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# Integration of Sequence Stratigraphy and Petrophysical Analysis for Reservoir Characterization: A Case Study of "KO" Field, Central Niger Delta

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## Abstract
Reservoir characterization is one of the most relevant steps taken in exploration and development stages of any prospective reservoir. Results obtained from various analyses are integrated with it to prevent/minimize the risk of doubtfulness. In this study, integration of sequence stratigraphy and petrophysical analysis for reservoir characterization: a case study of "KO" field Central Niger Delta. The evaluation was achieved using well logs. The data used comprises of three wells with relevant well log suites for the targets for further exploration. The petrophysical parameters calculated include porosity, permeability, shale volume, etc. using Schlumberger PETREL, Microsoft Excel, and Python programming language softwares. However, the stratigraphic studies aid the understanding of the reservoir sand distribution in the subsurface for modelling of the depositional settings. There is usually a gradual change in the depositional sequence determination and well log parameters study, there would be better understanding of the depositional system for better reservoir sand distribution prediction. The methodology encompasses the reconstruction of geologic lithofacies information from geophysical logs. The results obtained from this study shows that the integration of well logs and depositional sequence aid in the delineation of hydrocarbon bearing zones and prediction of sand distribution. All the sand intervals possess high porosity and permeability values and high volume of hydrocarbon in place. It is also seen that the rock properties in the reservoir units are influenced primarily by the depositional processes.

## 1. Introduction
For the Petrophysicists, well logging analyses is all about the use of varieties of petrophysical tools for the description of reservoir properties such as saturation, porosity, etc. Well log analysis is a process that gives a detailed background information about the well logs and evaluate the hydrocarbon production potential of a reservoir. Hydrocarbon saturation and determination of some hydrocarbon petrochemical properties are the main objectives behind well logging. Well logs are analysed for the study of the correlation of different zones, isopach mapping and determination of the depth and thickness of different zones(Vail and Wornarndt,1991). Initially, well logs were used for the correlation of wells with similar patterns of electrical conductivity and sometimes over large distances. Depositional sequence determination is one of the relevant tools for characterizing hydrocarbon bearing formations and modelling of the depositional settings. Petrophysical parameters are important in the exploration and production of hydrocarbon as well as stratigraphic sequence. Vail (1987)

Previously, reservoir characterization was carried out basically on quick look method of log interpretations as well as analysis of physical properties of reservoirs. Today, proper reservoir discernment and characterization of its lithology along with its fluid-content requires quantitative techniques of well log studies. These factors led to discerning and characterizing of hydrocarbon reservoirs from well log studies to obtain lithofacies templates that would be useful as mapping tools for reservoir characterization and discrimination. Therefore, reservoir parameter interpretation is no longer based on being primarily qualitative but has moved to being largely quantitative. During geophysical exploration, the foremost step is the identification of the physical properties (i.e., density, electrical conductivity: - if the medium is resistive or conductive, porosity, various stratigraphic sequences, etc.) which will aid in characterizing the reservoir. An integration of these properties obtained from well logs makes the reservoir characterization much easier as the addition of the depositional sequences in reservoir characterization is a plus to the geophysics/geology students in the classroom, the researchers and geophysicists/geologists in the fields.

Proper characterization of reservoirs, therefore, require an integration of the analyses of two or more types of data acquired from a particular area of interest in order to adequately define the reservoir model.The calculation of the petrophysical parameters of the reservoir units in was carried out using the following formula: Porosity is the percentage of void within the reservoir unit is determined using.

$$\phi = \frac{\rho ma - \rho b}{\rho ma - \rho f}$$

Where: $\rho b$ = bulk density
$\rho ma$ = density of the rock matrix
$\rho f$ = density of the formation
$\Phi$ = porosity of the formation
(Dresser, 1979)

The porosity of the formations in this study will be classified according to (Baker, 1992)

Table 1: Porosity classification modified from (Baker, 1992).

| S/N | POROSITY (%) | QUALITATIVE INTERPRETATION |
|---|---|---|
| 1. | <5 | Negligible |
| 2. | 5 –10 | Poor |
| 3. | 10 –15 | Fair |
| 4. | 15 –25 | Good |
| 5. | 25 –30 | Very Good |
| 6. | >30 | Excellent |

Gross thickness also referred to as reservoir thickness is the thickness of the various strata interval defined in which the reservoir units occur, this includes the non-productive intervals which may be inter-bedded between the productive intervals. The reservoir thickness is the thickness of the whole reservoir unit.

Reservoir thickness = bottom of reservoir unit – top of reservoir unit (that is $h_2 - h_1$).

Permeability: refers to the rock transmissibility and permeability variation, which is the ease at which fluids can flow through the reservoir. For this study, permeability is calculated using the expression (Emudianughe and Utah, 2019);

$$k = 307 + 26552\phi 2 - 3450\ (\phi Swirr)2$$

Classification of permeability in this study is done using the (Baker, 1992).

Table 2: Permeability classification modified from (Baker, 1992)..

| S/N | PERMEABILITY (mD) | QUALITATIVE DESCRIPTION |
|---|---|---|
| 1 | 1.0 – 15 | Poor – Fair |
| 2 | 15 – 50 | Moderate |
| 3 | 50 – 250 | Good |
| 4 | 250 – 1000 | Very Good |
| 5 | >1000 | Excellent |

### 1.1 Location of the Study Area

In the Gulf of Guinea, which is on the west coast of Africa, the Niger Delta basin is located. The Central Niger Delta consists of the "KO" field which is the study area, and it lies between longitude 6˚00' to 6˚51' East of the Greenwich Meridian and latitude 4˚40'1" to 5˚40'0" North of the Equator(Adejuwon, 2012).

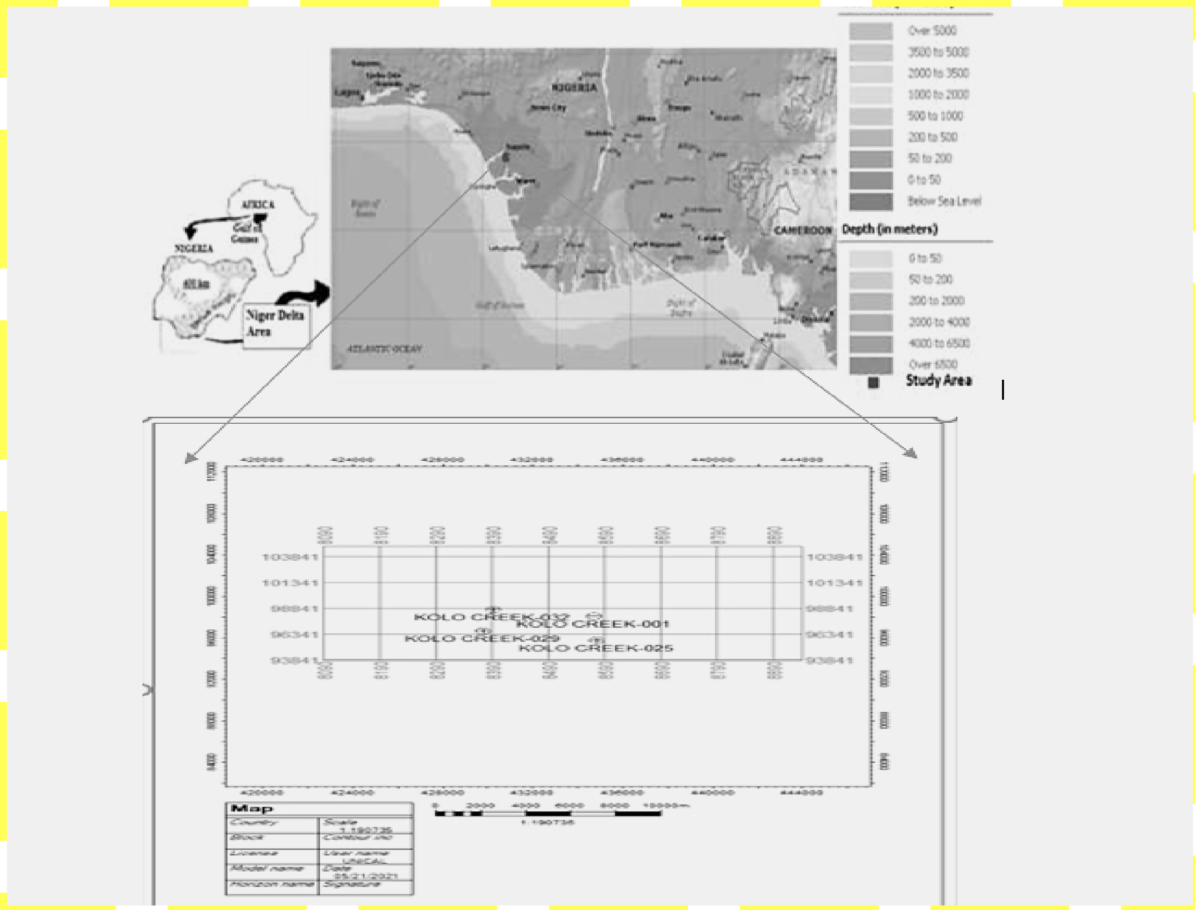



Figure 1: Location of the study area shown on the map of Niger Delta and the well locations shown on the map of the study area.

## 2.Materials and Methods

The data used for this research are as follows:

I. Well logs data
II. Online database of related academic journals
III. Online database of related academic literatures
- .

IV. Schlumberger Petrel 2014 software

### *2.1 Data Description*

The data used for this research study are:

- Well logs which detailed records are obtained by carrying out borehole logging

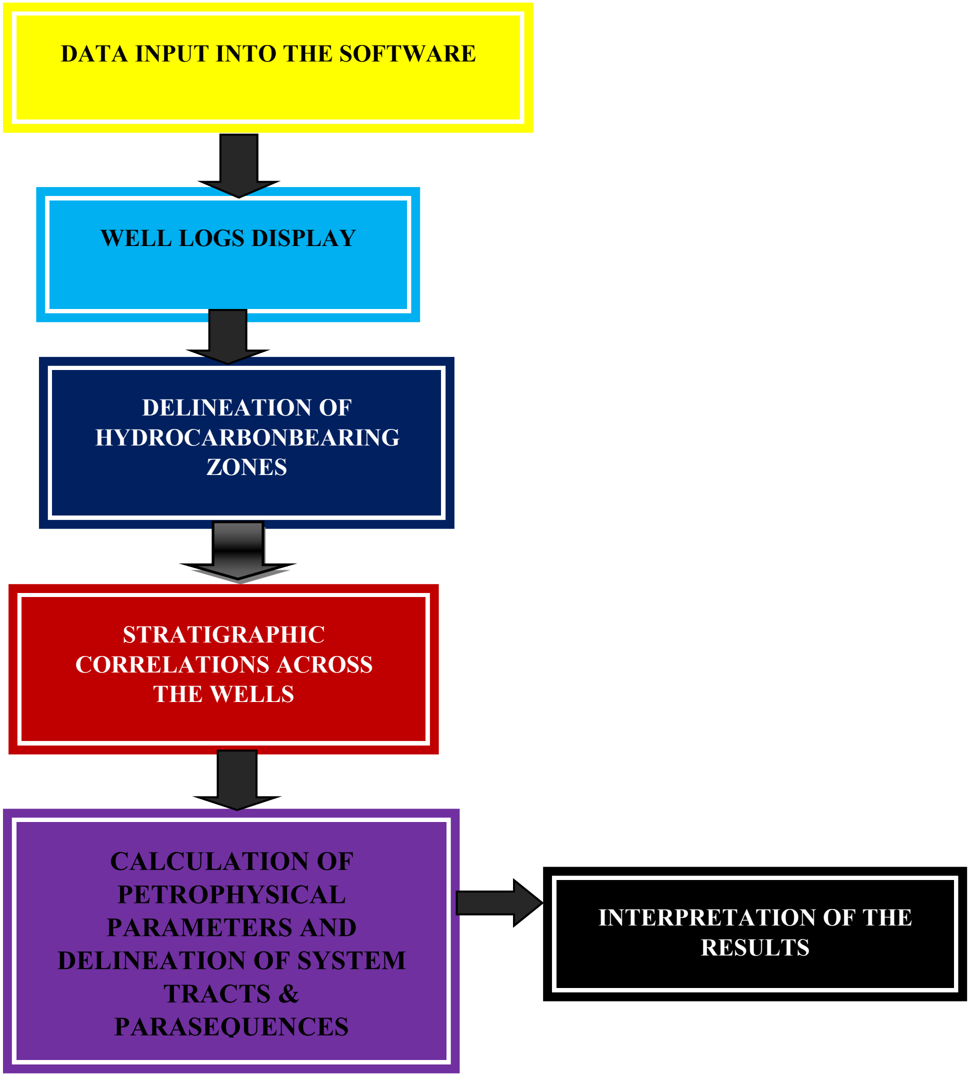
Table 2: Data set showing the wells information used for this study

| Wells | KO-001 | KO-025 | KO-029 | KO032 |
|---|---|---|---|---|
| Well Header | YES | YES | YES | YES |
| Well Deviation | YES | YES | YES | YES |
| GR log | YES | YES | YES | NO |
| SP log | YES | YES | YES | YES |
| Resistivity Log | YES | YES | YES | YES |
| Density Log | YES | YES | YES | NO |
| Den Log | NO | YES | YES | NO |
| Neutron Log | NO | NO | YES | NO |
| Sonic Log | YES | NO | NO | NO |
| Checkshot | NO | NO | YES | NO |

*2.2 Research Design /Method of Data Analysis*

**Research Design**

The workflow below was adopted.




Dataset used for this study is a secondary dataset obtained from the Shell Petroleum Development Company (SPDC) through the Department of Petroleum Resources, ministry of petroleum resources Port Harcourt.

***2.3 Method of Data Analysis***

For the fulfilment of this research, Schlumberger Petrel 2014 was used for the calibration of the well log data and extraction of the area (sqm) of the study area. Well log data for 3 wells were loaded into Petrel software. The software was used to perform well correlation and extraction of the area in sqm, interpret results and produce map. The dataset for each well consists of a suite of logs as follows; spontaneous potential (SP), gamma-ray (GR), resistivity log, density &neutron, and sonic logs. The suite of logs in each well were remodelled to support the division of different lithologies into sub-units (sand, shaly-sand, sandy-shale and shale) which were carried out on the basis of qualitative log interpretation. This description was achieved by the qualitative interpretation of the logs using GR log as well as stratigraphic correlation of the wells. The lithologies were defined by a cut-offline (the mid-line between the lowest and highest points on the wiggle) which denotes the boundary between the shale and sand units. Properties of the reservoirs were also obtained at each sample point across the depth of the three wells. Determination of the volume of the reservoir and the description of variety of petrophysical measurements that are used to address the important parameters like the porosity, fluid saturation and content of the volume of shale were determined from available well logs in the study area. However, likely hydrocarbon potential, source rock formations, delineation of reservoir top and bottom, fluid contacts identification, identification of reservoir using log suites. Porosity (ϕ), effective porosity, permeability (k) and hydrocarbon saturation ($S_h$) in all the reservoirs were obtained.

## 2. Results and Discussion

The diagram below shows that the Gas-Oil-Contact (GOC) of the well "KO-029" occur at 3621m below the surface and Oil-Water-Contact (OWC) occur at 3628.43m below the surface. The balloon effect displayed by the density-neutron logs show that there is an associated gas reservoir. Fluid contacts can be gradational in mixed-fluid reservoirs but are typically horizontal or nearly so because of the difference in density between gas, oil and water.

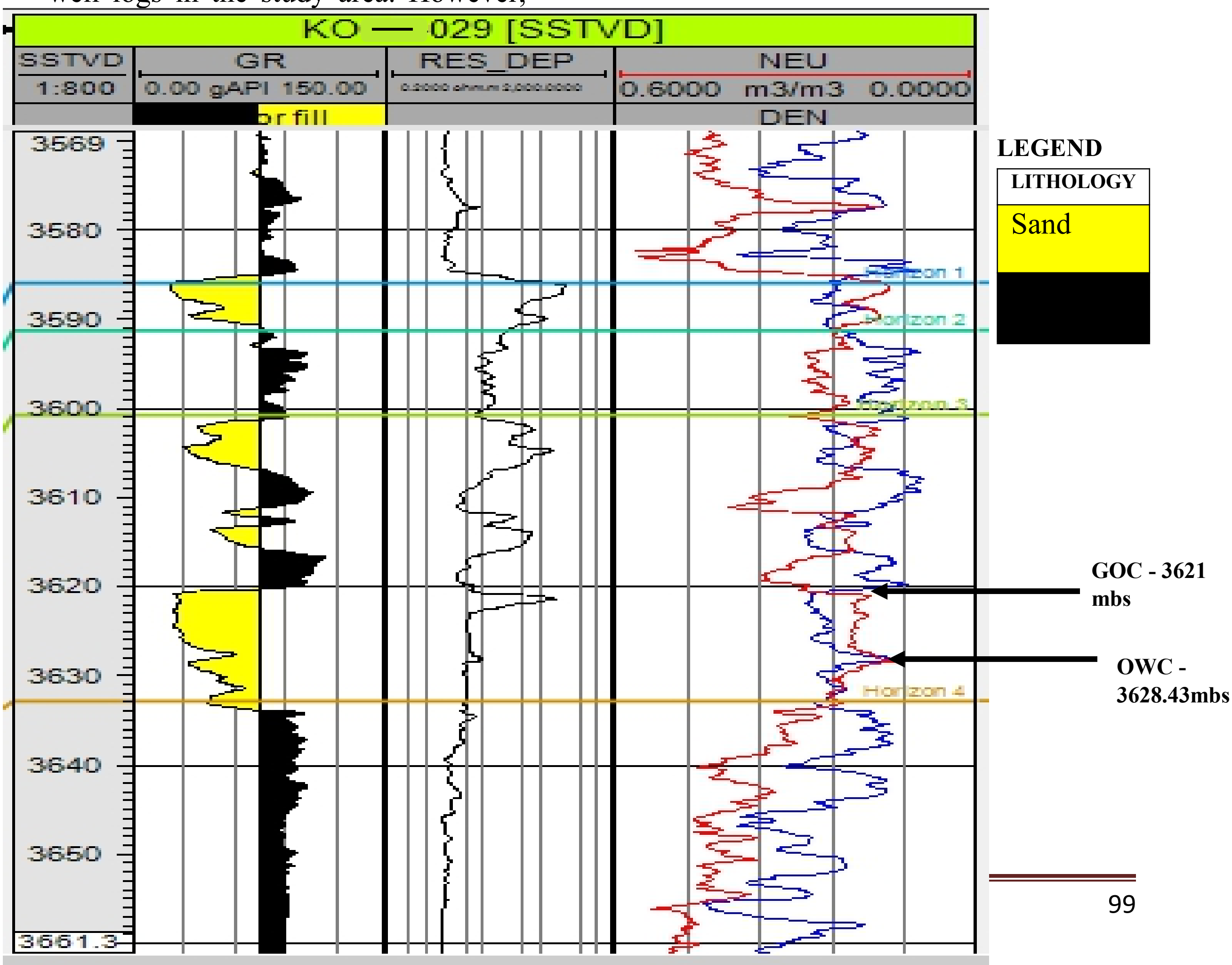





Figure 6: Reservoir fluid type and contact of well "KO-029".

Figure 7 and figure 8 show the correlation of the sands top and base across the three wells and the delineation of the reservoir top and bottom respectively using the gamma-ray and resistivity logs to furnish knowledge of the general stratigraphy of "KO" field. Two lithologies were identified using gamma ray log, these lithologies are the sand and shale. From the lithology logs below, the part-coloured yellow is sand, and the part-coloured black is shale. Three sand bodies marked as Sand 1, 2 and 3 were mapped across the field. Sand 1 which is the shallowest reservoir in all three wells, is located at depth 3,490m, 3,566m and 3,585m below the surface respectively in the three wells, is located beneath Sand 1 at about 3,500m, 3568m and 3,602m below the surface respectively in the three wells and have Sand 3 at a depth of about 3,590m and 3,620m below the surfaces of wells 025 & 029 respectively which have thicknesses of about 3m and 14m respectively in wells 025 & 029. These results obtained are based on the petrophysical analysis of the fields. From the analysis carried out using the well logs, it is revealed that each of the sand unit extends through the field and varies in thicknesses and depth occurrence than the unit adjacent wells. From the analyses, using particularly the gamma ray and resistivity logs all the three delineated reservoirs were identified as the hydrocarbon bearing units across the three wells KO-001, KO-025 and KO-029.

From the well correlation diagram below in figure 4.2, the sand of reservoir 2 showing high GR value is a radioactive sand that has hydrocarbon in it. That is the reason it also has high resistivity value.

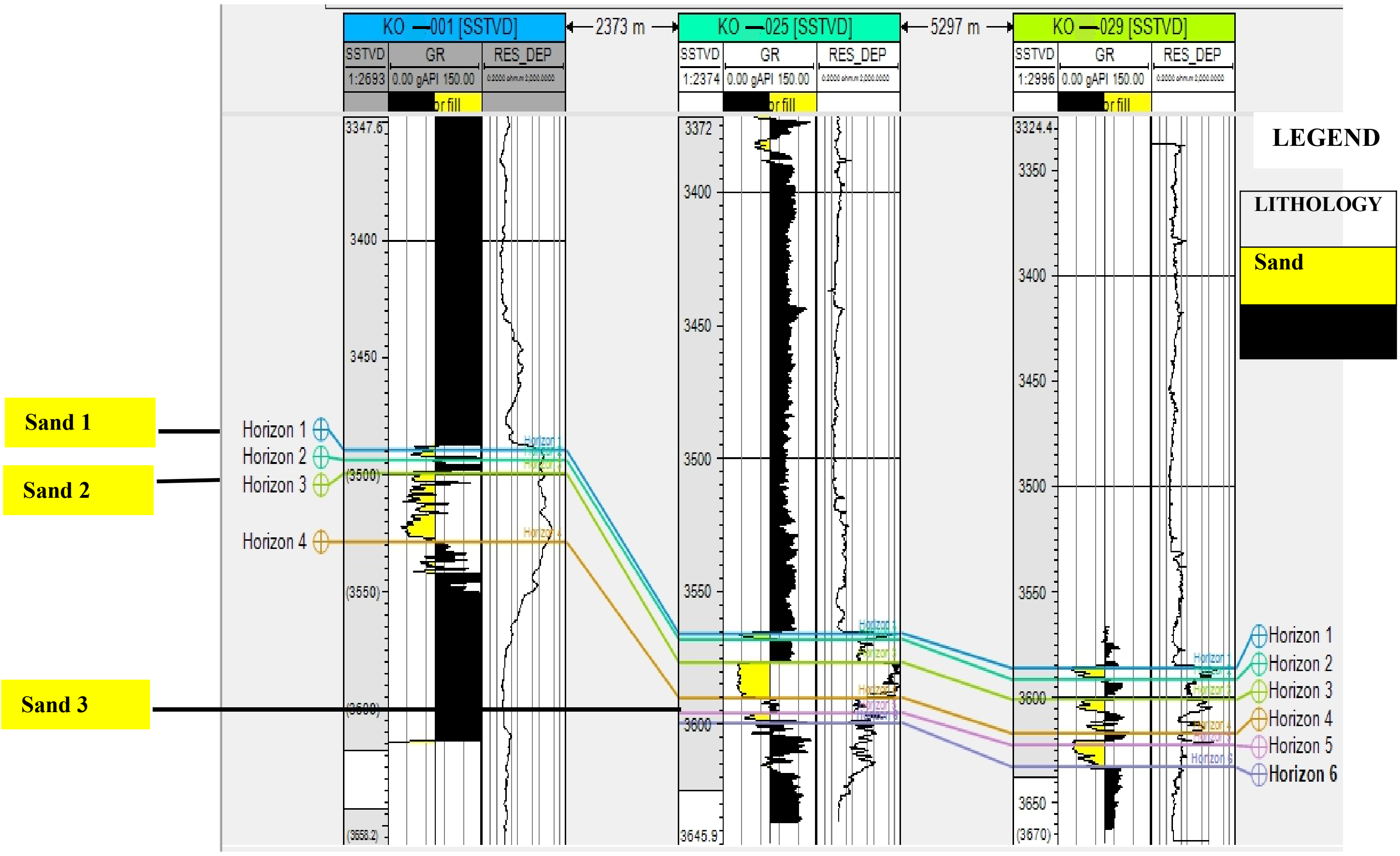



Figure 7: Well correlation of the reservoir sands on the well section.

### Well Delineation

The delineated lithology of "KO" field are majorly sand and shale formations with some occasional sand and shale intercalations.

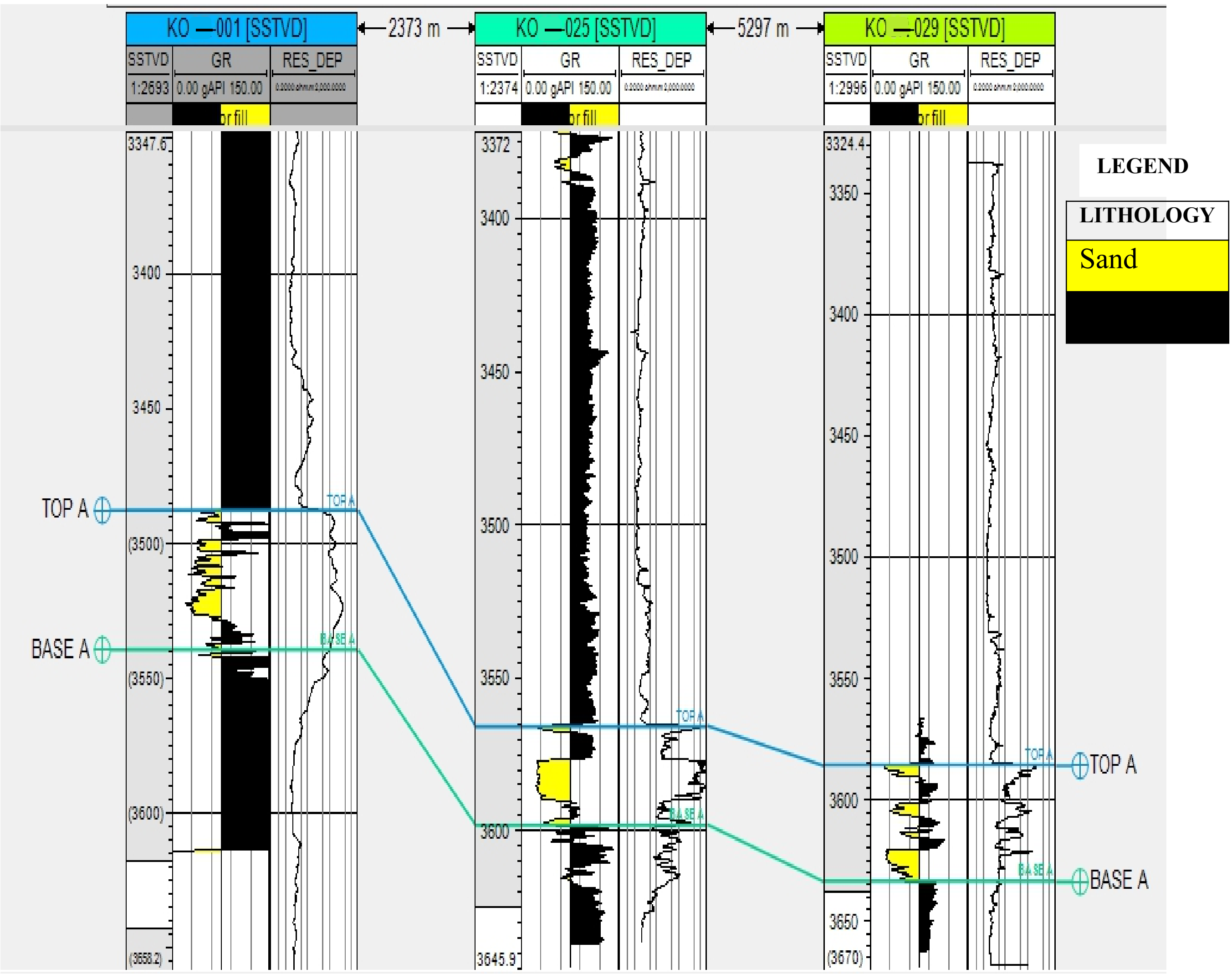



Figure 8: Delineation of the reservoirs on the well section.

## Reservoir Thickness

Table 3: Thicknesses of reservoirs 1, 2 & 3 across wells 001, 025 & 029.

| S/N | Reservoir | Quantitative Interpretation (M) |
|---|---|---|
| 1 | 1 | 95.40 |
| 2 | 2 | 83.25 |
| 3 | 3 | 81.34 |

## Rock Type

The reservoir rock types made up in the wells formations are basically sand and shale from the analyses of the data carried out using Schlumberger Petrel 2014.

## Reservoir 1

From the tables 4, 5 & 6 below, it is shown that across the wells 001,025 & 029, the reservoir1 was penetrated at depths 305.49m to 3600.89m, the volume of shale obtained across the wells ranges from 0.22 to 0.48 which is 22% to 48%, is relatively low. The porosity value ranges from approximately 0.22 to 0.26 which is indicative of a good to very good porosity which when converted to percentage will be 22% -26%. The connected pore spaces in reservoir 1 is between the ranges of 0.1728 to 0.1254 showing a decrease in interconnectedness of the pore spaces. From the water saturation ranging from approximately 12% -18% which is relatively low indicating a high hydrocarbon saturation this means that the reservoir is highly saturated with hydrocarbon. The permeability of the reservoir across well 001, 025 & 029 greater than 1000mD which permits the free flow of fluids within the reservoir, and this indicates an excellent permeability for a reservoir.

## Reservoir 2

From the tables 4, 5 & 6, it is evident that across the wells 001, 025 and 029 the reservoir was penetrated at depths 3523, 3590.97 and 3606.25m, the volume of shale obtained across the wells range from 2% to approximately 36% showing a relatively low percentage of volume of shale. Porosity value obtained for reservoir 2 across the wells is approximately 11% - 19% which is classified as fair to good porosity. The interconnectedness of the pores ranges from 0.0678 – 0.1833. Based on the obtained water saturation which ranges from approximately 13% - 44% which is fairly low indicating a high hydrocarbon saturation. Hence, reservoir 2 is a hydrocarbon bearing unit. The permeability of the reservoir across wells 001, 025 and 029 is 600mD – 1239mD which shows very good to excellent permeability for a reservoir.

## Reservoir 3

Tables 4, 5 & 6 show that the reservoir 3 was penetrated at depths 3534.39m – 3615.73m in wells 025 and 029, with volume of shale ranging from approximately 30% - 50% indicative of a fairly high shale volume. Porosity value for the reservoir ranges from 2% - 26% which is negligible to very good porosity. The interconnected pores range from approximately 10% to 19%. Water saturation percentage ranges from 11% to

52% which indicates moderate hydrocarbon saturation. The permeability of the reservoir across the wells is greater than 1000mD showing an excellent permeability for a reservoir.

Table 4: Result of computed petrophysical parameters for well "KO-001".

| Well | Start MD (m) | Vsh (%) | Φ(%) | $Φ_{eff}$ (%) | Sw (%) | ff | Swirr_H(%) | k(mD) | NTG(%) |
|---|---|---|---|---|---|---|---|---|---|
| KO-001 | 3505.49 | 22.21 | 21.86 | 17.28 | 13.889 | 115.680 | 17.49 | 1571 | 77.79 |
| KO-001 | 3523 | 35.87 | 10.64 | 6.78 | 12.492 | 488.019 | 41.37 | 600 | 64.13 |

Table 5: Result of computed petrophysical parameters for well "KO-025".

| Well | Start MD (m) | Vsh (%) | Φ(%) | $Φ_{eff}$ (%) | Sw (%) | ff | Swirr_D(%) | k (mD) | NTG(%) |
|---|---|---|---|---|---|---|---|---|---|
| KO-025 | 3588.79 | 47.33 | 2.55 | 13.18 | 11.601 | 19.173 | 9.76 | 2031 | 52.67 |
| KO-025 | 3590.97 | 2.11 | 18.75 | 18.33 | 31.458 | 45.454 | 14.79 | 1239 | 97.89 |
| KO-025 | 3599.69 | 50.34 | 2.22 | 9.65 | 16.296 | 46.083 | 13.42 | 1613 | 49.66 |

Table 6: Result of computed petrophysical parameters for well "KO-029".

| Well | Start MD(m) | Vsh (%) | Φ(%) | $ϕ_{eff}$ (%) | Sw (%) | ff | Swirr_D(%) | k (mD) | NTG(%) |
|---|---|---|---|---|---|---|---|---|---|
| KO-029 | 3600.89 | 48.95 | 24.6 | 12.54 | 17.88 | 21.350 | 10.27 | 1911 | 51.05 |
| KO-029 | 3606.25 | 7.69 | 16.64 | 15.28 | 43.64 | 64.875 | 17.47 | 1040 | 92.31 |
| KO-029 | 3615.73 | 31.94 | 2.19 | 13.92 | 51.51 | 42.545 | 13.34 | 1579 | 68.06 |

**Sequence stratigraphic system of the wells**

Sequence boundaries, system tracts and parasequence stacking patterns were recognized from the logs responses of the study area. The three types of sequence bounding surfaces [Sequence Boundary (SB), Maximum Flooding Surface (MFS) and Transgressive Surface (TS)] are recognized as well in the wells of the study area. The sequences and system tracts are subdivided by parasequencs into smally units for detailed prediction, correlation, and mapping of the environment of deposition, this is referred to as the sequence stratigraphic framework.

From figure 9 and Table 7, The inferred sequence boundaries represented by abrupt changes in lithology are described as $SB_2$, $SB_3$ and $SB_4$.They are seen at depths 3585.67m, 3601.35m and 3629.62m respectively in well 029.In well 025, the boundaries are recognized at 3565.49m, 3577.00m and 3596.33m respectively.The boundaries $SB_3$ and $SB_4$ are seen at depths 3498.94m and 3488.02m respectively. The $SB_2$ is not seen in well 001.

Transgressive surfaces which correspond to 3604,40m in well 029, 3587.18m in well 025 and 3522.10m in well 001 were recognized from the log response by the landward flooding surface above the second maximum flooding surfaces and below the third sequence boundary. Two of the depositional sequences seen in the study area are incomplete as LST is missing in the recognized sequence models 2 and 4, but present in sequence 3 where it is seen as aggrading LST also, HST is missing in sequence models 3 and 4 due to erosion. Sequence 2 comprises of TST and HST (3627.40m – 3633.30m and 3621.34m – 3623.64m respectively) capped by MFS$_2$ shale which is overlain by a TS in well 29, these tracts are not available in well 025 and well 001. Sequence 3 comprises of just LST seen at depths (3602.17m – 3606.12m) in well 029 as retrograding LST, (3577.86m – 3589.72m) in well 025 and (3499.30m – 3526.73m) in well 001 as aggrading LST in both wells.Sequence 4 comprises of TST (3584.95m – 3590.05m) in well 029 and 93487.98m – 3491.75m) in well 001. This tract is not seen in well 025.

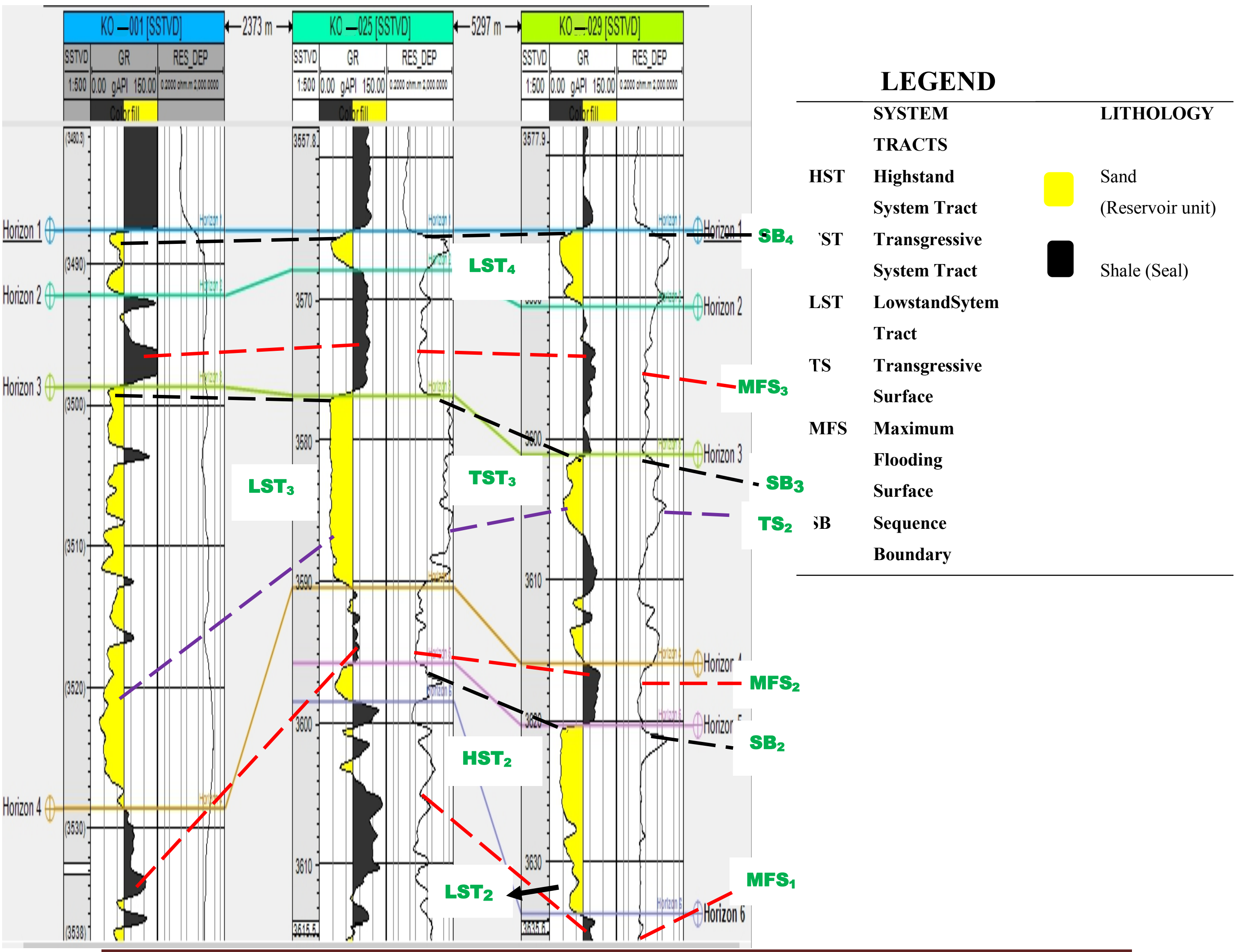



Figure 9: Stratigraphic surfaces and their associated system tracts identified in "KO" field.

Table 7: Key stratigraphic surfaces recognized from "KO" field well log data analysed.

| Key Surfaces | Wells depths of recognized surfaces | | |
|---|---|---|---|
| | Well 001 (m) | Well 025 (m) | Well 029 (m) |
| $SB_4$ | 3488.02 | 3565.49 | 3585.67 |
| $MFS_3$ | 3496.72 | 3571.99 | 3593.91 |
| $SB_3$ | 3498.94 | 3577.00 | 3601.53 |
| $TS_2$ | 3522.10 | 3587.18 | 3604.40 |
| $MFS_2$ | 3533.75 | 3594.11 | 3617.49 |
| $SB_2$ | | 3596.33 | 3620.62 |
| $MFS_1$ | | 3599.13 | 3634.34 |

**Reservoir 1**

Visible from depth 3487.44m, 3565.18m and 3585.22m respectively across wells 001, 025 & 029, the orange arrow shows the period of retrogradation with a low energy of subsidence in well 001 and across wells 025 and 029 there are evidence of progradation.

**Reservoir 2**

From depth 3498.69m – 3528.58m in well 001, there is clear evidence of long-term aggradation with abrupt retrogradations at intervals. In well 025, there is a constant undisturbed long-term aggradation from 3570.82m – 3590.45m and in well 029, there are periods of retrogradation at intervals of the period of aggradation from 3601.22m – 3615.99m. The type of aggradation pattern shown in well 001 & 029 are referred to as saw tooth aggradation. The aggradation parasequence indicates there is high sediment supply during this period. These parasequences are shown across the wells by the blue arrow.

**Reservoir 3**

There is evidence of progradation across well 025 and 029, which gradually changed to aggradation at 3628.62m in well 029. However, below 3633.64m there is a long term retrogradation which can be referred to as a sequence boundary. These are indicated across the two wells by the red arrow.

Between reservoirs 1, 2 & 3, there are evidence of retrogradations. These retrogradationalparasequences are composed of small and massive marine shale.

Each of the system tracts has a predictable set of associated reservoirs which are the main exploration targets. In this study the potential reservoirs, the hydrocarbon distribution and their associated system tracts are reported. From this study, it was observed that hydrocarbon was found mainly within the lithostratigraphic intervals of the highstand system tract of sequence 2, trangressive system tracts of sequences 3 & 4. The reservoir units within these sequences were deposited within the fluvio-deltaic to shallow marine environment. The organic rich shales may provide a petroleum source rock as well as regional seal.

Many the reservoir sand units belonging to the Highstand System Tract (HST) may contain sufficient quantity of hydrocarbon. These reservoir sand units were the prograding and aggrading complexes within sequences 2, 3 & 4 (Figure 10)

Table 8: System tracts recognized from "KO" field well log data analysed.

| System Tracts | Wells depths of recognized tracts | | |
|---|---|---|---|
| | **Well 1 (m)** | **Well 25 (m)** | **Well 29 (m)** |
| **TST$_2$** | NILL | NILL | 3627.40 - 3633.30 |
| **TST$_3$** | 3487.98 - 3491.75 | NILL | 3585.95 - 3590.05 |
| **LST$_2$** | 3499.30 – 3526.70 | 3577.86 – 3589.72 | 3602.17 – 3606.12 |
| **HST** | NILL | NILL | 3621.34 – 3623.64 |

Table 9: Parasequence of reservoirs across wells with corresponding depths.

| Reservoir Surfaces | Wells depths of recognized parasequences | | |
|---|---|---|---|
| | **Well 1 (m)** | **Well 25 (m)** | **Well 29 (m)** |
| **R1 Top** | 3487.44 | 3565.18 | 3585.22 |
| **Bottom** | 3492.34 | 3567.83 | 3590.77 |
| **R2 Top** | 3498.69 | 3576.82 | 3601.22 |
| **Bottom** | 3528.58 | 3590.45 | 3615.91 |
| **R3 Top** | | 3595.61 | 3620.27 |
| **Bottom** | | 3598.52 | 3633.64 |

Priority potential for prospect and play generation because it can be studied as comprising a single petroleum reservoir system and it can form a stratigraphic trap.
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The shales above and below the highstand and transgressive system tracts at the maximum flooding surfaces may act as seals for the hydrocarbon

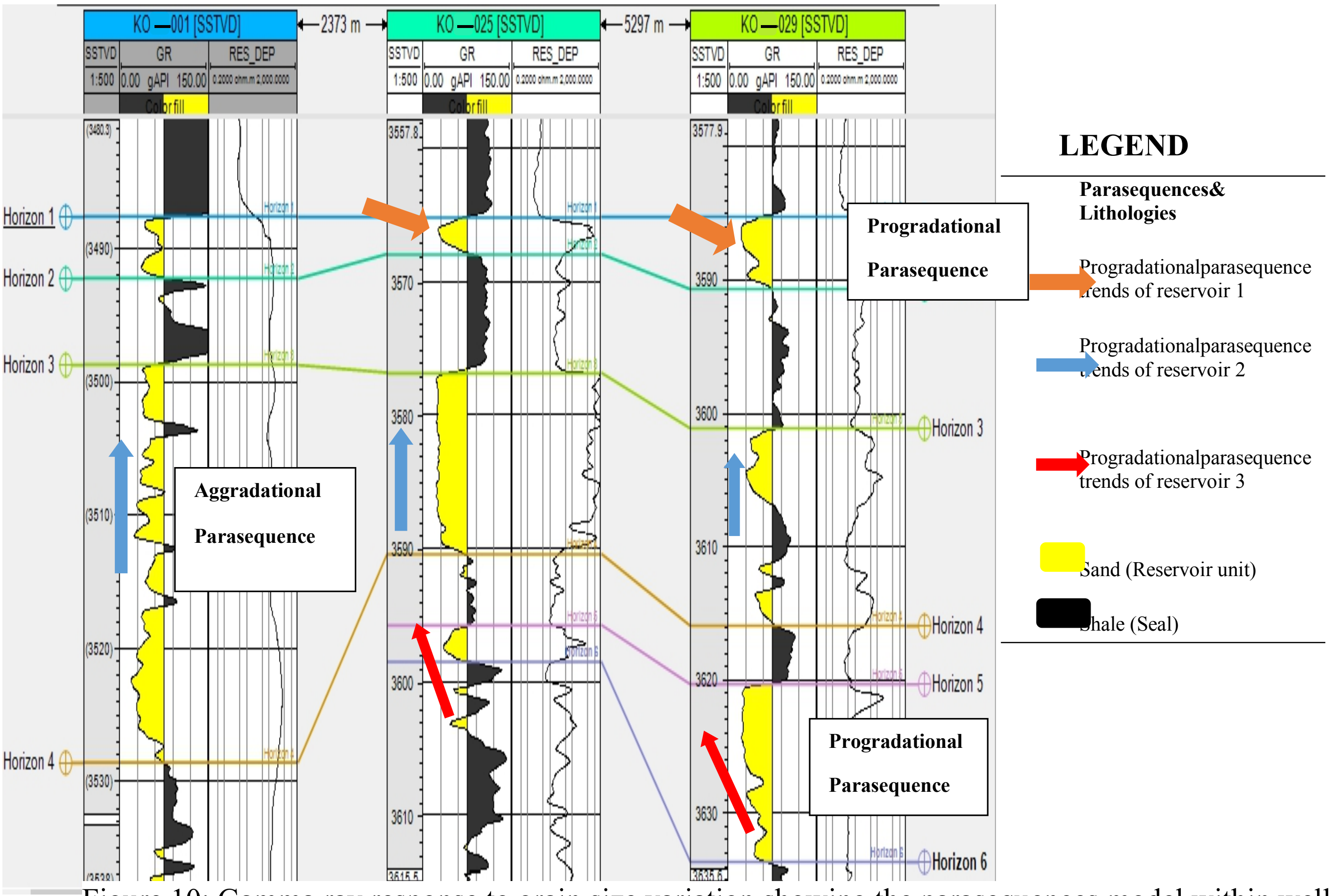


Figure 10: Gamma ray response to grain size variation showing the parasequences model within wells in "KO" field.

transgressive system tracts should be assigned a high

Three sequences were identified in the study area with incomplete system tracts over the interval 3487.44 – 3633.64m. table 11 shows the gamma-ray facies association,sequence-stratigraphic framework and depositional systems identified; well logs with the funnel shape have their sediments coarsening upwards and shows that the sediments are deposited on shore-face and the sequence stratigraphic framework for this kind of well log signature is progradational which indicates increasing upwards, well logs with the blocky (cylindriacal) shapes are tidal channels and their framework is the aggradational indicating equal/even sediment deposition and blocky (cylindrical) and funnel shape (coarsening upward) well log signatures show that the sediments are deposited along distributary channels and fluvial channels and the sequence stratigraphic framework is progradational. Marine shales and sands dominated sequences identified in the study area, reservoir quality sands are found in tidal channel lowstand system tract and distributary channels & fluvial channels highstand system tract, while the shales of the maximum flooding surfaces form their seal units.

Table 11:Gamma-ray Facies Association, Sequence-Stratigraphic Frameworkand Depositional Systems of "KO" Field.

| Well-log Signatures | Gamma-ray Facies and Depositional systems | Sequence-Stratigraphic Framework |
|---|---|---|
| Funnel shape (coarsening upward) | Shore-face deposits | Progradation |
| Blocky (cylindrical) | Tidal channels | Aggradation |
| Blocky (cylindrical) and Funnel shape (coarsening upward) | Distributary channels and Fluvial channels | Progradation |

**Conclusion**

This study enhances the understanding of reservoirs to store and release hydrocarbon based on their effective porosity and permeability, identification and interpretation of depositional environment based on their log signatures or gamma-ray response as well as the recognition of system tracts and genetic packages of potential reservoirs.

From the analysis of the data, the rock types that made up the formation are basically sand, and shale and it is discovered that the sand and shale units were continuous in all three wells. Reservoirs 1 & 2 were seen across the wells 001, 025 and 029 while reservoir 3 is evident in wells 025 & 029 only. The reservoirs' porosities are fair to very good, their permeabilities are very good to excellent. The result obtained from this research indicates that the lithologies are defined by three sequences. The three system tracts; high stand, low stand and transgressive seen in the reservoirs with shales above and below at the maximum flooding surfaces should be assigned high priority potential for prospect and play generation due to the fact that it can be studied as comprising a single petroleum reservoir system and it can form a stratigraphic trap. Each of these system tracts has a predicatable set of associated reservoirs, which are the main exploration targets. The shales seen at the maximum flooding surfaces may act as seals for the hydrocarbon. The depositional environment interpreted after comparing the log signatures within sequences, parasequences and parasequence sets are predominantly shoreface deposits, tidal channel, distributary channels and fluvial channels.The result of this study has confirmed that evaluation of hydrocarbon reservoir can be carried out with changing degree of effectiveness in various domains using the adopted approach for a particular research study. This indicates that the use of petrophysical parameters and the stratigraphic system obtained from the well logs to estimate and understand hydrocarbon reservoir would go a long way in saving time and resources. This study has revealed that integrating petrophysical methods of reservoir characterization and determination of its sequence stratigraphy enhances the understanding of the differences in the quality of reservoir and heterogeneity within the basin. From the result obtained, we can infer that "KO" field has potential hydrocarbon that is exploitable.

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