

## Using of Pickett's Plot in Shaly Formation to Estimate the Petrophysical Exponents of Bahariya Formation in Sidi Barani Area, North Western Desert, Egypt

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**Abstract:** The present study deals with the determination of the petrophysical exponents of Bahariya Formation in Sidi Barani Area in the north part of the Western Desert of Egypt by using eight wells distributed in the study area. These petrophysical exponents are very important for the accurate estimation of fluids saturation where there is a direct relation between these parameters and the total water saturation and then the hydrocarbon saturation. Pickett's plot is used to calculate the petrophysical exponents "m", "n" and "a" for the clean formation. This plot is developed by Aguilera where it is extended to determine the petrophysical exponents in case of shaly formation which includes laminated, dispersed and total shale models. The advantage of this cross plot is that all shaly intervals can be displayed in a single plot together with porosity and water saturation. The value of "m" for Bahariya Formation ranges from 1.8 to 2.3 while "a" for this formation is ranging from 0.6 to 1. The "n" value varies from 1.4 to 2.1. So, through one plot the estimated petrophysical parameters for the clean and shaly formation can be displayed with porosity and water saturation.

**Key words:** Cementation factor, tortuosity factor, saturation exponent, Bahariya Formation, Western Desert.

### INTRODUCTION

Determination of the petrophysical exponents "m", "n" and "a" are requiring for the accurate estimation of water saturation. The technique of pickett's plot was utilized for calculating these petrophysical parameters for Bahariya Formation in Sidi Barani Field which lies in the north part of Western Desert of Egypt by using eight wells scattered in the study area (Bassel-1X, Safir-N1X, Hayat-1X, Kenz-28, Salam-3X, TUT W3X, Salam-N, and Nour-1X) (Fig. 1). Pickett's plot is a very useful technique in log interpretation but it was restricted in the case of clean formation. One of the weaknesses of the Pickett plot is its inability to handle shaly formation (Aguilera, 1990). Aguilera (1990) demonstrated that laminas, dispersed and total shale can be analyzed by using log-log cross plots of porosity versus true resistivity as affected by a shale group ( $A_{sh}$ ).

So in this paper, the petrophysical parameter will be calculated in case of clean and shaly formation by Pickett and Aguilera plot respectively.

#### *Effect of Petrophysical Exponents on the Physical Properties of Rock:*

There are relationships between the petrophysical exponents and the physical properties of rocks. For example, the formation factor F can be expressed in the following equation:

$$F = a / \varphi^m \quad (1)$$

Where:

"F" is the formation factor, "a" is the function of the tortuosity factor, and "m" is a function of the number of reductions in pore opening sizes (known as the cementation exponent), and its values is between 1.5 (mostly for sandstones) and about 3 (for certain carbonates).

Over the years, Archie (1942) corrected the observed formation factors with the porosity and permeability. He showed that, the correction with the porosity is better and the formation factor could be expressed as:

$$F = 1 / \varphi^m \quad (2)$$

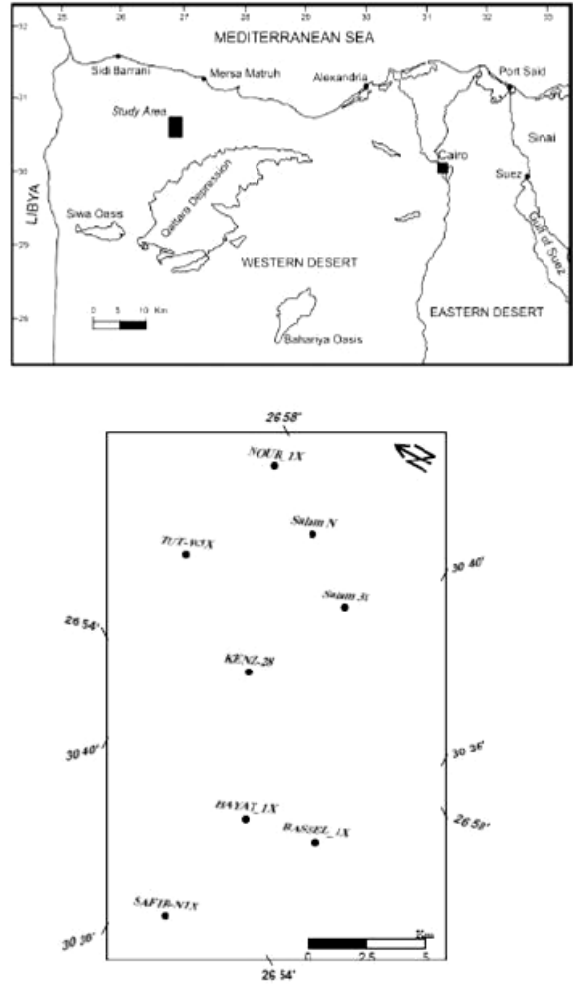
Where:  $\varphi$  is the fractional porosity.

Therefore, the formation factor is inversely relating to porosity, so the greater porosity of the formation, the lower of formation factor (Aguilera, 2001). Archie further reported that, the cementation factor is probably ranging from 1.8 to 2 for consolidated sandstone and for clean unconsolidated sandstone it is about 1.3. The following Table (1) shows the value of "m" with the comparable reservoir character. It may be noted that,

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cementation results is increasing the values of formation factor over that observed for uncemented aggregates. Furthermore, the cemented aggregates exhibit a greater change in the formation factor with change in the porosity than the unconsolidated aggregates (Aguilera, 1995).



**Fig. 1:** Location map and the investigated wells of the study area, north Western Desert, Egypt.

**Table 1:** Show the impact of cementation factor on the reservoir character.

Reservoir character.	Cementation factor 'm'
Unconsolidated	1.3
Very slightly cemented	1.4-1.5
Slightly cemented	1.6-1.7
Moderately cemented	1.8-1.9
Highly cemented	2-2.2

**Pickett's Plot:**

Pickett (1966 and 1973) plots have been long recognized as very useful in log interpretation. In Pickett's method, a resistivity index, "I", and water saturation, "S<sub>w</sub>" are calculated from log-log plots of true (in some cases apparent) resistivity versus porosity or response of a porosity tool. This technique not only gives estimation of water saturation (S<sub>w</sub>), but also helps in determination of: (1) formation water resistivity (R<sub>w</sub>) (2) cementation factor "m", and matrix parameters for porosity logs (Δt<sub>ma</sub> and ρ<sub>ma</sub>). The Pickett method based on the observation that true resistivity (R<sub>t</sub>) is a function of porosity, water saturation (S<sub>w</sub>), and cementation factor "m". Pickett cross plot developed by plotting porosity values with deep resistivity (LLD or ILD) values on two-by-three cycle log-log paper. The theory of this plot started with Archie's equation (1942), as follows:

$$S_w = I^{-1/n} \tag{3}$$

$$I = R_t / R_0 = R_t / (F \cdot R_w) \tag{4}$$

$$F = a \Phi^{-m} \tag{5}$$

Equations (3) and (5) can be combined to yield.

$$R_t = a \Phi^{-m} R_w I = a \Phi^{-m} R_w S_w^{-n} \tag{6}$$

If the logarithm with base 10 has been taken, the equation (Pickett, 1966) leads to:

$$\text{Log } R_t = -m \text{ log } \Phi + \text{log } (a R_w) + \text{log } I \tag{7}$$

Which is the equation of a straight line, on log –log paper, can be written in the form:

$$Y = mx + b \tag{8}$$

According to equation (7), a plot of log  $R_t$  vs. log  $\Phi$  can be drawn in a straight line with a negative slope controlled by "m", where  $m = 1/\text{slope}$ . The slope is determined manually by measuring a distance on the  $R_t$  axis (in cm) and dividing it by the corresponding distance on the porosity axis. The value of  $(aR_w)$  is derived from the intercept of such a line with the porosity axis at  $\Phi = 1$ . Pickett plots can be applied in various formations whether clean formation or Shaly formation as illustrated later in this paper.

**Pickett's Plot in Clean Formation:**

Clean formation is free from shale. In this formation resistivity value,  $R_t$ , plotted versus porosity on the log-log paper. Points of constant water saturation ( $S_w$ ) will plot on a straight line with negative slope of value "m". Figs. (2 - 9) show the Pickett's Plot in clean formation for the studied well. The cementation exponent "m" for this section has different values ranging from 1.3 to 1.8 which indicate the presence of consolidated sandstones. It may be noted that, cementation results is increasing the value of formation factor, while the tortuosity factor for this unit ranges from 0.6 to 1.25 in the studied wells. In case of intervals at irreducible water saturation that meet  $S_{wi} = \text{constant} = c$  (Morres and Bigges, 1967) the water saturation exponent "n" can be calculated by inserting  $S_w = c / \Phi$  into equation (6) as:

$$R_t = a R_w \Phi^{-m} (c / \Phi)^{-n} \tag{9}$$

Taking logarithm on both sides of the equation result in:

$$\text{Log } R_t = (n-m) \text{ log } \Phi + \text{log } (aR_w/C^n) \tag{10}$$

Crossplot of  $R_t$  versus  $\Phi$  on log-log coordinates should result in a straight line with slope equal to "n-m" by knowing the value of "m" the saturation exponent "n" can be determined. Table (2) shows the different values for these parameters in the studied rock interval, which used in the accurate estimation of the total water saturation through the studied wells.

**Table 2:** Shows, the results obtained from Pickett's Plot (clean formation).

No	Well name	aRw	a	m	n
1	BASSEL 1X	0.025	0.8	1.87	2.08
2	NOUR 1X	0.028	0.6	1.64	1.80
3	SAFIR-N1X	0.024	0.89	1.67	1.84
4	HAYAT 1X	0.025	0.83	1.90	2.11
5	SALAM-3X	0.024	0.8	1.70	1.89
6	SALAM N1	0.028	0.93	1.60	1.86
7	TUT-W3X	0.033	1.10	1.30	1.49
8	KENZ-28	0.018	0.6	1.68	1.86

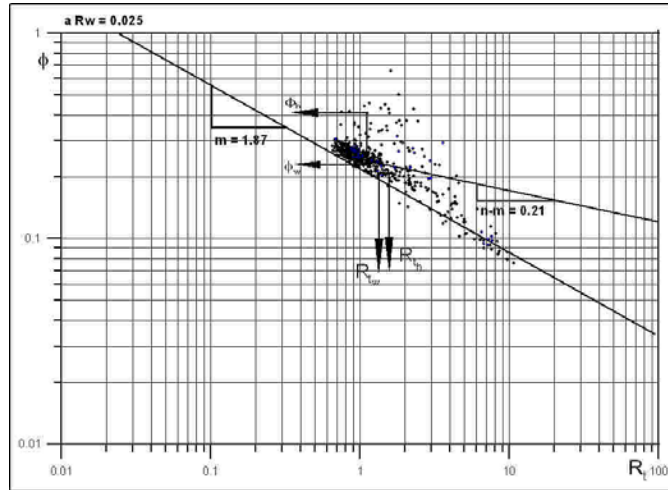
**Extending of Pickett's Plot in Shaly Formation:**

Throughout the years, some log analysts have indicated that one of the weaknesses of the Pickett Plot is its inability to handle shaly formation. This paper demonstrates that laminar, dispersed and total shale models can be analyzed by using log-log cross plots of porosity versus true resistivity as affected by a shale group ( $A_{sh}$ ).

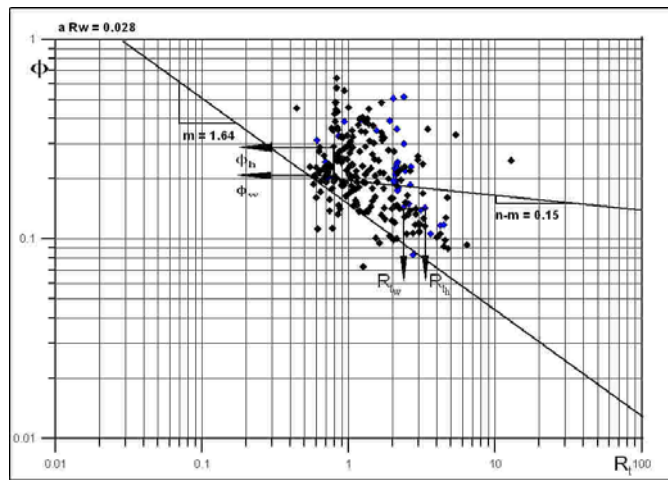
**Laminated Shale Model:**

Pouponet al. (1954) have used the following parallel conductivity model for the evaluation of laminated shaly formation:

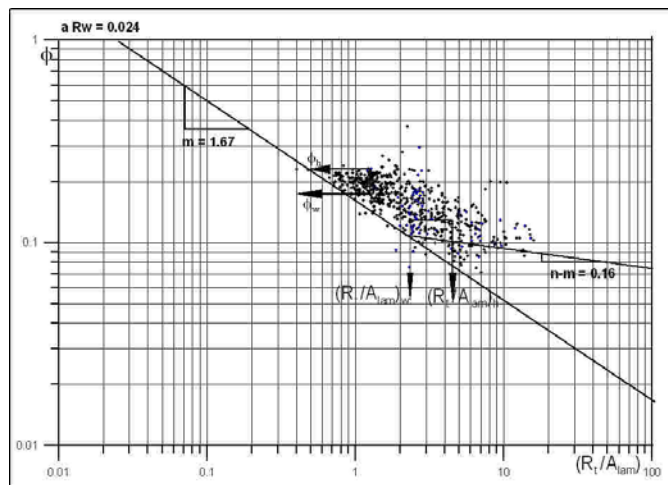
$$S_w^2 = [a(1-V_{lam})R_w / \phi^2] * [1/R_t - V_{lam}/R_{sh}] \tag{11}$$



**Fig. 2:** Pickett's plot of the Bahariya Formation in Bassel-1X well (clean formation).



**Fig. 3:** Pickett's plot of the Bahariya Formation in Nour-1X well (clean formation).



**Fig. 4:** Pickett's plot of the Bahariya Formation in Safir-N1X well (clean Formation).

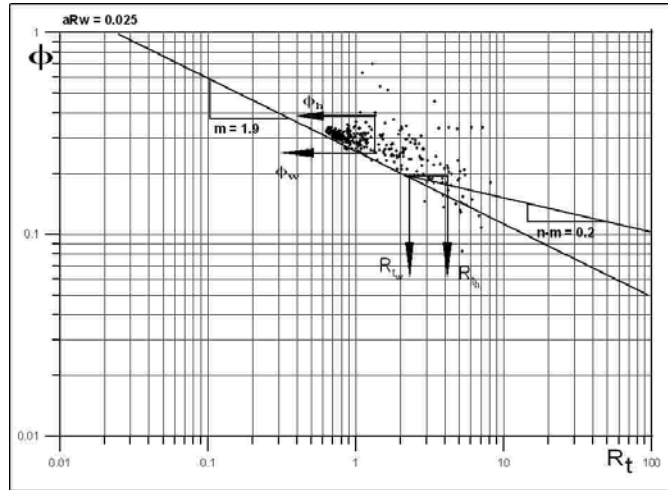


Fig. 5: Pickett's plot of the Bahariya Formation in Hayat-1X well (clean formation).

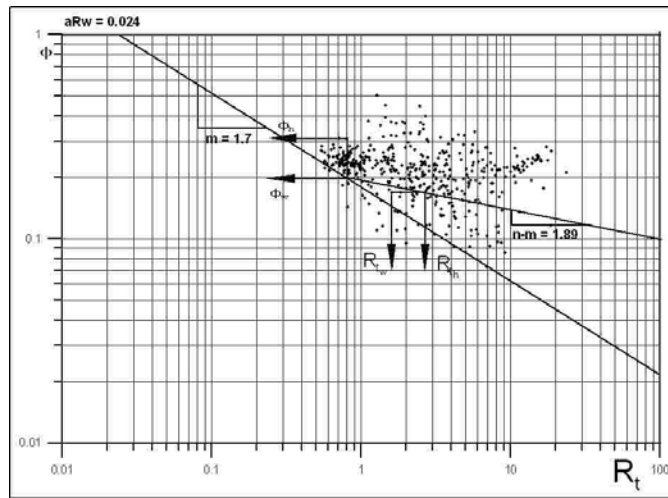


Fig. 6: Pickett's plot of the Bahariya Formation in Salam-3X well (clean formation).

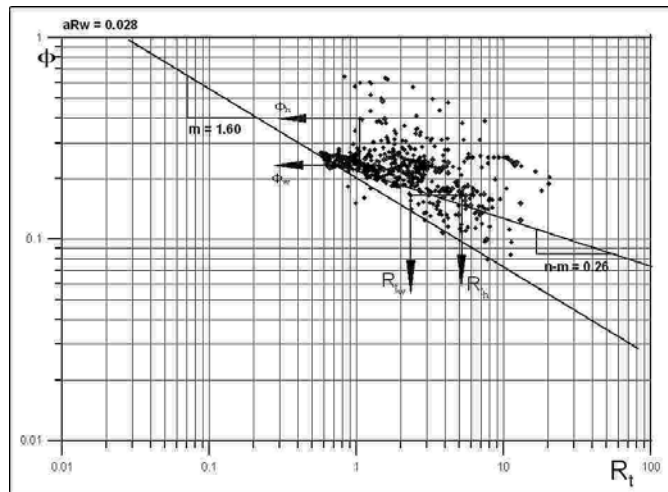
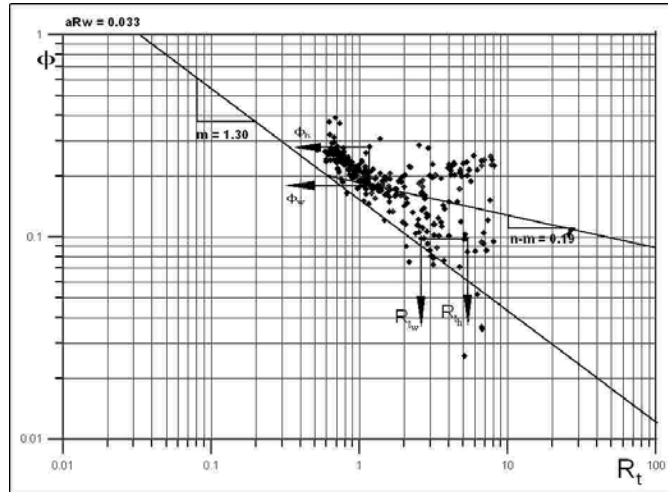
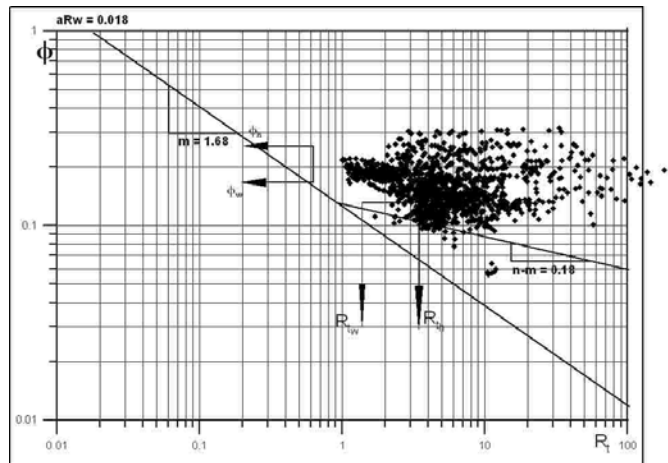


Fig. 7: Pickett's plot of the Bahariya Formation in Salam-N well (clean formation).



**Fig. 8:** Pickett's plot of the Bahariya Formation in TUT-W3X well (clean formation).



**Fig. 9:** Pickett's plot of the Bahariya Formation in Kenz-28 well (clean formation).

To make the equation more general, the water saturation and porosity exponents changed from 2.0 to "n" and "m", respectively (Aguilera, 1990). The equation is thus readily extending to the analysis of naturally fractured reservoir where the exponents' "m" and "n" are lower than usual, depending on the degree of fracturing (Aguilera, 1980). Equation (11) can be written as:

$$R_t/A_{lam} = a R_w \phi^{-m} S_w^{-n} \quad (12)$$

Where  $A_{lam}$  is a laminar shaly term given by

$$A_{lam} = [(R_{sh} - R_t V_{lam}) (1 - V_{lam})] / R_{sh} \quad (13)$$

Taking logarithms of both side of equation (12) leads to

$$\text{Log } (R_t/A_{lam}) = -m \text{ log } \phi + \text{log } (a R_w) + \text{log } (S_w^{-n}) \quad (14)$$

Equation (14) indicates that acrossplot of  $(R_t/A_{lam})$  versus  $\phi$  on log-log coordinates should result in a straight line with slope equal to "-m", provided that  $aR_w$ ,  $S_w$  and "n" are constants. When the line of 100% water saturation is extrapolated to the porosity of 100%, the value of  $aR_w$  can be read at that point on the  $R_t/A_{lam}$  scale. As mentioned before there are intervals at irreducible water saturation. That water saturation exponent, "n" can be calculated by inserting  $S_w = C/\phi$  into equation (12) as:

$$(R_t/A_{lam}) = aR_w\phi^{-m} (C/\phi)^{-n} \tag{15}$$

The criterion that  $S_w \phi = C$ , however, must be used carefully as it has been demonstrated (Aguilera, 1990), that in some cases it might lead to errors in the interpretation. Taking logarithms on both sides of the equation results in:

$$\text{Log } (R_t/A_{lam}) = (n-m) \log \phi + \log (aR_w/C^n) \tag{16}$$

Equation (16) indicates that a crossplot of  $(R_t/A_{lam})$  versus  $\phi$  on log-log coordinates should result in a straight line with slope equal to "n – m" for intervals at irreducible water saturation. Because the value of "m" has been determined already as the slope of the 100% water saturation line, it is possible to readily calculate the water saturation exponent "n".

Another possibility is to determine  $S_w$  directly from the log-log plot. These is accomplished by assuming that the same  $R_w$  exists in the water and hydrocarbon zone, and calculate a resistivity index of laminated shale hydrocarbons interval,  $I_{lam}$  from:

$$I_{lam} = (R_t/A_{lam})_h / (R_t/A_{lam})_w \tag{17}$$

And water saturation from:

$$S_w = I_{lam}^{-1/n} \tag{18}$$

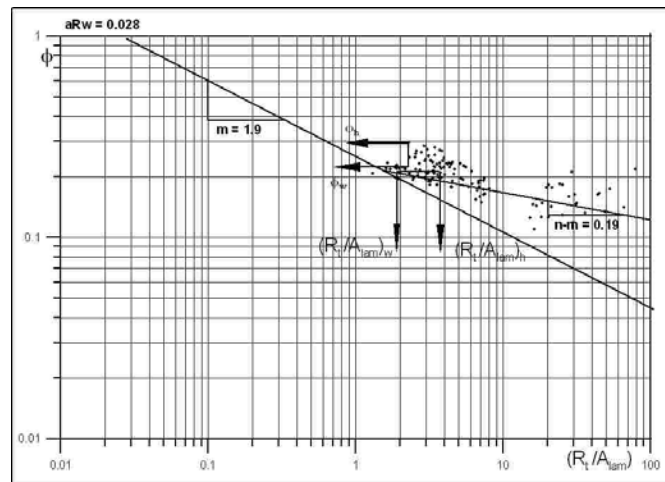
From the log-log plot, it is also possible to calculate water saturation with the use of:

$$S_w = (\phi_w / \phi_h)^{m/n} \tag{19}$$

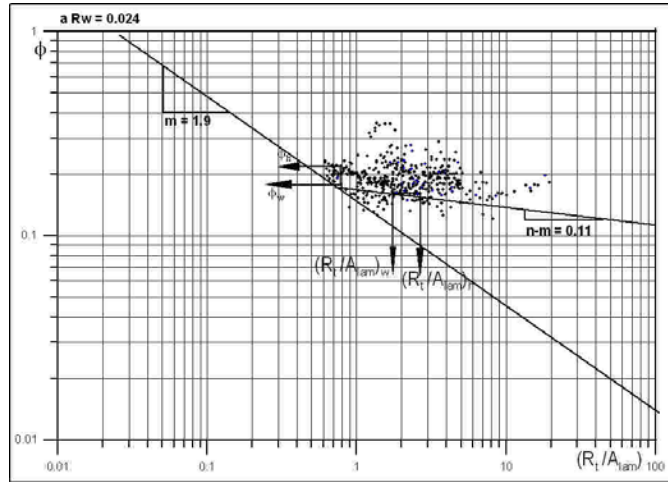
Where  $\phi_w$  = porosity read on the 100% water saturation line, and  $\phi_h$  porosity of the hydrocarbon bearing interval. Notice that  $\phi_w$  and  $\phi_h$  can be different, but must be read at the same value of  $R_t/A_{lam}$ .

From Dia-porosity crossplots (Islam *et al.*, 2013) showed that seven wells were represented by laminated and structural shales. Structural shale has properties similar to those of the laminar shale and near-by massive shales.

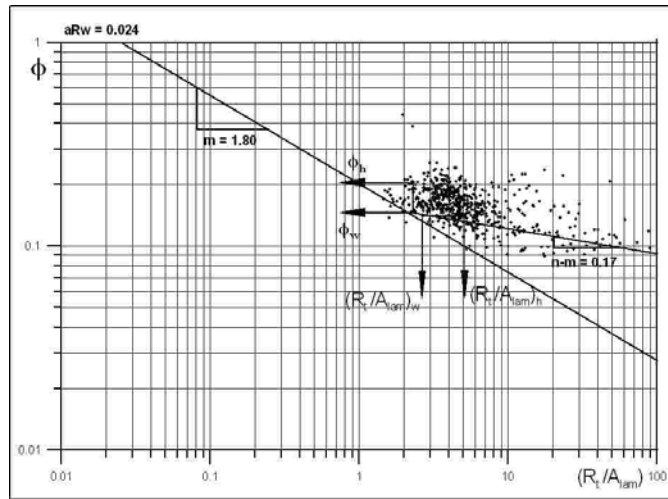
Figs. (10 - 16) show the Pickett's Plot for Laminated shale model of the studied wells. The cementation exponent "m" for this section has different values ranging from 1.6 to 2.1 which indicate the presence of consolidated sandstones. It may be noted that, cementation results is increasing the value of formation factor. While the tortuosity factor for this unit is ranging from 0.7 to 0.93 in the studied wells. The saturation exponent "n" is ranging from 1.80 to 2.25.



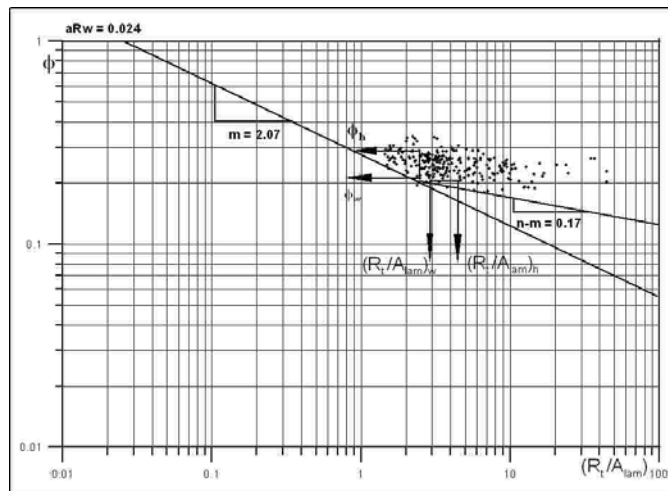
**Fig. 10:** Pickett's plot of the Bahariya Formation in Bassel-1X well (laminated shale).



**Fig. 11:** Pickett's plot of the Bahariya Formation in Nour-1X well (Laminated Shale).



**Fig. 12:** Pickett's plot of the Bahariya Formation in Safir-N1X well (laminated shale).



**Fig. 13:** Pickett's plot of the Bahariya Formation in Hayat-1X well (laminated shale).

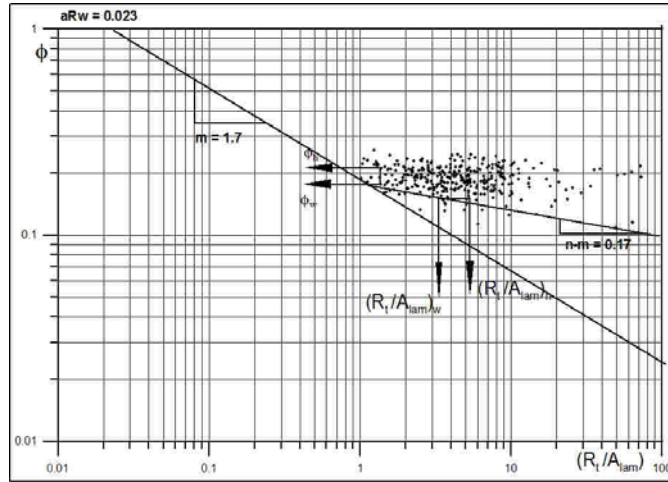


Fig. 14: Pickett's plot of the Bahariya Formation in Salam-3X well (laminated shale).

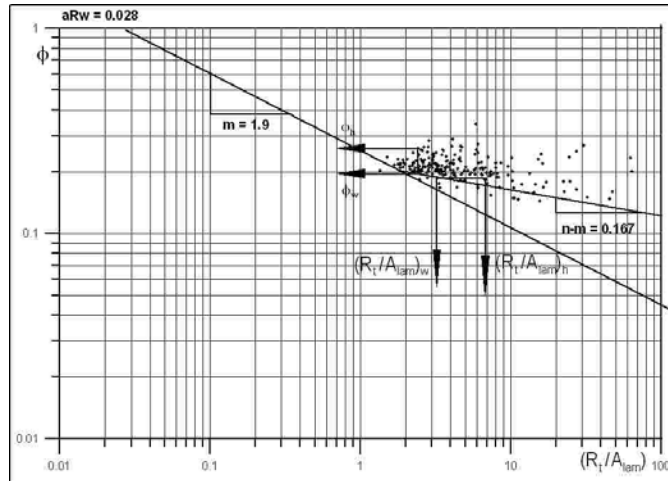


Fig. 15: Pickett's plot of the Bahariya Formation in Salam-N well (laminated shale).

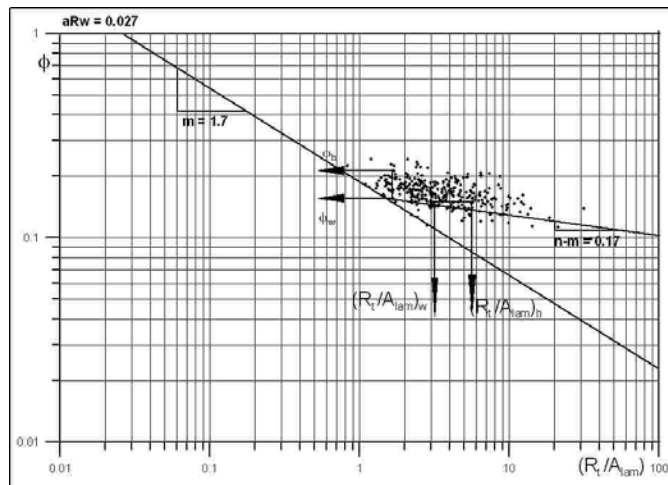


Fig. 16: Pickett's plot of the Bahariya Formation in TUT-W3X well (laminated shale).

Table (3) shows the different values for these parameters in the studied rock interval, through the studied wells.

**Table 3:** Results obtained from Pickett's Plot (laminated shale).

No	Well name	aR <sub>w</sub>	a	m	n
1	BASSEL 1X	0.028	0.93	1.90	2.09
2	NOUR 1X	0.023	0.76	1.90	2.01
3	SAFIR-N1X	0.024	0.80	1.80	1.97
4	HAYAT 1X	0.024	0.80	2.07	2.24
5	SALAM-3X	0.023	0.76	1.70	1.87
6	SALAM N1	0.028	0.93	1.90	2.067
7	TUT-W3X	0.027	0.90	1.70	1.87

**Dispersed Shale Model:**

In some cases, shales might be dispersed throughout sand, partially filling the smaller pores or coating the sand grain. Schlumberger (1979) has presented the following equation to calculate water saturation in the case of dispersed shale reservoir:

$$S_w = \sqrt{\frac{aR_w}{\phi^2 R_t} + \left( \frac{V_{dis} (R_{dis} - R_w)^2}{2 \phi R_{dis}} \right)} - \left( \frac{V_{dis} (R_{dis} + R_w)}{2 R_{dis}} \right) \quad (20)$$

Where the subscript 'dis' stands for dispersed shale.

There are many cases in which the exponent "m" is not equal to 2.0. To avoid the problem, the porosity exponent changed from 2.0 to "m" to make it more general. Equation (20) can now be written as

$$R_t / A_{dis} = a R_w \phi^{-m} S_w^{-n} \quad (21)$$

A<sub>dis</sub> is a dispersed shale group given by

$$A_{dis} = 1 + \frac{\phi^m R_t}{aR_w} \left( B_{dis} - 2 \sqrt{\frac{aR_w}{\phi^m R_t} + B_{dis}} + C_{dis} \right)^2 \quad (22)$$

$$B_{dis} = [V_{dis} (R_{dis} - R_w)] / 2R_{dis} \quad (23)$$

And

$$C_{dis} = [V_{dis} (R_{dis} + R_w)] / 2R_{dis} \quad (24)$$

Taking logarithms of both side of equation (20) results in:

$$\text{Log} (R_t / A_{dis}) = -m \log \phi + \log(a R_w) + \log(S_w^{-2}) \quad (25)$$

Equation (25) shows that a cross plot of log (R<sub>t</sub>/A<sub>dis</sub>) versus log φ on log-log coordinates should be result in a straight line with slope equal to "-m" for interval with constant aR<sub>w</sub> and constant S<sub>w</sub>. Extrapolation of 100% water saturation straight line will cut the porosity of 100% at point which give the read of aR<sub>w</sub> on the (R<sub>t</sub>/A<sub>dis</sub>) logarithmic scale. The value of "m" should be equal the value input in the previous steps where the value of "m" is refined by trial and errors. The assumption that "m" is equal to 2 is valid for many reservoirs with dispersed shale.

The resistivity index, I<sub>dis</sub>, can be calculated from:

$$I_{dis} = (R_t / A_{dis})_h / (R_t / A_{dis})_w \quad (26)$$

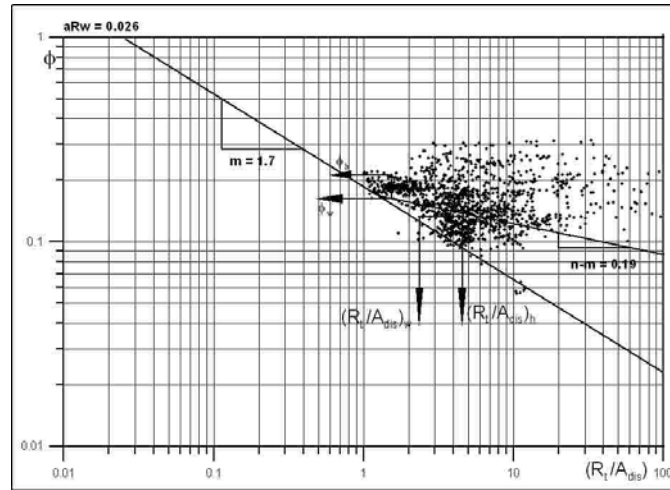
Wherea R<sub>w</sub> and φ are assumed to be the same in the hydrocarbon and water zone. Both numerator and denominator can be read directly from the log-log plot at the porosity value of the interval being analyzed. Also water saturation of the dispersed shale can be determined from:

$$S_w = I_{dis}^{-1/2} \quad (27)$$

Equation (27) implies the assumption that "n" equals 2.0 in formation with dispersed shale. When equation (20) is used in a conventional fashion, it is necessary to have a very good grasp of  $aR_w$  in order to come out with reasonable value of water saturation. Furthermore, "m" does not equal to 2.0. On the contrary, it can be determined directly from the log-log plot, provided that there are intervals with constant water saturation. From Dia-porosity cross plots (Islam *et al.*, 2013) showed that Kenz-28 well is represented by dispersed shale (Fig. 17). Table (4) shows the different values for the parameters in the studied rock interval, which are used in the accurate estimation of the total water saturation through the Kenz-28 well.

**Table 4:** Results obtained from Pickett's Plot (dispersed shale).

No	Well name	$aR_w$	a	m	n
1	KENZ-28	0.026	0.80	1.7	1.89



**Fig. 17:** Pickett's plot of the Bahariya Formation in Kenz-28 well (dispersed shale).

**3.2.3.Total Shale Model:**

Simandoux (1963) has shown that in some cases it is possible to use the following equation to calculate water saturation, independently of distribution of shale:

$$S_w = \sqrt{\frac{aR_w}{\phi^2 R_t} + \left(\frac{aR_w V_{tsh}}{2\phi^2 R_{tsh}}\right)} - \left(\frac{(aR_w + V_{tsh})}{2\phi^2 R_{tsh}}\right) \tag{28}$$

Where the subscript 'tsh' stands for total shale

One limitation is that the porosity exponent is set at 2.0 and the value of  $aR_w$  has to be well known. To circumvent these limitations, the cementation exponent changed from 2.0 to m as:

$$(R_t/A_{tsh}) = aR_w \phi^{-m} S_w^{-2} \tag{29}$$

The total shale group  $A_{tsh}$  is given by:

$$A_{tsh} = 1 + \frac{\phi^m R_t}{aR_w} \left( 2B_{tsh} - 2B_{tsh} \sqrt{\frac{aR_w}{\phi^m R_t} + B_{tsh}} \right) \tag{30}$$

And

$$B_{tsh} = (aR_w V_{tsh}) / (2\phi^m R_{tsh}) \tag{31}$$

Taking logarithm on both sides of equation (29) results in:

$$\text{Log } (R_t/A_{tsh}) = -m \log \phi + \log (aR_w) + \log(S_w^{-2}) \tag{32}$$

Equation (32) indicates that a log-log cross plot of  $R_t/A_{tsh}$  versus porosity should be result in a straight line with slope equal to  $-m$ , provided that  $aR_w$  and  $S_w$  are constant. The resistivity index of total shale,  $I_{dis}$ , can be calculated from:

$$I_{dis} = (R_t/A_{tsh})_h / (R_t/A_{tsh})_w \tag{33}$$

Also water saturation of the dispersed shale can be determined from:

$$S_w = I_{tsh}^{-1/2} \tag{34}$$

Where "n" is assumed to be equal to 2.0. Also  $S_w$  can be determined from  $\phi_w$  and  $\phi_h$  at the same value of  $R_t/A_{tsh}$ . Figs. (18 - 24) show the Pickett's Plot for the total shale model for the studied wells. The cementation exponent "m" for this section has different values ranging from 1.6 to 2.1 which indicate the presence of consolidated sandstones. It may be noted that, cementation results is increasing the value of formation factor, while the tortuosity factor for this unit ranges from 0.7 to 0.93 in the studied wells. The reading of "n" has a range between 1.90 and 2.20. Table (5) shows the different values for these parameters at the studied rock interval, which can be used for the accurate estimation of the total water saturation through the studied wells.

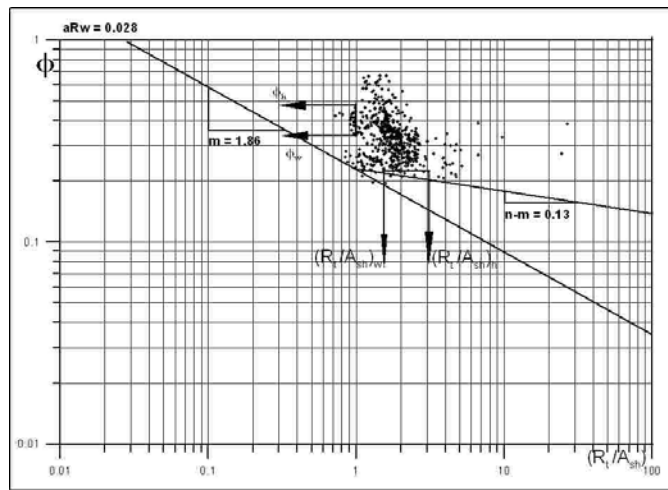


Fig. 18: Pickett's plot of the Bahariya Formation in Bassel-1X well (total shale model).

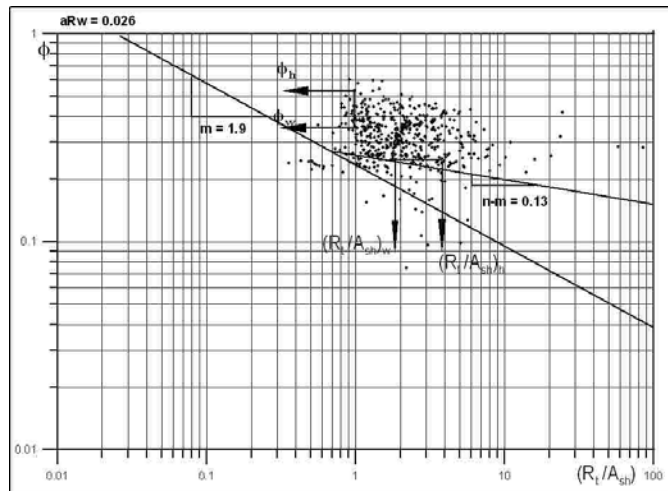


Fig. 19: Pickett's plot of the Bahariya Formation in Nour-1X well (total shale model).

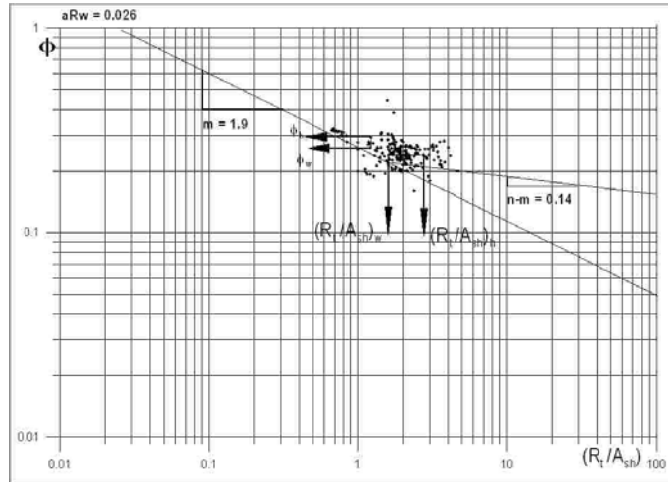


Fig. 20: Pickett's plot of the Bahariya Formation in Safir-N1X well (total Shale model).

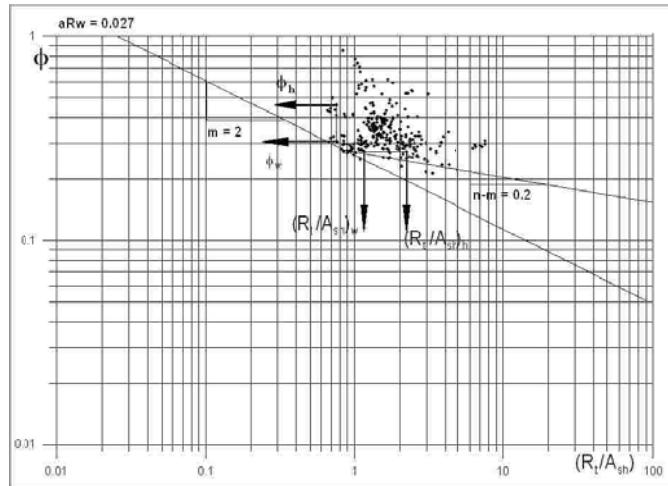


Fig. 21: Pickett's plot of the Bahariya Formation in Hayat-1X well (total shale model).

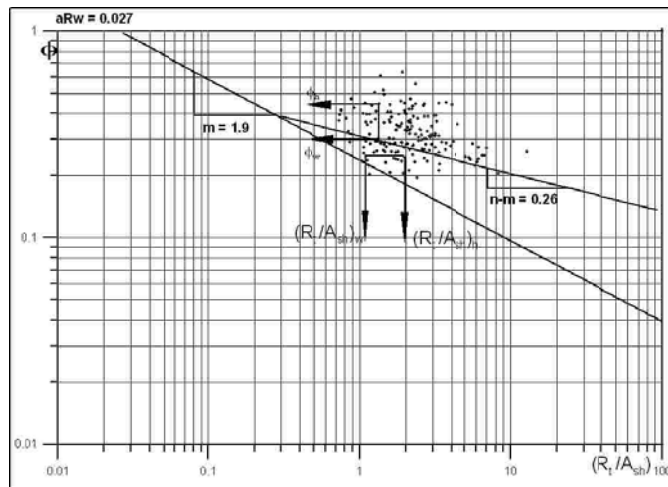


Fig. 22: Pickett's plot of the Bahariya Formation in Salam-3X well (total shale model).

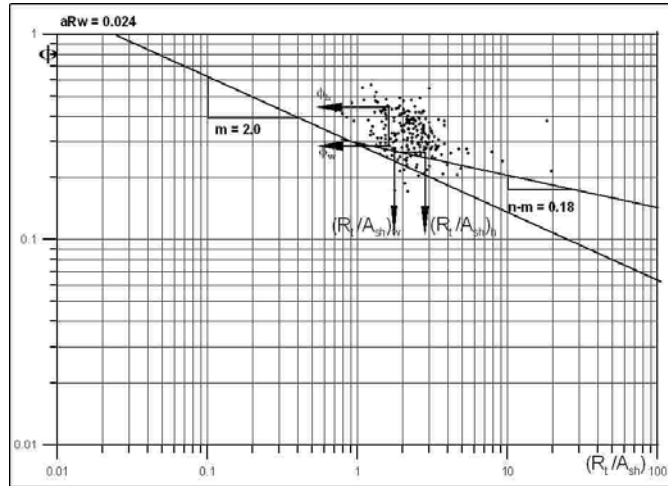


Fig. 23: Pickett's plot of the Bahariya Formation in Salam-N1 well (total shale model).

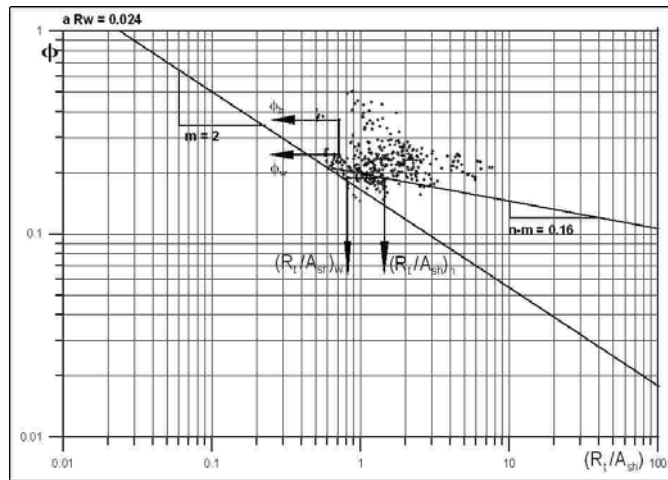


Fig. 24: Pickett's plot of the Bahariya Formation in TUT-w3x well (total shale model).

Table 5: The results obtained from Pickett's Plot (total shale model).

No	Well name	aRw	a	m	n
1	BASSEL_1X	0.028	0.93	1.86	1.99
2	NOUR_1X	0.026	0.87	1.90	2.03
3	SAFIR-N1X	0.026	0.87	1.90	2.05
4	HAYAT_1X	0.028	0.93	2.00	2.11
5	SALAM-3X	0.027	0.90	1.90	2.19
6	SALAM N1	0.024	0.80	2.00	2.18
7	TUT-W3X	0.024	0.90	2.00	2.16

**Conclusion:**

The conventional porosity – resistivity crossplot of Pickett's plot have been modified to be used in cases involving laminated, dispersed and total shale model. The method indicates that under favourable conditions, it is possible to determine the petrophysical parameters "m", "n" and "a" in case of clean and shaly formation. The advantage of this crossplot is that all shaly intervals can be displayed in a single plot together with porosity and water saturation. This method was applied to eight wells distributed in Sidi Barani Field in the northern part of Western Desert of Egypt. The value of "m" for Bahariya Formation has values ranges from 1.8 to 2.3 while "a" for this formation is ranging from 0.6 to 1. The "n" value varies from 1.4 to 2.1. These parameters can be used for the accurate estimation of water saturation and then the hydrocarbon saturation.

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