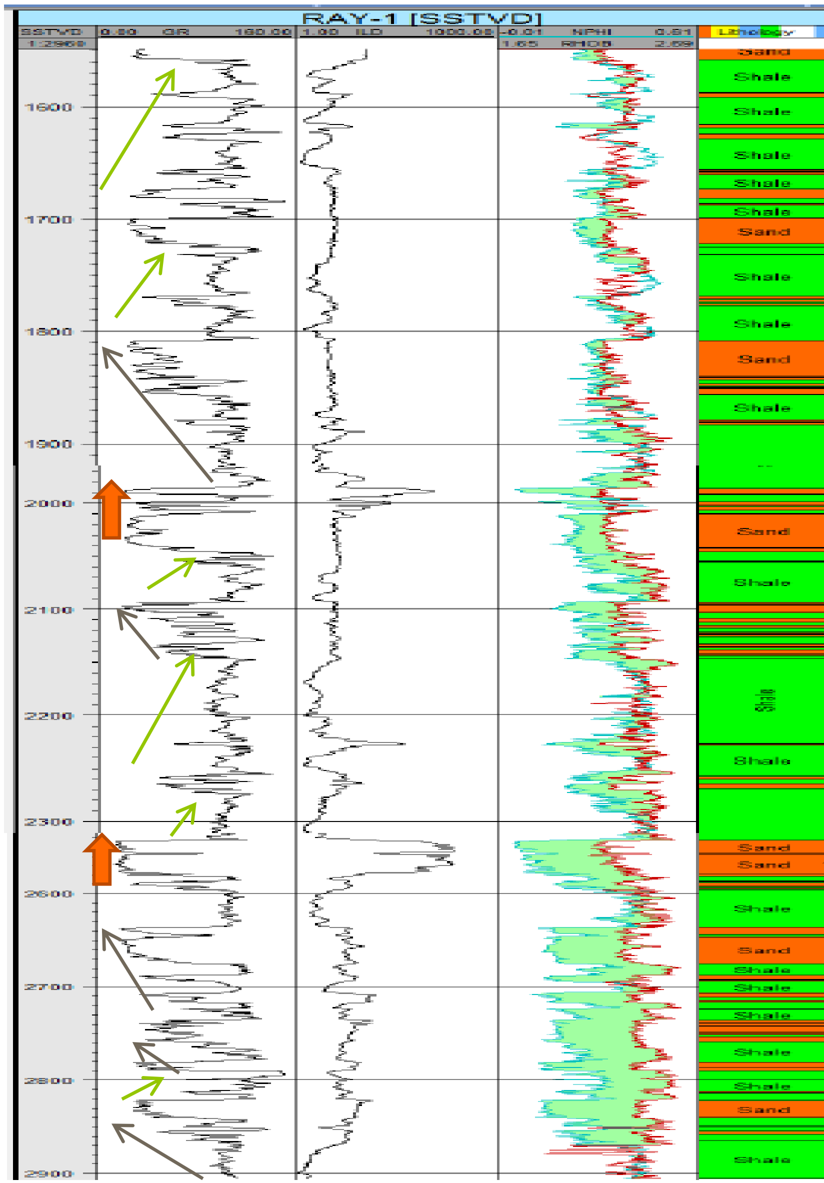


Figure 3.4: Qualitative Seismic Facies Analysis based on reflection configuration pattern summarized in Table 2.0, and reflection termination patterns

-PRESENTATION OF RESULTS-



Cycles	Environments
FU	Fluvial Channel
FU	Tidal Channel
CU	Shoreface
Blocky	Distributary Channel Fill
FU	Tidal Channel
CU	Tidal-Delta
FU	Tidal Channel
	Distributary Channel Fill
CU	Prograding Delta (Wave-delta)
	Tidal-delta
FU	Tidal Channel
CU	Shoreface

FU: Finning-Upward
CU: Coarsening-Up

Figure 3.5: Electrosequence Analysis of Study Area

In Figure 3.5, a vertical succession of electrofacies was constructed from the electrosequence analysis (developed by Serra and Sulpice in 1972), based on the electrofacies components summarized in Figure 2.2 and Figure 2.3. It create a high-resolution one-dimensional depositional hierarchy which can be interpreted in terms of possible depositional environment and facies successions. It also serve as a clear guide to reconstructing the depositional history of the area.

DISCUSSION AND CONCLUSION

- Four depositional sequences and lithofacies have been identified in the study area. These lithofacies are diagnostics of different depositional environments and conditions that existed during sediment transportation and deposition.

- The lithofacies succession described is characteristic of a prograding delta. Such delta succession has a shallowing-up pattern; a series of strata that consistently shows evidence of the younger beds being deposited in shallower water than the older beds they overlay

- The oldest facies, (prodelta shale F1 in Figures 3.0a and 3.1) are the finest grained as they are deposited in the lowest energy regime and found at the base of the sequence, while the youngest facies (sandstone F4), which capped the sequence and of coarse grains, were deposited in highest energy regime.

- Therefore, the delta succession shows a coarsening-upward sequence, with energy increasing up the sequence.

-DISCUSION AND CONCLUSION-

- The cycles and sequence hierarchical framework derived from electro-sequence analysis formed the bases for ranking the depositional processes and identifying the various depositional systems. Vertical stacking of the cycles assisted in reconstructing the Paleoenvironmental of deposition.

- About six distinct depositional systems and twelve cycles of deposition have been identified in the subsurface geology of the area (summarized in 3.5). The cycle began with the shoreface environment, succeeded shortly by tidal channel. The cycle continued progressively and periodically with fluvial channel system finally ending the episodes and capping the system.

- Integrated Electro-sequence and Seismo-sequence in basin analysis has provided new insights to the subsurface stratigraphy of the Onshore Niger Delta Basin, and overcome the major challenges often encountered by the conventional geological data. Hence, this method is an effective guide to investigating subsurface geology for hydrocarbon exploration and preliminary studies. When combined with geological methods, it can be used effectively to carry out high-resolution 3-D modeling of sedimentary basins and petroleum systems.

-DISCUSION AND CONCLUSION-

Reservoirs	Top (TVDSS)	Base (TVDSS)	Thickness (meters)	V_{sh} (%)	Porosity (%)	S_w (%)	S_h (%)	Deposition Environments
SAND A	1650	1700	50	13	31	100	0	Fluvial Channel
SAND B	1983	2045	70	26	24	48	52	Distributary Channel
SAND C	2093	2143	50	35	22	98	2	Shoreface
SAND D	2220	2240	20	41	19	82	18	Tidal Channel
SAND E	2254	2275	21	36	20	78	22	Tidal Channel
SAND F	2480	2506	26	34	18	70	30	Tidal Channel
SAND G	2540	2600	65	8	16	22	78	Distributary Channel
SAND F	2636	2674	38	42	16	97	3	Deltaic sand

Table 4.0: Summary of the petrophysical evaluations of wells RAY-1 and RAY-3 of ‘RAY’ field. The highlighted reservoirs are the potential hydrocarbon reservoir sands.

The petrophysical analysis summarized in Table 4.0 reveals that the area has a good hydrocarbon potential. Sand units of the distributary channels and tidal channels show good potential for hydrocarbon reservoir, with good thickness, porosity and hydrocarbon saturation. Shale units of the shoreface and deltaic environments are potential source rocks and seals.

SUMMARY

- Improvement in seismic data acquisition, processing and interpretation, as well as improved borehole-geophysical techniques, has made geophysical approach highly effective in basin analysis and subsurface geological investigation.

- This work concentrated on the geological framework of sediment accumulation and facies distribution in the context of time and space through electro-sequence and seismo-sequence analysis. It aimed at establishing the sedimentary facies, their succession and environments of deposition with a view to reconstruct the subsurface depositional history of the onshore Niger Delta basin.

- The study concluded that Onshore Niger Delta is characterized by typical prograding delta architecture with a shallowing-up pattern in which a series of strata consistently showed evidence of the younger beds being deposited in shallower water than the older beds they overly. The older beds tend to be of finer sediments (of marine and delta slope region) than the younger beds (of river mouth bars and fluvial systems).

- The depositional systems revealed information which was stimulated from the start of deposition to the present day, and was used to carefully reconstruct the paleo-depositional history of the study area. In addition, electrosequence analysis provided extra subsurface geological information which could be very useful in the accurate prediction of possible targets during hydrocarbon exploration, and helps reduce exploration risk, invariably.