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AN INTEGRATED METHOD FOR MODELING FLUID SATURATION PROFILES IN BAHARIYA FORMATION, FALAKFIELD, WESTERN DESERT, EGYPT

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طريقة متكاملة لاستنباط نموذج لتشبع السوائل في تكوين البحرية، حقل فلك، الصحراء الغربية، مصر

الخلاصــة: معادلة ليفريت تعتبر من المعادلات التى يمكن استخدامها فى تحديد معامل التشبع فى الخزانات وعمل نموذج له، وعلى ذلك فإن دراسة الخاصية الشعرية فى العينات الصخرية المختلفة لحقل فلك فى تكوين البحرية العلوى والذى ينتمى لعصر السينومانى السفلى (البسيونى وعبدالله، ١٩٨٩) يمكن الاستعانة بها فى استنتاج التشبع المائى للصخور عن طريق توقيع العلاقة ما بين نتائج الخاصية الشعرية مع معامل التشبع المائى الناتج من دراسة العينات الصخرية، ثم تحويل نتائج الخاصية الشعرية إلى حالة الخزان الفعلية، ومنها إلى الارتفاع والذى يمثل العمق بالنسبة إلى الخط الفاصل بين الهيدروكربونات والماء. ومن الجدير بالذكر أنه يمكن استنتاج معادلة موحدة يمكن استخدامها فى حساب التشبع المائى للصخر فى حقل ما باستخدام معادلة ليفريت ثم مضاهاة النتائج بتلك التى قد تم حسابها من قبل بالطريقة التقليدية باستخدام تسجيلات الآبار، وبعمل ذلك فى هذه الدراسة فقد وجدت مضاهاة متقاربة جدا بين طريقتى الحساب المذكورتين، وبذلك يمكن استخدامها مستقبلا لحسابات التشبع المائى بحقل فلك.

ABSTRACT: *In this work, Leveret J function methodology has been found ideal in characterizing water saturation within the reservoir and modeling fluid saturation profiles through a calculated software equation.Accordingly, the core capillary pressure data has been studied for the upper member of Bahariya Formation of Lower Cenomanian age (El-bassyouni and Abdullah, 1989) in Falak oil field area by plotting the capillary pressure of porous plate method versus the water saturation at which the pressure was applied, then capillary pressure curves were converted to reservoir condition in order to have more realistic capillary pressure curves similar to the reservoir conditions.*
The capillary pressure data were converted to height curves to simulate the reservoir fluid saturation along the depths above the free water level. Consequently, all the height curves that were plotted against the water saturation were normalized in order to have only one equation which directly represents the saturation profile in any well without using the resistivity tool data. Leveret J function has been used to extract an equation in this normalization process through the interactive petrophysics software.
The extracted equation, with a correlation coefficient reaches (92%) has been used to calculate the water saturation from this modeling process. The water saturation coefficients achieved for the upper member of Bahariya Formation in 4 wells in Falak oil field were correlated with the water saturation coefficients derived from log interpretation and were found to be in a very good match. Hence,the proposed equation could be safely used to obtain the water saturation and accordingly hydrocarbon volume for any other un-cored intervals in any upcoming wells within Falak area without resistivity input.

INTRODUCTION

The capillary forces in a petroleum reservoir are the result of the combined effect of the surface and interfacial tensions of the rock and fluids, the pore size and geometry, and the wetting characteristics of the system. Any curved surface between two immiscible fluids has the tendency to contract into the smallest possible area per unit volume. This is true whether the fluids are oil and water, water and gas (even air), or oil and gas. When two immiscible fluids are in contact, a discontinuity in pressure exists between the two fluids depending upon the curvature of the interface separating the fluids. This pressure difference is referred to as capillary pressure "Pc". The displacement of one fluid by another in the pores of a porous medium is either aided or opposed by the surface forces of capillary pressure. As a consequence, in order to maintain a porous medium partially saturated with non-wetting fluid and while the medium is also exposed to wetting fluid, it is necessary to maintain the pressure of the non-wetting fluid at a value greater than that in the wetting fluid. Pc is expressed as:

$$Pc = Pnw - Pw \quad (1)$$

(Tarek Ahmed, 2001)

where:

Pnw = Pressure of non-wetting phase.

Pw = Pressure of the wetting phase.

That is, the pressure excess in the non-wetting fluid is the capillary pressure, and this quantity is a function of saturation. This is the defining equation for capillary pressure in a porous medium.

The laboratory measured capillary pressure data must be converted to equivalent reservoir conditions through the following equation:

$$Pc(Res.) = Pc\ (Lab)\ \frac{(\sigma\ Cos\ \theta)Res.}{(\sigma\ Cos\ \theta)Lab} \quad (2)$$

(Harrison &Jing, 2001)

where (σ) and (θ) refer to the interfacial tension and the contact angle in oil/brine systemrespectively.

It is common to observe a higher capillary transition zone derived from core based drainage capillary pressure curves (air/brine or air/Hg) than that derived from resistivity logs. Assuming the log derived saturation is reliable, one main reason for any disparity may be due to the above conversion from laboratory to reservoir conditions failing to take into account reservoir interfacial tension and stress effects.

Converting capillary pressures to the height above the free water level:

Converting capillary pressure to the height above the free water level is believed to be of great importance in generating the saturation height modeling, as the pressure gradients for the oil and water phases are determined by the fluid densities, the water saturation distribution in the reservoir system above the free water level is controlled by the balance of capillary and buoyancy (gravity and density difference) forces.Equation (3) indicates the conversion between the capillary pressure and the height above the free water level (FWL):

$$Pc = (\rho w - \rho o)gh \quad (3)$$

(Tarek Ahmed, 2001)

where:

g = the gravity, cm/sec2

h = theheight above the free water level, cm.

ρw = water density, g/cc.

ρo = oil density, g/cc.

In oilfield units where the pressure measured in psi, h in feet, and fluid densities are in lb/ft3, the height above the free water level is calculated using the following equation:

$$h = \frac{Pc * 144}{(\rho_w - \rho_o)} \quad (4)$$

(Harrison & Jing, 2001)

Study Objectives:

The present study has five main objectives which can be summarized as:

1-Analyze the capillary pressure data extracted from measuring the capillary pressure on four core plugs from Bahariya Formation in one well of Falak oil field.

2-Plotting the capillary pressure data versus the water saturation at which the capillary pressure data was measured.

3-Converting the capillary pressure into a height curve above the free water level.

4-Extracting an equation using Leveret (J) function in order to have a water saturation equation that could be used to calculate saturation measurements in un-cored intervals.

5-Run the extracted equation in different wells in Falak Field and correlate its output with different saturations calculated from petrophysical well log analysis.

Data available:

Four core plugs have been selected to measure the capillary pressure through the porous plate method in Well-A in Falak area.The water saturation and capillary pressure measurements from the core analysis, electrical logs, porosity and water saturation from the petrophysical interpretationof the cored well and four different wells were all used to achieve this study. The other fourwells were used as they represent a range of reservoir fluids and a different wide range of porosity and permeability.The capillary pressure data for the four plugs are given in table (1).

In order to use the core data in this study, the depths of the core plugs have been matched with the wireline logs.Seven feet of difference have been found to be the shift between the drilling and real wireline depth.Accordingly, the depth difference was corrected in correlation with the logs and the new depths are considered.

Methodology:

The data have been used to plot the capillary pressure curves for the four samples against the water saturation and as an input in the software as two different curves, one for the capillary pressure and the other for the saturation, respectively as seen in figure (1).

All the plug samples were found more or less with the same porosity of high value reaching around 24% as an average.As a result,the data could be applied for the stress correction as an option in the software for both saturation and capillary pressure via the following equations:

$$Pc_{(Corrected)} = Pc * \left(\frac{\o res.}{\o lab}\right)^{-0.5} \quad (5)$$

(Interactive Petrophysics Manual, 2010)

$$SwPc_{(Corrected)} = 1 - \{(1-SwPc) * \{(\phi\,res.)/(\phi\,lab)\} \quad (6)$$

(Interactive Petrophysics Manual, 2010)

where:

Pc = Input raw capillary pressure curve.

SwPc = Input Pc saturation (wetting phase) curve.

Pc (Corrected) = Stress corrected Pc curve.

SwPc (Corrected) = Stress corrected Pc saturation curve.

Table (1): capillary pressure versus water saturation from special core analysis for the studied core plugs.

Depth	Plug Number	Porosity (%) and Permeability (mD)	Porosity (%) and Permeability (mD)	Pressure	Saturation
(ft.)		(Ambient)	(5000 psi)	(psi)	(%)
5942.93	**9**	26.30	24.90	0.5	97.6
				1	94.2
				2	86.1
				4	76.4
				10	65.1
		344.00	315.70	25	47.6
				50	33.4
				100	25.5
				150	22.9
				200	21.4
5643.83	**10**	25.40	23.60	**0.5**	**96.6**
				1	93
				2	65.4
				4	52.9
				10	41.5
		506.00	450.00	25	29.5
				50	20.2
				100	15.8
				150	14.7
				200	13.7
5944.83	**11**	**26.60**	**24.00**	**0.5**	**95.9**
				1	88.5
				2	78.9
				4	64.6
				10	51.7
		572	507.50	25	33.2
				50	22.6
				100	17.2
				150	15.6
				200	13.8
5960.45	**27 A**	**22.40**	**20.80**	**0.5**	**97.2**
				1	96.6
				2	88
				4	43.2
				10	31.5
		104	92.4	25	27
				50	25
				100	22.5
				150	21.2
				200	20.5

Øres. = Porosity at reservoir conditions.

Ølab = Porosity at ambient or lab conditions

The porosity in the reservoir conditions has been taken as the porosity with 5000 psi applied in the special core analysis while the porosity in ambient conditions was used as that of lab in order to use as the stress correction factor with value of (0.95) as an input from averaging the special and conventional core analysis porosities.

After stress correction, the capillary pressure curves have been converted to the reservoir conditions using equation (2) and the parameters of the interfacial tension were taken from table (2) where the contact angles in lab and reservoir are zero and 30 degrees respectively, while the interfacial tension in lab and reservoir conditions were applied as 72 and 30 dyne/cm respectively, then the conversion was applied as shown in figure (2).

Table (2): Interfacial tension and contact angles, (Core Laboratories, 1982).

Wetting phase	Non-wetting Phase	Contact angle θ	IFT σ
Brine	Oil	30	30
Brine	Oil	30	48
Brine	Gas	0	72
Brine	Gas	0	50
Oil	Gas	0	4
Gas	Mercury	140	480

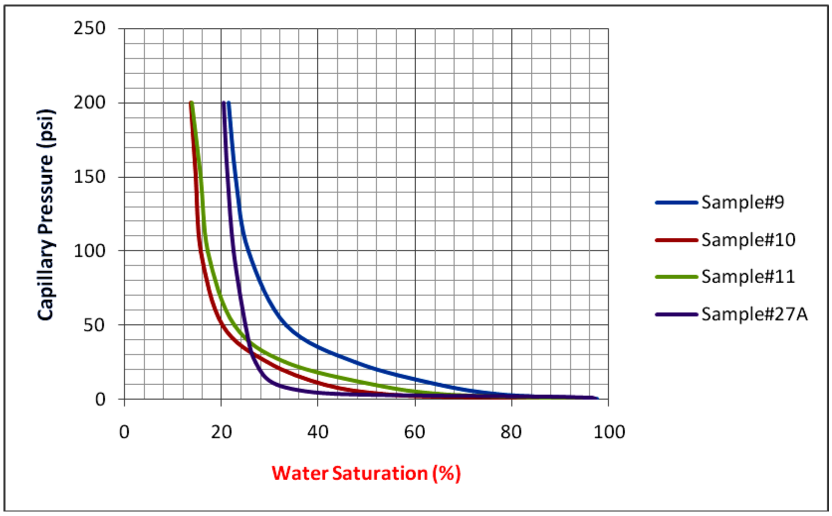


Figure (1) Capillary pressure versus water saturation for the core samples.

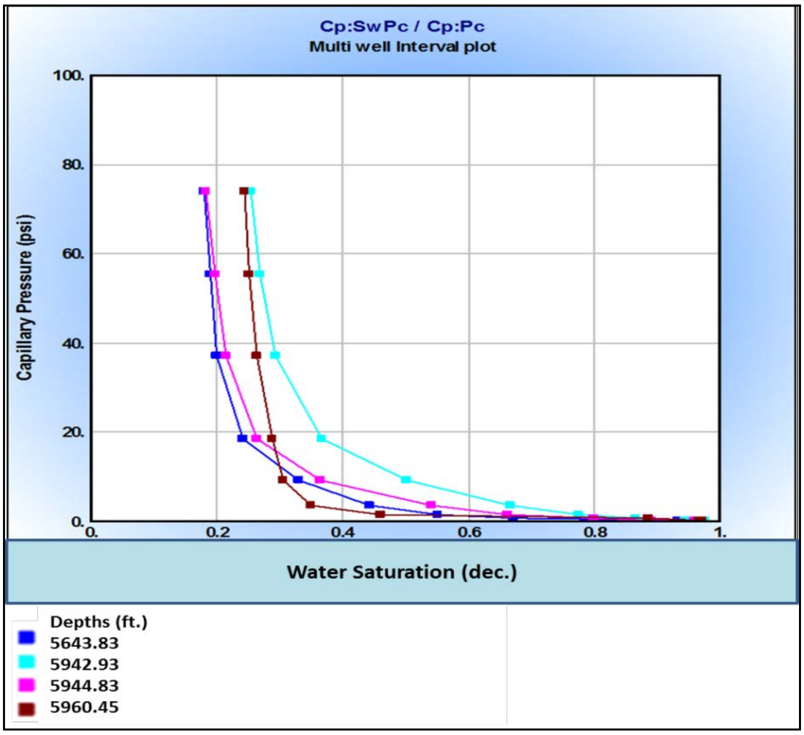


Figure (2): Corrected capillary pressure versus plugs saturation

Furthermore, it is of high importance to have the plugs recognized by their porosities and permeabilities. Accordingly, it has been found that the porosity of the plugs ranges between 20 to 30%as shown in figure (3) whereas figure (4) has been established to discriminate the plugs based on permeability flag; the permeability range was between 100 and 300 mD.

In fact, the correction applied on the capillary pressure curves in order to reach the actual reservoir conditions is not enough for the saturation height modeling, but it is considered as the first step for good fluid distribution model. The most important step in such process is converting the corrected capillary pressure to the height above the free water level. Equation (4) has been used for having the height in feet and the densities of water and oil were assumed to be 1 and 0.7 g/cc respectively. Figure (5) shows the height above the free water level after applying such conversion.

Leveret (J) function:

After estimating the height above the free water level, an equation should be defined in order to complete the saturation height modeling, the Leveret J function has been selected to complete the process.A capillary pressure analysishad been obtained on small core samples that represent an extremely small part of the reservoir and therefore, it is necessary to combine all capillary data to classify a particular reservoir.

Realizing that capillary pressure should depend on the porosity, interfacial tension, and mean pore radius, Leveret defined the dimensionless function of saturation as follows, (Ahmed, 2001):

$$J = 0.21654 * \left(\frac{Pc}{\sigma * Cos\theta}\right) * \left(\frac{K}{ø}\right)^{0.5} \quad \ldots\ldots\ldots\ldots\ldots\ldots (7)$$

(Harrison &Jing, 2001)

where:

J = Leveret J function.

Pc = Corrected capillary pressure (psi).

σ = Interfacial tension (dynes/cm).

θ = Contact angle of oil/water system.

K = Permeability (mD).

Ø = Fractional Porosity.

The J-function was originally proposed as a means of converting allcapillary-pressure data to a universal curve in a normalization process, which will be used further in establishing an equation for calculating the water saturation without true resistivity curve from conventional wireline logs. In this study, this dimensionless capillary-pressure function serves quite well in many cases to remove discrepancies in the Pc versus Sw curves and to reduce them into one common curve. By using this function, a J curve has been calculated for each plug and plotted in figure(6) against the water saturation, then Lambda regression equation has been applied for completing the normalization process as follows:

$$Sw = a * J^{-\lambda} + b \quad \ldots\ldots\ldots\ldots\ldots\ldots (8)$$

Lambda equation has been used with a correlation coefficient reaching92%, and a resulted universal equation has been established for calculating the water saturation in any well in the same area as shown in figure (7).

$$Sw = 0.41496 * J^{-0.33543} + 0.06028 \quad \ldots\ldots\ldots\ldots (9)$$

where:

a = 0.41496

λ = -0.33543

b = 0.06028

Results and correlation with log saturation:

The equation extracted in a saturation height function must be confirmed by application in the well in which the core data was taken, and then on different logs in the same field. On the other hand, the depth of the free water level must be an input in the software in order to start saturation correlation with the other different wells to have this equation proved in the field under investigation.

Well-1 with the core analysis has been used to tie the saturation extracted from the modeling process with the saturation extracted from formation evaluation of the conventional logs.Figure (8) demonstrates a correlation between water saturation from both methods in Well-Awith core while figure (9) demonstrated this relationship in a simple crossplot that shows a linear regression between the results.This good match indicatesthat the equation extracted from capillary pressure saturation height modeling may also be used to calculate the water saturation in absence of resistivity measurements in the borehole.

In order to have a complete saturation height modeling study in the area, the equation has been used in tying the core capillary pressure with the water saturation calculated from the conventional formation evaluation and must be applied in different wells to see how good the saturation equation will be in different boreholes as seen in figures (10 and 11).In Well-X, there is a very good match along the whole reservoir with small differences in the saturation value in small intervals, while in Well-Y the saturation calculated from the wireline logs is more complicated and shows some difference from that calculated through the saturation height function in the upper zonedue to low resistivity attached to this interval that is probably affected by some minerals in the reservoir rock. In Well-Z and N, the match between both saturations seems to be very good despite the thin laminations existing in Well-Z water saturation.

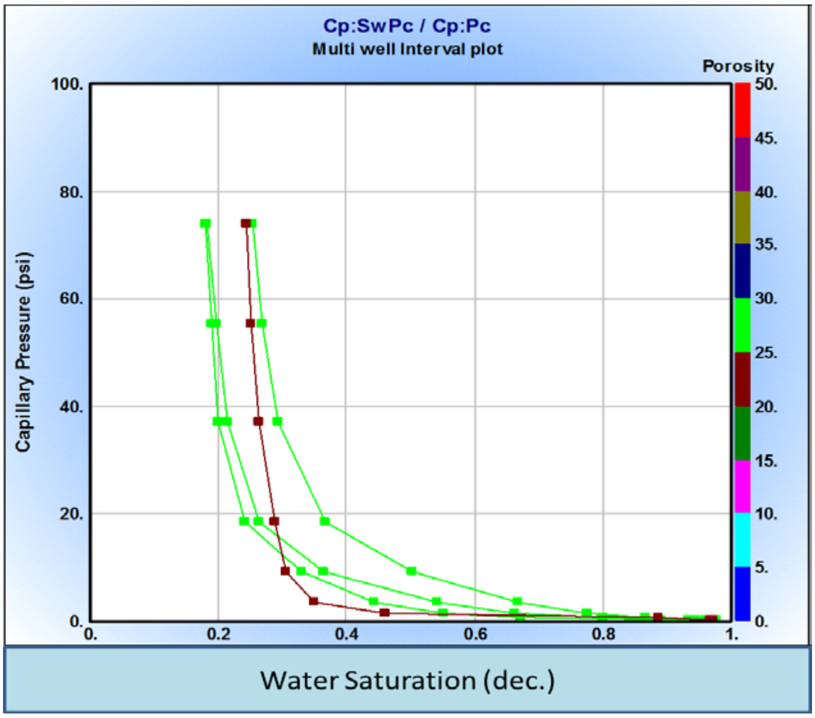


Figure (3): Corrected capillary pressure versus plugs saturation with porosity flag.

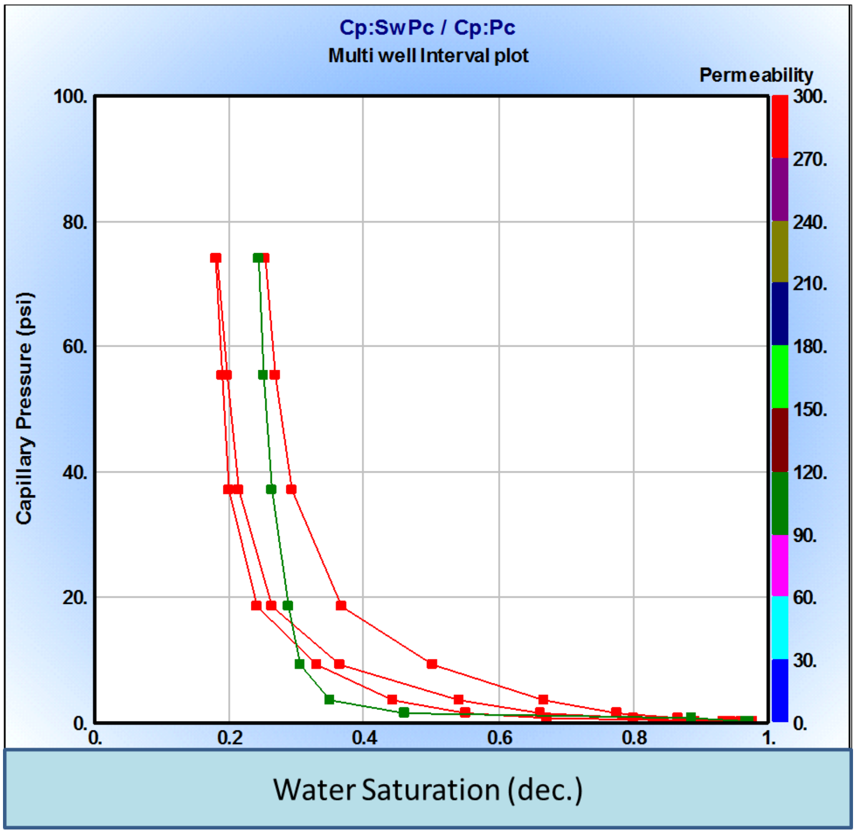


Figure (4): Corrected capillary pressure versus plugs water saturation with permeability flag.

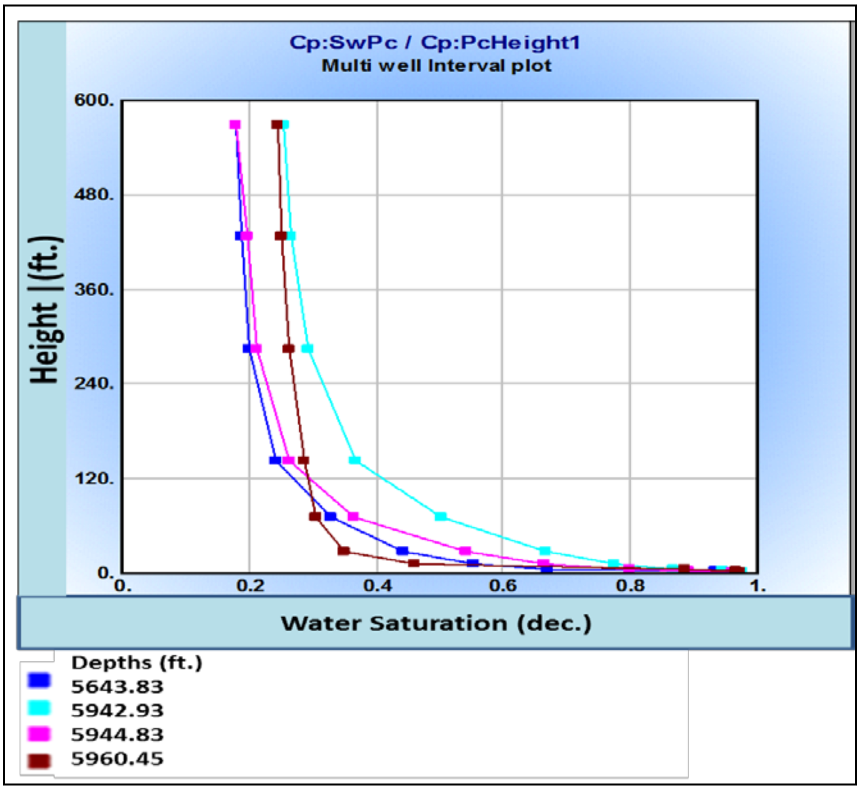


Figure (5): Theheight in feet above the free water level versus plugs saturation.

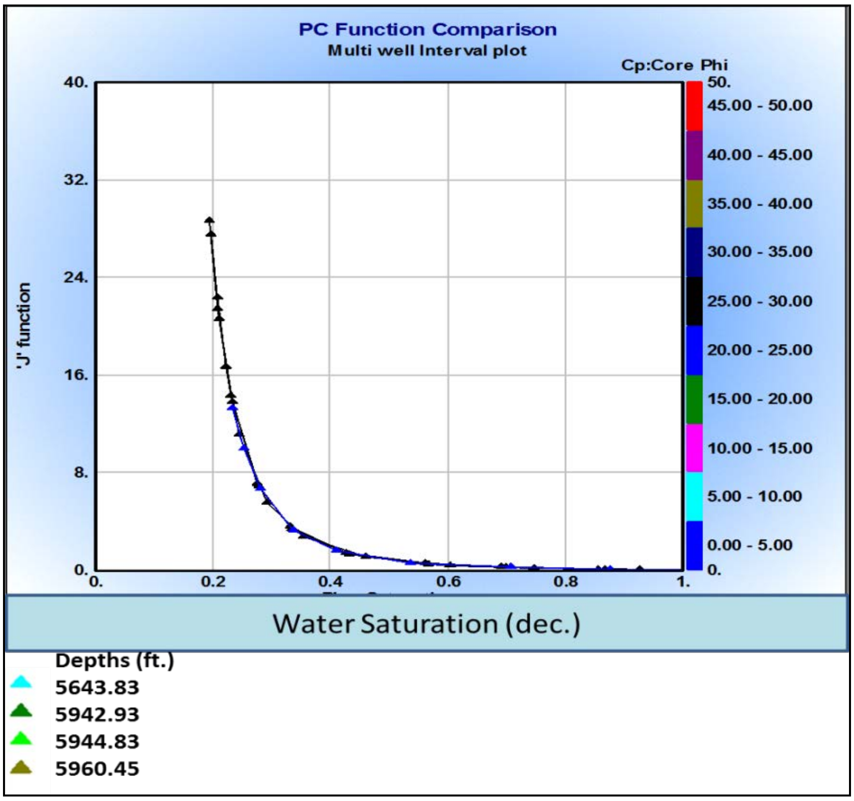


Figure (6): J-function versus plug saturation.

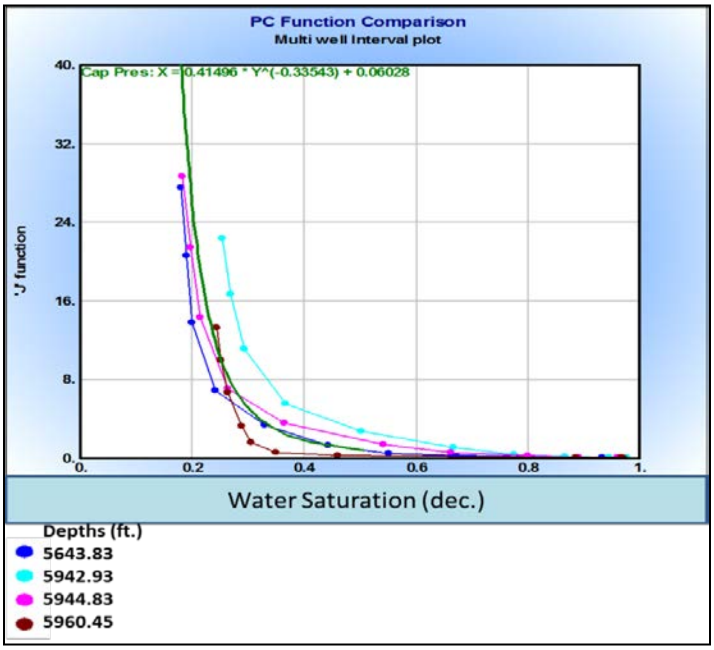


Figure (7): The universal equation estimated from the normalization process.

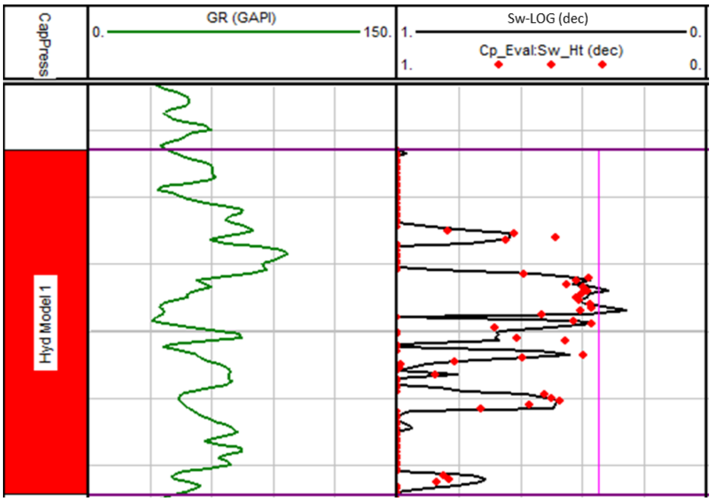


Figure (8): Correlation between water saturation from logs and capillary pressure function in Well-A.

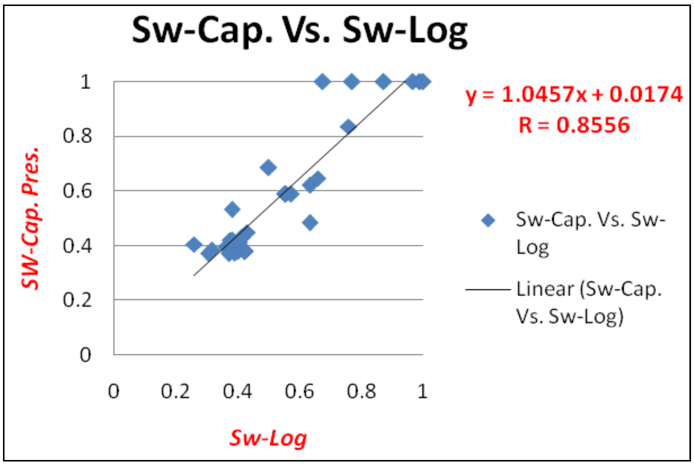


Figure (9): Crossplot between water saturation from logs and capillary pressure functionin Well-A.

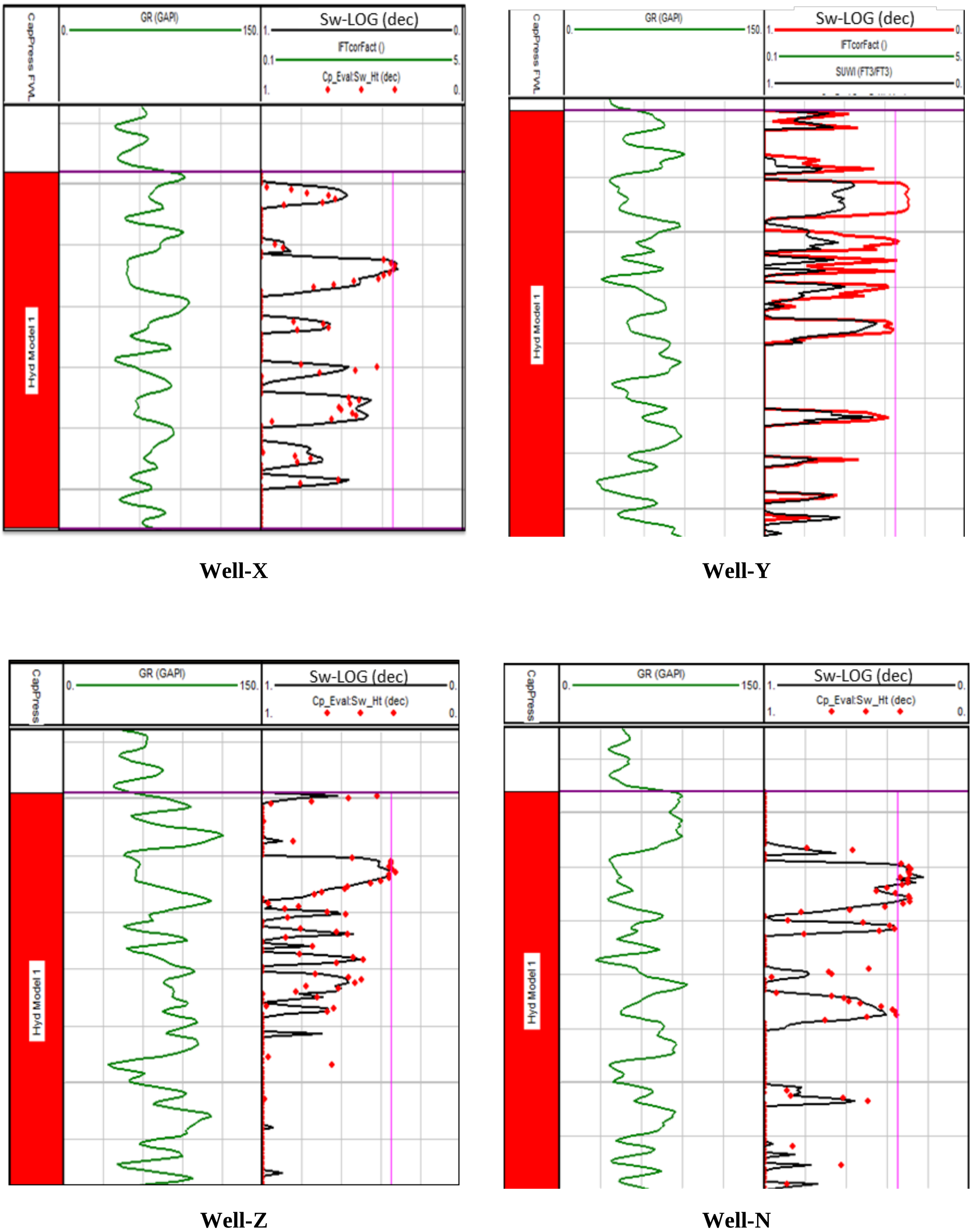
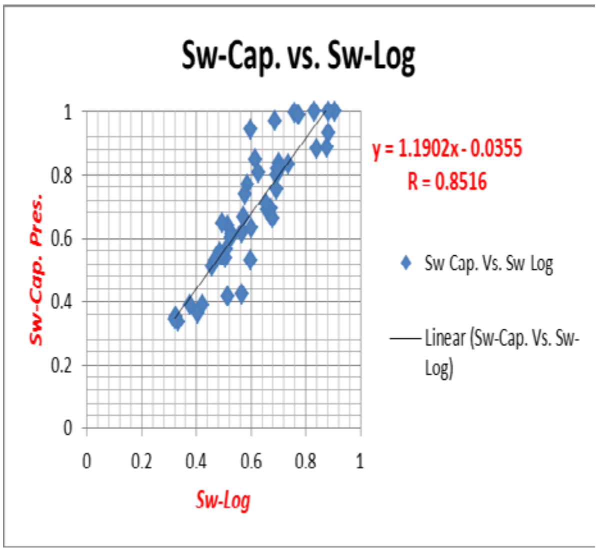
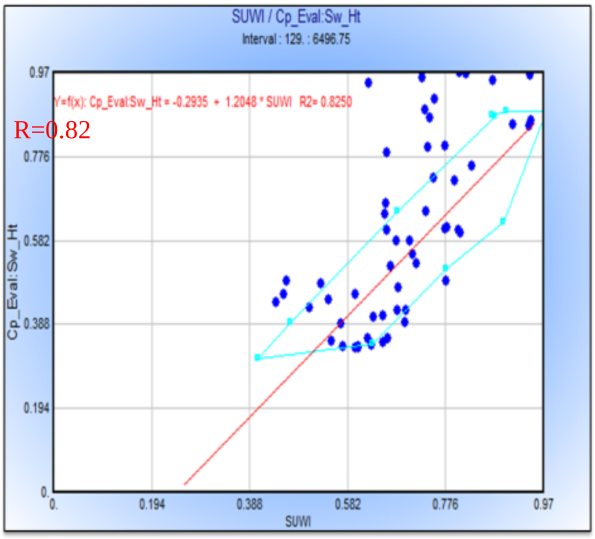


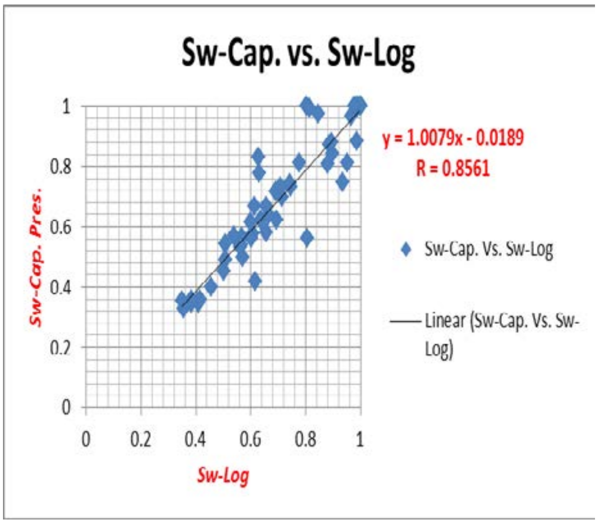
Figure (10): Correlation between water saturation from logs and from capillary pressure function in four different wells in the same field.



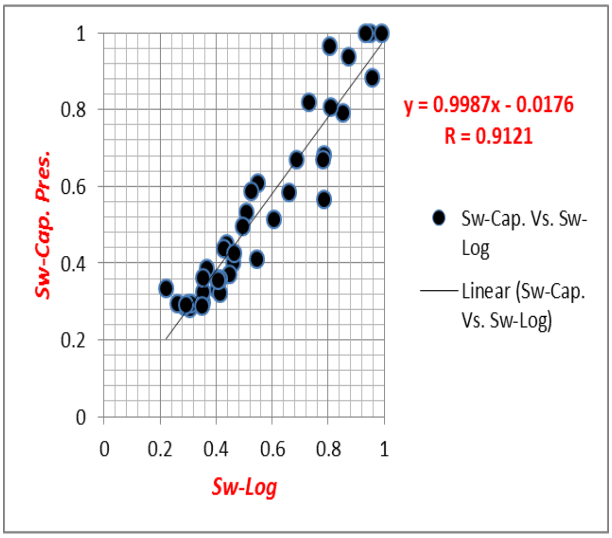
Well-X



Well-Y



Well-Z



Well-N

Figure (11): Crossplot between water saturation from capillary pressure function and water saturation from logs in four different wells in the same field.

CONCLUSION

Capillary pressure core data have been used to extract a water saturation equationcould be used for modeling the saturation profiles in Bahariya Formation reservoir in Falak oil field, Western Desert, Egypt.As a result, this equation could be used safely for any other un-cored intervals in any upcoming well in the Falak area without resistivity input to extract the water saturation and consequentlyfor the hydrocarbon volumeestimation in the Bahariya Formation reservoir.

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