Improved Technique to Determine Archie's Parameters and Consequent Impact on the Exactness of Hydrocarbon Saturation Values

Hamada, G.M and Assal, A.M., Faculty of Engineering Cairo University, Egypt
and **Ali, M.A.** Faculty of Engineering, UAE University, UAE

Abstract

Determination of Archie's Parameters a,m and n which are among the most uncertain parameters of log determination and conventional interpretation is sometimes wrong because of the erroneous porosity conversions and inaccurate water saturation exponent. Such uncertainty induces considerable effect on the values of hydrocarbon saturation.

A new approach to determine Archie's parameter which is based on standard resistivity measurements on core samples is presented in this paper. The proposed approach is an application of three-dimensional (3D) regression technique for the variables water saturation, electrical resistivity and porosity , and in it a,m and n parameters are determined simultaneously.

Examples are given of the application of this technique on sandstone core samples prepared from two producing wells in the Gulf of Suez. The comparison between the 3D technique, the conventional method, the Core Archie- Parameter Estimation (CAPE) method and the common values (1,2,2), has shown that proposed 3D approach provides an accurate and physically meaningful technique of averaging Archie's parameters for any given core samples. Using the deduced Archie's parameters, hydrocarbon saturation profiles are calculated for selected intervals of the studied wells. The results have shown sensible differences in the values of hydrocarbon saturation profiles which could be mainly attributed to the degree of uncertainty involved in the technique adopted in the determination of Archie's parameters.

Key Words: Archie's Parameters, Water Saturation, 3_D technique and Gulf of Suez

Introduction

Classic petrophysics holds that Archie's parameters a,m and n are constants 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. Field experience has also shown that the cementation factor, m, and the tortousity factor,a, depend on the petrophysical properties of a given rock.

Petroleum literature contains many reports of the results determining Archie's parameters and related water saturation. In quantitative log interpretation, an accurate water saturation requires good values of Archie's parameters,(Archie,1942; Sweeney and Jennings,1960; Licastro and Keller,1953; Atkins and Smith,1961; Ransom,1984; Borai,1987; Maute etal,1992; Worthington and Pallet,1992; Shouxiang and Xiaoyun, 1994 and Hamada,1994).

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 Rt/Rw vs. Sw andϕ. Water saturation profiles were calculated using common values (1,2,2), conventional, CAPE and 3D methods for two selected wells.

Conventional Determination of a,m and n

In 1942 Archie proposed an empirical relationship between rock rsistivity,Rt, with its porosity, ϕ , and water saturation Sw,.

$$Sw^n = a\,Rw / \phi^m\,Rt = 1/\ Ir \qquad (1)$$

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

$$Ro = F\,Rw \qquad (2)$$

where F is formation resistivity factor. Winsauer et al(1952) modified the Archie formula ($F = 1/\phi^m$) and introduced tortousity factor, a , to Archie's formula

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

Conventional Determination of a and m

The conventional determination of a and m is based on Eq. 3 and is rewritten as:

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

A Plot of log F vs. log ϕ is used to determine a and m for the core sample as shown on **Fig. .1** Cementation factor,m, is determined from the slope of the least square fit straight line of the plotted points. While tortousity factor is given from the intercept of the line where $\phi = 1$. Note that in this plot only points of $Sw = 1.0$ are used.

Conventional Determination of n

The classical process to determine saturation exponent,n, is based on Eq. 1. This equation is rewritten as:

$$\log Ir = -\,n \log Sw \qquad (5)$$

A logarithmic plot of Ir vs. Sw gives a straight line with negative slope n , **Fig.2.**

Sometimes data are plotted as log Rt vs. log Sw. This form is mathematically equivalent to the plot of Fig.2 and provides the same value of n.

It is obvious that the conventional method 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 Eq.1.

Core Archie-Parameter Estimation (CAPE)

Maute et al (1992) have presented a data analysis approach 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 minimizing the error between computed water and measured water saturations. The mean square saturation error ε, , is given by

$$\varepsilon = \Sigma_j \Sigma_i [Sw_{ij} \quad - (a\, Rw_{ij} / \phi_j^m\, Rt_{ij})]^2 \qquad (6)$$

where j = core index, i = index for each of the core j measurements, Sw_{ij} = ith laboratory measured water saturation for core j (fraction), Rt_{ij} = ith laboratory measured resistivity for core j, ohm meter, and ϕ_j = core j porosity (fraction). Eq.6 calculates the minimum error between measured core water saturation and computed water saturation. This is done by adjusting m , n and optionaly a in the equation.

Table 1 illustrates typical results from CAPE and Conventional methods. Table 1 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 (75 measurement points). Also, note that the saturation error decreases as we go from conventional to CAPE method. Note that the CAPE method is based on the idea that the two plots shown in Figs. 1 and 2 are not the optimum way of handling the problem . The comparison between the two methods showed that CAPE might not appear as optimal as the conventional method. Instead, we are presenting another approach, the 3D method. In this method, water saturation is treated as an independent variable in the 3D plot of electrical resistivity vs. water saturation and porosity.

3D Method

We contend that, so far as Archie's parameters are concerned, the error in the water saturation value should be kept minimum. This is because water saturation quantity is desired and physically meaningful quantity. Here, we have developed a method to termine Archie's parameters a,m and n using standard resistivity measurements on core samples.

Methodology

The basis of the 3D method is to view Sw in Archie's formula Eq.1 as a variable of three dimensional regression plot of Sw , Rw/Rt and ϕ. The 3D method determines Archie's parameters a,m and n by solving three simultaneous equations of Sw , Rw/Rt and ϕ . Eq.1 is rearranged after taking the logarithm of both sides.

$$\log Rw / Rt = - \log a + m \log \phi + n \log Sw \qquad (7)$$

The left hand side of Eq.7 is a dependent variable of the two independent variables Sw and ϕ. Eq.7 is an equation of a plane in three dimensional (3D) space of coordinate x, y and z ($x = \log \phi$, $y = \log Sw$ and $z = \log Rw/Rt$). The intersection of this plane with the plane ($x = 0.0$) gives a straight 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. Eq.7 will take the following form for i measurement points:

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

After normalizing Eq.8 for N reading , we can have the following three simultaneous equations

$$\Sigma Zi = - NA + m \Sigma Xi + n \Sigma Yi \qquad (9)$$
$$\Sigma Zi\, Xi = -A \Sigma Xi + m \Sigma Xi^2 + n \Sigma Yi\, Xi \qquad (10)$$
$$\Sigma ZiYi = -A\Sigma\, Yi + m\Sigma XiYi + n\Sigma Yi^2 \qquad (11)$$

The solution of Eqs. 9-11 provides the values of Archie's parameters a,m and n for one core sample. For j core samples, an average value of Archie's parameters is produced by running the same analysis for j core samples. Fig. 3 shows the flow chart of a computer program for 3D method determining a,m and n for j core samples. Also, this program calculates the standard deviation $\sigma_{(Sw)}$ between the computed and measured water saturations.

Assumptions

First, 3D method assumes that Archie formula is applicable to the examined core samples. Also, the core samples represent the zone of interest. For shale sandstone, Archie 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, (DeWhite,1950; Simadoux,1963; Fertl and Hamnock,1971; Dresser, 1982). The second assumption might be difficult to satisfy, it is concerned with the accuracy of the laboratory measurements under reservoir conditions.

The third assumption deals with the concept of the 3D method. This means that the user must be acquainted with the basis and limitations of each method before using it.

Application

Now, we develop the 3D method by considering field examples of effectively clean sandstone. Table 1 shows typical results from the conventional method, the CAPE method, the 3D method,and the common values (1,2,2). Note that for conventional and CAPE methods, cases where ,a, is fixed at unity and variable are given. In addition to m,n and a values, the average error $\sigma_{(Sw)}$ between measured and calculated water saturations is given.

For wells A1 and C1, we note that the values of a,m and n, deduced by the three methods, are different. Classic petrophysics holds Archie's parameters constants and commonly taken as 1,2 and 2. In fact this presumed constancy induces a certain error in the value of water saturation.

Also, note that the saturation error $\sigma_{(Sw)}$ decreases as we go from the case where (1) common values are used to the cases where the following methods are used: (2) conventional method with , a, fixed at unity, (3) conventional method with , a, variable, (4) CAPE method, a, forced to unity, (5) 3D method , and (6) CAPE with , a, variable. This behavior was expected and it could be attributed to the fact that conventional method tries to optimize the two functions F vs ϕ. and Rt vs. Sw rather than water saturation, while either CAPE or 3D optimizes water saturation. But 3D method is more credited than CAPE by less computer time consuming and by its optimization technique which is more physically concerned with water saturation and related factors than CAPE method. Therefore it is recommended to use the 3D method which provides us directly the values of Archie's parameters a,m and n and with an accepted water saturation error.

Variable Archie's Parameters and Water Saturation Values

Table 1 illustrates typical results of average water saturation for different Archie's parameters deduced from conventional method, CAPE , 3D method and common values. Fig. 4 depicts water saturation profiles calculated by the four options against selected interval for wells A1 and C1.

The examination of water saturation profiles has shown that (1) the use of common values yields water saturation values greater than the correct ones, and that (2) Unlike the case of common values the water saturation profiles calculated by conventional, CAPE and 3D methods have shown certain departure from each other. For application where highest possible accuracy in water saturation is desired, it is recommended to leave the conventional method and adopt any of the CAPE or the 3D method. Moreover, the 3D method is more preferred than the CAPE method because of its more physically representation of the data and because it overcomes the dilemma of whether, a, is to be considered or not by giving simultaneously the three variables a,m and n and then the water saturation.

Fig. 5 shows the flow chart for the developed computer program to calculate the effective porosity and water saturation for the appropriate Archie's parameters which are deduced from the selected method. For wells A1 and C1, the 3D method provided an acceptable standard deviation of water saturation with reference to CAPE or conventional methods. Note that the error in hydrocarbon saturation is identical to the error in water saturation because each one might be determined from the other by subtraction from unity.

Conclusions

1. Conventional method optimizes the two functions F vs. ϕ. and Rt vs. Sw rather than water saturation values.
2. The CAPE method confirms that the quantity one should optimize is not the two functions but rather the water saturation.
3. The 3D method provides simultaneously the values of Archie's parameters from standard resistivity measurements on core samples.
4. Unlike the conventional method, which ignored the values of $Sw < 1.0$ in the determination of a and m , the 3D method uses all data of Sw points.
5. The 3D method answer the controversial question of whether tortousity 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
6. For applications where the highest possible accuracy in hydrocarbon saturation is required, it is recommended to use the 3D method , unless, there are adverse conditions as mentioned in the text.

Acknowledgment

The authorrs would like to thank Suez Oil Company (SUCO) for providing us with the core samples and logging data and their cooperation during the preparation of this paper is also gratefully acknowledged.

Nomenclature

a = Tortousity factor
m = Cementation factor
n = Saturation exponent
Sw = Water saturation, fraction
Rt = Resistivity of rock, ohm meter
Rw = Resistivity of brine, ohm meter
Ro = Resistivity of rock , ohm meter with $Sw = 1.0$
Ir = Resistivity index
F = Formation resistivity factor
ϕ= Formation porosity, fraction
σ_{Sw} = Standard deviation in water saturation

References

Atkins, E.R. and Smith, G.H.,1961, The Significance of Particle Shape in Formation Resistivity Factor-Porosity Relationship: JPT, March, p. 285-291.

Archie, G.E.,1942, Electrical Resistivity Log as an Aid in Determining Some Reservoir Characteristics: Trans., AIME, v. 146, p. 54-62.

Borai, A.M.,1987, A New Correlation for the Cementation Factor in Low-Porosity Carbonates: SPE Formation Evaluation, December, p. 495-498.

DeWhite, L.,1950, Relation Between Resistivities and Fluid Contents of Porous Rocks: Oil and Gas J., August , p. 120-132.

Dresser Atlas,1982, Well Logging and Interpretation Techniques: Dresser Atlas Inc., 211p.

Fertl, W.H. and Hamnock, A Comparative Look at Water Saturation in Shaly Pay Sands: Trans., SPWLA 12 th Annual Logging Symposium, May 2-5, 1971.

Hamada,G.M., Effect of Archie's Saturation Exponent Values on the Hydrocarbon Evaluation Processes: Trans. Intrl. Symposium on Well Logginig Technology, Xian, China,p.76-81.

Licastro, P.H. and Keller, G.V.,1953, Resistivity Measurements as a Criteria for Determining Fluid Distribution in the Bradford Sand: Producer Monthly, Schlumberger, v. 17, p. 17-23.

Maute, R.E., Lyle, W.D. and Sprunt Eve,1992, Improved Data- Analysis Method Determines Archie Parameters From Core Data: JPT, January , p. 103-107.

Ransom, R.C.,1984, A Contribution Toward a Better Understanding of The Modified Archie Formation Resisivity Factor Relationship: The Log Analyst, March-April , p. 7-12.

Shouxiang, Ma. and Xiaoyun, Zh.,1994, Determination of Archie's Cementation Exponent From Capillary Pressure Measurements: Trans., Intr. Symposium on Well Logging Technology , X'ian, China, p. 83-103 .

Simadoux, P.,1953, Measures Dielectriques en Milieu Poreux; Application a Measure des saturations en Eau , Etude du Comportement des Massifs Argileux," Revue de L'IFP , Paris.

Sweeney, S.A. and Jenning, H.Y,1960, The Electrical Resistivity of Preferentially Water-Wet and Preferentially Oil-WEt Carbonate Rock: Producers Monthly, Schlumberger, v. 24, p. 29-32.

Winsauer, W.O., Shearin, H.M., Masson, P.H. and William, M,1952, Resistivity of Brine Saturated Sands in Relation to Pore Geometry: Bull., AAPG, v. 36, No. 2, p. 253-277.

Worthington, P.E. and Pallet, N,1992, Effect of Variable Saturation Exponent on the Evaluation of Hydrocarbon Saturation: SPE Formation Evaluation, December, p. 331-336.

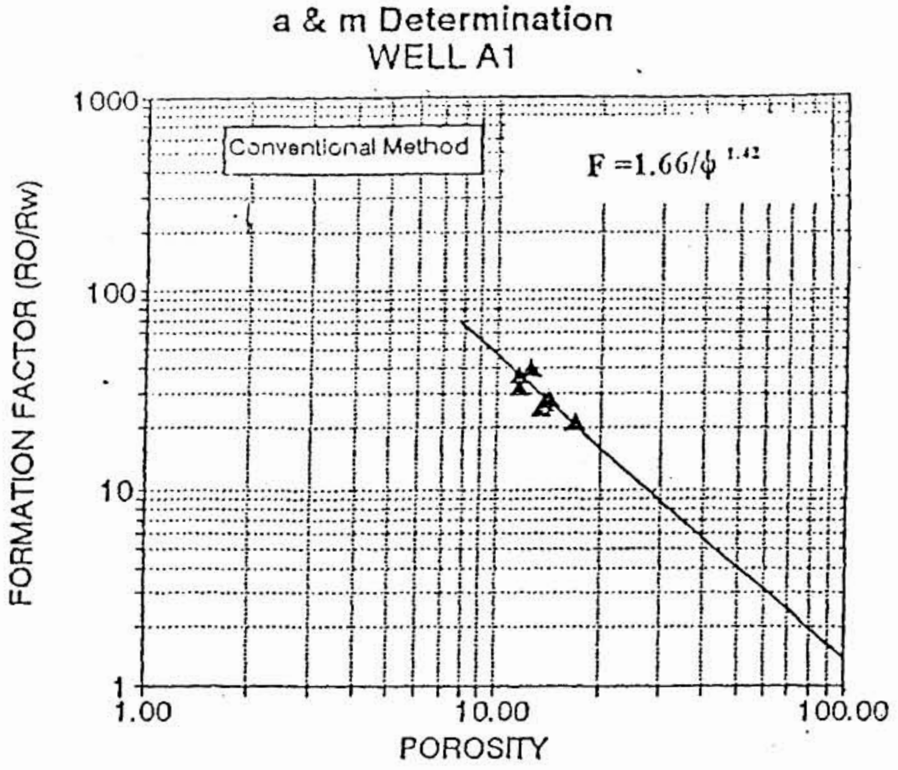
Table 1 Archie's Parameters From Different Techniques And Average Values Of Water Saturation And Standard Deviation Errors

Well A1

Method Used	a	m	n	$(S_w)_{av}$	σ_{sw}
Conventional Method a,m and n	1.66	1.42	1.596	0.078	0.0698
Conventional Method n and m	1	1.6712	1.596	0.0701	0.07346
Common Values	1	1	2	0.177	0.34
CAPE Method, a,m,n	3.289	1.0616	1.626	0.0735	0.0667
CAPE Method,a,m,n	1	1.644	1.652	0.0711	0.0716
3-D Method	2.937	1.144	1.546	0.073	0.06866

Well C1

Method Used	a	m	n	$(S_w)_{av}$	σ_{sw}
Conventional Method a,m and n	4.02	0.979	1.743	0.87	0.724
Conventional Method n and m	1	1.6016	1.743	0.0866	0.0819
Common Values	1	1	2	0.160	0.38
CAPE Method, a,m,n	2.466	1.896	1.784	0.912	0.0698
CAPE Method,a,m,n	1	1.59	1.93	0.097	0.0757
3-D Method	2.59	1.202	1.697	0.085	0.0715



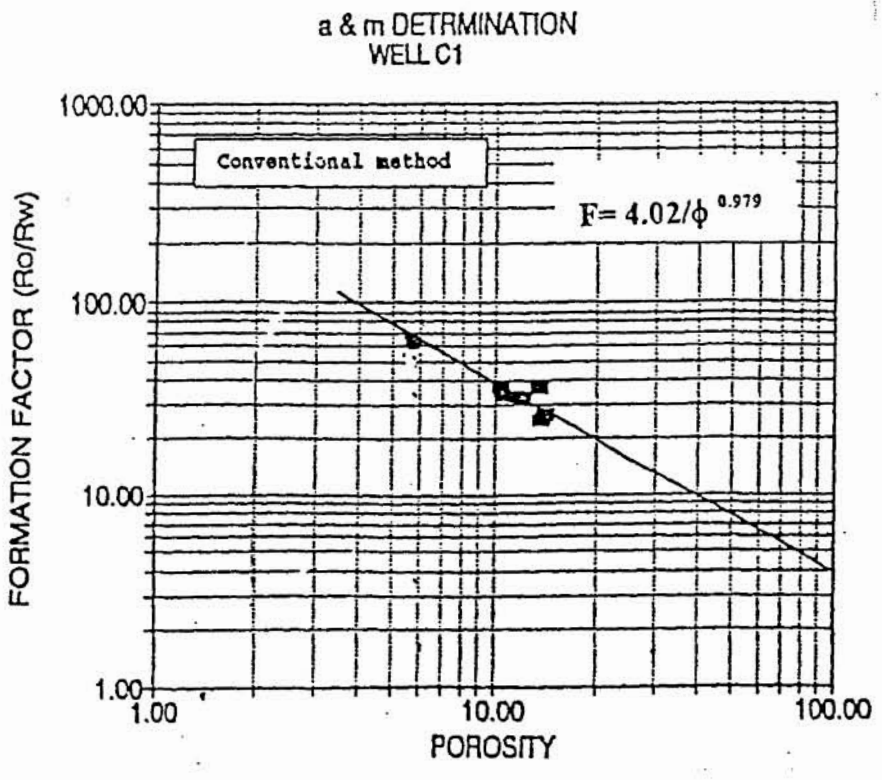


Fig.1 A And M Determination From Conventional Technique

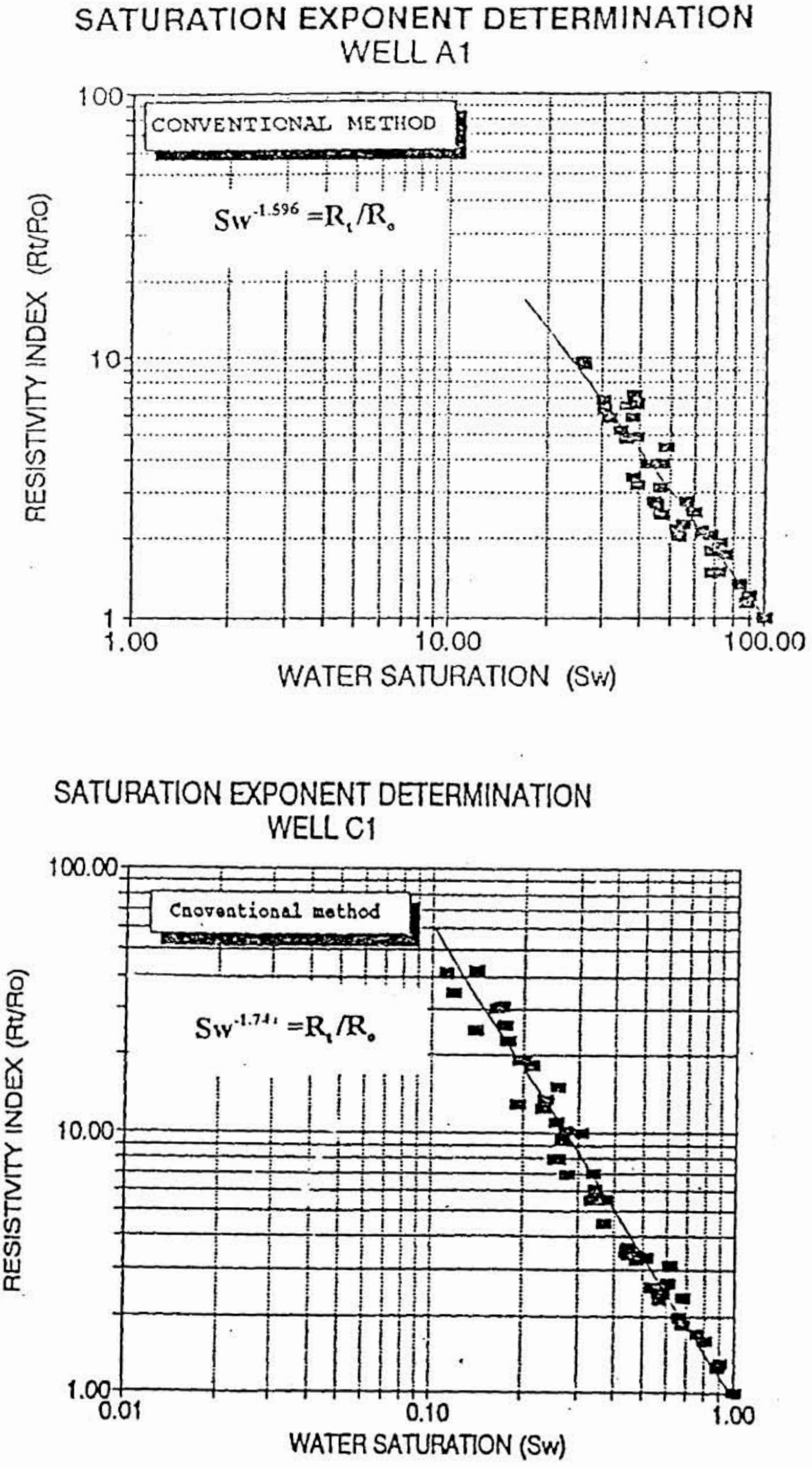


Fig.2 Saturation Exponent N Determination From Conventional Technique

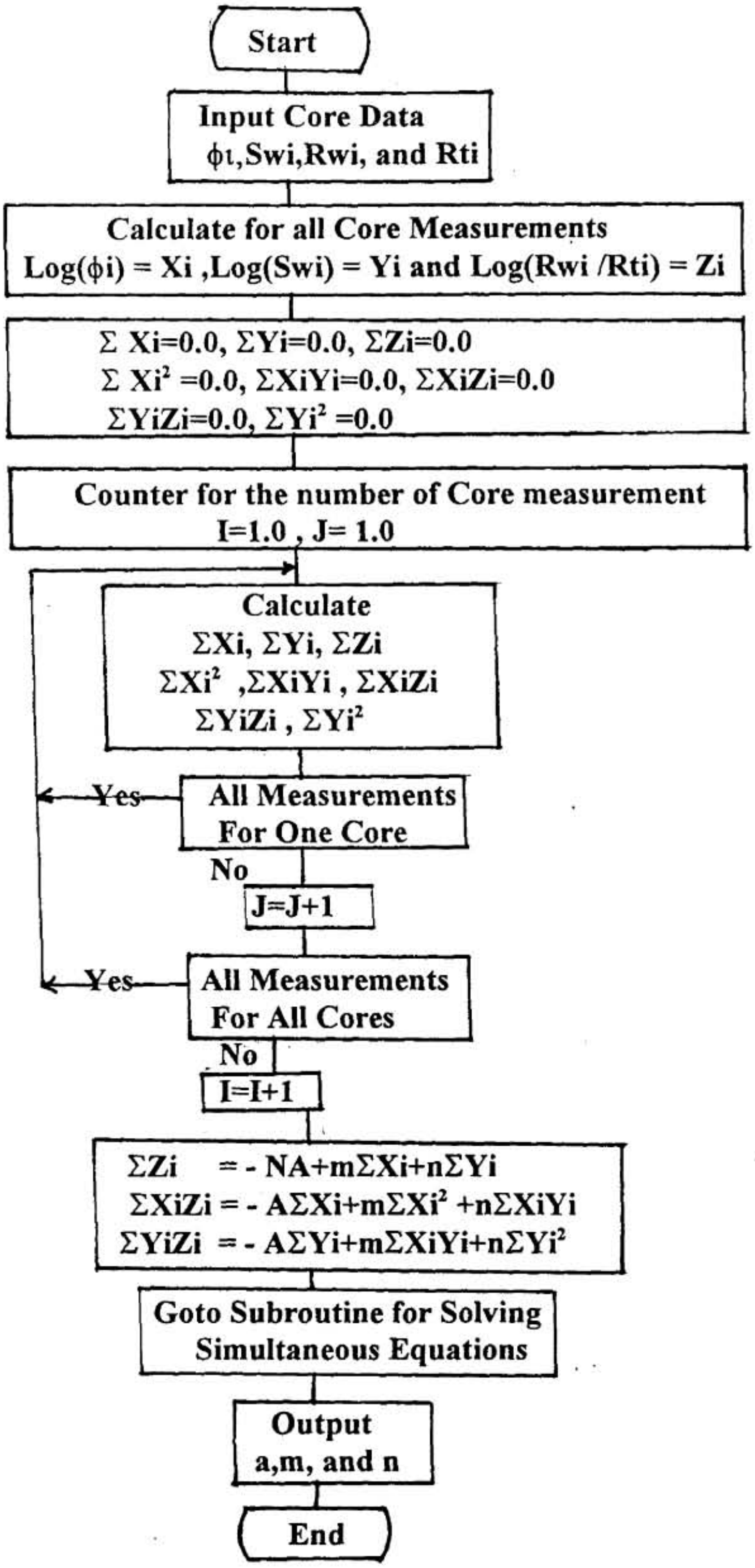
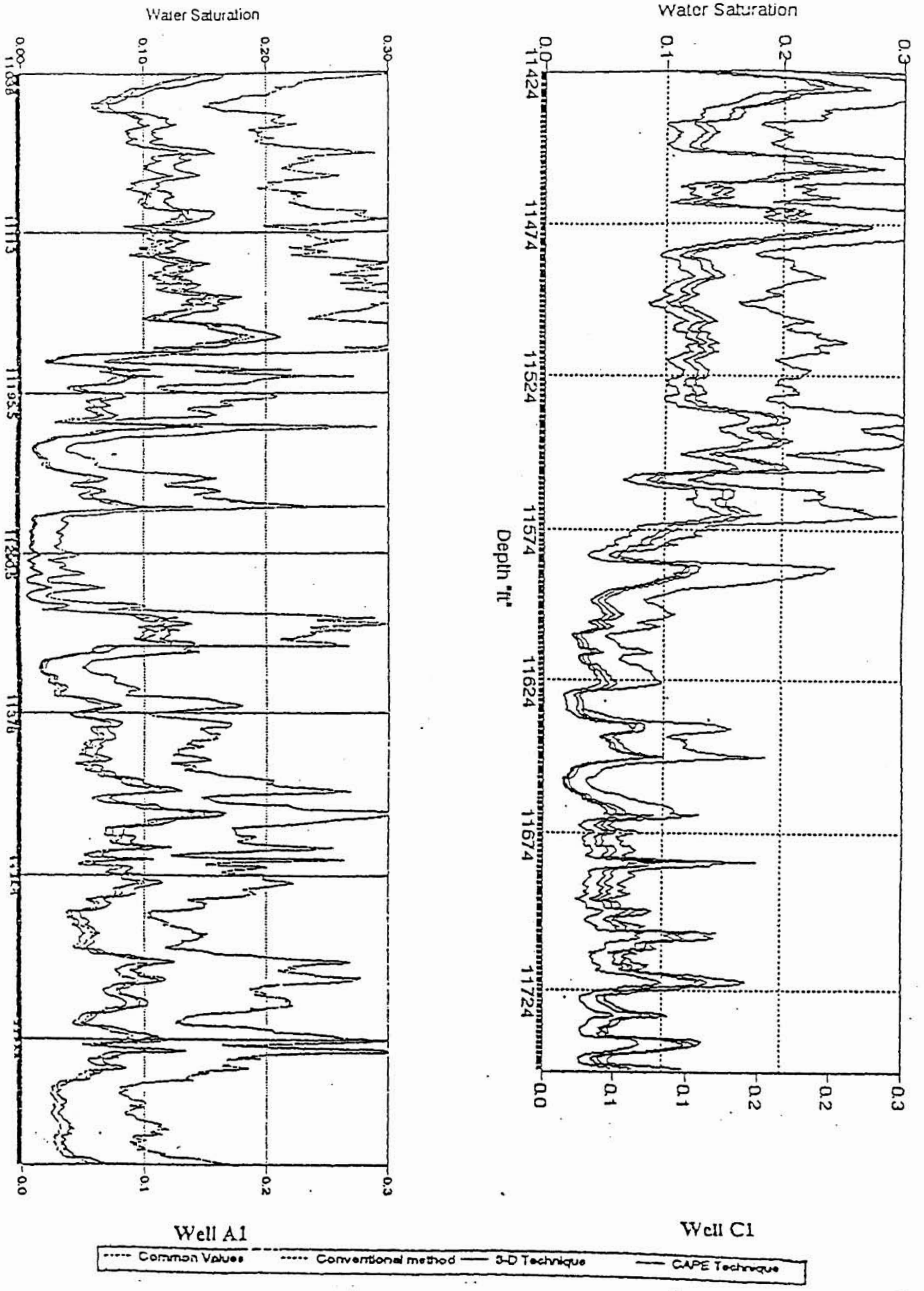


Fig. 3 Flow Chart For A,M, And N Determination From 3-D Regression Technique.



Well A1

Well C1

Fig.4. Water Saturation Curves For Different Archie's Parameters Values From

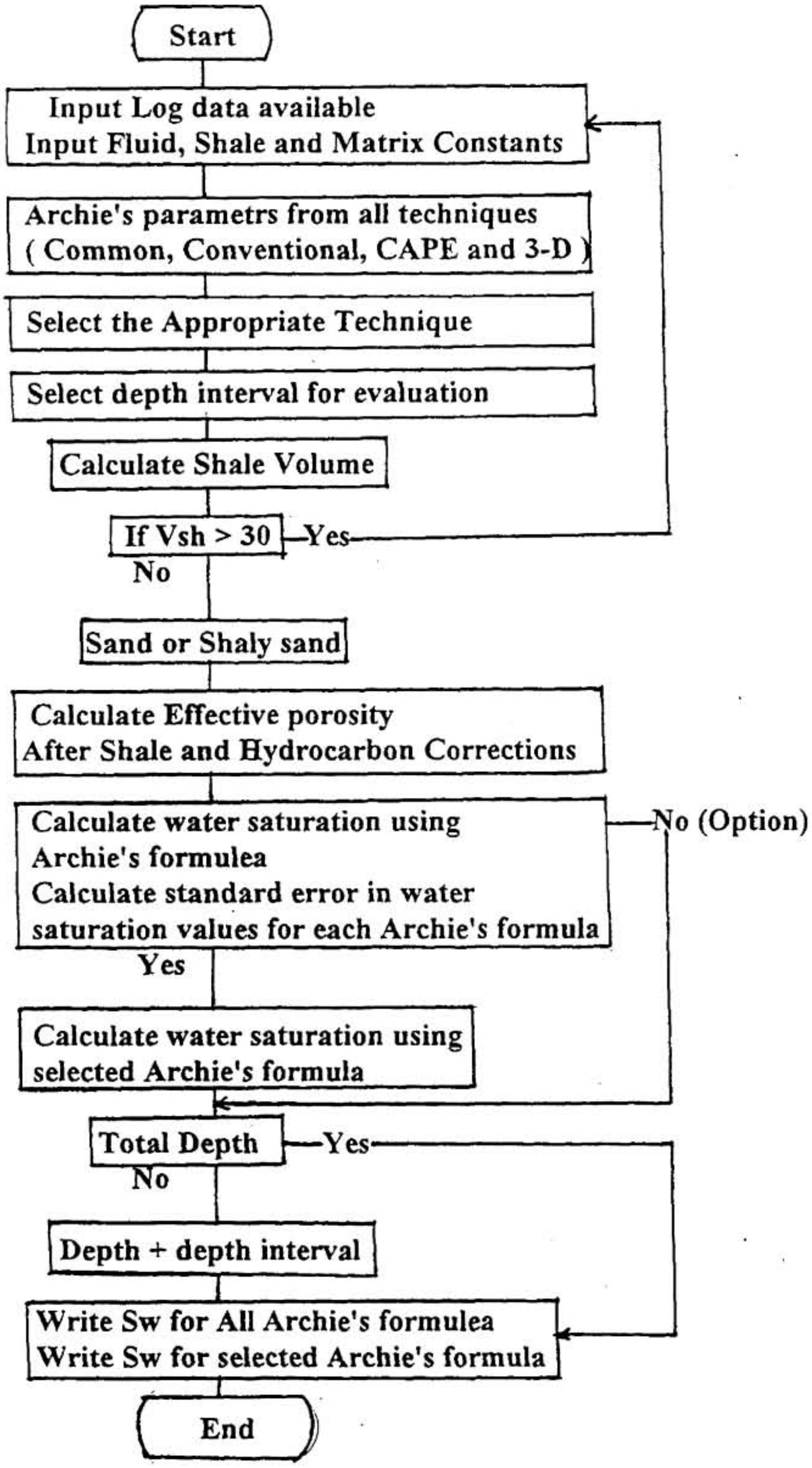


Fig. 5 Flow Chart For Water Saturation Values Using Different Archie's Parameters