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# Application of well log data analysis for enhancing the shaly gas reservoir performance of El-Wastani Formation, Main sand body, Sequoia field, Offshore West Nile Delta, Egypt.

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**Abstract—**Gas reservoir represents a special case, it affects the various well log curve shapes in varying ways. The neutron (ΦN) and density (ρb) logs represent the most logs affected by the presence of gas, hence it has very low hydrogen index (HI) and low density. This can led to extremely low neutron porosity and high density porosity (i.e. gas crossover). The presence of shale will complicates the situation, as the effect of shale on the well log data is in the opposite direction of that of gas. The presence of shale can mask the effect of gas on the well log data and can easily be on based potential zones. To obtain the effective porosity (Φeff) corrections are needed for shale and for the low density gas. This problem necessitated a special technique for treating such shale reservoir, as induced of El-Wastani formation, Sequoia Field, Offshore Nile Delta. The presented technique is based essentially on the available well log data for two development wells including the main sands in Sequoia D3 and D4 wells. A number of cross-plots between ΦN vs ΦD and (ΦD-ΦN) vs. gamma ray (GR) were constructed to address the problem and to differentia between the clean and shale gas zones. Irreducible water saturation (Swirr) was also calculated for each zone of interest, using the formation resistivity factor (F) as (Swirr =$\sqrt{F/2000}$ ). The reservoir quality performance was evaluated through cross- plotting Swirr vs. Sw and Sw vs.Φ to give more indication for the relative permeability to water and gas (Krw & Krg), grain size distribution and water cut (W.C). The permeability (K) was calculated using the Swirr and Timur model. The hydraulic flow unit (HFU) was defined through cross-plotting the reservoir quality index (RQI) vs Φz in logarithmic scale. The main sand body in the study wells a cording to applied techniques is mainly coarse grain sand. The Krg in this sand is more than 0.6 it also characterization by very low water saturation (>15%). The most important result is that, this studied sale gas reservoir is mainly homogenous at is followed very clearly one hydraulic flow unit on RQI vs Φz plot. The flow zone indicator (FZI) for this reservoir are 10 and 11µm this values indeed represent very good quality reservoir characterization.



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## 1 Introduction

THE Nile Delta has attracted significant subsurface interest in recent years, because it is a prolific gas province with several multitrillion-cubic-feet discoveries (Samuel et al., 2003 and Abd Aal., 2006.). El-Wastani Formation (Late Pliocene) is about 120m thick. The rock unit consists of thick quartozose sands with argillaceous interbeds. The depositional environment of the formation is transitional between the outer shelf facies of the overlying Mit Ghamr Formation and Kafr El Sheikh Formation. It exhibits well developed forests due to progradation (EGPC, 1994).

The study Sequoia Field is located on the Northwestern margin of the Offshore Nile Delta, approximately 90km offshore (Figure.1). It lies across the border between the West Delta Deep Marine (WDDM) Concession and the Rosetta Concession. Gas was encountered in the Pliocene sandstones. The reservoir consists of a succession of sandstone and mudstone in a general upward fining profile (soliman., 2015). There are 10 drilled wells in Sequoia field, 6 development and 4 exploratory. Two development wells, D3 and D4, were chosen for this study.

El Wastani Formation hosted the main gas reservoir in Sequoia Field, which has been deposited in many stages, starting with a great incision, then followed by depositing amalgamated between laterally extensive system and the slope gets flatter, sinuous channels begin to develop, then the story ends with channel abandonment with very distal and weak energy deposits on the top, before the background deposition dominates (Nigel cross, et. al., 2009). The stages of filling started with wide incision, which was filled in the early stages by closely stacked straight channels and in the later stages by sinuous channels stacked with low net to gross and ended with abandonment of mud filled channels.

The general stratigraphy of Sequoia Field is shown in (Figure.2), which is in El Wastani Formation of late Pliocene age. Sequoia area is a channelized system, which extends from the northern part of the Rosetta block through the western part of the WDDM concession.

The main challenging problem facing the interpretation of the shaly gas reservoirs, as the case of Main Sand Body reservoirs is that, the presence of shale masks the effect of gas on various well log data responses. This led to easy by passing the productive gas zones and appears as wet unit. This problem will be discussed in detail, using the well log data (resistivity, neutron, density and Gamma-Ray) available for D3 and D4 wells in Sequoia Field.

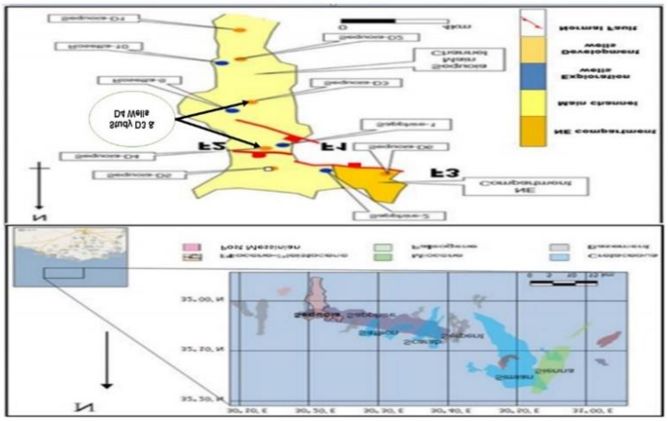


Figure .1. Sequoia field location map (Samuel et al., 2003).

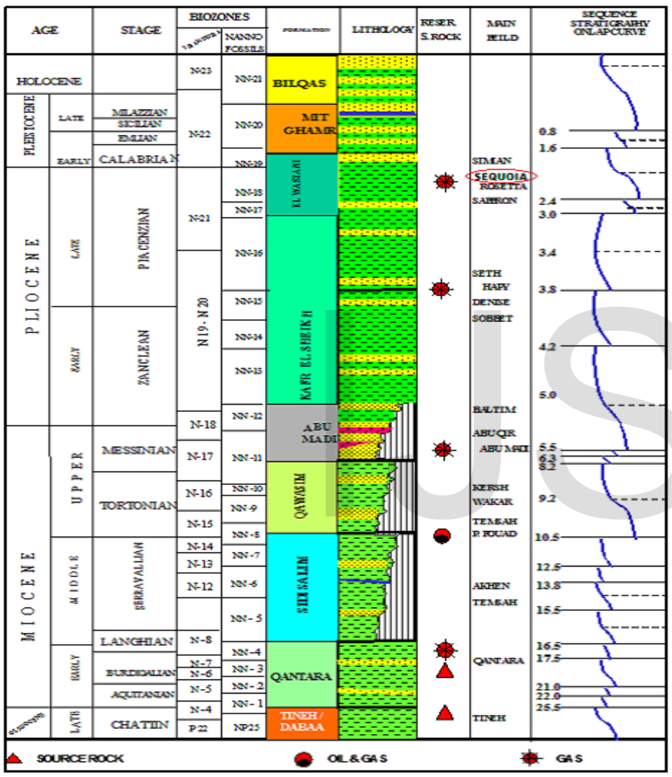



Figure .2. Stratigraphic column of the Nile Delta, (Nigel cross et al, 2009)

## 2. Data and Technique

This work is based essentially on the interpretation of the available well log data in the form of Neutron (CNL), Density (FDC), Resistivity (Rlld) and Total Gamma-Ray (GR). The following sections represent the various techniques applied for the Main Gas Sand Reservoir, D3 and D4 wells in Sequoia Field.

### 2.1. Neutron-Density Log Responses for Gas Effect:

Gas saturation near the wellbore in all types of formations causes an increase in the density log porosity (ΦD) and a decrease in the neutron log porosity (ΦN). Two factors determine the response of porosity logs in gas-bearing formations. These are, the actual porosity(Φeff) and the gas saturation (Sg). Therefore, more than one porosity tool is required. In this study, neutron and density combination will be used. It is important here to mention that, the sonic log is not recommended, because in addition to the gas and shale effects, compaction and secondary porosity effects can also be present (Bassiouni,1994).

### 2.2.Porosity Determination for Gas-Bearing Reservoirs:

When a porosity log response is converted to porosity, a lithology type is assumed. Porosity logs indicate an apparent porosity value in the gas zones. Estimation of the actual porosity in the gas zones requires expressions of the tool response (Bassiouni, 1994).

$$\Phi = \sqrt{\frac{\Phi N^2 + \Phi D^2}{2}} \quad (1)$$

The density and neutron log responses can be used to evaluate porosity in the presence of gas using equation (1).

### 2.3. Effect of Shale on Gas-Bearing Reservoirs:

The neutron log displays a relatively high porosity, due to the presence of shale. Thus, the shale effect is opposite to that of gas. The presence of shale in a gas-bearing formation, complicate the situation, as the shale masks the detection of gas. When both shale and gas exist, they completely offset each other. Accordingly, the shaly gas-bearing formation may, on the neutron log, looks just like a clean liquid-filled formation.

The difference of porosity values recorded by the neutron and density logs where $\Phi D \gg \Phi N$, is used as a direct method for gas detection. The presence of shale in a formation affects the density and neutron log values. The shale effect depends on the magnitude of the shale volume ($Vsh$ %). The presence of shale tends to compensate the gas effect, hence the shale tends to decrease the $\Phi D$ and increase the $\Phi N$, making the gas detection in a shaly formation more challenging.

### 2.4. Density-Neutron-GR Combination in Shaly Gas Reservoirs:

In shaly formations, neutron and density relations are as follow (Schlumberger, 1979):

$$\Phi_{Ncorr} = \Phi_N - V_{sh}\, \Phi_{Nsh} \quad (2)$$

$$\Phi_{Dcorr}=\Phi_D-V_{sh}\ \Phi_{Dsh} \quad (3)$$

$$\Phi_N-\Phi_D=V_{sh}\ (\Phi_{Nsh}\ \Phi_{Dsh}) \quad (4)$$

Accordingly, a plot of GR vs (*ΦN-ΦD*) results in a straight line of coordinate paper (Vohs, 1976). The slope of the line is determined by the shale properties in the analyzed interval. Because of lithology variations, clean water or oil bearing formations will plot in an area of low gamma ray value and little (S.S) or no (L.S) difference in neutron and density porosities. Shale will plot in an area of high gamma ray and high (*ΦN-ΦD*).

The presence of gas will cause the plotted points to shift downward from the straight line. Clean zones show negative (*ΦN-ΦD*) values and the shalier zones show positive (*ΦN-ΦD)* values (Bassiouni, 1994).

## 3. Reservoir Quality and Performance

Reservoir quality depends primarily on good porosity and permeability. On the other hand, evaluation of Irreducible Water Saturation (Swirr), Relative permeabilities to gas (Krg) and water (Krw), Water- Cut (W.C), grain size and Hydraulic Flow Unit identification are considered. The following sections represent evaluation of these parameters.



### 3.1. Irreducible Water Saturation (Swirr)

Formation factor (F) was used by Asquith and Gibson (1982) to derive the Swirr as follows:

$$Sw_{irr}=\sqrt{\frac{F}{2000}} \quad (5)$$

It should be used only as qualitative technique (cross-plots) with other petrophysical parameters (Φ and Sw) when trying to evaluate the dynamic properties of the reservoir.

### 3.2. Grain Size, Relative Permeabilities and Water Cut

$$K=\frac{\Phi e(rmh)^2}{2\tau^2} \quad (6)$$

The grain size, relative permeabilities to gas (Krg), water (Krw) and water cut (W.C.) are the most important petrophysical parameters which can tell something about the reservoir quality and performance. In this study, a number of cross-plots will be used to deduce such parameters. These cross-plots are the Φ vs Sw, Sw vs Swirr.

### 3.3. Flow Unit Characterization

The relation between permeability (K) and porosity Φ is not straight forward. There is no specifically well-defined trend lines between the K and Φ values. In this respect, this relation is qualitative and is not directly or indirectly quantitative in any way. It is possible to have very high Φ without having any K at all, such as pumice, clays and shales. The reserve of high K with low Φ might also be true such as micro-fractured carbonate.

Accordingly, there is no well-defined universal correlation between K and Φ. Different Φ - K relationships are evidence of the existence of different Hydraulic Flow Units (HFU). The key to improve the reservoir characterization of description and exploitation is the development and understanding of the complex variation in pore geometry within lithofacies. Core data provides information on the various depositional and digenetic controls on pore geometry. Variations in the pore geometrical attribute, in turn, define the existence of distinct zones, classified as Hydraulic Flow Units (HFU) (Egaz Ashraf, 1994). The Flow Unit is a continuous body over a specific reservoir volume, that practically possesses consistent petrographic and fluid properties, which uniquely characterize their static and dynamic communications with the wellbore.

The mean hydraulic radius (rmh) and its relation to porosity, permeability and capillary pressure (Pc) is the key to interpret HFU (Amaeful, et.al., 1993). Kozeny (1927) and Carmen (1937) derived the following relation:

Where: The K is the permeability in md.
Φe is the effective porosity (fraction).
τ is the tortuosity.
Amaeful, et.al. (1993) presented the following relation:

$$\sqrt{\frac{K}{\Phi e}}=\left[\frac{\Phi e}{1-\Phi e}\right]\frac{1}{\sqrt{fs\tau Sgv}} \quad (7)$$

$$Sgv=\frac{1}{rmh}\left[\frac{\Phi e}{1-\Phi e}\right] \quad (8)$$

Where: Sgv is the surface area per unit volume.
Fs is the shape factor (equals to one for circular cylinder).

For permeability expressed in (md), the measure of pore throat size of a hydraulic flow unit is expressed as (Amaeful, 1993):

$$RQI=0.0314\sqrt{\frac{K}{\Phi e}} \quad (9)$$

0.0314 is the conversion factor from (md) to (μm)

RQI is the Reservoir Quality Index (μm)

Amaefulet, et. al. (1993) introduced two new terms called Normalized Porosity Index (NPI) or □z and Flow Zone Indicator (FZI), as follow:

$$\Phi z=\frac{\Phi e}{1-\Phi e} \quad (10)$$

$$FZI=\frac{1}{\sqrt{fs\tau Sgv}} \quad (11)$$

Replacing Sgr and √fs by combining equations (11) and (12) gives:

$$\sqrt{\frac{K}{\Phi e}} = \left[\frac{\Phi e}{1-\Phi e}\right] FZI \qquad (12)$$

Combining RQI, □z and FZI yields:

$$FZI = \frac{RQI}{\Phi z} \qquad (13)$$

$$\log RQI = \log \Phi z + \log FZI \qquad (14)$$

The plot of RQI versus Φz on a log -log paper yields a straight line representing the specific HFU. Other HFU will fall on straight parallel lines with unity slope.

## 4. Application

The following section represents the application of the presented techniques for the Main Sand shaly gas reservoir of El-Wastani Formation in D3 and D4 wells, Sequoia Field, Nile Delta Province.

### 4.1. $\Phi_D$-$\Phi_N$ Cross-plot

The density -neutron porosity cross-plot for the main sand in Sequoia D3 and D4 wells (Figure 3.a and b) was constructed. Clean Gas –Bearing zones are clustered in cloud (A). Shaly Gas-bearing sand zones may be plotted inside cluster (B). Gamma-Ray interpretation is needed to confirm this statement. Effect of shale may be greater than that of gas, which led to the points plotted in cluster (C).

### 4.2. ($\Phi_N$-$\Phi_D$) vs. GR cross-plot

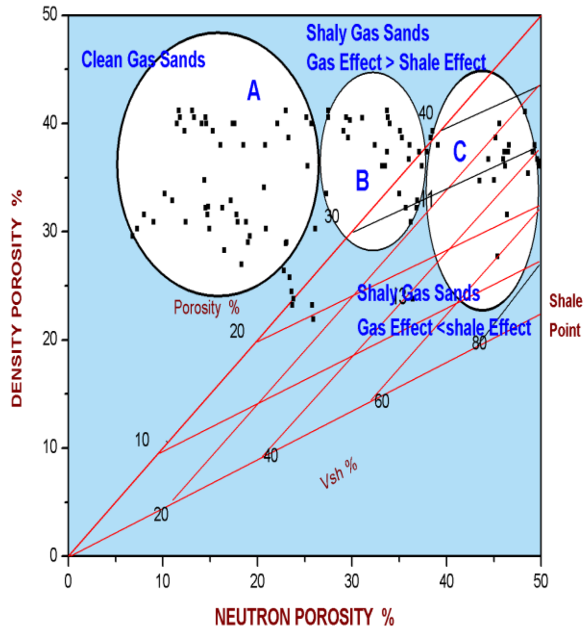
The Gamma-Ray effect when plotted versus ((ΦD-ΦN) can be helpful to differentiate between the clean wet sand and shaly gas one. Such a plot for the Main Sand Reservoir, Sequoia Field for D3 and D4 wells is presented as (Figure .4. a and b). This figure confirms that, cluster C (Figure.3.a and b) is indeed reflecting the shaly gas-bearing sand. In addition, cluster A is situated below ΦN-ΦD =0 line.

### 4.3. Relative Permeabilities to Water ($K_{rw}$) and Gas ($K_{rg}$)

### 4.3.1. D3 Well

Cross-plot of $S_{wirr}$ vs. $S_w$ for D3 well (Figure. 5a) is constructed to evaluate the relative permeability to water ($K_{rw}$). The plotted points on and near zero $K_{rw}$ (red color points indicate that, the reservoir is at irreducible state (i.e., produce clean gas without water). Points plotted near 0.01represent production of gas and water (yellow, grey and green color points). Water production is expected for points plotted near 0.06 line (blue color points). On the other hand, relative permeability to gas ($K_{rg}$) (Figure.5b) can be correlated with the $K_{rw}$ discussed above. Points represent clean gas production (red color on Fig.5a) are plotted near 1.0 $K_{rg}$ (red color, Figure.5b). The water zones (blue color on Fig.5a) are also plotted on 0.02 $K_{rg}$ (Figure.5b).

### 4.3.2. D4 Well

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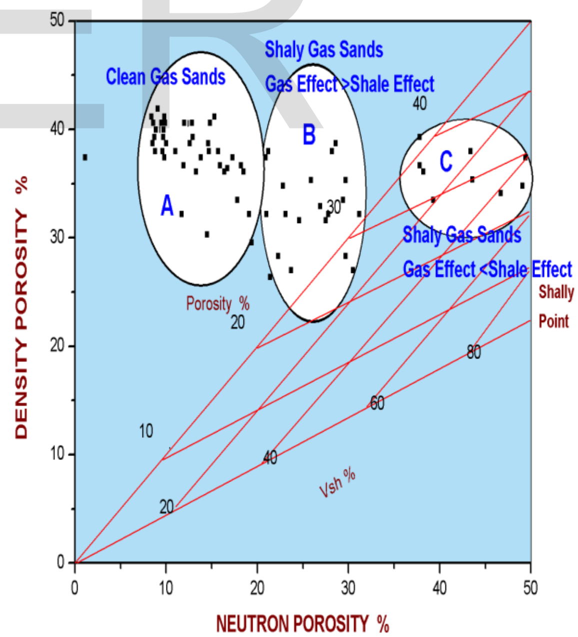


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Figure.3. ΦD vs. ΦN Cross-plot for the Main Sand in (a) D3 Well and (b) in D4 well, Sequoia Field.

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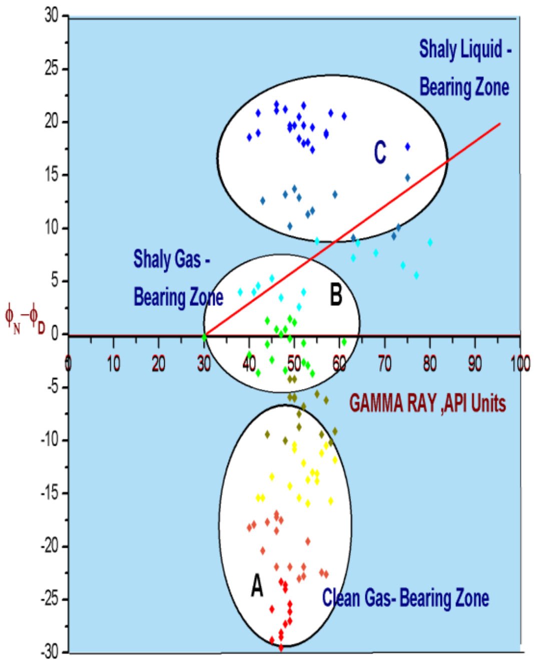


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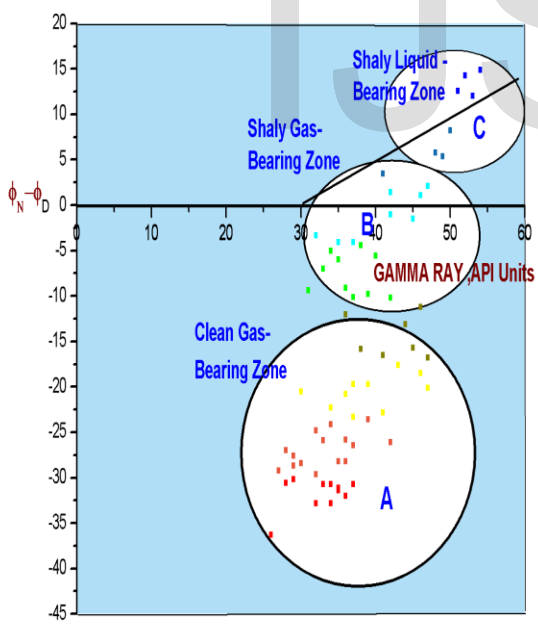


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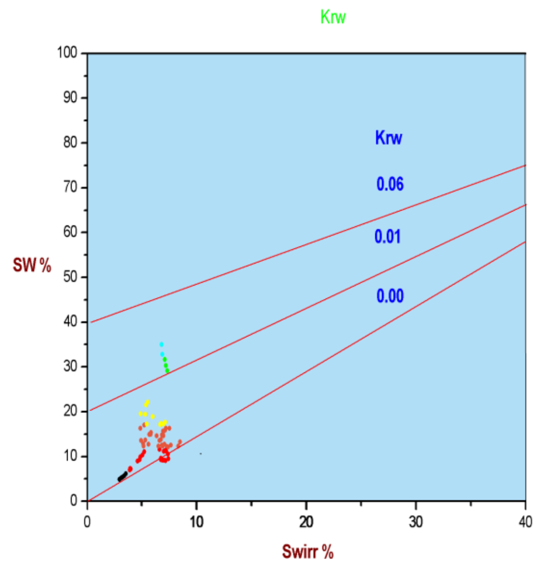
Figure.4. (ΦD-ΦN) vs. GR cross-plot for the Main Sand in (a) D3 Well and (b) in D4 well, Sequoia Field.

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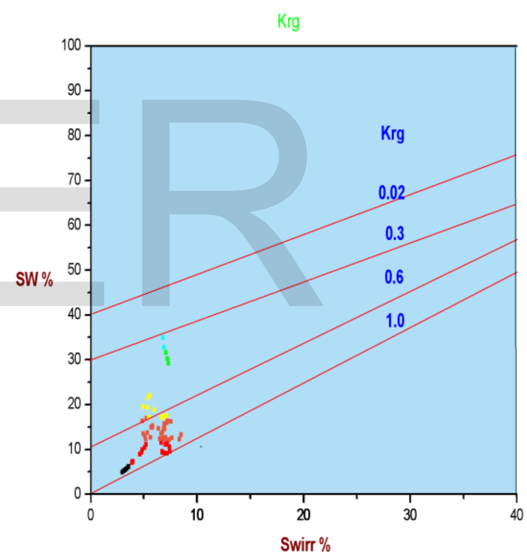
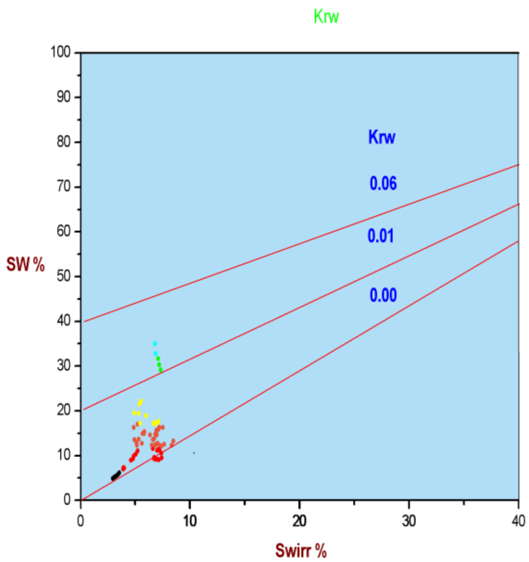
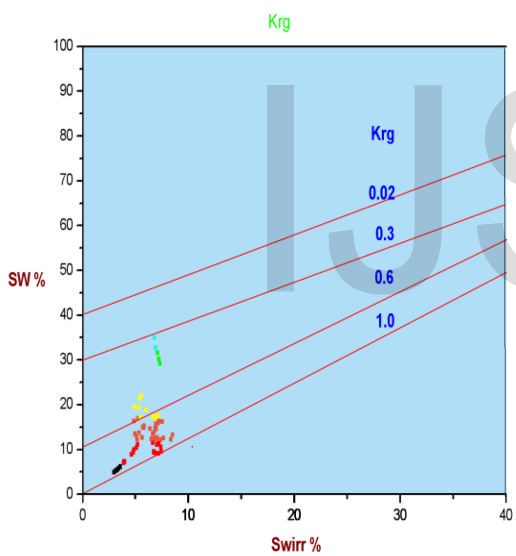



b

Figure.5. Irreducible water saturation (Swirr) versus water saturation (Sw) cross-plot for determining (a) the relative permeability to water (Krw) and (b) the relative permeability to gas (Krg) in the Main Sand, Sequoia D3 well.




**a**




**b**

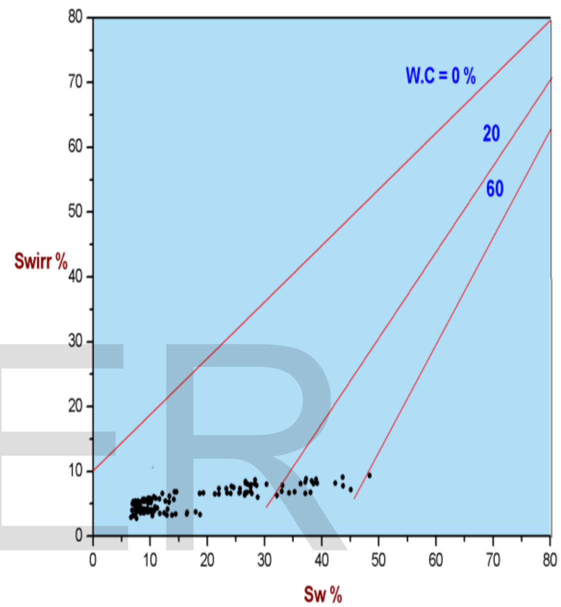
Figure.6. Irreducible water saturation (Swirr) versus water saturation (Sw) cross-plot for determining (a) the relative permeability to water (Krw) and (b) the relative permeability to gas (Krg) in the Main Sand, Sequoia D4 well.

### 4.3.2. D4 Well

The same procedure was followed, as discussed above for D4 well (Figure. 5a). The most important feature noticed in this well is that, the majority of points landed on or near 0.0 Krw (Figure.6a), reflecting excellent reservoir quality and performance. Very little points (Green color) are clustered around 0.01Krw). Again Krg confirmed the obtained conclusion that, this reservoir is mainly produce gas without water hence many points are plotted around 1.0 Krg (Figure.6b).

### 4.4. Water Cut (W.C)

The associate water during production is the water cut (W.C). For evaluating such important parameter, this will be through the relation between Sw vs Swirr, as discussed early. Cross-plot (Figure.7a) for the Main Sand, Sequoia D3 well reveals that, the water cut (W.C) in this well is ranged from percent 10 to 60%. On the other hand, the water cut of the sand reservoir in D4 well is generally below 20% (Figure.7b) with the majority of points landed around 10%. The results are correlated very well those that obtained above**.**

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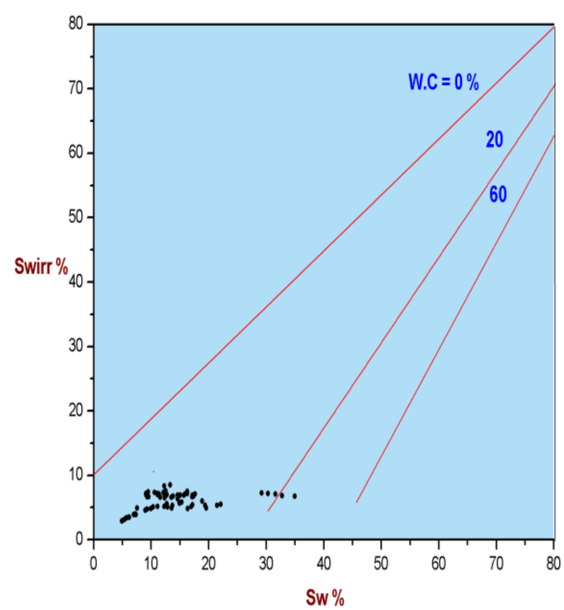


**b**

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Figure.7. Irreducible water saturation (Swirr) versus water saturation (Sw) cross-plot for determining the percent of water cut for the Main Sand in (a) D3 well and (b) in D4 well, Sequoia Field.

## 4.5. Grain size distribution

The grain sizes in sandstone reservoirs plays an important role for controlling the reservoir performance. Water saturation (Sw) versus porosity can help defining the gran size (Asquith, and Gibson, (1983). Figure, 8 represents such relation for the main gas sand reservoir in D3 and D4 wells. The most and important information which can be extracted is that, the coarse grain size (CG) represents good reservoir performance with high Krg and very low Krw (red color points in Figure.5 and 6). These points also plotted below 10% W.C.

Figure.8. Semi-log presentation for porosity against water saturation, for illustrating the grain size distribution of the Main Sand in (a) D3 Well and (b) in D4 well, Sequoia Field.

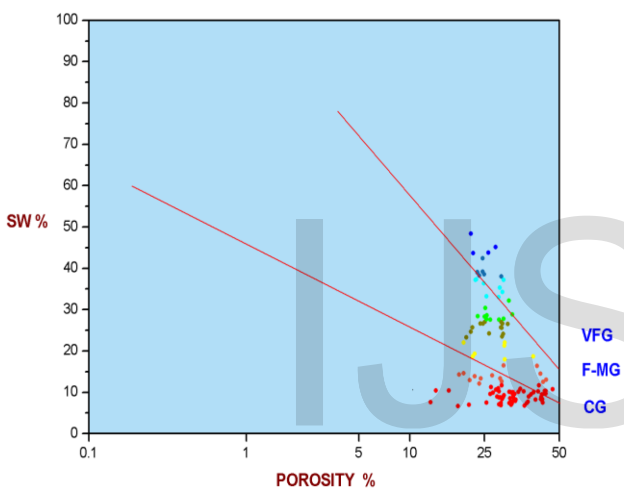
## 4.6. Hydraulic Flow units (HFU)

### 4.6.1. D3 Well

A log- log plot of the reservoir quality index (RQI) versus φz for D3 well (Figure.9a) reflects one unit, with FZI equals 10 µm. and RQI equals 0.5 µm, reflecting high pore radius.

### 4.6.2. D4 Well:

The same plot (Figure.9b) was constructed for D4 well and shows that, the reservoir quality index (RQI) = 0.7 µm. and Flow zone indicator (FZI) = 11 µm.

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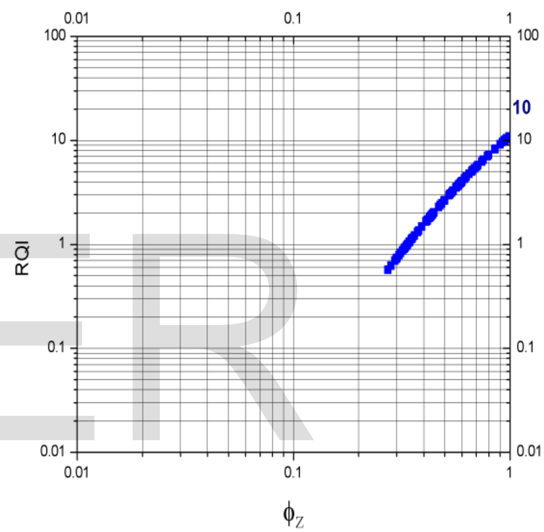


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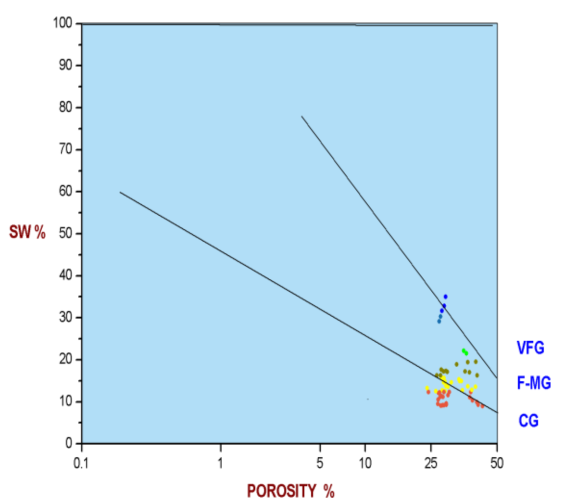


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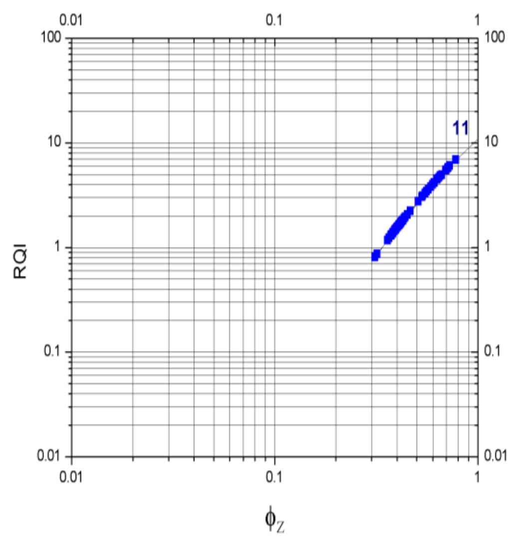


b

Figure.9. RQI versus Φz, showing flow unit for the Main Sand in (a) D3 well, (b) in D4 well, Sequoia Field.

## 5. Conclusions

Evaluation of gas reservoirs represents a challenging problem facing petrophysicist. The presence of shale adds another problem, hence it led to bypassing the productive intervals. In this study, the well log data available for two wells (D3 and D4) in Sequoia Field were used to apply different techniques to enhance the formation evaluation in case of shaly gas reservoirs.

The Neutron-Density cross-plot technique in this case is miss-leading, as the shaly gas-bearing zone will be appear as clean wet, while it contains potential gas. Addition of gamma ray values with ΦD-ΦN is very helpful to differentiate between clean, shaly gas and wet intervals. In addition, good porosities were obtained after correcting them for shale effect, if any.

Estimation of Irreducible Water Saturation (Swirr) using the formation factor values greatly enhanced the evaluation of reservoir performance and quality. This was performed through a number of relations between Sw, Swirr and porosity. Through these relations, Krw, Krg, W.C and grain size distribution were obtained. The results indicated that, the Main Sand reservoir in Sequoia Field has good to excellent reservoir performance, as it possess high Krg and very low W.C and very low or even zero Krw. The excellent reservoir qualities for gas are associated with coarse to very coarse grain sizes. Very fine grain sizes are related to water zones.

The studied Main Sand reservoir for each well has distinctive one Hydraulic Flow Unit. FZI=10 µm and 11 µm, and RQI=0.5 and 0.7 for D3 and D4 wells, respectively.

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