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Research Article
Petrophysical Analysis and Reservoir Characterization of Emerald Field, Niger Delta Basin, Nigeria

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Abstract
Background and Objective: Re-evaluation of the Emerald Field in the Niger Delta Basin, Nigeria was done to produce 3D structural model of the field as well as identify and estimate the petrophysical properties of the reservoirs in the field. **Materials and Methods:** This was achieved by the use of 3D seismic volume and 4 wells from the field and the combination of techniques of well log analysis, seismic facies analysis, petrophysical analysis and seismic attribute analysis. **Results:** Integrated analysis of Gamma Ray, Resistivity, Neutron and Density logs shows that 3 hydrocarbon bearing reservoirs-Emy A, B and C-were penetrated by the 4 wells studied. The petrophysical analysis of the field reveals that reservoir porosity ranges from 10-29%, hydrocarbon saturation ranges from 0.75-0.84, water saturation ranges from 0.16-0.25, volume of shale ranges from 0.24-0.33 and net-to-gross ranges from 0.72-0.93. Five seismic facies were identified within the study area. Integrating the log motifs and results from the seismic facies analysis suggests the environment of deposition at different locations within the field to be distributary channel fills, overbank and floodplain deposits, which depicts paralic zone. Two prospects (Emerald prospect A and Emerald prospect B) and one lead were identified within the study area. Results of risk evaluation and estimated volume of hydrocarbon in place ranked Emerald prospect B as highest. **Conclusion:** It is therefore concluded that prospect for hydrocarbon exist in the Emerald field and the identified prospect should be tested for production.

Key words: Reservoir characterization, petrophysics, Niger Delta, seismic facies, well log facies

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Reservoir characterization involves the determination of the physical properties of reservoir units and changes in their distribution throughout the reservoir. The physical properties include porosity, permeability and fluid saturation[1]. In the reservoir characterization process, 3D seismic amplitudes are calibrated against real and computer-generated well data in order to identify hydrocarbon accumulations and reservoir compartmentalization. The integration of various discipline such as complex structural interpretation, seismic and sequence stratigraphy, core and log data, basic geological knowledge and depositional facies and environment modeling which are all critical parts in the building of reservoir geological model are the dependent variables for the success of the characterization process[2].

Reservoir characterization integrates all available data to define the geometry, distribution of physical parameters and flow properties such as porosity, permeability and fluid saturations. This may involve expertise in sedimentology to define reservoir lithology and geometry, definition of flow units and boundaries within the reservoir and computer simulation of fluid movement and changes in reservoir properties during production.

Geologic models help capture reservoir heterogeneities as well as uncertainties resulting from sparse well control, inadequate resolution on geophysical data sets and problems with indirect measurement of reservoir parameters from seismic, log and production data. These models of the reservoir may aid in more accurate estimation of the probability distribution of hydrocarbon volumes, assist in geosteering wells to optimum locations and provide input to reservoir simulation.

The increase in demand for energy has placed pressure and greater challenge to enhance energy supply. In Nigeria, oil almost constitutes exclusively the revenue base for national development and as such it demands greater efforts from both the Government and the research institutions to ensure that this non-renewable resource is adequately and optimally tapped.

Geologic and seismic studies have shown that the Niger Delta Basin has spectacularly maintained a thick sedimentary apron and salient petroleum geological features favourable for petroleum generation, expulsion and trapping from the onshore through the continental shelf and to the deepwater terrains since the discovery of oil in Oloibiri well[3] in1956.

The Niger Delta Basin was formed by a failed rift junction during the separation of the South American plate and the African plate as well as the opening of the South Atlantic in the late Jurassic[4,5]. Rifting in this basin started in the late Jurassic and ended in the mid cretaceous. The Cenozoic Niger Delta Basin is situated at the intersection of the Benue Trough and the South Atlantic Ocean where a triple junction developed during the separation of the continents of South America and Africa in the late Jurassic[5]. Five depobelts are defined in the Niger Delta basin and they include the Northern Delta, the Greater Ughelli, the Central Swamp, the Coastal Swamp and the Off shore depobelts (Fig. 1). The study area is within the Coastal Swamp of the Niger Delta basin.

Three stratigraphic units are defined in the tertiary Niger Delta[6]. These stratigraphic facies includes: pro-delta facies (Akata Formation), paralic delta front facies (Agbada Formation) and continental delta top facies (Benin Formation). These units are stratigraphically superimposed on each other (Fig. 2). The Akata Formation is the basal unit in Niger Delta Basin. The Akata Formation (Paleocene-Recent) is a marine sedimentary succession that is laid in front of the advancing delta with a thickness[7] of about 7000 m. It consists of mainly uniform under-compacted shale, clays and silts at the base of the known delta sequence with lenses of sandstone of abnormally high pressure at the top[8]. The Akata formation is overlain by the Agbada Formation. The Agbada formation (Eocene-Recent) is characterized by paralic interbedded sandstone and shale with a thickness of over 3,000 m [3]. These paralicclastics are the truly deltaic portion of the sequence and were deposited in a number of delta-front, delta-topset and fluvio-deltaic environments. Some shales of the Agbada Formation were thought to be the source rocks, however, the main source rocks of the Niger Delta are deduced to be the shales of the Akata Formation[9]. 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. The Benin Formation (Oligocene-Recent) is the youngest lithostratigraphic unit in the Niger Delta. It has a minimum thickness of about 2000 m and is made up of continental sands and sandstones (>90%) with few shale intercalations[8].

The objectives of this study was to estimate the petrophysical properties of the reservoir rocks and infer the reservoir geometry distribution and reservoir quality trends using the reservoir correlation and also identify prospective zones for hydrocarbon production.

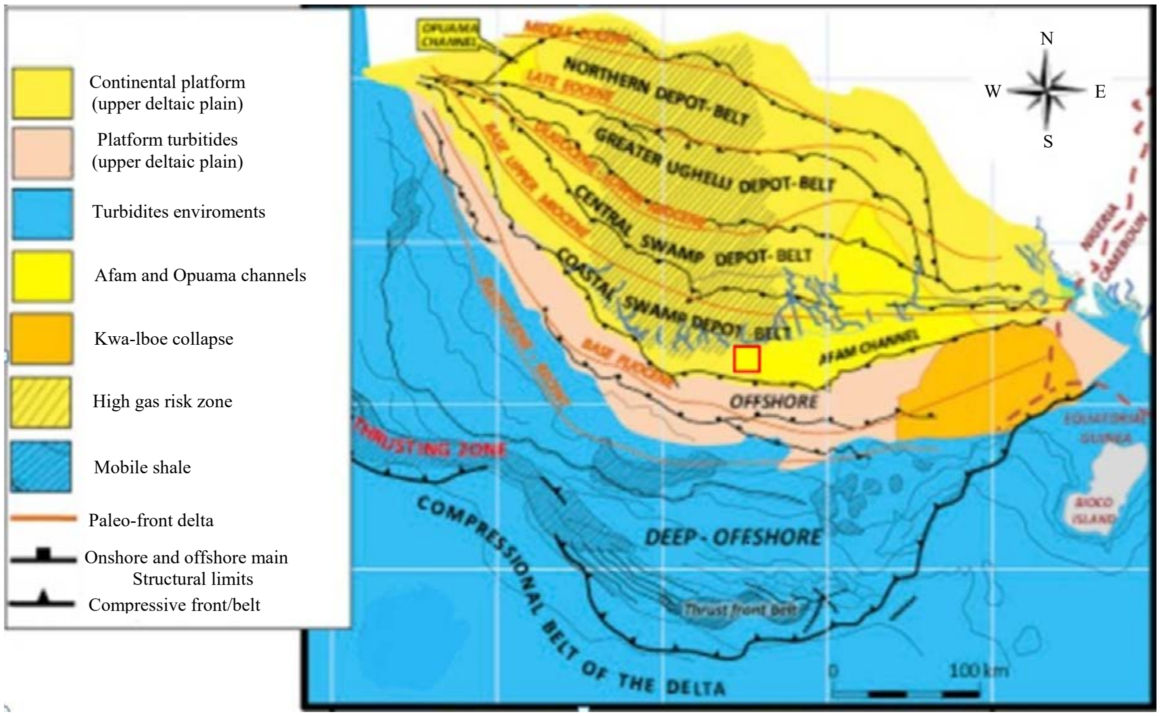

Fig. 1: Map of the Niger Delta Basin showing the study area highlighted in red rectangle

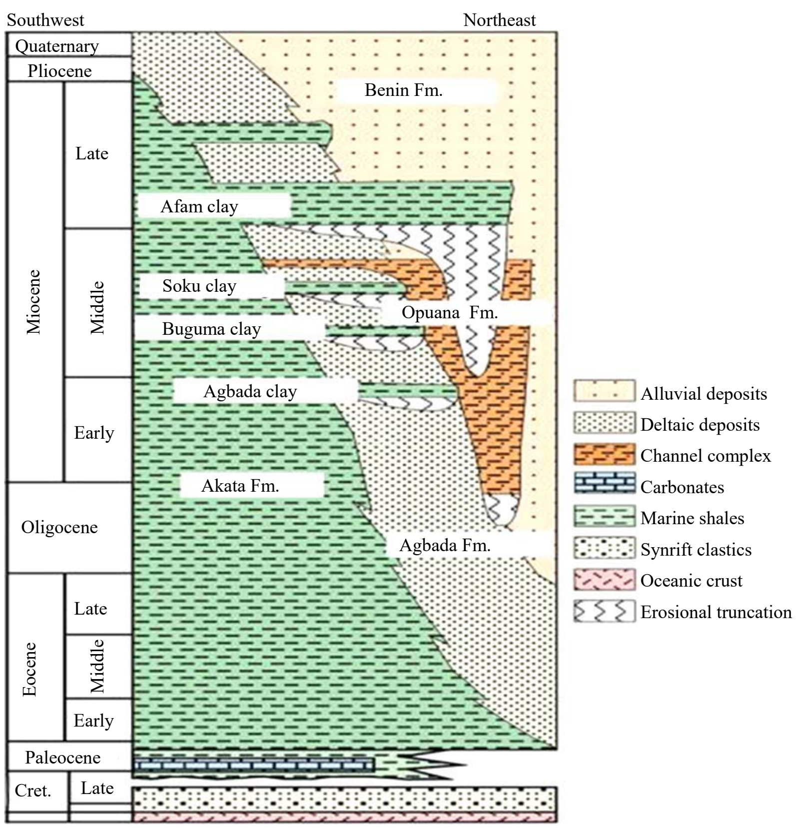

Fig. 2: Stratigraphic column showing the 3 formations of the Niger Delta[8]

MATERIALS AND METHODS

Study area: This research work was carried out from the month of October, 2016 till August, 2017. Literatures of the study area were reviewed from October-November, 2016. Preliminary report writing was done in December, 2016. Data interpretation was carried out from January-June, 2017. Compilation of results and final report writing was carried out from June-August, 2017.

Data quality: The data used for this research include well-log suites from 4 wells, checks hots and 3D seismic volume. The wells were drilled in a North to South Western direction, hence the well log analysis was carried for the location covered by the well. The seismic data covers an area of approximately 57 km^2 and is characterized by a series of parallel to near-parallel reflections that dip offshore to the southwest. The reflections are quite chaotic close to and behind faults but are continuous at zones away from faults.

Methodology: An integrated approach[10-15] employed in the interpretation of the available data for this study is summarized in the workflow (Fig. 3). Interpretation of the well-logs and seismic data were done using Schlumberger's Petrel "seismic-to-simulation" interpretation software. The software was used to carry out a detailed well log analysis, seismic data interpretation, synthetic seismogram generation, map construction and several 2D and 3D graphic presentations of the results. The datasets made available for this study were loaded into Petrel 2013.2 and were quality checked in order to make the most use of the information provided. Checks hot data was used to balance the inconsistency in results obtained between seismic data in the unit of time and well log data in the unit of depth by means of synthetic seismogram and well-to-seismic tie. Well-log cross-sections and corresponding seismic transects through the 3D volume were interpreted throughout the area to present the structural framework of the Field. Seismic attributes were studied to enhance signal-to-noise ratio of the seismic data, enhance the visibility of the faults and evaluate Direct Hydrocarbon Indicators (DHIs)[16-19]. Petrophysical analysis was carried out to evaluate the quality of the reservoir parameters. Volumetric calculations were made to determine the volume of recoverable hydrocarbon within the field[13,16].

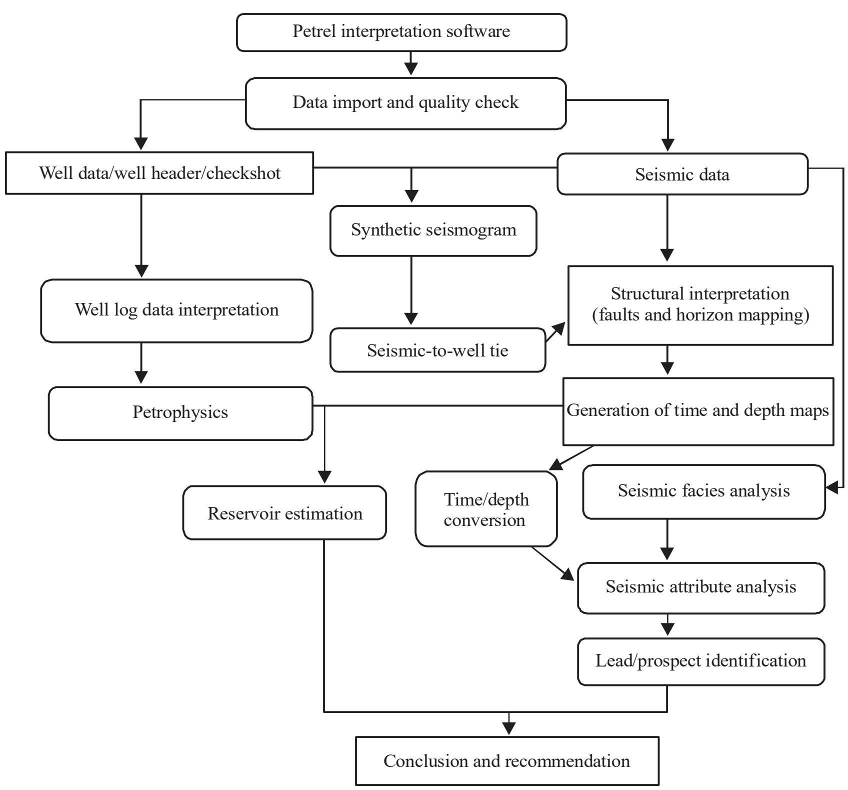

Fig. 3: Workflow showing methods of interpretation

RESULTS

Well log interpretation: Results from the well log interpretation gave the lithology penetrated by the wells in the study area to be mainly sand and sand-shale intercalation of the Benin Formation and Agbada Formation, respectively (Fig. 4). The lithologies of the area are dominantly sandstones, silts tones and shale.

Well correlation was carried out in a bid to identify the hydrocarbon bearing sands and this was done with the integration of Gamma Ray, Resistivity, Neutron and Density logs. Three hydrocarbon bearing reservoirs were identified and correlated in the four wells (wells EMY 002, EMY 004, EMY 006 and EMY 007). The reservoirs are EMY A, B and C. The well log correlation shows the reservoirs are laterally continuous (Fig. 5).

Petrophysical interpretation: Petrophysical parameters were calculated for all the reservoirs across the four wells. (EMY 002, EMY 004, EMY 006 and EMY 007). The reservoir parameters calculated include: reservoir thickness, net-to-gross (NTG), effective porosity (PHIe), volume of shale (Vsh), water saturation (Sw) and hydrocarbon saturation (Sh). Average petrophysical properties of the reservoir within the study area are summarized in Table 1.

Seismic interpretation: Synthetic seismogram was generated using EMY 004 well. The generated synthetic seismogram showed a near perfect tie with over 90% confidence limit between the generated synthetics and the original seismic. The reservoir tops corresponded to positive amplitudes and are represented by the peaks coloured blue, while the reservoir bases corresponded to negative amplitudes and are represented by the troughs coloured red (Fig. 6).

Structural interpretation: Seven faults were mapped in Emerald Field (Fig. 7). Three horizons were selected and mapped following detailed seismic analysis (Fig. 8). They were mapped on the in-lines and cross-lines across the study area. These mapped surfaces depict the geometrical configuration of the stratigraphic surfaces displayed as seismic density grids (Fig. 9). The density grids of the three horizons were used to generate the time surface maps (Fig. 10), which gave the

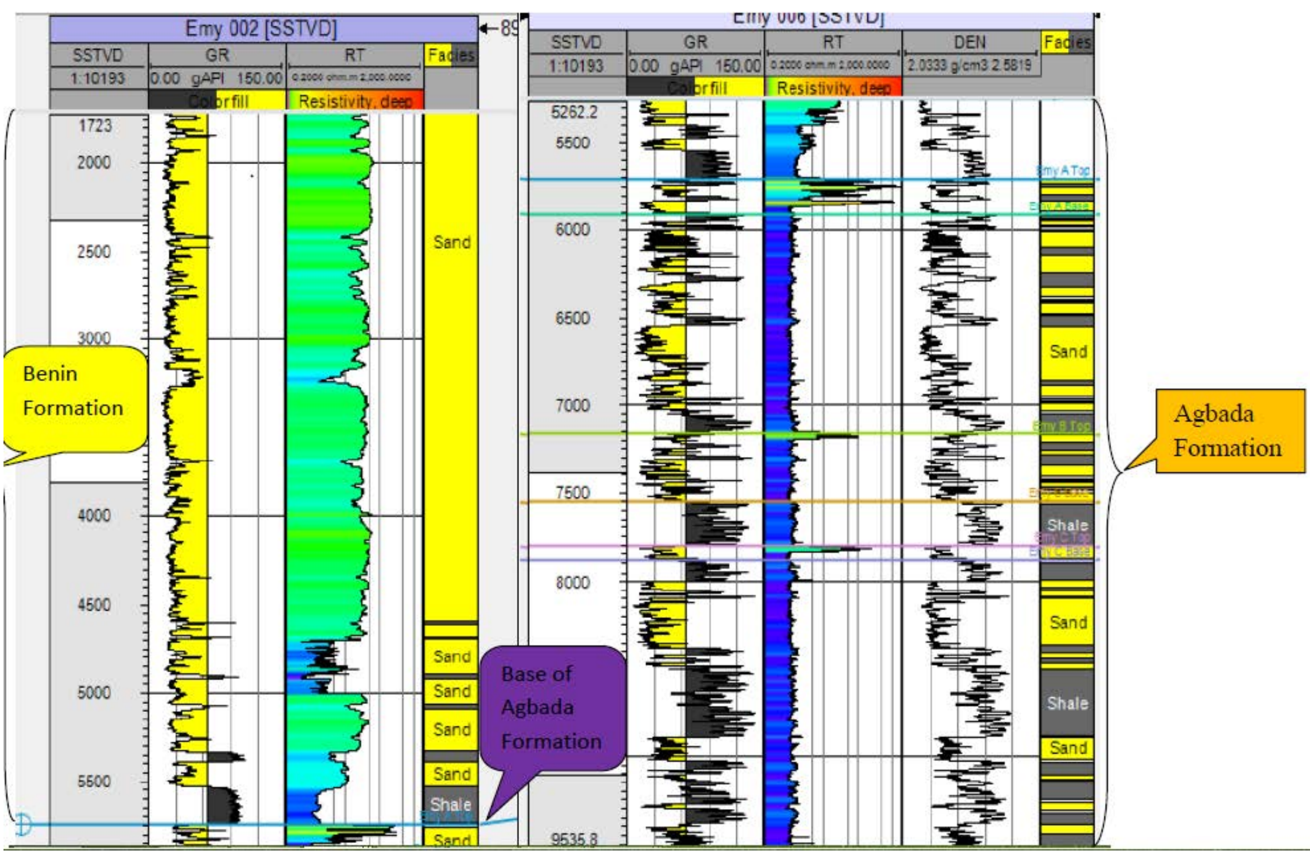

Fig. 4: Lithostratigraphic interpretation of wells EMY 002 and EMY 003 in the Emerald Field

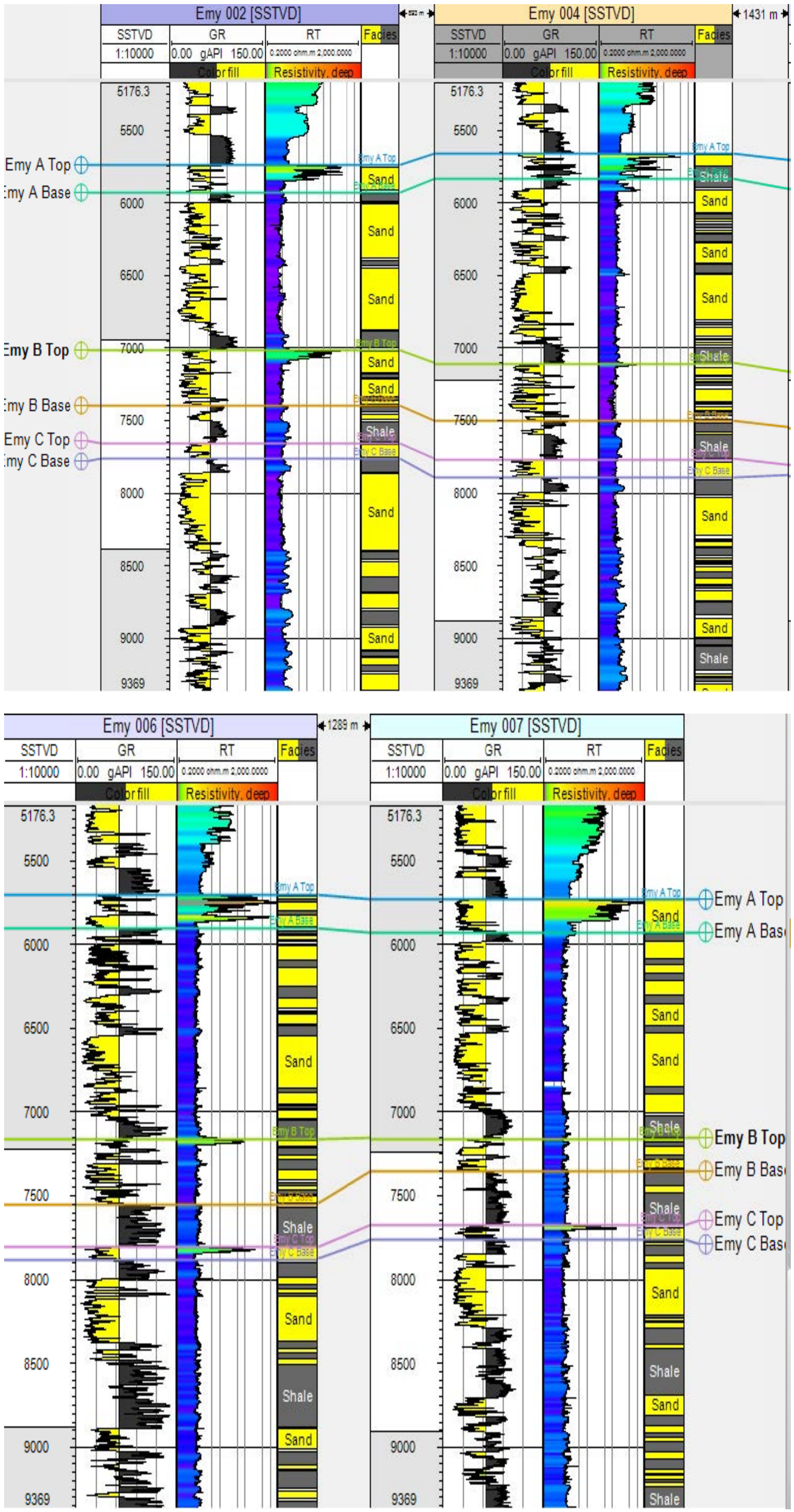

Fig. 5: Well correlation depicting the different lithologies

Table 1: Average petrophysical properties of the reservoir within the study area

Reservoir	Average thickness (M)	Average NTG	Average porosity	Average volume of shale	Average water saturation	Average hydrocarbon saturation
Emy A	56.81	0.86	0.22	0.33	0.23	0.77
Emy B	103.32	0.72	0.20	0.32	0.25	0.75
Emy C	32.59	0.93	0.25	0.24	0.16	0.84

Table 2: Interpreted gamma ray motifs and their inferred depositional environment

Interpreted gamma ray motifs	Sub facies	Sub environment	Inferred depositional environment
Cylindrical motif	Distributary channel	Upper delta plain	Marginal marine
Funnel motif	Distributary mouth bar	Upper delta plain	Marginal marine
Bell motif	Tidal channel	Lower delta plain	Marginal marine
Symmetrical motif	Offshore bar	Delta front	Marginal marine
Irregular motif	Flood plain	Pro delta	Marginal marine

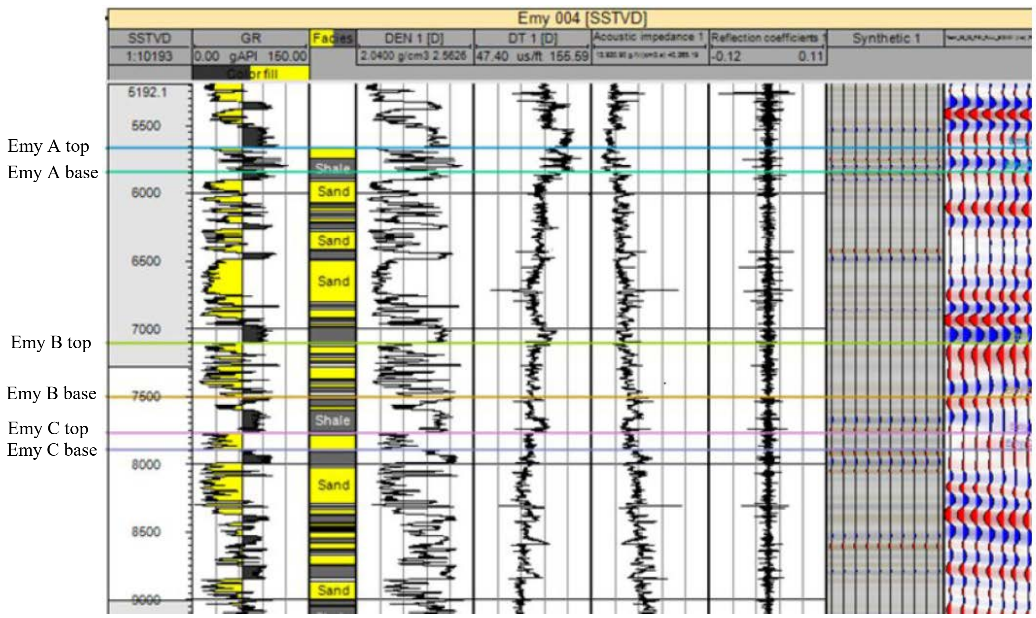

Fig. 6: Display of synthetic seismogram

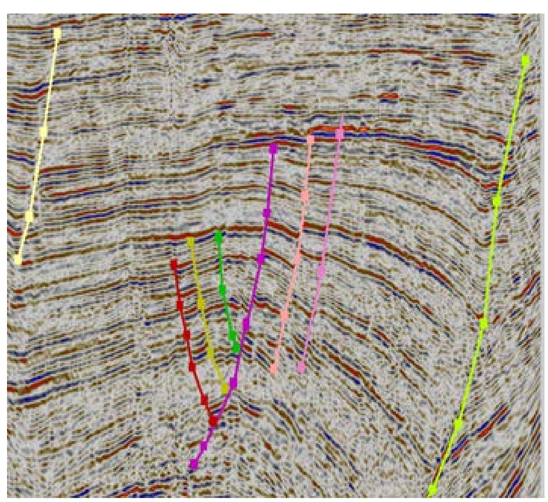

Fig. 7: Mapped faults and collapsed crestal structure in the Emerald Field

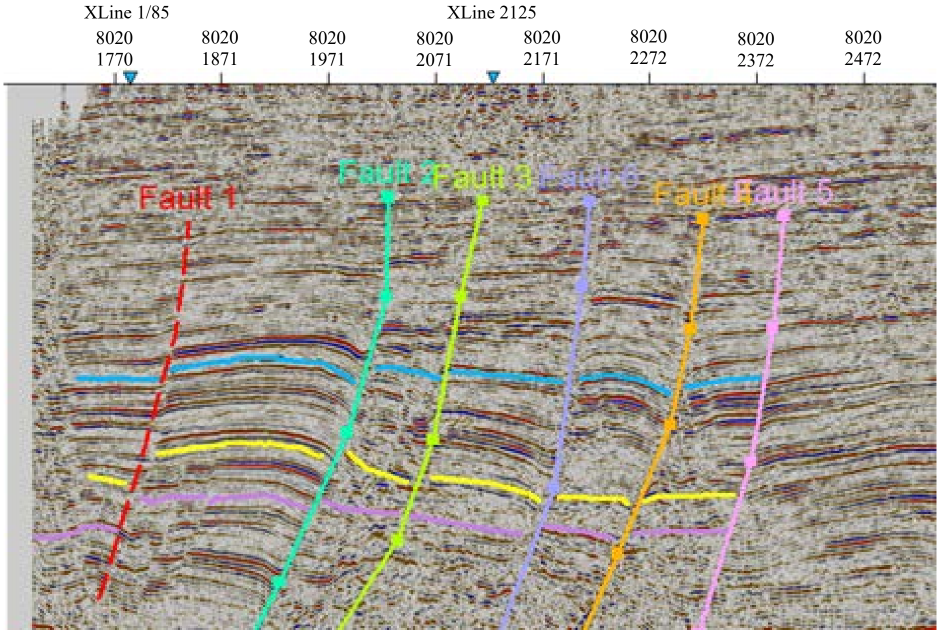

Fig. 8: Mapped horizon and faults in the Emerald Field

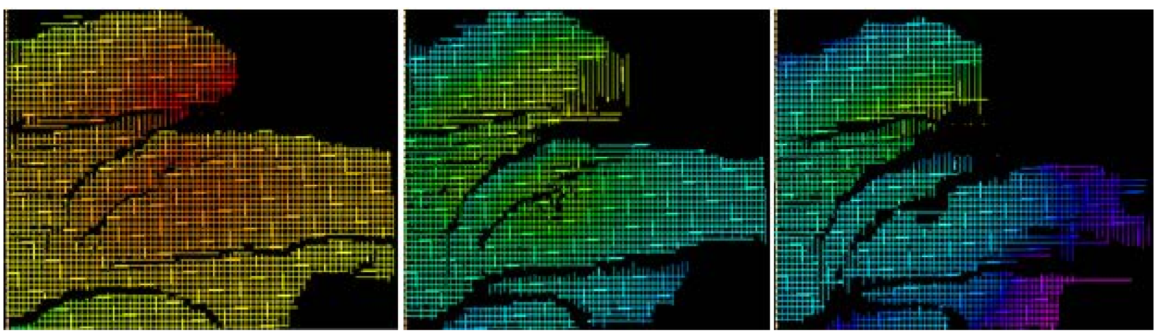

Fig. 9: Seismic density display of interpreted horizons with interpreted faults

representation of the subsurface geology. The time maps were depth converted to produce depth maps (Fig. 11).

Depositional environment: Following the Cant and Rider model, environment of deposition was inferred from the gamma ray logs as they reveal varying response to variations in grain size (Fig. 12). The log motifs interpreted from the logs in the study area include funnel, bell, symmetrical, cylindrical and irregular log patterns. Table 2 shows the interpreted gamma ray motifs, its subfacies, sub environment and inferred depositional environment.

Seismic facies analysis: Five seismic facies were identified within the study area (Fig. 13). They are seismic facies A, seismic facies B, seismic facies C, seismic facies D and seismic facies E.

Seismic attribute analysis: Seismic attributes analysis carried out within the study area revealed prospective zones where the drilled wells did not penetrate. RMS amplitude, envelope, sweetness, instantaneous frequency and reflection intensity attributes were selected and used in this study because of their application as Direct Hydrocarbon Indicators (HDI) (Fig. 14, 15). Correlating these attributes with the structural closures as seen on the depth structure maps depicts the presence of prospective zones within these areas.

Two prospects (Emerald prospect 1 and Emerald prospect 2) and one lead were identified based on the integration of the 5 seismic attributes interpreted on time slices and vertical transects (Fig. 14, 15, 16). The anomalies were identified based on their response to the seismic attributes which are indicative of the presence of hydrocarbon

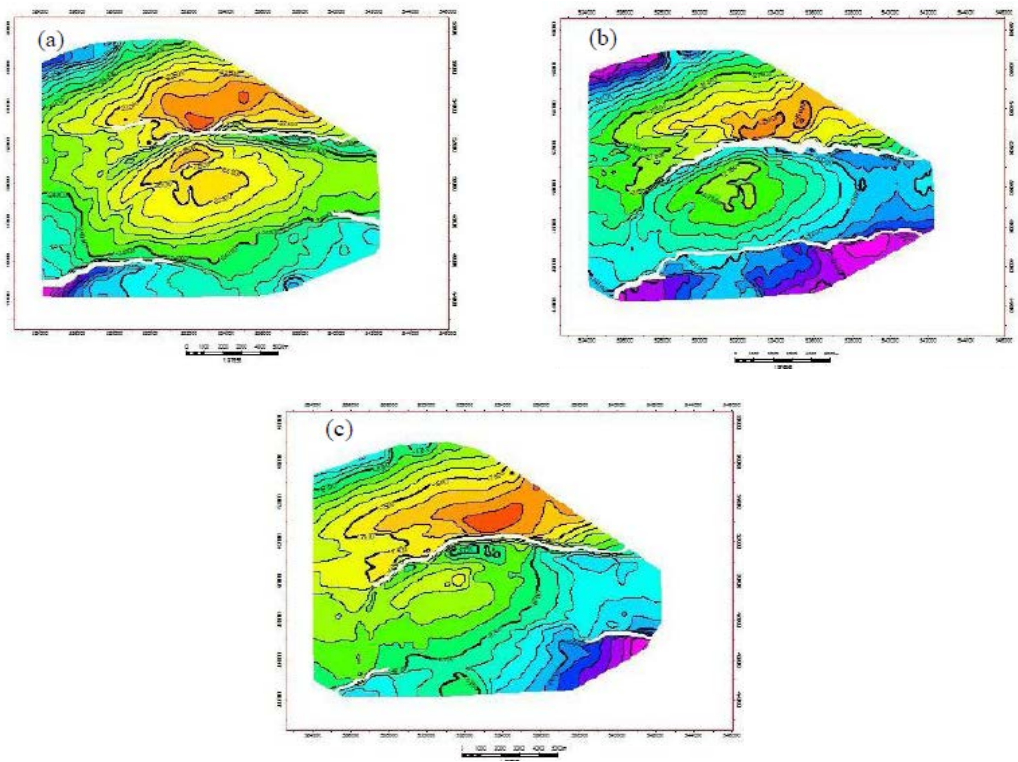

Fig. 10(a-c): Generated time maps of (a) 1, (b) 2 and (c) 3 horizon, respectively

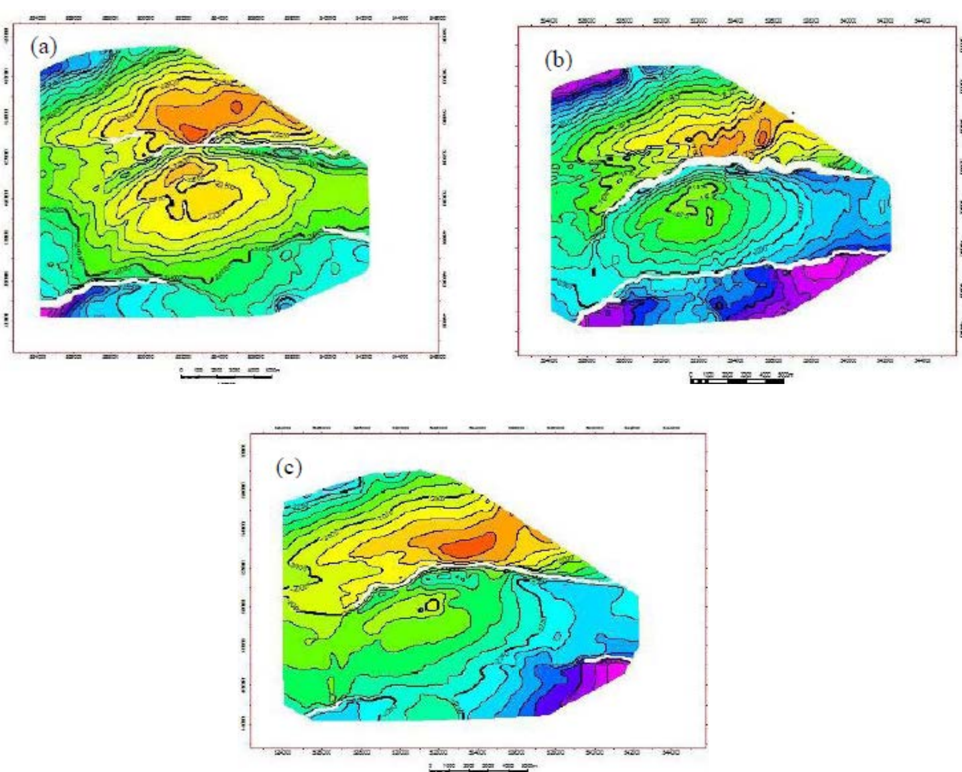

Fig. 11(a-c): Generated depth maps of horizon 1, 2 and 3 respectively

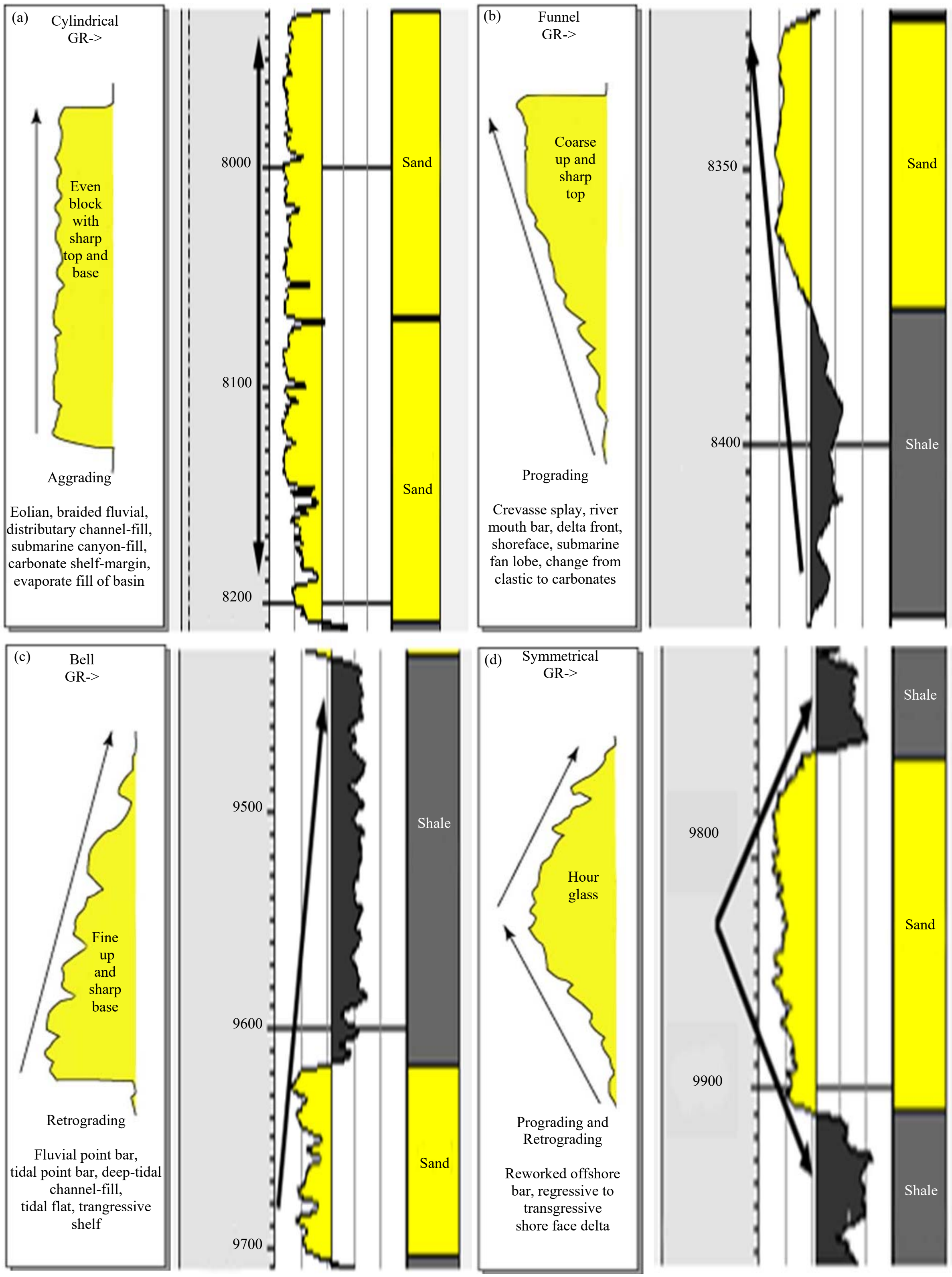

Fig. 12(a-e): Interpreted gamma ray log shapes for well Emy 002

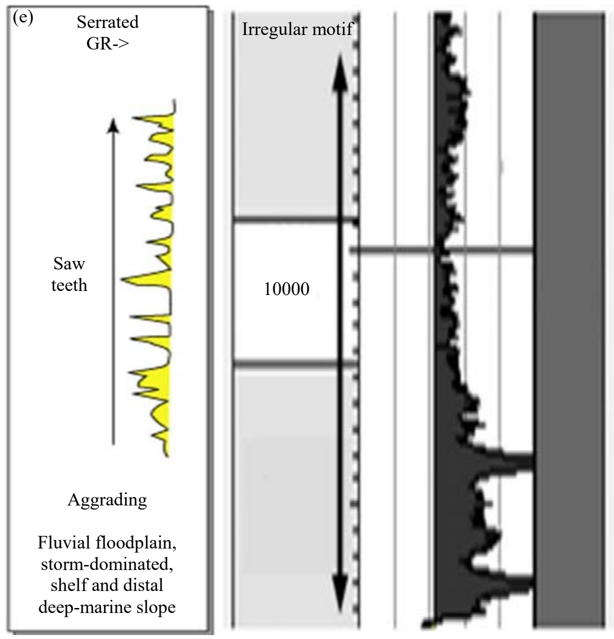

Fig. 12(a-e): Interpreted gamma ray log shapes for well Emy 002

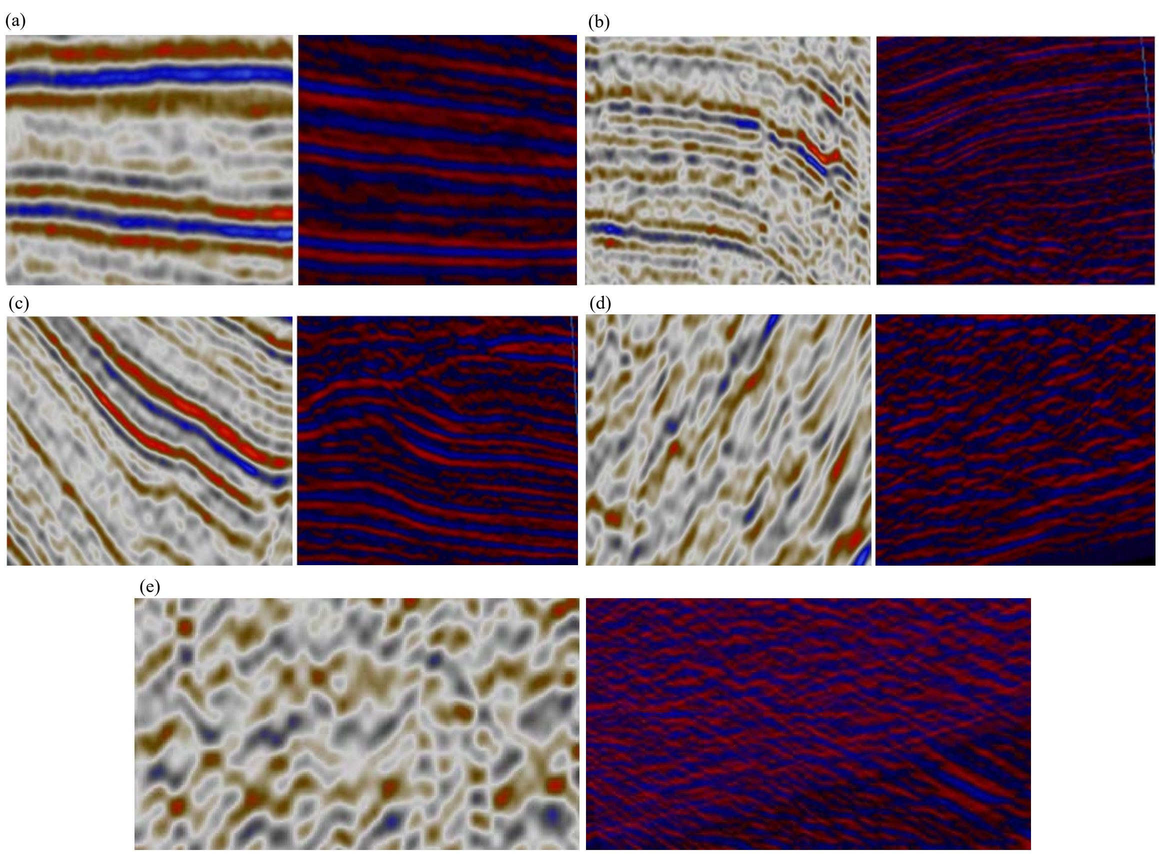

Fig. 13(a-e): Seismic facies characterization of the Emerald Field, (a) Seismic facies A, (b) Seismic facies B, (c) Seismic facies C, (d) Seismic facies D and (e) Seismic facies E

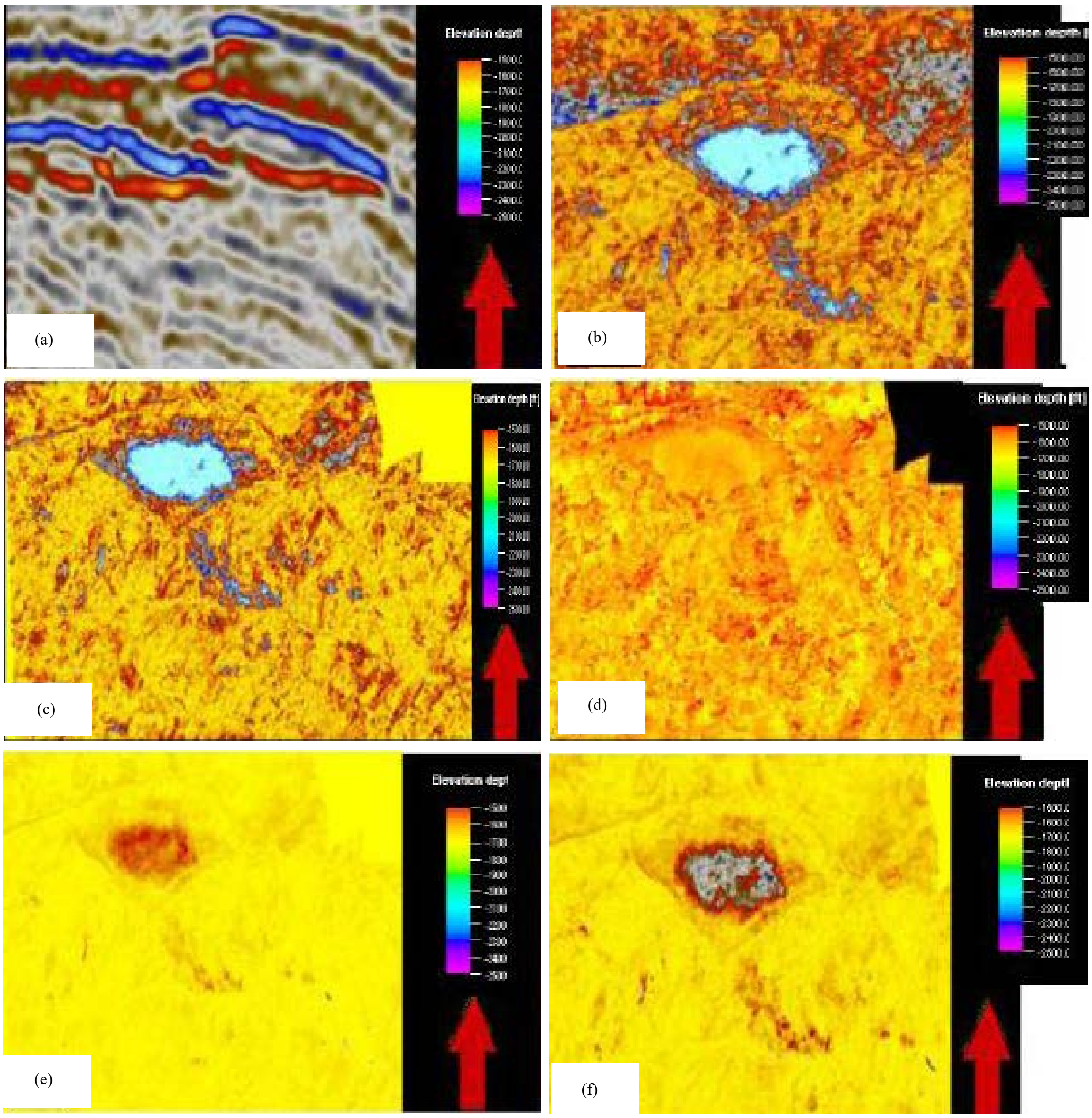

Fig. 14(a-f): Seismic attribute analysis at time slice-1294 ms, (a) Original seismic, (b) RMS amplitude, (c) Envelope, (d) Instantaneous frequency, (e) Sweetness and (f) Reflection intensity

attributes which are indicative of the presence of hydrocarbon accumulations. High values of original amplitudes (Fig. 14a, 15a) and localized high values of RMS amplitude attribute within the high original amplitude region reinforce the interpretation of hydrocarbon-filled sand (Fig. 14b, 15b). Localized high values of envelope attribute is indicative of porous lithologies which conforms to sands (Fig. 14c, 15c) while localized high values of instantaneous frequency attribute strengthens the presence of hydrocarbon (Fig. 14d, 15d). Localized high values of sweetness attribute within the high amplitude zones of the envelope attribute is indicative of hydrocarbon-filled sand (Fig. 14e, 15e) and localized high values of reflection intensity attribute within the high amplitude zone are indicative of hydrocarbon accumulation (Fig. 14f, 15f).

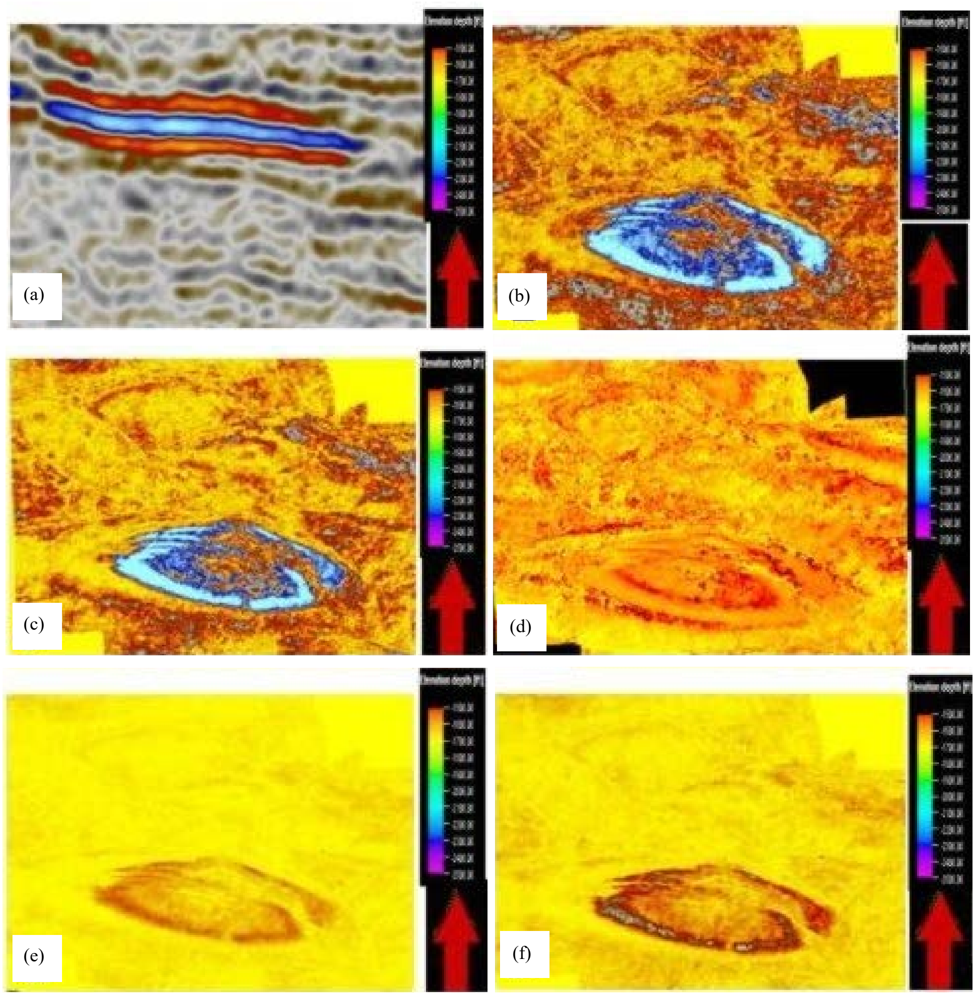

Fig.15(a-f): Seismic attribute analysis at time slice-1310 ms, (a) Original seismic, (b) RMS amplitude, (c) Envelope, (d) Instantaneous frequency, (e) Sweetness and (f) Reflection intensity

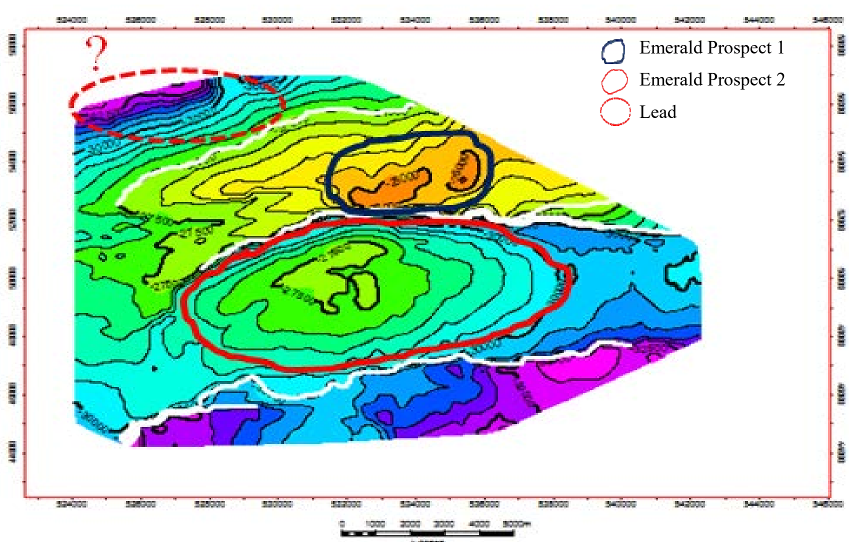

Fig. 16: Identified prospects and lead

Table 3: Result of the volumetric analysis

Reservoir	Bulk volume (m^3)	Net volume (m^3)	Pore volume (m^3)	HCPV (m^3)	OOIP	STOOIP	Recoverable oil (Barrels)
Emerald prospect A	32.295	27.019	6.034	4.747	44017.539	33859.646	276870.075
Emerald prospect B	222.531	186.184	4.158×10^{10}	3.271×10^{10}	303308.361	233314.124	1907809.589

Exploration risk assessment: Geologic chance of success (GCS) was estimated by carrying out a general overview on the existing key petroleum system elements which include the source rock, reservoir rock, seal, trapping mechanism and timing between hydrocarbon maturation and accumulation and trap formation. Confidence values were assigned to these elements:

Emerald prospect 1:

Source = 1
Reservoir = 1
Seal = 0.5
Trap = 0.6
Timing = 1
GCS = 0.3 (30%)

Emerald prospect 1 has a Geologic chance of success of 30% and failure risk of 70%. Emerald prospect 1 is a highly faulted zone and these faults compromised the integrity of the trapping mechanism as well as the seal.

Emerald prospect 2:

Source = 1
Reservoir = 1
Seal = 0.9
Trap = 1
Timing = 1
GCS = 0.9 (90%)

Emerald Prospect 2 has a Geologic chance of success of 90% and failure risk of 10%.

Volumetric parameters were calculated for the identified prospects (Emerald prospect A and Emerald prospect B). The parameters calculated include: bulk volume, net volume, pore volume, hydrocarbon pore volume, original oil in place and stock tank original oil in place. Results of the calculated volumetric parameters are summarized in Table 3.

DISCUSSION

The Benin Formation comprises uniform blocky sand with very thin shale interbeds, while the Agbada Formation consists of sand-shale intercalations. From the gamma ray log, the base of the Benin Formation was penetrated at about 1475 m. The Agbada Formation tends to exhibit thicker sandstone intervals towards the top and thicker shale intervals towards the base[20].

The identified faults are classed into major and minor faults. The major faults dip southward towards the basin and trends in the east-west direction. They extend through most of the stratigraphic interval and create large vertical displacement of the strata. The minor faults have less vertical extent and cause less vertical displacement. Chinwuko *et al.*[17] and Anakwuba *et al.*[21] reported that the interpreted faults may act as traps or migration pathway for hydrocarbon.

The cylindrical log pattern indicates constant depositional high energy. The funnel log pattern presents a coarsening upwards trend with increasing sand content towards the top, indicating increasing energy of deposition up-section as the coastline advances seawards[16,17,20]. The bell motif represents a fining upward trend with sand at the base and increasing silt and clay towards the top of the bed. Symmetrical log reveals an alternation of depositional energy with an upward change from shale-rich to sand-rich and back to shale-rich facies, reflecting a coarsening-upward and fining-upward sequence. The irregular log motif reflects uniform low depositional energy of shale-rich facies. They are indicative of mud prone succession and record accumulation within an overbank setting, which reveals a flood plain deposit.

Seismic facies A is characterized by moderate-to-high amplitude, variable continuous and parallel reflections truncated by faults. Parallel reflection patterns suggest uniform rates of deposition and are characteristics of a marginal marine environment. Seismic facies B is characterized by moderate amplitude, variable continuity and sub-parallel reflection patterns. The reflection geometry suggests a marginal marine environment. Seismic facies C is characterized by moderate amplitude, low continuity and divergent reflections. This seismic facie is interpreted to be a shore-face environment deposit. Seismic facies D is characterized by poor-to-low variable amplitude, package of short, irregular hummocky zones. This reflection pattern is interpreted to be distributary channel fills and overbank deposits within the shore-face environment. Obiadi *et al.*[11,15] stated that seismic facies E is characterized by low amplitude and chaotic internal reflection. The reflection geometry is indicative of soft sediment deposition. Reflections with poor continuity and chaotic zones suggest rapid sedimentation, mostly shale interbedded with sand. They have low-to-moderate frequency.

CONCLUSION

Integration of the available dataset has enabled the interpretation of the structure, lithology and depositional environment of the Emerald Field. The dominant lithology consists of sandstones, siltstones and shales. Petrophysical analysis of the study area reveal significant hydrocarbon saturation and porosity ranging from 10-29%. Several synthetic, antithetic and down to basin faults were mapped. The seismic facies and log patterns identified within the study area points to paralic depositional environment. Two prospects (Emerald prospect A and Emerald prospect B) and one lead were identified.

SIGNIFICANCE STATEMENT

This study has shown that the use of 3D seismic data to interpret old producing fields is very important in assessing field development. 3D seismic approach provides the best tool to identify the seismic stratigraphic and structural framework of an area for future field development.

This study therefore utilizes the predictive nature of 3D seismic interpretation to unravel an understanding of the litho-stratigraphy, structural complexity and economic potential of the Field with a view to reducing failure risks and enhancing future field development.

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