Water Saturation Computation from Laboratory, 3D Regression

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Résumé — **Estimation de la saturation en eau au laboratoire par régression 3D** — La détermination précise des réserves initiales d'un réservoir est très importante pour obtenir une bonne estimation de la capacité de production d'un gisement d'hydrocarbures. La formule modifiée d'Archie ($S_w = (a\, R_w/\phi^m\, R_t)^{1/n}$) constitue l'équation de base au calcul de la saturation en eau dans le sable ou l'utilisation d'un modèle de saturation pour le sable argileux. Une bonne évaluation de la saturation en eau dépend de la détermination la plus précise possible des paramètres d'Archie *a, m, n*.

Cet article presente une nouvelle technique destinée à déterminer les paramètres *a, m, n* d'Archie. Cette technique est basée sur le principe de régression en 3D. Elle surmonte le problème de l'incertitude des valeurs de saturation en eau.

Deux exemples de terrain sont présentés afin de bien tester les résultats de la technique de régression 3D et les comparer à trois autres techniques — méthode CAPE (*Core Archie-Parameters Estimation*) méthode conventionnelle et valeurs par défaut — concernant les valeurs des paramètres *a*, *m* and *n* de la formule d'Archie et de la saturation en eau.

Abstract — *Water Saturation Computation from Laboratory, 3D Regression* — *An accurate determination of initial oil in place in the early life of reservoirs or an evaluation of a developed reservoir is required to well estimate the hydrocarbon volumes. Modified Archie's formula ($S_w = (a\, R_w/\phi^m\, R_t)^{1/n}$) is the basic equation to compute water saturation in clean formation or suitable shaly water saturation model in shaly formation. The accuracy of water saturation value for given reservoir conditions depends on the accuracy of Archie's parameters a, m and n. The terms of Archie's relationship have been subjected to many laboratory investigations and even more speculations. There are many factors affecting porosity exponent, m, saturation exponent, n and tortuosity factor, a. Therefore, it is very difficult to fix Archie's parameters and neglecting reservoir characteristics such as rock wettability, formation water salinity, permeability, porosity and fluids distribution.*

This paper presents a new technique to determine Archie's parameters a, m and n. The developed technique is based on the concept of three dimensional-regression (3D) plot of water saturation, formation resistivity and porosity. This 3D technique provides simultaneous values of Archie's parameters. Also, the 3D technique overcomes the uncertainty problems due to the separate use of formation resistivity factor-porosity and water saturation equations to get a, m and n parameters.

Two field examples are given to show the applicability of the 3D technique in comparison with three other techniques:

– common values of Archie's parameters,

– conventional technique and

– Core Archie-Parameter Estimation (CAPE) technique.

The comparison among the four techniques has shown that 3D technique provides an accurate and physically meaningful way to get Archie's parameters a, m and n for given core samples. Water saturation profiles, using Archie's parameters obtained from the four techniques, have been obtained for the studied section in the wells. These profiles have shown a significant difference in water saturation values. This difference could be mainly attributed to the uncertainty level for Archie's parameters from each technique. The effect of saturation exponent on the accuracy of water saturation computation was tested using Archie's parameters derived from conventional technique and 3D technique in the two wells.

NOMENCLATURE

a =   tortuosity factor
m =   cementation factor
n =   saturation exponent
S_w =   water saturation, fraction
V_{sh} =   shale volume, $\Omega \cdot m$
R_{sh} =   shale resistivity
GR =   gamma ray reading, API
R_t =   resistivity of rock, $\Omega \cdot m$
R_w =   resistivity of brine, $\Omega \cdot m$
R_o =   resistivity of rock with $S_w = 1.0$, $\Omega \cdot m$
I_r =   resistivity index
F =   formation resistivity factor
ϕ =   formation porosity, fraction
σ_{Sw} =   standard deviation in water saturation.

INTRODUCTION

In routine formation evaluation Archie's parameters *a, m* and *n* are held constant for a given sample of a reservoir rock. In effect, this presumed constancy formulates the basis for the determination of hydrocarbon saturation from resistivity measurements for a particular lithology. An increasing number of cases are being encountered where the saturation exponent, *n*, has been observed to vary from the common value of 2 in strongly water wet reservoir rocks to 25 in strongly oil wet reservoir rocks. Wettability effects become important when brine saturation lowered. Field experience has also shown that the cementation factor, *m*, and the tortuosity factor, *a*, depend on the petrophysical and mechanical properties of a rock [1-3].

Petroleum literature presents an exhaustive review of the results determining Archie's parameters and also water saturation computation processes. In quantitative log interpretation, accurate water saturation requires good values of Archie's parameters. These parameters are used either in Archie's saturation equation in clean formation or in a shaly sand water saturation model in shaly formation.

In this paper, the authors propose a new technique to determine Archie's parameters, three dimensional regression (3D) technique which is based on the analytical expression of 3D plot of R_t/R_w *versus* S_w and ϕ. Water saturation profiles are calculated using common values (1,2,2), conventional, CAPE and 3D techniques for selected two wells. In the case of clean sands, Archie formula was used to compute water saturation. In the case of shaly sand sections three shaly sand models were applied and the chosen water saturation was an average value of the three models used.

1 CALCULATION OF ARCHIE'S PARAMETERS

An exact computation of water saturation using Archie's formula is based on an accurate values of Archie's parameters *a, m* and *n*. In this study, 10 clean sand core samples were selected for wells A and B. For each core sample, the electrical resistivity R_o at 100% water saturation and R_t at different water saturation percentages were measured at room temperature. The resistivity of simulated brine was fixed at 0.12 $\Omega \cdot m$. This resistivity value corresponds to formation water resistivity 0.054 $\Omega \cdot m$ at reservoir temperature.

Table 1 shows the values of formation resistivity factor F, (R_o/R_w) and porosity for 10 core samples of well A and well B. Table 2 contains the measured water saturation for well A and well B. The average water saturation value for well A was 30.5% and for well B was 12.25%. These

TABLE 1

Formation resistivity factor, *F* and porosity, ϕ for 10 core samples

Well A

F	17.8	14.4	10	11.3	10.9	9.5	22.7	16.8	10.2	11.5
ϕ	28.2	31.3	37.4	35.1	35.9	38	0.25	0.29	36.9	34.5

Well B

F	35	11	12.7	34	14.5	12.7	10.5	9.1	9.5	6.4
ϕ	14.2	26.7	24.6	14.3	23	25.4	27.2	30.2	28.5	35.6

TABLE 2

Laboratory measured water saturation of 10 especially preserved core samples

Well A

Sample	1	2	3	4	5	6	7	8	9	10
S_w	33	29.5	28.5	33	31.5	30.5	31	29	31	28

Average water saturation = 30.5%.

Well B

Sample	1	2	3	4	5	6	7	8	9	10
S_w	13	10.5	12	11.5	13	12.5	10.5	12	13	14.5

Average water saturation = 12.25%.

TABLE 3

Electrical resistivity, R_t; resistivity index, I_r; fractional water saturation, S_w;
and core sample porosity, ϕ for 6 core samples from well A and well B

Well A

Sample No.	ϕ	S_w	R_t	I_r	n
1	28.2	100	2.14	1	1.87
		83	3.09	1.44	
		63.9	4.9	2.29	
		56.9	5.92	2.77	
		28.3	22.2	10.4	
2	31.3	100	1.73	1	2.04
		83.6	2.47	1.43	
		41.2	10.57	6.11	
		30	19.37	11.2	
		21.7	38.93	22.5	
3	37.4	100	1.2	1	2.08
		93.6	1.38	1.15	
		81.7	1.82	1.52	
		25.6	19.08	15.9	
4	35.1	100	1.36	1	2.23
		75.5	2.42	1.78	
		67.2	3.06	2.25	
		27.6	18.9	13.9	
		12.9	90.98	66.9	
5	35.9	100	1.31	1	2.06
		93.3	1.52	1.16	
		72.8	2.49	1.9	
		27.3	18.47	14.1	
		16.3	53.7	41	
6	38	100	1.14	1	2.37
		87.1	1.58	1.39	
		78.6	2.02	1.77	
		27.3	24.74	21.7	

Average saturation exponent, n = 2.1.

TABLE 3 (continued)

Electrical resistivity, R_t; resistivity index, I_r; fractional water saturation, S_w;
and core sample porosity, ϕ for 6 core samples from well A and well B

Well B

Sample No.	ϕ	S_w	R_t	I_r	n
1	14.2	100	4.2	1	2.17
		71.1	8.81	2.09	
		66.6	10.11	2.41	
		55.4	15.16	3.61	
		40.8	28.74	6.84	
		35.9	38.18	9.09	
2	26.7	100	1.32	1	1.88
		57	3.78	2.86	
		25.3	17.36	13.15	
		16.3	39.84	30.18	
		15.9	40.88	31	
		15	47.60	36.06	
3	24.6	100	1.52	1	2.09
		90.2	1.91	1.26	
		73.3	3.24	2.13	
		35.5	12.98	8.54	
		25	28.04	18.45	
		24.5	29.17	19.19	
4	14.3	100	4.08	1	2.37
		77.1	7.52	1.84	
		45.2	26.6	6.52	
		40	34.87	8.55	
		36.9	42.41	10.39	
		35.9	45.32	11.11	
5	25.2	100	1.46	1	2.12
		75.5	2.66	1.78	
		52.3	5.78	3.96	
		26.2	24.75	16.95	
		21.5	39	26.71	
		21.1	40	27.39	
6	23	100	1.74	1	2.53
		40.9	16.46	9.46	
		39.4	18.55	10.66	
		29.8	36.65	21.01	
		19.9	99	56.89	
		19.3	110	63.21	

Average saturation exponent, $n = 2.19$.

laboratory water saturation values have been used in calculating Archie's parameters while the average values were being taken as references for the computed water saturation values from logging data with the use Archie's parameters by different techniques. Table 3 illustrates core sample resistivity, R_t at different water saturation, resistivity index, I_r, porosity, ϕ for 6 core samples from wells A and B. Using the same specially preserved core samples, the water saturation has been measured in the laboratory.

1.2 Conventional Determination of *a*, *m* and *n*

In 1942, Archie proposed an empirical relationship between rock resistivity, R_t, with its porosity, ϕ, and water saturation S_w.

$$S_w^n = a R_w / \phi^m R_t = R_o / R_t = 1/I_r \qquad (1)$$

Other terms I_r, m, and n represent the resistivity index, the cementation factor and the saturation exponent. He has also shown experimentally that the resistivity of rock fully saturated with brine, R_o, is related to the brine resistivity, R_w, by:

$$R_o = F R_w \qquad (2)$$

where F is formation resistivity factor. Archie's formula ($F = 1/\phi^{m'}$) has been modified and tortousity factor, a, was added to Archie's formula [4]. It has taken the following form:

$$F = a/\phi^m \qquad (3)$$

1.2.1 Conventional Determination of *a* and *m*

The conventional determination of a and m is based on Equation (3) and is rewritten as:

$$\log F = \log a - m \log \phi \qquad (4)$$

Plot of $\log F$ *vs.* $\log \phi$ is used to determine a and m for the core samples. The cementation factor m, is determined from the slope of the least square fit straight line of the plotted points, while the tortuosity factor is given from the intercept of the line where $\phi = 1$. Note that, in this plot, only points of $S_w = 1.0$ is used. Archie's parameters a and m were determined as 1.36 and 2.03 for well A and 0.95 and 1.85 for well B.

1.2.2 Conventional Determination of *n*

The classical process to determine saturation exponent n is based on Equation (1). This equation is rewritten as:

$$\log I_r = -n \log S_w \qquad (5)$$

The bi-logarithmic plot of I_r *versus* S_w gives a straight line with negative slope n. Table 3 contains the saturation exponent value for each core sample: this value is determined

form the bi-logarithmic plot of I_r and S_w for each core sample. Sometimes, data are plotted as $\log R_t$ *vs.* $\log S_w$. This form is mathematically equivalent to the bi-logarithmic plot of I_r and S_w and provides the same value of n. The retained saturation exponent is the average values of the 6 core samples measurements. The saturation exponent equals to 2.1 for well A and 2.19 for well B. It is obvious that the conventional technique treats the determination of n as a separate problem from a and m. This separation is not physically correct, thereby; it induces an error in the value of water saturation using Equation (1).

1.3 Core Archie-Parameter Estimation (CAPE)

A data analysis approach is presented in [5] to determine Archie's parameters m and n and optionally n from standard resistivity measurements on core samples. The analysis method, Core Archie-Parameters Estimation (CAPE) determines m and n and optionally a by minimising the error between computed water and measured water saturations. The mean square saturation error ε, is given by:

$$\varepsilon = \sum_j \sum_i [S_{wij} - (aR_{wij} / \phi_i^m R_{tij})^{1/n}]^2 \qquad (6)$$

Where j = core index, i = index for each of the core j measurements, S_{wij} = ith laboratory measured water saturation for core j (fraction), R_{tij} = ith laboratory measured resistivity for core j, $\Omega \cdot m$, and ϕ_j = core j porosity (fraction). Equation (6) calculates the minimum error between measured core water saturation and computed water saturation by Archie's formula, by adjusting m, n and optionally a in the equation.

Table 4 illustrates typical results from CAPE and conventional methods and shows a, m and n values calculated with the two methods for clean sandstone core samples. It is obvious that the values of a, m and n are different for a given set of points.

TABLE 4

Archie's parameters values from four techniques for well A and well B

Well A			
Technique	*a*	*m*	*n*
Common values	0.65	2.15	2
Conventional	1.36	2.03	2.1
CAPE	1.64	1.87	2.21
3D	1.43	1.97	2.15
Well B			
Technique	*a*	*m*	*n*
Common values	0.65	2.15	2
Conventional	0.95	1.85	2.19
CAPE	1.04	1.79	1.95
3D	0.92	1.87	1.87

1.4 Three-Dimensional Regression (3D)

In this technique it is contended that, so far as Archie's parameters are concerned, the error in the water saturation value should be kept minimum. This is because the water saturation quantity is desired and is physically a meaningful quantity. Here, a method is developed to determine Archie's parameters *a, m* and *n* using standard resistivity measurements on core samples [6-10].

Methodology: The basis of the 3D technique is to view S_w in Archie's formula Equation (1) as a variable in three-dimensional regression plot of S_w, R_w/R_t and ϕ. The 3D technique determines Archie's parameters *a, m* and *n* by solving three simultaneous equations of S_w, R_w/R_t and ϕ. Equation (1) is rearranged after taking the logarithm of both sides in the form:

$$\log R_w / R_t = -\log a + m \log \phi + n \log S_w \qquad (7)$$

The left hand side of Equation (7) is a dependent variable of the two independent variables S_w and ϕ. Equation (7) is an equation of a plane in 3D space of coordinates *X, Y* and *Z* ($X = \log \phi$, $Y = \log S_w$ and $Z = \log R_w/R_t$). The intersection of this plane with the plane ($X = 0.0$) gives a staight line of slope (*m*), with the plane ($Y = 0.0$) giving a straight line with slope (*n*) and with the plane ($Z = 0.0$) provides the value of (*a*) parameter.

For a given set of data for a core sample, we can obtain an equivalent set of variables *X, Y* and *Z*. Equation (7) will take the following form for *i* measurement points:

$$Z_i = -A + m X_i + n Y_i \qquad (8)$$

After normalizing Equation (8) for *N* readings, the following three simultaneous equations are resulted.

$$\Sigma Z_i = -NA + m \Sigma X_i + n \Sigma X_i \qquad (9)$$

$$\Sigma X_i Z_i = -A N \Sigma X_i + m \Sigma X_i^2 + n \Sigma X_i Y_i \qquad (10)$$

$$\Sigma Y_i Z_i = -A N \Sigma Y_i + m \Sigma X_i Y_i + n \Sigma Y_i^2 \qquad (11)$$

The solution of Equations (9-11) provides the values of Archie's parameters *a, m* and *n* for one core sample. For *j* core samples, running the same analysis produces average values of Archie's parameters. Figure 1 illustrates flow chart to compute Archie's parameters by 3D technique for *i* measurements on *j* core samples. Table 4 shows Archie's parameters calculated by 3D technique in addition to, CAPE, conventional and common values.

Note that the CAPE method is based on the idea that the two logarithmic plots of *F versus* ϕ and S_w versus I_r are not the optimum way of handling the problem. The comparison between the two techniques showed that CAPE might not appear as optimal as the conventional method. Instead, we are presenting another approach, the 3D technique. In this technique, water saturation is treated as an independent variable in 3D plot of electrical resistivity *vs.* water saturation and porosity.
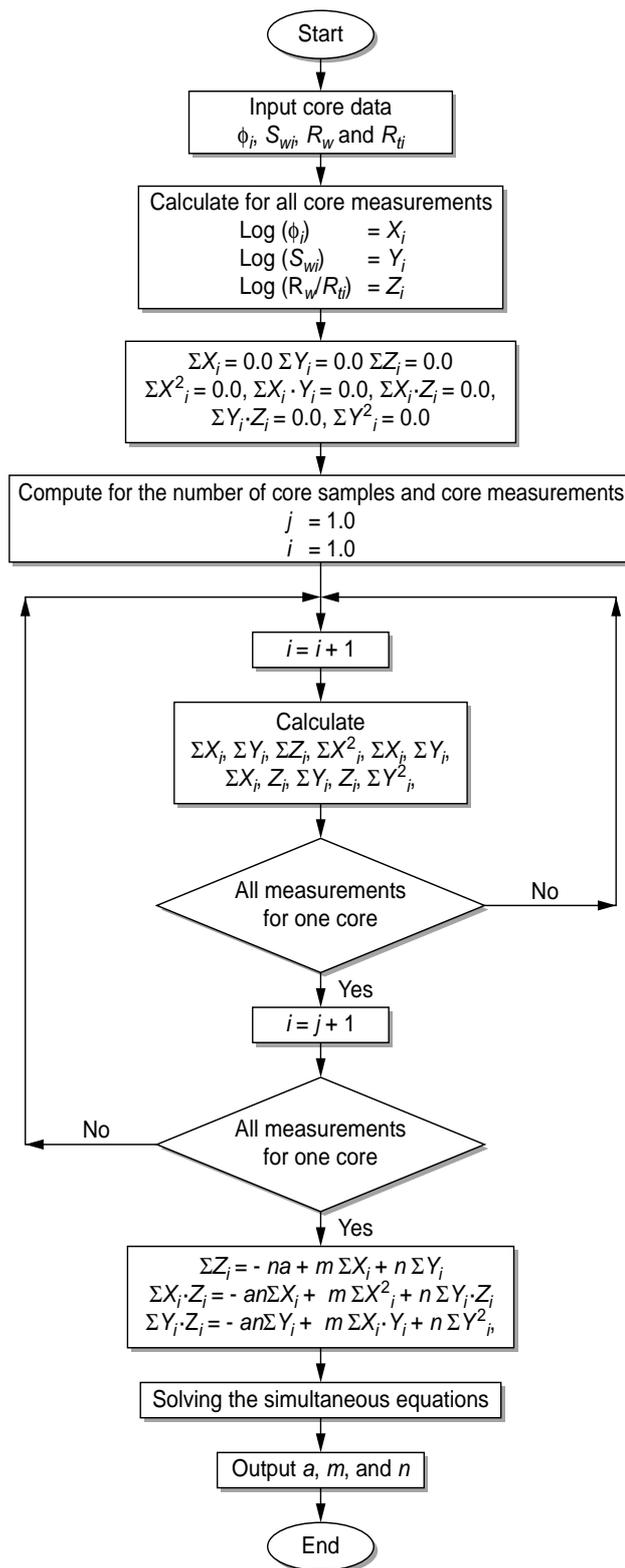

Figure 1

Flow chart to compute Archie's parameters with 3D technique.

1.4.1 Assumptions

First, 3D technique assumes that Archie's formula is applicable to the examined core samples. Also, the core samples represent the zone of interest. For shaly sandstone, Archie's formula must be modified to account for the presence of shale and its effect on resistivity measurements. The user is free to select the appropriate clay model, and consequently, the shaly sand water saturation equation. The second assumption might be difficult to satisfy since it is dealing with the accuracy of the laboratory measurements under reservoir conditions. The third assumption deals with the concept of the 3D technique, this means that the user must be acquainted with the basis and limitations of each method before using it.

2 APPLICATIONS

Two field examples are used for applying the calculated Archie's parameters to compute water saturation. Figures 2 and 3 are logging suites of resistivity, neutron, *GR* and density for wells A and B. *GR* was used to calculate shale volume ($V_{sh} = 0.33 \ (2^{2*GR} - 1)$, when V_{sh} is 0.10, section is considered clean sand and when V_{sh} is 0.75, it is taken as shale section. Neutron and density logs readings have been corrected from shale effect to give corrected porosity values for using either in Archie's formula or in shaly water saturation model. The studied field examples produce from clean sand sections and shaly sand sections. Figure 4 shows flow chart for a computer program used to compute water saturation in clean and shaly sections with the use of Archie's
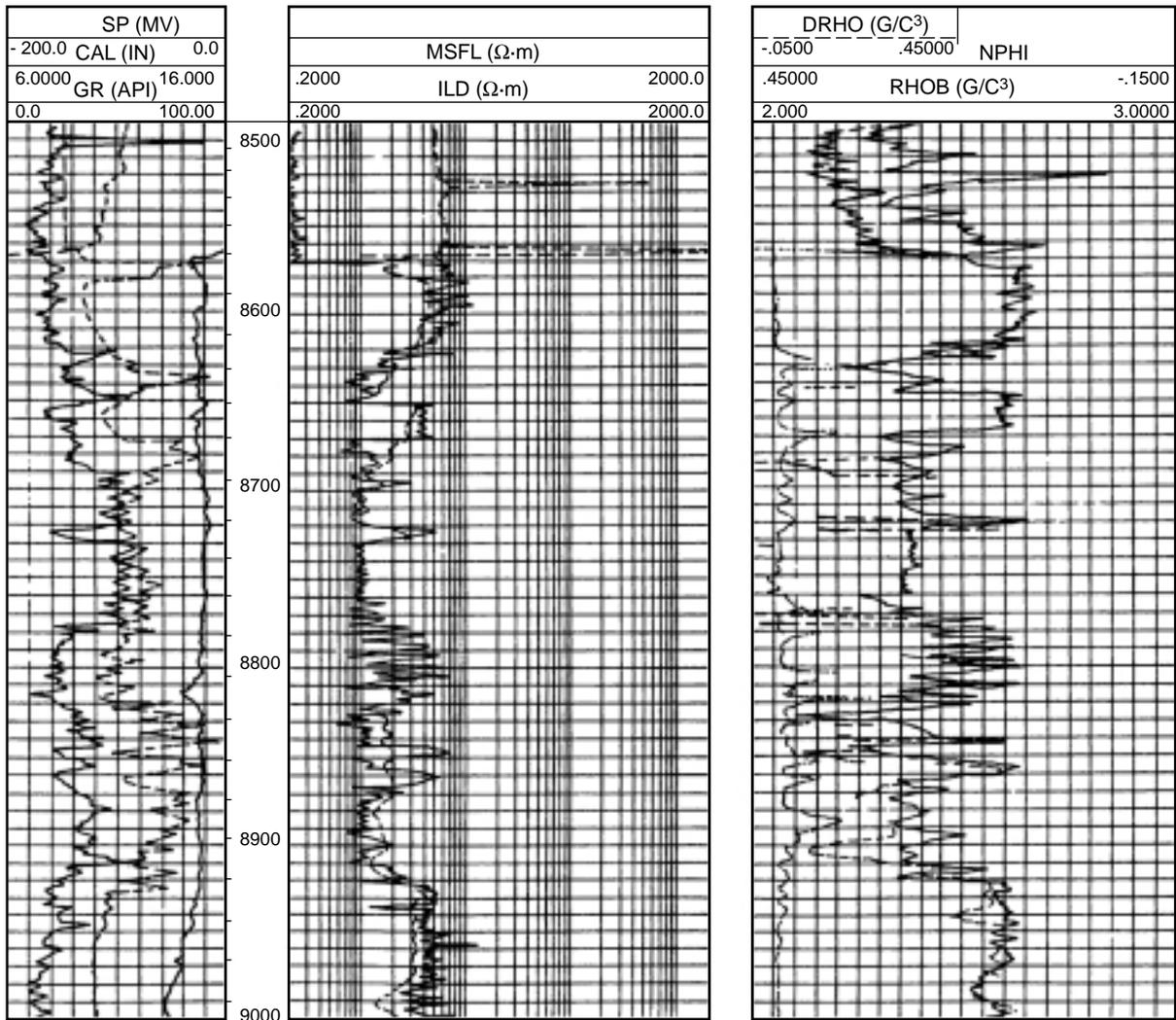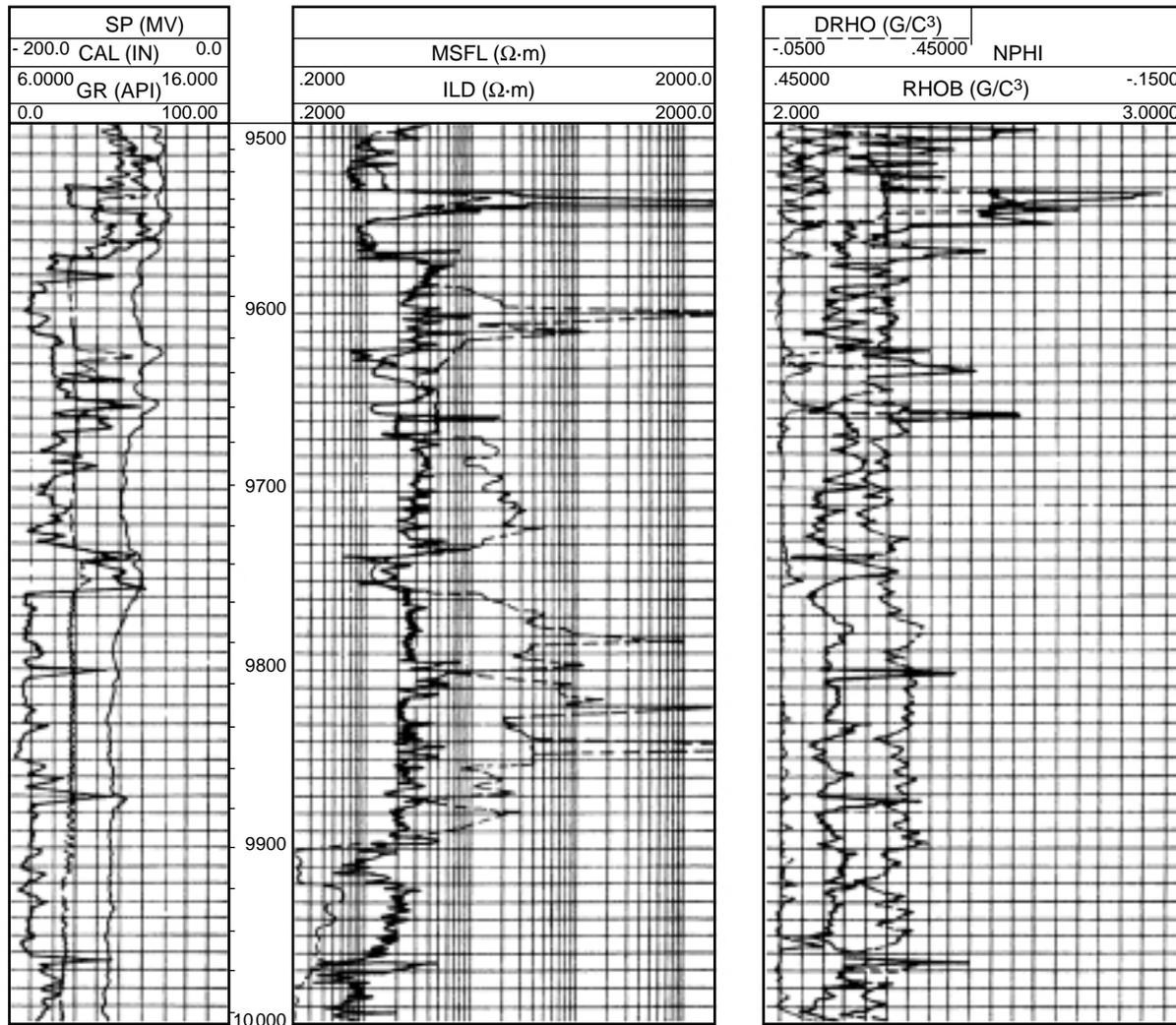

Figure 2

Well logging data for well A.

Figure 3

Well logging data for well B.

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parameters from each technique: Conventional, CAPE and 3D and also common Archie's parameters for sands ($a = 0.65$, $m = 2.15$ and $n = 2$).

In clean sand, water saturation is computed by Archie's formula:

$$S_w = (aR_w / \phi^m R_t)^{1/n} \qquad (12)$$

An accurate computation of water saturation in shaly sand is subjected to many uncertain parameters. It is necessary to integrate the information from several types of logs using different interpretation models and local experience, in order to accurately determine the desired formation properties. *GR* log is used to determine shale volume that has been used to correct density and neutron porosity values from shale effect to give a corrected effective porosity used in water saturation computation. In the analysis

program, clean sand is assumed for V_{sh} 0.10 and use Archie's formula to find S_w, shaly sand section is assumed for 0.10 V_{sh} 0.75 and use shaly sand water saturation model to find S_w and shale section is assumed for V_{sh} 0.75 and neglect it. Water saturations have been computed for clean sections and shaly sand sections using Archie's parameters calculated by conventional, CAPE, 3D techniques and common values. Repeating the computer program and each time with different Archie's parameters *a, m* has done this and *n* values as shown in Figure 4. Considering the fact that water saturation has been computed in high shale volume sections as well as in low shale volume sections, we used three shale models and final water saturation value is taken as the average value of the three shaly sand water saturation models. In effect, clays are dispersed within sand grains and,
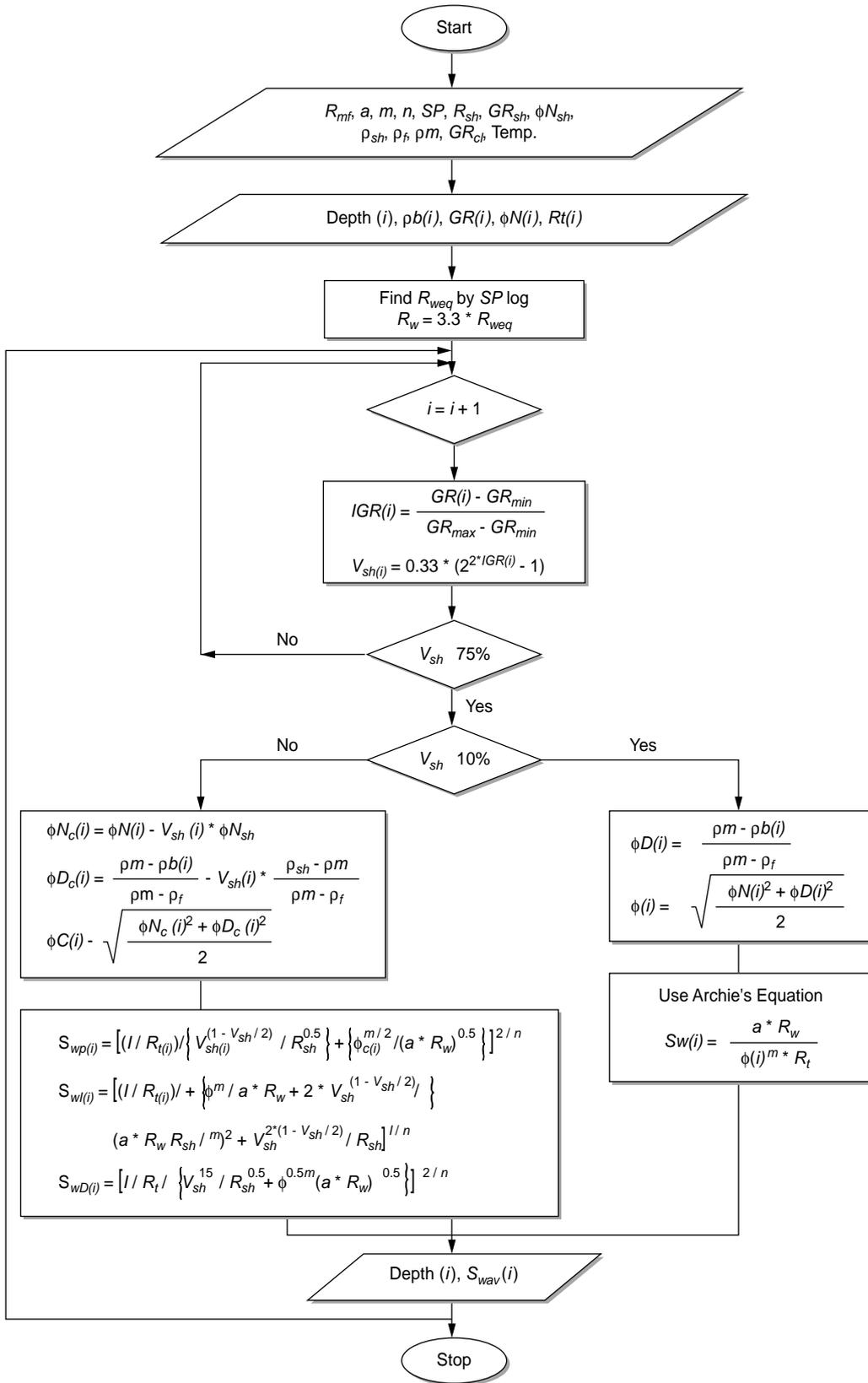
Start

R_{mf}, a, m, n, SP, R_{sh}, GR_{sh}, ϕN_{sh}, ρ_{sh}, ρ_f, ρm, GR_{cl}, Temp.

Depth (i), $\rho b(i)$, $GR(i)$, $\phi N(i)$, $Rt(i)$

Find R_{weq} by SP log
$R_w = 3.3 * R_{weq}$

$i = i + 1$

$$IGR(i) = \frac{GR(i) - GR_{min}}{GR_{max} - GR_{min}}$$

$$V_{sh(i)} = 0.33 * (2^{2*IGR(i)} - 1)$$

V_{sh} 75% — No / Yes

V_{sh} 10% — No / Yes

No branch:

$$\phi N_c(i) = \phi N(i) - V_{sh}(i) * \phi N_{sh}$$

$$\phi D_c(i) = \frac{\rho m - \rho b(i)}{\rho m - \rho_f} - V_{sh}(i) * \frac{\rho_{sh} - \rho m}{\rho m - \rho_f}$$

$$\phi C(i) - \sqrt{\frac{\phi N_c(i)^2 + \phi D_c(i)^2}{2}}$$

$$S_{wp(i)} = \left[(I / R_{t(i)}) / \left\{ V_{sh(i)}^{(1 - V_{sh}/2)} / R_{sh}^{0.5} \right\} + \left\{ \phi_{c(i)}^{m/2} / (a * R_w)^{0.5} \right\} \right]^{2/n}$$

$$S_{wl(i)} = \left[(I / R_{t(i)}) / + \left\{ \phi^m / a * R_w + 2 * V_{sh}^{(1 - V_{sh}/2)} / \right\} \right.$$

$$\left. (a * R_w R_{sh} /^m)^2 + V_{sh}^{2*(1 - V_{sh}/2)} / R_{sh} \right]^{I/n}$$

$$S_{wD(i)} = \left[I / R_t / \left\{ V_{sh}^{15} / R_{sh}^{0.5} + \phi^{0.5m} (a * R_w)^{0.5} \right\} \right]^{2/n}$$

Yes branch:

$$\phi D(i) = \frac{\rho m - \rho b(i)}{\rho m - \rho_f}$$

$$\phi(i) = \sqrt{\frac{\phi N(i)^2 + \phi D(i)^2}{2}}$$

Use Archie's Equation

$$Sw(i) = \frac{a * R_w}{\phi(i)^m * R_t}$$

Depth (i), $S_{wav}(i)$

Stop

Figure 4

Flow chart to compute water saturation.

so, we selected three dispersed clay models. In fact that there is no general shaly sand model can be applied in all modes of shale distribution and also at level of shale volume. For example Doll model [11] often gives optimistic results, but in very shaly pay zone can be unrealistic and Poupon et al. [12] model and Hossin model [13] often become pessimistic in shaly pay sand located in transition zones and their application may condemn pay zones of commercial significance.

Consequently, it is recommended in these field examples to compute water saturation by the three models; Poupon et al., Doll and Indonesia [14]. Final water saturation value will be the average value of the calculated water saturations derived from the three models. Water saturation equations of the three models are given as:

Doll model [11]:

$$S_{wD(i)} = [1/R_t/\{V_{sh}^{1.5}/R_{sh}^{0.5} + \phi^{0.5m}/(aR_w)^{0.5}\}]^{2/n} \qquad (13)$$

Poupon et al. model [12]:

$$S_{wp(i)} = [(1/R_{t(i)})/\{V_{sh(i)}^{(1-V_{sh}/2)}/R_{sh}^{0.5}\} + \{\phi_{c(i)}^{m/2}/(a^*R_w)^{0.5}]^{2/n} \qquad (14)$$

Indonesia model [14]:

$$S_{wI(i)} = [(1/R_{t(i)})/\{\phi^m/aR_w + 2^*V_{sh}^{(1-V_{sh}/2)}/(a^*R_w \cdot R_{sh}/\phi^m)^2 + V_{sh}^{2^*(1-V_{sh}/2)}/R_{sh}\}^{1/n} \qquad (15)$$

Figure 5 shows water saturation profiles for well A using Archie's parameters *a, m* and *n* calculated by four techniques. Water saturation was computed in clean sand section with Archie's formula while in shaly sand section it was computed using shaly sand water saturation models. Water saturation has been measured in the laboratory on 10 core samples from the studied section in the well; the average water saturation of all core samples was 30.5%. Figure 5a illustrates water saturation profile with depth using common values (*a* = 0.65, *m* = 2.15 and *n* = 2). Examination of Figure 5a shows that water saturation is generally high and the average water saturation for 85 points was 34.4% with standard deviation (σ_{S_w}) values equals to 0.34. Figure 5b is the water saturation profile *versus* depth with use of Archie's parameters calculated by conventional technique (*a* = 1.36, *m* = 2.03 and *n* = 2.1). The average water saturation of the studied section of 85 points was 47% with standard deviation (σ_{S_w}) = 0.17. It is still high, but it is better than in the case of
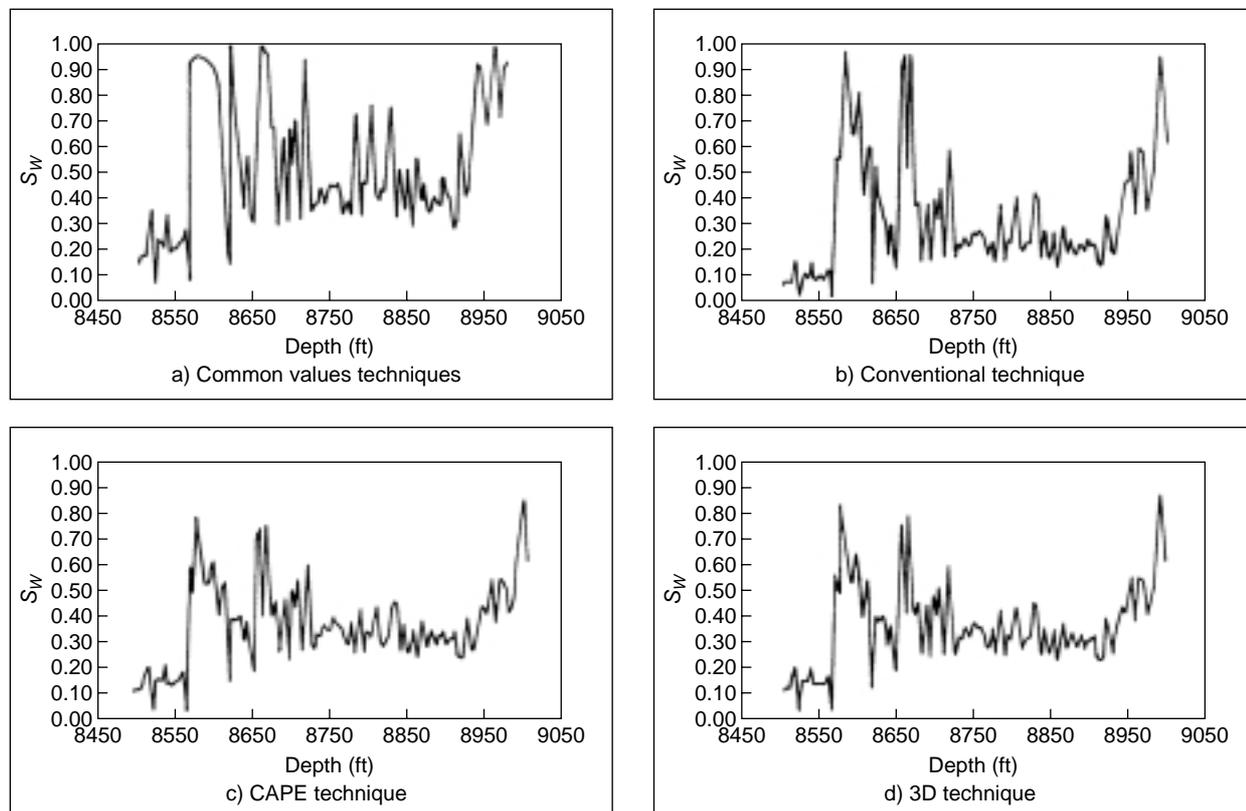

Figure 5

Water saturation profiles with different Archie's parameters using four techniques for well A.

common values. Figure 5c shows water saturation profile derived from water saturation equations using Archie's parameters calculated by using the CAPE technique ($a = 3.21$, $m = 1.7$ and $n = 2.21$). The average water saturation of the retained section was about 28% with standard deviation (σ_{S_w}) = 0.067. CAPE technique provided water saturation value much closer to the average value of core-measured water saturation ($S_{w\,core} = 30.5\%$) than conventional and common techniques. Figure 5d depicts the water saturation profile deduced from the use of Archie's parameters calculated by 3D technique ($a = 2.94$, $m = 1.56$ and $n = 2.15$). Average value of 85 water saturation points was found 31.2%. With standard deviation (σ_{S_w}) equals to 0.069. Table 5 summarises the average water saturation values computed by the Archie's parameters deduced from the three techniques. It is obvious that CAPE and 3D methods give water saturation more accurate than the other methods and also with lower standard deviation error. The 3D technique seems better than CAPE due to lower computing time and by its optimisation technique which is more physically

concerned with water saturation and related factors than CAPE technique.

TABLE 5

Average water saturation and standard deviations using Archie's parameters from four techniques for well A and well B

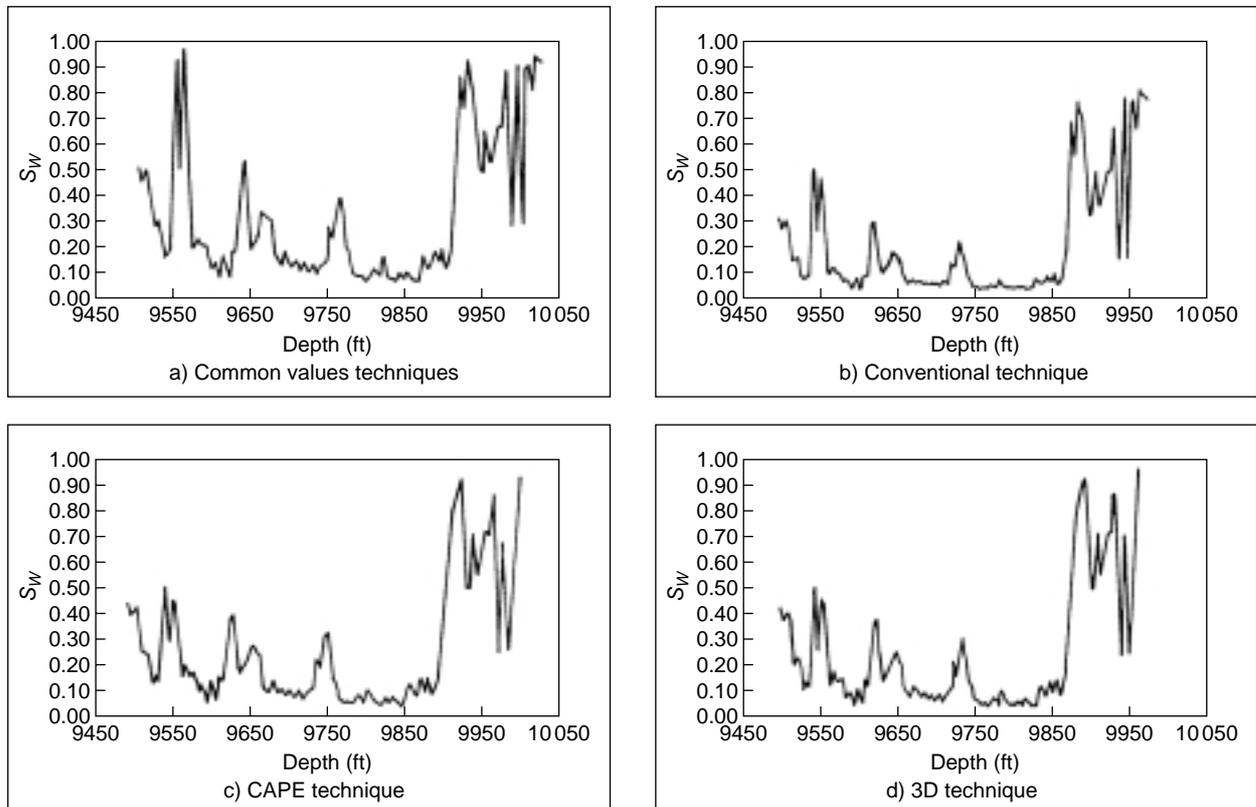| **Well A**		
Technique	S_w	σ_w
Common values	34.4	0.34
Conventional	47	0.17
CAPE	28	0.067
3D	31.2	0.069
Well B		
Technique	S_w	σ_w
Common values	10.2	0.38
Conventional	15.4	0.19
CAPE	6.5	0.072
3D	11.6	0.078

Figure 6

Water saturation profiles with different Archie's parameters using four techniques for well B.

Figure 6 shows water saturation profiles for well B deduced from different water saturation equations (Archie's water saturation equation in the case of clean sand and shaly water saturation equations in the case of shaly sand sections, 10 core samples) measurements that give an average water saturation of 12.25%. Figure 6a shows water saturation *versus* depth, the Archie's parameters used to compute water saturation with the common values ($a = 0.65$, $m = 2.15$ and $n = 2$). Using 85 saturation points, the average water saturation was 10.5% with standard deviation (σ_{S_w}) = 0.38. Water saturation profile with Archie's parameters derived by the conventional technique ($a = 0.95$, $m = 1.85$ and $n = 2.12$) is shown in Figure 6b. The average value of an 85 saturation points of this curve was in the range of 15.4% with standard deviation (σ_{S_w}) = 0.19. This reflects that water saturation calculated by conventional is much better than that derived from common Archie's parameters. Figure 6c illustrates the water saturation curve determined after the use of CAPE technique to Archie's parameters ($a = 2.44$, $m = 1.2$ and $n = 1.95$). Examination of this water saturation profile shows that water saturation values are low with an average of 6.5% and standard deviation (σ_{S_w}) = 0.072. This average value is much less than core sample water saturation value. Figure 6d shows water saturation profile with the use of Archie's parameters computed by 3D technique ($a = 2.59$, $m = 1.43$ and $n = 1.87$). The average water saturation of 85 saturation points was found 11.6% and their standard of deviation was 0.078. The average water saturation values using Archie's parameters calculated by the different techniques are presented in Table 5. It is clear that 3D technique gives better standard deviation and the closest average saturation to the core samples measured water saturation value. Therefore it is recommended to use the 3D technique which provides the values of Archie's parameters *a, m* and *n* and with an accepted water saturation error.

3 VARIABLE SATURATION EXPONENT AND WATER SATURATION

Laboratory measured saturation exponent (n) showed some variations. An exact value of saturation exponent is necessary for a good log interpretation analysis aiming to a precise water saturation determination. There are many factors affecting saturation exponent such as rock wettability, grain pattern, presence of certain authigenic clays, particulary chamosite, which may promote oil wet characteristics and history of fluid displacement. However, it is found that rock wettability is the main factor affecting saturation exponent (n). Archie's saturation equation makes three implicit assumptions:

– the saturation/resistivity relation is unique;
– n is constant for a given porous medium;
– all brine contributes in the electric current flow.

It has been found [8] that these assumptions are valid only in water-wet reservoir. This is because the saturation exponent n depends on the distribution of the conducting phase in the porous medium and therefore depends on the wettability. The saturation exponent (n) is about 2 in water-wet rock, where brines spread over grain surface and facilitate the flow of the electric current. While it may reach 25 in strongly oil-wet rock, where oil coats grain surface and causes disconnections and isolation of globules of brine and therefore this brine will be unable to conduct a current flow.

TABLE 6

Change of water saturation with saturation exponent
for well A and well B

A - Common values technique

Well A

n	2	4	6	8
S_w	0.344	0.676	0.781	0.825

Well B

n	2	4	6	8
S_w	0.154	0.367	0.510	0.601

B - 3D technique

Well A

n	2.15	4	6	8
S_w	0.312	0.641	0.745	0.811

Well B

n	1.87	4	6	8
S_w	0.116	0.378	0.521	0.621

In order to test the effect of saturation exponent on water saturation computation, parameters *a* and *m* were fixed and *n* took different values 2, 4, 6 and 8 in the case of common values technique and values of 1.87, 2.15, 4, 6 and 8 in using 3D technique for wells A and B. From experience, saturation exponents 1.87, 2, 2.15 correspond to water wet rock assumption and saturation exponents 4, 6 and 8 indicate preferably oil-wet rock. Water saturation was computed using the same 85 saturation points for well A and B. This sensitivity test was carried out using Archie's parameters calculated by common values technique and 3D technique. The average water saturation values shown in Table 6 clearly indicate the effect of saturation exponent on the water saturation computation in wells A and B using common values and 3D techniques. Figure 7a shows water saturation profiles with variable saturation exponents using common values technique and Figure 7b shows saturation profiles using 3D technique for well A. Water saturation profiles with the two techniques (common values and 3D) are shown in Figures 8a and 8b for well B. The comparison between Figures 7 and 5 for well A and Figures 8 and 6 for well B demonstrates clearly the increasing trend of water saturation profiles as saturation exponent increases. These computed
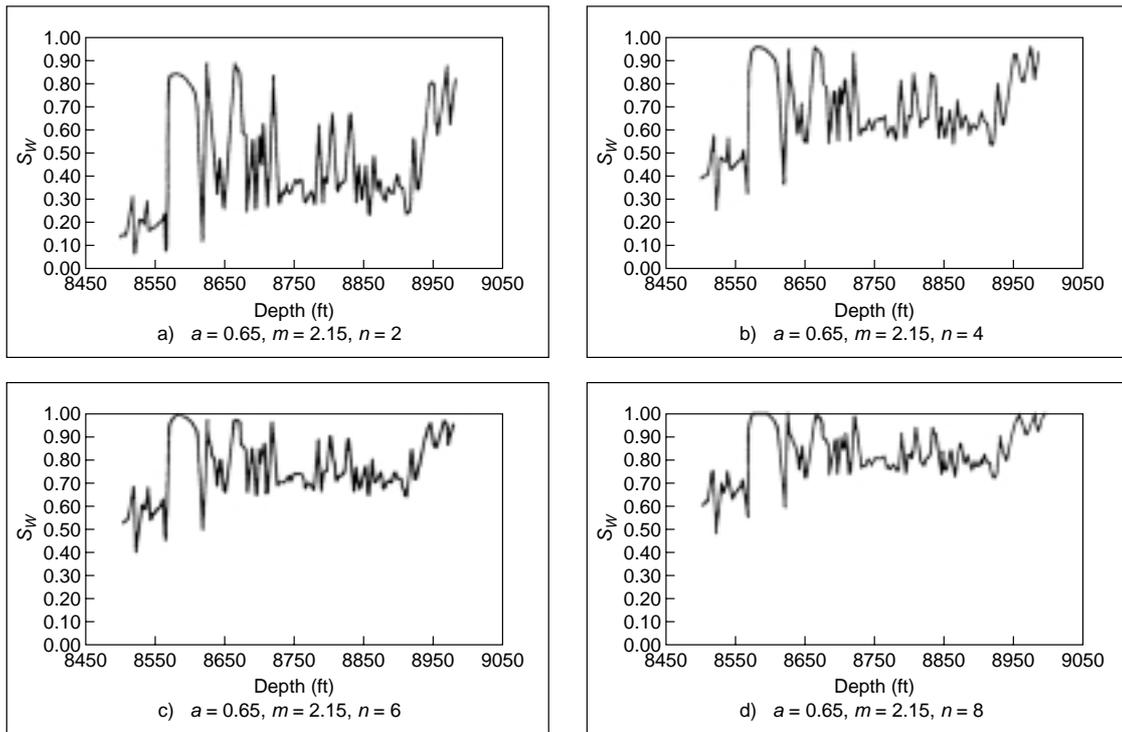
Figure 7a

Change of water saturation with change of water saturation exponent (conventional technique) for well A.
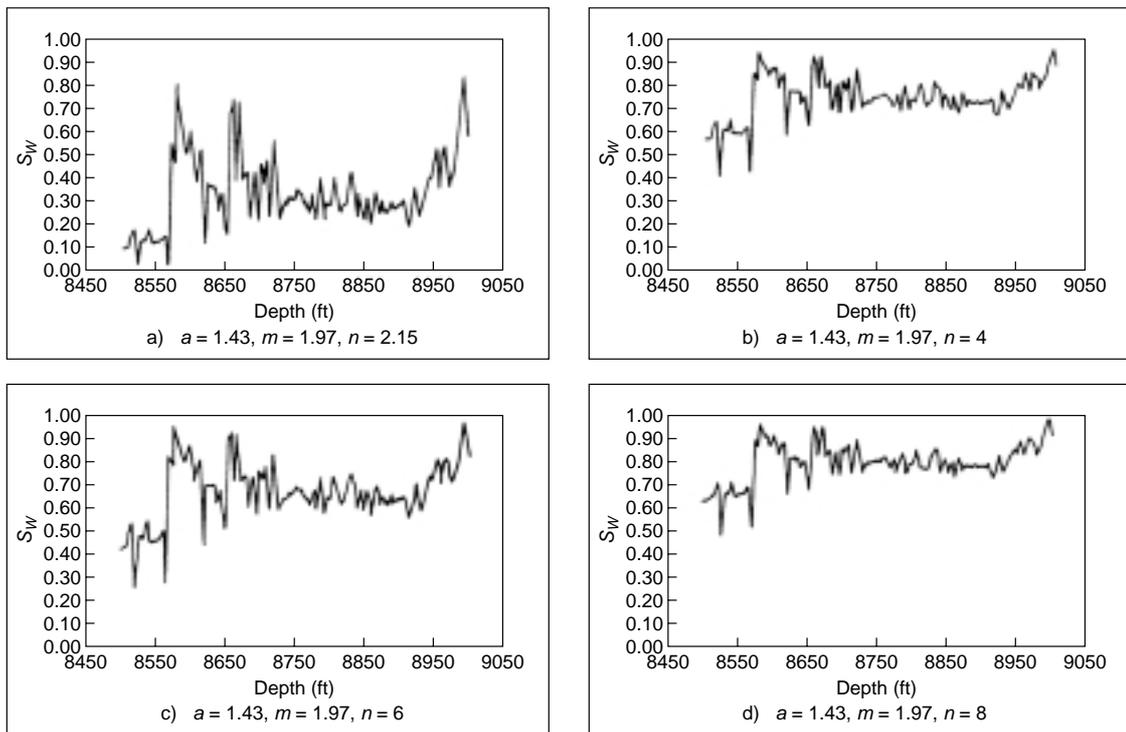

Figure 7b

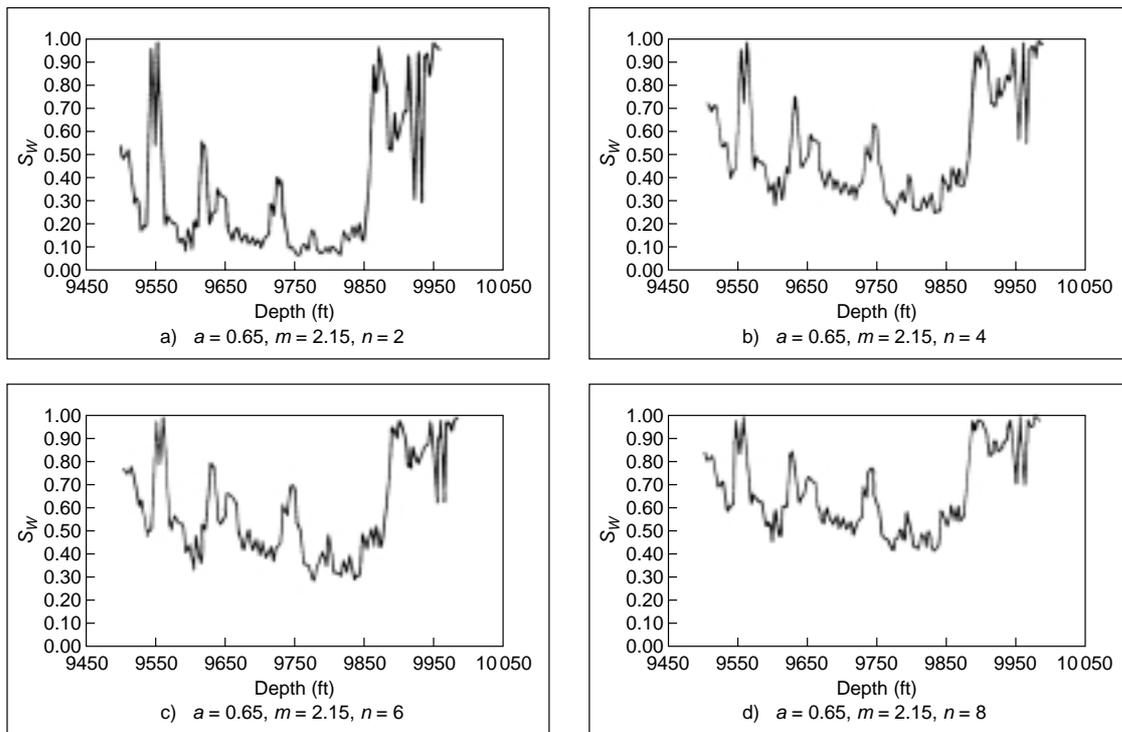Change of water saturation with change of water saturation exponent (3D technique) for well A.

Figure 8a

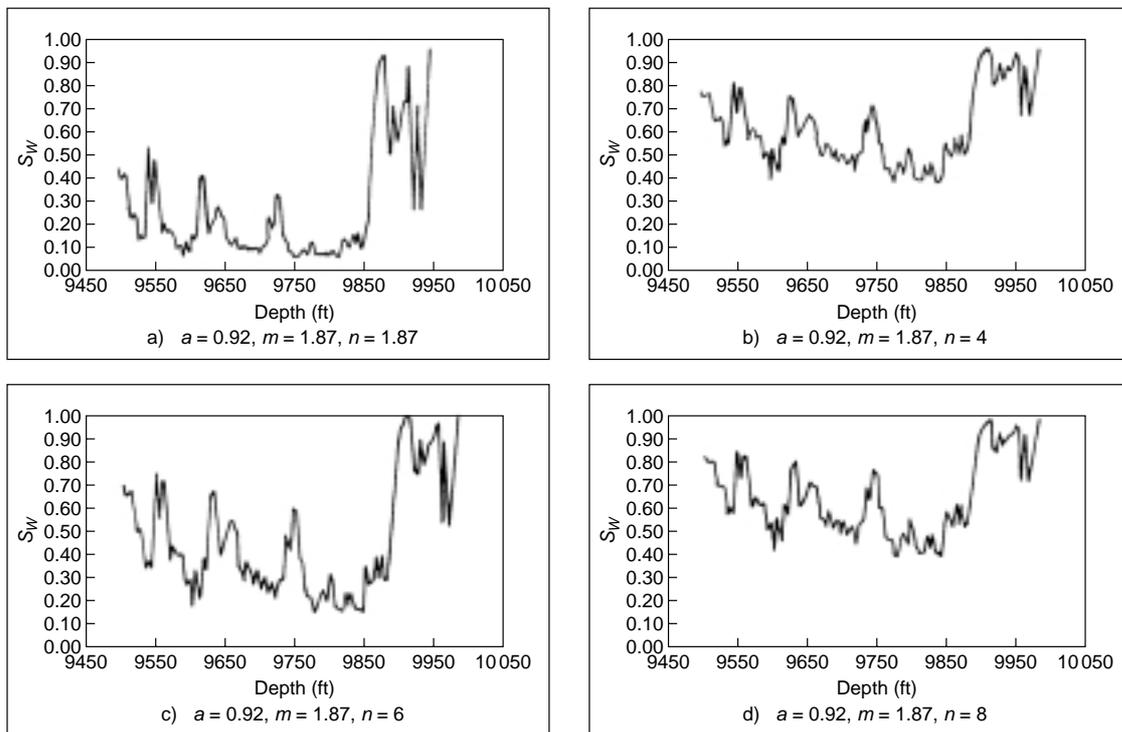Change of water saturation with change of water saturation exponent (conventional technique) for well B.

Figure 8b

Change of water saturation with change of water saturation exponent (3D technique) for well B.

water saturations for well A and B showed an exponential increase of water saturation with the increase of saturation exponent. It may follow the following relations between the average water saturation and saturation exponent using all points in Table 6 of wells A and B.

$$S_w = 0.634 \log 1.779 \, n \text{ for 3D technique} \qquad (16)$$

$$S_w = 0.794 \log 1.171 \, n \text{ for common values technique} \quad (17)$$

It is observed that the effect of saturation exponent on water saturation computation is more significant at lower water saturation values than at higher values. From the average water saturation values in Table 6 and water saturation profiles in Figures 7 and 8, we can conclude that the common values technique is more sensitive than the 3D technique to changes in the saturation exponent. This sensitivity reflects the exigency for an accurate saturation exponent determination to properly compute the water saturation either by Archie's formula or by the shaly water saturation model.

CONCLUSIONS

Archie's parameters have been determined by four techniques; common values, conventional, CAPE and 3D. From the analysis and application of these techniques in the computation of water saturation either in clean sands or shaly sands, the following conclusions may be drawn:

– Conventional technique optimises the two functions F *versus* ϕ and R_t *vs.* S_w rather than water saturation values. While CAPE technique confirms that the quantity to be optimised is not the two functions but rather the water saturation.

– The 3D technique provides simultaneously the values of Archie's parameters from standard resistivity measurements on core samples. Unlike the conventional method, which ignored the values of $S_w < 1.0$ in the determination of *a* and *m*, the 3D method uses all data of S_w points.

– 3D technique answers the controversial question of whether tortuosity factor, *a*, should be fixed at unity or not. It gives directly *a*, *m* and *n*, and thereby, it is recommended to consider the case of the three variables *a*, *m* and *n*.

– For applications where the highest possible accuracy in hydrocarbon saturation is required, it is recommended to use the 3D technique, unless, there are adverse conditions as mentioned in the text.

– The saturation exponent (*n*) has a great effect on water saturation computation. The saturation exponent is affected by many factors such as reservoir rock wettability and the presence of certain authogenic clays that may promote oil wet characteristics. Therefore, it is recommended to calculate the saturation exponent considering reservoir wettability conditions. On the side, there is no a significant effect of wettability alteration on the value of formation resistivity factor, *F*.

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