

Petrophysical Evaluation of Shaly Sand Reservoirs in Palouge-Fal Oilfield, Melut Basin, South East of Sudan

Rashid A.M. Hussein¹ and Motaz Eltahir Bakri Ahmed²

¹Sudan University of Science &Technology (SUST),
²Sudapet Co Sudan

Abstract- The performance of various shaly sand saturation equations was compared to the water saturation calculated from drainage capillary pressure. The wireline logging, mud logging, well testing, and core data had been carefully evaluated during the processing of the data; therefore, data quality was thought to be good. Almost all kinds of petrophysical parameters were used for log interpretation in the area of the study, and accomplished the six wells processing and interpretation, including interpretation of the results, tabling, plotting and cross-plots making for data quality control. The results obtained using the shaly sand evaluation techniques, were in good agreement with core and other data. Consequently, the methods and techniques in the shaly sand models can be used to improve petrophysical evaluation of shaly sand reservoirs. The result of the evaluation was utilized to investigate the low productivity from some zones and its relation with depositional process and petrophysical properties. Spectral gamma ray was introduced in this study as a new method to identify the reservoir quality.

Key words: Petrophysical Evaluation, Shaly sand reservoirs, density neutron logging, Palouge-Fal oil Field.

مستخلص:

أداء العديد من معادلات تشبع الرمل الغضاري قد قورنت مع تشبع الماء الذي تم حسابه من تصريف الضغط الشعري. التسجيلات الكبلية وتسجيلات الطين واختبارات الطين وبيانات اللباب تم تقويمها بدقة أثناء معالجة البيانات, لذا , جودة البيانات يعتقد انها جيدة . الي حد ما كل أنواع معايير الخواص البتروفيزيائية استخدمت في تفسير التسجيلات في منطقة الدراسة , واكتمال عمليات ست ابار وتفسيرها متضمنة تفسير النتائج والجدولة وتوقيع وتوقعات تقاطعية تمت معالجتها لضمان جودة البيانات.

أخيرا , النتائج المتحصل عليها مستخدمين طريقة تقويم الرمل الغضاري والتي تمت مناقشتها في هذه الدراسة, كانت في متوافقة مع بيانات اللباب وبيانات أخرى , عليه , الطرق والتقنيات في نماذج الرمل الغضاري والمقدمة في هذه الدراسة يمكن استخدامها في تحسين تقويم الخواص البتروفيزيائية لمكامن الرمل الغضاري . استخدمت نتيجة التقويم في تفصي انخفاض الانتاجية من بعض النطاقات وعلاقتها بالعملية الترسيبية والخواص البتروفيزيائية , عليه , تم استخدام أشعة قاما الطيفية في هذه الدراسة كطريقة جديدة للتعرف علي جودة المكامن .

Introduction

Shaly sand interpretation is still sprouting with numerous researchers conducting investigations of the clay minerals effect on rock conductivity through the theoretical and experimental approach. Well logs are usually the main tool of investigation and evaluation of the subsurface formations. The formation parameters such as porosity, permeability and water saturation are usually obtained from log analysis. The dominant function of those parameters is to assess the hydrocarbon content of subsurface formations. Simandoux⁽¹⁾ proposed a model based on experimental work on homogenous mixtures of sand and montmorillonite. Poupon and Leveaux⁽²⁾ developed a model based on field data from Indonesia where the reservoir rock has fresh formation water and high degree of shaliness. The model is known as “Indonesia formula”. Hill and Milburn⁽³⁾ indicated a non-linear logarithmic relationship between formation resistivity and formation water resistivity using large amount of water saturated shaly sand core samples. They also demonstrated that cation exchange capacity (CEC) can be used as an effective shaliness indicator. Waxman-Smits⁽⁴⁾ proposed a shaly sand model based on the data from Hill and Milburn⁽³⁾ in addition to data from their own measurements. The model showed that the conductivity of water saturated shaly sand (C_o) was directly related to the shaliness factor (Q_v), conductivity of formation water (C_w), and porosity (Φ). Clavier *et al.*,⁽⁵⁾ proposed a model called “Dual water”. The model considers that the conductivity of water is contributed by two types of water (clays bound water and free water). It suggested that shaly sand behaves just like clean sand but with the water conductivity of mixture from both Components. Brown *et al.*⁽⁶⁾ carried out geophysical work called the White Nile rift

that included the northern Earlier studies, conducted by Whitman⁽⁷⁾ and Vail⁽⁸⁾ shortly described the geology of history and structural styles of the basins were the study area.

The most studied basin in Sudan is Muglad basin, in contrast, the hydrocarbon exploration and petroleum geology of the part of Melut basin area around the White Nile. They did gravity study and they explained the great similarity in tectonic and structural. Salama⁽⁹⁾ investigated the evolution of the river Nile and suggested that the area of Melut basin was occupied by closed saline lakes. These lakes were connected together in the Tertiary time to form the river Nile. Kaska⁽¹⁰⁾ investigated the palynology of the cenetral Sudan rift basins. He subdivided the sedimentary sequences into five major palynological zones ranging from Early Cretaceous to Oligocene. Eisawi⁽¹¹⁾ conducted a palynological and Paleoenvironmental interpretation of the late Cretaceous to Tertiary Strata of the Melutbasin. The evaluation of shaly sands from log analysis provides estimates of total porosity, effective porosity and water saturation. It is convenient to estimate porosity and water saturation content in order to obtain the hydrocarbon in place. Total porosity is obtainable from density, neutron and sonic logs with appropriate transforms and cross-plots. Shale can be estimated from gamma ray, density, neutron, resistivity, spontaneous potential and other logs. The effective pore space contains formation water and hydrocarbon.

The amount of formation water can be estimated from deep resistivity log with an appropriate saturation model, e.g. Archie, Waxman-Smits and Dual Water. Hydrocarbon fills the remaining effective pore space. Porosity and permeability relationship, from the core, can be used to calculate the permeability. Because the Melut basin is farther from the Central African Shear Zone

(CASZ) and closer to the East African Rift System (EAS) than the Muglad basin, the influences of the strike-slip of CASZ and the Senonian basin inversion rejuvenation of rifting (Guiraud and Bosworth, 1999) had relatively weaker impact on the Melut basin. Therefore, the basin formation and evolution, structural styles and petroleum system are to some extent different from the Muglad basin. Since 2000, the Melut basin has been widely explored. This paper presents a review of the major structural and sedimentary events in the area of study.

The objective of this study was to build a comprehensive petrophysical evaluation in shaly sand reservoirs for Palouge-Fal oilfield, Melut basin, old South Sudan, in order to achieve greater accuracy in the petrophysical evaluation by integrating petrophysical data and reservoir engineering data.

Materials and Methods

Data sets from 6 wells (Palouge-1, Palouge-2, Palouge-3, Fal-1, Fal-2, and Fenti-1) were utilized to characterize the petrophysical properties of Palouge – Fal reservoir, Melut basin. Logs were used to confirm the derived porosity and permeability. Errors in porosity calculations will propagate to the saturation calculation since all saturation models require porosity input. Properly designed well tests can be used to confirm log derived reservoir fluids. Such process will be applied to assess the accuracy of petrophysical methods.

Reservoir and Shale Identification

The most reliable indicator of reservoir rock is the behavior of the density and neutron logs with the density moving to the left (lower density) and touching or crossing the neutron curve. All these cases were corresponded to a fall in the gamma ray log, in addition to the presence of the mud cake, right deflection of the Spontaneous Potential (SP) and the separation between three resistivity curves,

respectively. The greater cross over between the density and neutron indicate the better quality of the reservoir and vice versa, Figures 1 and 2 show good and bad reservoir identification from log. Shale was clearly identified as zones where the density lies to the right of the neutron, associated with increase in gamma ray. Also, the shale was identified in addition to the density and neutron from the presence of wash out, left deflection of SP and when the three resistivity curves overlies each other.

Lithology Reconstruction

There are two independent sources of lithology data available from oil wells, one set data coming directly from the drilling cuttings (mud logs), and another set from wire line logging. For reliable lithological reconstruction, the two sets of data are essential. When any two log values are cross plotted, the resulting series of points is used to define the relationship between the two variables, or to define fields, using both x and y axis values, giving the upper and lower limits of both variables. The neutron – density cross plot is the best method for lithology identification. Density – neutron cross plot values were used to identify the pure matrix and/or the related porosity. This cross plot uses a straight line relationship between two variables to quantify the desired characteristic and to identify lithology Figure 3.

Shale Volume Model

In this study after the gamma ray log has been checked, the minimum (sand line) and the maximum (shale line) values were not at one gamma ray value, in one part of the well and at another gamma ray value at the other parts Figure 4, due to the existence of radioactive minerals in sands. The influence of the radioactive minerals was clearly identified from the spectral gamma ray log, which gives high thorium and potassium value in the sand zone Figure 5.

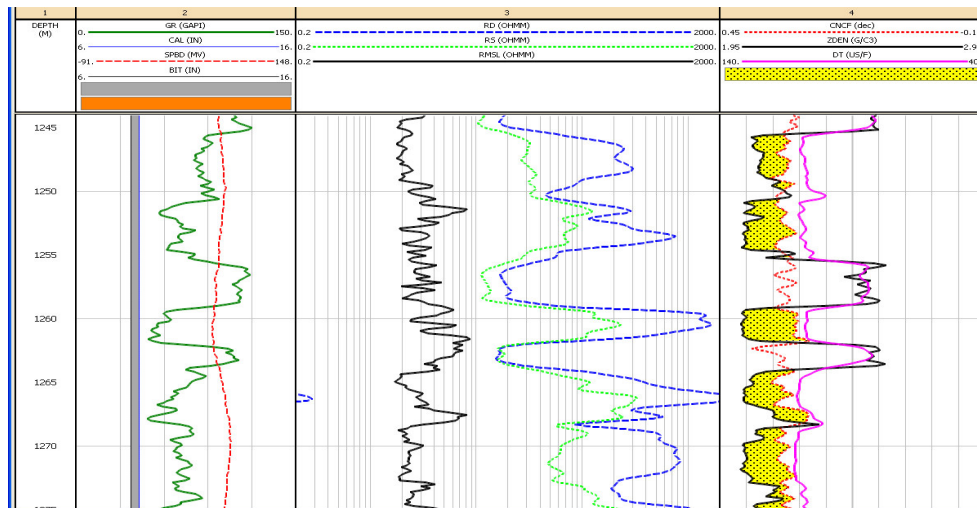


Figure1: Good reservoir quality (Fal-2)

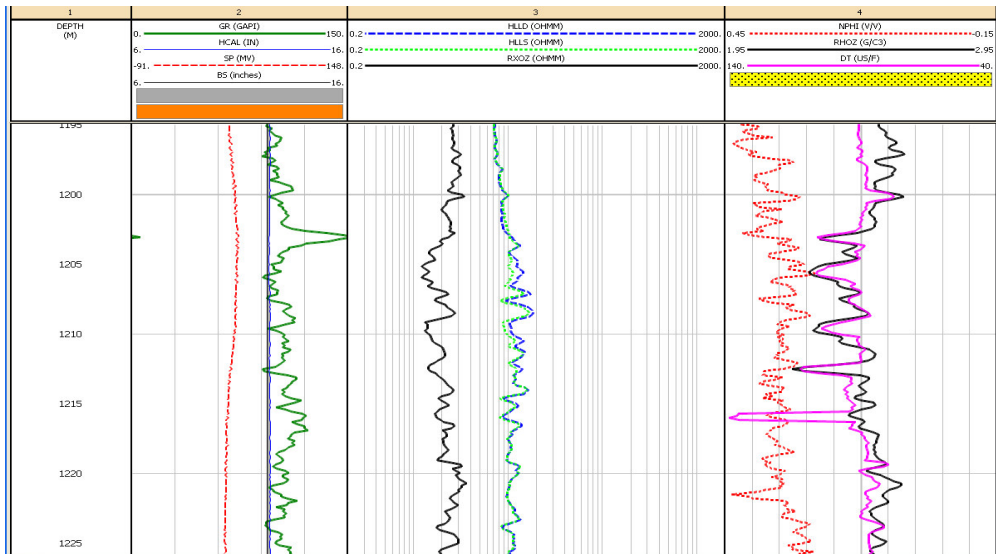


Figure 2: Bad reservoir quality (Fal-1)

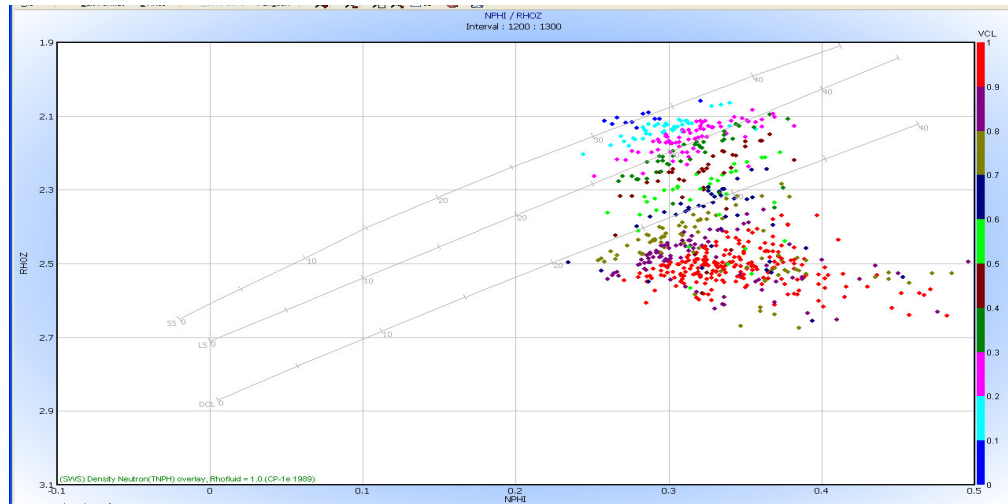


Figure 3: Lithology identification from density-neutron cross-plot

Those hot sands (Radioactive) are usually high in potassium or thorium and potassium content show high API value indicative of shale. So the gamma ray is not reliable indicator to calculate the shale volume for this area. The distribution of clay or shale in detrital formations has different impacts on some of the logs measurements. Ransom⁽¹²⁾, identified three types of distributions for shales: laminar, structural and dispersed shale. Many logs and/or log combinations can be used to estimate volume of shale because most log responses are influenced by the presence of shale in the formation such as Resistivity, SP, GR, RHOB, NPHI and DT. These logs are often called shale indicators⁽¹³⁾. There are two types of shale indicators: Single curve shale

indicators and two curve shale indicators. The density neutron technique has been preferred two curve shale indicator method to calculate shale volume, where radioactive sand occurs. Sand shale models of density and neutron cross plots are used to determine the percentage of shale. A clean sand line is typically established using the common sandstone parameters for density (2.65 g/cm³) and neutron ≈ -0.07 . A clay line is established from dry solid point (density= 2.3-2.85 g/cm³, neutron $\approx 0.1-0.4$) to the 100% porosity fluid point Fig 6. Density (RHOB)-neutron (NPHI) cross plot was used to estimate the shale volume for Adar, Yabus and Samma formations using the following relationship:

$$V_{clND} = \frac{(\text{DenCl2} - \text{DenCl1}) * (\text{Neu} - \text{NeuCl1}) - (\text{Den} - \text{DenCl1}) * (\text{NeuCl2} - \text{NeuCl1})}{(\text{DenCl2} - \text{DenCl1}) * (\text{NeuClay} - \text{NeuCl1}) - (\text{DenClay} - \text{DenCl1}) * (\text{NeuCl2} - \text{NeuCl1})}$$

Where: DenCl1 & NeuCl1 and DenCl2 & NeuCl2 are the density and neutron values for the two ends of the clean line. The shale parameters for Yabus and Samma formations have been determined statistically using the

cross plots and compared with the histograms for all wells Figure 7.

Porosity Model:

The density neutron cross plot is the most accurate log analysis method for determining porosity. Both tools are calibrated against a

water filled limestone basic calibration fixture. The density log measurement is more sensitive to pore space and the neutron measurement is more sensitive to lithology changes. This tendency also balances out in cross plotted results. This technique as well as the technique which was used to estimate the shale volume. For the shaly sand models, the following sets of equations are used:

$RHOB = RHOB_{matrix} + (RHOB_{shale} - RHOB_{matrix}) * V_{shale} + (RHOB_{fluid} - RHOB_{matrix}) * \Phi_{effective}$ And $\Phi_{Neutron} = \Phi_{neutron_{matrix}} + (\Phi_{neutron_{shale}} - \Phi_{neutron_{matrix}}) * V_{shale} + (1 - \Phi_{neutron_{matrix}}) * \Phi_{effective}$ The total porosity is given by:

$\Phi_{Total} = \Phi_{effective} + WCLP \times V_{shale}$
Where: RHOB is the density log, and $\Phi_{Neutron}$ is the neutron log and WCLP is the wet clay porosity from core analysis.

Applying this technique for porosity calculation, the porosity model has been constructed for Yabus and Samma formations. The core porosity calibration was performed by plotting overburden corrected core porosity versus the total porosity calculated from the logs. The core porosity was depth- shifted to match the logs, due to the error in depth while drilling. There is a very good match between porosity from core and porosity from logs, which indicate the accuracy of interpretation, Figures 8, 9 and 10.

Up to now none of the current well logging techniques can be used to measure permeability directly; therefore, in this study the core analysis method has been used to estimate formation permeability. The most obvious control on permeability is porosity.

This is because larger porosities mean there are many more and broader pathways for fluid flow. The POROPERM cross plot was

constructed from five wells by plotting the permeability against porosity (fraction) on a logarithmic scale from the core data, result in a clear trend with a degree of scatter associated with the other influences controlling the permeability Figure 11. It is clear from this figure that the permeability of the sandstone is extremely well controlled by the porosity. From the POROPERM cross plot the permeability model has been established using the following relationship:

$$\text{Permeability} = 0.0009 \times e^{45.845 \times \text{porosity}}$$

As well as the porosity, Figure 12 and 13 show the comparison between core and log permeability.

Determination of Formation Water Resistivity (RW)

Formation water is the water uncontaminated with drilling mud. The resistivity of the formation water (Rw) is an important interpretation parameter since it is required for the calculation of saturations. There are several sources for formation water resistivity information (Schlumberger⁽¹⁴⁾). In all cases, a good value of Rw can be easily found from the water sample measurement. Water resistivity in this study was obtained from the following methods:

Permeability

Water Resistivity from Water Sample Measurement

Water sample from the well Palouge_1 had been taken from the Yabus formation at the interval 1351-1358m, and water resistivity for this sample was measured in the laboratory at 60° F(surface temperature), and the resistivity at this temperature was 1.365 ohm-m. The resistivity was converted to the formation temperature by using the following equation (Shlumberger,⁽¹⁵⁾):

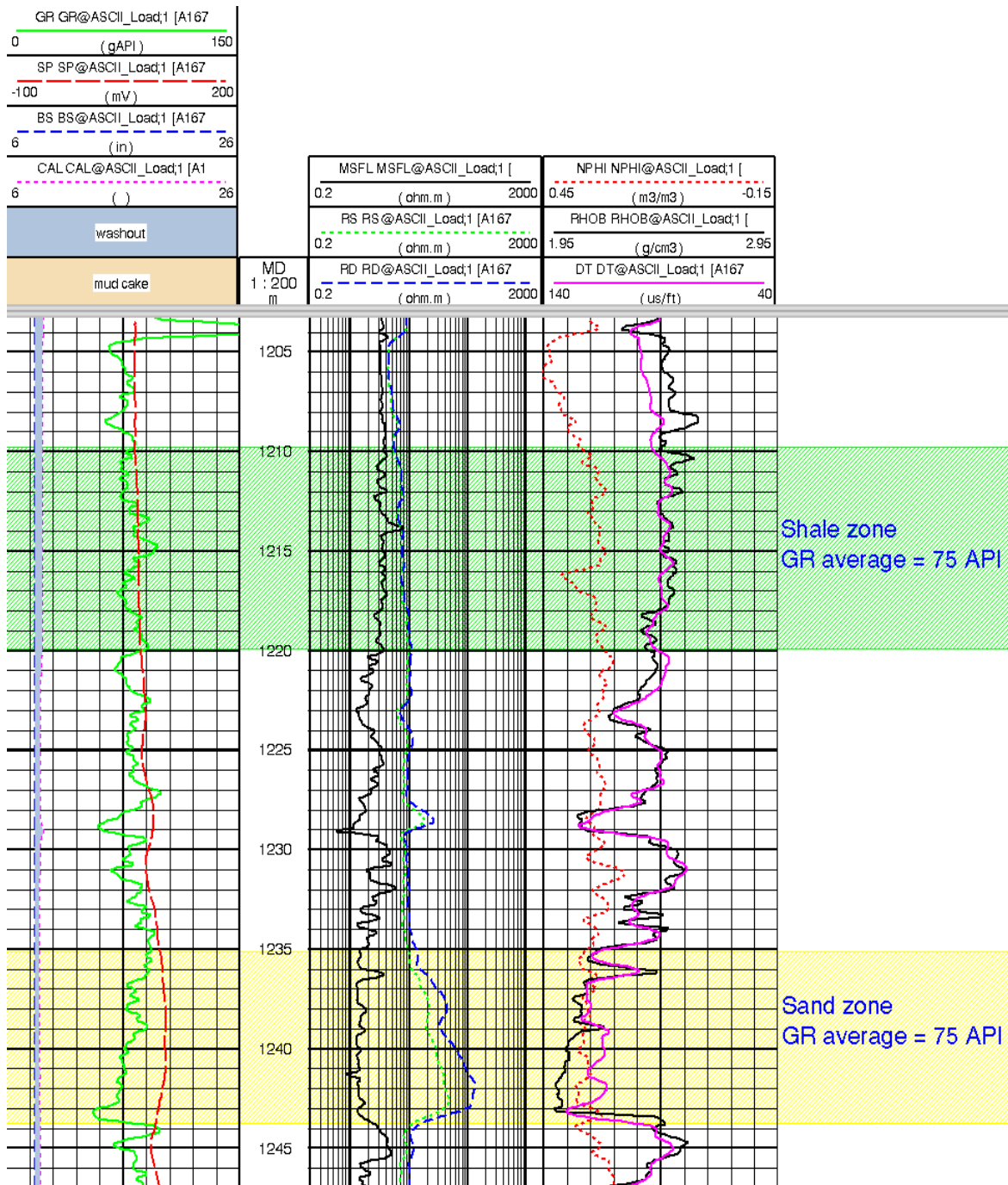


Figure 4: GR reading in the shale and hot sand (Paloug-3)

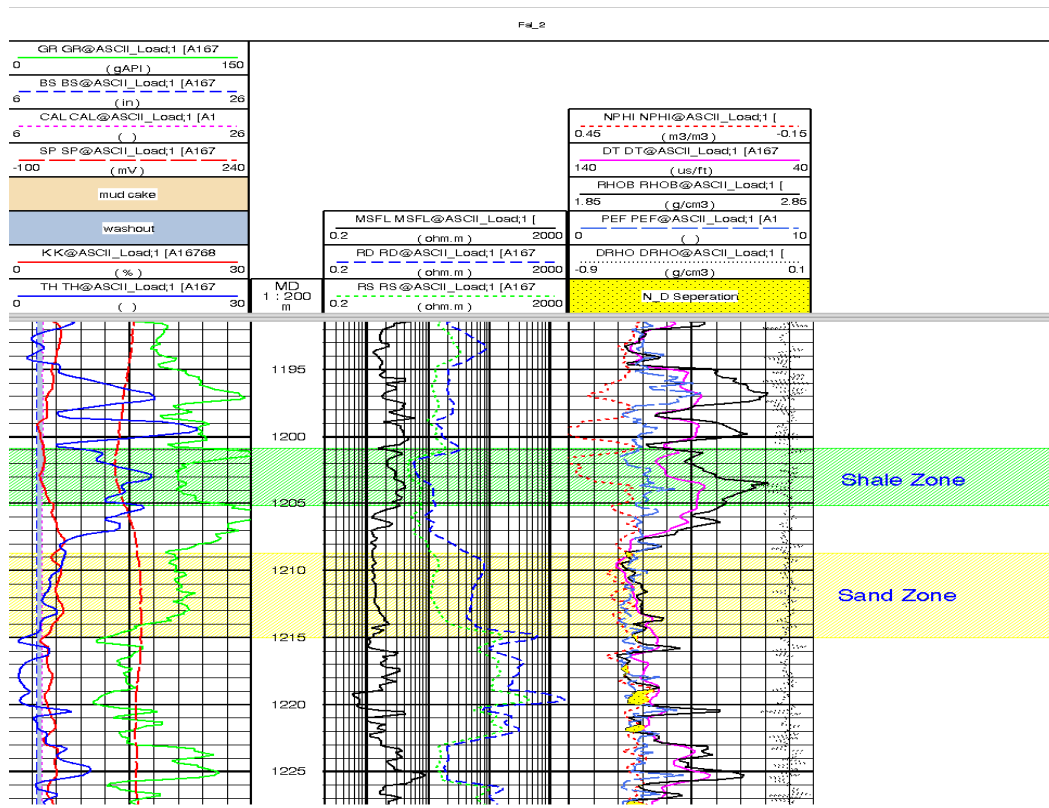


Figure 5: TH and K readings in shale and hot sand (Fal-2)

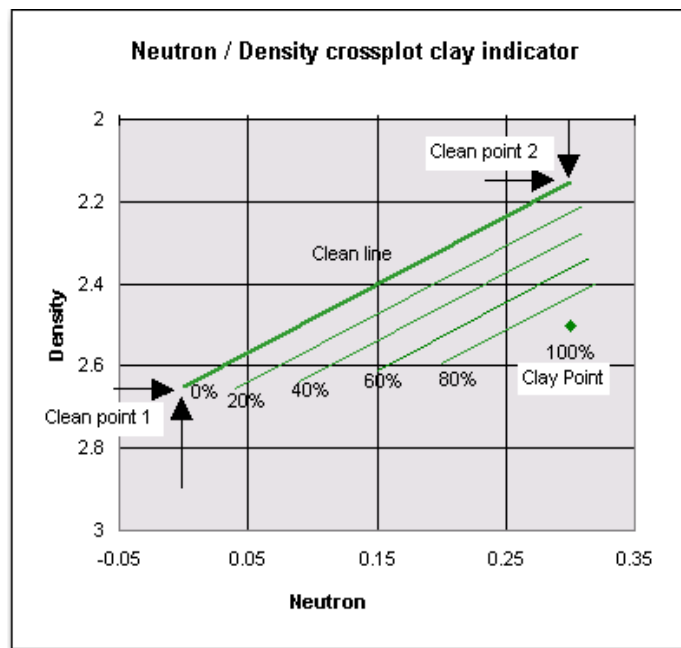


Figure 6: Density – Neutron cross plot

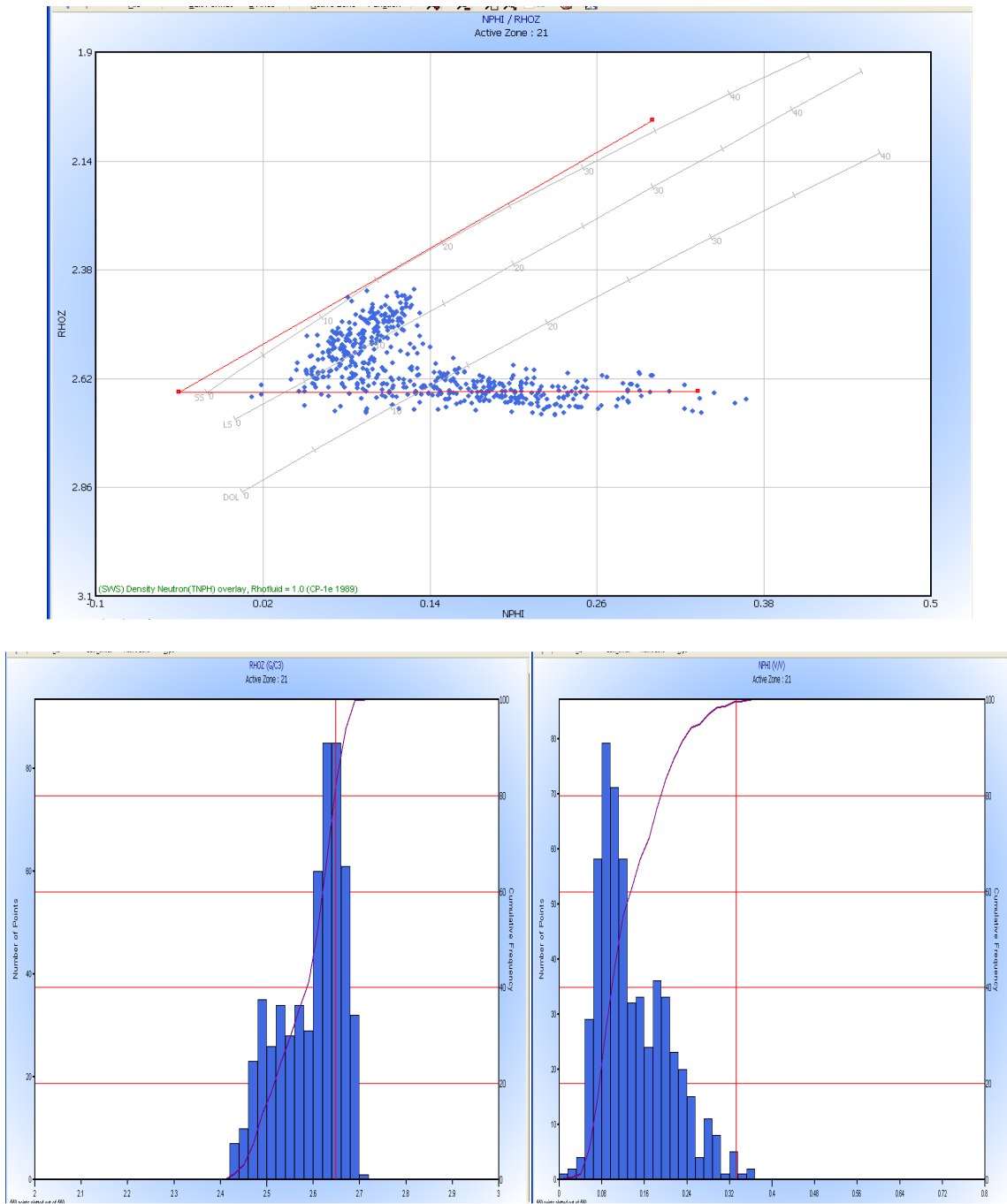


Figure 7: Density-Neutron cross-plot compared with the Histogram

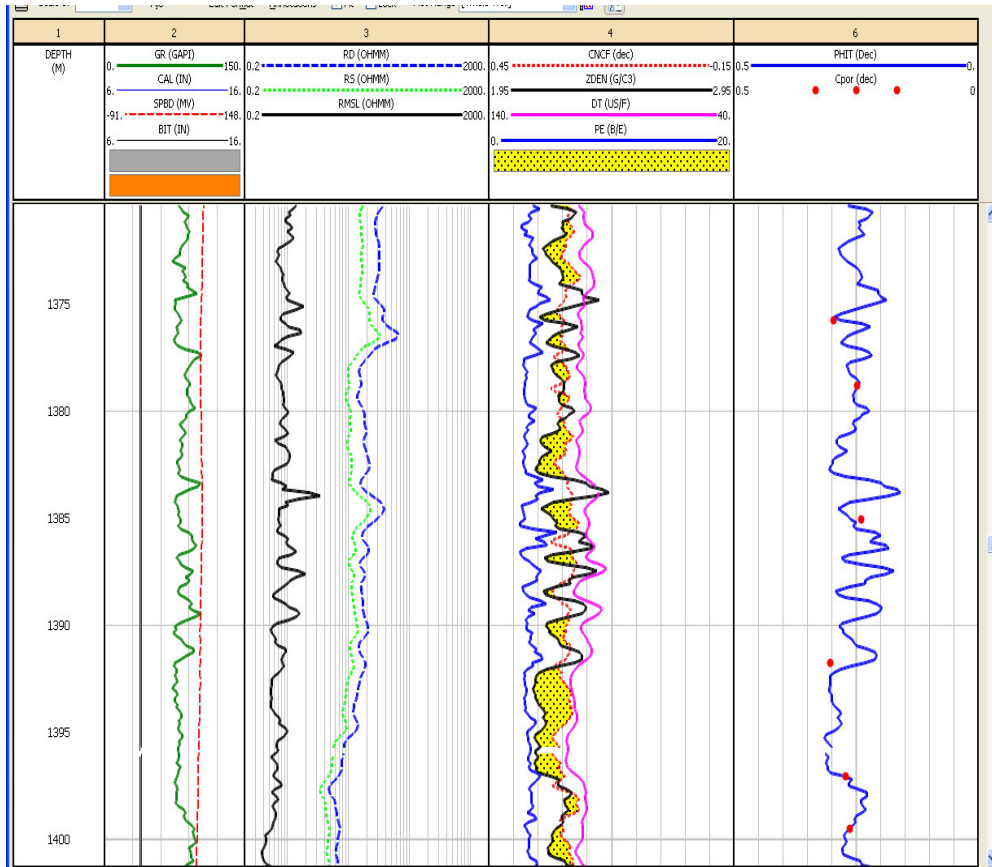


Figure 8: Comparison between log and core porosity for Fal-2 well

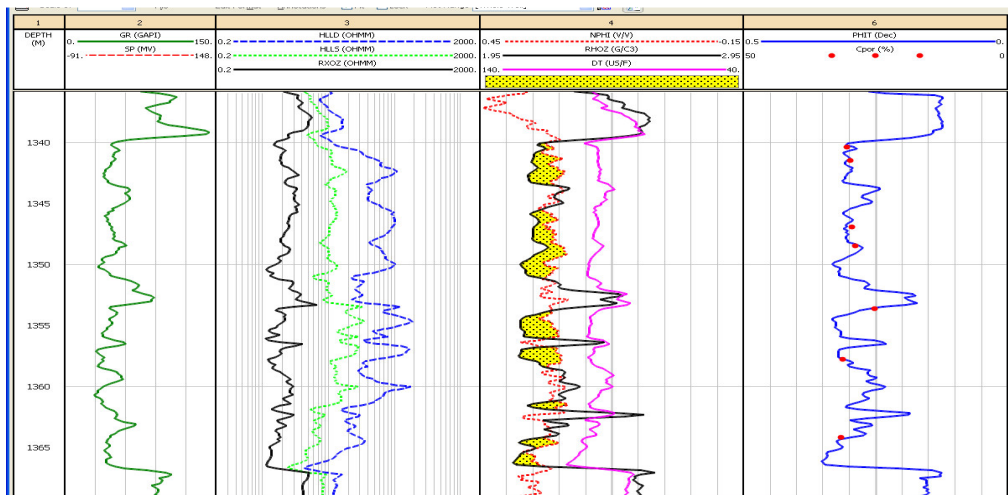


Figure 9: Comparison between log and core porosity for Palouge-2 well

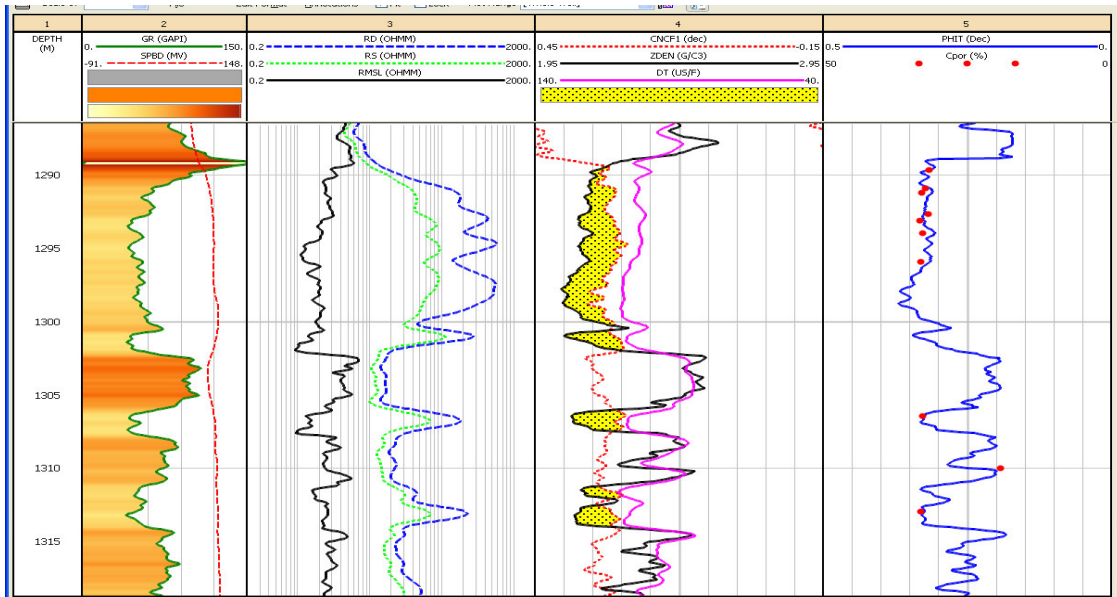


Figure 10: Comparison between log and core porosity for Palouge-3 well

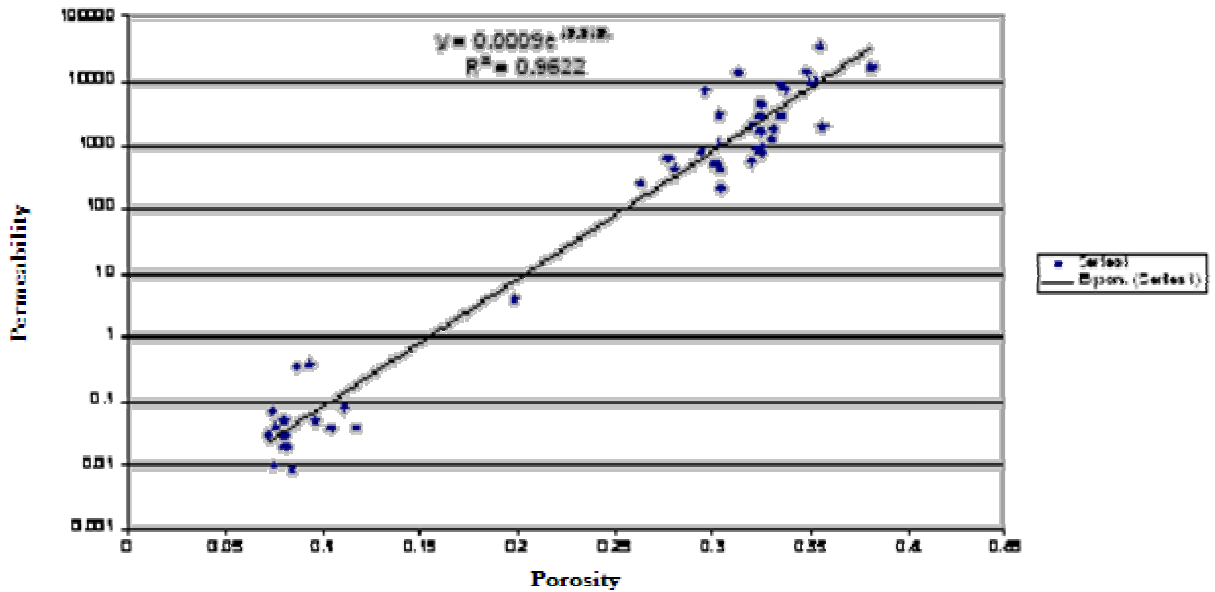


Figure 11: POROPERM cross plot for the area of study

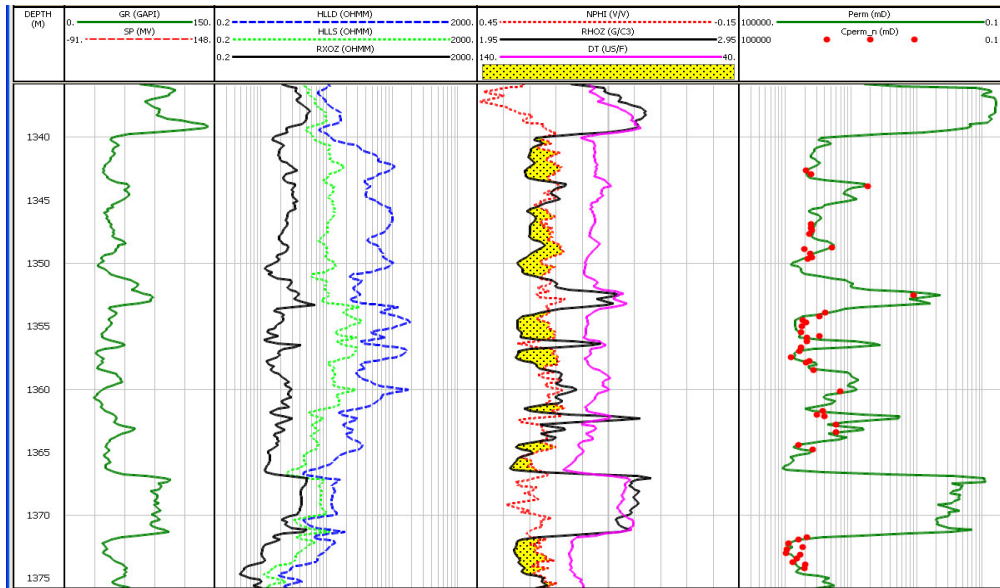


Figure 12: Comparison between log and core permeability for Palouge-2 well

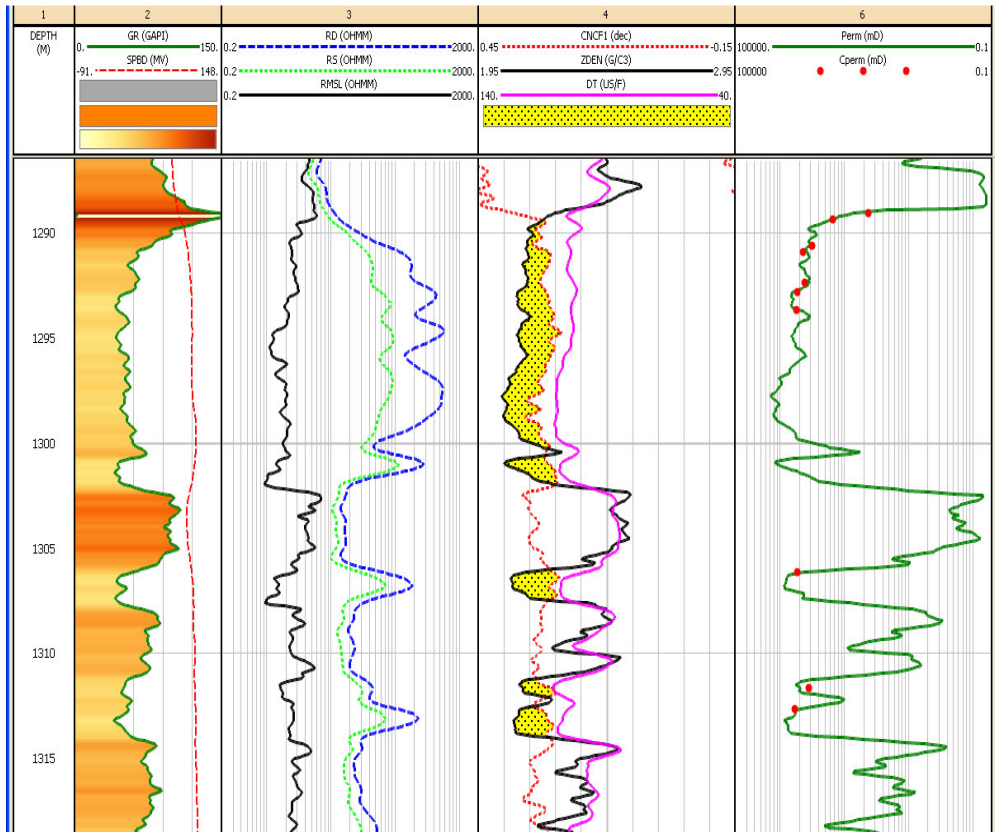


Figure 13: Comparison between log and core permeability for Palouge-3 well

$$R_2 = R_1 [(T_1 + 21.5) / (T_2 + 21.5)] ^{\circ}C$$

Where:

R₂ = water resistivity at formation temperature

R₁ = water resistivity at surface temperature

T₁ = surface temperature

T₂ = formation temperature

Hence:

$$R_2 = 1.365[(15.5 + 21.5) / (73 + 21.5)]$$

$$R_w = 0.5 \text{ Ohm-m}$$

Water Resistivity From The Deep Resistivity Log

For water zone, if its porosity is known, the water resistivity can be calculated from deep resistivity log by using the following Archie equation:

$$R_w = \phi^m \times R_t$$

Hence

$$R_w = (0.30)^2 \times 50 = 0.5 \text{ ohm-m}$$

Water Saturation

There are several techniques for modeling water saturations in shaly sands. All of them start with Archie's equation and introduce into it additional factors to account for the extra conductivity caused by shale or clay presence in shaly sands.

Water Saturation from Capillary Pressure

A total of 14 samples were collected from Pal-2 and Pal-3, by using oil-brine drainage centrifuge method, 8 samples from Pal-3 and 6 samples from Pal-2. For each well, the core analysis data validation step was carried out, and all data were categorized into various classes. After systematic data validation and processing, quality laboratory capillary pressure data, corrected for specific reservoir situations, was translated into height above free water level (FWL) at reservoir conditions. In a first attempt to derive such profiles, the popular Leverett J- function approach was used to generate normalized saturation curves for the field. The main data class omitted from analysis consists of non-reservoir data (data with exceptionally low permeability and/or porosity), a typical data (data which appears a

typical or non-representative for particular deposition) and scattered data (data scattering on porosity-permeability plot). In total, 3 of the samples were removed from the analysis and the remaining data set was used for further, detailed analysis and study. All the capillary pressure and J-function curves are shown in Figure 14 and 15. Based on the above analysis two different rock types were classified.

Comparative Performance of Capillary

Water Saturation

The performance of various shaly sand saturation equations was compared to the water saturation, calculated from drainage capillary pressure. The variable clay conductivity of the Dual Water model has the virtue of being related to electrolyte salinity and apparent shale conductivity, which can be derived from logs. All of equations require correction of porosity for the bound water component, or shale porosity. In all of the shaly sand equations considered, except for the Dual water model, the bound water component was subtracted from the porosity value before being input to the equation, with saturations calculated as fractions of effective pore volume. This mitigates the log analyst from task, required when using a Dual Water type equation of checking to see that calculated hydrocarbon volumes do not exceed effective porosity.

Results were first calculated with the Dual Water equation which seemed to agree reasonably well with production test data. Then, required adjustments were made to the shale resistivity used in the other equations to produce comparable results. The agreement between water saturation from core capillary drainage and log calculations is acceptable considering some uncertainty in the selection of shale parameters (shale porosity, shale water resistivity or shale resistivity).

In addition to the shale parameters, also we can see the effect of changing m and n parameters on the analysis in Figure 16. The effect of using the inappropriate m and n value lead to overestimation in water saturation, which would finally lead to underestimation of the reserve. On the other hand, it was noted that no fine tuning was necessary to achieve comparable results to the capillary pressure model when presumably correct values for parameters and variables were used.

All of the shaly sand equations evaluated can show acceptable saturation results for the shaly sand reservoir that have been part of this study as long as suitable shale parameters selected. The success in using a given equation depends mainly on the skill of the log analyst who integrating all available information into his analysis as well as familiarity with the equation(s) that were used.

Production by Swabbing and Low Flow from the Reservoir

One of the important purposes of this study was to establish a relationship between the depositional processes with the development of current petrophysical parameters of the formations in order to see how these processes affect the reservoir quality in term of deterioration of porosity and permeability and producing a tight reservoir unit, to come out with better understanding of low flow rate of fluid in some DST zones and production by swabbing, despite the oil produced from such zones sometimes have high API values. Spectral gamma ray analysis, comprehensive petrophysical evaluation, cores and testing data were integrated to identify the reservoir quality in the area of study.

The most reliable indicator of reservoir quality was checked from the behavior of the Thorium and Potassium logs. These logs were

compared with the cored interval to see the relationship between them. Thorium and Potassium curves were put in one track with same scale in interpreted composite log. Shales, silts and fine grained sandstones can be clearly identified as zones where the Thorium lies to the right of Potassium curve, according to the crossover magnitude between them Figure 17.

The greater crossover between the Thorium and Potassium logs, the worst quality of the reservoir. Coarse grained and clean sandstones can be identified also, when the Thorium curve moving to the left (lower thorium), and touching or crossing the Potassium curve Figure 18. The greater crossover between the Potassium and Thorium logs, the better quality of the reservoir. Finally, the method to identify reservoir quality using spectral gamma ray log in this study gave very good results.

Discussion

According to the petrophysical evaluation and depositional environment interpretation, it can be seen that the low producing and swapping zones are vertically distributed in the massive shale zone. This shows that the sand bodies are fine grained and with high shale volume, because they are deposited in low energy environment (flood and Constructional plains). From the petrophysical evaluation, all the tested swapping zones show the characteristics of tight zone such as poor permeability, small porosity, high shale volume and shallow invasion depth, Figure 19.

According to the cut-off determination and Drill Stem Test (DST) results, 15% is considered as the effective porosity lower limit for reservoirs in Yabus and Samma formations. The tested tight zones can be classified into 2 types: low oil saturation (S_o) tight zone and high (S_o) tight zone.

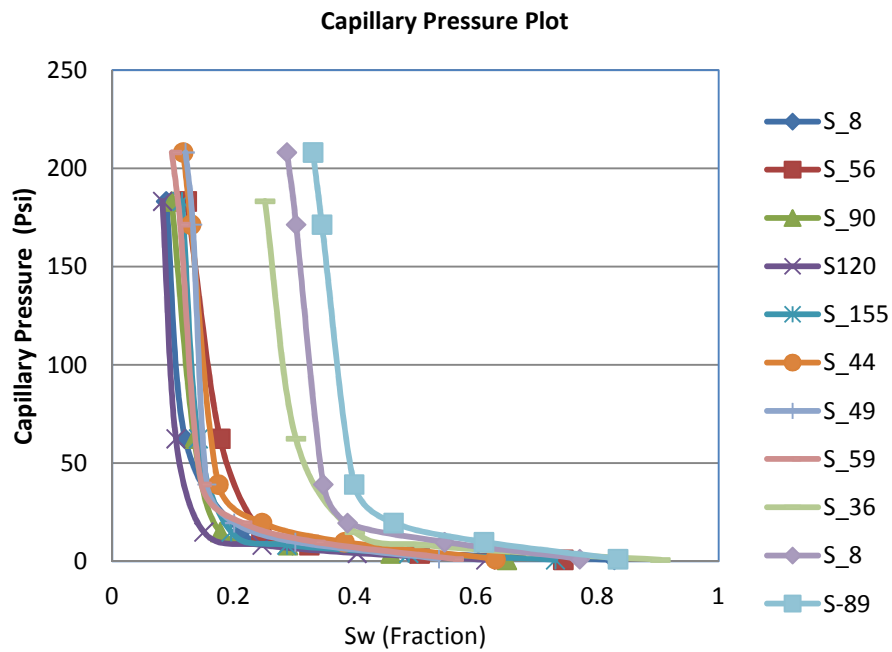


Figure 14: Drainage capillary pressure at reservoir conditions

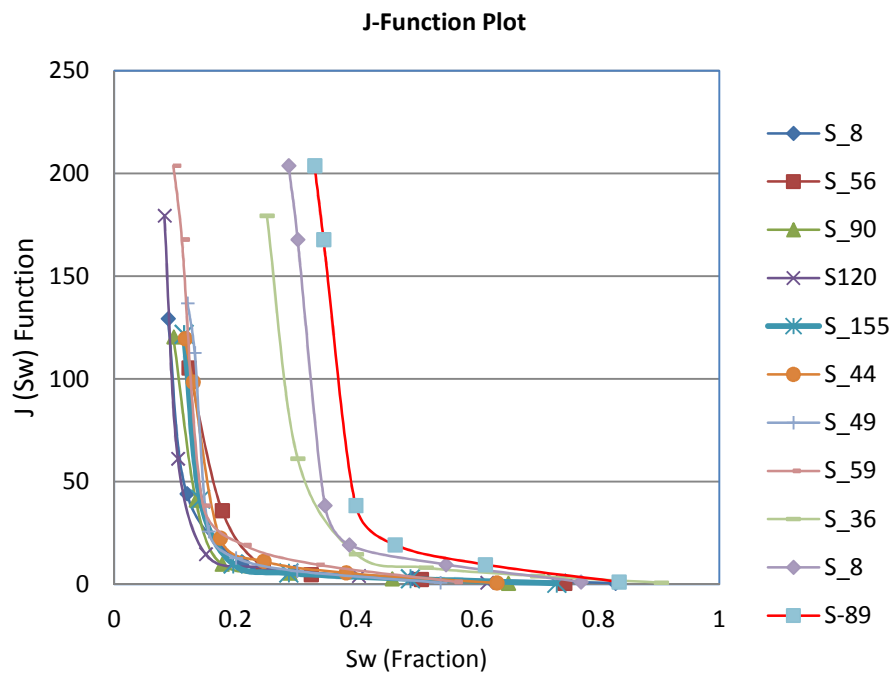


Figure 15: Leverett J-function: normalized capillary pressure

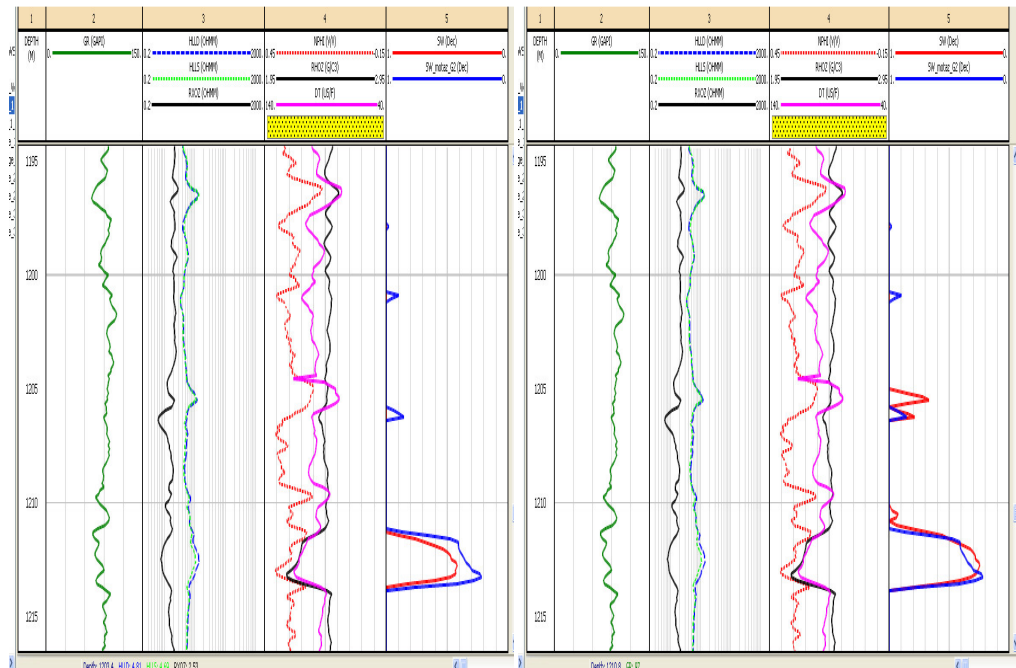


Figure 16: Effects of using inappropriate m and n values

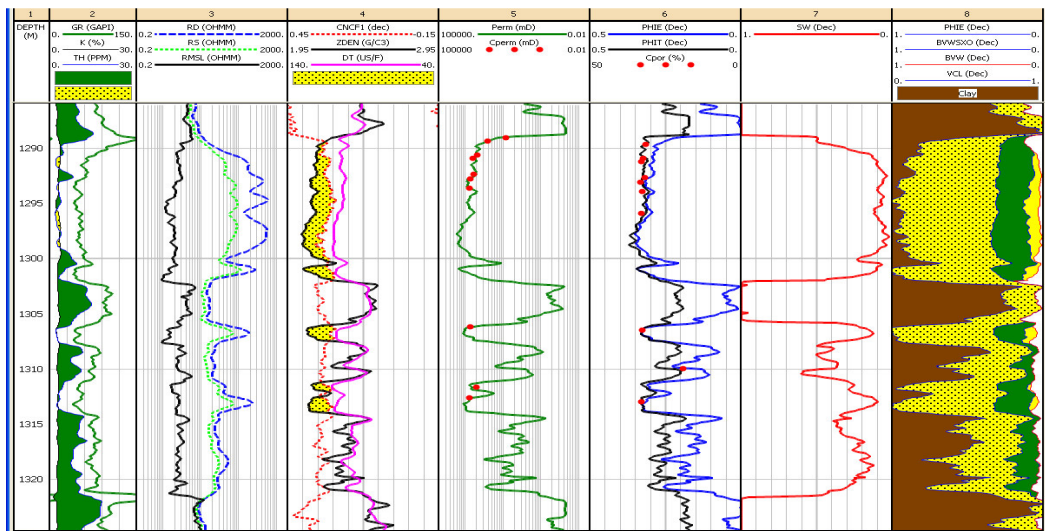


Figure 17: Shale and Fine grained sandstone from TH & K compared with core and petrophysical evaluation (Palouge-3 well)

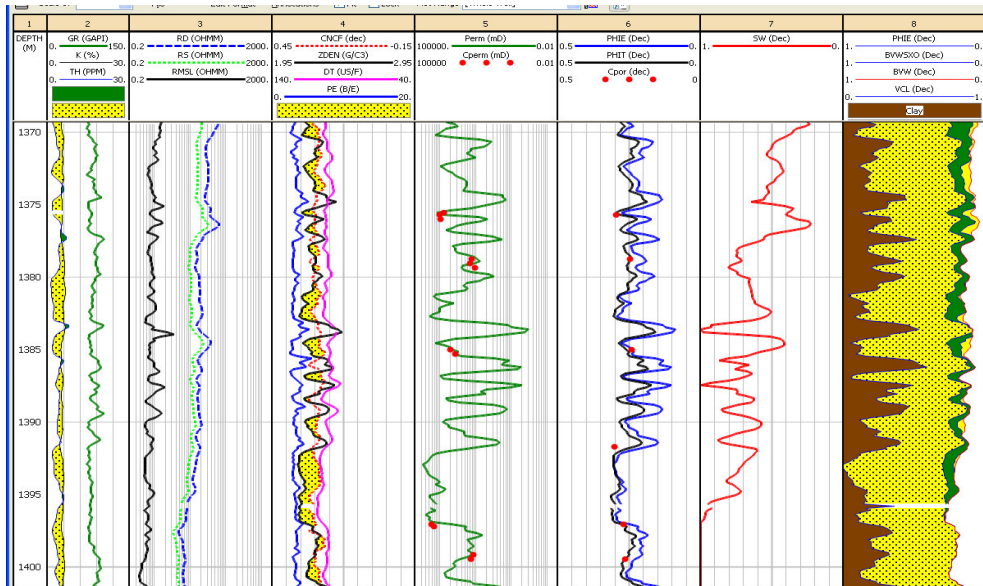


Figure 18: Coarse grained sandstone from TH & K compared with core and petrophysical evaluation (Fal-2)

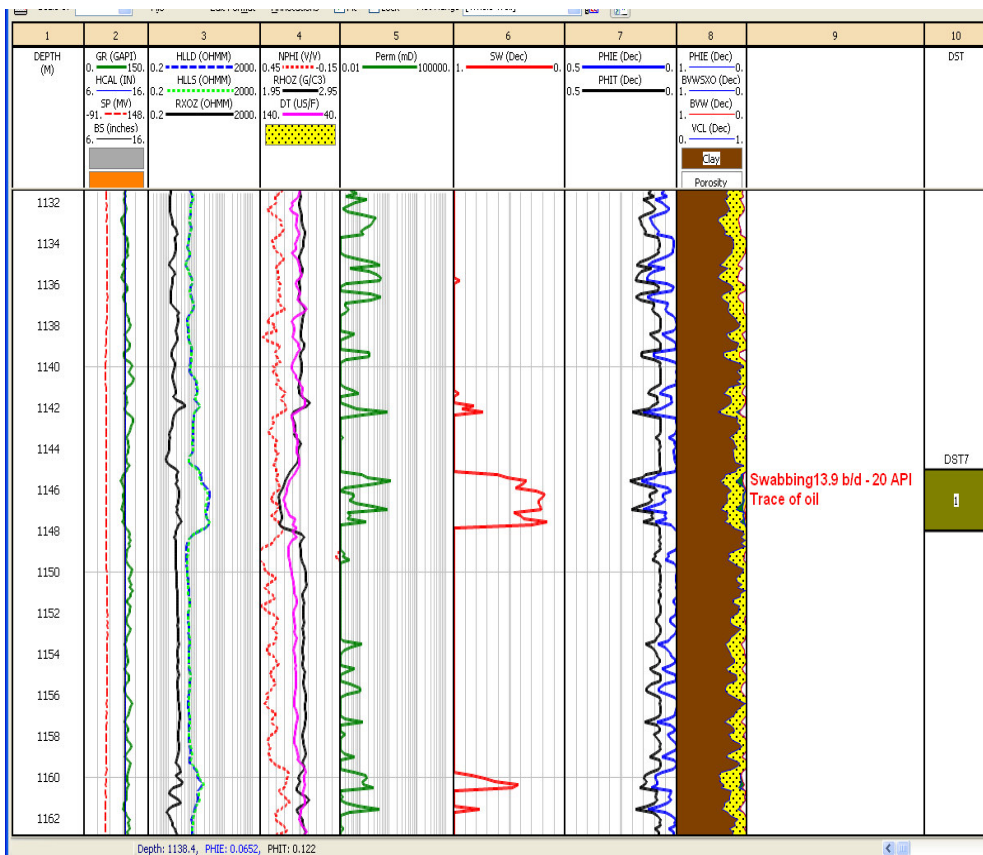


Figure 19: Tight zone (Fal-1 well)

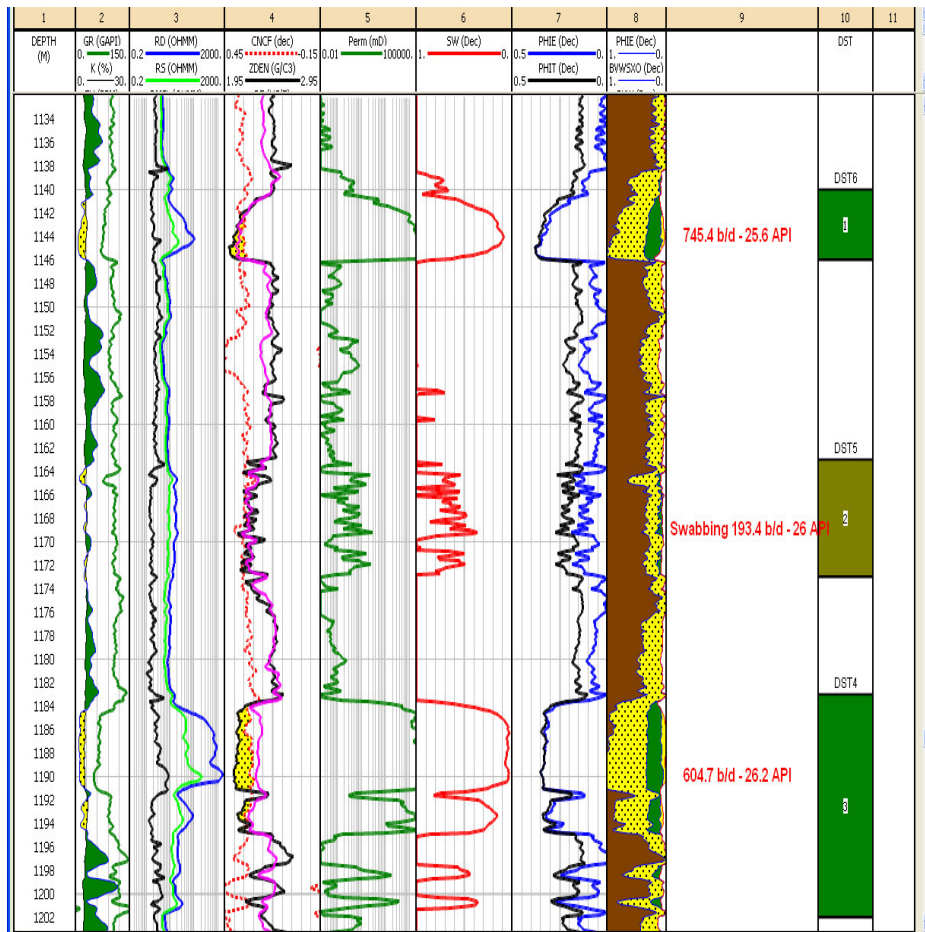


Figure 20: Good & bad quality reservoirs confirmed with DST (Fal_2)

The characteristics of high (S_o) tight zone is (S_w) < 50%, porosity is low but exceeds the lower limit of tight zone, and its mud logging shows is completely the same as that of an oil zone. The difference between the high (S_o) tight zone and oil zone is the deep and shallow resistivities are overlaid to each other, and also the crossover between the Thorium and Potassium logs. The characteristics of the low (S_o) tight zone are: fine lithology, high shale volume, low porosity and shallow mud filtrate invasion depth. On the other hand the good reservoir sandbodies deposited in high energy environment (Braided and Meandering channels). The characteristics of good reservoir quality are: coarse lithology, clean or low shale volume, high porosity, deep mud

filtrate invasion and big crossover between the Potassium and Thorium logs. Eventually, the result of this study to identify the reservoir quality from the spectral gamma ray technique and petrophysical evaluation was very good. Figure 20 shows very obvious section including good and bad quality reservoirs. The results of this study verified by the DST simulation.

Conclusions:

Comprehensive petrophysical evaluation for shaly sand reservoir in Palouge-Fal Oilfield were attempted and assessed. The results obtained using the shaly sand modeling techniques, discussed in this paper, were in better agreement with core and test data. Consequently, the methods and techniques in

the shaly sand model, presented in this paper, can be used to improve petrophysical evaluation of shaly sands.

A new method was used to identify reservoir quality by using spectral gamma ray, which gives very good results from this study. Also this method was used to investigate the production by swabbing and low flow rate despite the oil produced from such zones sometimes have high API value.

All of the evaluated shaly sand equations evaluated produced acceptable saturation results for the shaly sand reservoirs that have been part of this study as long as suitable shale parameters are selected. The success in using a given equation depends mainly on the skill of the log analyst in integrating all available information into his or her analysis as well as familiarity with the equation(s) s/he is using.

Recommendations

Currently, open hole logging data are competent for oil/water zone identification. But in order to acquire relatively accurate oil saturation, more works should be carried out, for instance:

1. Strengthen the works of shale analysis, core oil/water saturation analysis, in order to acquire the exponent for saturation calculating in conditions of various V_{sh} .
2. Run Log while Drilling (LWD) in a few wells, to compare the LWD resistivity with open hole logging resistivity, in order to analyze the difference between the two resistivity's, and how it can affect the reservoir saturation calculation, and finally to decide if the log resistivity.
3. Both Elemental Capture Spectroscopy (ECS) and Combinable Magnetic Resonance (CMR) tools are highly recommended to be used to compensate the lack of cores and give more accurate evaluation. Development and Field

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