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Department of petroleum Exploration Engineering

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Project of:

Formation Evaluation and Reservoir Characterization: case study (Jake South oilfield Block-6 Muglad Basin Sudan)

Prepared by:

- **Abdulaziz Mohammed Hajsaeed Idress**
- **BadrEldin Abdelgadir Ali Abdelgadir**
- **Osama Mohammed Ahmed Taha**
- **WalaEldin Hamdan Mohammed Mudawi**

Supervisor:

Eng. Eltayeb Adam Mohammed

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بسم الله الرحمن الرحيم

قال تعـــالى :

(ومـا أُوتِـيتُـم من العـــــلم إلا قـليلاً)

صدق الله العظيم

الإهــــداء

الى من كلت أنامله ليقدم لنا لحظة سعادة

الى من حصدوا الاشواك عن دروبنا ليمهدوا لنا طريق العلم

الى رمز الحب و بلسم الشفاء

شكر و تقدير

الى من أخلصت النية في التعليم فنورت عقولنا

و هذبت نفوسنا و ربيت اجيالاً الى السراج

الذي يحرق نفسه لينير الطريق لغيره

Abstract:

In this research, a comprehensive and integrated petrophysical analysis of a single and multi-oil wells has been interpreted using an available core data and wireline logging data with a view to characterizing the reservoir utilizing TechLog software.

Petrophysical well log and core data were integrated and analyzed of the reservoir characteristics of (Jake S-2, Jake S-34, Jake S-28 and Jake S-3) Wells, Jake oil field of Block-6, Muglad basin Sudan. The study essentially determined reservoir properties such as lithology, shale volume porosity (Φ), permeability (K), fluid saturation, net pay thickness, from well logs and cores, which are variables that determine reservoir quality. Saturation, gross rock volumes and net-to-gross ratios identified five (5) hydrocarbon-bearing zones. Average water saturation values of the net pay is above 45%, while porosity values ranged between 23-30%, reflecting well sorted coarse grained sandstone reservoirs with minimal cementation, indicating very excellent reservoir quality. Fluid types defined in the reservoirs on the basis of resistivity log signatures higher than 25-30 ohm-m in the reservoirs of Jake south field.

Core analysis for the reservoirs showed best fit with petrophysical models.

petrophysical properties of the reservoirs in Jake south Wells are enough to permit hydrocarbon prediction.

التــجريـد:

في هذا البحث تم عمل تحليل بتروفيزيائي شامل و متكامل لأبار النفط منفردة و متعددة و تم التفسير باستخدام عينات اللب الصخري و بيانات تسجيلات الابأر و عرض البيانات باستخدام برنامج (TechLog) .

بيانات تسجيلات الابار و اللب الصخري كانت لاربع أبار (Jake S-2, Jake S-34, Jake S-28 and Jake S-3**) في حقل (Jake South) مربع (6).**

الدراسات والتحاليل تم اجراءها لتعيين خواص النفط مثل النفاذية, المسامية, التشبع وسمك الطبقات الخازنة و ذلك لعدد خمس طبقات موضحة ل لمعرفة جودة المكمن

من القياسات وجدنا ان نسبة تشبع المكمن بالماء حوالي 45% والمسامية بين 23-30 % و نسيج الحبيبات خشن نسبيا.

تم التنبوء بنوع المائع داخل المكمن اعتمادا على بيانات تسجيل المقاومية التي سجلت بين 25-30 (اوم.متر) لحقل (Jake South) .

تحاليل عينات اللب الصخري اظهرت افضل تماثل مع النماذج البتروفيزيائية .

الخواص البتروفيزيائية في المكمن لأبار الحقل كافية لتوقع الهيدروكربون.

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Chapter 1

Introduction

1.1 The Formation Evaluation and Reservoirs Characterizations Challenges:

Formation Evaluation has been identified as the process of interpreting a combination of measurements taken inside a wellbore to detect and quantify oil and gas reserves in the rock adjacent to the well. Formation evaluation data can be gathered with wireline logging instruments or logging-while-drilling tools. Study of the physical properties of rocks and the fluids contained within them.

The researcher has specified that the presence of clay particles or shale within the sand is a parameter which must be considered in the evaluation of a clastic reservoir. Since, both formation characteristic and logging tool response can be affected by the existed shaliness in the sand formation. on the other hand, limestone and dolomite are the characterization of carbonates, non-clastic reservoirs and their importance should not be under estimated as reservoirs rocks. In addition, the chemical nature of matrix and pore fluids primarily impact on the response of well logging tools. Any porous network is related to its host rock fabric, therefore petrophysical parameter, such as porosity (φ), permeability (K) and saturation (S), for any given (type of rock) are controlled by pore sizes and their distribution and interconnection. In order to predict the spatial distribution of such petrophysical parameter on a field scale, the reservoir characteristics must be studied. The interpretation of reservoir geophysics observation, petrophysics' theory and rock physics data should be analyzed carefully and purposefully.

Petrophysical evaluation has been identified as the continuing process of integrating and interpreting geological, petrophysical, fluid and performance data of a reservoir sand body to form a unified, consistent description of reservoir properties throughout the field. Furthermore, the quality, quantity, recoverability of hydrocarbon in a reservoir can be determined by applying petrophysical evaluation within the rock proportion of the reservoir. Therefore, the potential and performance of a reservoir include porosity, permeability and fluid saturation which are fundamental parameters of a reservoir that has the capacity to store fluid and the ability to release and flow in it. A reservoir can be evaluated and identified by knowing the relationships among these properties. Moreover, shaliness which is a measure of the cleanliness of the reservoir is a parameter to be considered in the evaluation of clastic reservoirs as it can give a wrong impression of estimated petrophysical values, such as: porosity and hydrocarbon saturation when they are not corrected for **(Hawez, et al, 2000).**

1.2 The Study area:

Jake Oilfield is lying on the Western Escarpment of Fula Sub-basin in Muglad Basin. It has been structurally subdivided into three main structures which are Jake, Jake Central and Jake South.

The target study is Jake south structure. Figure (1.1).

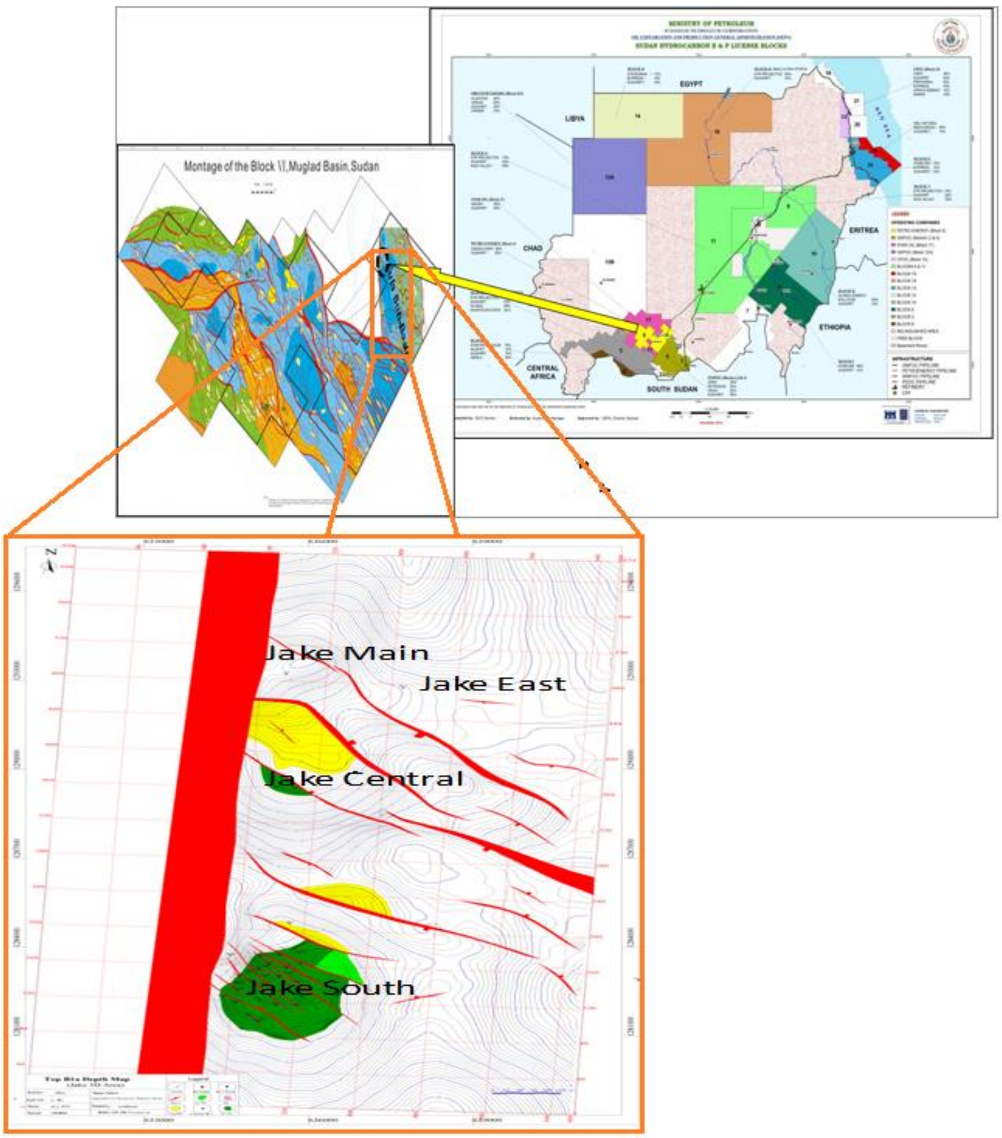


Figure (1.1): location map of Jake oilfield in Fula Sub-Basin. Block-6 of Sudan.

1.3 Objectives of the Study:

The aim of this study is to integrate petrophysical log data with core data to qualify and quantify reservoirs in order

to identify an accurate reservoir property. The objectives include:

- Determination of reservoir depth and thicknesses in the well.
- Knowing the lithology through the identification of sand units from chosen top sand to the last hydrocarbon bearing sand, using Gamma Ray and density neutron Logs.
- Build a petrophysical model for clay volume, porosity, permeability, and water saturation based on log curves and core data.
- Comparison of the petrophysical log data with the core data.
- Estimate electrical properties (a, m, n).
- Establish the porosity-permeability relationship from the core data.
- Shift the core data relative to logs.
- Provide single and multi-wells analysis.

1.4 Motivation of the Study:

Single and multi-wells interpretations carried out in this study, for better reservoirs descriptions and accurate parameters selection.

1.5 Data available:

The study was initiated with the collection of data out of four wells to perform detailed formation evaluation and reservoirs characterization of Jake South oil-field with total 31 drilled wells.

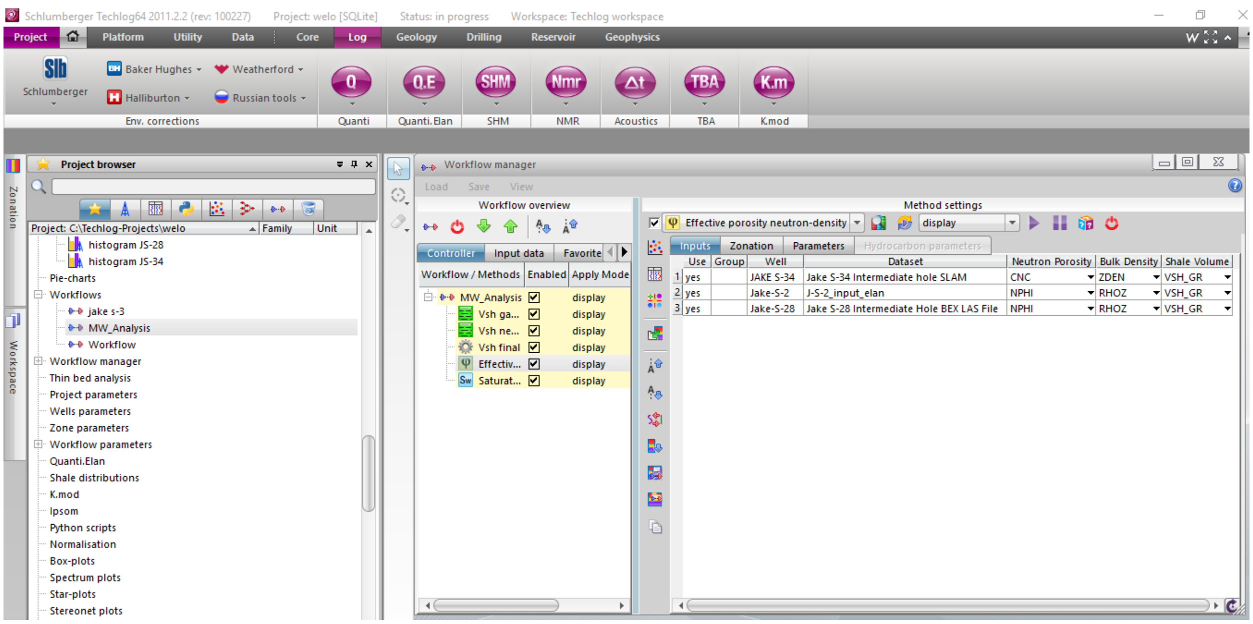
The core data of Jake S-2 and Jake S-34 used as reference in this study, and a part of core data quality of Jake S-3 not valid to be used in this study.

Totally 4 drilled wells with full set of the logging data integrated with available core to provide the formation evaluation and characteristic of Bentiu Formation.

Table (1.1): available data used

Well name	Core data	Well logs
Jake South-2	Available	GR,SP,Caliber,Bit,Resisitivity,Density,Neutron
Jake South-3	Not Valid	GR,SP,Caliber,Bit,Resisitivity,Density,Neutron
Jake South-28	Not Available	GR,SP,Caliber,Bit,Resisitivity,Density,Neutron
Jake South-34	Available	GR,SP,Caliber,Bit,Resisitivity,Density,Neutron

1.6 TechLog software for logging analysis:



Quanti is an ensemble of solutions for conventional log interpretation. It includes tools to help you with precomputations, creating flag curves, determining the standard petrophysical properties, and developing summaries.

Quanti uses our Application Workflow Interface (AWI), a generic tool that allows you to work in a multi-well and multi-zone environment, while controlling your parameters in an efficient manner.

The ensemble of tools offered in the AWI will help you analyse data.

The program own equations and applications using PythonTM and integrate them into the workflow.

The sample workflows are composed of several computational methods. In each method, you are introduced to new tools and concepts. Most of the processes, best practices and other instructions are applicable to all Quanti computational methods. The dataset required for this process contains the following curves - calliper, gamma ray, neutron, density and resistivity. Before beginning the processing, verify that these curves have been assigned to family and a unit.

Chapter 2

2.1 Geological characteristics of reservoir:

2.1.1 Formation characteristics:

For Jake-S Oilfield, from bottom to top, the formations are: Sharaf, Abu Gabra, Bentiu, Aradeiba, Zarqa, Ghazal, Baraka, Amal, Tendi/Senna, Adok and Zeraf.

Aradeiba：Lithology is thick mudstone and sandstone interbed; Bentiu: lithology is massive sandstone with mudstone.

The target of this study is Bentiu and it can be classified as 6 sands and 12 sublayers

(see Table 2.1).

Table (2.1) Numbers of sands and sublayers

Horizon	Sand formations	Number of sublayer
Bentiu	B1a	B1a-1,B1a-2,B1a-3
	B1b	B1b-1,B1b-2,B1b-3,B1b-4
	B1c	B1c-1,B1c-2
	B1d	B1d
	B2	B2
	B3	B3

2.1.2 Characteristics of structure:

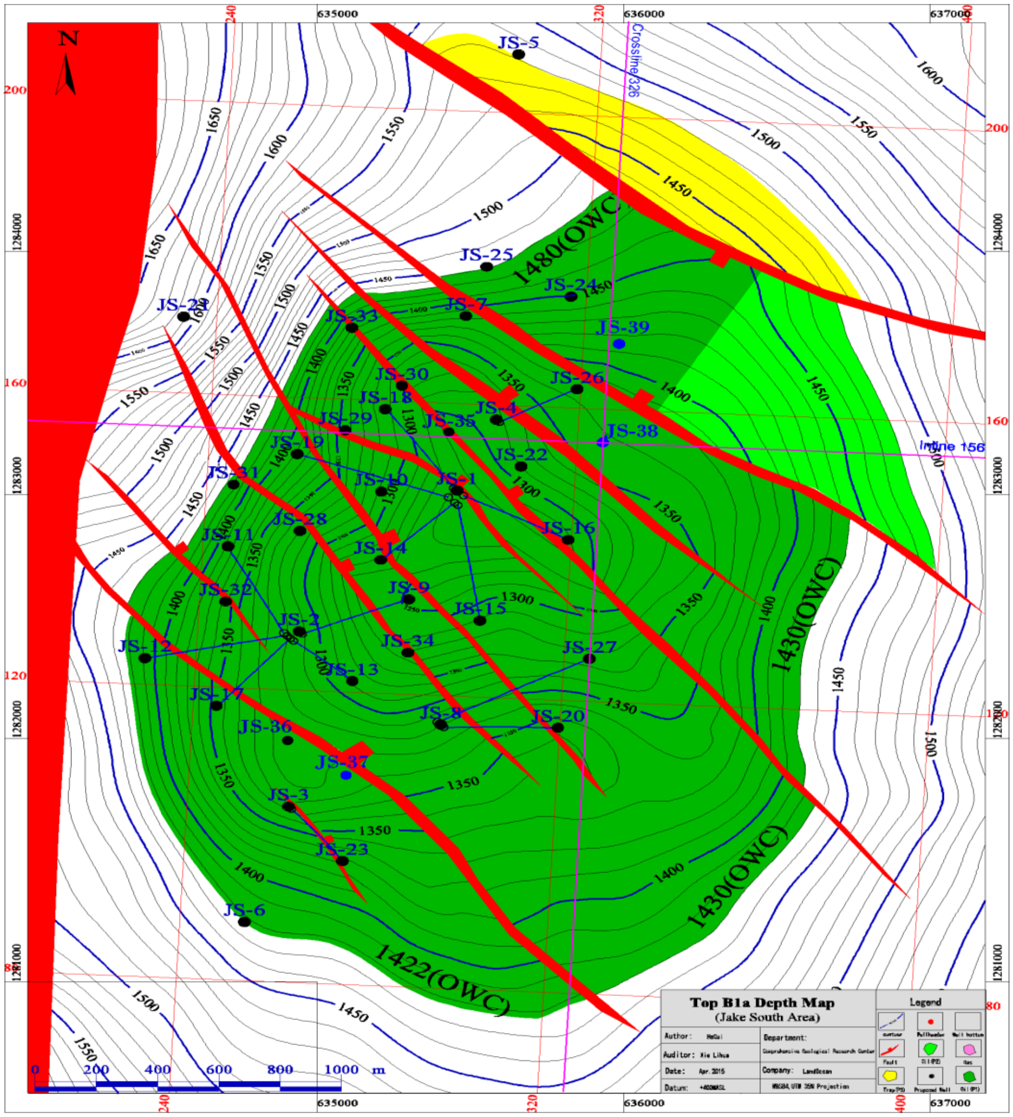


Figure (2.1) Structure map of Jake South Oilfield

Jake South Oilfield is located in the southeast of the Fula depression. Fula depression represents strike of SN with Fula East fault being east boundary and controlled by Fula West fault in the west. Jake South structure is located in the south of the Jake 3D survey and is fault anticline structure cut by cluster of small faults with strike of WN.

2.1.3 Sedimentary Characteristics:

Bentiu formation is a set of sediment of braided river to meandering river and the channel is filled with fine to coarse crystalline particles of medium grading. The formation is composed of sandstone tending to be finer upward with local stratum of glutinite, representing cross bedding in shapes of trough and plane and parallel bedding, massive appearance and local structure of deformation. The sedimentary setting is flood plain. Based on the analysis of the subsurface facies, the Bentiu formation can be further divided into 3 sections of lower, middle and upper and each section features different characteristics of facies assemblage and different sedimentary modes. The sandstone facies crisscrosses large scale horizontal bedded sandstone from trough and plane. The fine crystalline phase comprises large amount of sandstone and mudstone facies of ripple fine sandstone layer, which indicates that the association of the sedimentary facies is the setting of channel, sand bar, river shoal and constructional plain.

2.1.4 Physical property of reservoir:

2.1.4.1 Lithology:

Bentiu formation is composed of massive medium and coarse quartz sandstone with multiple thin mudstones in thick layers. The thickness of formation is 380～487 m and can be divided into three sections of upper, middle and lower with fairly thick massive gray mudstone interbed in between. Based on the comprehensive geological analysis of the work area and the neighboring oilfield, the oil layers are mainly distributed in the upper section (B1) of the Bentiu formation. Mainly lithology analysis is conducted for Bentiu 1, which is composed of sandstone of small scale interbed of mudstone and shale. The data of the rock samples of wells of JS-2，JS-3 indicate that the sandstone is mainly secondary Arcose of light gray color in unconsolidated and weak cementation pattern with distribution from aleurolite to conglomerate, but mainly is fairly coarse cross bedding sandstone with gravels. The median size is 0.128mm and the grading of sandstone is from bad to good, but in general, worse than Aradeiba formation. Kaolinite is main cementing material and is dominated by point contact between particles. The type of pore is dominated by primary pore and the selection of pore throat is not very good, being 0～400μm. The content and distribution characteristics of the authigenic mineral are the same as that of the sandstone of Aradeiba formation.

2.1.4.2 Pore structure of reservoir:

The pores of reservoir are dominated by intergranular pores with intergranular pores locally. The main of the intergranular pores is the pores partially dissolved by potassic feldspar and the secondary intergranular pores featuring excellent internal connectivity. Autogenic quartz features auxiliary characteristics of being thin and discontinuous because quartz is dyscrystalline (poorly crystallized). Kaolinite represents characteristics of crystal association with curly and short vermicular minute pore-filling, therefore, there is little authigenic mineral in the pore structures. The pore structure is mainly composed of medium heterogeneity, large to small and secondary medium to small pore throats.

2.1.4.3 Reservoir characteristics:

Via core analysis, the porosity is 23%～30%，average is 26.5%. The reservoir is of middle and high porosity and high permeability. The diagenesis of the rock is weak, featuring unconsolidated cementing of sandstone and good physical property.

It can be seen from the result of logging interpretation that the top (shale) of Bentiu is shown as high density, relatively high acoustic travel time, high neutron, low resistivity and high gamma ray; in contrast with shale, the reservoir represents low density, relatively small acoustic travel time, low neutron, high resistivity, low gamma ray and obvious abnormal spontaneous potential in oil zone. There is good shale barrier from top to bottom for the reservoir. The quality of sand on top section of Bentiu is good.

2.2 Theoretical Background:

2.2.1 Well logging:

Well logging, also known as borehole logging is the practice of making a detailed record (a well log) of the geologic formations penetrated by a borehole. The log may be based either on visual inspection of samples brought to the surface (geological logs) or on physical measurements made by instruments lowered into the hole (geophysical logs). Some types of geophysical well logs can be done during any phase of a well's history: drilling, completing, producing, or abandoning. Well logging is performed in boreholes drilled for the oil and gas, groundwater, mineral and geothermal exploration, as well as part of environmental and geotechnical studies.

The oil and gas industry uses wireline logging to obtain a continuous record of a formation's rock properties. Wireline logging can be defined as being "The acquisition and analysis of geophysical data performed as a function of well bore depth, together with the provision of related services.

Wireline logging is performed by lowering a 'logging tool' - or a string of one or more instruments - on the end of a wireline into an oil well (or borehole) and recording petrophysical properties using a variety of sensors**. (Harald Bolt, 2012).**

2.2.1.1 Electrical logs:

2.2.1.1.1 Resistivity log:

Resistivity logging measures the subsurface electrical resistivity, which is the ability to impede the flow of electric current. This helps to differentiate between formations filled with salty waters (good conductors of electricity) and those filled with hydrocarbons (poor conductors of electricity). Resistivity and porosity measurements are used to calculate water saturation. Resistivity is expressed in ohms or ohms/meter, and is frequently charted on a logarithm scale versus depth because of the large range of resistivity. The distance from the borehole penetrated by the current varies with the tool, from a few centimeters to one meter. **(Harald Bolt, 2012).**

2.2.1.2 Porosity logs:

Porosity logs measure the fraction or percentage of pore volume in a volume of rock. Most porosity logs use either acoustic or nuclear technology. Acoustic logs measure characteristics of sound waves propagated through the well-bore environment. Nuclear logs utilize nuclear reactions that take place in the downhole logging instrument or in the formation. Nuclear logs include density logs and neutron logs**. (Sengel, E, 1981).**

2.2.1.2.1 Density:

The density log measures the bulk density of a formation by bombarding it with a radioactive source and measuring the resulting gamma ray count after the effects of Compton Scattering and Photoelectric absorption. This bulk density can then be used to determine porosity.

2.2.1.2.2 Neutron porosity:

The neutron porosity log works by bombarding a formation with high energy epithermal neutrons that lose energy through elastic scattering to near thermal levels before being absorbed by the nuclei of the formation atoms. Depending on the particular type of neutron logging tool, either the gamma ray of capture, scattered thermal neutrons or scattered, higher energy epithermal neutrons are detected. The neutron porosity log is predominantly sensitive to the quantity of hydrogen atoms in a particular formation, which generally corresponds to rock porosity. **(Schlumberger Oilfield Glossary).**

2.2.1.3 Lithology logs:

2.2.1.3.1 Gamma ray:

A log of the natural radioactivity of the formation along the borehole, measured in API units, particularly useful for distinguishing between sands and shales in a siliclastic environment. This is because sandstones are usually nonradioactive quartz, whereas shales are naturally radioactive due to potassium isotopes in clays, and adsorbed uranium and thorium. **(Darling, 2005).**

2.2.1.3.2 Self/spontaneous potential:

The Spontaneous Potential (SP) log measures the natural or spontaneous potential difference between the borehole and the surface, without any applied current. It was one of the first wireline logs to be developed, found when a single potential electrode was lowered into a well and a potential was measured relative to a fixed reference electrode at the surface.

2.2.1.4 Miscellaneous:

2.2.1.4.1 Caliper:

A tool that measures the diameter of the borehole, using either 2 or 4 arms. It can be used to detect regions where the borehole walls are compromised and the well logs may be less reliable. **(Harald Bolt, 2012).**

2.2.2 Coring:

Coring is the process of obtaining an actual sample of a rock formation from the borehole. There are two main types of coring: 'full coring', in which a sample of rock is obtained using a specialized drill-bit as the borehole is first penetrating the formation and 'sidewall coring', in which multiple samples are obtained from the side of the borehole after it has penetrated through a formation. The main advantage of sidewall coring over full coring are that it is cheaper (drilling doesn't have to be stopped) and multiple samples can be easily acquired, with the main disadvantages being that there can be uncertainty in the depth at which the sample was acquired and the tool can fail to acquire the sample. (**Schlumberger Oilfield Glossary. Core).**

2.3 Literature review:

They have done a Petrophysical Data Correlation in which Extensive efforts were made to integrate and correlate the core and well log data for Womack Hill Field. In summary, the porosity was determined from well logs may be corrupt, or at least the vintage of the well logs used to estimate porosity may not be properly calibrated — no consistent correlations of well log porosity and core porosity were found. The reservoir permeability was elected to be correlated with core porosity, Gamma Ray well log response, and one of the resistivity log responses. They have found it was an exercise in correlation since a prediction would require core porosity (or an accurate surrogate). **(J.C. Avila, et al, 2002).**

Petrophysical well log and core data were integrated in an analysis of the reservoir characteristics of Uzek Well, Offshore Depobelt, Niger Delta Basin, Nigeria. Their goal was to integrate petrophysical log data with core data to qualify and quantify reservoirs in order to assess the production potential of Uzek Well. it was located in the offshore depobelt of the Niger Delta Basin, where thick Late Cenozoic Clastic sequence of Agbada Formation were deposited in a deltaic fluvial-marine environment**. (Adaeze, and et al ,2012).**

The development of petrophysical models for unconventional reservoir porosity and permeability estimation was accomplished by using conventional well logs. And the comparison of computed porosity from well logs was derived from the proposed approach with core porosity, the density model achieved the best match, density-sonic model achieved fair to good result, and single sonic log model indicated reasonable porosity estimates. Leading to present the petrophysical models and demonstrate the method for porosity and permeability calculations from conventional logs of the middle Bakken reservoir in North Dakota. **(Kezhen Hu, et al, 2015).**

Their work has been done for a single oil well based on the use of wireline logs and core data from the well to identify and quantify hydrocarbon reserves and evaluate rock properties in the subsurface. The petrophysical analysis with wireline logs provides reservoir qualities (porosity, permeability, and fluid saturation), which were integrated with other data provided a guide and enhanced exploration and development of the reservoir sand bodies. Each sequence was being sub-divided into smaller sediment packages called systems tracts on the basis of characteristic well-log patterns Sequence analysis and system tract. The petrophysical analysis and integration was used to predict the environment of deposition and this was related to the petrophysics value obtained. They recommend that analysis of core and wireline log data must be checked after depth matching. **(Hawez, and et al ,2016).**

Chapter 3

3.1 Methods, Analysis and Workflow:

In this study, a comprehensive workflow adopted for petrophysical analysis of a single and multi-oil wells (Jake S-2, Jake S-34, Jake S-28 and Jake S-3) using an available core data and wireline logging data with a view to characterizing the reservoir. In addition, petrophysical analysis initiated with lithology identification and lithological panels interpreted from well log data show that the study area is characterized by massive sand.

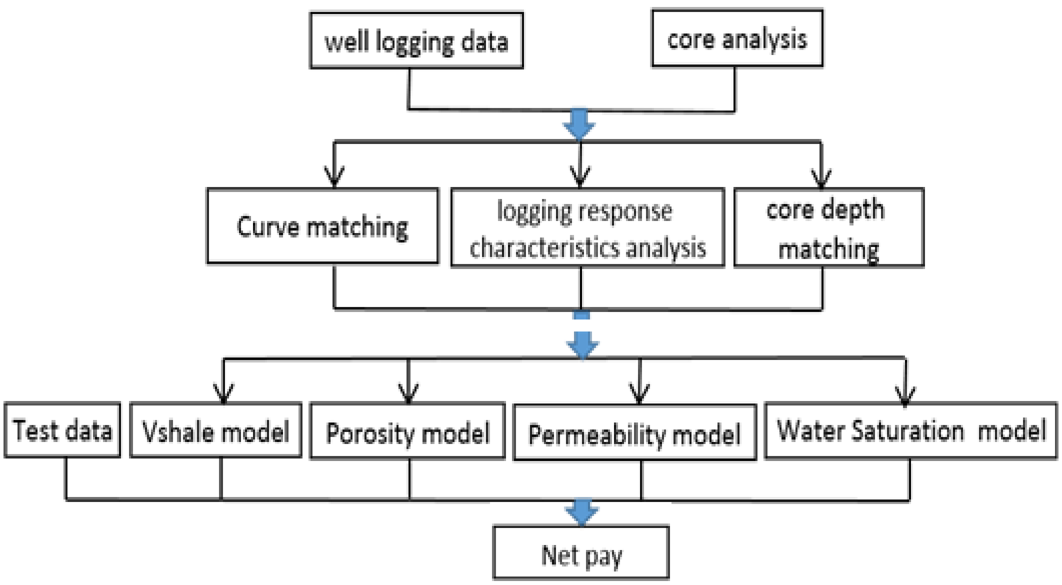


Figure (3.1): methods and analysis workflow

3.2 log data QC:

Log data pre-processing is the basis of formation evaluation. It includes the following work scope:

- Loading all the log data and core data.
- Validating all the logs are normal.
- Aligning depth among logs in each well.
- SP and Caliper logs as quality indicator.

3.3 log analysis:

3.3.1 Gamma Ray Analysis Method:

The minimum of gamma ray was used to compute shale volume as shown in equation 1.

$$VCL = \frac{GR_{log} - GR_{min}}{GR_{max} - GR_{min}} \quad (3.1).$$

Where,

VCL =Volume of Clay.

GR_{log} = Gamma Ray Log reading of formation.

GR_{min} = Gamma Ray Matrix (Clay free zone).

GR_{max} = Gamma Ray Shale (100% Clay zone).

3.3.2 Density and Neutron Porosity:

Total porosity was calculated from density-neutron log as shown in the following relationship:

$$\Phi = \frac{\rho ma - \rho b}{\rho ma - \rho f} \quad (3.2).$$

Where,

Φ=porosity derived from density log.

ρma =matrix (or grain) density.

ρb = bulk density (as measured by the tool and hence includes porosity and grain density).

ρf = fluid density.

Effective porosity was estimated according to equation (3.3).

$$\Phi e = \frac{\rho ma - \rho b}{\rho ma - \rho f} - VCL \times \frac{\rho ma - \rho sh}{\rho ma - \rho f} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(3.3).$$

Where,

Φe = Effective porosity.

ρsh = Density of shale.

ρf = fluid density.

ρma =matrix (or grain) density

$$\text{Clay Bound Water} = VCL \times \frac{\rho ma - \rho sh}{\rho ma - \rho f} \quad \ldots\ldots\ldots\ldots\ldots\ldots(3.4).$$

(ρma = 2.65g/cc, ρf = 1.0g/cc, ρsh = 2.6g/cc).

3.3.3 Resistivity and Formation water (RW) Analysis:

There are various methods in determining formation water resistivity (RW)

Including the following:

3.3.3.1 Pickett plot:

The purpose of the Pickett plot is to help to determine Rw using a double logarithmic plot of a resistivity measurement (on the X axis) versus a porosity measurement (on the Y axis).

In addition to the points that have appeared after the selection of the well(s), four lines are also present in the Cross-plot figure (3.5). These lines correspond to the water saturations for different resistivity values. The four lines correspond to a water saturation from bottom to top of 100 %, 75 %, 50 % and 25 %. The slope of these lines is - m and the intersection of the 100 % SW line with the porosity axis is a * Rw.

When these parameters are adjusted, the positions of the lines will change until a satisfactory result is reached.

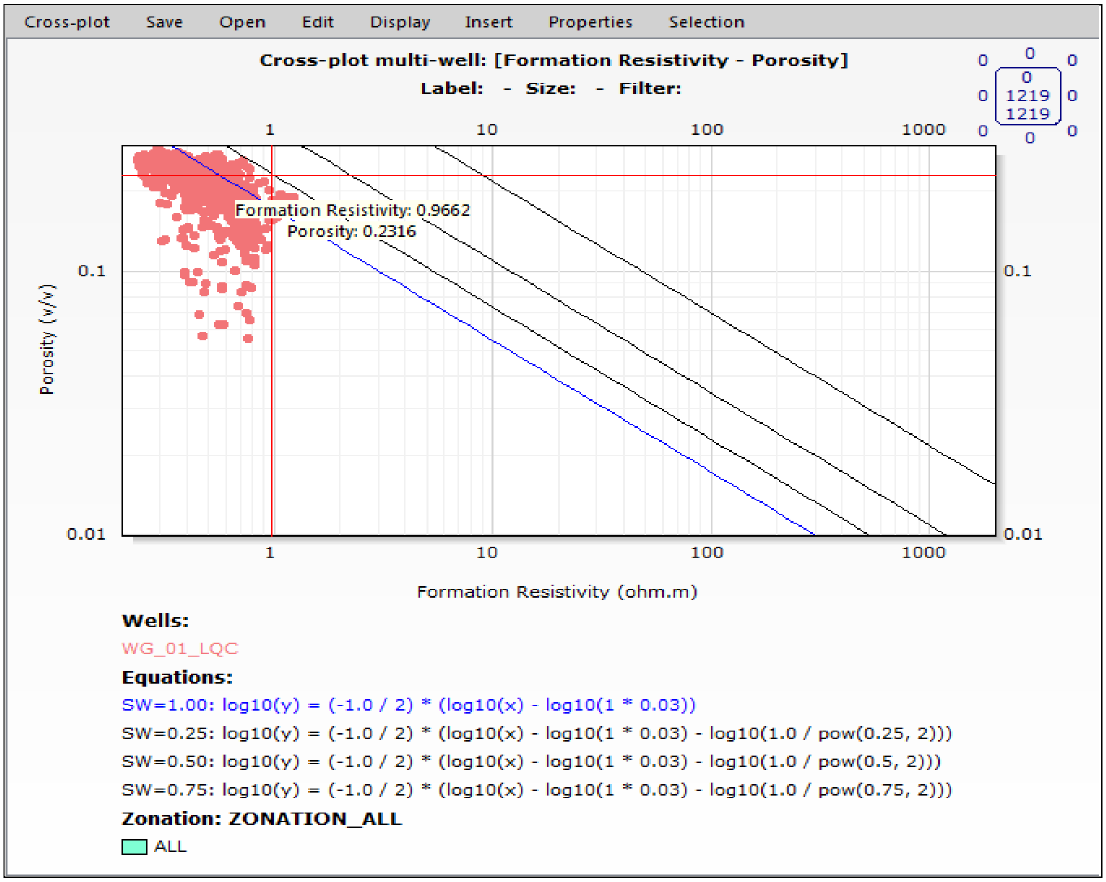


Figure (3.5): Picked plot for Jake S-2 RW determination

At the bottom of the Cross-plot, the equations of each line are given and are updated when one or several parameters are modified.

Note: a zonation can be used to reduce the points displayed in the Cross-plot to a specific zone only.

A left click on a saturation line in the Cross-plot activates the property window. In this window, in properties, the user can modify the appearance of the line (color, thickness of the line ...), see window below.

In the "Information" tab, the user can modify the name of the line and access to the equation (which is in read only).

3.3.4 Water saturation methods:

Archie Equation was used to calculate the water saturation as shown in equation (3.5), and the Indonesian Equation was used to calculate the effective water saturation as shown in equation (3.6),

$$Sw = \sqrt[n]{\frac{a.Rw}{\phi^{m}.Rt}} \quad \ldots\ldots(3.5).$$

$$Swe = \sqrt[n]{\frac{1}{\left(\frac{Vcl^{2}}{Rtcl} + \frac{\Phi em}{a.Rw}\right) \times Rt}} \quad \ldots\ldots (3.6).$$

Where,

Rt = Deep Resistivity.

Rtcl = Deep resistivity in clay (read from log).

Swe = Effective water saturation.

VCL =Volume of Clay.

Rw = Down hole water resistivity.

Φ = Effective porosity.

Sw = water saturation.

a = Archie's exponent.

m = cementation factor.

n = Saturation exponent, it is the gradient of the line defined on the plot.

3.4 Core Data Analysis:

3.4.1 Core Porosity Analysis:

The core data was used to establish the range of Porosity for Bentiu formation.

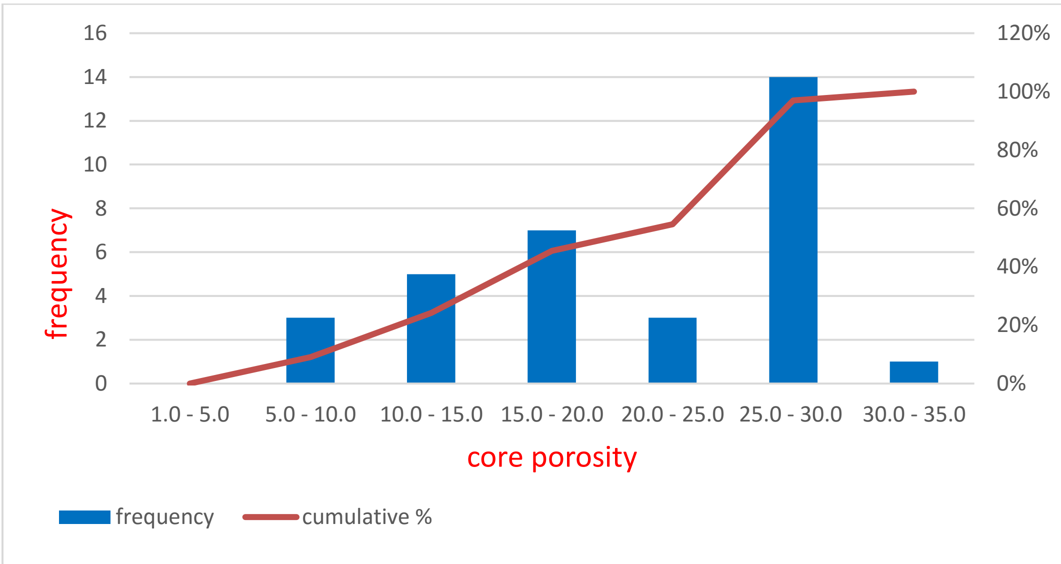


Figure (3.6): Wells Jake S-2 Bentiu: The main range of core porosity is 24 - 30%.

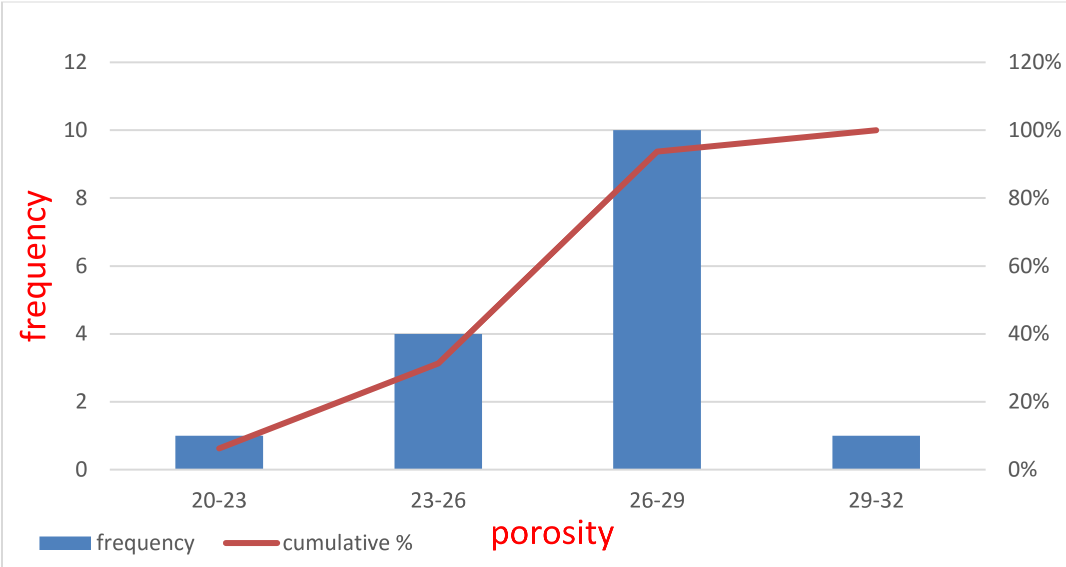


Figure (3.7): Wells Jake S-34, Bentiu: The main range of core porosity is 23 - 29%.

3.4.2 Core Permeability Analysis:

The core data was next used to establish the range of Permeability for Bentiu formation.

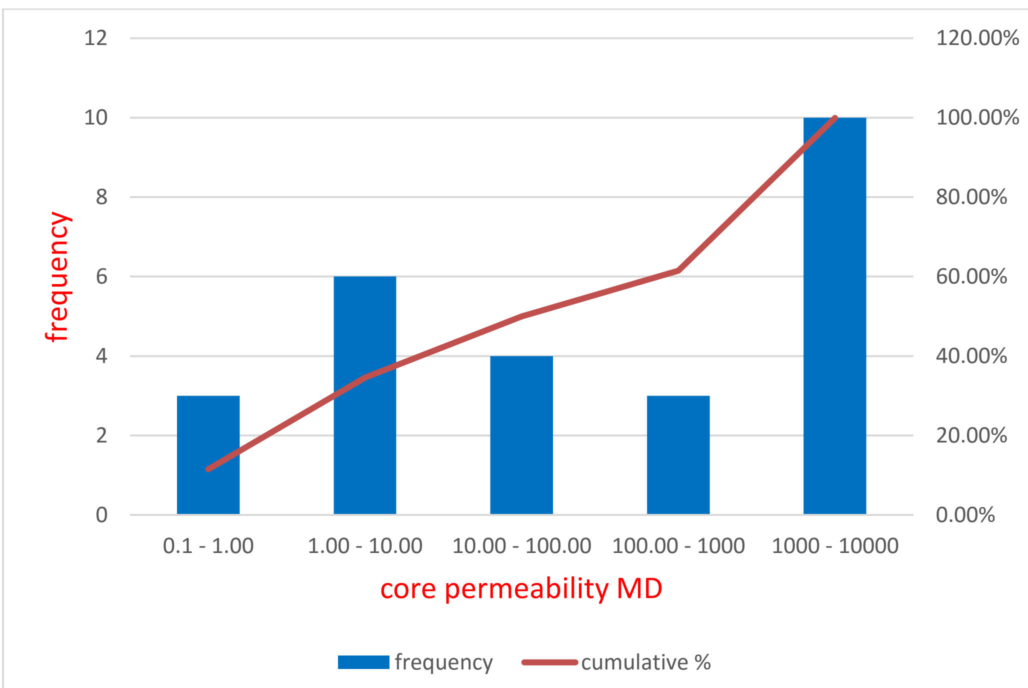


Figure (3.8): Wells Jake S-2 Bentiu formation: The main range of core permeability is 1.0 – 10000 MD.

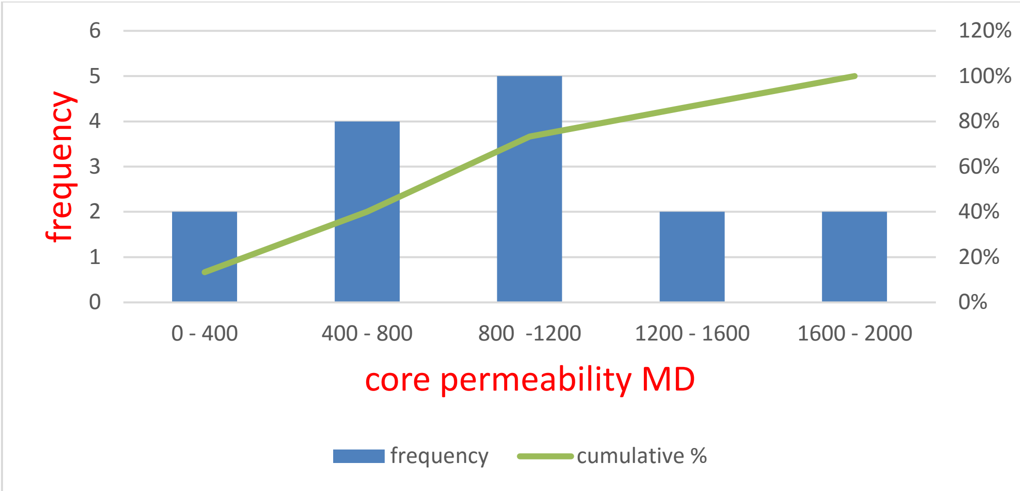


Figure (3.9): Wells Jake S-34 Bentiu formation: The main range of core permeability is 400 – 1200 MD.

3.4.3 Core Grain Density Analysis:

The range of grain densities were established for Bentiu formation.

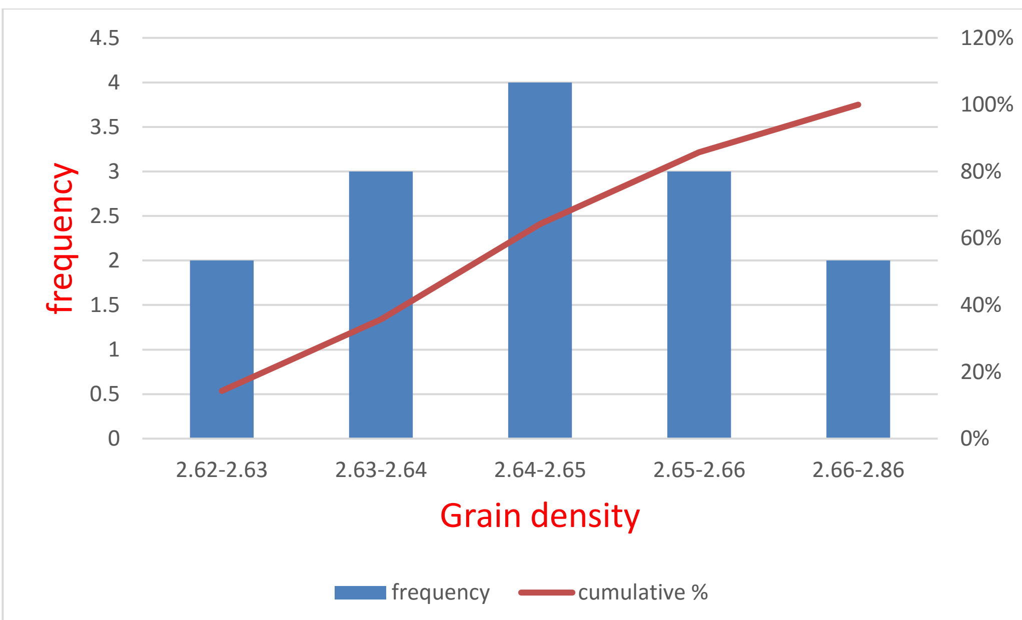


Figure (3.10): Wells Jake S-2 Bentiu: The main range of grain densities is 2.647 g/cm3.

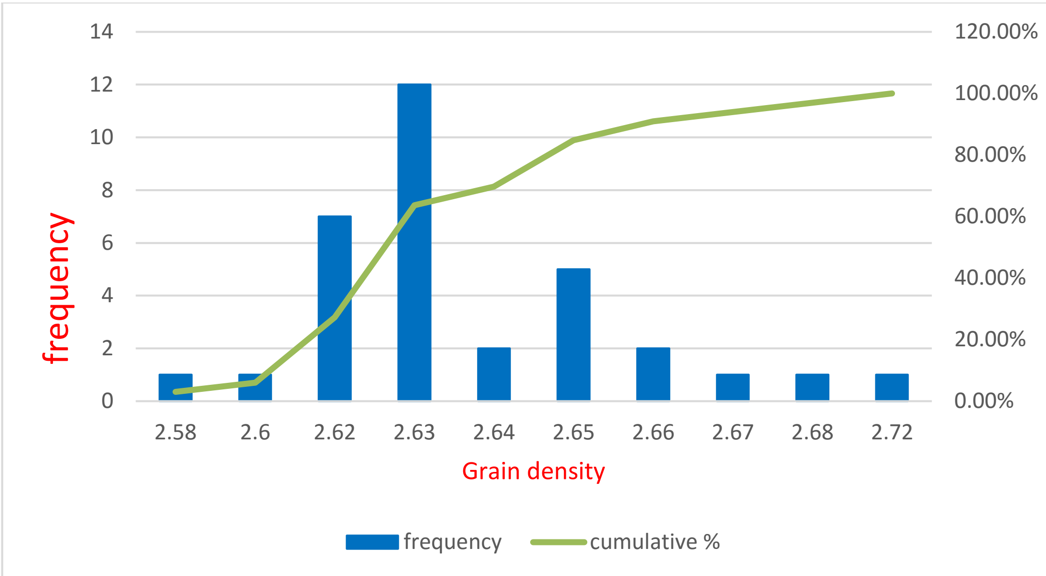


Figure (3.11): Wells Jake S-34, Bentiu: The main range of grain densities is 2.63 g/cm3.

3.4.4 Core Porosity and Overburden Pressure Relationship:

Data collected from six samples of Bentiu formation wells Jake S-2 and Jake S-3, the analysis indicate that the porosity decreases as the overburden pressure increases.

Table (3-1): Helium Porosity versus Overburden Pressure.

Well	Sample No.	Depth (meter)	Gas Permeability (md)	Overburden Pressure	400	1000	1500	2000	2725	2988
Jake S-2	4	1450.47	1873.9	Helium Porosity (%)	25.43	25.25	25.04	24.9	24.56	24.56
	9	1451.65	1729.6		26.77	26.58	26.43	26.31	26.08	26.07
	21	1454.64	813.3		20.38	20.24	20.1	20.1	19.96	19.96
Jake S-3	2	1448.27	90.8		24.22	24.22	23.9	23.24	22.99	22.9
	27	1455.1	1187.3		24.51	24.28	23.94	23.7	23.59	23.47
	30	1455.79	424.5		24.48	24.18	23.88	23.58	23.12	22.97

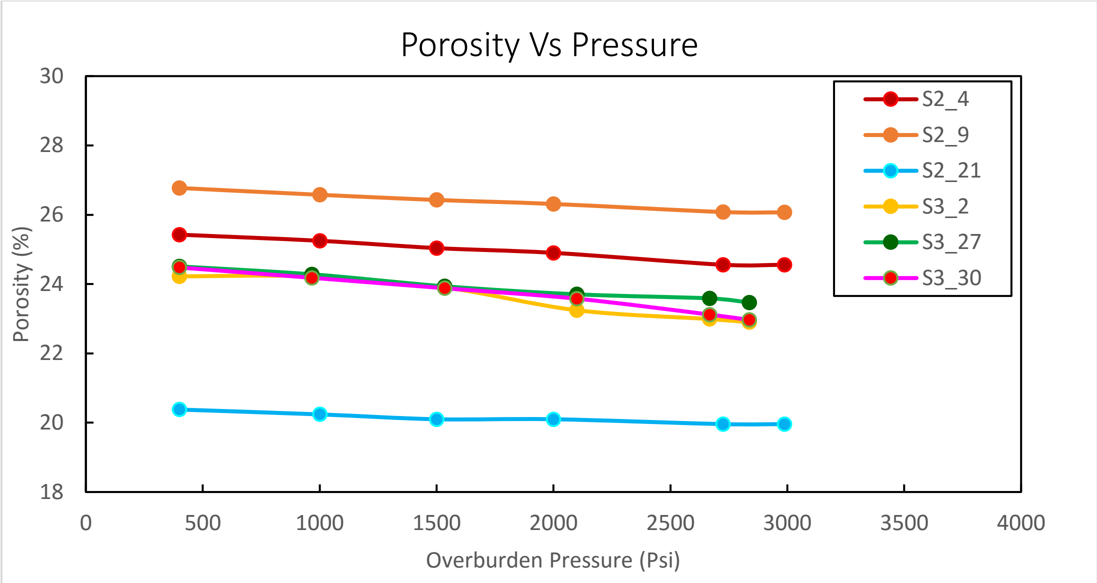


Figure (3.12): Porosity vs. Pressure, Bentiu Formation.

3.4.5 Porosity and Permeability Core Analysis Method:

The permeability was calculated based on the relationship with porosity from core data. Only the values from clean sands were plotted and use to generate a best-fit the equation. For the Bentiu formation data from core samples from wells Jake S-2 and Jake S-34 were used.

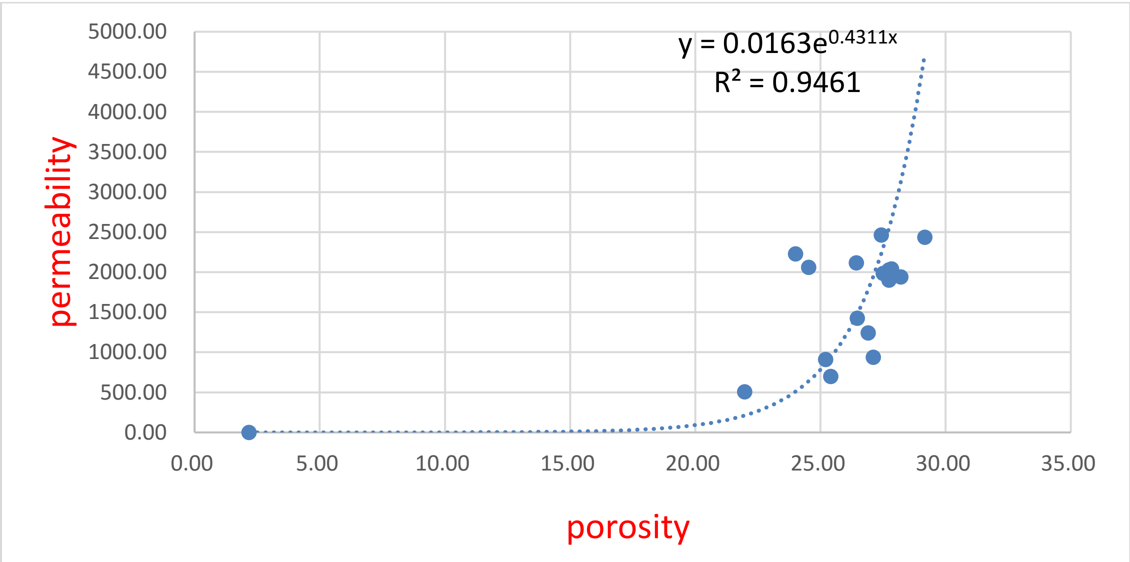


Figure (3.13): Jake S-2 Porosity vs. Permeability – Bentiu Formation.

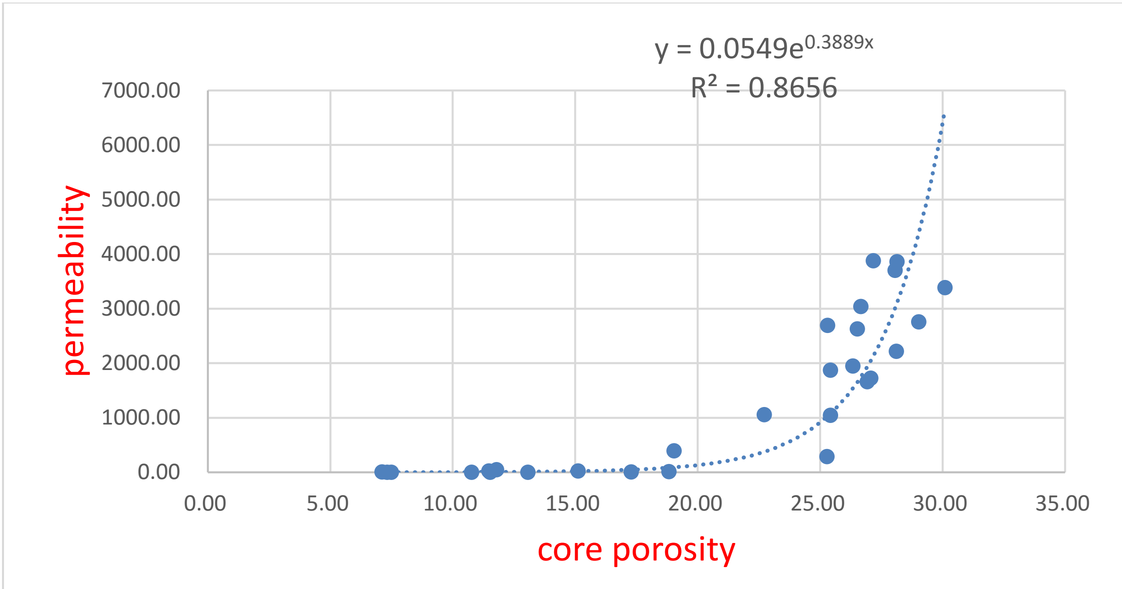


Figure (3.14): Jake S-34 Porosity vs. Permeability – Bentiu Formation.

CHAPTER 4

4.1 Logging Interpretation Results:

Appropriate logs have been used to interpret the reservoir for their, shale volume, porosity, permeability and fluid content. The lithology identified, furthermore the reservoir parameters verified to build the petrophysical models. The core data are relatively collated to wireline data to assess and survey the reservoir rock petrophysical properties.

The interpretation sequence performed with target zones (B1a-1, B1a-2, B1a-3, B1b-1, B1b-2) as the following:

4.1.1 Single well interpretation:

The logs QC investigated and corrected if required, after loading the las file to the software and display the logs (figures 4.1), moreover the zonation loaded and the minimum and maximum GR, density and neutron identified by histogram and cross plot respectively. The uncertainties regarding the reservoir parameters selection for single well it is only around the borehole not represent 3D reservoirs.

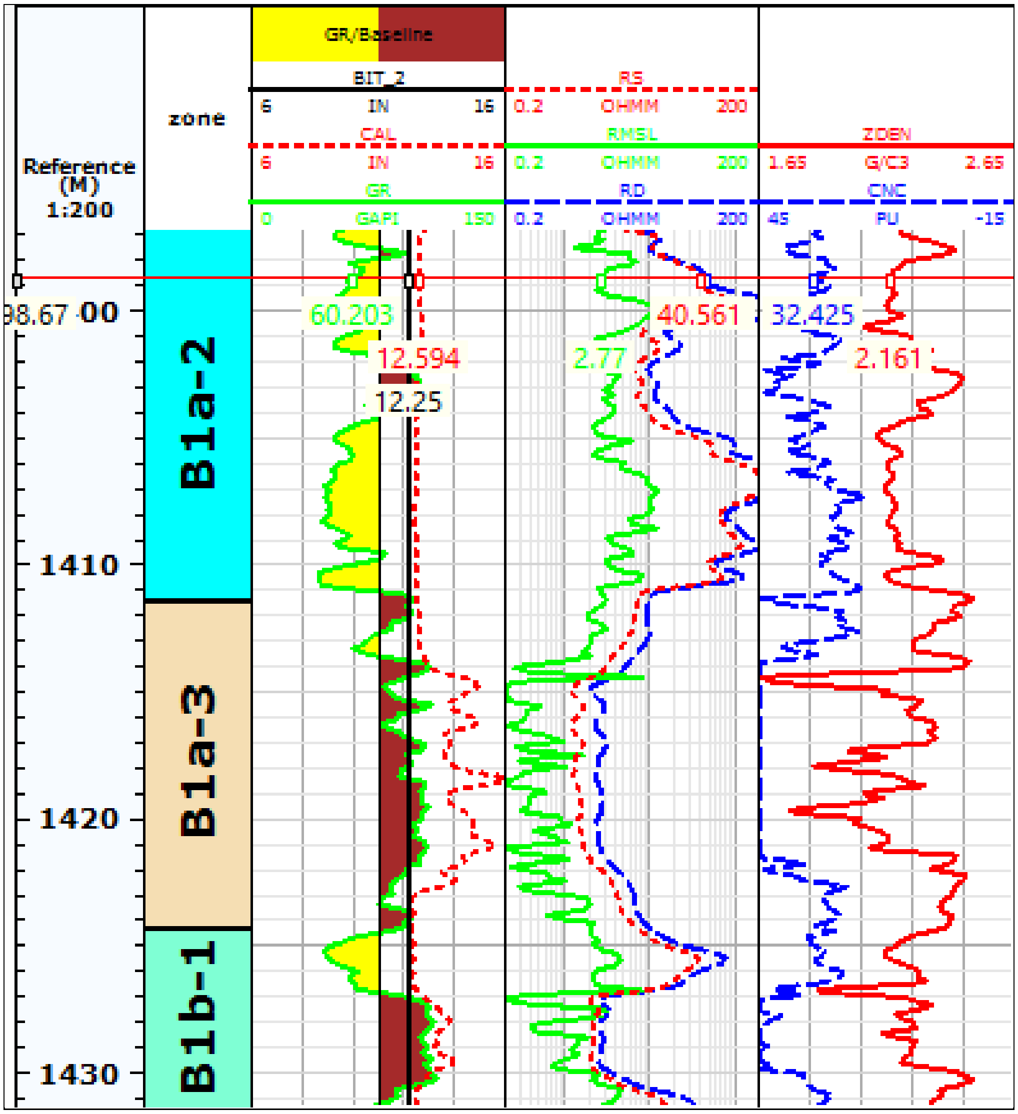


Figure (4.1): Log Curves display- Well Jake S-34.

4.1.2 Multi wells interpretation:

Same workflow adopted as in single wells analysis, and the advantage of this interpretation method, the uncertainties for parameter selection to build the petrophysical models reduced.

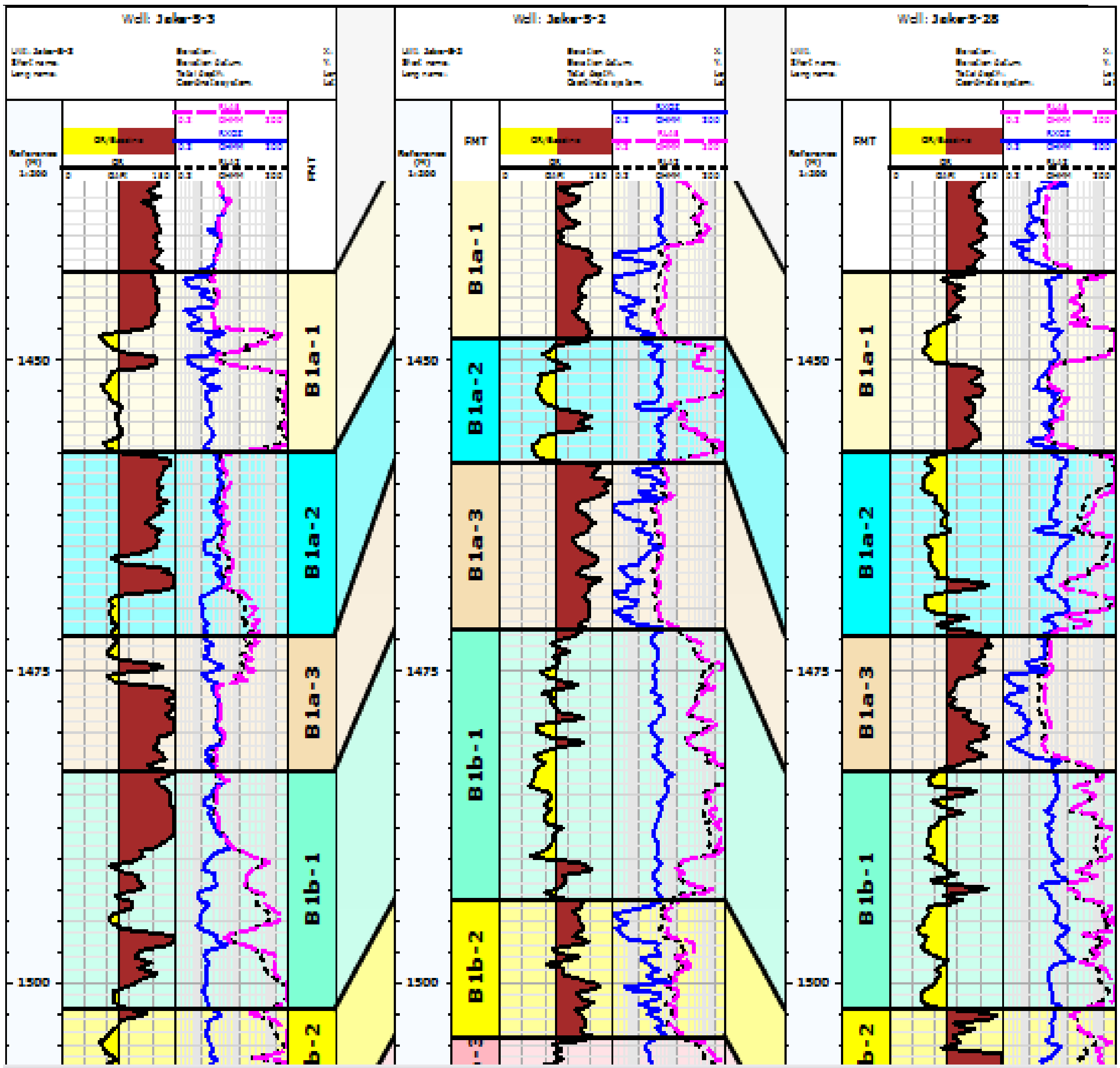


Figure (4.2): Multi wells Log Curves display- Wells Jake S-3, Jake S-2, Jake S-28.

4.2 The Clay/Shale Volume Model Results:

There are two methods used to determine V_{sh} values, the first is based on the gamma ray (GR) logs and the second uses neutron-density logs (NPHI and RHOB).

The average of the GR and NPHI-RHOB results is used if all of the curves are stable and usable. When there are problems with the neutron-density logs, the gamma ray logs alone will be used to establish V_{sh}.

Table (4.1): Gamma Ray and NPHI-RHOB Formulas for Vsh

Method	**Formulas**
Method 1: Use Gamma Ray logs	$I_{GR} = \frac{GR - GR_{clean}}{GR_{shale} - GR_{clean}}$ $Vshale_{GR} = 0.33 \times (2^{(2 \times I_{GR})} - 1.0)$ ………………….(4-1)
Method 2: Use NPHI-RHOB logs	$Vshale_{dn} = Rho - Rho_m + \frac{\phi_n \times (Rho_m - Rho_f)}{Rho_{sh} - Rho_m + (NPHI_{sh} \times (Rho_m - Rho_f))}$ ....(4-2)

Where,

Rho =density from log.

Rho_m =matrix density.

Rho_{sh} =shale density.

Rho_f =fluid density.

Φ_n = porosity from neutron.

$NPHI_{sh}$ = shale neutron porosity.

The following figure shows an example of an unusable neutron-density log from well Jake S-28 and so only the gamma ray logs were used to interpret the shales for that well Figure (4.3).

The Gamma ray curve should be consistent with the density-neutron curves in shale zones and show separation in shales. In the logs Figure (4.3), the reverse holds and there is no proper match between the gamma ray, neutron and density curves for the shale. Thus the neutron-density cannot be used to estimate V_{sh} for this zone, only gamma ray curves.

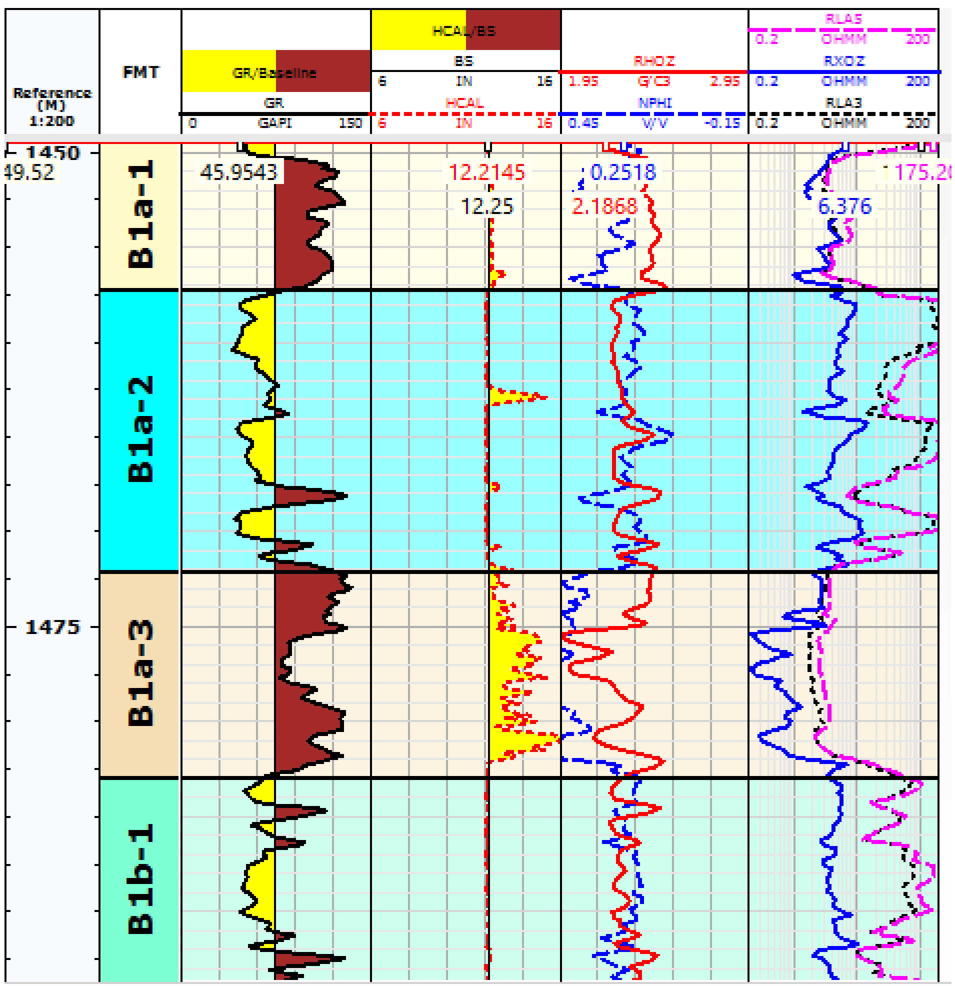


Figure (4.3): Logs QC – well Jake-S 28.

The final shale volume estimated based on average values from Gamma ray, density-neutron as in figure (4.4), figure (4.5) for single and multi wells result respectively.

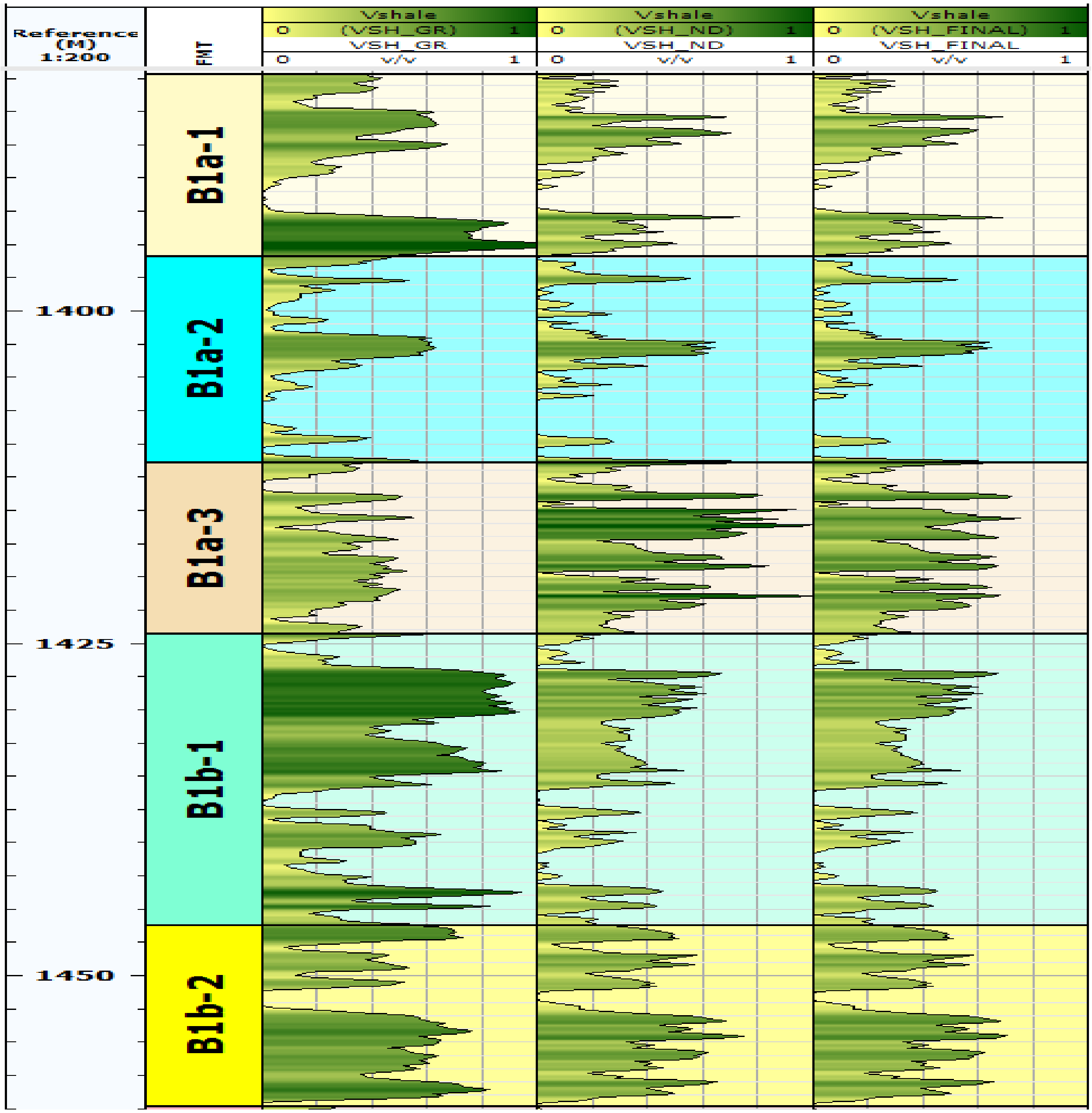


Figure (4.4): Final shale volume – single well Jake-S 34.

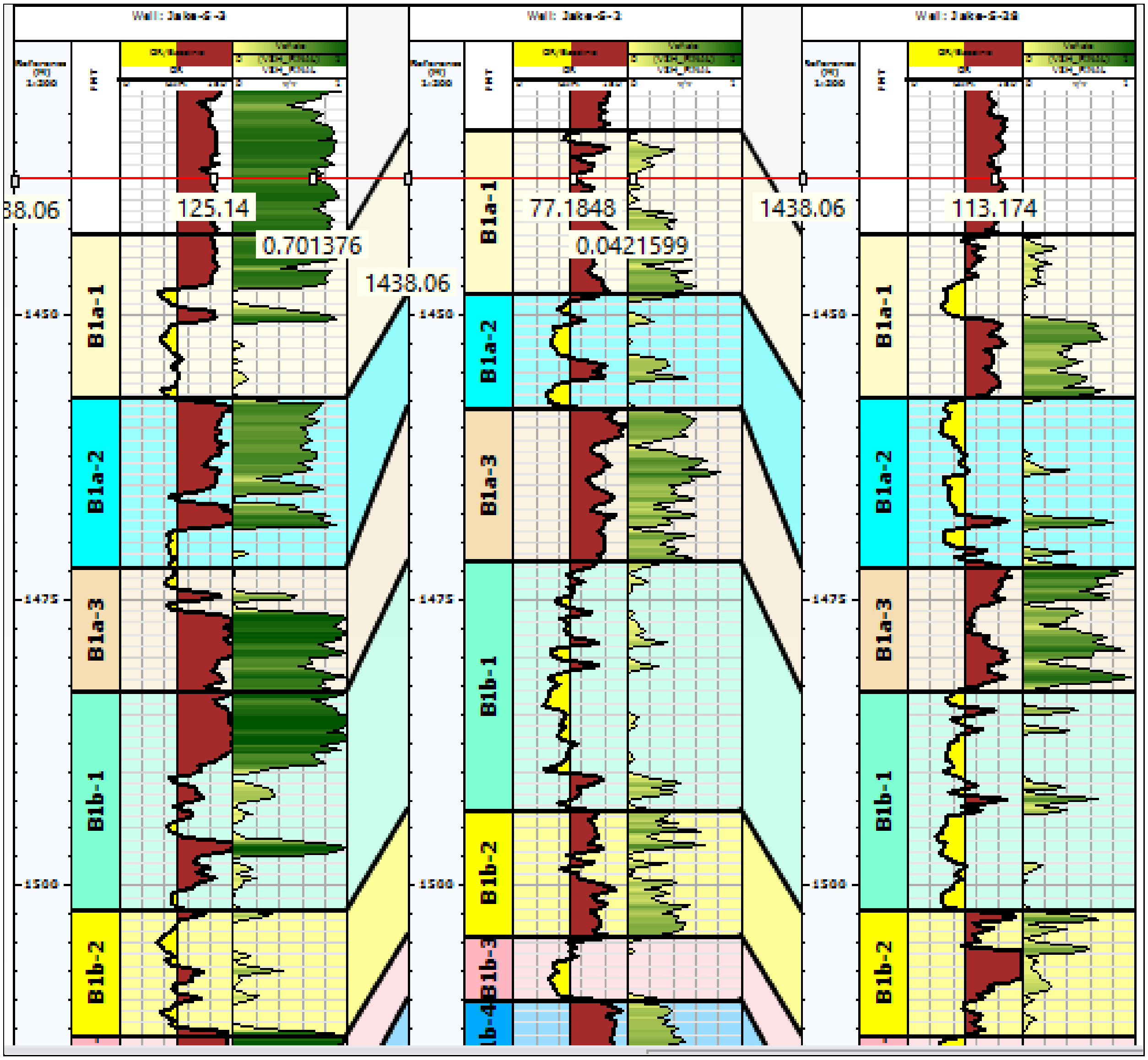


Figure (4.5): Final shale volume – Multi Wells Jake S-3, Jake S-2, Jake S-28.

4.3 Porosity Model:

For this model we used two porosity techniques to determine the porosity and to calibrate to core data. These techniques are:

- Neutron-density cross-plot.
- Density porosity.

In both cases, it was necessary to apply a correction based on Vclay (clay content) in order to match the computed porosity to the core porosity data. Therefore, in this study it is the effective porosity that is being calibrated rather than the total porosity.

Unfortunately, we only have a few core data points to compare with the calculation results but are getting good matches for the data that we do have. In cases where the neutron log is suspect, the density method is used. The grain density was obtained from the core data analysis results in different stratigraphic units.

The two porosities models are based on the density and neutron curves or just the density curves as shown in table (4.2). If all of the curves are usable we choose the neutron-density model, otherwise use the density model for porosity.

Table (4.2): RHOB-NPHI and RHOB Formulas for Porosity

Method 1: Use NPHI and RHOB logs	$\rho = \rho_{ma} + (\rho_{sh} - \rho_{ma}) \times Vsh + (\rho_f - \rho_{ma}) \times \Phi d$ $\varphi_n = \varphi_{nma} + (\varphi_{nsh} - \varphi_{nma}) \times Vsh + (1 - \varphi_{nma}) \times \Phi n$ $\Phi = (\Phi_d + \Phi_n)/2$ …. ………..(4.3)
Method 2: Use RHOB logs	$\phi = \frac{RHOB - RHOB_{matrix}}{RHOB_{fluid} - RHOB_{matrix}} - V_{sh} \times \frac{RHOB_{shale} - RHOB_{matrix}}{RHOB_{fluid} - RHOB_{matrix}}$ ……….(4.4)

Where,

ρ = density.

ρsh = Density of shale.

ρf = fluid density.

ρma =matrix (or grain) density.

Φ_n = porosity from neutron.

Φ_{nma} = matrix neutron porosity.

Φ_{nsh} = shale neutron porosity.

RHOB = density from log.

$RHOB_{matrix}$ = matrix density.

$RHOB_{shale}$ = density of shale.

$RHOB_{fluid}$ = fluid density.

V_{sh} = shale volume.

Φ= porosity.

The core porosity calibrated to the porosity model to validate an accuracy of the parameters and interpretation. There is good match between the interpreted results as showing in figure (4.6).

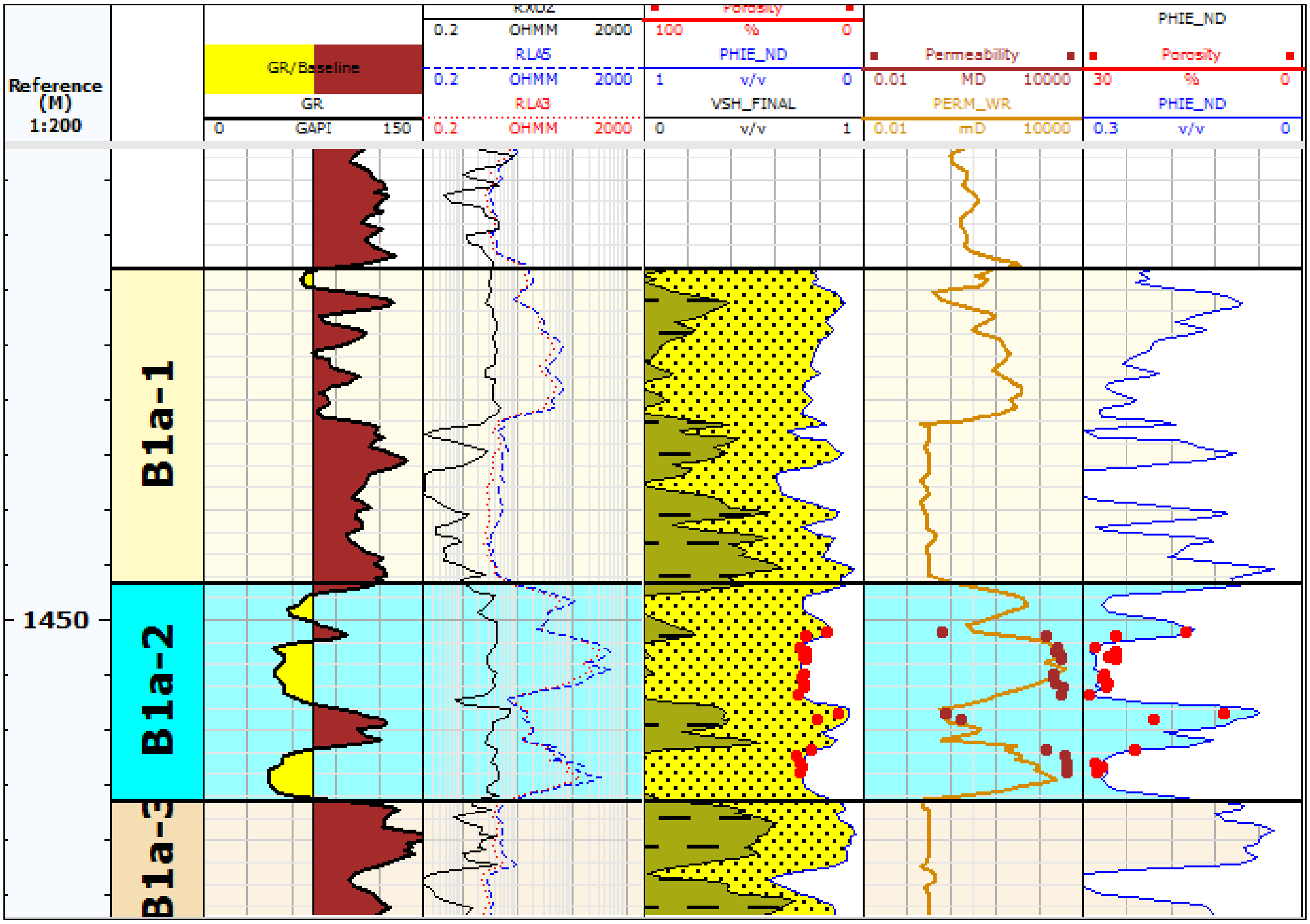


Figure (4.6): Interpreted Porosity vs. Core Porosity – Well Jake S-2.

4.4 Permeability Model:

The permeability was calculated based on the relationship with porosity from core data. Only the values from clean sands were plotted and used to generate a best-fit equation. For Bentiu formation the data from core samples from wells Jake S-2 and Jake S-34 were used. The final result of the model overlay with core permeability as in figures (4.7) and (4.8).

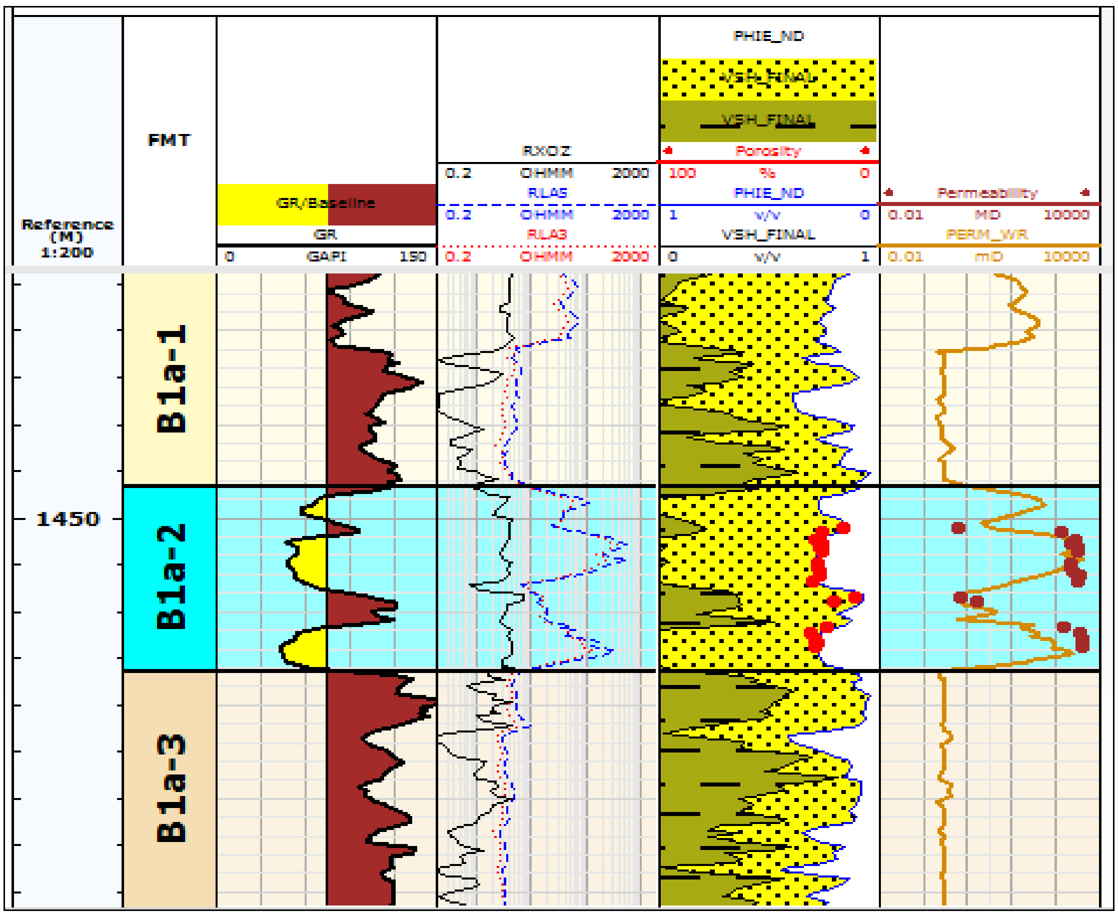


Figure (4.7): Computed Permeability vs. Core Permeability – Well Jake S-2.

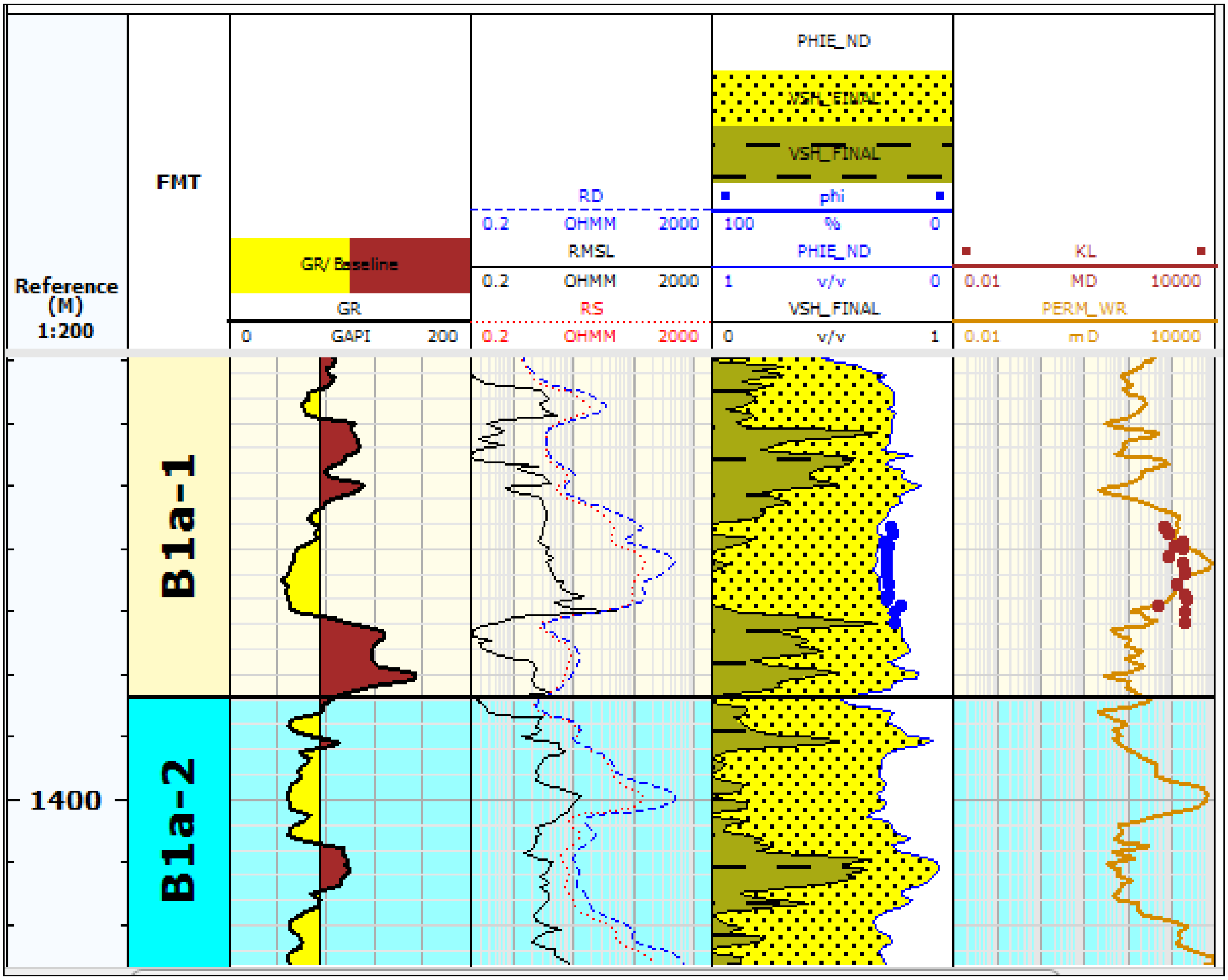


Figure (4.8): Computed Permeability vs. Core Permeability – Well Jake S-34.

4.5 Water Saturation Model:

Archie Equation was used to calculate the water saturation as shown in equation 4.5

$$Sw=\sqrt[n]{\frac{a.Rw}{\phi^{m}.Rt}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(4.5)$$

According to the available core data from wells Jake S-2 and S-3, for the Bentiu formation calculated as the following values figures (4.9) and (4.10):

m (cementation factor).

n (saturation exponent).

a (formation factor).

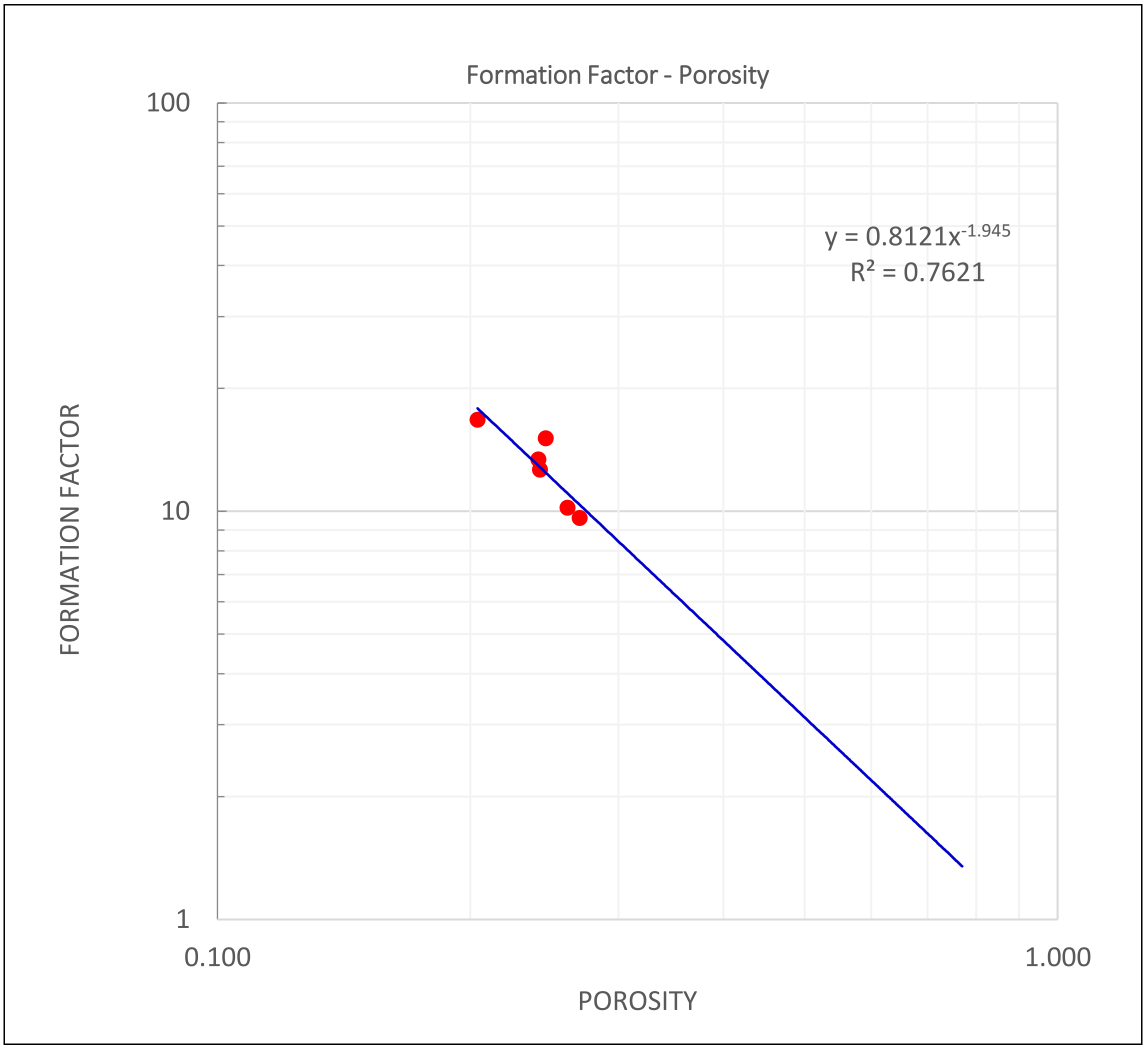


Figure (4.9): Formation Factor and porosity – for (m) value

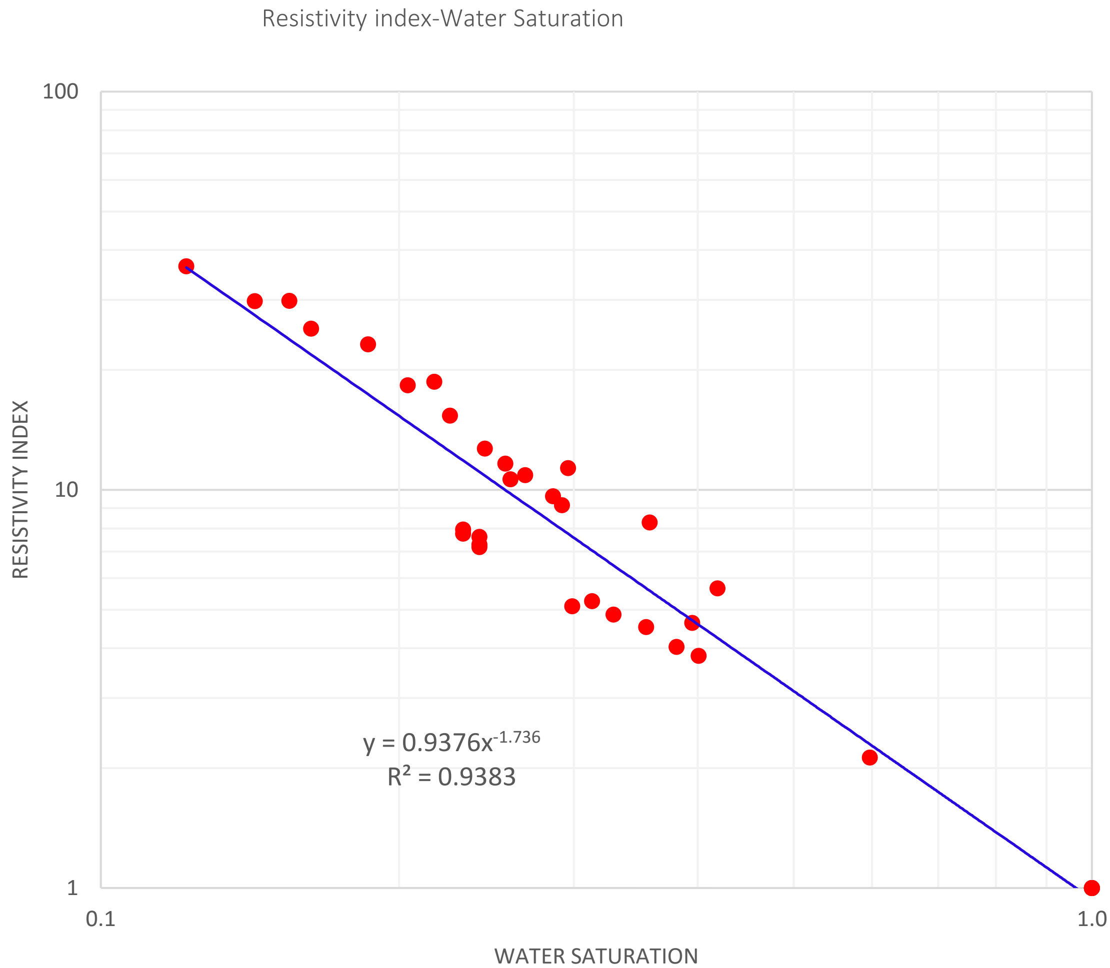


Figure (4.10): Formation Factor and Resistivity Index – for (n) value

Table (4.3): Petrophysical and formation evaluation final results of Jake South-34(Single well)

NO	Well	Zones	Top	Bottom	Gross	Net	Not Net	Net to Gross	AV_Shale Volume	Av_Water Saturation	Av_Effective Porosity
			m	m	m	m	m	m	v/v	v/v	v/v
1	JAKE S-34	B1a-1	1382.2	1395.9	13.7	11.726	1.906	0.856	0.184	0.396	0.271
2	JAKE S-34	B1a-2	1395.9	1411.4	15.5	13.8	1.7	0.89	0.086	0.264	0.277
3	JAKE S-34	B1a-3	1411.4	1424.3	12.9	5.484	7.416	0.425	0.302	0.667	0.304
4	JAKE S-34	B1b-1	1424.3	1446.2	21.9	16.002	5.898	0.731	0.168	0.395	0.237
5	JAKE S-34	B1b-2	1446.2	1459.8	13.6	6.131	7.469	0.451	0.213	0.459	0.22
6	JAKE S-34	B1b-3	1459.8	1467.6	7.8	6.353	1.447	0.814	0.032	0.292	0.28
7	JAKE S-34	B1b-4	1467.6	1480.9	13.3	3.928	9.372	0.295	0.172	0.683	0.226
8	JAKE S-34	B1c-1	1480.9	1501.2	20.3	14.753	5.547	0.727	0.126	0.227	0.23
9	JAKE S-34	B1c-2	1501.2	1526.6	25.4	16.46	8.94	0.648	0.1	0.441	0.194
10	JAKE S-34	B1d	1526.6	1571.7	45.1	36.348	8.752	0.806	0.083	0.259	0.235
11	JAKE S-34	Bentiu2	1571.7	1586.6	14.9	4.877	10.023	0.327	0.151	0.644	0.193
12	JAKE S-34	Bentiu3	1586.6	1997.4	410.83	184.634	201.508	0.449	0.07	0.402	0.198

Table (4.4): Petrophysical and formation evaluation final results of Jake South-2 (Single well)

NO	Well	Zones	Top	Bottom	Gross	Net	Not Net	Net to Gross	AV_Shale Volume	Av_Water Saturation	Av_Effective Porosity
			m	m	m	m	m	m	v/v	v/v	v/v
1	Jake- S-2	B1a-1	1434	1448.3	14.3	10.515	3.701	0.735	0.167	0.685	0.239
2	Jake-S-2	B1a-2	1448.3	1458.2	9.9	8.114	1.786	0.82	0.052	0.249	0.245
3	Jake-S-2	B1a-3	1458.2	1471.7	13.5	5.45	8.05	0.404	0.296	1	0.283
4	Jake-S-2	B1b-1	1471.7	1493.4	21.7	19.05	2.65	0.878	0.037	0.256	0.223
5	Jake-S-2	B1b-2	1493.4	1504.4	11	6.096	4.904	0.554	0.194	0.814	0.235
6	Jake-S-2	B1b-3	1504.4	1510	5.6	5.334	0.266	0.953	0.018	0.169	0.269
7	Jake-S-2	B1b-4	1510	1519.9	9.9	2.301	7.599	0.232	0.068	0.706	0.185
8	Jake-S-2	B1c-1	1519.9	1547.1	27.2	13.854	13.346	0.509	0.023	0.334	0.204
9	Jake-S-2	B1c-2	1547.1	1573.5	26.4	11.278	15.122	0.427	0.022	0.395	0.201
10	Jake-S-2	B1d	1573.5	1609.8	36.3	21.487	14.813	0.592	0.028	0.354	0.226
11	Jake-S-2	Bentiu2	1609.8	1626	16.2	5.792	10.408	0.358	0.055	0.581	0.172
12	Jake-S-2	Bentiu3	1626	2906.3	1280.3	300.989	972.726	0.235	0.009	0.591	0.176

Table (4.5): Petrophysical and formation evaluation final results of Jake South-28 (Single well)

NO	Well	Zones	Top	Bottom	Gross	Net	Not Net	Net to Gross	AV_Shale Volume	Av_Water Saturation	Av_Effective Porosity
			m	m	m	m	m	m	v/v	v/v	v/v
1	Jake-S-28	B1a-1	1443	1457.3	14.3	7.315	6.909	0.512	0.091	0.274	0.245
2	Jake-S-28	B1a-2	1457.3	1472.1	14.8	12.04	2.76	0.813	0.023	0.206	0.237
3	Jake-S-28	B1a-3	1472.1	1483	10.9	3.806	7.094	0.349	0.302	0.714	0.305
4	Jake-S-28	B1b-1	1483	1502.2	19.2	16.152	3.048	0.841	0.021	0.215	0.237
5	Jake-S-28	B1b-2	1502.2	1513.1	10.9	7.243	3.657	0.664	0.077	0.193	0.208
6	Jake-S-28	B1b-3	1513.1	1519.8	6.7	6.176	0.524	0.922	0.003	0.135	0.278
7	Jake-S-28	B1b-4	1519.8	1533.4	13.6	6.401	7.199	0.471	0.329	0.717	0.239
8	Jake-S-28	B1c-1	1533.4	1551.9	18.5	12.05	6.45	0.651	0.025	0.298	0.233
9	Jake-S-28	B1c-2	1551.9	1574.9	23	10.96	12.04	0.477	0.027	0.488	0.187
10	Jake-S-28	B1d	1574.9	1611.3	36.4	29.567	6.833	0.812	0.011	0.389	0.202
11	Jake-S-28	Bentiu2	1611.3	1622.7	11.4	5.583	5.816	0.49	0.274	0.67	0.225
12	Jake-S-28	Bentiu3	1622.7	1976.323	353.624	176.229	176.175	0.498	0.01	0.464	0.181

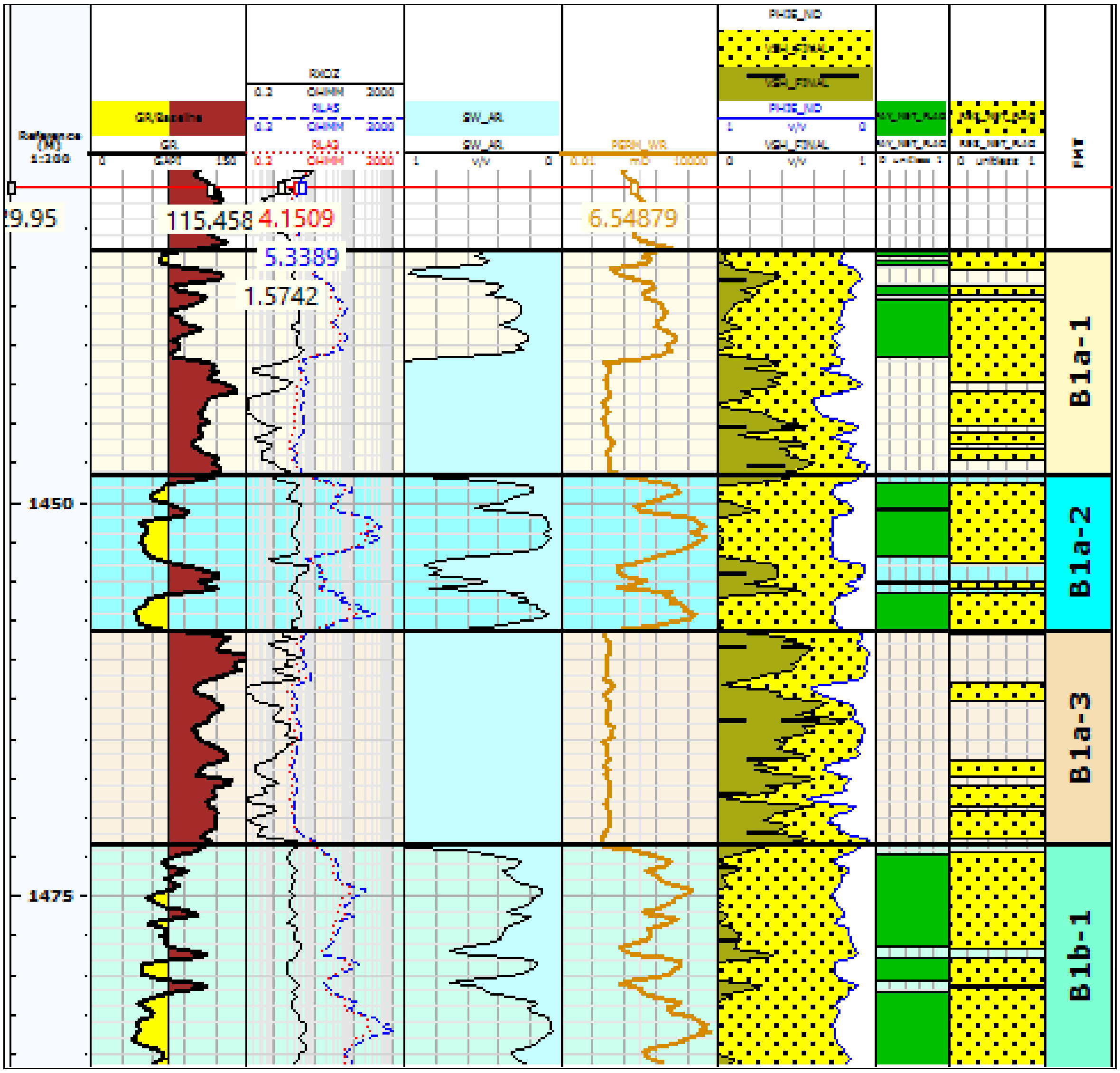


Figure (4.11): Formation evaluation result for Jake S-2(Single well)

Table (4.6): Petrophysical and formation evaluation final results of Wells Jake S-3, Jake S-2, Jake S-28 (Multi wells)

No	Well	Zones	Top	Bottom	Gross	Net	Av_Shale Volume	Av_Water Saturation	Av_Effective Porosity	Result
			m	m	m	m	v/v	v/v	v/v	
1	JAKE S-34	B1a-1	1382	1395.9	13.7	8.07	0.233	0.456	0.249	Oil
2	JAKE S-34	B1a-2	1396	1411.4	15.5	13.5	0.166	0.352	0.244	Oil
3	JAKE S-34	B1a-3	1411	1424.3	12.9	2.819	0.362	0.868	0.253	Oil
4	JAKE S-34	B1b-1	1424	1446.2	21.9	13.87	0.23	0.49	0.204	Oil
5	JAKE S-34	B1b-2	1446	1459.8	13.6	3.771	0.234	0.542	0.208	Oil
6	Jake-S-2	B1a-1	1434	1448.3	14.3	4.267	0.283	0.652	0.132	Oil
7	Jake-S-2	B1a-2	1448	1458.2	9.9	7.01	0.134	0.316	0.201	Oil
8	Jake-S-2	B1a-3	1458	1471.7	13.5	1.067	0.44	1	0.216	Oil
9	Jake-S-2	B1b-1	1472	1493.4	21.7	13.11	0.142	0.292	0.166	Oil
10	Jake-S-2	B1b-2	1493	1504.4	11	1.067	0.312	0.783	0.152	Oil
11	Jake-S-28	B1a-1	1443	1457.3	14.3	5.943	0.203	0.327	0.184	Oil
12	Jake-S-28	B1a-2	1457	1472.1	14.8	11.89	0.131	0.272	0.178	Oil
13	Jake-S-28	B1a-3	1472	1483	10.9	2.282	0.396	0.952	0.263	Oil
14	Jake-S-28	B1b-1	1483	1502.2	19.2	15.85	0.113	0.298	0.183	Oil
15	Jake-S-28	B1b-2	1502	1513.1	10.9	1.299	0.232	0.228	0.124	Oil

Chapter 5

5.1 Discussion:

The study of the cores and the wire line logs analysis of Bentiu formations that were penetrated in the studied wells; however, the sub layers were identified and interpreted easily with wire line logs. The integration between the core analysis results and wire line log responses optimized to identify the lithology and petrophysical models, reference to work done by (Hawez, and et al ,2016).

The Shale Volume Model Results:

The shale volume model results in this study modified by the combined the Gamma ray and density neutron logs used to compute the final shale volume model, while in the literature review as done by (Hawez, and et al, 2016), the Gamma ray is the main source of shale volume estimation.

In this research we realized that, the Gamma ray estimate maximum shale volume in the reservoirs and the density-neutron provided the minimum shale content in the reservoir, so the optimum result will be the average between the two models, for example in figure (4.2) (volume of shale – well Jake-S 2).

The high volume of shale which is observed by the high gamma ray and low resistivity logs responses, verify the shale layers of this formation for being a non-reservoir rocks.

The Permeability Model Results:

The calculation of the permeability, based on core analysis is the main source of the model in this study, because the log based permeability has more uncertainties.

Figure (3.13) Show good correlation between porosity and permeability core data with high coefficient value (R^2=0.9) this indicate the validity of the model in Bentiu formation.

The Porosity Model Results:

Density and neutron are essential logs to calculate total and effective porosity models, but as we found in the literature review as done by (J.C. Avila, et al, 2002), that: the porosity determined from well logs may be corrupt, and no consistent correlations of well log porosity and core porosity were found.

According to the core analysis results the formation is high porosity (23-30%), this is supported by the logging interpretation results and the calibration with core data. The total and effective porosity computed with correction of shale content. In the wire line log interpretation, there is good evidence of overlay between density and neutron logs, in clean-sand intervals, which indicate the permeable intervals or high porosity in the formation, which is match with core porosity, however in shaly sand intervals if the shale content is high maybe no best fit in correlation between log and core porosity.

The existence of coarse-grained sandstone as distinct intervals with low gamma ray combined with low volume of clay matrix; make this formation a reservoir with good quality.

In single well analysis the average effective porosity was 0.22 and in multi wells 0.23.

The water Saturation Model Results:

The oil is observed in the sand intervals according to the low water saturation estimation. This is supported by the high resistivity log responses along with the low density and neutron values in the clean sandstone intervals.

The Archie equation is used to calculate the water saturation model of Bentiu reservoir, because of relatively low shale content and resistivity logs responded to the fluid more than lithology effect, and the core water saturation showed best fit with log water saturation based on Archie equation.

5.2 Conclusion and recommendations:

Analyzing the data of an available core and a suite of well logs has resulted in detailed Petrophysical analysis of the target wells. Adequate lithological interpretation and description was also carried out with the delineation of hydrocarbon bearing reservoir sands.

In general, the grain size is medium to coarse sand with good porosity value 23-30%.

The average water saturation about 45%, with an average net pay in Bentiu upper sand about 8.0 meters; it may increase significantly laterally for the layers.

Two depositional environments have been interpreted namely: the bradded channel and the meandering channel porosity estimates is highest observed in the channel environment.

The logging interpretation results from single well is more accurate compare with multi wells results with tolerance of errors about 4-6%.

The single wells analysis is recommended for formation evaluation, and more core data is recommended for better formation evaluation.

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