ELECTROFACIES CHARACTERIZATION OF SEQUENCE IN RAY FIELD, NIGER DELTA, NIGERIA

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Abstract: Electrofacies and depositional systems of sequence penetrated in 'Ray' Field, Niger Delta were analyzed, using well log and 3-D seismic data, with a view to enable accurate prediction of source and reservoir rocks in the study area. Lithofacies were delineated through analysis of well logs using signatures of gamma ray, cross-plot of neutron-density logs and seismic facies analysis. The identified lithofacies were subjected to electrofacie analysis through diagnostic characteristics of gamma ray log indicative of a given depositional environment. Sands of different environments were subjected to seismic attribute and petrophysical analyses to assess the hydrocarbon potentials of such reservoirs. Results showed the presence of four lithofacies: Shale, Heterolithic, Shaly-Sandstone and Sandstone Facies. The electrofacies analysis revealed five depositional systems of Shoreface, prodelta, distributary, tidal and fluvial systems. Lateral variations of lithology and facies distribution, as well as presence of channels were imaged by seismic attribute. The sand units of the distributaries and tidal channels having thickness of 70 m and 65 m, and porosity of 16% and 24% respectively were viewed to have good quality for hydrocarbon reservoir.

Keywords: Channels, depositional system, electrofacies, facies, hydrocarbon, seismic attribute

Introduction

A depositional system is the product of sedimentation in a particular depositional environment which includes the assemblage of strata whose geometry and facies lead to the interpretation of a specific paleo-depositional environment (Galloway, 1989). The environment of deposition of sediment is the sum of the physical, chemical and biological condition under which it was deposited. These conditions are recorded in the form of sedimentary facies from which a judgment can be made of the paleo-depositional conditions and thereby predict the quality of the reservoir units. Electrosequence analysis is a systematic approach to sequence interpretation for the prediction of depositional environments from well logs (Serra & Sulpice, 1975). The analysis of depositional environments of rock units can beaccomplished with geophysical well logs interpretation (Serra & Abbott, 1982; Van Wagoner *et al*., 1990; Cant, 1992; Rider, 1990; Posamentier & Allen, 1999; Catuneanu, 2006).

Lithology can be interpreted from wireline logs using a variety of log types, such as gamma-ray, sonic, resistivity, density, and photoelectric (Selley, 1998). Electrosequence analysis of reservoir plays prominent role in determination of hydrocarbon bearing intervals (Torghabeh *et al.,* 2014, Kuroda, *et al.,* 2012, Zee, 2011). Klett *et al.* (1997) applied the concept of Electrosequence analysis in the Tertiary Lower Rhine Basin fill for the interpretation of shallow marine and continental environments in a sequence stratigraphic approach. Siliciclastic reservoir rocks owe much of their diversity and stratigraphic heterogeneity to the many different depositional environments in which they are deposited. These environments range from non-marine to marine settings. In non-marine settings, sandstone reservoirs are deposited in fluvial, eolian, and lacustrine environment, whereas in marine settings these reservoir rocks are in deltaic, shallow marine and deep marine settings (Magoon & Dow, 1994). Ability to accurately predict hydrocarbon source and reservoirs in any geological setting largely depends on the level of understanding of the paleo-environment of deposition of rocks within the basin.

The 'RAY' Field is situated in the distal part of the northern depositional belt of the Niger delta. The Northern depobelt (Fig. 1) is the oldest depobelt in the delta (Late Eocene to Early Miocene), and the first focus of sedimentation during the build out of the modern Niger Delta (Doust & Omatsola, 1990). The onshore Niger Delta is highly prolific with simple structural architecture, and formed the first focus of exploration in the basin. However, large portion of the onshore delta has not been fully explored, while some fields have been abandoned, basically due to lack of adequate understanding of the depositional environment of facies in the onshore delta. The effect of facies variations on reservoir quality has been widely studied and closely linked with different depositional conditions and settings (Ezenwaka *et al.,* 2018; Oluseun *et al.,* 2017; Ebuka *et al.,* 2017; Ulasi *et al.,* 2012). Understanding the depositional environment of rocks through the conventional core and biostratigraphy data is often rigorous and quite expensive.

This study aimed at establishing the sedimentary facies, their succession and environments of deposition using less rigorous and inexpensive geophysical approach with a view to assess the hydrocarbon potential of the study area. Log and seismic facies analyses have been combined to study the depositional environments and lithofacies preserved in the RAY Field to enable accurate prediction of the hydrocarbon potential of the area.

Stratigraphic and tectonic setting

The Niger Delta, located in the southern Nigeria margin of the Gulf of Guinea (Fig. 1), is made up of materials deposited under marine to continental settings (Frankl & Cordry, 1967).

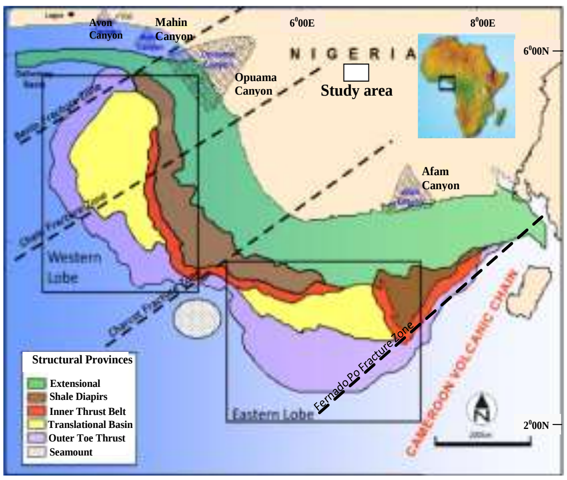


Fig. 1: Map of Niger Delta showing the structural provinces and the fracture zones (Modified from Matthew *et al.*, 2010)

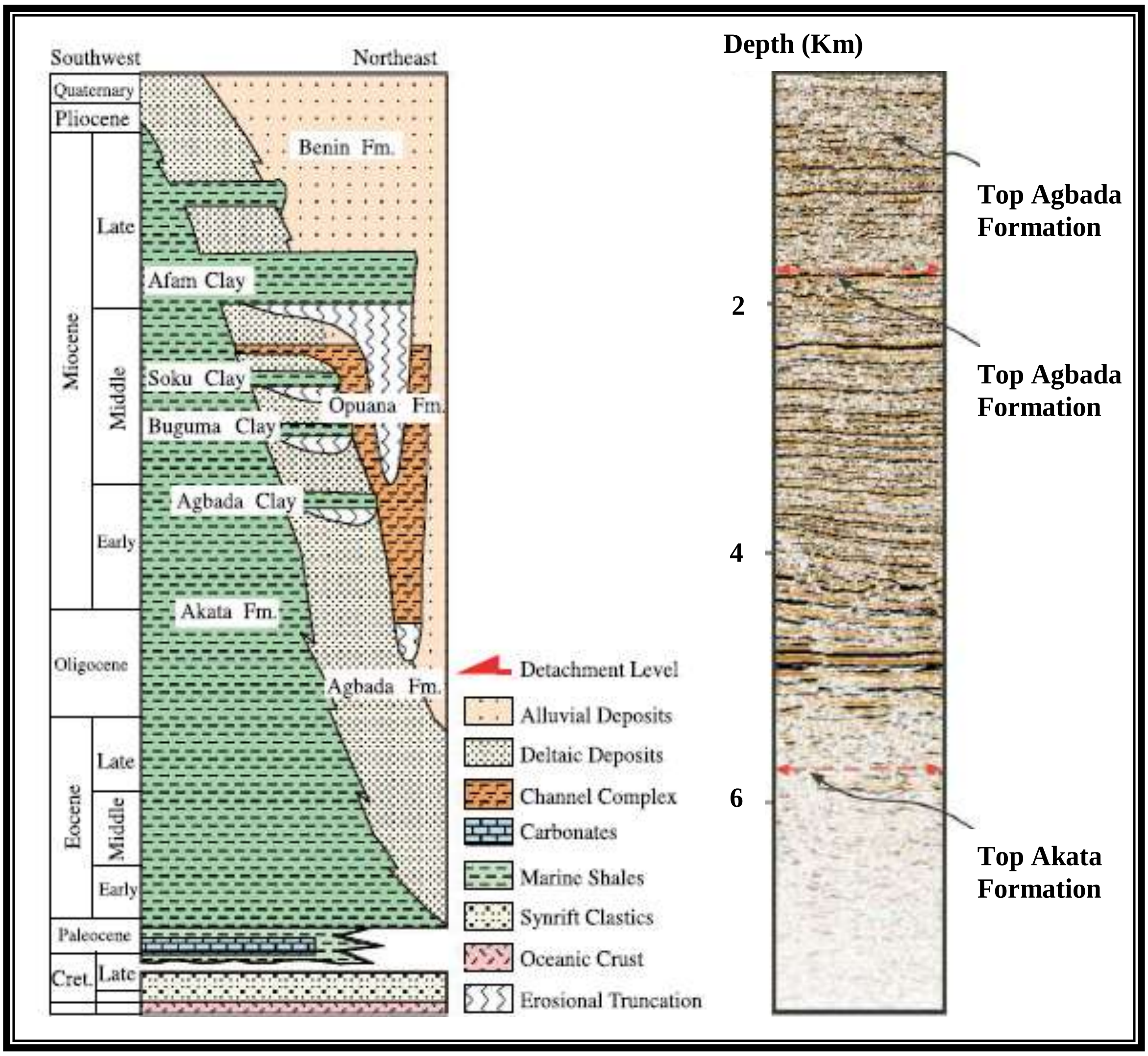


Fig. 2: Schematic diagram of Niger Delta regional stratigraphy and variable density seismic display of the main stratigraphic units with corresponding reflections (modified from Evamy *et al.*, 1978)

The stratigraphy and geological setting of the Delta have been well studied (Short & Stauble, 1967; Burke, 1972; Weber & Daukoru, 1975; Avbovbo, 1978; Whiteman, 1982; Kulke, 1995). The Niger Delta stratigraphy (Fig. 2) is separated into three major Megasequences of the Benin, Agbada and Akata Formations. The Tertiary succession of the Niger Delta consists of marine Akata Formation that is characterized by a homogenous shale development which formed the hydrocarbon kitchen. The overlying paralic Agbada Formation has been described by Weber (1986) to be cyclic sequence of sandstones and shales. Most hydrocarbons produced so far in the Niger delta have been hosted in the sandstone unit of the Agbada Formation. The sequence is capped by the continental Benin Formation which is made of freshwater bearing sandstones that is locally interbedded with thin shales considered to be of braided stream origin. This formation is of little petroleum hosting strata. Tectonically, the Niger delta can be regionally divided into the western and southern lobes separated by the Charcot Fracture Zone (Corredor *et al.*, 2005). The Chain Fracture zone confines the western lobe to the north while the Fernando Po restricts the southern delta lobe to the southeast. Five depobelts which include the Northern depobelt, Greater Ughelli, Central swamp, Coastal swamp and offshore depobelts are preserved in the Niger delta (Lawrence *et al.*, 2002). Three main structural styles are frequent in the Niger delta. They include extensional (growth fault), translational (diapirs), and compressional (imbricate trust) zones. Growth faults and associated rollover anticlines are ubiquitous in virtually all depobelts of the Niger Delta. The duo combined to form the dominant structural traps for hydrocarbon in the delta. This study aimed at establishing the sedimentary facies, their succession and environments of deposition through electrosequence analyses of geophysical logs. This approach is novel in that it is less rigorous and inexpensive way to assess the hydrocarbon potential of the study area.

Materials and Methods

Wireline logs from RAY-1 Well and 3-D seismic covering 546 square kilometres with 1409 seismic lines: 545 in-lines and 864 cross-lines were employed for this study.

Delineation of lithofacies through log and seismic facies analyses

Diagnostic signatures of gamma ray and neutron-density combination logs were used to delineate the major lithofacies present in the sections penetrated by the wells. Gamma ray log cut-off of 75 API (shale: > 75 API and sandstone: < 75 API) coupled with sand-shale analysis from cross-plots of gamma ray, density and neutron logs were employed for lithofacies identification. Seismic facies analysis (with wider lateral coverage than well log analysis) was implemented using visible reflection configuration, amplitude of reflections and reflection continuity within seismic sequences in order to determine lateral facies changes.

Electrosequence analysis

The identified lithofacies were subjected to electrosequence analysis (Serra & Sulpice, 1975) from the base of the well to the top. It involved analysis of gamma ray log from RAY-1 Well for diagnostic characteristics such as trends, shapes, and abrupt breaks; which are indicative of the depositional environment and energy of deposition. The vertical succession of electrofacies was interpreted in term of possible paleo-depositional environments and facies successions and then and integrated with seismic facies analysis.

Seismic attributes extraction

Seismic attribute calculation was carried out on time slices for the visualization of geomorphological and stratigraphic features that may be suggestive of depositional systems. The chaos (sensitive to faults), iso-frequency (68 Hz)-sensitive to lithofacieschanges and RMS amplitude attributes were generated on seismic time slices at intervals of geologic interest to detect fault edges, lateral variation of lithology and facies distribution, as well as presence of depositional or statigraphic features.

Petrophysical analysis of reservoir sands

Reservoir sands of different environments were subjected to petrophysical analyses to delineate possible hydrocarbon reservoirs and assess the hydrocarbon potentials of such reservoirs.

Results and Discussion

Seven reservoir sands (Sands A – G) were delineated in the study area (Fig. 3). Cross-plot of neutron, gamma and density logs (Fig. 4) revealed fourmajor lithofacies: Shale Facies, Heterolithic Facies, Shaly-Sandstone Facies and Sandstone Facies in vertical succession based on sand-shale ratio and lithological characteristics of the facies preserved in the field. Seismic facies (Fig. 5) also showed the presence of similar lithofacies which began with pro-delta shale, followed upward by delta front sandy-shale facies, which is succeeded by delta plain parallic facies, and capped by fluvio-deltaic sandstone. Electrosequence analysis (Fig. 6) reveals five depositional systems with twelve distinct depositional cycles portrayed by series of funnel, bell, blocky, and jagged shapes of the Gamma Ray log signature within the study area.

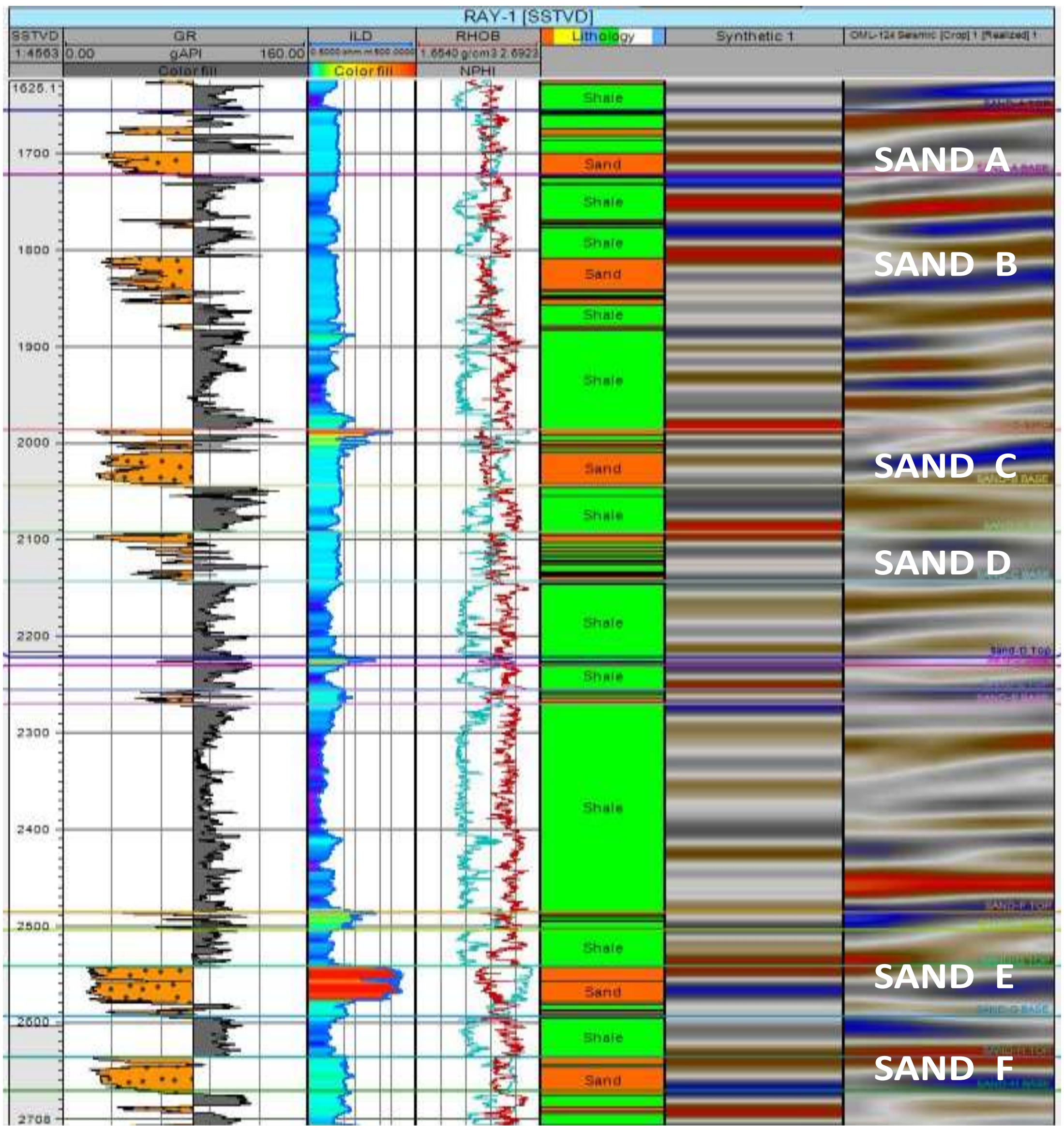


Fig. 3: Studied reservoir sand intervals along Well RAY-1 Well

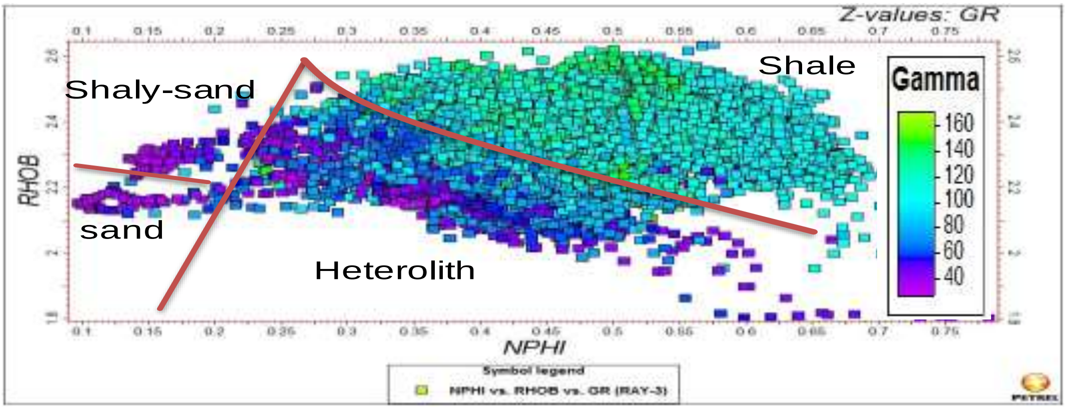


Fig. 4: Cross-Plot of gamma ray, neutron and density logs for shale-sand analysis

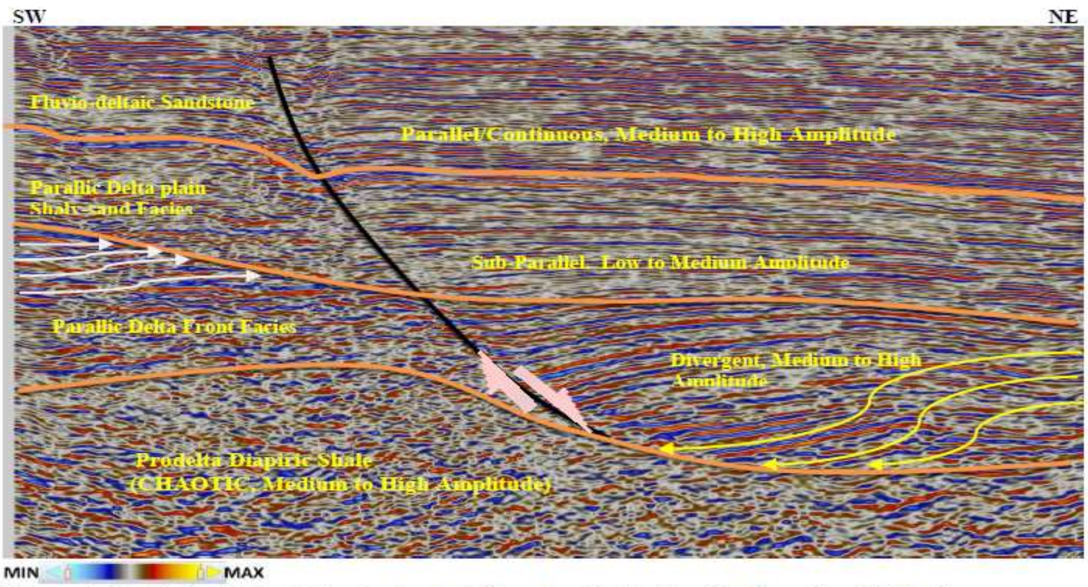
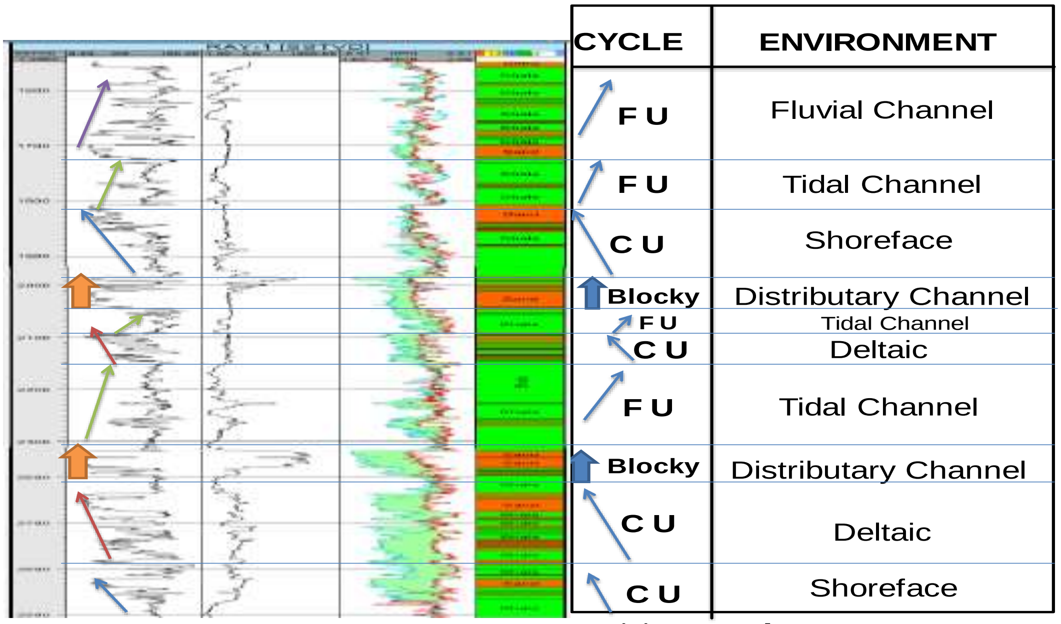


Fig. 5: Seismic facies analyses based on reflection configuration/pattern



FU: Fining upward. CU: Coarsening upward.

Fig. 6: Electrosequence Analysis of 'RAY' Field for depositional systems

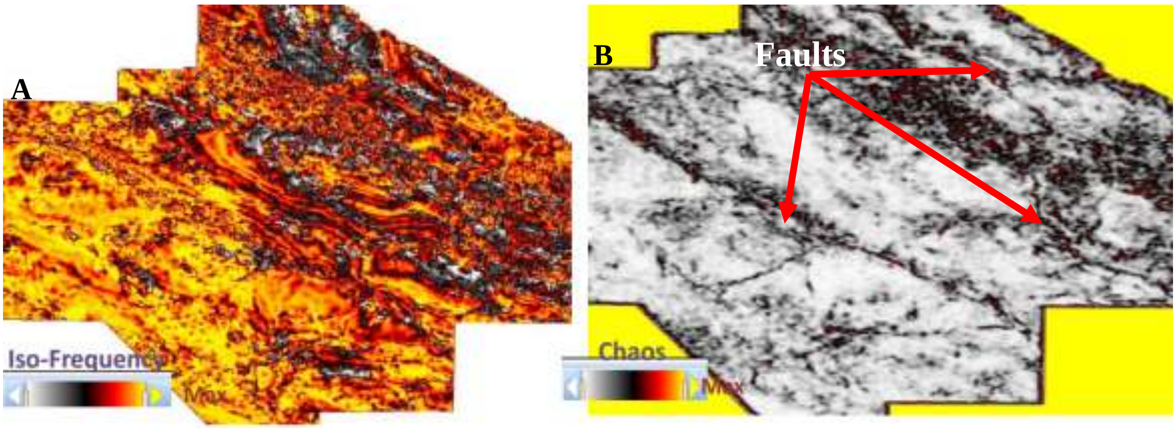


Fig. 7: Attribute maps (A) Iso-frequency showing local variation of facies (B) Chaos showing fault offsets of the horizon (Time slice extracted from the seismic volume at 1140 ms)

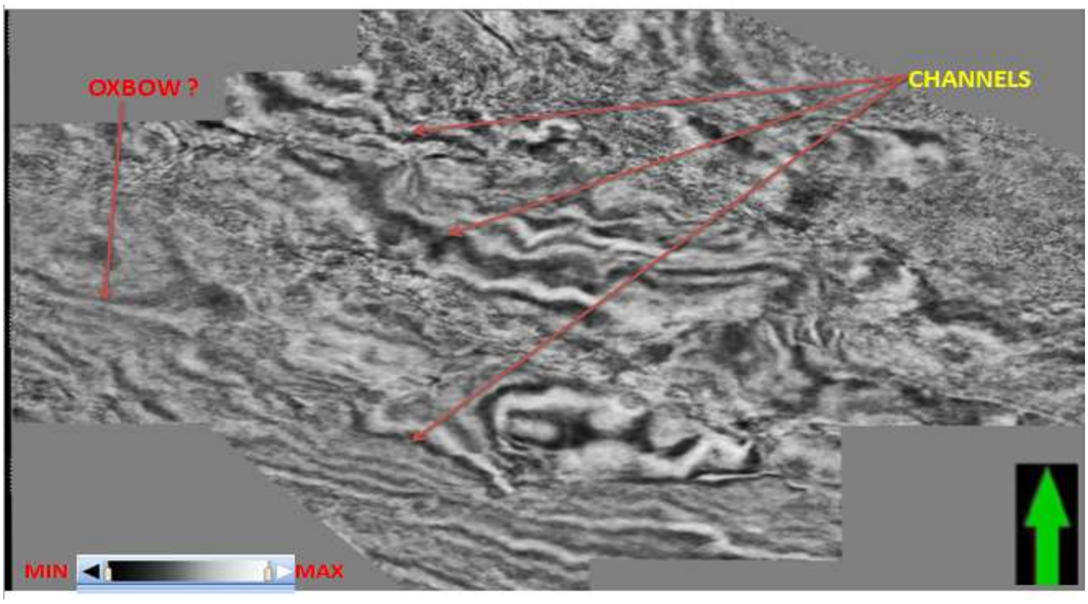


Fig. 8: RMS-Amplitude attribute in black and white display showing sedimentary features (Time slice extracted from the seismic volume at 1450 ms)

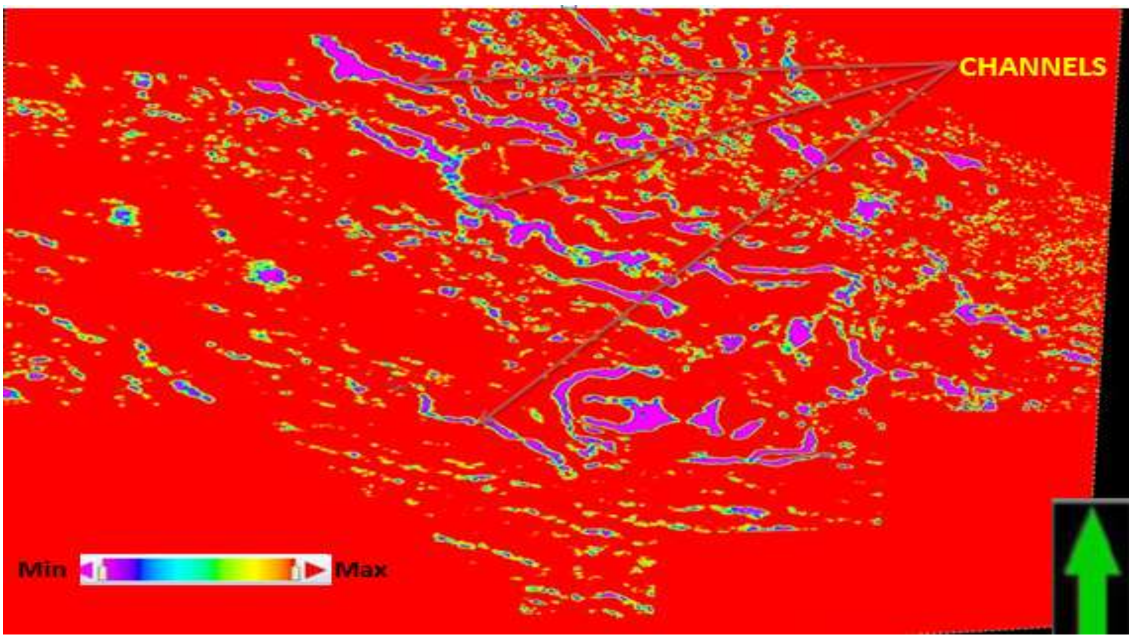


Fig. 9: Time slice (-1449 mS) of the RMS-Amplitude attribute in variance display showing sedimentary features

Table 1: Summary of the petrophysical evaluations of 'Ray'-1 Well

Reservoirs	Top (TVDSS)	Base (TVDSS)	Thickness (m)	V_{sh} (%)	Porosity (%)	S_w (%)	S_h (%)	Depositional Environments
SAND A	1650	1700	50	13	31	100	0	FluvialChannel
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	2840	2506	26	34	18	70	30	Tidal Channel
SAND G	2540	2600	65	8	16	22	78	Distributary Channel
SAND H	2636	2674	38	42	16	97	3	Deltaic Sand

Figs. 7a and 7b show iso-frequency and chaos attribute responses. Iso-frequency attribute displays the changing facie of the slice while the chaos attribute delineates the fault offsets. Figs. 8 and 9 show the rms amplitude map of time slice extracted from the seismic volume at 1450 ms. The summary of the petrophysical evaluations of sands in 'Ray'-1 Well is presented in Table 1.

The Shale Facies is the oldest in the area, occurring at the base of the sequence and is of marine origin (delta front environment). Heterolithic Facies succeeds the basal Shale, followed upward by Shaly-Sandstone Facies. Heterolithic Facies was differentiated from the Shaly-Sandstone Facies on the basis of sand-shale ratio which is higher in the latter and nearly equal in the former. The Heterolithic and Shaly-sandstone Facies constitute the parallic sequence of the study area. The youngest of the sequence is Sandstone Facies deposited in deltaic plain environment and formed the top of the sequence.

Paleodepositional systems and cycles

Deposition in the 'Ray' Field began in the shoreface environment with a coarsening-up sequence that was formed during marine regression when the shelf was exposed. Serrations on the Gamma ray curve reflect energy fluctuation during sediment deposition. The shoreface facies was succeeded by tidal channel deposition when the sea level gradually began to rise. The change in energy regime from high to low during this phase gave rise to a finning-up sequence (bell shape gamma ray log motif). Prograding delta facies began to form when the sea level gradually drops. The delta was largely controlled by tides as it builds out into the sea giving rise to a tide-dominated delta; a coarsening-up sequence (serrated funnel shape gamma ray signature) with energy increasing up the sequence. The tidal-deltaic facies was succeeded upwards by wave-dominated delta formed at low tide as sediments were re-distributed into the shallow marine by waves. The relatively thick sequence of deltaic facies indicated a long period of sea level fall. Another episode of sea level rise lead to uniform deposition of distributary channel facies (blocky gamma ray log) formed by channel aggradation as the energy of the river abruptly dropped leading to the accumulation of transported bedloads (sandstone) within the channels. The distributary facies was succeeded by another episode of tidal channel deposition in form of parasequence sets. This facies was further followed by a second cycle of tidal-deltaic facies deposition. Afterwards, the third thin tidal channel facies was deposited. Relatively thicker distributary channel sand immediately succeeded it due to sudden drop in sea level a little below the spring tide. As the sea level further decreased, deposition of another shoreface facies was initiated during the neap tide when the shelf was exposed. The tide further increased, initiating the formation of tidal channel system directly overlaying the shoreface facies. The tidal system showed two parasequence sets which reflected a short term sudden drop in sea level within the major sea level rise during the deposition of the facies. After deposition of the tidal channel facies, marine influence on the depositional environment seized and the depositional activity was largely controlled by fluvial and alluvial processes. The fluvial processes gave rise to the channel-levee system which was represented by a finning-up sequence. The channel sands (coarse) formed the base of the sequence, capped by the overbank deposits or levees (fine grains). The sequence is represented by bell shape signature on the gamma ray. Minimal serration shows the absence of tidal influence. The fluvial system formed the last episode of depositional cycle in the 'Ray' Field.

Facies distribution and geomorphological features

The wide variation in iso-frequency and chaos attribute responses (Figs. 7a and 7b) revealed that local variation exists within the facies laterally (SW to NE) across the field. This may be attributed to variation in conditions of deposition across the area or juxtaposition of different lithofacies through faulting.While the iso-frequency attribute is more sensitive to facie variation, the chaos attribute better delineates the fault offsets. Low iso-frequency response corresponds to possible reservoir sand. On the rms amplitude map (Figs 8 and 9), the curvilinear segments of low rms amplitude were suspected to be associated with geomorphological/depositional features such as sinuous channel complexes or other stratigraphic features.

Petrophysical Properties of reservoir sands

In terms of hydrocarbon potential, the sand units of the distributary channels and tidal channels show good potential for hydrocarbon reservoir (Table 1). The distributary channel sands are good possible hydrocarbon prospects with thickness of 70 and 65 m, and porosity of 16 and 24%, respectively. Shale units of the shoreface and deltaic facies serve as potential source rocks and seals. The average volume of shale within the reservoir sands delineated ranges from 0.10 to 0.56. The reservoir sands in 'Ray' Field have generally low shale content (average value of 0.15). Low shale content occurrence recorded at these intervals indicates the hydrocarbon reservoir is fairly clean.

Conclusion

The facies and depositional environments of the sequence penetrated in 'Ray' Field, Niger Delta have been successfully analyzed using well log and 3-D seismic data. Vertical succession of depositional facies revealed four major lithofacies, which include the Shale Facies, Heterolithic Facies, Shaly-Sandstone Facies and Sandstone Facies. The electrosequence analysis revealed five depositional systems with ten distinct depositional cycles of deltaic, distributary, tidal shoreface, and fluvial systems within the study area. The cycle began with deposition indeltaic environment and ended with fluvial environment. The sand units of the distributary and tidal channels (deposited in the delta plain and delta front environment respectively) having thickness of 70 m and 65 m, and porosity of 16 and 24%, respectively were viewed to have good potential for hydrocarbon reservoir. Shale units of the shoreface and prodelta environments would serve as potential source rocks and seals. Depositional features such as sinuous channel that may be significant for hydrocarbon prospectivity were imaged by seismic attribute slices. Information extracted from the analyses resulted in more understanding of the depositional environment of rocks, and enabled the accurate prediction of hydrocarbon source and reservoir rocks in the study area.

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Conflict of Interest

Authors have declared that there is no conflict of interest reported in this work

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