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ISSN: 2350-0743

International Journal of Recent Advances in Multidisciplinary Research
Vol. 02, Issue 10, pp.0848-0863, October, 2015

RESEARCH ARTICLE

A COMPARATIVE REVIEW ON THE PETROPHYSICAL EVALUATION OF THINLY BEDDED RESERVOIRS USING CONVENTIONAL AND 3D EXPLORER DATA

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ARTICLE INFO

Article History:
Received 26th July 2015
Received in revised form
19th August, 2015
Accepted 21st September, 2015
Published online 31st October, 2015

Keywords:

Conventional-logs,
3D-Explorer, Petrophysical, and
Thinly-Bedded-Reservoirs.

ABSTRACT

This study demonstrates the efficiency of the multi-component induction tool (3DEX) that simultaneously measures the vertical and horizontal resistivity of the formation, by presenting a comparative petrophysical evaluation of thinly bedded reservoirs using Conventional logs and 3DEX data acquired from two different fields of which one is an oil-bearing reservoir formation from Olu field in the Niger Delta province and the other is a gas-bearing reservoir formation from Balda field in North Sea. Various graphs and charts were displayed to showcase the difference between the two evaluation techniques. From the oil-bearing reservoir field the 3DEX results indicate an average hydrocarbon reserves of 83% while the Conventional interpretation techniques presents an average of 17% and in the gas field the 3D-Explorer model gives an average of 53% and the Conventional model shows 47%. These results have demonstrated the effectiveness and successful application of the multi-component induction tool(3DEX) in evaluating thinly bedded reservoirs for effective decision making and proper well placing and performance predictions.

INTRODUCTION

The exploration and production of hydrocarbon is increasingly becoming a major area of concern in the global-scale due to the high rate of energy demand in recent times. As demonstrated by the BP Energy Outlook (2013), the key drivers following the high energy demand are population growth and increase in income. The world population is estimated to increase by 1.3 billion and the income increase is projected to twice the amount in real time by 2030 making a rough estimation of 8.3 billion people in the globe demanding for energy consumption. Figure 1.0 shows the world population and income increase with regards to energy consumption.

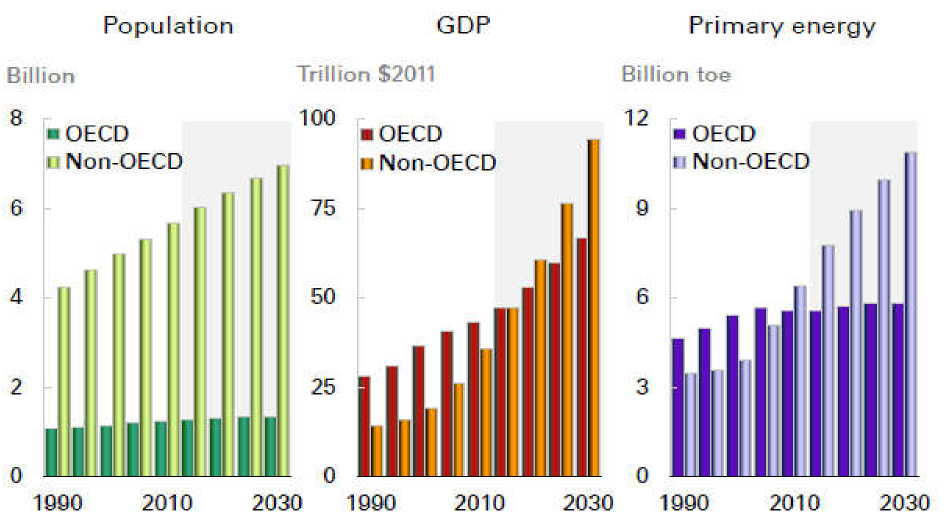

Figure 1.0. Population and income growth (BP, 2013)

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The world energy consumption grows by 890,000 barrels per day with China and India accounting for 31% of the world energy consumption as a result of growing trends in economy, motorisation, urbanization and industrialization (EIA, 2011). As illustrated in Figure 1.1.According to the EIA's world energy report (2011), Energy sources are diversified as the global energy continues to advance, new innovations and technologies are invented by the energy industries to discover and produce the numerous energy forms required to sustainably meet the growing energy demand. EIA Annual Energy Review (2012) expressed that 62% of the world energy supply comes from oil and gas with coal, nuclear energy and renewable energy accounting for the rest percentage (see Figure 1.2). The current world proved oil reserves are approximately 1668.9 thousand millions with a global production rate of 86152 thousand barrels per day andconsumption rate of 89774 thousand barrels per day (BP, 2013). To meet this higher rate of energy consumption with respect to production; exploration and production activities are been carried out in every part of the world from Australia to Asia, South America to North America, Antarctica to Europe and to Africa, and also in every habitat from arctic to desert, from tropical rainforest to temperate woodland and from mangrove to offshore (Joint and Forum, 2013).

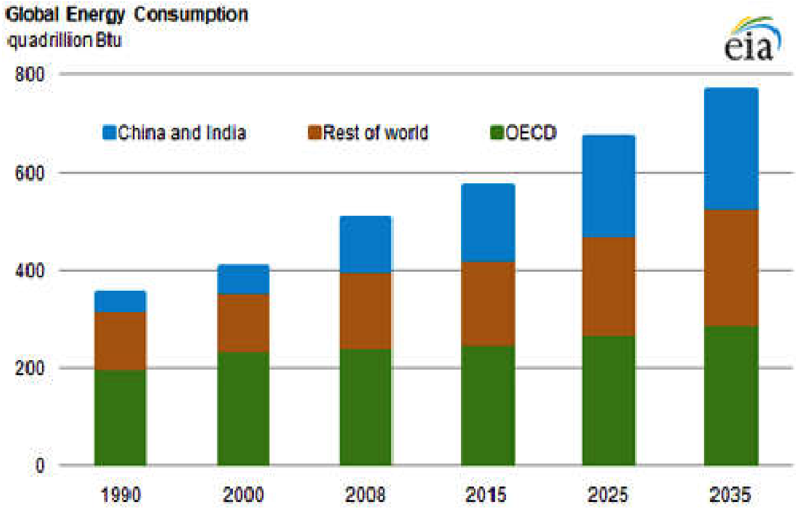

Figure 1.1. Global energy consumption (EIA, 2011)

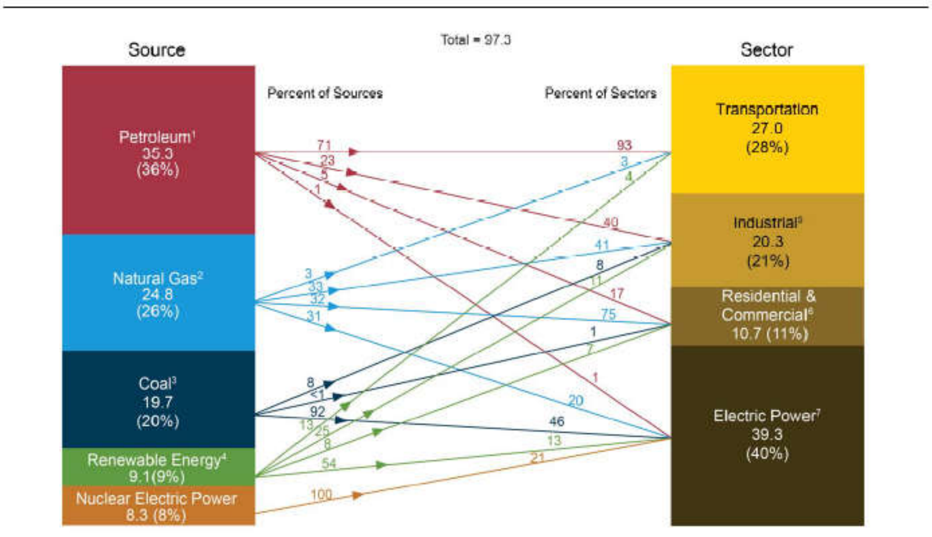

Figure 1.2. Primary Energy sources and consumption sectors (EIA, 2012)

Consequently, hydrocarbon exploitation begins with the recognition of a likely geologic province, after which a seismic survey is conducted and then one or two exploratory wells are drilled; these wells may possibly encounter hydrocarbons. Afterwards, subsequent downhole measurements are made to evaluate and quantify the hydrocarbon reserves for possible development (Claverie *et al.,* 2006). Analysis has shown that the prospect for easy production of oil and gas is over, and it is now time to explore complex and challenging formations such as thinly bedded reservoirs to supply the world with the needed energy. According to Passey *et al.* (2006) thinly bedded reservoirs are reservoirs with geological beds and laminae less than 2-feet (6m) in thickness; the 2-ft thickness is selected as a bench mark for thin-beds because it is relatively equivalent to the vertical resolution of the porosity logs and highest-resolution resistivity logs. In addition, Tyagi *et al.* (2008) noted that the thinly bedded reservoirs display heterolithicinterbedding and a broad range of reservoir properties, they differ in thickness from millimetres to metres with igh permeability, but the laminated clay components affects the permeability of the layers, thereby leading to a change in reservoir properties and well productivity.

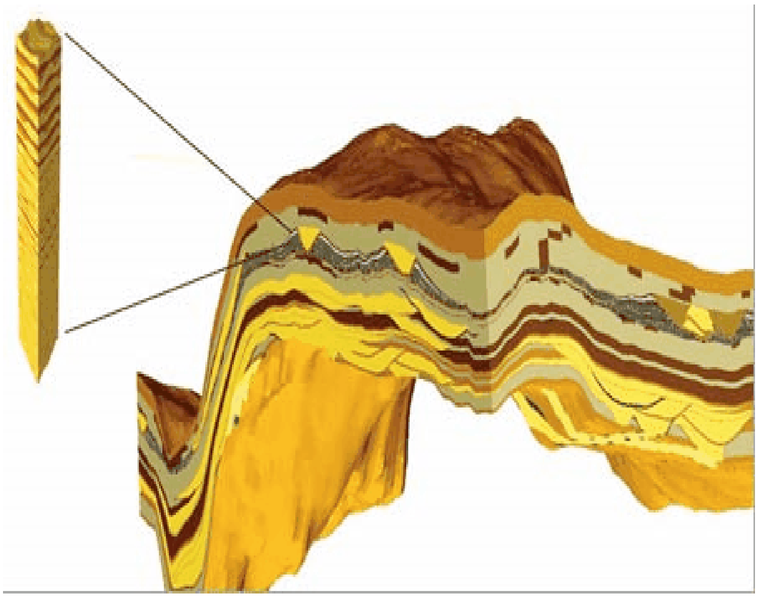

Figure 1.3. A schematic of a thinly bedded reservoir (Charter Consulting, 2013)

Petrophysical evaluation is concerned with the interpretation of a set of measured dataacquired from a wellbore to detect and quantify oil and gas reserves in the rock adjacent to the wall; these data are gathered with wire line logging tools or logging while drilling (LWD) instruments that presents the physical properties of rocks and the fluids contained within these rocks.The main reservoir petrophysical parameters are: the bed thickness, porosity, permeability, water saturation and hydrocarbon saturation (Worthington, 2010).

The evaluation of thinly bedded reservoirs are difficult because of their complex geometry, the quality of the reservoir is determined by connection and length of beds below the resolution of usual reflection data; which leads to high reserve uncertainty and also frequently associated with unpredictable well performance (Kiatpadungkul *et al.,* 2010). As a result of this, so many hydrocarbon bearing reservoir formations in the past have been neglected, because they arecomposed of thin laminated sand and shale sequences that are either not properly identified to contain hydrocarbons or the hydrocarbon reserves are not accurately quantified. Accordingly, Peter (2010) pointed out that the acquisition of data from wells with conventional logging tools do not accurately measure the actual resistivity of the thin-bed pay zones as a result of the low vertical resolution of the tools with respect to the bed thickness thereby leading to an observed macroscopic anisotropy. This results in low contrast between the hydrocarbon zone and the water bearing interval given rise to under estimation of the hydrocarbon in place (Peter, 2010). Figure 1.4 shows an observed macroscopic anisotropy when layer thickness is below tool resolution. Furthermore, the multinational oil and gas companies have come up with several technologies to resolve the uncertainty of evaluating thinly bedded reservoirs. These technologies include; Multi-component induction tools (3D-Explorer), Nuclear Magnetic Resonance tool, Electrical Borehole Imagers, Azimuthal Resistivity Imager and different others (Passey *et al.*, 2006).

This research highlights the benefits of 3D-Explorer (3DEX) logging tool in characterizing reservoir petrophysical properties as compared to the conventional tools. Passey *et al.* (2006) also highlighted the environments of deposition in which thinly bedded reservoirs are prone to occur. Similarly, Table 1.0 summarised the depositional environments where thin beds were prone to occur. Significantly, in the world today, the exploration and production of large reservoirs are no longer feasible and as a result of the high energy demand in a global scale the oil and gas industry are developing new and unconventional technologies to produce complex and thin reservoirs. Schlumberger (2013) discussed the use of the ARI azimuthal resistivity imager tool which is incorporated with azimuthal electrodes in a dual laterolog array that makes directional measurements around the circumference of the borehole with higher vertical resolution and deep oriented resistivity than the conventional laterolog tools. Halliburton (2013) highlighted the application of Electrical Micro Imaging (EMI^{SM}) tool in evaluating thin reservoirs which provides a real time electrical image of the sedimentary layers in the formation as indicated in the wellbore.

Baker Hughes (2013) also expressed the use of a 3D Explorer (3DEX) that distinguish the productive low-resistivity zones from non-productive zones, this is actualized by identifying anisotropic formations and measuring horizontal resistivity and vertical formation resistivity. Hence, this project is relevant because it critically analyse the useful techniques in evaluating complex reservoirs that may be useful to exploration and production companies that intend to produce challenging reservoirs. The project demonstrates the importance of using multi-component induction tool (3DEX) to unravel the uncertainties in exploring thinly bedded reservoirs by comparing data sets from conventional logging tools and 3D-Explorer (3DEX) data set acquired from two different fields of which one is an Oil-bearing reservoir from Olu field in the Niger Delta province and the other is a Gas-bearing reservoir from Balda field in North sea. This research will also be a useful source of information for academic researchers.

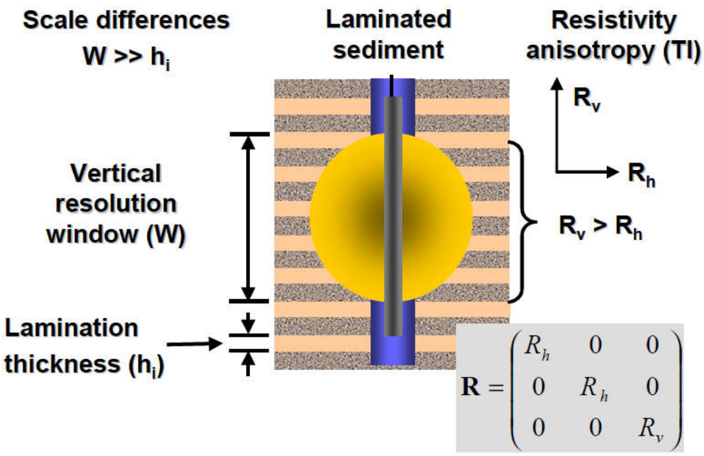

Figure 1.4. The observed macroscopic anisotropy when layer thickness is below tool Resolution (Damodaran *et al.*, 2002)

Table 1.0. A summary of the depositional environments where thin beds are prone to occur (Adapted from Passey *et al.*, 2006)

Depositional system	Thin-bed prone	Non thin-bed prone
Deep-water	Overbank/levee deposits, Distributive lobe, Channel margin and Hemipelagic	Channel axis, Debrites (sand or muddy)
Beach/shoreface	Lower shoreface and Distal lower shoreface	Foreshore, Upper shoreface
Deltaic	Delta front and Prodelta	Stream-mouth bars
Tidal/estuarine	Sandy tidal channel and Intertidal sand flats	Subtidal
Fluvial	Point bars (meandering stream), levees and Terminal splay overbank	Braided streams, Channel sands, Channel lag deposits, Fluvial bars, Alluvial fans
Aeolian	Interdune and Wind ripple deposit	Cross-bedded dunes

Therefore, this paper is aimed at conducting a comparative review on the petrophysical evaluation of thinly bedded reservoirs using conventional and 3d explorer data. In addition, this aim was realized based on the underpinned objectives: to identify the reservoir petrophysical properties; to critically analyse various logging tools for evaluating reservoir petrophysical properties; to evaluate the economic importance of the 3D-Explorer tool in characterizing thin beds with relation to the conventional tools; and to produce a set of recommendations for the application of the 3DEX tool.

MATERIALS AND METHODS

Overview of the Research Design

The preparation of the research design is the most challenging issue after the research problem have been defined. According to Kothari (2004) the theoretical structure within which a research is conducted is regarded as the research design. It involves the procedures of data collection and analysis in a significant and economical approach that defines the research purpose. Marczyk*et al.* (2005) stated that there are several types of research but the correlational and experimental research pattern are the two types commonly used. The correlational research describes the relationship between two or more variables (such as time, weight and height). While the experimental research involves comparing two groups on one outcome measured to test some hypothesis, this research is basically an experimental research type. The research compared Conventional logs and 3DEX data sets obtained from two different fields to evaluate the petrophysical parameters of the formations.

Research Approach

Hakim (1987) opined that there is no method that can be regarded as the best approach in research because every methodology stands alone and depends on the study phenomena. On the basis of this argument, this research was designed as a low risk study that relied entirely on secondary data, this is as a result of the time frame scheduled for the research and the characteristics of the study. The research combines both qualitative and quantitative (predominantly quantitative) methods of analysis in terms of data handling. For the research not to be generic and vague it was streamlined using a case study approach. As stated by Phophalia (2010) case study enables the researcher to make an in-depth research and analysis of a specific scenario. Two case studies have been selected to effectively demonstrate the comparative petrophysical evaluation of thinly bedded reservoir using conventional logs and 3D-Explorer data sets. An Oil bearing reservoir from Olu field in the Niger Delta province and a Gas-bearing reservoir from Balda field in the North Sea comprising of thinly laminated beds; were used in analysing the petrophysical properties of the reservoirs by comparing the conventional logging tool and the 3D-Explorer tool data sets extracted from these reservoirs. Figure 3.1 indicates the map of the two study areas. The reason for collecting the data from two different fields is to justify the efficiency of the 3D-Explorer logging tool for evaluating the petrophysical properties of thinly bedded reservoirs as compared to the conventional logging tools in both Oil and Gas bearing reservoirs.

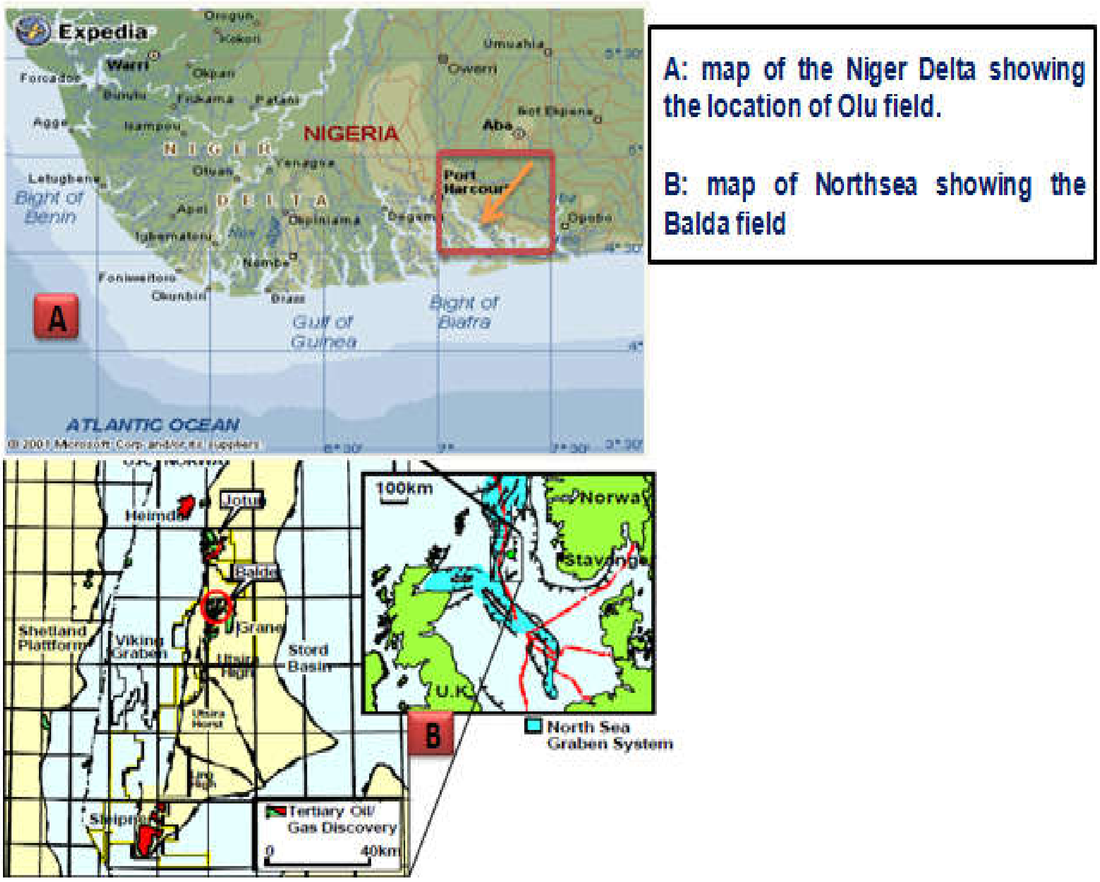

Figure 2.0. A-Map of the Niger Delta showing Olu field (Adapted from Okiwelu *et al.*, 2012). B-Schematic section of the Balda field location (Adapted from Wang *et al.*, 2003)

Method of data Collection

The main idea of collecting data is to verify the research hypotheses (Kothari, 2004). Since the study was designed as low risk, secondary data collection techniques were adopted to achieve the set aim and objectives of this research. According to Breach (2009) data that have been obtained by a different person which have already been passed through the statistical process are referred to as secondary data. All the data used for this study are secondary and collected from variety of credible sources relevant to the study area.

The sources include:

- Relevant Oil and Gas journals sourced from science direct and the university catalogue.
- Published Oil and Gas articles, conference and technical papers and symposia accessed from SPE and One Petro data base.
- Professional Oil and Gas company websites and bulletins.

Data Analysis Method

Selltiz*et al.* (1965) in an early research noted that general data analysis is concerned with several operations performed to organize and summarize the collected data in a manner that interprets the research problem. This study used the content analysis approach adopted by Allen (2010) in a recent research project, where collected data are structured into a standardised form intended to make comparative deductions that depict the set aim and objectives of the research.

This technique allows room for flexibility, and the data gathered for this research are analysed both qualitatively and quantitatively. Two major statistical tools were used to analyse the data collected for the purpose of this study, these were:

- Minitab: A statistical analysis and process management package which was used in generating bar charts to showcase the comparative petrophysical analysis between the conventional logs and 3D-Explorer model for the oil-bearing and gas-bearing reservoir fields.
- Microsoft excel: A spreadsheet application with graphing tools which was used in producing the net-to-gross graph of both reservoir fields. The package was also used in generating the pie charts of the economic analysis.

Data Justification

As stated by Saunder *et al*. (2007) the set aim and objectives gives a justification of the research design. The secondary data which were collected from the Oil-bearing reservoir in Olu field, Niger Delta and the Gas-bearing reservoir from Balda field in the North Sea where used for the analysis because they depicts and effectively defines the rationale of the research study.

The data are presented in various charts with the results of the charts displaying the difference between the Conventional logs and the 3D-Explorer model for each of the fields. Two major assumptions were made and used in the economic analysis for this study, these two assumptions are:

- The oil formation volume factor (B_O) of the oil-bearing field and
- The gas formation volume factor (B_g) of the gas-bearing field.

Research limitations and problems

The use of secondary data for the analysis was a major problem for this research, this is because the secondary data may be biased and could have affected the outcome and accuracy of the results and finally sourcing for data also limited the research as a result of high cost and restricted access to some important data which could have been relevant to the study area, thereby limiting the research to only economical data.

RESULTS AND DISCUSSION

As earlier expressed in this study, the application of the multi-purpose induction (3DEX) measurement conquers the limitations associated with standard induction (conventional) measurements in accounting for the petrophysical parameters of complex and challenging reservoirs for a proper estimation of hydrocarbon reserves. For the purpose of this research two case studies have been chosen to showcase the successful application of the 3D-Explorer tool over the Conventional logging tools. Conventional and 3D-Explorer data sets from two different fields are acquired for a comparative petrophysical evaluation and analysis of the reservoirs. The data where acquired from Olu field in the Niger Delta basin (an Oil-bearing thinly bedded reservoir) and a Gas-bearing thinly bedded reservoir from Balda field in the North Sea.

The oil-bearing reservoir (Olu field, Niger delta)

Regional Context

The Niger Delta basin is a huge petroleum-producing tertiary basin formed during the continental break-up of the cretaceous forming the triple junction. The field is located in the equatorial West Africa at the peak of the Gulf of Guinea; between latitudes 3° and 6° N and longitudes 5° and 8° E. It comprises of an upper continental Benin formation composed of predominantly sand bodies, a paralicAgbada formationcontaining alternating units of sandstones and shales which is regarded as the reservoir rock of the Delta, and a lower marine Akata formation which is the source rock of the Niger Delta basin (Doust, 1990).

Field Location and Description

The Olu filed is located at about 60km Southwest of Port-Harcourt in the Niger Delta basin, It lies between latitudes 4° and 5° North of the Equator and longitudes 7° and 8° East of the Greenwich meridian. As shown in figure 3.1A. The field was first discovered in 1960 by Schlumberger exploratory well (SB-1) it is an oil bearing field, part of the Eastwest trending Krakama-Awoba – Ekulama – Robertkiri- SB- field microstructure a large roll over anticline in the hanging wall of the Santa Barbara fault.

The formations in the field are composed of fluvial channel to fluviomarine (Barrier bar) sand and fluviomarine or lagoonal shale sequences. Four reservoirs; $W_{2000,}$ $X_{7000,}$ Y_{3000} and Z_{4000} were penetrated by four wells; $A_{03,}$ $B_{04,}$ C_{06} and D_{08} in the field (Adeoti *et al* 2012). The reservoir layers Y_{3000} and Z_{4000} penetrated by well D_{08} with Conventional logging tools comprising of Gamma ray log, Resistivity log and Porosity logs (Neutron/Density logs) and multi-component induction imager, 3D-Explorer (3DEX) data were extracted out from Olu field for the purpose of this research. Figure 3.0 is the well log for the D_{08} that generated the data.

As highlighted by Adeoti *et al.* (2010)the gamma ray log was used precisely for estimating the Net-to-Gross (N/G) in the well, the porosity values were obtained from the density log using equation (3.0), the water saturation was derived from the Archie's equation (equation 3.1), the hydrocarbon saturation was estimated using equation (3.2) and the gross rock volume (GRV) of each of the reservoir layers were estimated from the plot of the area/depth map which was derived from a planimeter, and the values are substituted into equation (3.3) to compute the Hydrocarbon Pore Volume (HCPV). The summary of the results are given in table 3.0 and 3.1.

$$\varphi_D = \frac{\rho_{ma} - \rho_b}{\rho_{ma} - \rho_f} \quad \ldots\ldots\ldots \quad 3.0$$

$$S_w = \sqrt{\frac{FR_w}{R_t}} \quad \ldots\ldots\ldots \quad 3.1$$

$$S_h = 1 - S_w \quad \ldots\ldots \quad 3.2$$

$$HCPV = GRV \times \frac{N}{G} \times \varphi(1 - S_w) \quad \ldots\ldots \quad 3.3$$

Where:

φ_D = Density Porosity.
ρ_{ma} = Matrix Density.
ρ_b = Bulk Density.
S_w = Water Saturation.
S_h = Hydrocarbon Saturation.
R_t = True Formation Resistivity (Ωm).
R_w = Formation Water Resistivity (Ωm).
F = Formation Factor = $\frac{1}{\varphi^2}$
φ = Effective Porosity.
$\frac{N}{G}$ = Net-to-Gross.
GRV = Gross Rock Volume
$HCPV$ = Hydrocarbon Pore Volume.

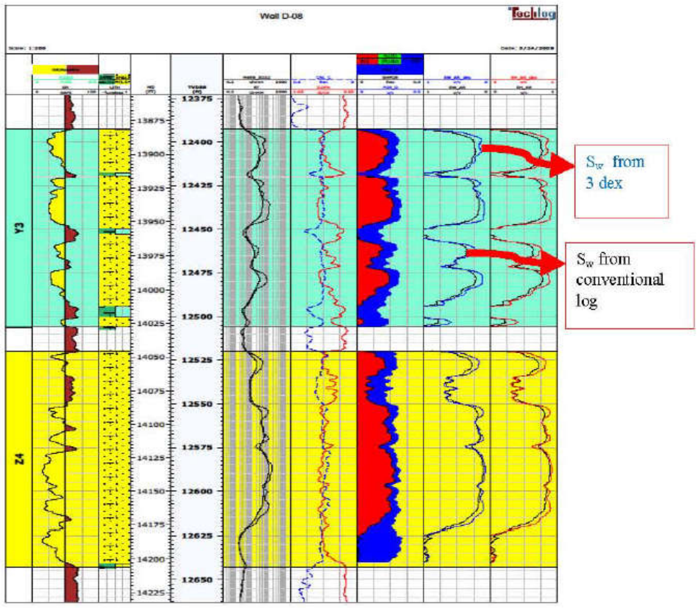

Figure 3.0. Well log for Well D_{08} (Adeoti *et al.*, 2010)

Table 3.0. Well $D_{08:}$ Conventional model data. Sourced from (Adeoti *et al*., 2010)

Layers	N/G	Porosity (Ø)	Water Saturation (S_W)	Hydrocarbon Saturation (S_H)	HCPV (MMSTB)
Y_{3000}	0.62	0.27	0.38	0.62	9798
Z_{4000}	0.64	0.26	0.30	0.70	1774.44

Table 3.1. Well $D_{08:}$ Multi-component induction tool (3DEX) model data

Layers	N/G	Porosity (Ø)	Water Saturation (S_W)	Hydrocarbon Saturation (S_H)	HCPV (MMSTB)
Y_{3000}	0.89	0.31	0.0I	0.99	34024.8
Z_{4000}	1	0.3	0.08	0.92	12770.4

Soured from (Adeoti*et al.*, 2010)

Net-to-Gross Ratio of the Oil Field

The Net-to-Gross is used to express the percentage of the sedimentary rock that is composed of reservoir rocks commonly characterized by the porosity and permeability of the rock. It is a useful variable in estimating the hydrocarbon pore volume (Connolly, 2007). Since the Net-to-Gross value of the reservoir influences the outcome of the hydrocarbon pore volume as shown in equation 3.3. Higher value of net-to-gross ratio in an oil reservoir will have a significant effect on the Oil volume. From the graph in figure 3.1 the 3DEX Net/Gross value for layer Y_{3000} and Z_{4000} is higher than the Conventional value in each of the layers which is a clear indication that the 3DEX explorer used in determining the N/G of the reservoir will present a better result in estimating the volume of Oil in the formation and also enhance well performance predictions as compared to the conventional tools.

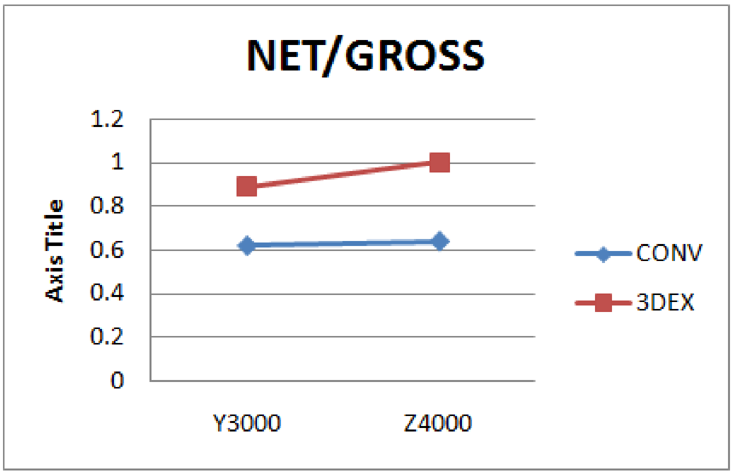

Figure 3.1. Graph of Net-to-Gross ratio of the Oil field

Porosity Analysis of the Oil Field

Porosity measures the capacity of a reservoir rock to hold fluid; it is an essential property in evaluating reservoir potential. Its values are used in evaluating fluid saturations and reservoir characterization qualitatively, high porosity values indicates high capacity of the reservoir rock to contain fluids while low porosity values indicates the opposite (Ezekwe, 2011). Therefore it is important that accurate values of porosity are measured and validated by different methods. From the porosity chart presented in figure 3.2 the effective porosity results determined using the 3D-Explorer tool in both layers of the well is more accurate compared to the porosity obtained from the conventional logs it is obvious from the higher value presented by the former. This is a clear indication that more authenticated results in estimating the Oil volume for proper decision making is achieved using the 3D-Explorer data in characterizing the well.

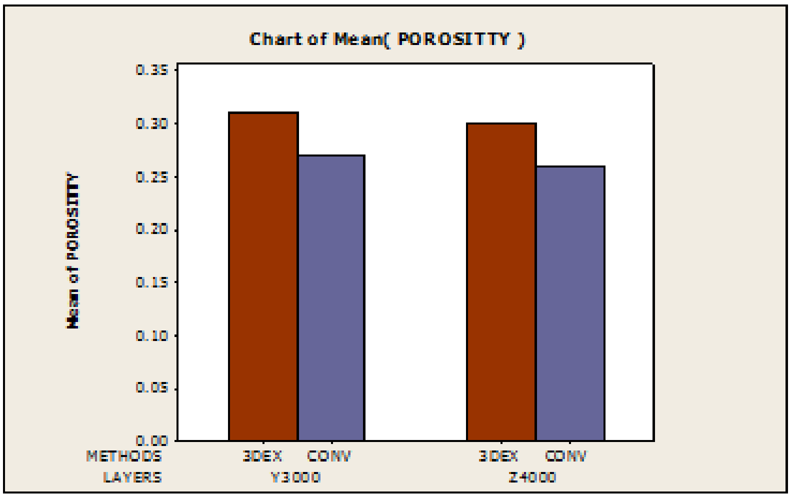

Figure 3.2. Mean chart of the Oil field porosity

Water and Hydrocarbon Saturation Analysis of the Oil Field

As expressed by Dandekar (2013) the measure of the level of water saturation present in a reservoir is a direct measurement of the hydrocarbon saturation present in that reservoir. The importance of accurately determining water saturation is demonstrated from equation 3.2. Therefore the presence of low water saturation in the reservoir indicates the presence of high hydrocarbon saturation conversely high water saturations are interpreted as low hydrocarbon saturations which is applied frequently to assess the potential hydrocarbon content of a reservoir after it has been penetrated with a well (Ezekwe, 2011).

From the mean chart presented in figure 3.3 the water saturations using 3DEX in the two different layers are extremely low compared to the water saturation values using the conventional logs, this is evidence that the hydrocarbon saturations of the different layers using the 3DEX model presents higher value as compared to the Conventional logs. As illustrated in the hydrocarbon saturation chart in Figure 3.4. This result indicates that there are more prospects for good decision making in terms of producing the field

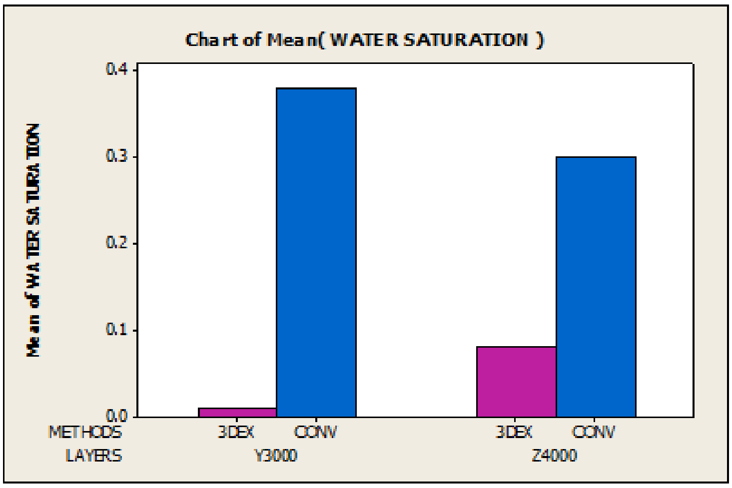

Figure 3.3. Mean chart of the Oil field water Saturation

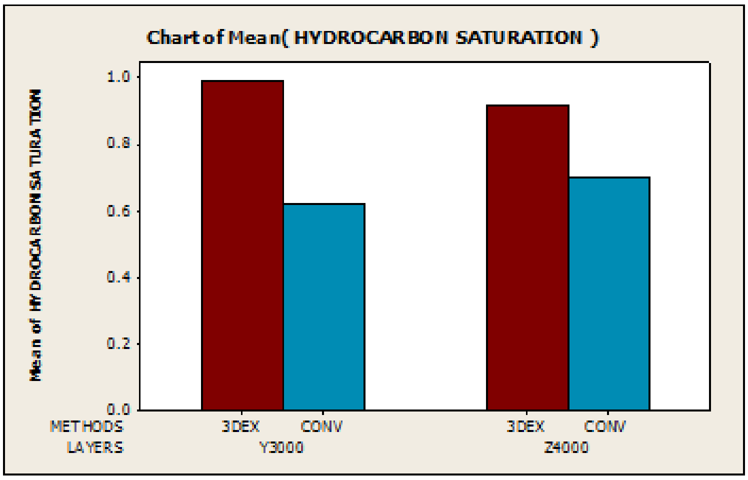

Figure 3.4. The mean chart of the Oil Saturation

Hydrocarbon Pore Volume Analysis of the Oil Field

The hydrocarbon pore volume (HCPV) are used in all phases of the reservoir evaluation, it is the main constituent in deciding whether or not further explorations and development can be made in a reservoir field (Marchand *et al* 2002). From the chart presented in figure 3.5 there is a clear expression of the difference in value between the 3DEX tool and the Conventional logs used for the evaluation of the well penetrating the two different layers (Y_{3000} and Z_{4000}) of the formation.

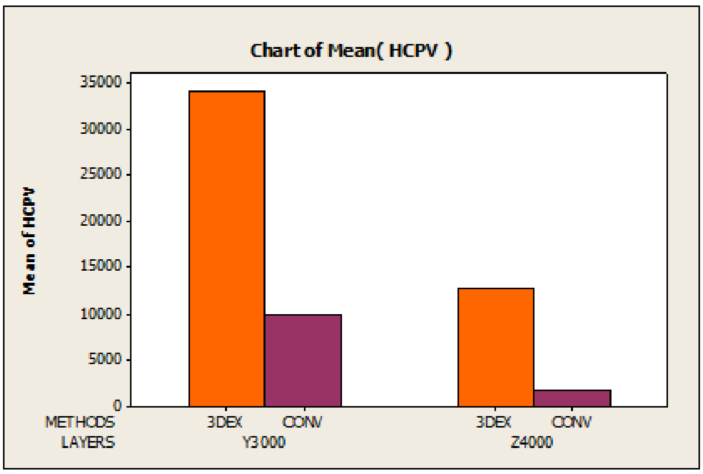

Figure 3.5. The mean chart of the Oil pore volume

These results will influence the decision making concerning the production and development of the reservoir as well as the well performance. The 3DEX gives a higher value of HCPV as a result of the accurate estimation of the reservoir properties by the tool as compared to the Conventional logging tool with lower value due to the logs inability to accurately evaluate the reservoir parameters thereby leading to the under-estimation of hydrocarbons present in the reservoir.

$$STOIIP = \frac{GRV \times \frac{N}{G} \times \varphi(1 - S_w)}{B_O} \quad \ldots\ldots 3.4$$

Where:

$STOIIP$ = Stock Tank Oil Initially In Place.

$\left[GRV \times \frac{N}{G} \times \varphi(1 - S_w)\right]$ = Hydrocarbon pore volume (HCPV)

B_O = Oil Formation Volume Factor = 1.2 rb/stb

Table 3.3. Summary of the Stock Tank Oil in Place for the two different models

Stock Tank Oil Initially In Place (MMSTB)		
Layers	Conventional	3D-Explorer
Y_{3000}	8165	28354
Z_{4000}	1478.7	10642

From the current Brent Oil (sweet light crude) price which is 105.8 US Dollars **($105.8)** per barrel as stated in the EIA short-term energy outlook (2013),It is interesting to note that the use of the 3D-Explorer model will yield an amount of 2999853.2US Dollars ($2999853.2)for layer Y_{3000} and 1125923.6US Dollars ($1125923.6) for layer Z_{4000} as compared to the Conventional model yield of $863857 and $156446.46 for layer Y_{3000} and Z_{4000} respectively when the hydrocarbon reserves are completely recovered. The 3DEX model shows an increment of 56% in layer Y_{3000} and 76% in layer Z_{4000} compared to the Conventional model. As indicated in the charts of figure 3.6 and 3.7.

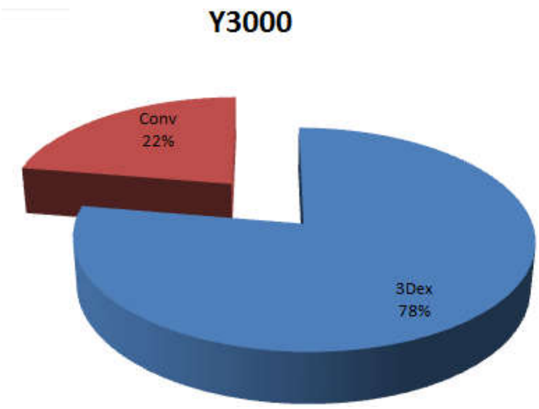

Figure 3.6. Percentage Chart of the layer Y_{3000} yield

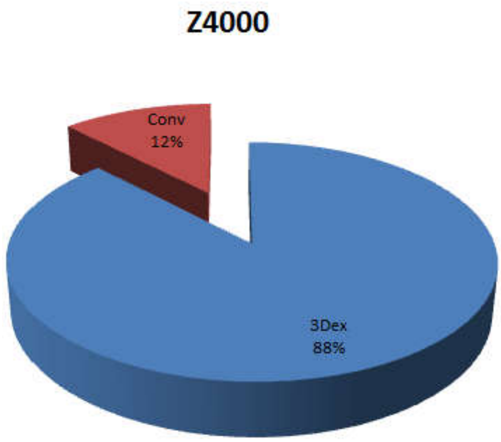

Figure 3.7: Percentage Chart of the layer Z_{4000} yield.

The gas-bearing reservoir (Balda field, Northsea)

Regional Context (Field Location and Description)

The Balder Field is situated in the Norwegian sector within the North Sea, about 190km west of Stavanger along the eastern flank of the Viking Graben. It is made up of three main stratigraphic units; the Mid Paleocene, the Late Paleocene and the Early Eocene. The field is composed of complex geology with sediments been transported by high density and gravity currents into the basin where large volumes of laminated sand and shale sequences are deposited in submarine fan complexes (Wang *et al.,* 2003). The schematic of the map location is shown in Figure 3.1B. The formation is composed of thin laminated sand and shale sequences comprising of Gas-bearing pay zones. A well B-1 containing Convention logs and 3DEX evaluation models was penetrated through the formation made up of four reservoir layers A_1, B_2, $C_3$and D_4 (Damodaran *et al.,* 2002). The responses of the log models are illustrated in figure 3.8 and the data collected for the analysis are summarized in Table 3.3.

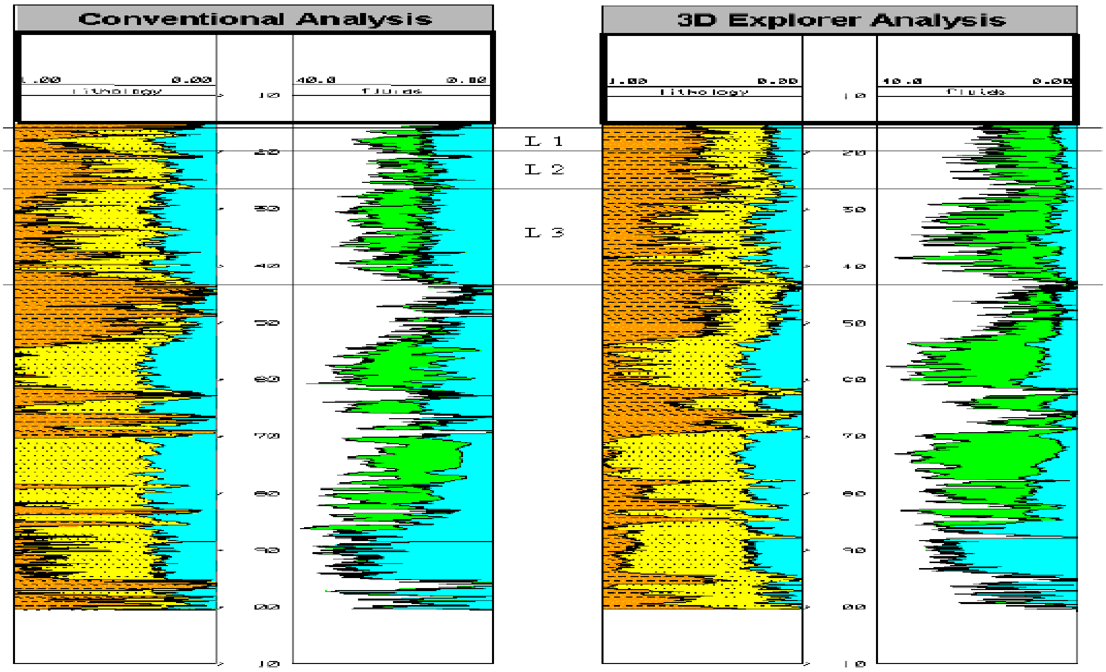

Figure 3.8. The log response of the reservoir fluids comparing the 3DEX and Conventional models (Damodaran *et al.*, 2002)

In the Gas-bearing field the same principle as stated in the Oil field is applied in determining the N/G, the porosity, the permeability, water saturation and hydrocarbon saturation which are used in evaluating the hydrocarbon pore volumes of the reservoir formation using the same equations stated above. The summary of the data is presented in table 3.4 and 3.5 for the Conventional and 3DEX models respectively.

Table 3.4. Well B-1: Conventional model data. Source (Damodaran *et al.,* 2002)

Layers	N/G	Porosity (Ø)	Water Saturation (S_W)	Gas Saturation (S_G)	HCPV (M)
A_1	0.98	0.25	0.52	0.48	0.53
B_2	0.99	0.21	0.53	0.47	0.67
C_3	0.11	0.28	0.47	0.53	2.13
D_4	0.71	0.16	0.61	0.39	0.53

Table 3.5. Well B-1: Multi-component induction tool (3DEX) Model data

Layers	N/G	Porosity (Ø)	Water Saturation (S_W)	Gas Saturation (S_G)	HCPV (M)
A_1	0.98	0.16	0.24	0.76	0.54
B_2	0.97	0.15	0.20	0.8	0.82
C_3	0.11	0.20	0.24	0.76	2.22
D_4	0.28	0.13	0.31	0.69	0.94

(Source: Damodaran*et al.*, 2002)

Net-to-Gross of the Gas Field

The Net-to-Gross value for the Conventional and 3DEX logs in layer A_1, B_2 and C_3 are relatively the same for both the conventional and the 3DEX evaluation as shown in the graph of figure 3.9. But there is an increase in the Conventional log value as compared to the 3DEX value in layer D_4 this variation is as a result of the over estimation of the shale volume in that layer by the conventional tool, of which the 3DEX tool gives an accurate estimation of the shale content due to its ability to measure vertical and horizontal resistivity values in thin sands and shaly formations.

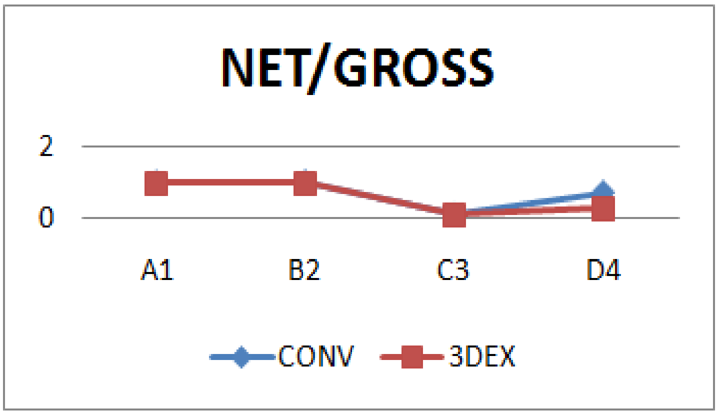

Figure 3.9. Net-to-Gross ratio of the Gas-bearing field.

Porosity Analysis of the Gas Field

The conventional logging tool presents 22% average effective porositywhile the 3DEX tool present 17% average effective porosity. This is as a result of small increase laminar shale content present in the reservoir. The Conventional log give an over estimation of the shale content that leads to the increase in the porosity value compared to the 3D-Explorer tool that measures the actual vertical and horizontal resistivity of the formation thereby presenting an accurate shale volume of the reservoir rock and its accurate effective porosity.

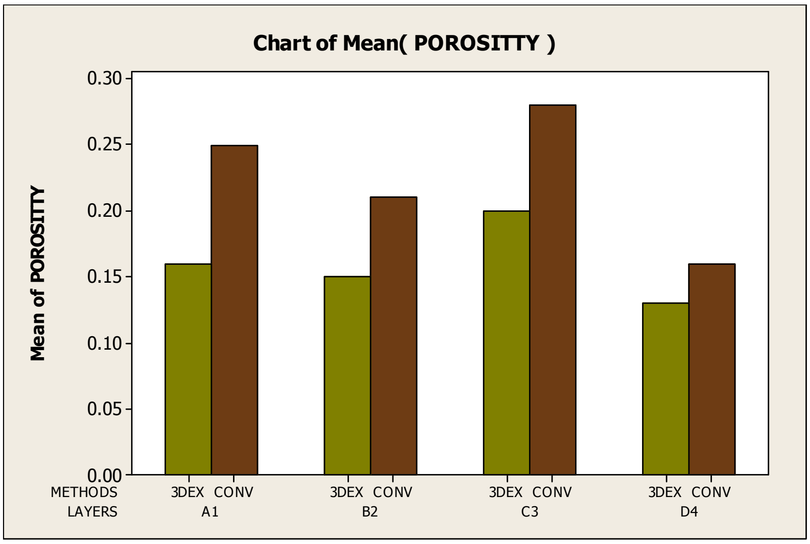

Figure 3.10. The mean chart of the gas porosity

Water and Hydrocarbon Saturation Analysis of the Gas Field

For the fluid saturation in the gas field it is evidence that there is a reduction in the values of the water saturation for the 3DEX evaluation model as compared to the conventional log values in each of the reservoir layers as shown in the chart in figure 3.11. Equation 3.2 expressed that a high percentage of water saturation is a direct interpretation of low hydrocarbon saturation likewise low water saturation represents high hydrocarbon saturation. From the charts in figure 3.11 and 3.12 the 3DEX model indicates a low value (about 25%) of water saturation and a massive equivalent gas saturation value of about 75% whereas the conventional evaluation presents a higher value (about 53%) of water saturation with a lower value of about 47% gas saturation. These values demonstrate the over-estimation of water saturation leading to an under-estimation of gas saturation by the conventional logs with regards to the value presented by the 3DEX data.

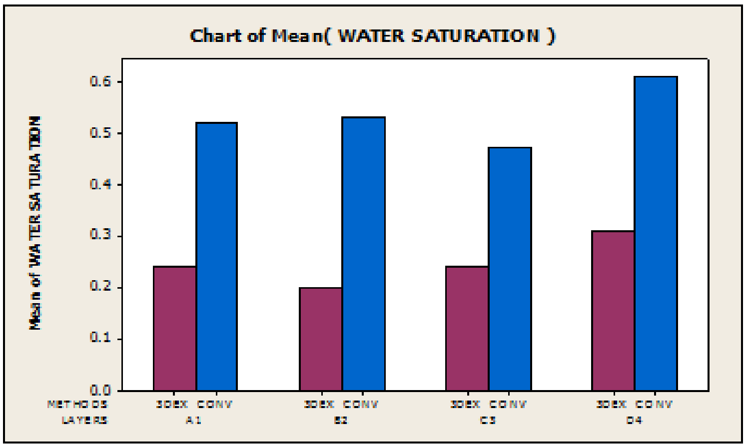

Figure 3.11. Chart of the water saturation in the Gas-bearing field

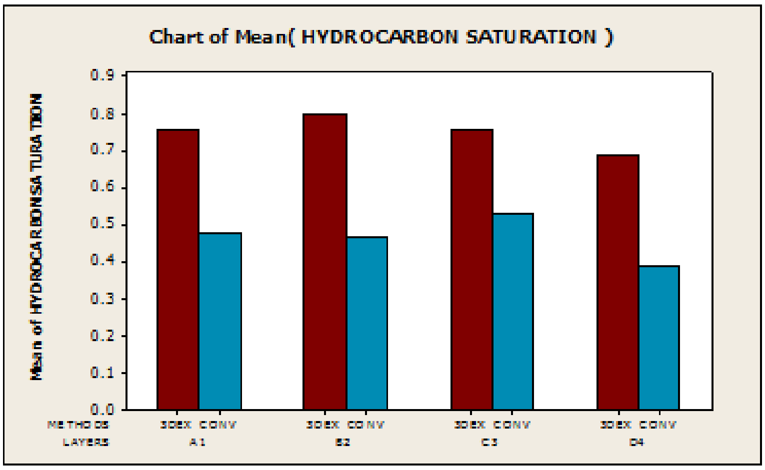

Figure 3.12. Mean chart of Gas Saturation

Hydrocarbon Pore Volume Analysis of the Gas Field

The hydrocarbon pore volume determines whether or not a well is to be developed or abandoned therefore proper estimation is required for effective decision making. The chart in figure 3.13 shows the HCPV of the four reservoir layers in the formation evaluated with 3DEX and Conventional logging tools. The chart clearly indicates the different between the two methods. It shows that the conventional log interpretation involves inaccurate evaluation reservoir parameters leading to under-estimation of hydrocarbon pore volume that may result in inappropriate decision making with regards to well development and well performance predictions.

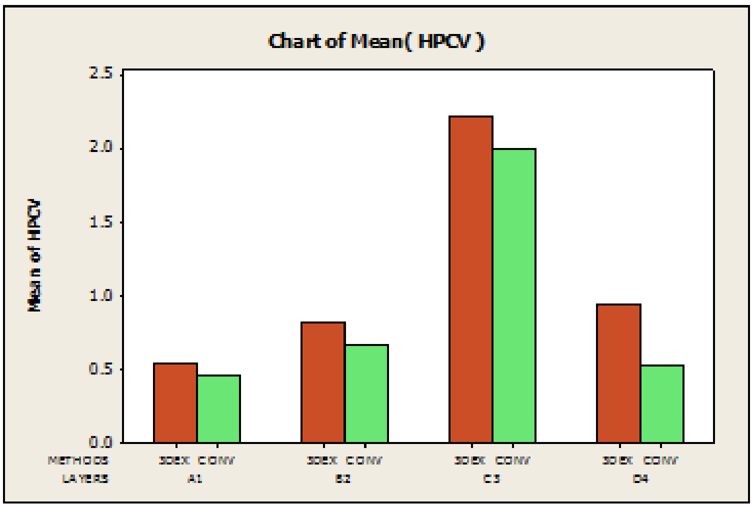

Figure 3.13. Mean chart of Gas volume

Economic Analysis of the Gas Field

The economic analysis of the gas field involves the estimation of the Gas Originally in Place (GOIP) using equation 3.5. An assumed gas formation volume factor (B_g) of 1.3 for the field is inputted into the equation to estimate the GOIP of each layer. The summary of the results is given in table 3.6.

$$GOIP = \left[GRV \times \frac{N}{G} \times \varphi(1 - S_w)\right] \times B_g \quad \text{.......} \quad 3.5$$

Where:

$GOIP$ = Gas Originally in Place

$\left[GRV \times \frac{N}{G} \times \varphi(1 - S_w)\right]$ = Hydrocarbon pore volume (HCPV)

B_g = Gas formation factor = 1.3 rb/stb

.

Table 3.6. Summary of the Gas Originally in Place for the two different models

Gas Originally In Place (MMBTU)		
Layers	Conventional	3D-Explorer
A_1	689000	702000
B_2	871000	1066000
C_3	2769000	2886000
D_4	810900	1222000
Total GOIP	5139900	5876000

From the EIA Short-Term Energy Outlook (2013), the market price of the natural gas is stated to be 3.58 US Dollars ($3.58) per MMBTU. Using this value the total Gas in the formation evaluated with the 3DEX model will amount to 21036080 US Dollars ($21036080) which is a huge value compared to the Conventional yield of 18400842 US Dollars ($18400842). From the chart in figure 3.12 the total GOIP yield for the formation employing the 3DEX interpretation is 6% greater than the Conventional model used in the evaluation. This increment will technically have an effect in the decision making procedures for the development and well performance predictions.

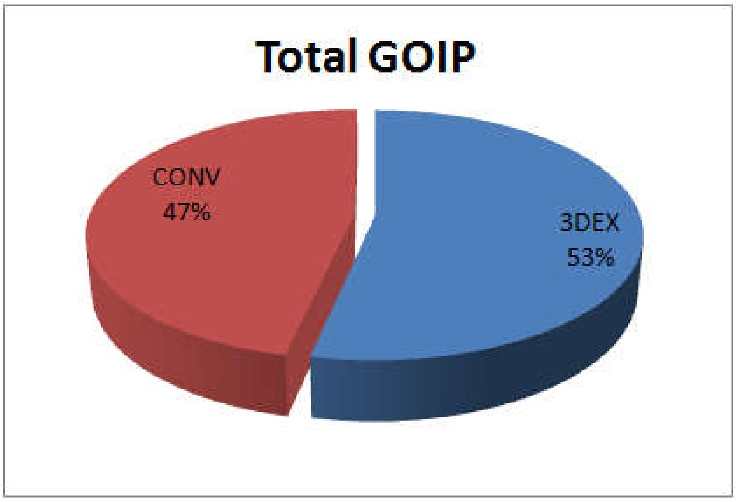

Figure 3.14.Pie chart of the total GOIP yield of the Gas-bearing field.

Conclusion and Recommendation

From the findings and results of this study the following conclusions have been drawn:

- Conventional measurements and interpretation techniques cannot fully evaluate the Intervals of thinly bedded hydrocarbon bearing sands and laminar clay, this is because the logging tool deep resistivity measurements are been suppressed by the lamina nature of the clay components resulting in artificially high water saturation with an equivalently low value of hydrocarbon saturation thereby presenting an under-estimated hydrocarbon reserves.
- The challenges in effectively evaluating thinly bedded reservoirs can easily be addressed by interpretation techniques that simultaneously measure the horizontal resistivity and vertical resistivity of the formation, which is a key feature of the 3DEX model.
- The laminated sand/shale sequences exhibit macroscopic electrical anisotropy and the multicomponent induction tool (3DEX) is capable directly measuring the vertical and horizontal resistivity of the formation. Simultaneously applying the

verticalresistivity and horizontal resistivity in evaluating reservoir parameters presents an improve predictions of well performance.

- The economic analysis of the Oil-bearing field using the 3DEX model in the evaluation produces a drastic increment yield of 83% while the Conventional interpretation techniques presents an average of 17% a massive difference of about 66% between the two evaluation techniques.
- In the Gas-bearing field the 3D-Explorer model gives an average of 53% and the Conventional model shows 47% resulted in an approximately 6% increase by the 3DEX model in estimated gas-in-place, compared with results presented by the Conventional model.
- These results demonstrate the efficiency and success of using a multi-component induction tool in evaluating thinly bedded reservoir for effective decision making and optimal well performance predictions.

Based on these background findings of evaluating thinly bedded reservoirs, the research has propose the following recommendations for improving the evaluation of thinly bedded reservoirs for effective decision making.

- Before drilling a well in a reservoir formation a proper logging and coring program should be designed to address potential thinly bedded sand/shale sequences.
- After drilling a well identify if all the beds can be resolved if not identify the thin-bed intervals within the bed boundaries for proper evaluations.
- In evaluating thinly bedded reservoirs much reliance should not be given to the conventional interpretation techniques because this can result in under-estimation of hydrocarbon reserves.
- The 3DEX interpretation model accurately characterizes the hydrocarbon reserves in shaly sand reservoir, therefore should be applied in evaluating thin laminated shaly sand sequences.
- Horizontal wells should be drilled in developing thinly bedded reservoirs for maximum contact and optimum long-term recovery.

Finally this study has focus only on the successful application of the 3D-Explorer tool only, therefore; further studies should be conducted on other various techniques (such as the Electrical Micro- Imaging EMI tool, Nuclear Magnetic Resonance NMR tool, Azimuthal Resistivity Imager ARI tool etc.) in resolving the uncertainty of evaluating thinly bedded reservoirs.

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