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E.E.EPUH (Department of Surveying and Geoinformatics, University of Lagos)

D. O.OLORODE (Physics Department, University of Lagos)

P.C. NWILO (Department of Surveying and Geoinformatics, University of Lagos)

C. U EZEIGBO (Department of Surveying and Geoinformatics, University of Lagos)

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Author (s)

E.E.Epuh
Department of Surveying and Geoinformatics, University of Lagos.
E-mail: eeepuh@yahoo.com

D. O. Olorode
Physics Department, University of Lagos.

P. C. Nwilo
Department of Surveying and Geoinformatics, University of Lagos.

C. U Ezeigbo
Department of Surveying and Geoinformatics, University of Lagos.

Abstract

Qualitative and quantitative analysis were carried out in Kolmani River -1 exploratory wells to determine the shaly-sand reservoir petrophysical parameters such as: shale volume effective porosity, effective water saturation, free water resistivity and hydrocarbon saturation. The reservoir at depth between 6720ft and 7117ft contains a non associated gas and it occurs within the Yolde/Bima stratigraphic formations. The presence of igneous intrusive and the pressure and temperature observations from the well logs show that the basin has been subjected to high geothermal effects which have destroyed a substantial part of the hydrocarbon in place. The geothermal effects converted the hydrocarbon to a dry gas with an estimate of 680Mcf (six hundred and eighty thousand cubic feet) available for production. Also, the 12% effective water saturation shows that the well will not flow during production. The gas volume within the Gongola basin is insignificant.

Introduction

The Gongola basin (OPL 803/806/809) was investigated for hydrocarbon accumulation using extensive geological and geophysical evaluation techniques. In the application of the geophysical techniques, gravity and seismic reflection data were utilized. The gravity data available was reprocessed in order to develop a coherent map along the seismic lines. The new map was corrected for gravity effects of tertiary sediments and crust mantle discontinuity. First and second degree polynomial models in one and two variable were applied in the determination of the optimum residual gravity anomaly. A least squares multivariate statistical analysis was carried out on the polynomial models to determine the model that gives an optimum residual gravity anomaly for basin analysis. The second degree polynomial in two variables gave the minimum residual and was adopted for basin analysis. The step and two dimensional models were adopted in the analysis of the basin's crustal structure and tectonics through the determination of the fault parameters (depth to hanging wall, depth to the foot wall, sediment thickness and dip angles), basement depth, geometry and density contrast of the intrusive igneous bodies. The basement depth was also determined using the second vertical derivative as input anomaly profile (Epuh et al, 2011). To enhance the interpretation of the results of the gravity models, downward continuation of the residual gravity anomaly was carried out using density log. In this, the residual anomaly was found to be stabilized at depths between 2015 and 2170m. This region marked the upper and lower limits of the anomalous mass horizon with a density contrast of 0.86gcc suggesting that the anomalous mass is hydrocarbon (Epuh, et al, 2011). In the application of the seismic reflection data, six horizons and the top basement obtained from the seismic sections were mapped for structural and stratigraphic analysis. The seismic depth conversion was carried out using the checkshot curve and the iterative depth algorithm (IDA) process. Table 1 shows the summary of the seismic computations.

The analysis of the gravity maps and models showed that the basin's structure is a reflection of the basement architecture and is compatible with the prevailing geological model of NE-SE trend of graben and horst structure and the associated block faulting in the mid-continent basin. The characteristic high and low negative anomalies present in the residual gravity anomaly are due to intra-basement (intrusive) features and the presence of metamorphic basement. The southwest area has shallow and unproductive basement with maximum depth of 2.0km. The favourable hydrocarbon accumulation areas exist at the flanks of the basin with sediment thickness of 5.0km. From the results of the seismic time /depth structural maps, two leads at Garin Habu (L-A) and Kolmani River (L-B) were obtained. The presence of a gas prospect in the Kolmani lead was confirmed at depth between 2100m and 2700m in the Yolde/Bima stratigraphic formations.

The integration of the residual gravity anomaly and seismic reflection data maps showed the matching of the two leads. Figure 1 shows the overlay of the gravity map over the seismic maps. The integration of the two methods shows that the structural and stratigraphic geometry is a combination block faulting and up-dip stratigraphic pinch-out (Epuh et al, 2011) and the basement depth is between 5.0km in the southeast and 7.0km in the northeast part of the project area. Based on the structural analysis using the time/depth structural maps, interval and depth normalized interval velocities; it was found that lead A is as a result of velocity gradient (Epuh et al 2011). The Kolmani River lead (L- B) has the trapping potentials for hydrocarbon accumulation. This corroborates the results obtained using gravity models. However, the presence of igneous intrusive shows that the basin has been subjected to a high geothermal effect which may have destroyed a substantial part of the hydrocarbon in place (Bird, 2001). In the evaluation of the Kolmani wells, the primary targets are the sand formations of horizon H4 and H5 at depths between 2100m and 3900m respectively. These horizons lie in the Yolde/Bima stratigraphic formations as shown in Figure 2 (Epuh, et al, 2011). A petrophysical characterization of the Kolmani River reservoir is required to determine if the producible hydrocarbon in place is of commercial quantity.

In this research, the dual water model was utilized in the determination of the petrophysical characterization of the shaly-sand reservoir because it utilizes the cation exchange capacity (CEC) of the shale proportion. The CEC is the measurement of positive surface charge usually in terms of milli-ions equivalent per 100 grams of dry clay minerals (Schlumberger, 1989). Besides, both the dual water model and Waxman-Smith Models utilizes the cation exchange capacity (CEC). However, one major problem with the Waxman-Smith model is that it predicts that the water sands of increasing shaliness will have increasing effective water conductivities to the point that shales should appear to contain quite saline water. There is a good deal of evidence to the contrary when it was applied to the log observations

Geology of the Basin

The Gongola basin of the upper Benue Trough is a North-South trending arm of the 1000km long Benue Trough. The Benue Trough has been described by several authors as a rift structure whose evolution is linked to the opening of the South Atlantic (King, 1950, Cratchley and Jones, 1965, Wright, 1976, Whiteman, 1982). It is a rift basin with plate dilation leading to the opening of the Gulf of Guinea (Benkhelil, 1989; Fairhead and Binks, 1991). Benkkhelil (1989) also suggested that the evolution trough could also be as a result of tension resulting in a rift or wrench related fault basin. Mesozoic to Cenezoic magmatism has accompanied the evolution of the tectonic rift as it is scattered all over and throughout in the trough (Coulon et al, 1996; Abubakar et al, 2010). A magmatic old rift was also suggested for the Gongola basin by Shemang et al (2001) while Abubakar et al (2010) suggested the evolution as a combination of mantle upwelling or rise of a mantle plume which resulted in crustal stretching and thinning and the emplacement of basic igneous material within the basement and sediment which resulted in rifting. The structural history of this area commenced towards the beginning of the upper cretaceous with the rifting of the upper Benue Trough and the accumulation of considerable thickness of sediments. A number of depocentres have been identified within this NW-SE trending depression. The sub-basins in the northern half of the trough include Bornu, Gongola (Dukku-Bagoja, Ako), Bashar, Lau, Damaturu, Numan etc.

The volcanic rocks are widely distributed in the northeastern Nigeria. This area also includes the project area. The age of the major volcanic epoch cannot be precisely determined by stratigraphic means. For example, minor volcanic activity is believed to have occurred throughout the upper cretaceous and at most exposures, it is difficult to obtain suitable specimen for petrographic study (Carter et al, 1963). The major epoch of volcanic activity took place in the late Tertiary and Quaternary. All through, there are no outcrops of volcanic rocks in the project area. The evidences are presented by the presence of lava interbedded in the cretaceous sediments.

Dual Water Model Formulation

In the dual water model, the conductivity of the non-invaded zones is expressed as (Schlumberger, 1989; Dewan, 1995):

$$C_t = \frac{\phi_t^m S_{wt}^n}{a}\left[C_w + \frac{S_{wb}}{S_{wt}}(C_{wb} - C_w)\right] \quad (1)$$

Where a= constant, m= cementation factor=2, and n= saturation exponent=2

C_t = conductivity of the non-invaded zone, C_w = free water conductivity

ϕ_t = *total* porosity, S_{wb} = bound water saturation, S_{wt} = total water saturation

C_{wb} = bound water conductivity

The effective porosity of the sand (clean formation) phase (that is the non-clay phase) of the formation is obtained by subtracting the bulk volume fraction of the bound water $(\phi_t S_{wb})$ from the total porosity. In order to evaluate a shaly formation using the dual water model, four parameters were determined. They are:

R_w (Free water resistivity),

ϕ_e (effective porosity),

S_{we} (effective water saturation)

and V_{clay} (average clay volume).

Methodology

Six well logs obtained from Kolmani River were evaluated using the dual water model. The equation and techniques with which the dual water model petrophysical translations can be accomplished are found in several geophysics texts. Example: Rider (2006), Dewan (1995) and Sclumbeger (1989). Of the six wells drilled in the Kolmani River, only well 4 and 6 were used for petrophysical analysis. Wells 1,2, 3 and 5 do not contain neutron and density logs.

The Interactive Petrophysics (Log Analysis version 3.4) software was used the evaluation of the wells.

Results and Analysis

Results

One pay zone was obtained from well 4 at depth between 7018.75ft and 8200ft, while two pay zones were obtained from well 6 at depth between 6720 and 7006, and between 7073.75 and 7117.50ft respectively. The petrophysical analysis of well 4 is shown in Figure 3 and 4 while that of well 6 is shown in Figure 5, and 6. The statistical representation of the pay zones are shown in Figures 7,8 and 9 respectively.

Analysis

Well 4 log Analysis

One pay zone was identified from the well log at depth between 7018.75ft and 8200ft. Using a mean interval thickness of 4.7, the pay summary shows that the average clay volume obtained is 0%, the average water saturation is 34%, the average porosity is 35%. The average effective porosity is 32%. The gross thickness of the pay zones is 1181.25ft. The gas volume is obtained as 33.7BCF (Figure 5., track 7). The statistical summary of the pay zone is shown in Figure 7

Well 6 Log Analysis

Two pay zones were identified from the well log at depth between 6720 and 7006.25 and between 7073.75 and 7117.50ft. Using a mean interval thickness of 5.58, the pay summary shows that the average clay volume obtained is 51%, the average water saturation is 49%, the average porosity is 41% and the gas saturation is 51%. The pay summary for zone 2 shows that the average clay volume is 38%, the average water saturation is 36% while the average porosity is 30%. The average effective porosity is 22% and 31% respectively. The gross thickness of the pay zones is 350ft. The gas volume is 34BCF (Figure 6, track 10) with an effective water saturation of 12% (Figure 6, track 7). The resistivity of the clean sand (free water resistivity) is 0.70ohm-meter (Figure 6, track 8). The statistical summary of the pay zones in terms of gas and effective water saturation are shown in Figures 8 and 9 respectively. A tabular representation of the petrophysical analysis of the wells is shown in Table 2.

From the above analysis of the two wells, the following are inferred:

- **i.** The potential reservoirs are the upper cretaceous shallow marine sandstone of the Yolde formation and the lower cretaceous continental sandstone of the Bima formation.
- **ii.** The average amount of gas in place from the two wells in standard cubic feet is 34BCF and it is non-associated. The reasonable estimate for primary production for gas is 70% value for volumetric fraction of hydrocarbon. However, the 20% volumetric fraction of 34BCF $(9.63x10^8 m^3)$ volume in situ, gives a recoverable gas volume of 6.8BCF $(1.93x10^8 m^3)$. The gas volume estimate is valued in billion cubic feet (BCF). The anomalous mass based on the volume in situ is computed as $7.46x10^5 kg.$
- **iii.** The depth of the gas accumulation is between 2071 and 2192.9m.
- **iv.** The well 6 water saturation in the effective pore space is 12% for zone 1 and 9% for zone 2. Since the effective water saturation is not tied to entrained clay but is associated only with the clean sand fraction, it is probable that the zone would not produce considerable water with any gas and hence, the well will not flow.
- **v.** The high geothermal gradient associated with the intrusive igneous and Gongola rift basin environment was observed in the pressure and temperature observations from the logs. The pressure gradient stepped up from 0.15psia per feet to 0.46psia per feet at the depth of 7200ft; which gave rise to a pressure value of 3312psia, while the temperature rose from 238^{o}F to 255^{o}F. At this high pressure and temperature, the available hydrocarbon has been converted to dry gas. A dry gas is a natural gas that is always in the gaseous state in the reservoir and produces little condensable hydrocarbon when brought to the surface. Dry gas contains very small portion (less than 0.1 gallon of natural gas liquid vapours per 1,000 cubic feet) of hydrocarbon. Based on the 6.8BCF recoverable gas volume, the total gas volume available for production is 680Mcf (680,000 cubic feet) or $1.93x10^4 m^3$. The gas volume in the Gongola basin is marginal.
- **vi.** The basin OPL 809 gas deposit is a low reward prospect.

Conclusion

The extensive geophysical techniques applied in the investigation of Gongola basin have shown that the basin contains a marginal gas deposit. However, a geochemical analysis is required to test the maturity of the hydrocarbon in-situ. The state of maturity will show if the volume will improve in the years to come. Finally, it is observed from gravity models that the basin is a good target for solid minerals and ground water resources.

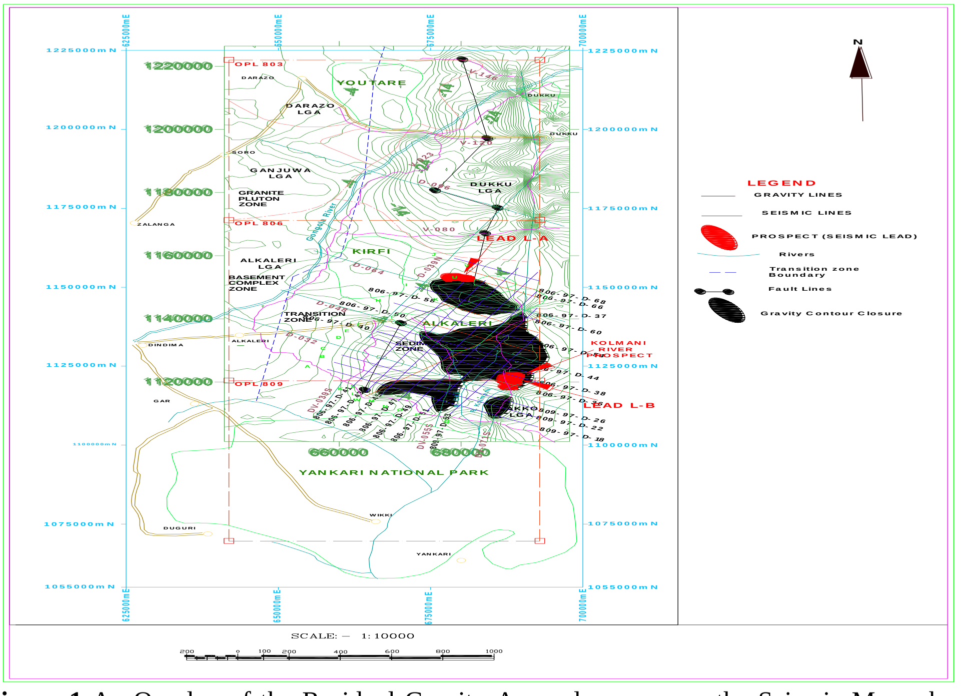

Figure-1 An Overlay of the Residual Gravity Anomaly map over the Seismic Map; showing the lead locations(Epuh et al, 2011).

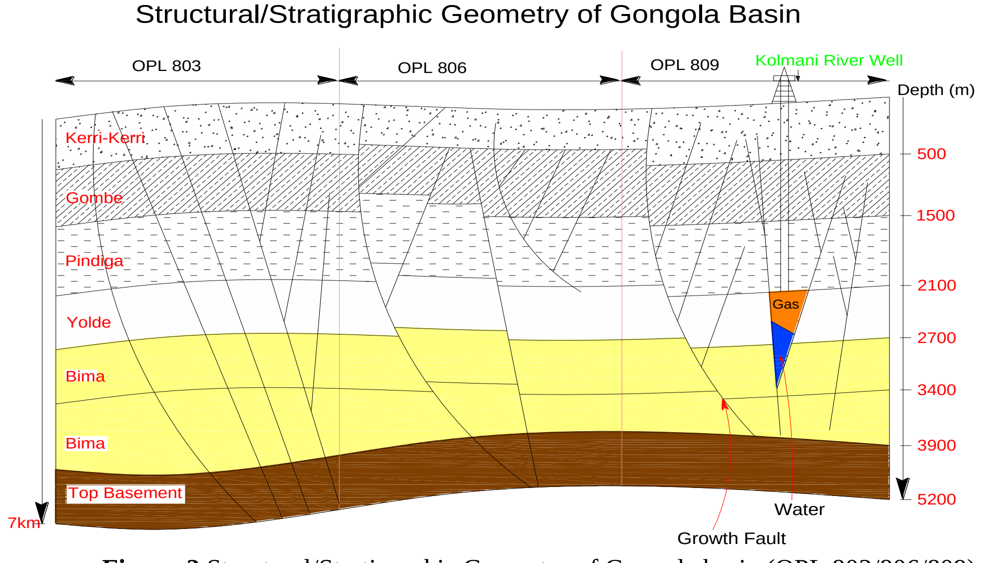

Figure-2 Structural/Stratigraphic Geometry of Gongola basin (OPL 803/806/809)

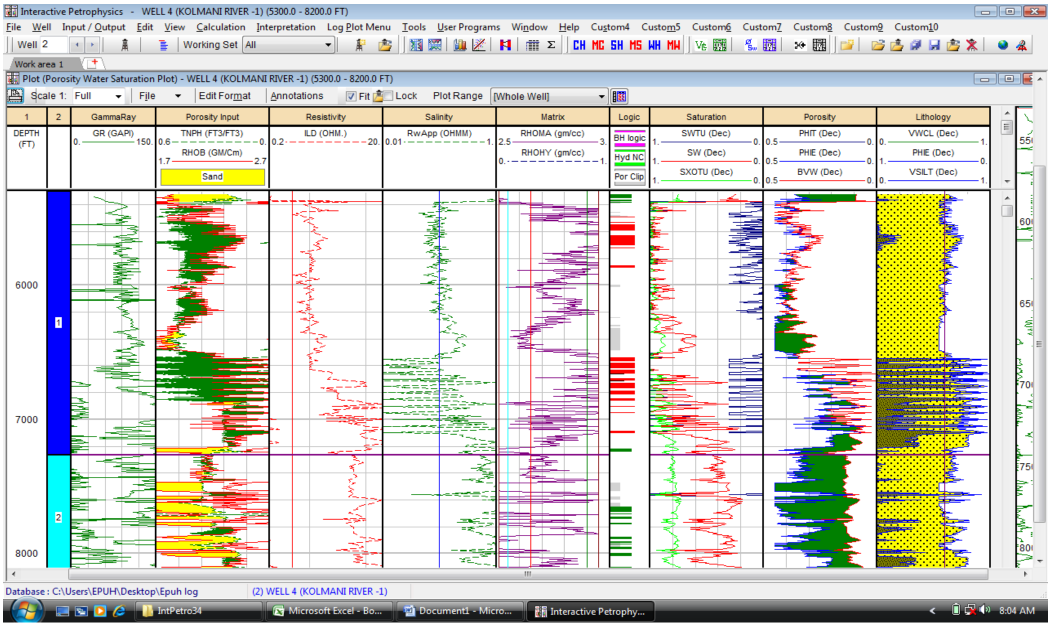

Figure -3 Showing Porosity, water saturation and Lithology of well 4

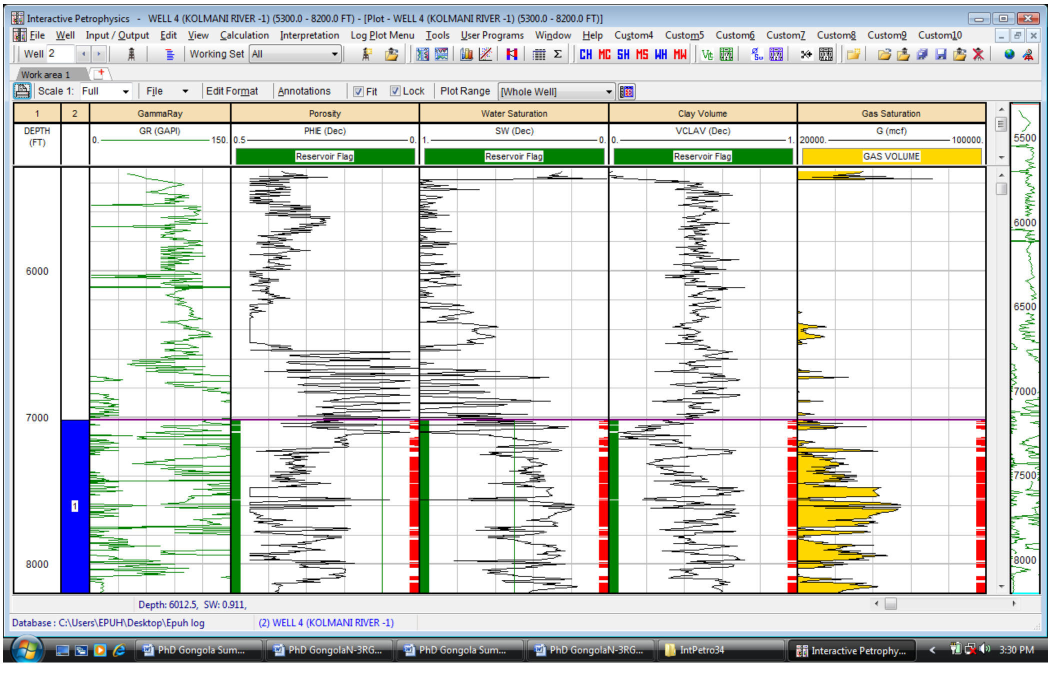

Figure-4 Showing effective porosity, water saturation, average clay volume and the gas volume of well 4

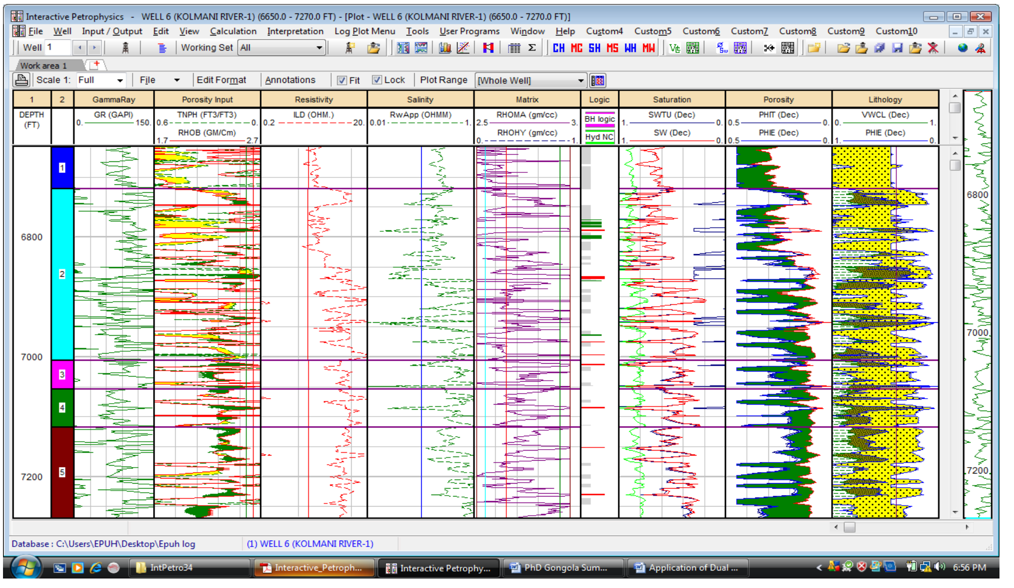

Figure-5 Showing porosity, water saturation and Lithology of well 6

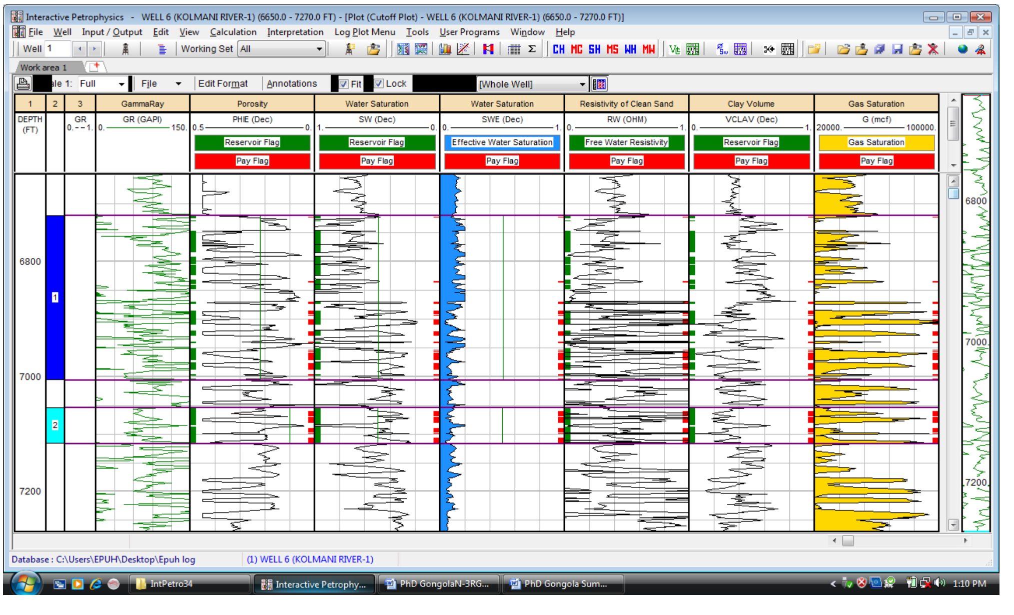

Figure -6 Showing effective porosity, effective water saturation, average clay volume , free water resistivity and the gas volume for well 6

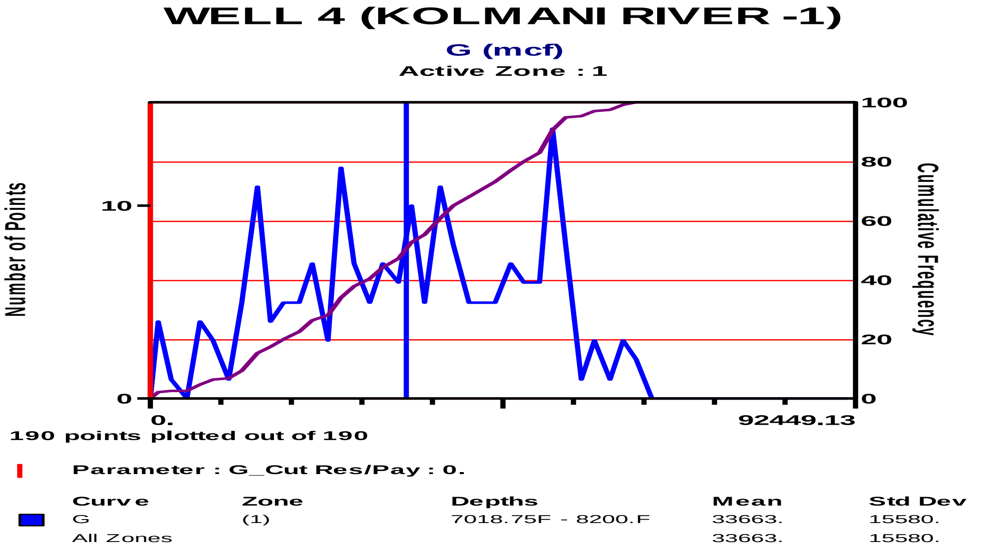

Figure-7 Statistical representation of well 4 gas saturation

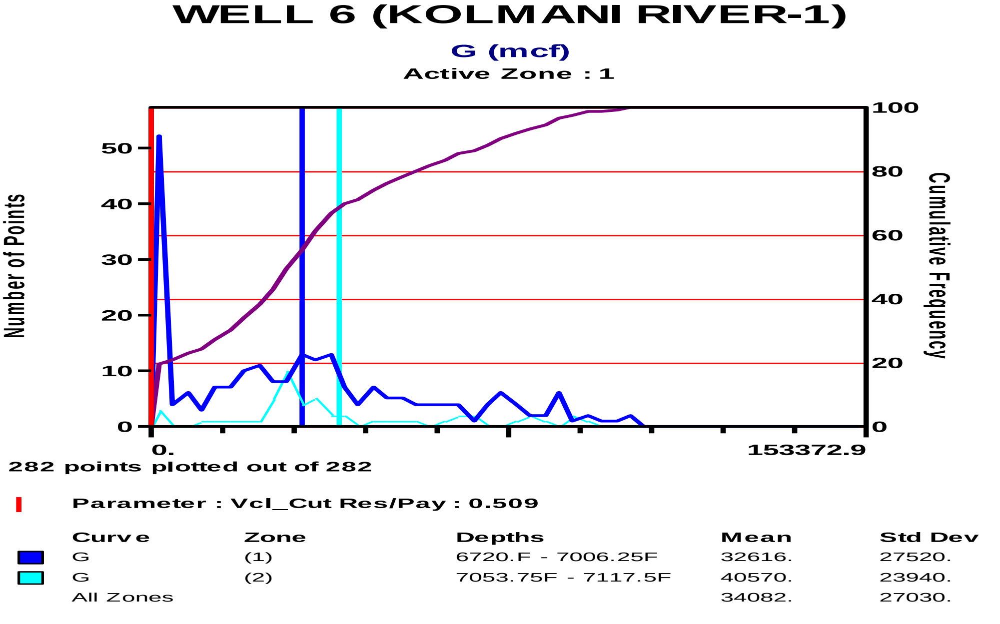

Figure-8 Statistical representation of well 6 gas saturation

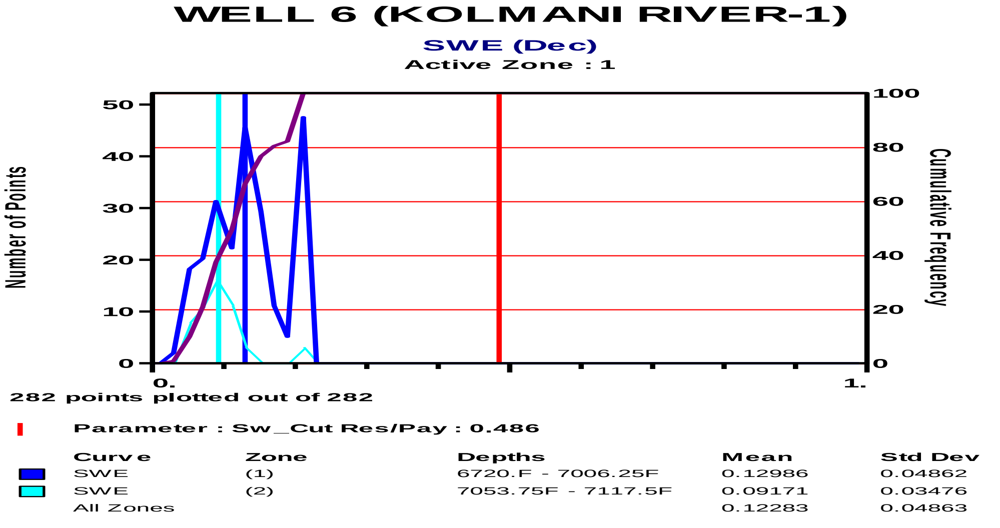

Figure-9 Statistical representation of well 6 effective water saturation

Table-1 Interval velocity, density, Reflection Coefficient, Acoustic Impedance and Lithology for lead L-B (Epuh et al, 2011)

Horizon	Depth (m)	Structural Lead		Interval Velocity x1000 (m/s)		Normalized Interval Velocity x1000 (m/s)		Density (gcc)		Reflection Coefficient		Acoustic Impedance X1000		Lithology	
		Time	Depth	L-A	L-B	L-A	L-B	L-A	L-B	L-A	L-B	L-A	L-B	L-A	L-B
H1	0-500	NIL	NIL	2.70	2.80	2.81	2.91	2.23	2.26	1.00	1.00	6.03	6.31	Shale	Shale
H2	500-1500	NIL	NIL	2.70	3.10	2.81	3.22	2.23	2.31	0.00	0.06	6.03	7.17	Shale	Shale
H3	1500-2100	NIL	NIL	2.70	3.30	2.81	3.43	2.23	2.35	0.00	0.04	6.03	7.75	Shale	Shale
H4	2100-2700	L-A/ L-B	L-A/ L-B	2.75	3.20	2.86	3.33	2.24	2.33	0.01	-0.02	6.17	7.46	Shale	Gas sand
H5	2700-3900	L-A/ L-B	L-A/ L-B	2.80	4.96	2.91	5.16	2.26	2.60	0.01	0.27	6.31	12.9 0	Shale	Water Sand
H6	3900-5200	L-A/ L-B	L-A/ L-B	4.45	5.58	4.62	5.80	2.53	2.68	0.28	0.07	11.2 7	14.9 5	Dolo-mite	Dolo- Mite
Base-ment	5200	NIL	NIL	4.50	6.20	4.68	6.45	2.54	2.75	0.01	0.07	11.4 3	17.0 5	Dolo-mite	Gneiss

Table-2 Summary of Dual Water Model Results

Well Name	**Kolmani River 1**
OPL	809
Fluid present	Gas (non –associated)
Free water resistivity (R_w)	$0.70Wm$
Effective porosity (f_e)	22%
Shale volume (V_{sh})	51%
Total water saturation (S_{wt})	49%
Effective water saturation of shaly sand (S_{we})	12%
Volumetric fraction of hydrocarbon (f_h)	20%
N/G	51%
Effective water conductivity C_{we}	1.58 mho/m
Conductivity of the hydrocarbon bearing sand C_t	0.063mho/m
Hydrocarbon interval	6720-7006.25ft, 7053-7117.5ft
Reservoir thickness	350ft
G (volume in situ)	34BCF $(9.63x10^8 m^3)$
Anomalous Mass $(M = r_{av}G)$	$7.46x10^5 kg$

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