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Facies model building of integrated multiscale data in Dn-Field, Onshore, Niger Delta, Nigeria

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Abstract

This study employs 3D Post-Stack Time-Migrated seismic data from the DN-Field, within the Coastal Swamp depobelt of the Niger Delta in predicting lithofacies and fluvial facies of OVK-1 sand bodies in the Agbada Formation, as a tool to identify new drillable prospects. A lithofacies model for OVK-1 reservoir sand body was generated after upscaling using Most Of, as the averaging method. Calibrated by fluvio-facies at the well locations, channel sands were identified in OVK-1 reservoir interval using Stochastic Sequential Indication Simulation (SSIS) algorithm. Based on lithofacies, fluvial facies and biofacies analyses, a terrigenous and shallow fluvio-deltaic fill within a lowstand system tract was evident. Petrophysical properties including porosity, volume of shale and effective porosity were upscaled, guided by facies model and then Stochastic Gaussian Simulation (SGS) algorithm was used to produce the model. Porosity model predicted sand layers having maximum porosity of 27.5% which implied very good reservoir potential. However, the volume of shale model with values from 0.45 to 0.50 incorporates silt and clay and indicates marginal reservoir potential. The study identifies four potential reservoir intervals with thickness ranging from 9.1 to 38.5 m. The effective porosity in OVK-1 ranges from 0.10 to 0.30 and identified fluvial facies such as floodplain, channel sand, levee and crevasse splay sand. Facies model show a good sand distribution with minor shale localized in the western part of the Field. The central part of the model has good reservoir qualities, evident by low volume of shale values and high porosities. This study helps to identify a potential unexplored drillable prospect on OVK-1 sand body south-west of DN-2 well. Successful drilling of the identified prospect could increase the reserve of the Field.

Keywords: Facies modeling; stochastic sequential indicator simulation; sequential gaussian simulation; Niger Delta; Nigeria.

Introduction

The Niger Delta is an active sedimentary basin [1] which is situated in the Gulf of Guinea (Figure 1a). It lies between Latitudes 3^{o} and 6^{o} N and Longitudes 5^{o} and 8^{0} E, and extends throughout the Niger Delta province as defined by Klett *et al* [2]. From the Eocene to the present, the delta has prograded south-westwards, forming depobelts that represent the most active portion of the delta at each stage of its development [3]. These depobelts form one of the largest regressive deltas in the world, with an area of 300,000 km^2 [4], sediment volume of 500,000 km^3 [5], and thickness of over 10 km in the basin's depocentre [6].

The Niger Delta is the most prolific sedimentary basin in sub-Saharan Africa, containing the 12th largest known accumulation of recoverable hydrocarbons, with reserves exceeding 34 billion barrels of oil and 93 trillion cubic feet of natural gas [7]. There is renewed exploration interest currently in the deepwater depositional systems, as about 50% of global oil production is currently from shallow marine, paralic and fluvial strata [8]. This necessitated the application of improved approaches for facies modelling in order to properly integrate multi-scale data in the exploration and field development of the vast hydrocarbon resources locked in these areas of the Niger Delta basin.

Facies modelling is a critical step in the life cycle of a reservoir characterization process. All petro-physical modelling is based on facies; geometric distributions are determined by geologic knowledge of facies

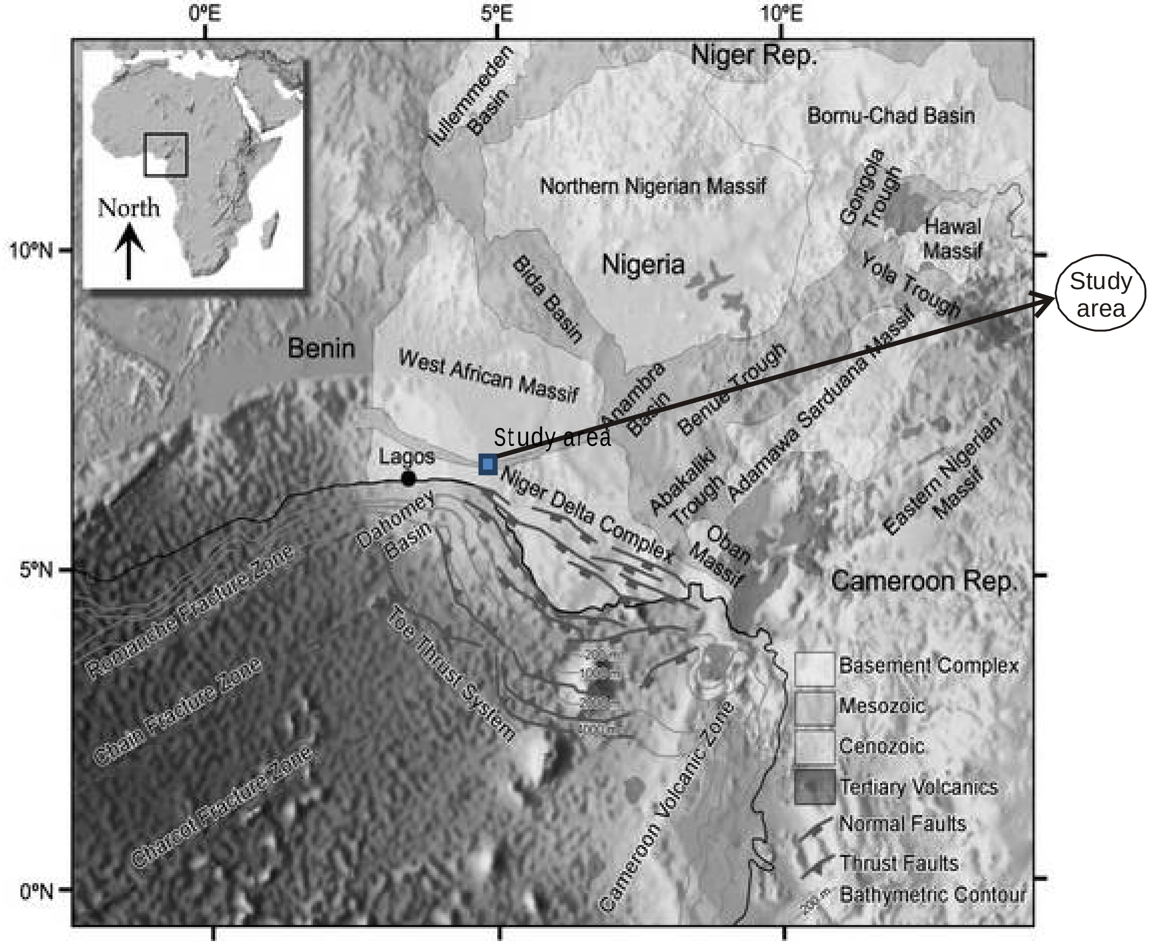

Figure 1a. Map of Nigeria showing the location of Niger Delta and associated tectonic features. Inset is the Map of Africa showing southern Nigeria (Corredor *et al* 2005).

deposition and the flow units controlling the production of a reservoir are generated directly from facies, or representation of the facies distributions [9]. As rightly remarked, a common challenge of facies modelling is the integration of multiple scale data to create a reliable facies model [9].

The sequential indicatior simulation (SIS) technique is a statistical tool that can be used to simulate a large number of equiprobable realizations of a particular property or attribute. It is a cell- (pixel) based modelling algorithm that uses the upscaled well observation as the basis to segregate the facies types to be modelled and also honour semivariogram (commonly referred to as variogram) and trends to constrain the distribution and connection of each facies as well as the histogram. Journel [10] states that the differences between the realizations themselves should provide a measure of spatial uncertainty about the input. This method is particularly useful as it produces geologically reasonable results in data-challenged areas with few well controls [11].

Ataei [12] applied the principle in the modelling of a turbidite reservoir in the Gulf of Mexico, where he found the reservoir lithology to be grossly heterogeneous. Afuye *et al* [13] developed 3D depositional and lithofacies models using Truncated Gaussian with Trends (TGT) and Truncated Gaussian Simulation (TGS) algorithms. With the available data set for this work, Sequential Indicator Simulation algorithm was found appropriate and ideal for producing the reservoir facies model with the limited well control. This study attempts to predict reservoir facies of OVK-1 sand bodies using stochastic sequential indicator simulation, facies architecture and petro-physical properties to identify potential unexplored drillable prospects. This no doubt if drilled, will help boast additional reserves in the Niger Delta Basic.

Study area and geology

The study area, DN Field, lies within the coastal swamp depobelt (Figure 1a) of Niger Delta and it is operated by Shell Petroleum Development Company of Nigeria Limited. The in-lines and cross-lines are in the ranges of 11,228 to 12,028 and 2,673 to 3,373 respectively with a spacing of 100 m between lines (Figure 1b).

The onshore portion of the Niger Delta Province is

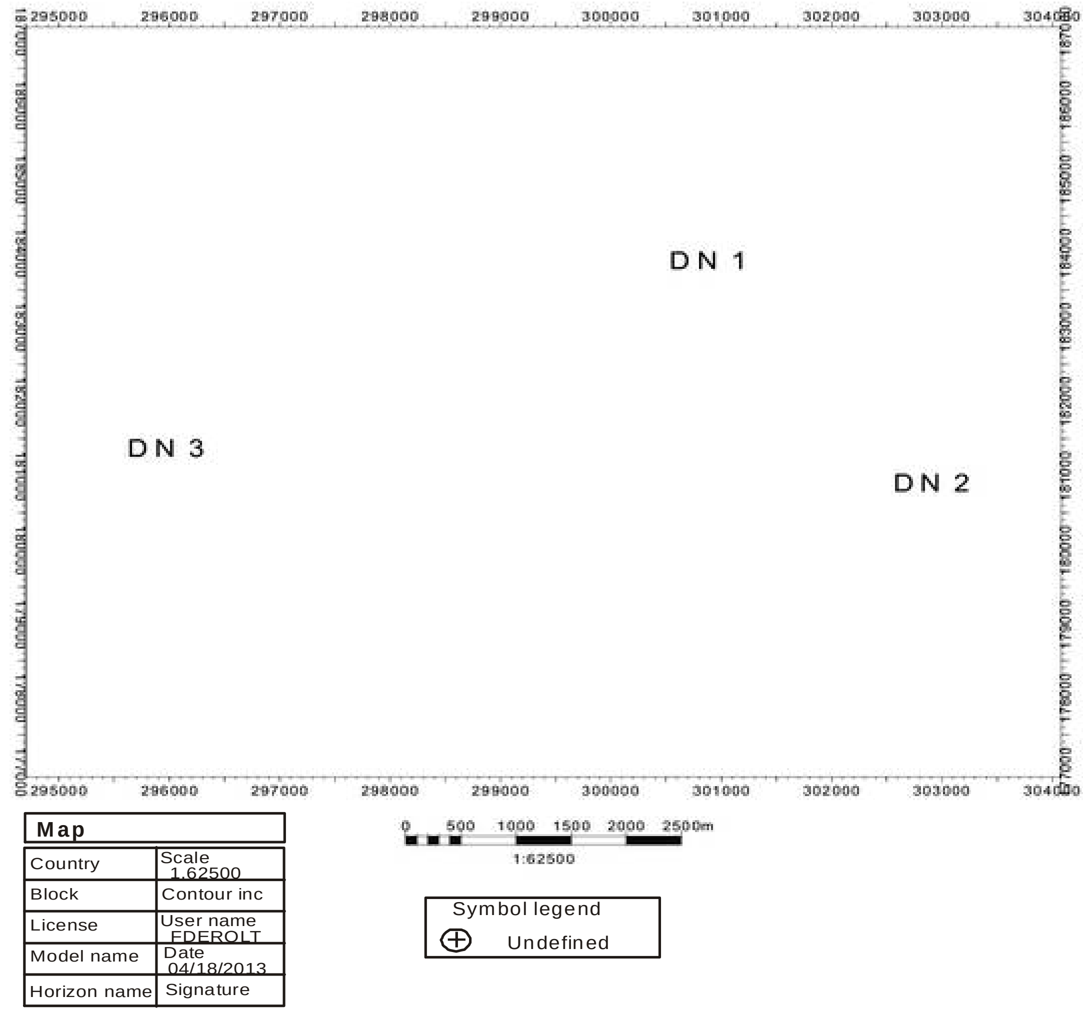

Figure 1b. Base map of DN Field showing the positions of the three Wells within the Field available for this study.

delineated by the geology of southern Nigeria and south-western Cameroon. The northern boundary is the Benin Flank, an east-north-east trending hinge line south of the West Africa basement massif. The north-eastern boundary is defined by outcrops of the Cretaceous on the Abakaliki High and further east-south-east by the Calabar Flank, a hinge line bordering the adjacent Precambrian Basement Complex [1]. The offshore boundary of the Niger Delta Province is defined by the Cameroon volcanic line to the east, the eastern boundary of the Dahomey Basin to the west, and the 2 km sediment thickness contour or the 4,000 m bathymetric contour in areas where sediment thickness is greater than 2 km to the south and south-west. The province covers an area of approximately 300,000 km^2 and includes the geologic extent of the Tertiary Niger Delta (Akata-Agbada) Petroleum System.

Stratigraphy

The sedimentary sequences of the Niger Delta are made up of three stratigraphic units which are from oldest to youngest; the marine shales of the Akata Formation, middle paralic Agbada Formation and the topmost Benin Formation [1, 14].

Akata Formation

The Akata Formation, the oldest formation in the Niger Delta, is of Paleocene age to the present. It comprised pro-delta marine shales with local sandy and silty beds which have been transported to deep water areas. The sediments are characterized by low energy conditions and oxygen deficiency [15] laid down as turbidites and continental slope channel fills. It is estimated that the formation is up to 7,000 meters thick [3]. The formation underlies the entire delta, and is typically overpressured. Turbidity currents likely deposited deep sea fan sands within the upper Akata Formation during development of the delta [16]. This formation constitutes the effective source rocks in the Niger Delta.

Agbada Formation

This formation overlies the Akata Formation in the Niger Delta and is made up of paralic sands and shales. The sands constitute the main petroleum-bearing unit in the Niger Delta while the shales provide lateral and vertical seals [17]. Deposition of the Agbada Formation, began in the Eocene and continues into the Recent. The formation is over 3,700 meters thick and represents the actual deltaic portion of the sequence. The clastics accumulated in delta-front, delta-topset, and fluvio-deltaic environments. In the lower Agbada Formation, shale and sandstone beds were deposited in equal proportions, however, the upper portion is mostly sand with only minor shale interbeds.

Benin Formation

The Benin Formation is the youngest stratigraphic sequence in the Niger Delta. It is about 2,000 m thick , and consists mainly of fresh-water fluvial sands and gravels which are occasionally interspersed with shale beds towards the base of the unit. The sands are generally fine to coarse-grained and very poorly sorted. Occasional streaks of lignite and thin scattered grayish brown shale beds are intercalated with the sands and gravels. The grains are subangular to well rounded and varies in colour from clear white to yellowish brown quartz with subordinate hematite and feldspar grains [14]. It ranges in age from Oligocene to Recent.

Structures

The Niger Delta is subtly disturbed at the surface but the subsurface is affected by large scale synsedimentary features such as growth faults, rollover anticlines and diapirs [3,15]. The structural style, both on regional and on the field scale, can be explained on the basis of influence of the ratio of sedimentation to subsidence rates. The different types of structures are namely, simple non-faulted anticline rollover anticline with multiple growth faults, or anticline faults and complicated collapse crest structures [18]. Other structures are sub-parallel growth fault (k-block structures) and structural closures along the back of growth faults.

Materials and methods

Dataset

The dataset used for this study includes 3-D seismic, composite logs of three wells, biofacies data of the three wells and checkshot data containing velocity information. The three wells used for this study are namely; DN-1, DN-2 and DN-3 with respective total depths; 7,700 ft (2,333.3m), 7,500 ft (2,272.7 m) and 10,000 ft (3,030.3 m). The dataset were obtained from the Shell Petroleum Development Company of Nigeria. The 3-D seismic data, which was in ZGY bricked format was imported into the Petrel 2009.1™, following some loading steps for the data already in the industrial format acceptable to the software. The header information and mapping coordinates were carefully inputted during the loading exercise. To effectively cover the study area, the seismic data was interpreted at a scroll increment of 10 lines on both in-lines and cross-lines. The well data was in the ASCII format and was also imported into the Petrel 2009.1™ software. The methodology involved making additional well logs like volume of shale, seismic attribute generation, facies modeling, petrophysical modeling, determination of the environment of deposition using well logs and biofacies.

The work flow for the different aspects of the study is shown in Figure 2.

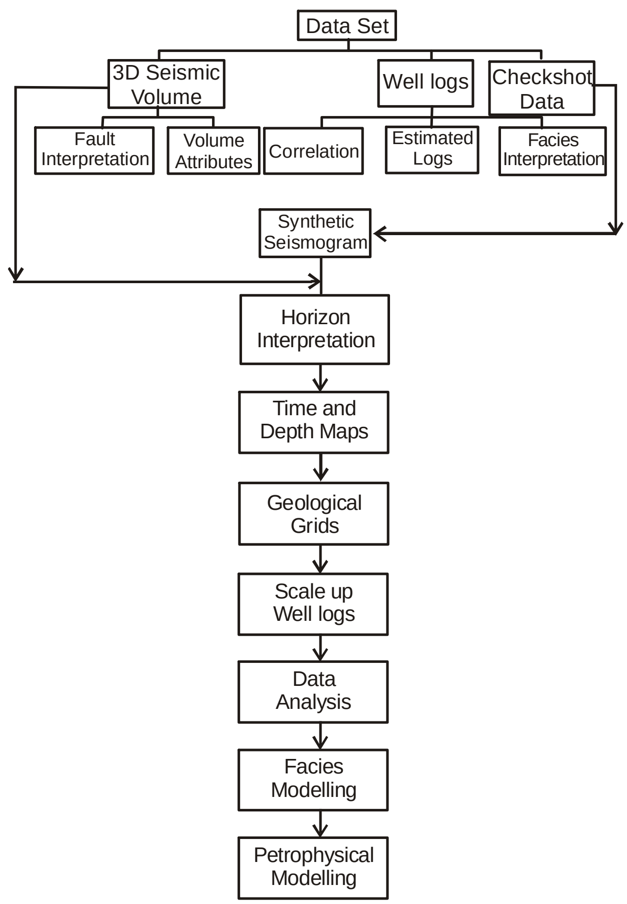

Figure 2. Workflow of study.

Deductions from well logs

Well log data (GR, Vshale, Porosity, FDC well log suite) were used to train a seismic classification. This is based on the fact that these logs provide first hand information about the properties of a Formation before using seismic attributes as a follow-up. Seismic volume attribute cubes (Figure 3) notably; acoustic impedance, iso-frequency and envelope, capable of recognizing the properties of interest such as porosity, volume of shale and effective porosity respectively were generated.

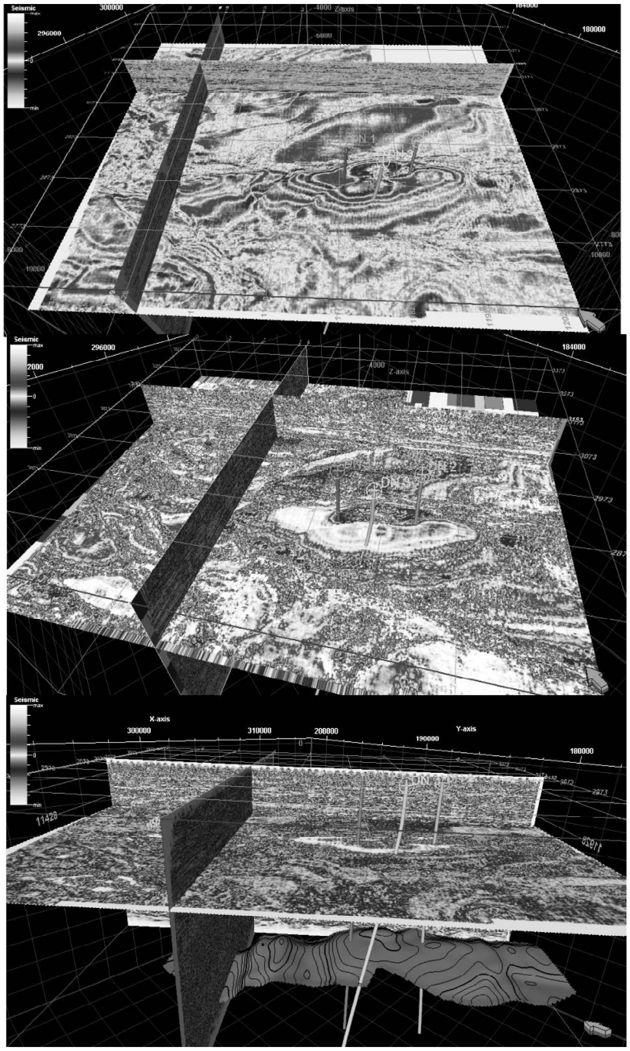

Figure 3. Seismic volume attributes showing acoustic impedance, iso-frequency and envelope respectively.

In this study, a Principal Component Analysis (PCA) was first run on all the properties to be modeled and the correlation coefficient ascertained. Principal Component Analysis (PCA) is a technique for simplifying any dataset by reducing the multidimensional dataset to lower dimensions for analysis. As reported by Jungmann *et al* [19], principal component analysis and stepwise discriminant analysis are two major methods used for feature extraction; they help to emphasize variation and bring out strong patterns in the dataset which can improve the accuracy and stability of classifiers by removing unwanted, non-distinctive and interrelated features. The already generated lithofacies model was used to constrain the petrophysical models generated. The properties to be modeled such as volume of shale and effective porosity were first upscaled and Stochastic Gaussian Simulation (SGS) algorithm was utilized to produce the model. It should be noted that Sequential Gaussian Simulation (stochastic) uses well data, input distributions, variograms and trends [20]. The variograms and distribution were used to create local variations even away from input data. Fluvial facies interpretations from well logs were upscaled and stochastic object modeling algorithm was used to produce a fluvial facies model.

Palaeodepositional environment

Palaeodepositional environment was determined based on gamma ray log shapes as reported by Morris and Biggs [21] and biofacies analysis result. According to Emery and Myers [22], clean-up, dirtying-up and boxcar trends can be recognised when examining well log curves. Selley [23] opined that the environments of shallowing-upward and coarsening successions is divided into three categories namely; regressive barrier bars, prograding marine shelf fans and prograding delta or crevasse splays. Boxcar trend could indicate a slope channel and inner fan channel environments [24].

According to Emery and Myers [22], the greater range of thickness indicates turbidites sands and lesser thicknesses indicate inner fan channel environments. In a non-marine setting, dirtying-upward is predominant within meandering or tidal channel deposits with an upward decrease in fluid velocity within a channel [22]. The irregular shape has no character, representing aggradation of shales or silts and in the analysis classifies the log facies as belonging to a flood plain environment.

Biofacies analysis was based on a checklist constructed by occurrence, abundance and diversity of planktonic and benthonic foraminifera, and pollens [25]. Maximum abundance and diversity values generally reflect transgressive conditions and minimum values reflect regressive conditions.

Results and discussions

Based on well logs and seismic interpretation, a number of models and cross plots were generated. Four reservoir sands were identified namely; OVK-1, OVK2, OVK-3 and OVK-4 with intervals from 4,645 to 4,700 ft [1407.6 to 1,424.2 m]; 4,773 to 4,864 ft [1,446.4 to 1,473.9 m], 5,748 to 5,778 ft [1,741.8 to 1,750.9m] and 5,889 to 6,016 ft [1,784.5 to 1,823.0 m] respectively. In this study, OVK-1 reservoir sand being the reservoir of interest has an interval of 4,529-4,584 ft [1,372.4 to 1,389.1 m] in DN-1 well and 4,562-4,617 ft [1,382.4 to 1,399.1 m] in DN-2 well and 4,645-4,700 ft [1,407.6 to 1,424.2 m] in DN-3 well (all depths are in SSTVD) (Figure 4).

Lithofacies' model

Stochastic sequential indicator simulation algorithm approach was used to generate a lithofacies model for OVK-1 reservoir sand body. This was achieved by

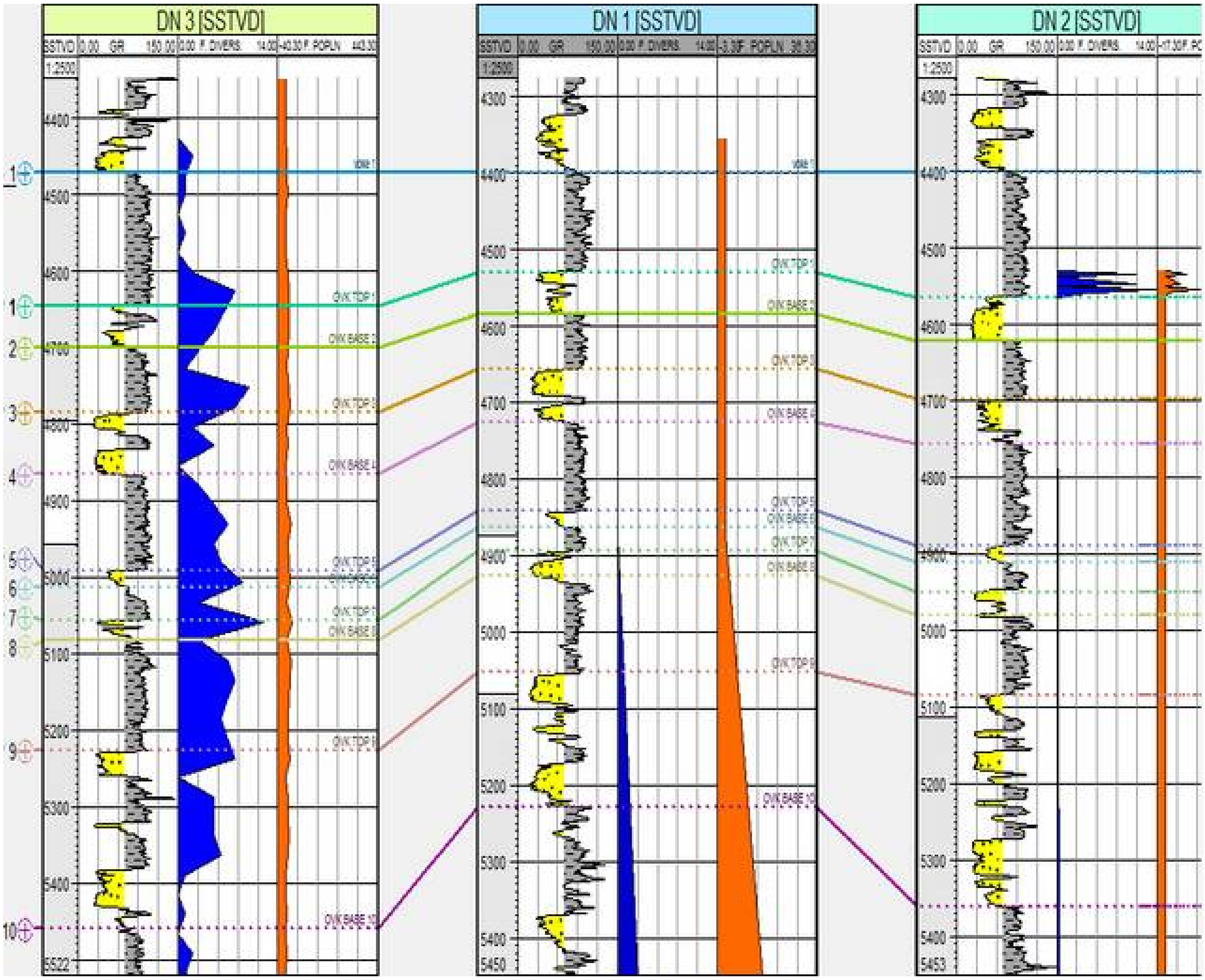

Figure 4. Well log correlation and biofacies information of DN-Field Wells showing the potential reservoir intervals, the seals and continuity across the wells.

assigning discrete values to each point to show sand and shale. Sand was assigned a value of '0' and colour coded as yellow, fine sand was assigned a value of '1' and colour coded as orange while shale was assigned a value '2' and given a grey colour (Figure 5); this is as opposed to property modeling, that is continuous, which was able to show the gradual lateral change of petrophysical properties towards the flanks of the reservoir unit. In the lithofacies model, the central part of the OVK-I reservoir sand body shows cleaner sands (Figure 5) with minor shale development in the western part of the Field. In the fluvial facies model, majority of the channels are concentrated there with attendance highest values of porosity and hydrocarbon saturation recorded. Modelled channels show geometry and N-S orientation within the Agbada Formation across the field as shown by the compass direction (Figure 6). It could also be seen that all the wells fall within the channel sand area, having the highest porosity. The fluvial facies model indicates areas covered by channel sands, back ground flood plains, and levee deposits (Figure 6). Clean reservoir sands and marginal shaly sands are superimposed on top of the background facies. The flanks of the reservoir area have more

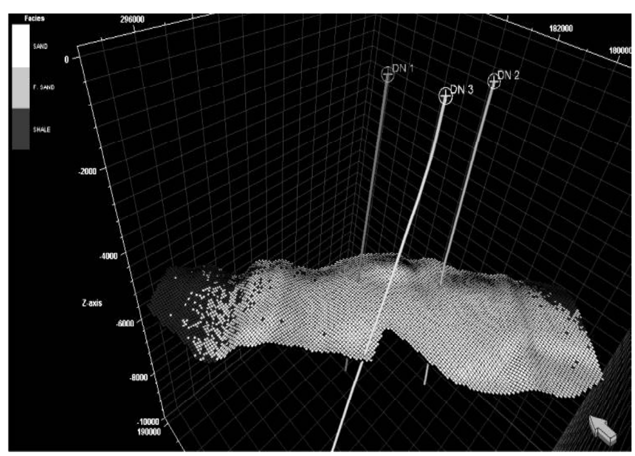

Figure 5. Facies model of OVK-1 reservoir showing good sand distribution and minor shale in western part with positions of existing wells. Enclosed loop shows the identified drillable prospect.

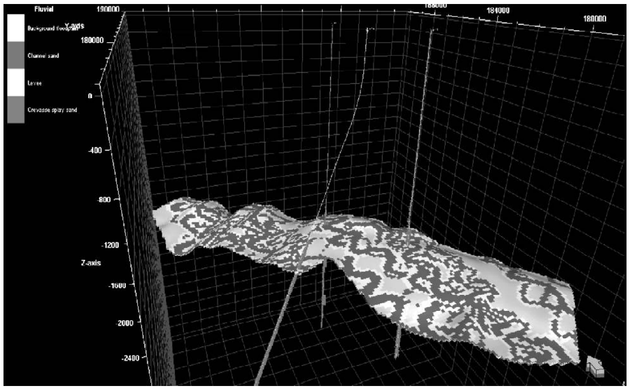

Figure 6. Fluvial facies model of OVK-1 reservoir with positions of existing wells showing distribution of background flood plains, channel sand , levee and crevasse splay sands.

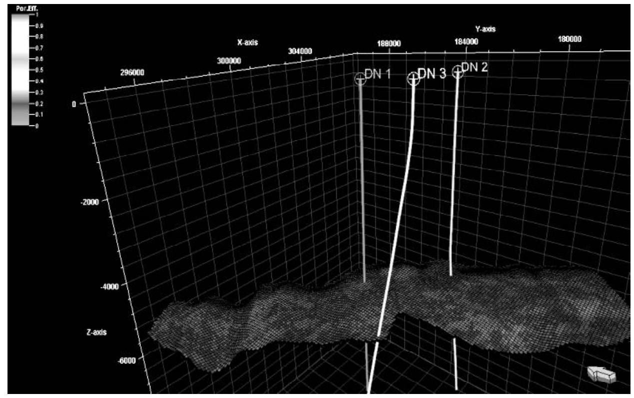

Figure 8. Effective porosity model of OVK-1 reservoir with ranging between 0.2 and 0.4.

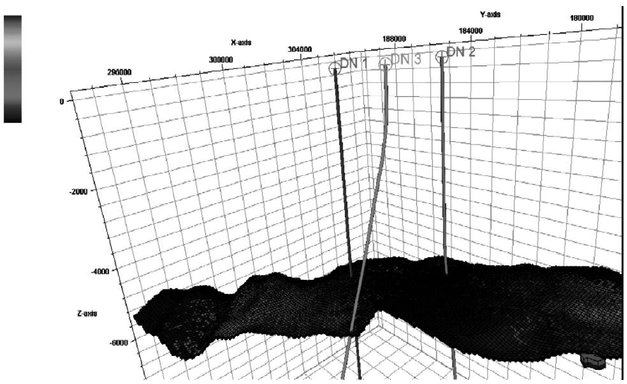

Figure 7. Volume of shale model of OVK-1 reservoir; areas with blue colour have the best reservoir qualities, followed by areas with yellow/green while areas in red are highest volume of shale.

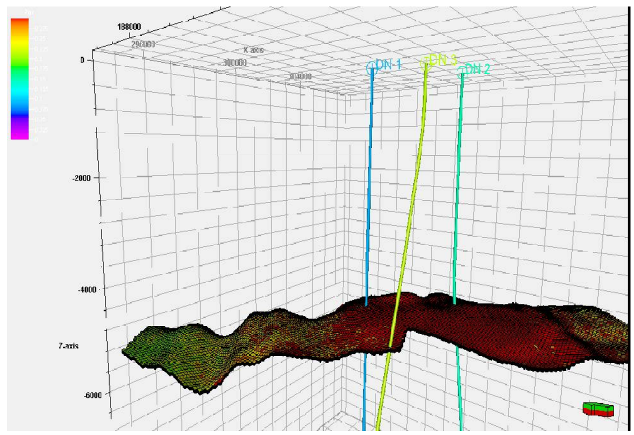

Figure 9. Porosity model of OVK-1 reservoir following the distribution of volume of shale; central portion of the model has the highest porosity values.

flood plain materials such as shales and silts, hence the very high volume of shale (Figure 7) and low effective porosity (Figure 8).

Petrophysical properties

Petrophysical properties which include porosity, volume of shale and effective porosity were modeled. The distribution of petrophysical properties gives clues to the petroleum potential of the DN-Field. The areas with high porosity values having shades of yellow and red, ranges from 19 to 27.5% and are potential areas for hydrocarbon prospecting (Figure 9). The areas with low values of effective porosity allow little or no flow of hydrocarbon (Figure 8). As reported by Ajibola and Brian [26], the porosity values of the Agbada Reservoir Sands range from 10 to 30 %, with formation thickness in the order of between 9,600 to 14,000 feet.

The volume of shale (Figure 7) represents the distribution of properties from the upscaled version of the well logs. The volume of shale as well as other petrophysical properties modelled in this work was upscaled using 'Arithmetic Mean' as the averaging method as they are continous variables as opposed to facies which is discrete. The grid was calibrated into fractions which define the 3D model into various depositional environments; the part which captures values of 0.15-0.23, signifies potential reservoir rocks while areas with high volume of shale are poor reservoirs. Bamidele and Ehinola [27], reported the volume of shale as ranging from 0 to 0.65 for offshore Niger Delta. The effective porosity model gives the degree of interconnectivity of the reservoir. In this study, areas with blue colour which capture 0.20-0.40, show high effective porosity while those with purple colour in the model indicate regions in the DN-Field with low effective porosity values.

Lithological identification

The different cross plots show overlay of points with common lithology. As reported by Schlumberger [20], responses of the logging tools used in any particular interval, will plot as a point on a crossplot. These crossplots give a quick view of the lithology in qualitative and quantitative ways. The gamma ray/density and gamma ray/neutron crossplots for DN-3 well (Figure 10) show that the reservoir sand (shades of red) and shaly facies (shades of purple) plot in same zone, implying the reservoir facies to be dominantly sand with some silt.

Palaeodepositional environment

The log shapes of OVK-1 reservoir at interval between 4,678 (1,417 m) and 4,700 ft (1,424 m) in DN well 3 (Figure 3) can be inferred to indicate a crevasse splay. This 28 ft (6.7 m) thick reservoir unit according to Chow *et al*[28], is comparatively thin to be a prograding delta. Crevasse splay deposits also occur at intervals 5,368-5,414 ft (1,627-1,641 m), 5,741-5,771 ft (1,740-1,749 m), and 6,504-6,456 ft (1,971-1,956 m) (DN-1); 5,516-5,550 ft (1,672-1,682 M) (DN-2) and 5,444-5,461 ft (1,650-1,655 m)(DN-3) (Figure 3). Blocky trend, characterised by sharp upper and lower boundaries occur at intervals; 6,071-6,143 ft (DN-1), 7,133-7,200 ft (DN-2), 5,894-5,952 and 6,200-6,234 ft (DN-3). It is observed that the sands here are not as thick as 25 m, hence they are in inner fan channel environment as reported by [22]. The irregular trend in DN-1 well, showing from a depth of 6,200-6,510 ft and 6,250-6,525 ft in DN-2 well, classifies the log facies as flood plain [22]. The environment is characterised by a blanket of clays and silts, deposited from suspension, with high lateral continuity and low lithologic variation related to a gradual upward change in the clay mineral content or an upward thinning of sand beds in a thinly

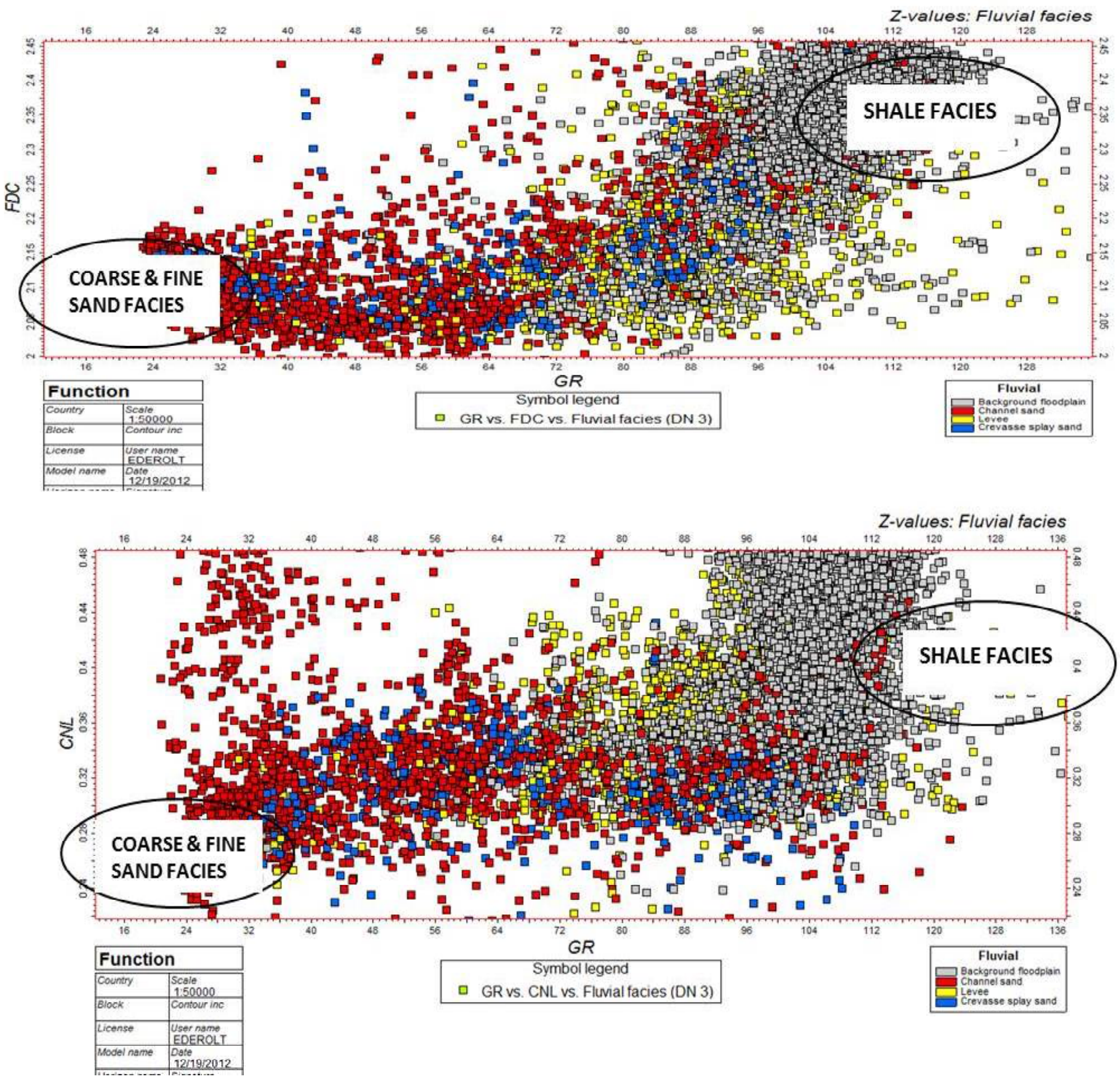

Figure 10. Lithological identification from GR/FDC and GR/CNL crossplots of DN-3 well areas with red and blue signifying coarse and fine sand facies respectively while grey represents the shale facies.

interbedded sand-shale unit, both of which imply a decrease in depositional energy.

From the biofacies data of DN-3 well (Table 1), depths 4,700-4,782 ft (1,424-1,449 m), 4,816-4,834 ft (1,459-1,465 m), 4,864-4,993 ft (1,474-1,513 m), 5,027-5,056 ft (1,523-1,532 m) , 5093-5,230 ft (1,543-1,585 m), 5,269-5,382 ft (1,597-1,631 m), 5,467-5,623 ft (1,657-1,703 m), 9,200-9,818 ft (2,788-2,975 m) (SSTVD), having high foraminifera diversity, all correlate with the shales and silts of both the flood plain and levee which are low energy depositional environments. There are very little benthic foraminifera in the study-area but an abundance of planktonic and shallow marine forams, validating the environment of deposition as fluvio-marine.

Table 1. Biofacies interpretation for DN-3 well showing the environment of deposition and population of both benthic and planktonic foraminifera.

S/N	Depth	Type	Environ-ment	Foram diversity	Foram population	Plankton diversity	Plankton population
1	5000	3	B	0	0	0	0
2	5030	3	B	0	0	0	0
3	5060	3	B	0	0	0	0
4	5090	3	B	0	0	0	0
5	5120	3	SH.IN	2	5	0	0
6	5150	3	SH.IN	1	2	0	0
7	5180	3	SH.IN	1	8	0	0
8	5210	3	B	0	0	0	0
9	5240	3	B	1	1	0	0
10	5270	3	B	0	0	0	0
11	5300	3	SH.IN	2	7	0	0
12	5330	3	IN-MN	8	14	2	2
13	5360	3	IN	5	12	0	0
14	5390	3	IN	3	11	0	0
15	5420	3	IN	1	4	0	0
16	5450	3	SH.IN	1	4	0	0
17	5480	3	MN	10	14	2	2
18	5510	3	IN-MN	8	21	2	3
19	5540	3	SH.IN	2	2	0	0
20	5570	3	IN	5	8	1	1

Conclusions

Facies model building of integrated data in Dn-Field, onshore Niger Delta was undertaken to predict lithofacies and fluvial facies of OVK-1 sandbodies in the Agbada Formation, as a tool in identifying new drillable prospects. A stochastic sequential indicator simulation method which uses a nonlinear function with better connectivity, higher repeatability and shorter turn-around time, was used to generate a lithofacies model for OVK-1 reservoir sand body in the Niger Delta. Calibrated by fluvio-facies at the well locations, channel sands were identified in OVK-1 reservoir sands with the channels concentrated in the central part, where there are more sands in the lithofacies model. Based on lithofacies, fluvial facies and biofacies analysis, a terrigenous and shallow fluvio-deltaic fill, within a lowstand system tract is evident.

Porosity model predicts sand layers to have maximum porosity of 27.5% while silt and clay have porosity below 20%. Porosity values of 0.15-0.23 for areas around the central portion were interpreted as channels. Integrating structural, petrophysical properties' distribution and seismic volume attribute analysis; a new drillable prospect, located on clean sand, with high porosity and good effective porosity has been identified. The identified drillable prospect is southwest of DN-2 well, coinciding with 3,500 m contour line on the structure map. However to better ascertain lithofacies both horizontally and vertically, it is imperative that core data be provided. A chronology of depositional episodes can be established from careful analysis of cross-cutting relationships observed on core pictures and seismic time slices at different times.

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