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Geological Evaluation of Hydrocarbon Prospect of FOB-field, Coastal Swamp Depobelt, Onshore, Niger Delta Basin, Nigeria

Frankie O. Balogun[1], Franklin A. Lucas[2] and Osarodion Ebomwonyi[3*]

[1]Department of Geology, Federal University of Lafia, Lafia P.M.B. 146, Nigeria.
[2]Department of Geology, University of Benin, Benin City P.M.B. 1154, Nigeria.
[3]Department of Physics, University of Benin, Benin City P.M.B. 1154, Nigeria.

Authors' contributions

This work was carried out in collaboration amongst all Authors. Author FOB designed the study, performed the statistical analysis, wrote the protocol and the first draft of the manuscript. Author FAL managed the analyses of the study. Author OE managed the literature searches and wrote the final draft of the manuscript. All Authors read and approved the final manuscript.

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ABSTRACT

Well logs, biostratigraphic data, seismic data and semblance map which together form a multidisciplinary data approach, were utilized in the geological evaluation of hydrocarbon prospect FOB-Field, onshore Coastal Swamp Depobelt in the Niger Delta Basin. Structural interpretation of faults, correlation of wells and 3D seismic interpretation were carried out using Schlumberger's window based petrel software integrated with various lines of evidence such as sequence boundaries and maximum flooding surfaces. The penetrated sedimentary succession was established to constrain the alternation of sand packages from proximal to distal. The studied wells were dated mid to late Miocene based on the geological position of the sequence boundary (10.35Ma) and geological ages of the Mfs (9.5MaMfs) and (10.4MaMfs) respectively corresponding to the Coastal Swamp Depobelt of the Niger Delta Basin. Integration of well logs, seismic, semblance, paleobathymetric and biostratigraphic data indicated mid to late Miocene and neritic to

*Corresponding author: E-mail: osarodion.ebomwonyi@uniben.edu;

bathyal paleoenvironment of deposition. Integration of fault integrity, seismic, well logs and key stratigraphic markers were utilized to build a seismic facies model and a gross depositional environment model for the FOB-Field.

Keywords: Paleobathymetric; correlation; semblance cube; depobelt; paralic.

1. INTRODUCTION

The subsurface Niger Delta Sedimentary Basin is ranked as a highly productive hydrocarbon region and one of the biggest Tertiary Deltaic Systems in the world [1]. This sedimentary Basin is located in the Southern part of Nigeria with age ranging from the Cretaceous to present [2]. Also, the Basin is located at the region where both the Benue Trough and the South Atlantic Ocean intersects, a point where a triple junction developed during the Late Jurassic separation of South America and Africa plate with location within longitudes 3º-9ºE and latitudes 4º-6ºN [3].

The Akata, Agbada and Benin Formations are the three subsurface stratigraphic units in the Niger Delta Basin [1,2]. The Basin contains only one identified petroleum system referred to as the Tertiary Niger Delta (Akata –Agbada) Petroleum System [4,5]. The Benin Formation is made up of mainly non-marine sand deposits in the coastal plain environments [6], while the Agbada Formation is the main hydrocarbon prospective sequence, deposited in a transitional to marine paralic environment [7]. Furthermore, the Akata Formation is of marine origin and the basal unit made up of thick shale sequence; that is, the potential source rock within the basin [8].

Geological assessment of hydrocarbon prospect is an important tool in the petroleum industry as a tool for defining geologic constraints on predictions of exploration and evaluation of prospects. In order to determine the continuity and equivalence of lithologic units for the reservoir sands and marker sealing shales of the wells in the studied area, correlation was carried out. Using the gamma ray logs as a preliminary investigation to correlate the wells, major sandstone units were identified; and detailed correlation work with emphasis on the shale sections were obtained using the deep resistivity log. The reasons for concentrating on shales include but are not limited to the fact that, clay and mud particles which make shales are deposited in low energy regimes. These low energy environments are responsible for shale deposition commonly over large regional areas. Consequently, the log signatures in the shale are highly correlated from well to well and can be recognized regionally. Secondly, prominent sand beds are often not good correlation markers because they frequently exhibit significant variation in thickness and character from well to well and are often laterally discontinuous.

Previous studies on the geological evaluation of hydrocarbon prospect of fields have always been done using only sequence stratigraphy, well logs, biostratigraphic and paleobathymetric data which does not give a clear reflection of the hydrocarbon prospects of these fields; hence the need for this study which is aimed at integrating seismic data and semblance cube to obtain detailed evaluation of these fields of interest, thus bridging the existing knowledge gap in this area.

As a result of the difference in hydrodynamic conditions common in the Niger Delta, reservoirs exhibit a wide range of complexities in their sedimentological and petrophysical characteristics in the Niger Delta depositional settings. The Niger Delta basin lies within the Gulf of Guinea continental margin in equatorial West Africa between longitudes 50º and 80ºE and latitudes 30º and 60ºN. How best the field will produce lies on the petrophysical evaluation of the reservoir quality of sand bodies. Petrophysical assessment is concerned with the rock proportion that determines the quality, quantity, recoverability of hydrocarbon in a reservoir rock. A reservoir rock therefore, has to be a formation that has the ability to release and allow flow of fluid, and having the capacity to store the fluid. The potential and performance of a reservoir rock include porosity, permeability and fluid saturation which are fundamental parameters. The relationships among these properties are used to identify and evaluate reservoir rocks. The study was aimed at carrying out a detailed hydrocarbon evaluation of reservoir rock of FOB-field using a multi-disciplinary data approach in reconstructing a high resolution biostratigraphic and sequence stratigraphic framework for the FOB- field in the onshore western Niger Delta Basin.

2. BRIEF REVIEW OF RESEARCH

2.1 Geologic Setting

The Niger Delta Basin, due to its economic importance as a result of the abundance of hydrocarbon has been subjected to in-depth studies over the years by researchers [5,8]. The basic geology, evolution and structural setting, sequence stratigraphy, biostratigraphy, lithology and depositional environment of the Niger Delta Basin have been explored and evaluated by most researchers [9,10]. Other works carried out by researchers include field development strategies, production characteristics and optimization mechanisms of the Niger Delta Basin [7,11].

Studies in the Niger Delta has been based on its origin and it is confirmed that the Tertiary deltaic fill is constituted by a strong diachronous (Eocene-Recent) sequence which is outlined in its general geology [2]. The Niger Delta Basin is sub-divided into three stratigraphic units namely: the Akata Formation, Agbada Formation and Benin Formation. According to Evamy et al. [12], two possible migration pathways in the Niger Delta were identified. They are the migration along the structure building faults which terminate in the Akata Formation and the migration from the seaward facies which change up-dip into the rollover structures. Furthermore, the fault blocks in the Niger Delta were classified into a hierarchy of macro-structural blocks, which make up distinct provinces in terms of time, stratigraphy, deformation, sedimentation, generations and migration of hydrocarbons and their distribution. Ekweozor and Okoye [8] carried out petroleum source bed evaluation of Tertiary Niger Delta and established that the humic and mixed types kerogen are the dominant sedimentary kerogen in the Niger Delta. It was also stated that habitats of the hydrocarbons are mainly the sandstone reservoirs in the paralic sequence of the Agbada Formation, where the hydrocarbons are characteristically trapped by growth faults at the crest of rollover anticlines. Omatsola [13] concluded that reservoir sands of more than 15 m thick in most places represent composite bodies, and may consist of two to three stacked channels. The sands are poorly consolidated and have porosities as high as 40% in oil bearing reservoirs. Porosity reduction with depth is gradual and permeability in hydrocarbon reservoirs are commonly in the range of 1-2 Darcy.

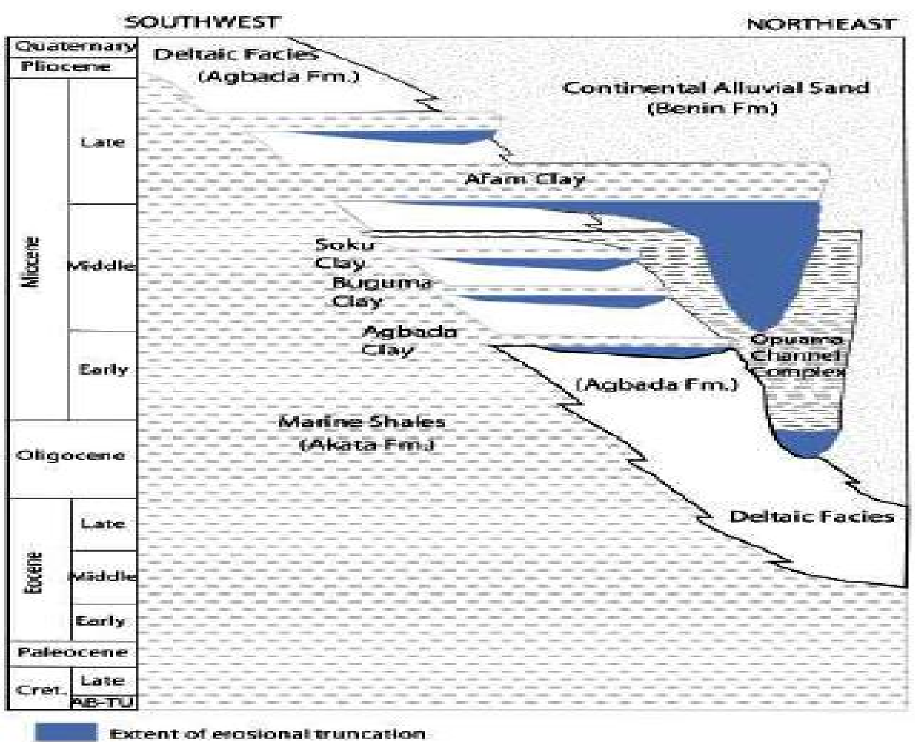

Fig. 1. Stratigraphy of the Niger Delta Basin [11]

2.2 The Stratigraphy of the Niger Delta

The central part of the delta is made up of about 8534 m of the section at the approximate dopecenter [9]. As one moves from proximal to distal end of the basin, there is decrease in age, showing the total regression of depositional environments within the Niger Delta clastic wedge. The three formations i.e. the Akata, Agbada and Benin Formations are found mainly in the southern part of Nigeria. They reflect a gross coarsening-upward progradational clastic wedge [2]; with the Akata Formation deposited in marine, the Agbada Formation deposited in deltaic, and the Benin Formation deposited in fluvial environments [14]. The Akata Formation is approximately 4586 m thick in the central part of the clastic wedge composing of undercompacted and overpressured sequence of shales and siltstone [6]. The formation where there is alternation sequence of paralic sandstone and shale and occurring throughout Niger Delta clastic wedge is the Agbada Formation. It has a maximum thickness of about 3658 m. It outcrops in southern Nigeria between Ogwashi and Asaba, hence it is popularly referred to as the Ogwashi-Asaba Formation [1]. Overlying the Agbada formation is the Benin formation, consisting mainly of sands and gravels with thickness ranging from 0 – 1829 m as shown in Fig. 1.

3. MATERIALS AND METHODS

3.1 Study Location

The field under study is pseudo-named FOB-Field in accordance with Shell Petroleum Development Company of Nigeria (SPDC) confidentiality agreement. The field is an onshore field located within the Coastal swamp Depobelt of the Niger Delta as shown in Fig. 2.

3.2 Experimental Procedures

Biostratigraphic data and the interpretation of well log data, 3D seismic volume and semblance cube are the analytic approaches used in the study. Schlumberger's windows based PETREL software was used in the interpretation

Fig. 2. Concession map of Niger Delta showing the study area, the FOB-field

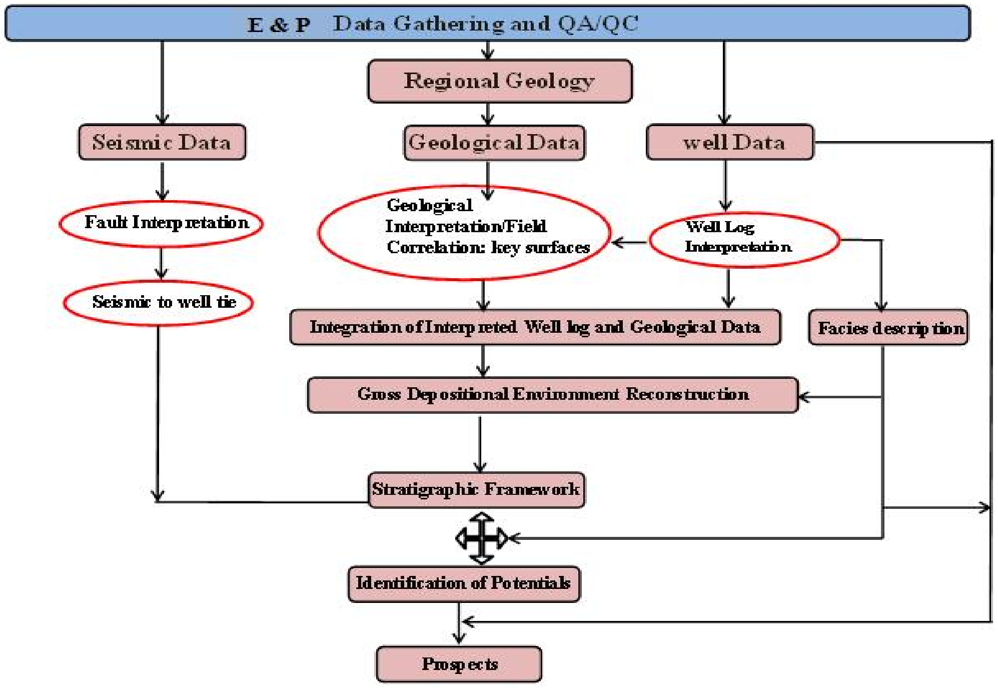

Fig. 3. Integrated workflow

of faults, correlation of well logs on the correlation panel, with integrated approach through consideration of various lines of evidence, such as maximum flooding surfaces and sequence boundaries. Every form of data obtained by researchers, account for the distinct section of geological problems faced during exploration and evaluation of prospects. Seismic data for instance, provides the largest scale framework of strata geometries, both locally and regionally. Finer scale information on lithology and depositional system are supplied by well log interpretation. Condensed sections, chronostratigraphic surfaces, paleobathymetry and climatic conditions can be ascertained using biostratigraphic data. Thus, expertise in these disciplines as well as an integrative strategy is required to generate a model, implying the need for a multidisciplinary data approach, upon which this study is predicated. A schematic workflow is presented in Fig. 3.

4. RESULTS AND DISCUSSION

4.1 Correlation of Wells

Correlation was carried out to determine the continuity and equivalence of lithologic units for the reservoir sands and marker shales of the five wells in the study area as shown in Fig. 4.

The wells were correlated using the gamma ray logs as an initial quick look to identify the major sandstones unit; and the deep resistivity log for detailed correlation work with emphasis on the shale sections. The reasons for concentrating correlation work on shales include but are not limited to the fact that, clay and mud particles which make shales are deposited in low energy regimes. These low energy environments are responsible for shale deposition commonly over large geographic areas. Therefore, the log curves in the shale are highly correlated from well to well and can be recognized over long distances. Secondly, prominent sand beds are often not good correlation markers because they frequently exhibit significant variation in thickness and character from well to well and are often laterally discontinuous. In addition, the resistivity curves for the same sand and two well logs being correlated may be due to fluid in the sand [15]. The correlation is focused at deriving information from the subsurface such as: Lithologic continuity, Formation tops and bases, Depth to and thickness of hydrocarbon bearing zones and Integration of the information derived from well logs, seismic to infer the reservoir sand bodies and gross depositional environment of the FOB-Field. Therefore, well (HOB-01 Well) has two reservoir sands at 2195-2377 m and 3018-3505 m depth respectively.

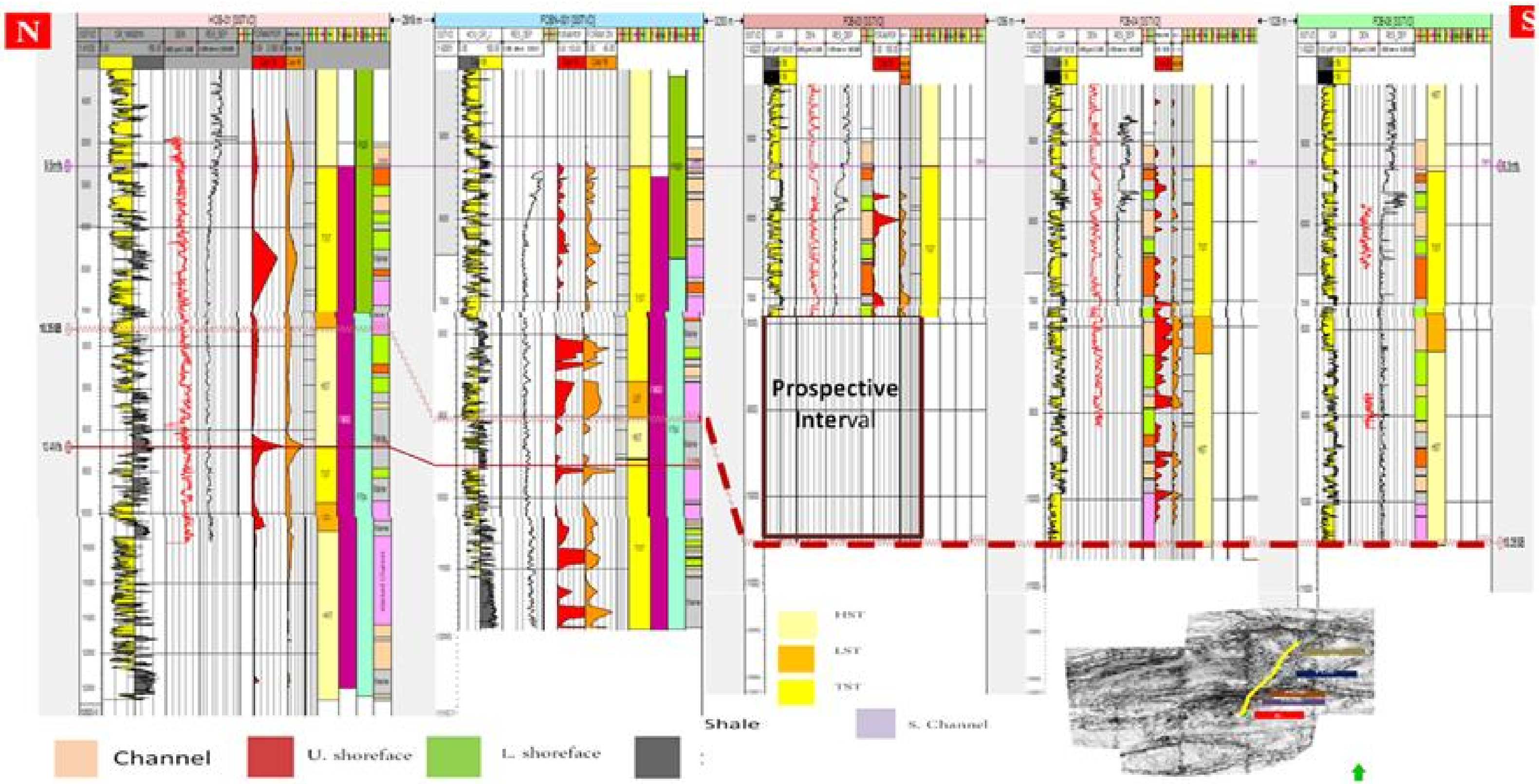

Fig. 4. Dip Section Correlation of FOB-Wells

4.2 Horizon Interpretation and Time-depth Conversion

Horizon interpretation was done by trying to identify the major stratigraphic packages, unconformities, maximum flooding surfaces or sequence boundaries which were observable on the vertical seismic display of a seismic line, see Fig. 5. The procedure was to first identify observable horizons or group of horizons with similar attributes. This was followed by creating the horizons or group of horizon and lastly picking of the horizons of interest to digitize them. Peaks in the seismic data that correspond to these surfaces were traced along the available seismic transects and the interpretations were viewed independently of the data. The two horizon mapped in this study were 9.5Ma and 10.4Ma respectively, which represent the key stratigraphic top surfaces. A time structural map was derived and converted into depth for accurate subsurface prospect identification. The major faults identified are mainly growth faults and listric faults which flatten with depth.

4.3 Structural Interpretation

The dominant structure in the area of interest is growth fault triggered by contemporaneous deformation of the deltaic sediments. Most faults are listric, that is, shows marked flattening with depth. They affect the paralic and marine facies and die out upwards the massive continental facies. Near the top of the paralic sequence, the dip of the fault planes can be steep but flatten out with depth, partly due to the curvature of the fault planes and in part as a result of the effect of compaction [13]. The most active fault is the F_1 because it is active from depth to the surface as shown in Fig. 6, while the least active fault is the F_4, because it started late and ended early. The activeness of these faults enhances the sand packages, the tilting of these sands result in rollover structures. The F_1 is active between 750-3750ms while F3 is active between 750-3225ms respectively.

4.4 Seismic Facies Analysis

Seismic reflection parameters, such as configuration, continuity, amplitude and frequency, within the stratigraphic framework of a depositional sequence as shown in Fig. 7 is described and interpreted using seismic facies analysis. The aim is to ascertain all variations of seismic parameters within third-order sequences and their systems tracts in order to determine lateral lithofacies and fluid type changes. Of these parameters, reflection pattern geometries are perhaps the most useful for

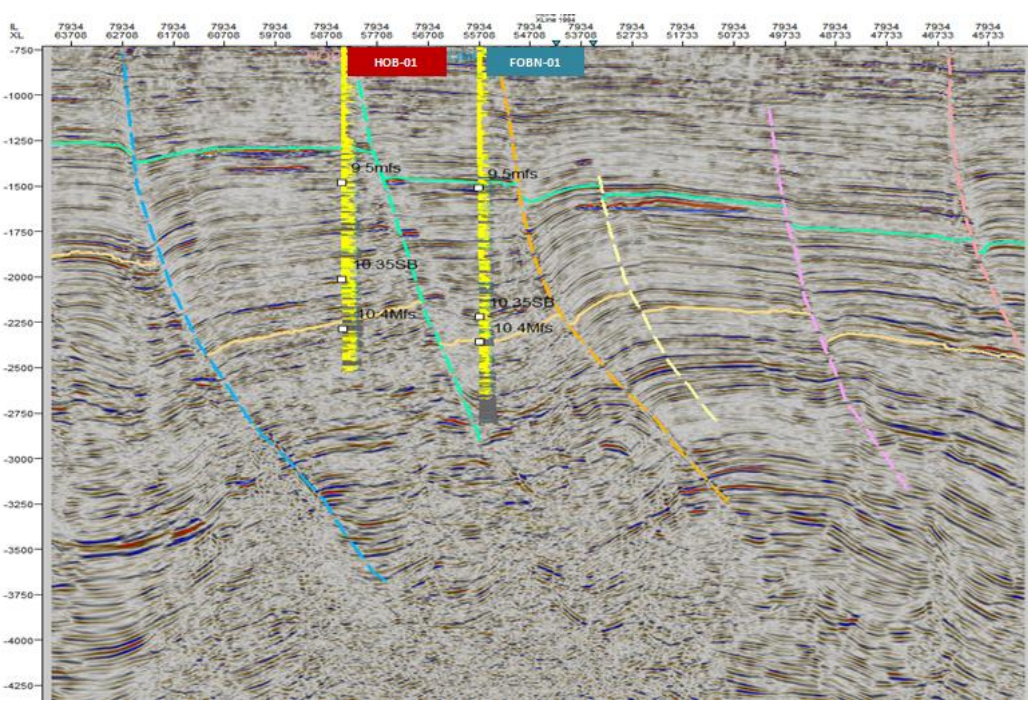

Fig. 5. Seismic section showing horizons and fault sticks

calibration with lithofacies interpreted from well logs, cores, and cuttings. The seismic facies interpretation and the subsequent depositional environments are given below:

1) Between 0-1500ms: A discontinuous low amplitude somewhat chaotic reflection character punctuated by discontinuous high amplitude events. From the superimposed logs (Fig. 7), a high net to gross which conforms to no change in acoustic impendence observed This seismic reflection character is characteristic of the continental-transitional environments (Benin Formation).
2) Between 1750ms-3000ms: A high-medium amplitude parallel continuous high frequency reflections; the decrease in net to gross from the superimposed logs conforms to high acoustic impedance contrast. There exist no inclinations of reflection or divergence. These are characteristic of the inner to mid shelf (shoreface) environment as shown in Fig. 7.
3) Below 3000ms: A relatively low amplitude discontinuous and continuous events: the presence of divergent inclined reflections, low-medium acoustic impedance contrast, which are characteristic of outer margin environment (Shelf Edge Delta's).
4) Discontinuous low frequency dipping seismic reflections characteristics of slope environments, thus integrating all of these evidences, it is inferred that the study area lies within the Outer Shelf-Shelf margin environment.

4.5 Gross Depositional Environment Model (GDE)

The Gross Depositional Environment (GDE) model for the study area, Fig. 8 was also defined using an integration of evidences from paleobathymetric profile, log motif, seismic facies analysis and gross depositional environment model for Niger Delta.

The conceptual environment of deposition is an integration of the well logs, semblance cube, seismic data, fault, biostratigraphy and paleobathymetry. Facies is a body of sedimentary rock distinguished from others by its lithology, geometry, sedimentary structures, proximity to other types of sedimentary rock, and fossil content, and recognized a characteristic of a particular depositional environment.

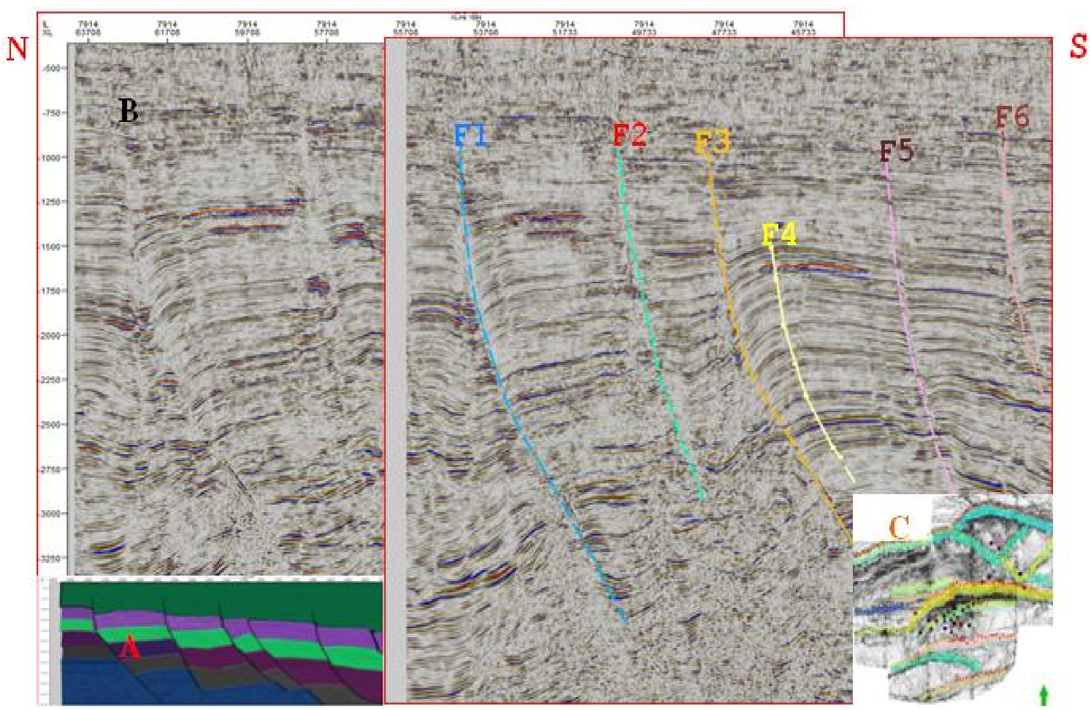

Fig. 6. (A) Structural data interpretation, (B) model of fault sticks, (C) semblance showing structural trend of fault

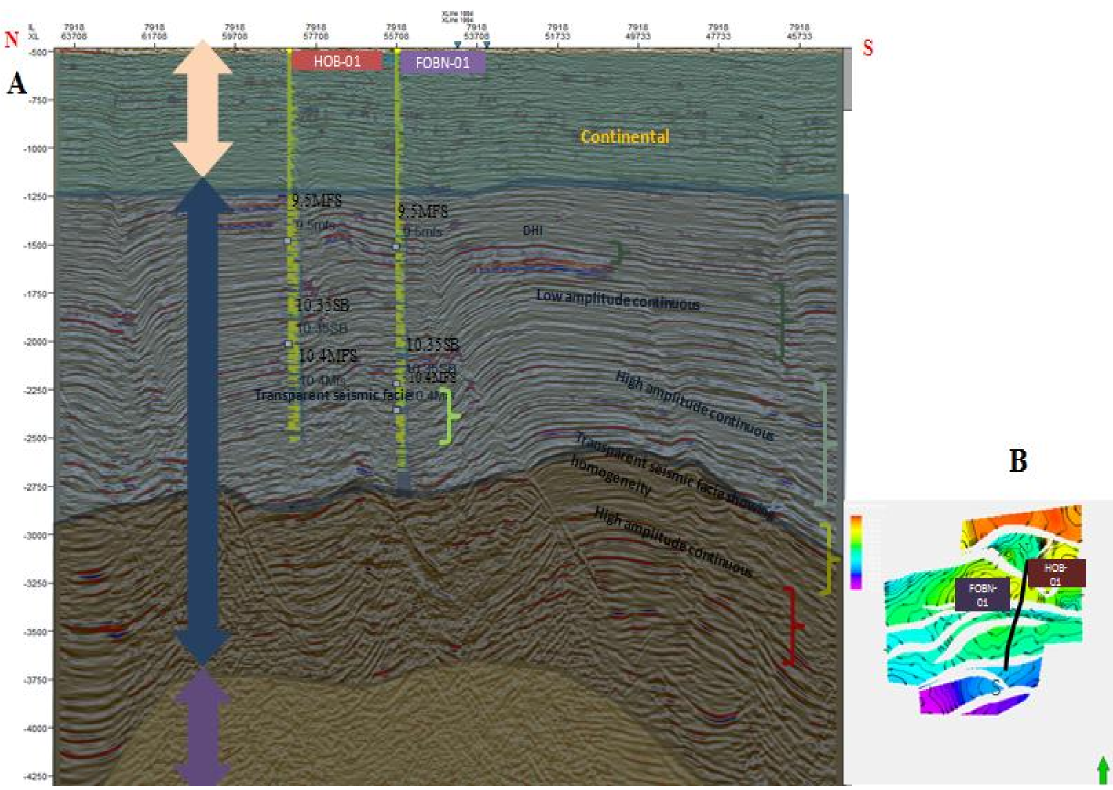

Fig. 7. (A) Seismic facie analysis, (B) semblance map

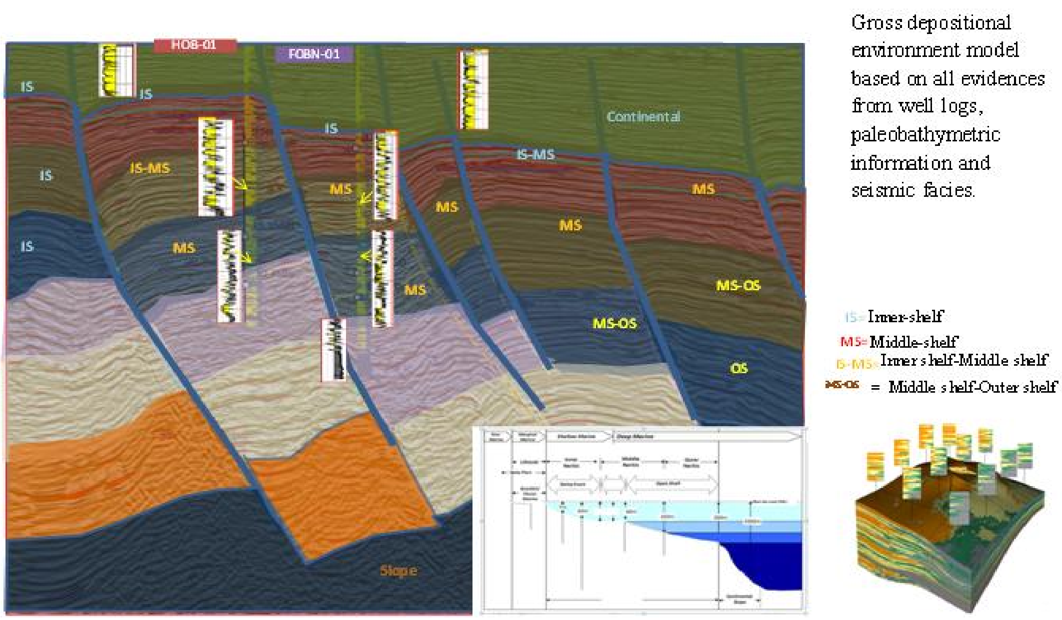

Fig. 8. Gross depositional model

Typically water depth in this domain ranges from 50-300 m and the stratigraphy comprises many different sedimentary environments (including slump scars and their deltaic infill, distributary channels, outer shelf mud's and sands, slope mud's and silt etc.). Sedimentary environments are influenced strongly by relative base level change; during relative sea-level falls; shelf and deltaic sands can reach the shelf edge, accumulating in thick sand parasequence sets that are often referred to as Shelf Margin deltas [15]. These parasequences are dominantly of falling stage or lowstand systems tract, but may form anywhere in the sea-level cycle so long as the sediment supply exceed the accommodation space on the shelf allowing rivers to advance to the shelf edge.

During transgressive (or high stand periods), shelf edge deltas are largely areas of mud deposition, as sands are trapped in growth-fault induced accommodation proximal.

The steps taken for GDE definition follows from Grant et al. [15] and are below:

i. Sand bodies with blocky or upward coarsening log motifs encased in high-gamma ray mudstones with an outer neritic/bathyal (ON-BA) biofacies environment. Sands are thought to have poorer lateral continuity and are more channelized than regular Highstand System Tract/Transgressive System Tract shelf sequences.
ii. Clinoform sets with height that exceeds the water depth on the shelf.
iii. Intervals displaying a flat-lying or gently upward or down tilting shelf-edge trajectory.
iv. A range of synsedimentary deformational features, such as growth fault.

The ideal method of analyzing facies is through core data which is the closest representation of the reservoir. In the absence of core data, log motif is used to analysis facies. Due to absence of core data, facies identification was based strictly on log motifs. Generally, facies with sharp base, fining upward/blocky signatures are taking as possible channel deposits in the clastic environment, while coarsening upward signatures are taking as shoreface deposits. This is based on the process of deposition associated with each deposit type; Fig. 9 was used as a guide in identifying the various facies and log motif.

The reservoir sands delineated are shoreface, channel and stacked channel sands. The major trapping mechanisms (structures) are growth faults. The geologic age of SB interpreted is10.35Ma while the MFS are 9.5MaMfs and 10.4MaMfs respectively corresponding to Coastal Swamp Depobelt. Reservoirs penetrated are at 2195-2377 m and 3018-3505 m depth respectively. The geologic age of SB interpreted

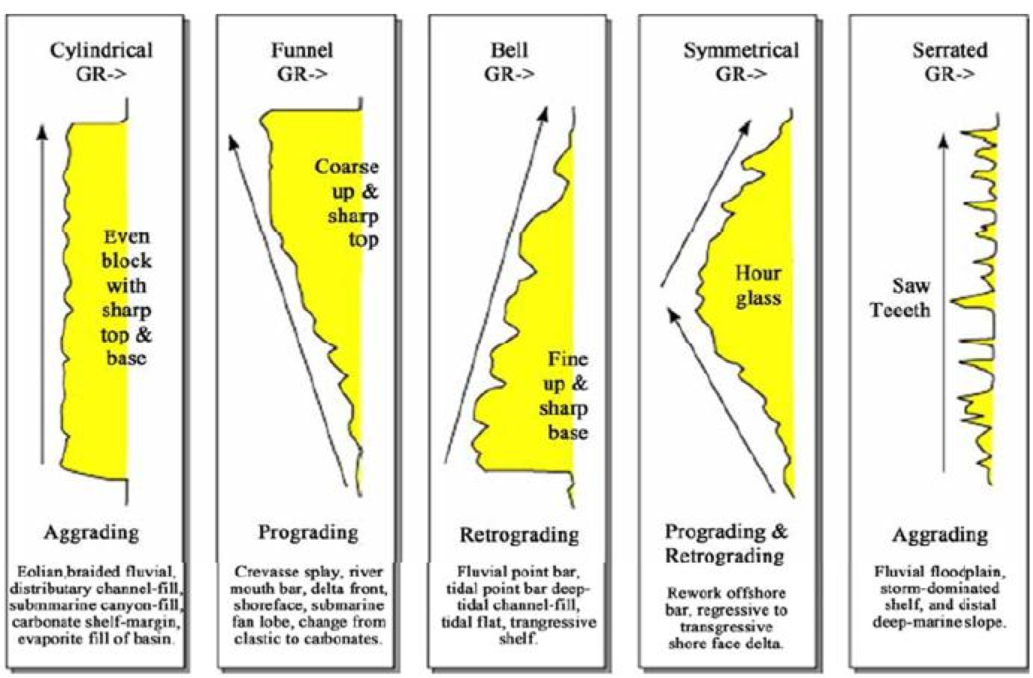

Fig. 9. Well log response character for different environments [16]

are 10.35Ma while the MFS are 9.5MaMfs and 10.4MaMfs respectively corresponding to Coastal Swamp Depobelt. The studied wells in the FOB-field were dated Mid-Late Miocene. The delineated sequences comprises of Lowstand System Tract (LST), Transgressive System Tract (TST) and Highstand System Tract (HST). The sand of the LST and HST shows good reservoir qualities while the shales of the TST could form potential reservoirs. These sequences are deposited within the neritic to bathyal paleoenvironment.

The gross depositional environment model was built based on the integration of well log, seismic data, biostratigraphic data and paleobathymetric data to further ascertain the direct hydrocarbon indicator. The model can also be utilized to delineate subsurface strata with high acoustic impedance. The biostratigraphic data act as the stratigraphic boundary, the paleobathymetry defines the environment of deposition, while the seismic data interpret the seismic facies and the homogeneity or heterogeneity of the seismic amplitude. The well log signature reveals the log motif pattern of reservoir sand. Therefore, with the acquisition of similar data from any location, the developed gross depositional environment model can be replicated in those locations to determine the direct hydrocarbon indicators and also to delineate the acoustic impedance of the subsurface formation of that location.

5. CONCLUSION

Integration of well logs, seismic, semblance, paleobathymetric and biostratigraphic data was utilized to build a Gross Depositional Environment (GDE) model for FOB-Field. The geologic ages of position of SB interpreted was 10.35Ma while the MFS were 9.5Ma and 10.4Ma respectively corresponding to Coastal Swamp Depobelt. Reservoirs penetrated are at 2195-2377 m and 3018-3505 m respectively. From the analysis and discussion above, the following conclusions are made:

(i) The studied intervals of FOB wells were dated Mid-Late Miocene (10.35 Ma) based on the geological ages of sequence boundaries (SB) and positions of Maximum Flooding Surfaces (MFS) interpreted which range between sequence I (F9600, P820)-9.5MaMfs, sequence II (F9500, P780)-10.4MaMfs respectively corresponding to Coastal Swamp Depobelt. Reservoirs penetrated are at 2195-2377 m and 3018-3505 m depth respectively.
(ii) The alternation of shale and sand revealed that the studied interval belongs to paralic Agbada Formation of the Niger Delta Basin.

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COMPETING INTERESTS

Authors have declared that no competing interests exist.

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