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EFFECTS OF DEPOSITIONAL ENVIRONMENTS ON RESERVOIR QUALITY IN GABO FIELD NIGER DELTA

[1]Nduaguibe, T. W, [2]Ideozu, R. U and [3]Sam, E.

[1,2]Department of Geology,
[3]Department of Geology/Mining University of Port Harcourt, Rivers State, Nigeria.
Corresponding author email: richmond.ideozu@uniport.edu.ng

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ABSTRACT

The focus of this research is on the Effects of Depositional Environment on Reservoir Quality in Gabo Field. Data used in this research comprise Suits of Well logs, Core data and core photos for Wells 51 and 52 in the study area. The methodologies involved determination of petrophysical parameters from both core and well logs, delineation of the reservoir interval from well logs and sedimentological analysis were carried out on core photographs. Thirteen reservoir units were identified in wells 51 and 52 which had 5 reservoirs cored in each of them and correlated across the field. The lithofacies units identified in reservoirs across the study area comprise pebbly sands, coarse - very fine-grained sands, sandy mud, silty sands and sandy/muddy heteroliths. Ophiomorpha and skolithos are the major trace fossils identified and sedimentary structures such as ripple lamination, wavy lenticular and planar beds and cross bedding. The facies associations interpreted are Channel and Coastal barrier and the environment of deposition as distributary channel, upper and lower shoreface respectively. The sedimentary processes ranged from high energy regimes, reworking by waves to low energy with periodic influx of silts and muds. The average porosity and permeability for reservoirs in Well 51 is 16.7% and 1317 Md, well 52 has 28.2% and 2330Md whereas the porosity ranged from 2% - 32% and permeability 1.2 – 10600 Md in the studied sections. The reservoir quality of the sand units in Well 51 (7, 9 and 13) and Well 52 (5, 7, 9, 11 and 13) is excellent - good, this is because of the dynamics of the environments of deposition as well as the mechanisms that played out during and after deposition such as bioturbation, sorting and sedimentary structures. Whereas poor quality reservoirs were observed in lower shoreface and prodelta facies which may have been influenced by lack bioturbation, connectivity and multiplicity of burrows that may have been plugged by clay and shale. The conclusions reached in this research, is in agreement with similar works that environments of deposition have direct influence the reservoir quality in terms of porosity and permeability.

Key words: Porosity, permeability, skolithos, *Ophiomorpha*, lithofacies, reservoir, bioturbation, channel and coastal barrier systems.

INTRODUCTION

The quality of a reservoir unit in a typical depositional environment may be related to porosity, permeability, sediment type, depositional environment, thickness and lateral continuity which in turn is influenced by cement, clay content, the presence of trace fossils, sedimentary process, sedimentary structures as well as the energy of deposition of medium; in addition to textural features such as sorting, grain size, roundness, sphericity, (Gerard *et al*,. 1992). According to McDonald and Surdam (1984) the initial pore network of newly deposited sediments and the quality of shallow buried reservoirs are generally determined by the environment of deposition. Thus grain characteristics, a product of the depositional process control porosity and permeability. In clastic rocks, these characteristics include grain size and sorting, sphericity, angularity, packing, and the abundance of matrix materials. The best reservoir quality rocks are well-sorted, have well-rounded grains, and contain no matrix material. Sedimentary structures affect initial reservoir quality by imparting a preferential flow pattern in the reservoir. Planar bedding, laminations, or other stratification features can create stratified planar flow, especially if permeability barriers such as clay partings, finer-grained laminae, or graded beds are present. Slump structures may reduce permeability by creating a tortuous flow path, or may increase permeability (and porosity) by causing a looser grain packing and by producing small faults. Bioturbation typically decreases reservoir quality by mixing adjacent sands and clays, introducing the clay into the interstices among the sand grains (Gerard *et al*,. 1992). Some recent researches in the Niger Delta comprised those of Iheaturu *et al*, (2012) who looked at the Reservoir Properties and Sealing Potentials of the Akani Oil Field Structures, Eastern Niger Delta, Nigeria using well logs and 3-D seismic profiles, they observed that the Akani reservoirs 6C-sand and 3C-sand are very good reservoirs with average porosity of 28.5%, permeability of 2100mD, net-to-gross ratio of 0.5 and volume of clay of 0.4. A total of twenty-three faults where mapped and modeled from the 3D seismic profile. The hydrocarbon column height of 266.6ft was found in the Akani reservoir-6C sand and seen to be structurally controlled. Akpan *et al*, (2016) in their work on Depositional Environment and Reservoir Studies of the AB sands, Ubie Field, Niger Delta, looked at the reservoir characterization of a hydrocarbon bearing sand in Ubie Field using integrated analysis of cores from wells, as well as biostratigraphic data and wireline logs to examine environment of deposition to produce a model of the sub-surface reservoir. The petrophysical analysis was carried out through the use of well logs, showed that amalgamated sand was more porous and permeable than the tidal channels. The depositional model of the reservoir sands also consists of upper transgressive estuarine deposits overlying a lower progradational shallow marine shoreface deposit. Odigi and Onyinyechukwu (2016), in their work on Facies Analysis and Depositional Environment of Obua Field, Niger Delta, reconstructed the paleoenvironment of reservoir sand bodies across the field based on log motif and side wall core samples. Their result showed that two lithologies (sand and shale) were recognized in Obua

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Field. Three log facies were recognized in the study area comprising funnel-shaped facies representing prograding delta and submarine fans; cylindrical-shaped facies representing delta distributary channel and grain flow fill (submarine channel); bell-shaped facies representing turbidite fill (submarine channel). Acra *et al*, (2017), carried out studies on Sedimentology and Reservoir Studies of Odirin Well, Niger Delta, Nigeria using sedimentological attributes integrated with reservoir quality of the sand bodies. Cores were utilized in their study which showed good to excellent porosity and permeability in the fine to medium grained sands. The study also showed that the bioturbation also enhanced fluid flow and vertical permeability. Accra and Ofuyah (2017) carried out studies on sedimentology and reservoir studies of Alo Well, Niger Delta Basin, using sedimentological attributes and integrated reservoir quality of the sand-bodies. The study was carried out to determine the depositional environment and to evaluate the reservoir potentials of the Alo Well. Well logs and cores were utilized in their study. The results of their study showed good to excellent porosity and very good permeabilities. Grain size of the sand-bodies are fine to medium grained and moderately sorted depicting a moderately high energy environment and suggesting that the presence of bioturbations may be responsible for the high vertical permeability values recorded. Based on findings, they inferred the depositional environment as a tidally influenced probably a distributary channel fill. Momta (2016) carried out a study on sedimentary facies description and sedimentology of parts of the Coastal Swamp Depobelt, Niger Delta, using well logs and core data. The identified in their study five facies types based on sedimentary structures (such as cross-bedding), lithology, and biostratigraphic analysis comprising sandstone, bioturbated cross-bedded sandstone, bioturbated interbedded sandstone and mudstone, bioturbated heterolithic sandstone/siltstone, and silty mudstone facies. Depositional environments were interpreted as tidal channel, upper and lower shoreface, and proximal shelf mudstones. Ardo, (2016) carried out petrophysical evaluation on Stezyca Oil and Gas Field using well logs and core analysis and revealed the relevance of core and log correlation as a necessary procedure in analyzing and comparing data for calibration to characterize lithology. Ideozu *et al*., (2015) studied the depositional environment of "XY" reservoir sands, Pamma, Field, Niger Delta, Nigeria using core samples and wireline log shapes. The deciphered environment of deposition includes; distributary channels, mouth bar, point bar, tidal channel, tidal flat, upper and lower shoreface. Also, the cored hydrocarbon bearing intervals showed key sedimentary structures reflected heterogeneities associated with sedimentary processes; that may have impact on hydrocarbon recovery. The stratigraphy of the Niger Delta comprises the Akata, Agbada and Benin Formations. The geology of the Niger Delta is well established as well as the stratigraphy, structural framework and petroleum potentials by Doust and Omatsola (1989, 1990), Reijers (1996), Kulke 1995), Ekweozor and Daukoru (1994), Evamy *et al* (1978). See Figures 1-4. This research seeks to evaluate the effect of depositional environment and its mechanisms on reservoir quality of Gabo Field in relation to porosity and permeability and how it can contribute to increased production in Gabo Field. The objectives of this research are to determine the environment of deposition, the reservoir quality, determine types of biogenic and sedimentary structures and the effects of depositional environment on reservoir quality in Gabo Field. This research is limited to the data provided (Core Photographs, Core data and well logs). The Gabo Field is a field in the Niger Delta Basin where several sandstone units in the Agbada Formations have been separated by clay/shale brakes (Reyment, 1965).

METHODS AND METHODS

Materials.

The materials and data used for this this research has been provided by an International Oil Company in Nigeria (for propriety reasons, the name of the company and field has been omitted) through the Department of Petroleum Resources (DPR). The data set and materials provided include the following:

1. Base / location map
2. Core photographs (for wells 51 and 52)
3. Core data (porosity and permeability for wells 51 and 52)
4. Well logs (for wells 53, 54,51, 52 and 57)

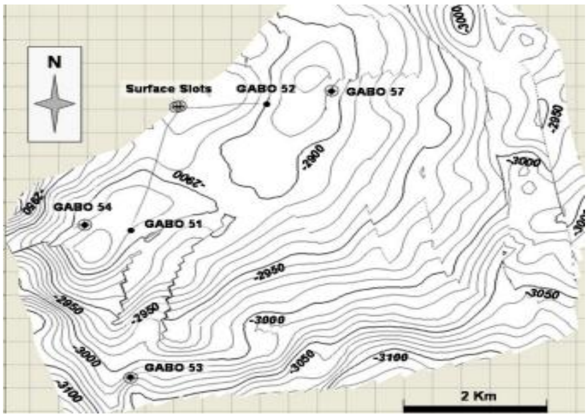

Figure 1 Base map of Gabo Filed

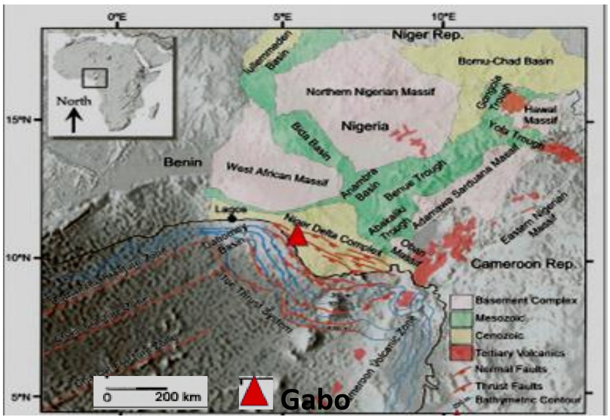

Figure 2 Location of Gabo Filed (modified from Mitchum, 2006)

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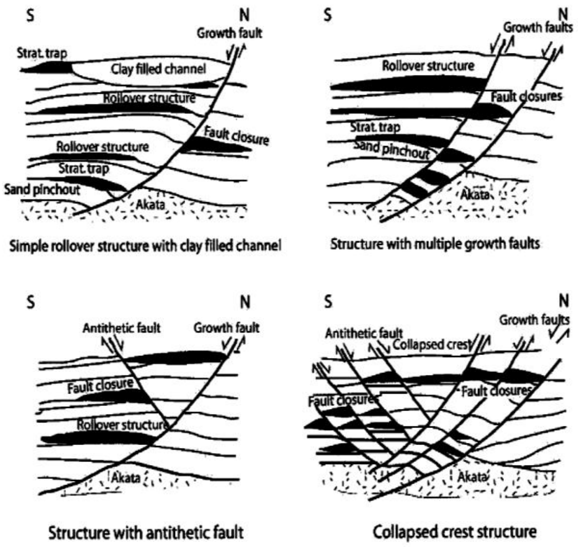

Figure 3 Niger Delta trapping systems
(Modified from Doust and Omatsola (1990)

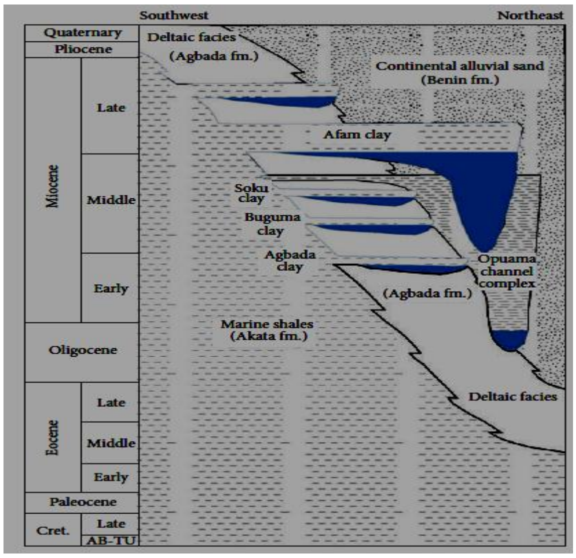

Figure 4 Stratigraphic structure of the Niger Delta
(After Shanon and Naylor 1989; Doust and Omatshola (1990)
and Stacher (1995).

Methods

The methodology used in this research are standard methods used in petrophysical analysis using well logs, core photograph interpretation and determination of porosity and permeability from core data. The work flow diagram illustrates the methodology applied in this research (Figure 5). The data set were provided by the asset owner were in digital format and the coordinates and unit systems for the field were set in Petrel software prior to the loading of dataset (well log suites). The data used for this research was carefully assessed in terms of quality and found to be adequate. The well logs were provided in LAS format. After well header information were loaded in Petrel, the next data loaded were the well logs. Logs were loaded using. Las format in Petrel and the available logs were tied with their global well log equivalents in Petrel. Quantitative petrophysical analysis and evaluation was carried out on the two wells to determine their Porosity (ϕ) and Permeability (K) from the well logs compared with core data correlated across the field. The well logs enabled identification of lithology and type of depositional environment, delineation of the sand/shale units, evaluation of reservoir thickness and determination of petrophysical properties such as porosity and permeability. The core photograph enabled evaluation of textural features, energy regime, sedimentary processes and sedimentary structures. The core data enabled the evaluation of the core porosity and permeability.

Petrophysical evaluation

The petrophysical parameters such as volume of shale, porosity, effective porosity, permeability, water saturation, hydrocarbon saturation and net to gross were estimated from the well logs responses using Schlumberger Petrel software.

The petrophysical parameters from well logs were evaluated from the relationships below.

Effective Porosity

$$\phi_{eff} = \phi_D - (V_{sh} \times \phi_{Dsh}) \quad (1.0)$$

Where:

ϕ_{eff} = Effective porosity

ϕ_D = Total porosity

V_{sh} = Shale volume

ϕ_{Dsh} = Shale porosity from density log

Shale Volume (V_{SH})

The volume of shale in a reservoir plays a key role in hydrocarbon production. The higher the reservoir shaliness, the poorer the reservoir productivity. The magnitude of the gamma ray count in a formation of interest (relative to that of nearby clean and shale zones) is related to the shale content of the formation. This relationship may be linear or non-linear. The gamma ray log was used to evaluate the volume of shale by first determining the gamma ray index (I_{GR}) using Asquith and Gibson, (1982) equation:

$$I_{GR} = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (3.1)$$

Where;

I_{GR} = Gamma ray index which describes a linear response to shale content.

GRlog = log reading at the depth of interest.

GRmin = Gammar Ray value in a nearby clean sand zone.

GRmax = Gamma Ray value in a nearby shale.

Shale volume was then calculated using the Larionov (1969) non-linear relationship for Tertiary rocks as follows;

$$V_{SH} = 0.083 * \left(2^{(3.7 * GR_{index})} - 1\right) \quad (3.2)$$

Where;

V_{SH} = is the volume of shale

I_{GR} = Gammar ray index

Permeability Estimation

The permeability of a reservoir is its ability to transmit fluids from one point to another. The permeability of a reservoir in clastic sedimentary rocks is directly linked to effective porosity. The higher the effective porosity, the higher the permeability and vice versa. Some of the factors which affects permeability of a reservoir are; size of the pores, size of the pore throat, grains sorting, grain roundness, packing and cement. In this study, permeability was estimated using Owolabi *et al. (1994)* empirical model. This model was preferred because of its widespread acceptability and usability in the Niger Delta sedimentary Basin. The equation is as follows;

$$K(mD) = 307 + 26552(\emptyset_e^2) - 34540\,(\emptyset_e \times S_w)^2 \quad (3.3)$$

Where;

$K(mD) = permeability\ in\ milliDarcy$

$\emptyset_e = effective\ porosity$

$S_w = water\ saturation$

Water Saturation Estimation

The reservoir sand body is porous, and fluids are contained within those pore spaces. The fluids that occupy the pores could either be oil, gas, water or a combination of two or all fluids present.

To determine the amount of water saturation in the reservoirs, Archie's empirical model was utilized as follows;

$$S_w = \sqrt{\frac{R_o}{R_t}} \quad (3.6)$$

Where;

$S_w = water\ saturation$

$R_o = Resistivity\ of\ the\ oil\ leg$

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$R_t = True\ resistivity\ reading$

Procedure for Core Photograph Analysis

The core photographs analyzed are those of Wells 51 and 52 at depths were the reservoir sands have been identified (reservoirs of interest) and correlated across the field. They were studied and described in the studied depths.

a. Close observation of the core photographs was undertaking, nothing the characteristics and sedimentary sequence in the studied sections.
b. The lithologic boundaries of each unit were noted.
c. The studies of the sedimentary and biogenic structures were carried out with emphasis on nothing the following features crossbedding, lamination, ichnogenera and the degree of bioturbation.
d. Based on the descriptions, lithology, grain size and dominant sedimentary structures the lithofacies types were determined and interpreted using the Niger Delta Lithostratigraphy Illustrated Ichnofacies Atlas.
e. Core / log calibration was carried out by using core information to characterize the studied sections.

Core Porosity and Permeability

The core porosity and permeability was read off from the core porosity and permeability data.

RESULTS AND DISCUSSION

The results of this research are presented in Figures 6 - 8 and Tables 1 – 15. Well 51 has total cored intervals of 3687 – 3719m (32 m), 3764 – 3794 (30m) and 34078 – 4129 (51m). Three reservoir units were delineated 7 (a. and b), 9 (a. and b) and 13 (a. and b). See Tables 1 - 5. Well 52 has total cored intervals as 3687 – 3719m (32 m), 3764 – 3794 (30m) and 34078 – 4129 (51m). Three reservoir units have been delineated 7 (a. and b), 9 (a. and b) and 13 (a. and b). See Tables 6 - 10.

Discussion

Environments of deposition (EoD) play a key role in reservoir quality assessment and performance predictions across a field (Toba and Ideozu, 2017, 2018). The EoD of the studied sections was interpreted from well logs (based on well log motifs) and core photographs based on sedimentary structures, trace fossil type and sedimentary textures (See Figures 6 - 8). Reservoir sand bodies deposited in different depositional environments are characterized by different sand shape and geometry, size and heterogeneity.

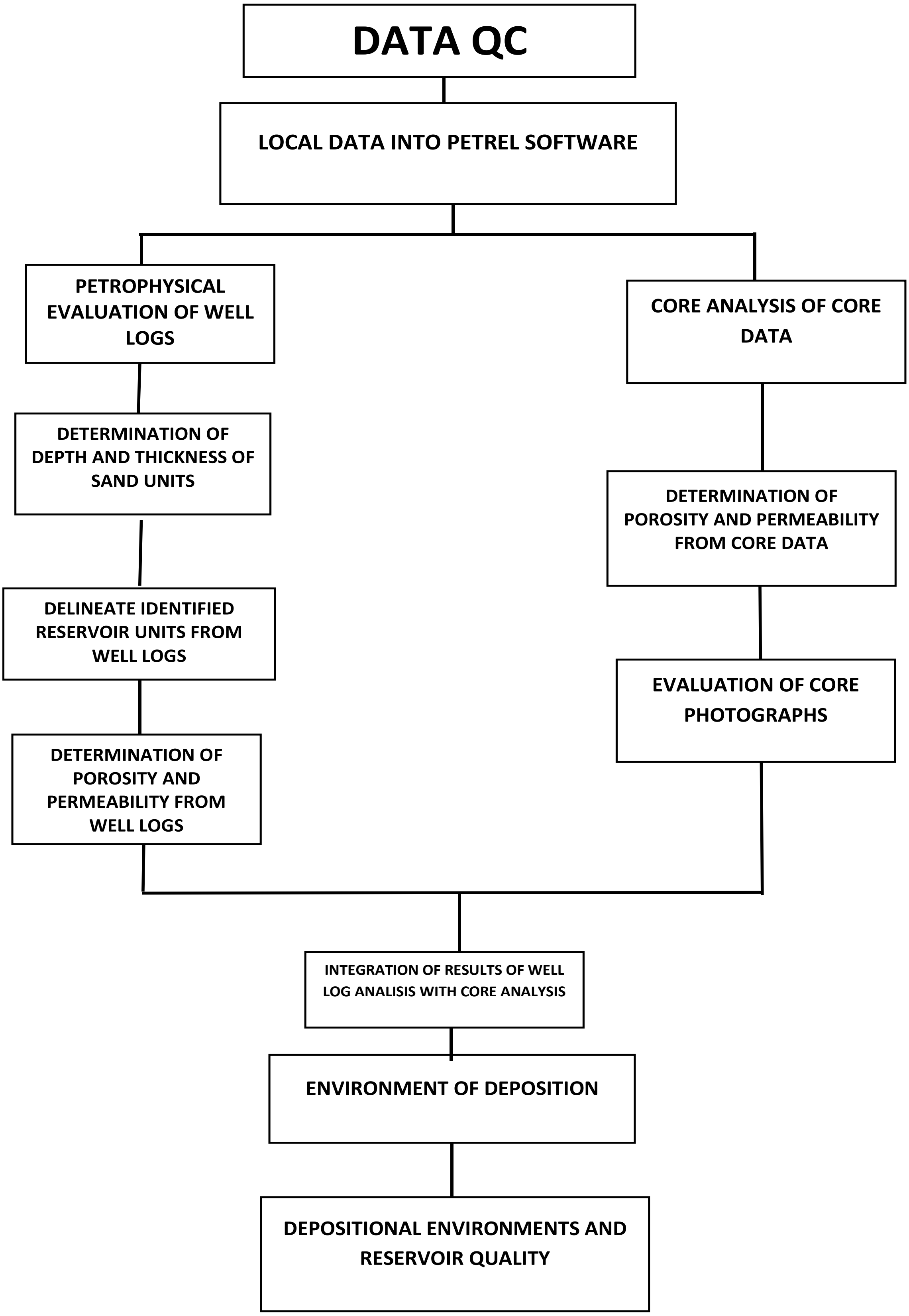

Figure 5 Work Flow Diagram

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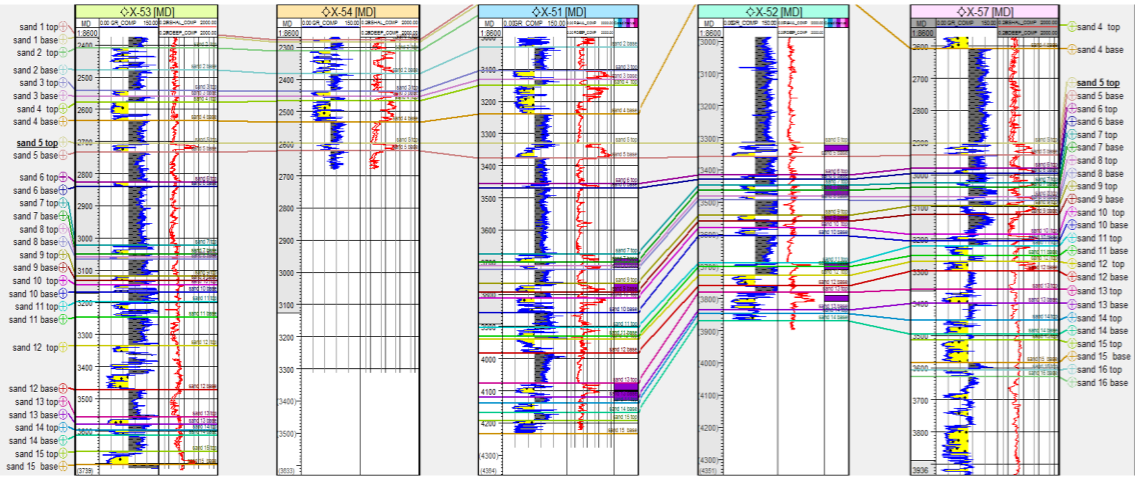

Figure 6 Correlation Panel of wells 53, 54,51, 52 and 57 in Gabo Field

Figure 7 Lithology and Lithologic Description for Well 52 Reservoir 9.

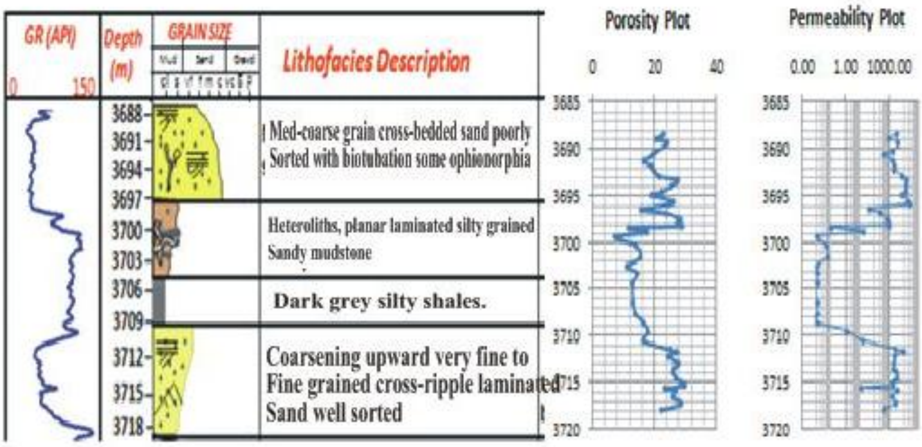

Figure 8 Porosity and Permeability data for Well 52 Reservoir 9.

The depositional environment of the reservoirs has been interpreted based on well logs motifs using standard shape of GR-log (Figures 6) and interpretation from core photographs. Sedimentary facies display characteristic vertical profiles based on which grain size, fining upward sequence or coarsening upward sequences. Vertical variations in grain size from Gamma Ray logs is valuable in the interpreting depositional environments of the studied sections, in Well 51 the environments of deposition comprise fluvial and distributary channels, upper and lower shoreface and prodelta while in Well 52 the environments of deposition are made up of flood plain, fluvial and distributary channels, upper and lower shoreface and prodelta correlated across the wells in the study area (Figures 6 and Tables 2 – 10). According to Ideozu *et al*., (2015) reservoir quality is defined by the hydrocarbon storage capacity (porosity) and deliverability (permeability) and the hydrocarbon storage capacity is a function of the effective porosity, pore size, pore throat, reservoir thickness and lateral continuity of the hydrocarbon bearing sand units while deliverability is a function of its permeability (the ability of the reservoir sands to transmit the stored fluids). The quality of the reservoirs in the studied sections were evaluated in terms of porosity and permeability of the reservoir units, the processes which took place in their environments of deposition as well as the mechanisms that play out in them such as bioturbation, sedimentary textures and structures. The high quality reservoirs are those of the distributary channels, fluvial channels and upper shoreface (See Tables 2 -3 and 6) while the least quality reservoirs occur probably due to the absence of bioturbation and type of lithology (heteroliths, sandy shale and shale). The low quality reservoirs are those of the flood plain, lower shoreface (heteroliths) and prodelta shales. See Tables 4 – 5 and 8 – 9 (McDonald and Surdam, 1984; Gerard *et al*,. 1992). Sands units 7, 9 and 13 in Wells 51 and 52, have similar log signatures while sands units 5 and 11 in wells 51 and 52 different log signatures while sand unit 11 has a funnel signature indicating different environments of deposition see Figure 6. Well log porosity and permeability result for all sand units in both wells have higher values than the results obtained from analyzing the core plugs, (Tables 11-15). This could be because of the absence of bioturbation and digenesis within the sand units. The quality of a reservoir (contained reservoir fluid) is also related to the textural features, sedimentary structures and depositional environment which in turn control the porosity and permeability of the reservoirs (McDonald and Surdam 1984). When reservoir sands are thick, highly porous and permeable they give better prospects, higher volume of hydrocarbon and profit and the major Oil Companies indicate interest in such reservoir sands (Acra *et al*,. 2017; Akpan *et al*,. 2016).

CONCLUSION

The reservoirs sands from the studied sections in the Gabo Field have been deposited in a Channel system - in the following EoD distributary channel, flood plain and fluvial channel. The distributary channel and fluvial depositional environments have higher reservoir quality in terms of porosity and permeability (Sands units 7, 9 and 13 in Wells 51 and

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52). While the other reservoirs (sands units 5 and 11 in wells 51 and 52), were deposited in a Coastal barrier system - in the following EoD upper shoreface, lower shoreface and pro-delta, only the upper shoreface has high quality in terms of porosity and permeability. The grain size ranges of all the reservoir sands is medium to coarse (0.5 – 1.75 Φ), high energy of deposition and some reservoir sands reworked by wave action. Reservoir sand units in the studied section shows that the distributary channel and fluvial field excellent reservoir quality except sand units 5 of Well 52 which has a lower quality in terms of porosity and permeability.

Table 1 Reservoir thickness in well 51.

Reservoir	Lithology	Top (m)	Bottom (m)	Thickness (m)	Number of cores	Cored length m
7	Sand	3686	3699	13	1	30
9	Sand	3773	3791.5	18.5	1	30
11	Sand	4087	4109.40	22.4	2	46.3
13	Sand	4097.3	4098	0.7	Un cored	_

Table 6 Reservoir thickness in well 52.

Reservoir	Lithology	Top (m)	Bottom (m)	Thickness (m)	Number of cores	Cored length m
5	Sand	3324	3336	12	1	17
7	Sand	3445	3468	23	1	30
9	Sand	3542	3556	14	1	18
11	Sand	3690.5	3698	7.5	1	18
13	Sand	3797	3810	13	1	17

Table 2 Core Description, Deposition Environment, Porosity and Permeability for reservoir units in Well 51

Reservoir	Reservoir unit	Depth range (m)	Thickness (m)	Lithologic description / sedimentary processes	Environment of Deposition	Core Porosity Mean and Range (%)	Permeability Mean and range (md)
7	a	3687 – 3697	10	Medium to coarse grained, cross bedded sandstone, poorly sorted, low angle crossbedding, bioturbated-ophiomorpha. High energy flow regime	Fluvial channel	21.5 16 - 28	1047 600 –1600
	b	3710 – 3718	8	Coarsening upward very fine to fine-grained cross ripple laminated sandstone,	Upper shoreface	25.25 16 - 29	1037.5 500 –1400

				low angle crossbedding to current ripple bedding. High energy regime reworked by waves			
9	a	3773 – 3783	10	Pebbly-coarse medium grained cross bedded fining upward sandstone, planar cross bedded to low angle crossbedding, poorly sorted with bioturbation. Trace fossil present include ophiomorpha and skolithos. High energy flow regime.	Fluvial Channel	21.89 8 - 29	1210.07 500 –1800
	b	3783 – 3790	7	Fine to very fine-grained well sorted sandstone, wave rippled to current bedding and planar bedding. High energy regime reworked by waves	Upper shoreface	22.2 4 – 29	780 6 - 1800
13	a	4088-4101	12	Medium to coarse-grained cross bedded blocky sandstone, low angle crossbedding moderate to poorly sorted, bioturbated, present is *ophiomorpha* and *planolites*. High energy flow regime.	Distributary Channel	21.89 8 – 29 (Estimated)	1215 510 –1800 (Estimated)
	b	4101 – 4106	5	Fine to very fine-grained sandstone, well sorted, wave ripple lamination, current ripple and planar current bedding. High energy regime reworked by waves	Upper shoreface	25.25 16 – 29 (Estimated)	1039 520 –1400 (Estimated)

Table 3 Core Description and Reservoir quality for reservoir units in Well 51

Reservoir	Reservoir unit	Depth range (m)	Thickness (m)	Lithologic description / sedimentary processes	Environment of Deposition	Porosity (%)	Permeability (md)
7	a	3687 – 3697	10	Medium to coarse grained, cross bedded sandstone, poorly	Fluvial channel	Good to very good	Very good to excellent

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				sorted, low angle crossbedding, bioturbated-ophiomorpha. High energy flow regime			
	b	3710 – 3718	8	Coarsening upward very fine to fine-grained cross ripple laminated sandstone, low angle crossbedding to current ripple bedding. High energy regime reworked by waves	Upper shoreface	Good to very good	Very good to excellent
9	a	3773 – 3783	10	Pebbly coarse–medium grained cross bedded fining upward sandstone, planar cross bedded to low angle crossbedding, poorly sorted with bioturbation. Trace fossil present include ophiomorpha and skolithos. High energy flow regime.	Fluvial Channel	Poor to very good	Very good to excellent
	b	3783 – 3790	7	Fine to very fine-grained well sorted sandstone, wave rippled to current bedding and planar bedding. High energy regime reworked by waves	Upper shoreface	Negligible to very good	Moderate to excellent
13	a	4088-4101	12	Medium to coarse-grained cross bedded blocky sandstone, low angle crossbedding moderate to poorly sorted, bioturbated, present is *ophiomorpha* and *planolites*. High energy flow regime.	Distributary Channel	Poor to very good (Estimated)	Very good to excellent (Estimated)
	b	4101 – 4106	5	Fine to very fine-grained sandstone, well sorted, wave ripple lamination, current ripple and planar current bedding. High energy regime reworked by waves	Upper shoreface	Negligible to very good (Estimated)	Moderate to excellent (Estimated)

Table 4 Core Description, Depositional Environment, Porosity and Permeability of Non-Reservoir units in Well 51

Reservoir	**Reservoir unit**	**Depth range (m)**	**Thickness (m)**	**Lithologic description / sedimentary processes**	**Environment of Deposition**	**Porosity (%)**	**Permeability (md)**
7	a	3697 – 3704	7	Heteroliths, planar laminated slightly mudstone trace fossils present include ophiomorpha and planolites. Low energy regime with periodic influx of silt.	Lower shoreface	17 8 - 28	288.21 0.1 -1000
	b	3704 – 3710	6	Dark grey silty shales. Low energy.	Prodelta	13.67 12 - 16	83.42 0.1 -500
9	a	3764 – 3773	9	Wavy bedded heterolithic and bioturbated, trace fossils present include ophiomorpha, planolites and skolithos. Low energy regime with periodic influx of silt.	Lower shoreface	16.7 9 – 25	241.1 0.1 - 1000
	b	3791 – 3794	3	Very fine-grained ripple laminated, interlaminated clay, intensely bioturbated. Trace fossil present include skolithos and planolites. Low energy regime with periodic influx of silt.	Lower shoreface	18.5 12 – 25	278.5 7 - 600
13	a	4078-4088	10	Siltstone, light brownish grey, wave ripple laminated, inter laminated with mudstone. Heterolithic wavy bedding. Trace fossil present is planolites. Low energy regime with periodic influx of silt.	Lower shoreface	16.7 9 – 25 (Estimated)	241.1 0.1 – 1000 (Estimated)
	b	4121 – 4129	8	Dark grey silty shales. Low energy.	Prodelta	13.67 12 – 16 (Estimated)	83.42 0.1 -500 (Estimated)

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Table 5 Core Description, Depositional Environment and Reservoir Quality of the Non-Reservoir units in Well 51

Reservoir	Reservoir unit	Depth range (m)	Thickness (m)	Lithologic description / sedimentary processes	Environment of Deposition	Porosity (%)	Permeability (md)
7	a	3697 – 3704	7	Heteroliths, planar laminated slightly mudstone trace fossils present include ophiomorpha and planolites. Low energy regime with periodic influx of silt.	Lower shoreface	Poor to very good	Very good to Excellent
	b	3704 – 3710	6	Dark grey silty shales. Low energy.	Prodelta	Good	Good to very good
9	a	3764 – 3773	9	Wavy bedded heterolithic and bioturbated, trace fossils present include ophiomorpha, planolites and skolithos. Low energy regime with periodic influx of silt.	Lower shoreface	Poor to very good	Good to very good
	b	3791 – 3794	3	Very fine-grained ripple laminated, interlaminated clay, intensely bioturbated. Trace fossil present include skolithos and planolites. Low energy regime with periodic influx of silt.	Lower shoreface	Good to very good	Poor to very good
13	a	4078-4088	10	Siltstone, light brownish grey, wave ripple laminated, inter laminated with mudstone. Heterolithic wavy bedding.	Lower shoreface	Poor to very good	Poor to very good

				Trace fossil present is planolites. Low energy regime with periodic influx of silt.			
	b	4121 – 4129	8	Dark grey silty shales. Low energy.	Prodelta	Poor to good	Poor to very good

Table 6 Core Description, Deposition Environment, Porosity and Permeability for reservoir units in Well 52

Reservoir	**Reservoir unit**	**Depth range (m)**	**Thickness (m)**	**Lithologic description / sedimentary processes**	**Environment of Deposition**	**Porosity Mean and Range (%)**	**Permeability Mean and range (md)**
5	a	3324–3328	4	Medium to coarse grained, cross bedded sandstone, moderate to poorly sorted and laminated. High energy flow regime	Fluvial channel	18.44 8 - 32	747.67 8 – 4000
	b	3328 – 3335	7	Coarsening upward fine to very fine-grained well sorted sandstone. High energy regime reworked by waves	Upper shoreface	22.71 6 - 30	6198.53 12 – 80000
7	a	3324–3328	4	Medium to coarse grained, moderate to poorly sorted, and laminated. High energy flow regime	Fluvial Channel	18.82 8 - 32	902.2 0.6 – 600
	b	3328 – 3334	6	Coarsening upward fine to very fine-grained cross rippled, laminated, trough bedded, well sorted sandstone. High energy regime reworked by waves	Upper shoreface	22.76 10 – 30	915.32 11 - 10500
9	a	3444-3468	24	Medium to coarse-grained cross bedded blocky sandstone, low angle crossbedding moderate to poorly sorted, bioturbated, present is *ophiomorpha* and *planolites*. High energy flow regime.	Distributary Channel	21.89 4 – 28	9025.04 0.7 –19000

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	b	3472 – 3480	8	Medium to coarse-grained cross bedded blocky sandstone, low angle crossbedding moderate to poorly sorted, bioturbated, present is *ophiomorpha* and *planolites*. High energy flow regime.	Distributary Channel	25.25 16 – 29 (Estimated)	1039 520 –1400 (Estimated)
13	a	3790 – 3793	3	Coarsening upward fine to very fine-grained cross rippled, laminated, trough bedded, well sorted sandstone. High energy regime reworked by waves	Upper shoreface	22.76 10 – 30 (Estimated)	915.32 11 – 10500 (Estimated)
	b			Pebbly-coarse medium grained cross bedded fining upward sandstone, planar cross bedded to low angle crossbedding, poorly sorted with bioturbation. Trace fossil present include ophiomorpha and skolithos. High energy flow regime.	Fluvial channel	18.44 8 – 32 (Estimated)	747.67 8 – 4000 (Estimated)

Table 7 Core Description and Reservoir quality for reservoir units in Well 52

Reservoir	**Reservoir unit**	**Depth range (m)**	**Thickness (m)**	**Lithologic description / sedimentary processes**	**Environment of Deposition**	**Porosity (%)**	**Permeability (md)**
5	a	3324–3328	4	Medium to coarse grained, cross bedded sandstone, moderate to poorly sorted and laminated. High energy flow regime	Fluvial channel	Poor to Excellent	Poor to Excellent
	b	3328 – 3335	7	Coarsening upward fine to very fine-grained well sorted sandstone. High energy regime reworked by waves	Upper shoreface	Poor to very good	Moderate to Excellent

7	a	3324–3328	4	Medium to coarse grained, moderate to poorly sorted, and laminated. High energy flow regime	Fluvial Channel	Poor to Excellent	Poor to Excellent
	b	3328 – 3334	6	Coarsening upward fine to very fine-grained cross rippled, laminated, trough bedded, well sorted sandstone. High energy regime reworked by waves	Upper shoreface	Poor to very good	Moderate to Excellent
9	a	3444-3468	24	Medium to coarse-grained cross bedded blocky sandstone, low angle crossbedding moderate to poorly sorted, bioturbated, present is *ophiomorpha* and *planolites*. High energy flow regime.	Distributary Channel	Negligible to very good	Poor to Excellent
	b	3472 – 3480	8	Medium to coarse-grained cross bedded blocky sandstone, low angle crossbedding moderate to poorly sorted, bioturbated, present is *ophiomorpha* and *planolites*. High energy flow regime.	Distributary Channel	Good to very good (Estimated)	Very good to Excellent (Estimated)
13	a	3790 – 3793	3	Coarsening upward fine to very fine-grained cross rippled, laminated, trough bedded, well sorted sandstone. High energy regime reworked by waves	Upper shoreface	Moderate to very good (Estimated)	Moderate to Excellent (Estimated)
	b			Pebbly-coarse medium grained cross bedded fining upward sandstone, planar cross bedded to low angle crossbedding, poorly sorted with bioturbation. Trace fossil present include ophiomorpha and skolithos. High energy flow regime.	Fluvial channel	Poor to Excellent (Estimated)	Poor to Excellent (Estimated)

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Table 8 Core Description, Deposition Environment, Porosity and Permeability for Non-reservoir units in Well 52

Reservoir	**Reservoir unit**	**Depth range (m)**	**Thickness (m)**	**Lithologic description / sedimentary processes**	**Environment of Deposition**	**Porosity Mean and Range (%)**	**Permeability Mean and range (md)**
5	a	3322–3324	2	Sandy mudstone, grey and intensely bioturbated, trace fossil present is skolithos. Low energy	Flood plain	12.11 3 - 23	33.00 10 – 120
	b	3335 – 3339	4	Heteroliths, alternation of sandy and muddy heteroliths, planar laminated mudstones, moderately bioturbated. Trace fossils present include ophiomorpha and skolithos. Low energy regime with periodic influx of silt	Lower shoreface	6 8 - 28	288.21 0.1 -1000
	c	3339 – 3341	2	Dark grey silty shales. Low energy.	Prodelta	12.11 3 - 23	33.00 10 – 120
7	a	3334 – 3342	8	Heteroliths, alternation of sandy and muddy heteroliths, planar laminated mudstones, moderately bioturbated. Trace fossils present include ophiomorpha and skolithos. Low energy regime with periodic influx of silt	Flood plain	12.11 3 - 23	33.00 10 – 120
9	a	3468 - 3472	8	Dark grey silty shales. Low energy.	Prodelta	21.89 4 – 28	9025.04 0.7 –19000
	b	3555 – 3559	4	Wavy bedded heterolithic and bioturbated, trace fossils present include ophiomorpha, planolites and skolithos. Low energy regime with periodic influx of silt.	Lower shoreface	12.11 3 - 23	33.00 10 – 120
	c	3698 – 3708	10	Heteroliths, alternation of sandy and muddy heteroliths, planar laminated mudstones, moderately bioturbated. Trace fossils present include ophiomorpha	Lower shoreface	12.11 3 - 23	33.00 10 – 120

				and skolithos. Low energy regime with periodic influx of silt			
	d	3708 – 3710	2	Dark grey silty shales. Low energy.	Prodelta	12.11 3 - 23	33.00 10 – 120
13	a	3793 – 3796	3	Heteroliths, planar laminated slightly mudstone trace fossils present include ophiomorpha and planolites. Low energy regime with periodic influx of silt.	Lower shoreface	12.11 3 - 23	33.00 10 – 120
	b	3798 – 3810	2	Dark grey silty shales. Low energy.	Prodelta	12.11 3 - 23	33.00 10 – 120

Table 9 Core Description, Deposition Environment and Reservoir Quality of the Non-reservoir units in Well 52

Reservoir	**Reservoir unit**	**Depth range (m)**	**Thickness (m)**	**Lithologic description / sedimentary processes**	**Environment of Deposition**	**Porosity Mean and Range (%)**	**Permeability Mean and range (md)**
5	a	3322–3324	2	Sandy mudstone, grey and intensely bioturbated, trace fossil present is skolithos. Low energy	Flood plain	12.11 3 - 23	33.00 10 – 120
	b	3335 – 3339	4	Heteroliths, alternation of sandy and muddy heteroliths, planar laminated mudstones, moderately bioturbated. Trace fossils present include ophiomorpha and skolithos. Low energy regime with periodic influx of silt	Lower shoreface	6 8 - 28	288.21 0.1 -1000
	c	3339 – 3341	2	Dark grey silty shales. Low energy.	Prodelta	12.11 3 - 23	33.00 10 – 120
7	a	3334 – 3342	8	Heteroliths, alternation of sandy and muddy heteroliths, planar laminated mudstones, moderately bioturbated. Trace fossils present include ophiomorpha and skolithos. Low energy regime with periodic influx of silt	Lower shoreface	12.11 3 - 23	33.00 10 – 120

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9	a	3468 - 3472	8	Dark grey silty shales. Low energy.	Prodelta	21.89 4 – 28	9025.04 0.7 –19000
	b	3555 – 3559	4	Wavy bedded heterolithic and bioturbated, trace fossils present include ophiomorpha, planolites and skolithos. Low energy regime with periodic influx of silt.	Lower shoreface	12.11 3 - 23	33.00 10 – 120
	c	3698 – 3708	10	Heteroliths, alternation of sandy and muddy heteroliths, planar laminated mudstones, moderately bioturbated. Trace fossils present include ophiomorpha and skolithos. Low energy regime with periodic influx of silt	Lower shoreface	12.11 3 - 23	33.00 10 – 120
	d	3708 – 3710	2	Dark grey silty shales. Low energy.	Prodelta	12.11 3 - 23	33.00 10 – 120
13	a	3793 – 3796	3	Heteroliths, planar laminated slightly mudstone trace fossils present include ophiomorpha and planolites. Low energy regime with periodic influx of silt.	Lower shoreface	12.11 3 - 23	33.00 10 – 120
	b	3798 – 3810	2	Dark grey silty shales. Low energy.	Prodelta	12.11 3 - 23	33.00 10 – 120

Table 10 Sedimentology and depositional environment of Sand Units in Well 51 Gabo Field.

WELL 51						
Reservoir	Thickness (m)	Sorting	Grain size (Φ)	Log shape	Depositional Environment	Porosity-permeability
7	13	Poorly sorted	1.75 – -.25	Cylindrical	Fluvial channel	Good
9	18.5	Well sorted	-2 - 4	Funnel shaped	Upper shoreface	Good
13	13	Poorly sorted	-.25 – 1.75	Blocky	Distributary channel	Excellent
	9.4	Well sorted	2 – 4	Funnel shaped	Upper shoreface	Excellent

Table 12 Sedimentology and depositional environment in Well 52, Gabo Field.

WELL 52						
Reservoir	Thickness (m)	Sorting	Grain size (Φ)	Log shape	Depositional Environment	Porosity-permeability
5	12	Well sorted	1.75 to -.25	Funnel shaped	Upper shoreface	Good
7	23	Moderately sorted	1.75 to -.25	Blocky	Distributary channel	Excellent
9	14	Moderately sorted	1.75 to -.25	Blocky	Distributary channel	Excellent
11	7.5	Well sorted	1.75 to 4	Funnel shaped	Upper shoreface	Good
13	13	Poorly sorted	-2 to -1	Blocky	Fluvial channel	Very Good

Table 13 Reservoir quality of Well 51, Gabro Field (Core plug values) – (Rider, 1986; Etu – Efeotor, (2007)

Sand	Permeability (md)		Porosity (%)	
	Quantitative	Qualitative	Quantitative	Qualitative
7	980.0	Good	23.5	Very good
9	950.0	Good	16.0	Good
13	_	_	_	_
Range	950.0 – 980.0		16.0 – 23.5	Good - Very good
average	965.0		19.75	Good

Table 14 Reservoir quality of Well 51, Gabro Field (based on Well log) - (Rider, 1986; Etu – Efeotor, (2007)

Sand	Permeability (mD)		Porosity (%)	
	Quantitative	Qualitative	Quantitative	Qualitative
7	1,978.7	Excellent	24.8	Very Good
9	1238.3	Excellent	21.8	Very Good
13	1565.2	Excellent	22.4	Very Good
Range	1238.3 – 1978.7	Excellent	21.8 - 24.8	Very good
Average	1594.1	Excellent	22.73	Very good

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Table 15 Reservoir quality of Well 52 Gabro Field (based on Well log) - (Rider, 1986; Etu – Efeotor, (2007)

Sand	Permeability (mD)		Porosity (%)	
	Quantitative	Qualitative	Quantitative	Qualitative
5	1009.7	Very Good	14.8	Good
7	1156.3	Excellent	17.9	Good
9	1068.0	Excellent	18.5	Good
11	1317.4	Excellent	16.7	Good
13	2330.0	Excellent	28.2	Very Good
Range	1009.7 -2330.0	Good - excellent	14.8 -28.2	Good – very good
Average	1376.24	Excellent	19.22	good

	Well log signatures	Log patterns/ motifs (0 API 150)	Lithofacies Descriptions	Lithofacies Interpretations
A	Low serrated gamma	I 20m	Stacked up of bell shape (coastal barrier bar) and funnel shape (fluvi-al/tidally influence channel sand	Undifferentiated Continental deposits (Benin Formation)
B	Blocky and cleaning upwards	I 20m	Funnel shape morphology with average thickness of about 50m bounded at the basal part by candidate sequence boundary or transgressive surface	Coastal barrier bar
C1	Blocky and dirtying upwards	I 20m	Bow/ bell shape morphology, shows some high gamma values anomalies, the top units marked the transgressive surfaces while the basal marked the sequence boundaries.	Tidal/Fluvial channel fills
C2-5	Blocky sharp base	I 20m	Blocky and sharp base shape morphology, shows some high gamma anomalies within the clean sand. The top and the basal contacts correspond to transgressive surfaces and sequence boundary respectively	Slope channel/Channel sand
D	Gradual cleaning upwards	I 20m	Funnel shape morphology and less blocky than coastal barrier bar. The upper contact is defined by the transgressive/flooding surfaces while the basal part is defined by shallow marine deepening.	Upper shoreface sand
E & F	High serrated gamma	I 20m	High serrated gamma ray value with aggrading stacking patterns. this can differentiated from each other by their neutron and density log characters	Offshore mudstone/ Lower shoreface deposit

Figure 9 Gamma ray facies association from well log pattern used in defining depositional environments within the study area. **(**Rider, 1986)

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