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Reservoir Characterization of Sand Units Penetrated by Four Wells in the Nigerian Sector of the Chad Basin and its Implication for Hydrocarbon Generation and Accumulation

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Abstract

The reservoir properties of over six hundred sand units penetrated by four exploratory oil wells (Zy-01, Kt-01, Ks-01 & Kd-01) in the Nigerian sector of the Chad Basin Northeastern Nigeria was carried out using the PRIZM GeoGraphix software. Results of the evaluation show that eighty-seven sand units have good reservoir properties for all the wells. Their sand thicknesses are between -1 m and -160 m while averages of effective (φE), density (φD) and sonic porosities (φS) are between 10 & 41%, 10 & 54% and 10 & 89% respectively. These porosity results are fair to very good. Average shale volume content (Vshl) is between 23% & 67%, these values are beyond the acceptable limit in reservoirs. The averages of permeability (k) and fluid saturation (SwA & Sh) are between 15md & 7477.8md, 11% & 71% and 29% & 89% respectively. The permeability values are therefore moderate to excellent. Bulk volume water (BVW) is between 0.028 & 0.188, suggesting very fine to silty grained sands. A comparison of the values of apparent water resistivity (RwA) with water resistivity (Rw), suggest imprints of hydrocarbon in these sands. Also a further comparison of water saturation of flushed zone (SxO) with the Archie's water saturation (SwA), moveable hydrocarbon index (MHI) and moveable oil saturation (MOS) revealed possible hydrocarbon mobility in the flushed zone by invading drilling fluid. Calculated temperatures and pressures of the wells show increasing trend with depth. Geopressures were encountered at some shale beds within the wells. The sand units of the wells with the good reservoir properties correlate fairly well along Ks-01, Kt-01 & Zy-01 wells. This study has shown that some of the sand units in the study wells have favourable reservoir properties that will enable the generation, accumulation and preservation of hydrocarbons, especially within Ks-01 and Zy-01 wells. However, the very high values obtained for Vshl requires that further estimation of SwA be carried out using other methods and models for a better understanding of the hydrocarbon potential of the Basin. Furthermore, drilling to deeper depths is strongly recommended due to the very favourable reservoir properties observed at deeper depths for Ks-01 and Zy-01 wells respectively.

Keywords: Reservoir; Hydrocarbon; Porosity; Permeability; Water saturation; Lithology

List of Abbreviations and Terms

Sp – Spontaneous potential
GR – Gamma Ray
MSFL – Micro spherically focused log Rt – Archie-predicted true resistivity SwA – Archie-derived water saturation Vshl – Shale Volume Content
md – millidarcy
SwMS – modified Simandox (1963) equation
Sw – Water Saturation
Sh – Hydrocarbon Saturation
Swr – saturation moveable hydrocarbon index
Rxo – flush zone resistivity
Rwa – apparent water resistivity
Ro – Resistivity of water filled formation
Swr – Ratio Water Saturation
Rw – water resistivity
SxO – Water saturation of the flushed zone MHI – moveable hydrocarbon index (MHI) v/v – Volume/Volume
MOS – moveable oil saturation
ROS – hydrocarbon saturation
Rmf – resistivity of mud filtrate (Rmf) SN – short normal log
ILD – Deep Induction Resistivity log
TD – total depth KB – Kelly bushing k – Permeability
PHID or (φD) – Density Porosity PHIS or (φS) – Sonic Porosity PHIAVE – Average Porosity
PHIE or (φE) – Effective Porosity
PHIR – Resistivity derived Porosity
DiffCal – Differential Calliper
Temp – Temperature
PRES – Pressure

Introduction

To achieve successful hydrocarbon exploration and production targets in the inland Basins of Nigeria requires that detailed and systematic studies and analyses of available geoscientific data be heightened. Recently the Nigerian National Petroleum Corporation (NNPC) launched a renewed effort to acquire additional data and carryout further exploration work on the Nigerian end of the Chad Basin based on the reports of the discovery of hydrocarbons on the other side of the structurally related contiguous Chad Basin in Cameroon, Chad and the Niger republic. Crude oil search began in the Nigerian sector

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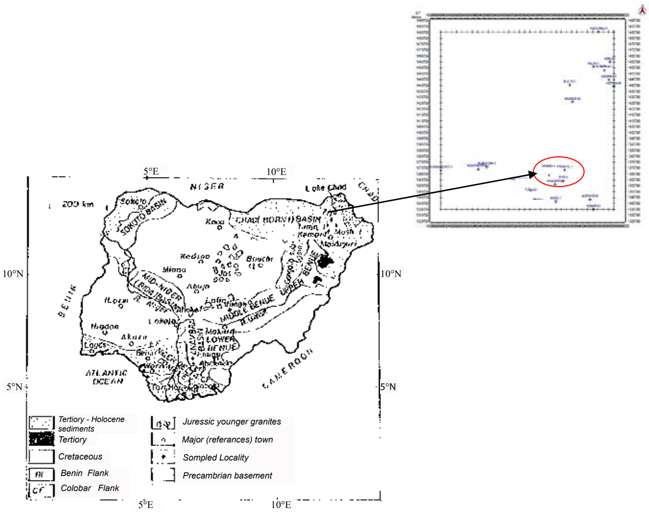

Figure 1: Geologic map of Nigeria showing the Chad Basin and the base map of the Basin showing the study wells

Figure 2: Red broken arrows used to encircle the Chad Basin and the countries where the Basin can be found.

of the Chad Basin in 1976 with about twenty-three (23) exploratory oil wells drilled and 2D seismic data acquired in the area. However, due to the very poor and non-commercial discovery of oil & gas in the Basin, interest for further search dwindled. This interest has once again rekindled due to the recent commercial discovery of oil & gas in nearby countries where the Basin extends. Any potential discovery will add to the nation's proven reserves asset which is put at 35bbl for oil and 170tscf for gas [1]. Many scholars such as Avbovbo et al., Olugbemiro et al., Okosun, Gazali and Zarma, Christopher, Obaje et al., Nwankwo et al., Nwankwo and Ekine [2-8] have separately carried out different geoscientific studies on the Chad Basin of Northeastern Nigeria and their findings have largely been in favour of possible presence of hydrocarbons in the Chad Basin.

This study, therefore, x-rays the reservoir properties of sand units penetrated by four wells in the Nigerian end of the Chad Basin with a view to ascertaining if those properties are good enough to support hydrocarbon generation, preservation and accumulation. About twenty-eight log curves from four exploratory oil wells ks-01, Kt-01, Zy-01 & Kd-01 (Figure 1) drilled in the Nigerian end of the Chad Basin were used for this evaluation. The log data are digitized in ASCII format at 0.125 m intervals. Reservoir properties characterizations are useful models of reservoirs that are pertinent to the knowledge of the ability of the reservoir to store and transmit hydrocarbons. They are also useful in simulating the behavior of the fluids within the reservoirs under different sets of circumstance and to find the optimal production techniques that will maximize production [9].

Geologic Setting

The Chad Basin is a large intracratonic Basin in central West Africa and one-tenth (about 21%) of its surface area lies in Northeastern Nigeria (Figure 1). It covers an area of approximately 2,500,000 km^2 [8] extending over portions of Niger Republic, Chad, Sudan and Northern parts of Cameroon and Nigeria (Figure 2). The origin of the Chad Basin is believed to be related to a series of Cretaceous and later rift system in central and West Africa that expanded during the separation of the African and South American plates [1,7]. Pre-Santonian Cretaceous sediments were deposited within the rift system. The Nigerian end of the Chad Basin lies between latitudes 110N & 140N and longitudes 90E & 140E, covering Borno, parts of Yobe and Jigawa states of Nigeria [10]. Sediment thickness in the Basin is believed to be more than 4.650 km and comprises marine and continental deposits made up from the oldest; the Bima Sandstone which is sparsely fossiliferous, poorly sorted and medium to coarse grained, a transitional calcareous Gongila Formation, Fika Shale, Kerri Kerri and Chad Formations in that order (Table 1). Also commonly occurring are crystalline rocks of granite, gneisses, mica schists, basalts and minor basic and acidic intrusives [8].

Methodology

The digital log data used for this study included the gamma ray, caliper, density, sonic and resistivity logs. The requisite environmental corrections were applied to the logs and the formulas below were inputted into the user define equation (UDE) of the PRIZM GeoGraphix software and used for the evaluation.

a. Density Porosity

PHID[] = (RhoM - RHOB[]) / (RhoM - RhoF)

b. Sonic Porosity (Wyllie); Enter Compaction Coefficient below, Cmp = 1.0

PHIS[] = (1/Cmp) * (DT[] - DTma) / (DTfld - DTma)

c. Average Porosity from Density Porosity and Sonic Porosity

PHIAVE[] = (PHID[] + PHIS[]) / 2

d. Shale volume content

Vshl[] = min(1, max(0, (GR[]-GRcln) / (GRshl-GRcln)))

e. Effective Porosity

Age	Formation	Depth (m)
Pliestocene – Miocene (23.5 – 84.0Ma)	Chad Formation	800
Coniacian – Santonian (84.0 – 91.1Ma)	Fika Shales	1800
Turonian (84.0 – 91.1Ma)	Gongila Formation	2350
Albian – Cenomanian (97.0 – 110Ma)	Bima Sandstone	5000

Table 1: Generalized well lithology for the Nigerian sector of the Chad Basin (Adapted from Nwankwo et al., [7]).

PHIE[] = PHIAVE[] * (1-Vshl[])

f. Resistivity Derived Porosity

PHIR[] = a * Rw / ILD[]^m

g. True Resistivity

Rt[] = 1.67 * ILD[] - 0.67 * SN[]

h. Archie Water Saturation

SwA[] = (a * Rw / (ILD[] * PHIAVE[]^m))^(1/n)

Modified Simandoux SwMS; Requires, PhiE[], Vshl[] & RT[] If (Vshl[] < 1)

SwMS[] = (sqrt((Vshl[]/Rshl)^2 + 4*PHIE[]^m/(a*Rw*(1-Vshl[])*RT[])) - Vshl[]/Rshl)/(2*PHIE[]^m/(a*Rw*(1-Vshl[]))) Else SwMS[] = 1 End If

i. Water Saturation of the Flushed Zone

SxO[] = (a * Rmf / (SN[] * PHIAVE[]^m))^(1/n)

j. Apparent Water Resistivity

Rwa[] = ILD[] * PHIAVE[]^m

k. Hydrocarbon Saturation

Sh[] = (1 - SwMS[])

l. Moveable Hydrocarbon Index

MHI[] = (SwMS[] / SxO[])

m. Residual Oil Saturation

ROS[] = 1.0 - SxO[]

n. Moveable Oil Saturation

MOS[] = SxO[] - SwMS[]

o. Resistivity of Water filled formation

Ro[] = a * Rw / PHIAVE[]^m

p. Ratio Water Saturation

Swr[] = (SN[] / ILD[] / (Rmf / Rw))^0.625

q. Differential Caliper

DiffCal[] = CALI[] – Bit Size

r. Pay Flag with Porosity and Water Saturation Cutoffs

Pay[] = PHIAVE[] > PhiCutoff and SwMS[] < SwCutoff

s. Hydrocarbon Pore Thickness if Pay Exists

If (Pay[]) Then HydPhiTh[] = (1 - SwMS[]) * PHIAVE[] * <Step> Else HydPhiTh[] = 0

t. Bulk Volume Water

BVW[] = PHIAVE[] * SwMS[]

u. Hydrocarbon Pore Volume

SoPhiH[] = (1- SwMS[]) * PHIAVE[] * <Step>

v. Timur Permeability

K[] = (100 * PHIE[]^2.25/SwIrr)^2

w. Environmental corrections of Temp & PRES Temperature 'C; Degrees C & Depth in Meters

Temp[] = 17.5 + .02 * DEPTH[]

x. resssure in .Mpa, Mudwt in kg/m3, Depth in Meters

PRES[] = Mudwt * DEPTH[] / 102000

The results generated from the evaluation were thereafter posted as signatures or wiggles on the PRIZM display. The quality control/assurance (QC/QA) measures taken to minimize errors were the comparison of the results obtained using the software with those obtained from both formulae and charts. The results obtained from the software agreed closely with those obtained from formulae and charts.

Results and Discussion

The log packages run for the study wells are partially complete. For instance the Sp, MSFL, neutron and dip-meter logs are not available. Visual examination of the gamma ray log curves for the study wells show a fairly constant low to moderate values through most of the sand units, indicating that the sands are somewhat shaly. Also, gamma ray signatures of the sands have predominantly cylindrical and serrated shapes, suggesting probably braided fluvial type environment, distributory channel-fill, submarine canyon-fill, evaporate fill, distal deep marine slope and/or carbonate shelf margin depositional environment [11,12]. The resistivity readings are moderate to high in some sand intervals and show evidence of invasion. The caliper curves show evidence of mudcake on the walls of the porous and permeable sands for all the wells. This is based on the results obtained from differential caliper estimation which are conspicuously negative. The caliper logs also show relatively constant hole diameter and no significant differential enlargement. Consistency of hole diameter indicates that log measurements are reliable. The digitized and interpreted log curves for some of the sand units of the four wells is presented in Figures 3 and 4, while the coordinates, total depth (TD), Kelly bushing (KB), elevation (m) and spud date for the study wells (Zy-01, Kt-01, Ks-01 & Kd-01) is contained in Table 2. More than six hundred sand units were delineated from the study wells, and their reservoir properties determined.

About eighty-seven (87) of these sand units were observed to be of good quality (Appendices 1-4). Their thicknesses range between -1m and -160 m and show some significant amount of shale inter-fingering. The stacked bar plots (Figure 5) for the average shale/sand volume in percentages show that shale volume content for most of the sand units of the four wells are greater than 10%. The acceptable value of less than 10% in reservoir sands has been proposed by Hilchie [13]. The results show average Vshl of between 23% & 67% for all the wells. These abnormally high values of shale content in the sands of the Chad Basin can adversely affect the determination of in-place hydrocarbon volume, prediction of reservoir production rate(s), estimation of effective porosities, permeability and Archie-predicted true resistivity (Rt). Also, in shaly sands, where shales and clays contribute to electrical conductivity, Archie- derived water saturation (SwA) is sometimes pessimistic. However, the modified [14] equation for evaluating Sw in shaly reservoirs was used as an alternative to the Archies equation. Other estimations for porosity and permeability were equally compensated for the effect of the shales in the sands [15]. The scatter plot of Vshl against gamma ray log reading for the sand units of the wells (Figure 6) correlate reasonable well with each other. A direct relationship exists between the plotted Vshl and the gamma ray log reading for the sands. The gamma ray log readings for the sands did not exceed 90API and

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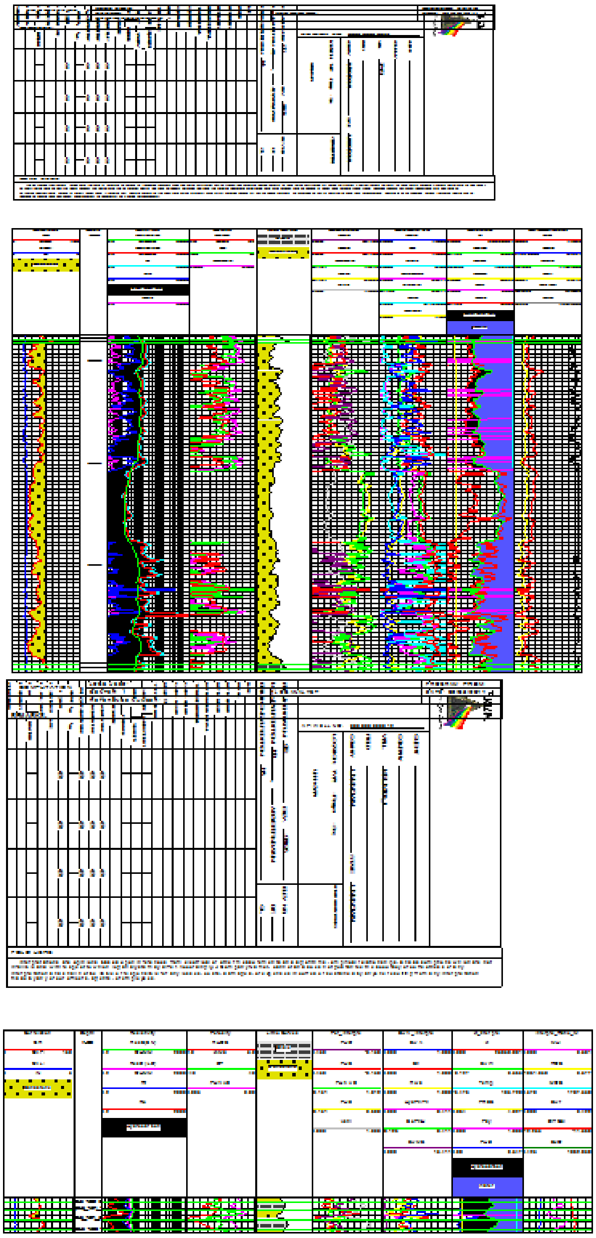

Figure 3: Log curves for sand unit 78 (Zy-01) well and sand unit 121 (Kt-01) well.

calculated Vshl is up to 70%. Calculated Vshl greater than 100% are spurious and may be related to poor logs [9,16].

The density and sonic log readings were used to estimate porosity. Column plots of average effective, density and sonic porosities against depth (Figures 7-9) for the sands of the wells are fair to very good for hydrocarbon accumulation [9,17,18]. Further investigations on the porosities of the sands have revealed for instance in Ks-01 well that the deeper (>2900 m) sand units have good to very good porosity indices. Plots of porosity versus depth (Figure 10) for all the wells show that porosity decreases with depth and also varies with lithology [19,20]. Negative density porosity values were observed in some of the wells indicating probably the presence of anhydrites or other forms of heavy minerals [21]. This may be true if we consider the geology of the area which is characterised by basement rocks. The scatter plot of density porosity against sonic porosity for the sand units (Figure 11) revealed dispersed points and also showed that density porosities are much less than the sonic porosities, the difference in the result of these two components may probably signify fractures [22]. This is further corroborated by the low density log readings and higher porosity values than the sonic log readings observed on the log display (Figures 12 and 13).

Permeability values is between 15md & 7477.8md for the sand units of the study wells (Figure 14) and are therefore moderate to excellent for hydrocarbon production [23]. The Permeability values for Ks-01 & Zy-01 wells at deeper depths (>2500 m) show predominantly good to very

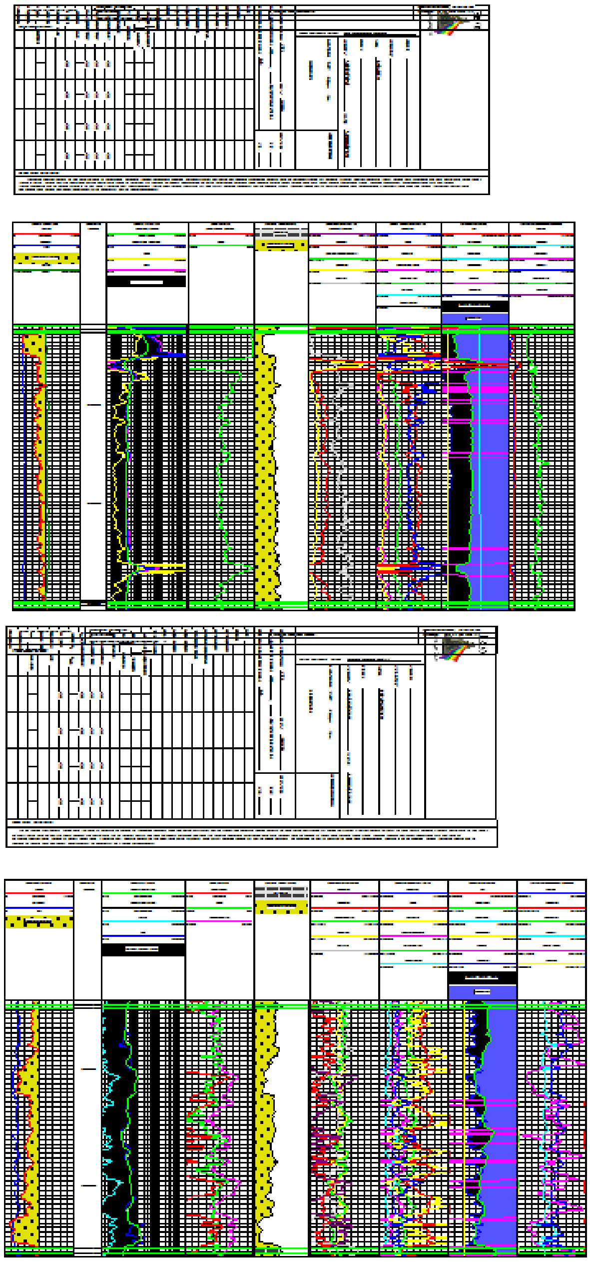

Figure 4: Log curves for sand unit 68 (Kd-01) well and sand unit 107 (Ks-01) well.

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SN/ Wells	Coordinates	Total Depth (m)	Kelly Bushing (K.B) (m)	Elevation (m)	Spud date
1 – Zy-01	E or X: 321924.600000 (Longitude); N or Y: 1362806.100000 (Latitude)	3375	303.7	295	Jan., 1997
2 – Kt-01	E or X: 323251.030000 (Longitude); N or Y: 1372072.100000 (Latitude)	2950	299.52	291	Dec., 1988
3 – Kd-01	E or X: 307750.000000 (Longitude); N or Y: 1372500.000000 (Latitude)	3050	306.45	298	Dec., 1985
4 – Ks-01	E or X: 314088.400000 (Longitude); N or Y: 1359838.500000 (Latitude)	4665	303.7	295	Apr., 1986

Table 2: Showing the Coordinates, Total depth (m), K.B, Elevation (m) and Spud date for the study wells.

good indices (Figure 15). Scatter plots of permeability against porosity (Figure 16) show exponential increases in the plotted points and can be characterized as lying along the same general porosity-permeability trend. Also very few plotted points show slightly higher porosity and low permeability, suggesting probably early concentration by illitic clay prior to burial [16]. The average Archie's water saturation (SwA) and hydrocarbon saturation (Sh) is 11 & 71% and 29 & 89% respectively. Due to the shaly nature of the sands, the modified Simandox (1963) equation (SwMS) for evaluating Sw in shaly sands was employed. Average SwMS is between 5 & 72% and its Sh is between 28 & 95%. It is observed that some of the sand units are hydrocarbon bearing and some are water bearing. The average values of SwA and SwMS for the sand units of the study wells were observed to be greater than the average values of water saturation moveable hydrocarbon index (Swr) suggesting that the flush zone resistivity (Rxo) is too low because invasion is very shallow. Therefore, the SwA and SwMS are considered a good value for the zones actual water saturation estimation.

The average values of apparent water resistivity (Rwa) are greater than the average values of water resistivity (Rw), indicating probably presence of hydrocarbon in some of the sands of the study wells. Water saturation of the flushed zone (SxO) was used as an indicator of hydrocarbon mobility. For most of the sands in the study wells SxO values are much greater than the Archie's water saturation values (SwA) and the modified Simandox water saturation (SwMS) values, implying that probably hydrocarbons in the flushed zone have been moved by invading drilling fluids [24]. A further evidence to show that hydrocarbon mobility occurred in the sands of the wells was the use of the moveable hydrocarbon index (MHI) which showed values of less than 0.7v/v for most of the sands in the study wells. Asquith and Krygowski [24] have also suggested that values of MHI equal or greater than 1.0 indicate that hydrocarbons were not moved whereas MHI less than 0.7v/v for sandstone indicates that hydrocarbon has been moved especially in a formation with good porosity and permeability. The average values of moveable oil saturation (MOS) are slightly high, (b/w 0.3 & 2.7v/v) signalling another evidence of hydrocarbon mobility in the formation. The averages of residual hydrocarbon saturation (ROS) are negative. This result is quite disturbing if we consider the good results obtained for MHI and MOS. ROS is expected to be low atleast less than 0.7v/v to show evidence of hydrocarbon mobility. Two reasons are considered for the negative results for ROS, either that the values of the resistivity of mud filtrate (Rmf) used as input parameter to generate the SxO is not correct and/or the use of the short normal (SN) log resistivity readings as flush zone resistivity (RxO) instead of the log reading of the microspherically focused logs (MSFL) which was not available. Although, SN can be used in the absence of MSFL, it tends to read fluid resistivity that is a mix of Rw and Rmf especially if the formation were invaded. The latter reason is most likely the problem for the negative values for ROS.

The correlation of the subsurface sands of Ks-01, Kt-01 and Zy-01 wells (Figure 17) broadly define an anticlinal geometry at deeper depths. Sands at shallower depth tend to flatten out. The correlation also shows

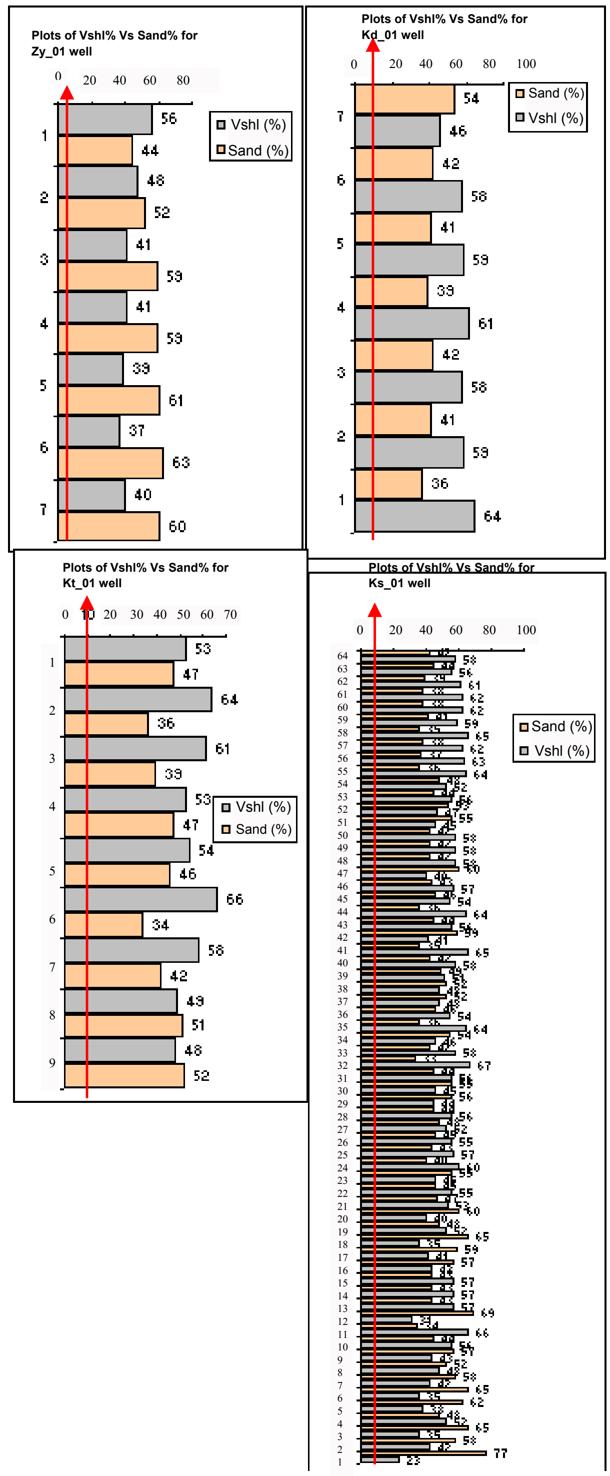

Figure 5: Stacked bar plot of Vshl (%) Vs Sand (%) for sand units of the study wells.

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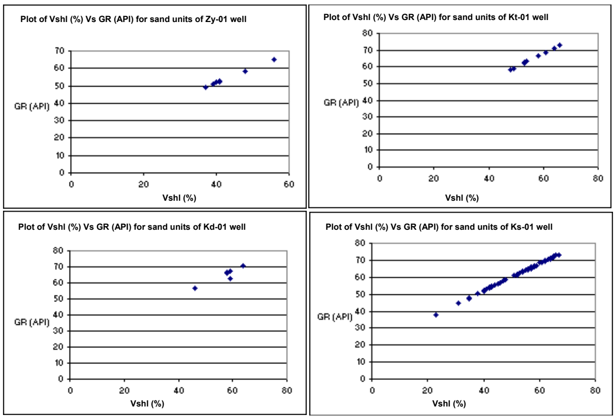

Figure 6: Plots of Vshl (%) Vs GR (API) for sand units of the study wells.

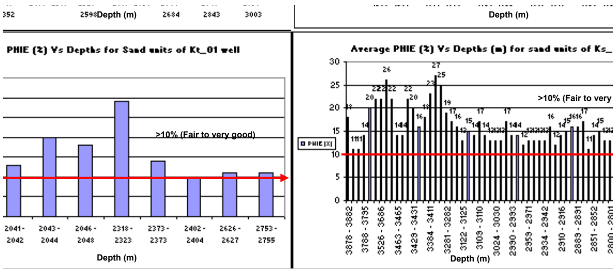

Figure 7: Column plot of PHIE (%) Vs Depths (m) for sand units of the study wells.

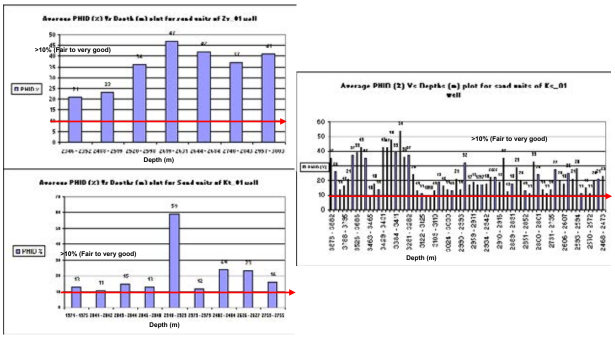

Figure 8: Column plot of PHID (%) Vs Depths (m) for sand units of the study wells.

that the sands are continuous within the wells. This is evident from the similar gamma ray log signatures found in all the wells. Thicker sand bodies are observable within Ks-01 well relative to the other two wells. Lateral pinch-out and juxtaposition of the sands is observed more at the deeper parts of the wells. The suspected pinch-out may support a case for stratigraphic traps in the Basin and the juxtaposed sands may have provided drainage for generated hydrocarbons to migrate. It is also possible that the juxtaposed sands in the deeper sections of the wells is the outcome of post Santonian effects [25].

Implications of the results for hydrocarbon generation and preservation in the Basin

The three most essential elements of reservoir properties are porosity, permeability and fluid saturation. The overall average porosity and permeability values of the sand units with the good reservoir properties for the four wells (Kd-01, Ks-01, Kt-01 and Zy-01) are within limits that are required for hydrocarbon generation,

Figure 9: Column plot of PHIS (%) Vs Depths (m) for sand units of the study wells.

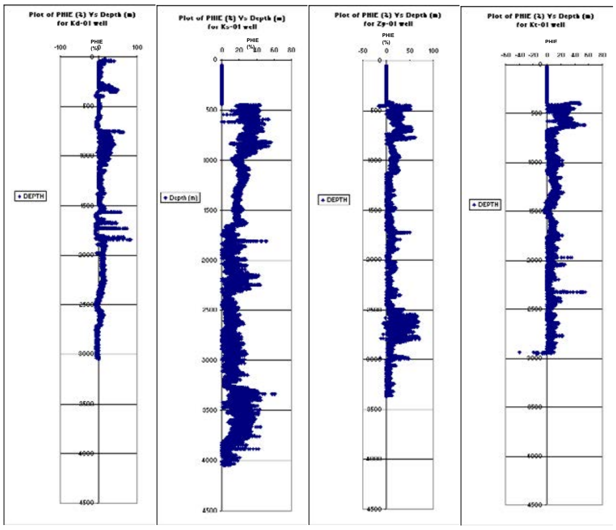

Figure 10: Plots of porosity against depth for all the study wells.

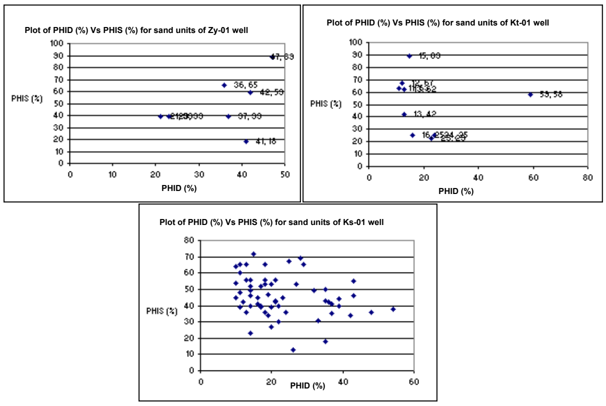

Figure 11: Plots of PHID (%) Vs PHIS (%) for sand units of the study wells.

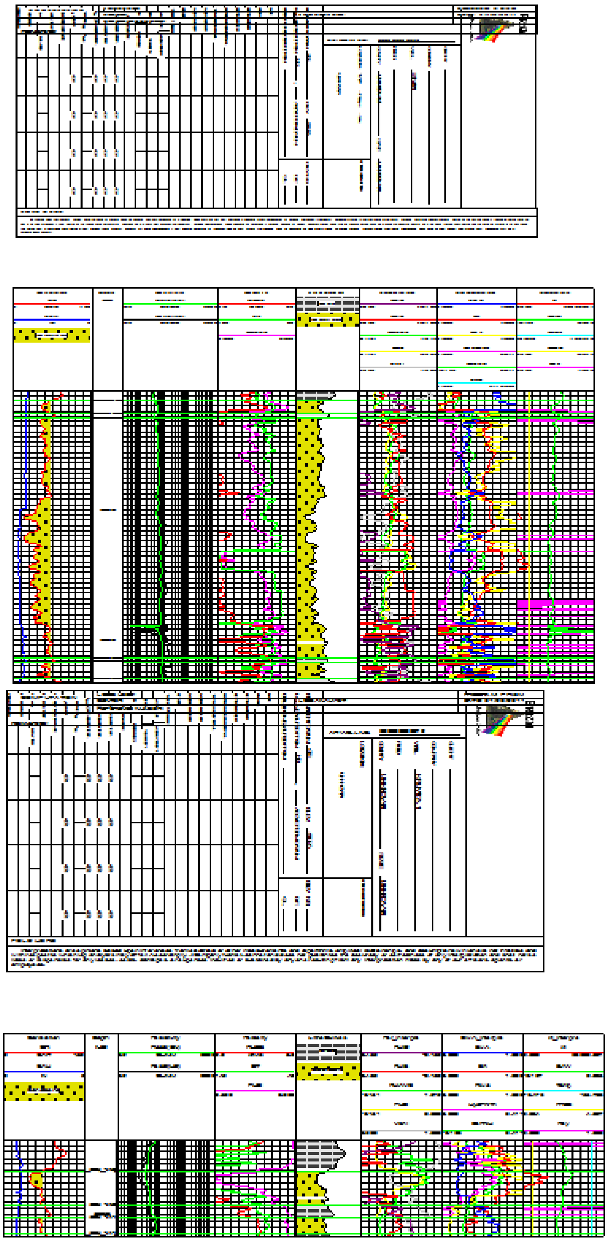

Figure 12: Identified fractures on some of the sand units (sand unit 60 for Zy01 and sand unit 142 for Kt01 wells). This was done by plotting the bulk density and sonic logs on a compatible porosity scale.

accumulation and preservation. The predominantly fair permeability results, if we consider the entire evaluation, are perhaps as a result of the silty nature of the sands. The results further show that sediments within deeper depths have better reservoir properties relative to the shallower parts. Correlation of the wells has revealed that sands within Ks-01 well are thicker and better developed. Also, sands within the deeper parts of the Basin are somewhat juxtaposed suggesting probably block faulting and post Santonian effects. The juxtaposed nature of the sands may have provided avenue for the drainage of generated hydrocarbons. Stratigraphic traps are also suggested in the Basin in addition to other trapping mechanisms based on the observed pinch-out of the sands. Further studies on this using seismic data, velocity track analysis (VTA), ground water simulation method and differential interformational velocity analysis (DIVA) is advocated. MHI and MOS have revealed hydrocarbon mobility in the sands of the wells, although, commercial discovery of hydrocarbons is yet to be made in the Basin. Further analysis on the Basin using 2D/3D seismic data is suggested.

Conclusion

The digital log data used for this study were evaluated using the PRIZM GeoGraphix software, a windows based geology and geophysics (G&G) software. On the strength of the evaluations, the following summary and conclusions are deduced:

(1) Eighty-seven (87) sand units with good reservoir properties were delineated and their thicknesses range between -1m and -160m

(2) Shale volume content in the sand units is abnormally high and may give incorrect results for in- place hydrocarbon volume and reservoir production rates. It may also cause reduction in the effective porosity values, lower permeability values and alter the Archie-predicted true resistivity results. However, these effects were compensated for, by the final equations that were used in the evaluations.

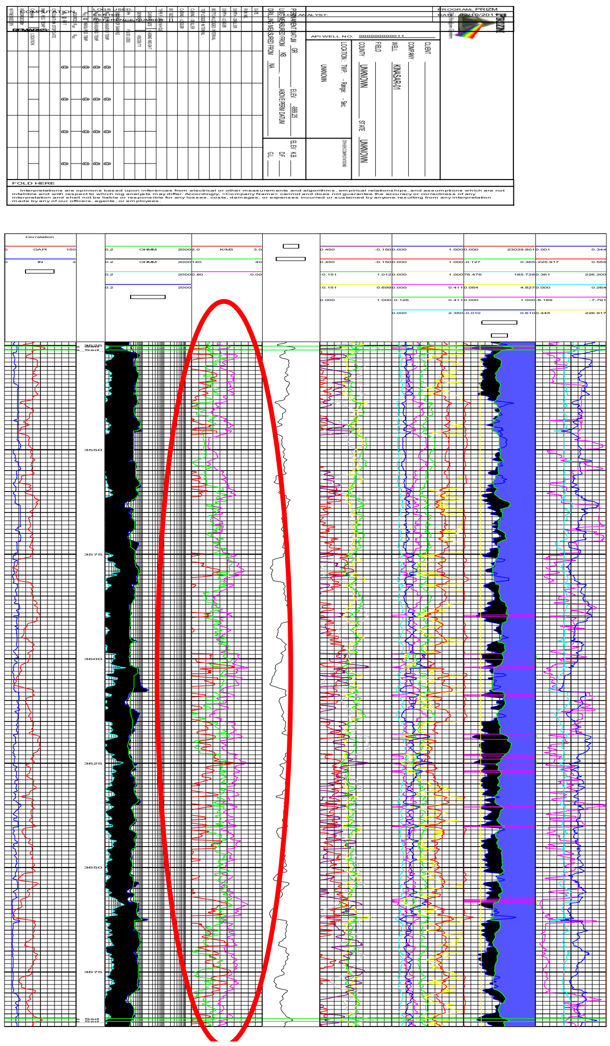

Figure 13: Identified fractures on some of the sand units (sand unit 108 for Ks01). This was done by plotting the bulk density and sonic logs on a compatible porosity scale.

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(3) The bulk volume water (BVW) estimation has shown that the sands of the Basin are fine grained to silty. Porosity versus water saturation plots have shown that some sand units are at irreducible water saturation and some are at semi-irreducible water saturation.

(4) The overall porosities and permeabilities of the sand units of the study wells are within limits that are required for hydrocarbon accumulation and preservation. However, permeability estimations in some sands are poor and excellent in others. Perhaps, the silty nature of most of the sands may probably have contributed to the poor permeability observed in some of the sands. The deeper sand units were observed to have good and better reservoir quality relative to other shallower sand units.

(5) The Archie's water saturation and the modified Simandox water saturation estimations have revealed depths where water is most likely to predominate.

(6) Evidences on hydrocarbon mobility exist in the sands of the study wells. However, the only exception is with the values obtained for ROS. This could be as a result of using the SN log reading instead of the MSFL reading as input parameter for RxO.

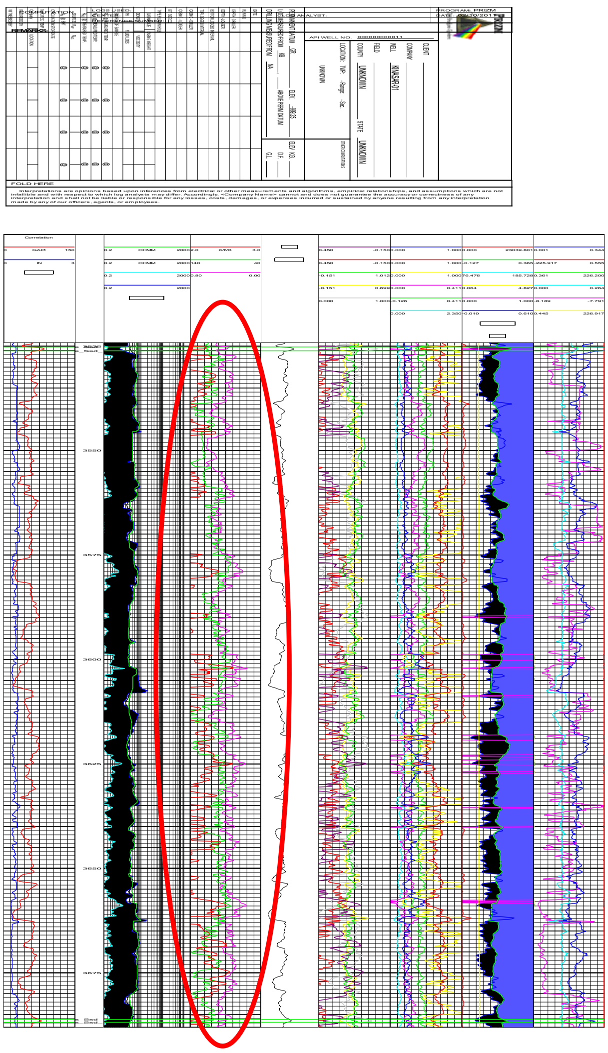

Figure 14: Column plot of Permeability (md) Vs Depths (m) for sand units of the study wells.

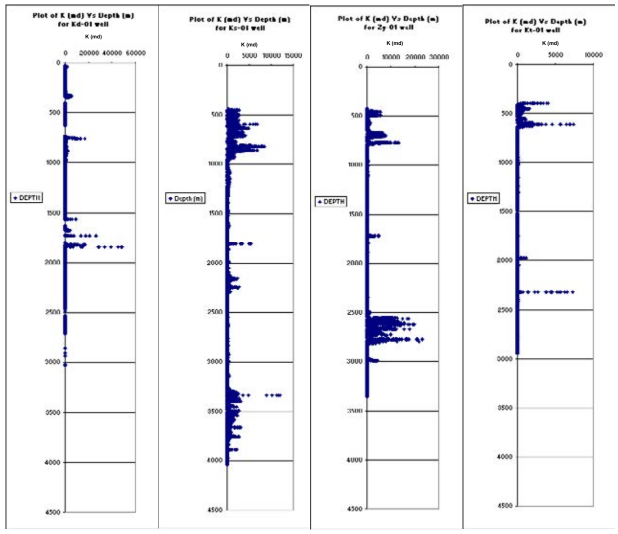

Figure 15: Plots of permeability against depth for all the study wells.

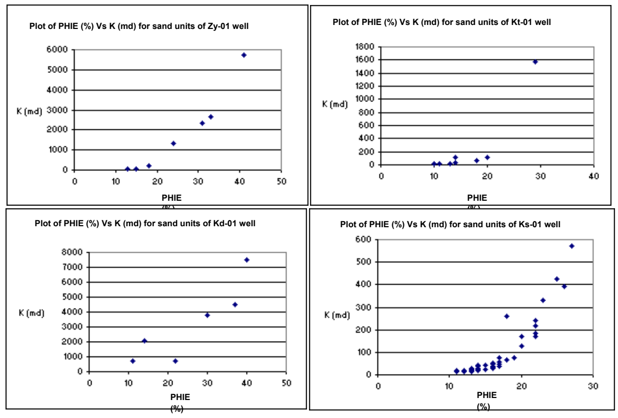

Figure 16: Correlation of wells Ks-01, Kt-01 and Zy-01 using the XSection application of the GeoGraphix software

(7) The correlations between Ks-01, Kt-01 & Zy-01 wells have revealed that anticlinal structures exist at deeper depths as well as juxtaposed sand bodies. Also thicker sand bodies are observed in Ks-01 well relative to the other wells. There is evidence to show that sand bodies are continuous within the wells, and in some cases these sand bodies tend to die-out before reaching the other well, suggesting probably sand pinchout.

(8) Drilling to deeper depths is strongly recommended due to the very favourable reservoir properties observed at deeper depths for Ks-01 and Zy-01 wells. Also the drilling should concentrate within the location of these wells.

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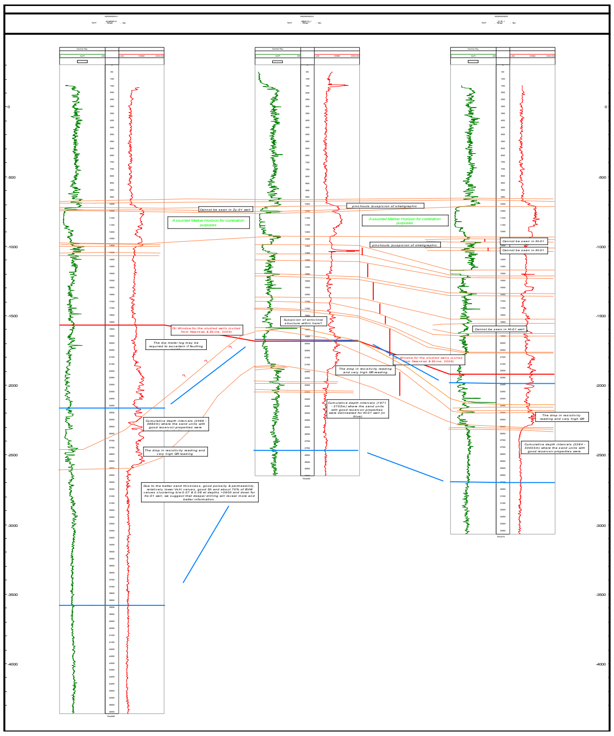

Figure 17: Correlation of wells Ks-01, Kt-01 and Zy-01 using the XSection application of the GeoGraphix software

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