ANALYSIS OF ARCHIE'S PARAMETERS DETERMINATION TECHNIQUES

BY

ABDELRIGEEB ALI ALGATHE

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This thesis is written by **ABDELRIGEEB ALI AL-GATHE** under the direction of his Thesis Advisor and approved by his Thesis Committee, has been presented to and accepted by the Dean of Graduate Studies, in partial fulfillment of the requirements for the degree of **MASTER OF SCIENCE IN PETROLEUM ENGINEERING.**

Thesis Committee

10/6/09

Dr. Gharib M. Hamada (Thesis Advisor)

Dr. Abdulaziz A. Al-Majed (Member)

10/6/09

Dr. Taha M. Okasha (Member)

Dr. Sidqi A. Abu-Khamsin
(Department Chairman)

Dr. Salam A. Zummo
(Dean of Graduate Studies)

21/6/09

Date

عمادة الدراسات العليا
DEANSHIP OF GRADUATE STUDIES

بسم الله الرحمن الرحيم

DEDICATED

TO

MY PARENTS AND FAMILY

ACKNOWLEDGMENT

First and foremost thanks are due to Allah who gave me strength, patience and ability to accomplish the present work.

Acknowledgment is due to the King Fahd University of Petroleum & Minerals for supporting this research.

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THESIS ABSTRACT

NAME: **ABDELRIGEEB ALI MOHAMMED AL-GATHE**

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Determination of hydrocarbon saturation is the vital parameter in oil reserve calculation processes. Archie's formula is the water saturation model for the determination of hydrocarbon saturation. In carbonate rocks, Archie's parameters become more sensitive to pore system distribution and lithofacies properties. Consequently more attention must be paid to the accuracy of Archie's parameters in carbonate rocks. Uncertainty in these parameters will lead to non acceptable errors in the water saturation values.

In this study three techniques are presented to determine Archie's parameters using carbonate core samples. These techniques are; conventional technique, CAPE technique and 3D technique. The objective of this study is to calculate and analysis the Archie's parameters in order to get the accurate water saturation. Water saturation profiles, using Archie's parameters determined by the three techniques, have been produced for the studied section in the well. 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. Error analysis of these methods has been

applied to adopt the suitable determination technique to better evaluation of Archie's parameters.

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ملخص الرسالة

الاســــــــــــم :عبد الرقيب علي محمد القاضي

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يعتبر تقييم كمية الزيت مهم جدا في حسابات المكامن البترولية. وتعتبر معادلات آرتشي من العلاقات الأساسية لحساب نسبة الإشباع الصخري.و في حالة الصخور الجيرية الكربونية تصبح معاملات ارشي أكثر حسّاسية لنظام توزيع المسام وخصائصها. ولذلك يجب تحري الدقةِ في معاملات آرتشي للصخور الجيرية. عدم الدقة في حساب المعاملاتِ يؤدي إلى خطأ غير مقبول في قيم حساب نسبة المياه.

في هذه الدراسةِ استخدمت ثلاث طرق لحِساب معاملات آرتشي باستعمال عينات صخريةِ اسطوانية. هذه الطرق هي: الطريقة التقليديةُ و الطريقة الثلاثية الأبعاد (3D) وطريقة تقدير معاملات آرتشي للعينات الاسطوانية (CAPE). إن الغرض من هذه الدراسة هو حساب و تحليل معاملات آرتشي وذلك بغرض الحصول علي قيم صحيحة لنسبة تشبع الصخور بالماء. نتائج مخططات إشباع الماء للقسمِ المدروسِ في البئر تم حسابها باستخدام ارشى والمحسوبة بالتقنيات الثلاثة. هذه المخططات عكست اختلافات مهمة في قيم تشبع الماء. هذا الاختلاف يُمْكِنُ أنْ يُنْسَبَ بشكل رئيسي إلى مستوى قيم مختلفة لمعاملات آرتشي مِنْ كُلّ تقنية. تحليل الأخطاء لهـــذه التقنيات طبق لتبنّى تقنية التصميمِ المناسبةِ والأفضل تقييما لمعاملاتِ آرتشي.

درجة الماجستير في العلوم

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CHAPTER 1

INTRODUCTION

Archie's parameters which consist of tortousity factor (*a*), cementation factor (*m*), and water exponent (*n*) are considered constants for a given sample of a reservoir rock in petrophysics. This helps in determining the hydrocarbon saturation from resistivity measurements for a certain lithology. From field experience it has been shown that there are variations of saturation exponent (*n*), the cementation factor (*m*), and tortousity factor (*a*), are dependent of rock petrophysical properties. The petroleum engineering literature contains a lot of papers and reports of finding out the Archie's parameters and the corresponding water saturation. 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. The accuracy of water saturation value for given reservoir conditions depends on the accuracy of Archie's parameters *a, m* and *n*. Uncertainty in these coefficients causes many errors in saturation evaluation especially in the carbonate reservoir. Archie's equations are the basic relations for evaluating rock saturation. The coefficients of these equations are determined by laboratory experiments. This work focuses on three techniques to determine Archie's parameters as following: 1) conventional technique, 2) Core Archie Parameter Estimation (CAPE) technique and 3) three dimension (3D) technique. This study addresses also a comparison between the three techniques and their impact on water saturation profiles in studied wells.

CHAPTER 2

LITERATURE REVIEW

2.1 Archie's Equation

Rock resistivity measurement is necessary in formation evaluation to determine their hydrocarbon saturation. The use of electrical properties for formation evaluation has evolved a great deal since the fundamental experiments by Archie to correlate the resistivity of sand cores saturated with brine to the porosity of the rock.

Archie (1942) noted experimentally that the resistivity of a rock completely saturated with a conductive fluid (R_o) increased linearly with brine resistivity (R_w). He called the proportionality constant the rock's formation factor (F) and wrote:

$$R_o = F R_w \quad \text{(2-1)}$$

Archie then plotted formation factor against porosity (Ø) on logarithmic graph paper, finding another linear trend. This was equivalent mathematically to:

$$F = Ø^{-m} \quad \text{(2-2)}$$

Where (m) is define as a cementation factor. Archie next considered partially saturated, hydrocarbon-bearing rock. He proposed a second factor, later called the resistivity index

(*RI*) to determine raise the rock's resistivity:

$$R_t / R_o = RI \quad \text{(2-3)}$$

Archie reported already data and plotted them again using logarithmic graph paper. Archie noted:

$$RI = S_w^{-n} \quad \text{(2-4)}$$

In which S_w is water saturation, and n, later called the water saturation exponent, appeared about 2. Combining the two logarithmic trends gives Archie's law:

$$R_t = R_w / (Ø^m S_w^n) \quad \text{(2-5)}$$

The saturation exponent (n) is an empirically determined constant. It has been studied extensively and is known to vary from its expected value of 2. It is dependant upon the wettability of the rock, the rock texture, the presence of clay and the net overburden pressure.

Later Archie's equation was modified by Winsauer et al. (1952). They added the influence of tortuosity factor as indicated below:

$$F = a\, Ø^{-m} \quad \text{(2-6)}$$

Where the constant a, was introduced to account for the presence of solid conductors

and/or clay in the formation.

The reason for the observed variation in cementation factor has been attributed to a number of different factors, Tabib (2003), Borai (1987), Helander (1983):

1. Degree of cementation.
2. Shape, sorting and packing of particulate system.
3. Type of pore system-intergranular, vuggy.
4. Tortuosity of the pore system.
5. Constrictions existing in porous system.
6. Presence of conductive solids.
7. Compaction due to overburden pressure.
8. Thermal expansion.

Then, the Archie's relationship can be expanded to equation below:

$$S_w^{\,n} = a\, R_w / \varnothing^{m} R_t \quad \text{(2-7)}$$

For rocks following the Archie model, parameter *a* equals one and cementation factor is close to 2.

Thus, the resistivity of a rock is dependant upon the following factors, Keller (1953), Han (2007), Dernaika M. et al. (2007), Donaldson and Siddique (1989) :

1. Water saturation.

2. Wettability.
3. Salinity of formation water.
4. Rock structure.
5. Reservoir temperature.
6. Presence of clay.
7. Degree of cementation.
8. Net overburden pressure.

Archie's equation is not easy to apply to carbonate rocks because formation parameters (*a, m, n*) are functions of changes in the pore geometry, clay content, tortuosity of the pores, as well as formation pressure. The straightforward application of the conventional method in carbonate rocks has severe limitations. Therefore, three methods are presented in this study to calculate the Archie's parameters.

2.2 Archie's Parameters

Tortuosity is one of the most popular concepts for explaining this variation in cementation factor. The tortuosity coefficient is a measure of the tortuous path available for current flow, with respect to the direct path available in a conductive solution. Using this concept alone to explain the relationship of pore geometry to the cementation factor implies that the increased resistance in some rocks having the same porosity is due to one having more tortuous passages than the other. Hence, increase in formation factors can be

accounted for to increase the value of the tortuosity. Archie's equation is not easy to apply to rocks because formation parameters (*a, m* and *n*) are functions of electrical tortuosity. Electrical tortuosity is determined by pore geometry, tortuosity of the pore system and wettability which, affects oil-water distribution in the pores, Saleh and Hilal (2004).

A value other than one is sometimes appropriate for "*a*" to compensate for variation in compaction, pore structure and grain size distribution in the relationship between *F* and porosity. The numerical value for "*a*" generally falls between 0.6 and 1.0, Helander (1983).

Pirson (1958) established a scale indicating the degree of cementation using m values (**Figure 2-1**).The cementation values range from 1.3 to 2.2. Tight cementation rocks are represented by higher *m* values than poorly cemented rocks.

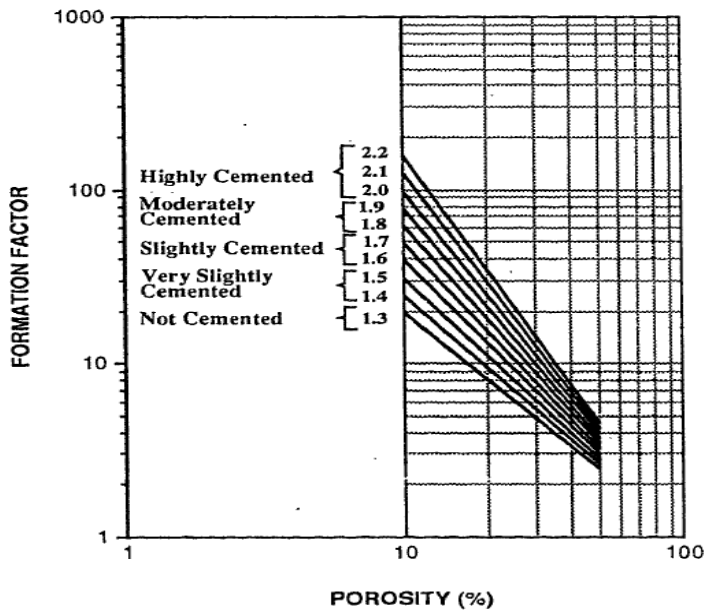

Figure 2-1 A scale indicating the degree of cementation factor "*m*", Pirson (1958)

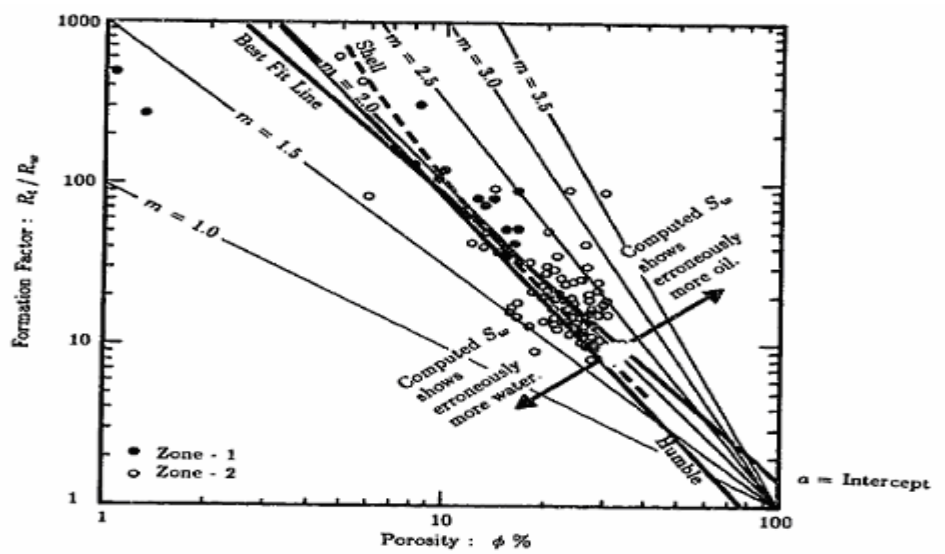

Figure 2-2 A cross plot of formation factor versus porosity for core data from two carbonate reservoir and shows the best linear line for this data, Amin et al. (1987)

Amin et al. (1987) observed the Archie factor (*m*) varies over a wide range in the carbonate reservoirs of the Middle East. **Figure 2-2** shows core data results, plotted on a log-log scale, of the formation factor against Ø for two zones of interest. Superimposed on this plot are the following lines:

a- Lines of iso-*m* values in the range of 1.0-3.5.

b- A line representing the Shell formula form.

c- A line representing the Humble formula for the formation factor.

d- A best fit line using least squares fit. This line gives *a* value form 1.9 and *a* = 1.65.

Focke and Munn (1987) found out that cementation parameter is a function of the rock lithology and it varies significantly in carbonate rocks. Results of electrical properties studies on the carbonate rocks indicate that the variation of the cementation factor is a function of grain size and the geometric configuration, which ultimately controls the rock porosity.

Authors also found that rock types with intergranular porosity and sucrosic dolomites show *m* values close to 2. Rock types with matrix porosity only, such as mudstones and wackestones, also show *m* values close to 2. Rock types with both matrix and vuggy or moldic porosity show *m* values generally greater than 2, in proportion to the amount of unconnected porosity, but no firm values can be provided. Fractured and fissured rock

types may have m values less than 2 that theoretically could become as low as 1. Moldic lime (oolitic) grainstones show *m* values that range from about 1.8 at 5% porosity to 5.4 at 35 % porosity.

Borai (1987) noted that Archie's relationship with cementation factor of *m*=2 is applicable for formations with medium to high porosity.

Maute, R.E et al. (1992) evaluated the Archie's parameters in both sandstone (16 cores) and carbonate (8 cores) reservoir rocks. The results show that the cementation factor varies from 1.55 to 1.83 and water exponent factor varies from 1.79 to 2.19 in sandstone whereas the variation in the cementation factor in the carbonate rocks started from 1.67 to 2.67 and water exponent from 1.75 to 2.95 using different methods.

Wang Z. et al. (1991) studied the electrical and petrophysical properties of carbonate rocks from different oil reservoirs and determined empirical correlation between formation factor and porosity, permeability and porosity, permeability and residual water saturation, saturation exponent and residual water saturation, sonic velocities porosity and formation factor. The formation factors were best-fit to Archie's equation so that the coefficient *a* and cementation exponent *m* were obtained. The results show that the cementation factor varies from 1.84 to 2.20 in sandstone whereas the variation in the carbonate rocks started from 1.14 to 1.89 at different pressures.

Harris et al. (1992) determined the values for porosity and cementation exponent from

core analysis. The results of the core analysis are plotted and curve fit to obtain a relationship between the porosity and the cementation exponent for a particular zone. Next, dielectric water saturations are compared to Archie's water saturations in the flushed zone. The Archie exponents were obtained from the porosity versus *m* relationship and the *n* value, which is varied until the least error in flushed zone saturations is obtained using the two methods and least squares summation. The results show that the cementation factor varies from 1.96 to 2.20 and the value of water exponent (2.45) indicates that the reservoir is dominantly water-wet.

Talia S.A. et al. (2001) performed a series of experiments in order to derive the correct form of the Archie's Equation that can be applied to carbonate rocks. The parameter *a* is further split to account for the composition, pore geometry and formation pressure. By separating these parameters, it is possible to find more precise correlation with formation resistivity and formation water saturation for carbonate reservoirs. Also, they derived the correlations between resistivity and the composition of the carbonate rock as well as formation pressure. Finally, an equation is proposed for taking into account changes due to the presence of critical fluids. The generalized equation can then be applied to any fluid in a carbonate formation with varied geometry and clay content.

Hamada et al. (2002) presented a new technique to determine Archie's parameters *a, m* and *n* based on the concept of three dimensional-regression (3D) plot of water saturation, formation resistivity and porosity. The 3D technique provides simultaneous values of

Archie's parameters. It also overcomes the uncertainty problems due to the separate use of formation resistivity factor porosity and water saturation equations to get the *a, m* and *n* parameters.

Tabib M. Emadi (2003) explained a new method of achieving variable m using the most effective reservoir parameters for any arbitrary interval of reservoir. The cementation factor is not a constant value, but it largely varies according to many parameters in a field peculiar to reservoir characteristics.

Knacksted et al. (2007) presented results of a 3D pore scale study of the resistivity properties in twelve model and reservoir core samples. Samples include sintered bead packs, homogeneous consolidated sandstones, thinly bedded sands, sucrosic dolomites, dual porosity samples and heterogeneous carbonate core material. Predictions of Archie's cementation exponent *m* and saturation exponent *n* (under well defined wettability conditions) are in good agreement with experiment where available. They note a consistent increase in *m* with decreasing porosity in sandstones. The value of *m* in carbonates may be empirically related to the fraction of disconnected macroporosity. Under water wet conditions the simple clastic and carbonate samples exhibit Archie-type behavior.

Fleury et al (2004) presented an extensive laboratory study to determine initial water saturation as well as remaining oil in water flooded regions in a carbonate field. The

initial water saturation was estimated using the resistivity index (*RI*) curves in drainage. Very low saturation was reached covering the range of saturation of interest in the field; *n* values around 1.7 are typical. In imbibition, a strong hysteresis was generally observed and RI curves are strongly non-linear in log-log scale with typical *n* value of 2.5 at high saturation. Therefore, the log calibration in water flooded regions must be performed using different curves. A calibration methodology for non-Archie *RI* curves is presented. Despite mixed-wet conditions, *n* values are lower than the default value of 2 and much lower than expected in strong oil wet conditions. When considering the saturation range [0.05 – 0.2], the choice of an appropriate *n* value is critical. For the water-flooded regions, the existence of a drainage-imbibition hysteresis has severe consequences on the evaluation of water saturation. In general, the laboratory measurements reduced the uncertainties in the oil in place estimations and allowed a realistic evaluation of the water flooding performance. Formation factor and resistivity index were measured on seven rock types (RRT) representing the entire reservoir. The resistivity index curves measured in drainage at reservoir temperature with dead oil were much more variable and the saturation exponent *n* varied from 1.4 to 2.1.

Knacksted et al (2007) noted that the laminated sand exhibit strong anisotropy and the complex carbonate systems exhibit values of *n* that vary strongly with water saturation. Large values of $n>4$ were observed under idealized oil wet conditions. Pore and fluid phase connectivity is examined for the image data and used to explain trends observed in

the data.

Han et al (2007) studied the influence of the pore space structure on resistivity index curves of sandstones and carbonates. They present a new method for measuring the resistivity index (*RI*) curve in air-brine system in drainage and imbibition. Below this saturation, a bending down deviation is sometimes observed. On carbonates (about 10 different structures), for single porosity granular structures, they observed quasi-linear *RI-Sw* curves in log-log scale with exponent *n* value of about 1.6 in drainage. They concluded that the water film conduction has an important influence on the decrease of *n* at low saturation range.

Dernaika et al (2007) estimated the initial water saturation by using the *RI-Sw* curves in drainage. Very low saturation was reached covering the range of saturation of interest in the field. The saturation exponents ''*n*'' appear to be around 2 for the reservoir rock types (RRT) while the tighter RRT's show lower values. Small hysteresis has been noticed in the imbibition cycle which tends to increase the saturation exponent ''*n*'' above 2.

2.3 Archie's Parameters Determination Techniques

2.3.1 Conventional Determination of *a, m* and *n*:

Equation 2-7 was an empirical relationship between rock resistivity, R_t and its porosity, and water saturation S_w. Equation 2-3 also showed that the resistivity of a rock fully saturated with brine (R_o) was related to the brine resistivity (R_w).

2.3.1.1 Conventional Determination of *a* and *m*:

The conventional determination of *a* and *m* is based on the equation 2-6 and rewritten as:

$$\text{Log } F = \log a - m \log Ø \quad \text{.....} \quad (2\text{-}8)$$

The plot of Log (*F*) versus Log Ø should give a liner trend, where m represents the slop of this trend and the intercept at Ø =1 gives the coefficient a.

2.3.1.2 Conventional Determination of the saturation exponent *n*:

The saturation exponent *n* may be estimated using equations (2-3) and (2-4) that relate to the rock resistivity partially saturated with water to the rock resistivity 100% saturated with water. These equations can be rewritten as:

$$Log\ (R_t\ /\ R_o) = -n\ Log\ S_w \quad \text{.....} \quad (2\text{-}9)$$

$$Log\ (RI) = -n\ Log\ S_w \quad \text{.....} \quad (2\text{-}10)$$

being the resistivity index bilogarithic plot of Log *RI* versus S_w gives a straight line with negative slop *n*.

2.3.2 Core Archie's Parameters Estimation Method (CAPE):

Maute et al. (1991) introduced a mathematical technique to determine Archie's parameters *m, n* and optionally *a* from standard resistivity measurements on core

samples. The derivation and details of that technique called Core Archie Parameter Estimation (CAPE) is explained by this group.

The idea of this technique is to determine the Archie's parameters by minimizing the mean-square error between the measured and the computed saturations using the Archie equation. There are two separate cases to be considered.

In the first case, the parameter *a* is set equal unity, and the mean-square saturation error ε_1 defied by

$$\varepsilon_1 = \sum_{j=1}^{P} \sum_{i=1}^{Q_j} \left[S_{ij} - \left(\frac{R_{wj}}{R_{ij}} \phi_j^{-m} \right)^{\frac{1}{n}} \right]^2 \quad \text{..... (2-11)}$$

Where the *j* index sums over the *P* cores that were measured, and the *i* index sums over the number of measurements *Qj* made on each core.

In the second case, the parameter *a* is not fixed at unity, and the mean-square saturation error ε_2 defined by

$$\varepsilon_2 = \sum_{j=1}^{P} \sum_{i=1}^{Q_j} \left[S_{ij} - \left(\frac{aR_{wj}}{R_{ij}} \phi_j^{-m} \right)^{\frac{1}{n}} \right]^2 \quad \text{..... (2-12)}$$

To minimize the error between the measured and calculated water saturation in laboratory

the partial derivative of the error with respect to Archie's parameters should be equal to zero;

$$\delta\varepsilon / \delta a = 0 \quad \text{(2-13)}$$

$$\delta\varepsilon / \delta m = 0 \quad \text{(2-14)}$$

$$\delta\varepsilon / \delta m = 0 \quad \text{(2-15)}$$

By differentiation of Equ.2-12 to *a, m,* and *n* the three equations results will be as follows:

$$F1 = \delta\varepsilon / \delta a = 2/n \sum\sum \left(S_{wij} - h_{ij}\right) h_{ij} \ln h_{ij} = 0 \quad \text{(2-16)}$$

$$F2 = \delta\varepsilon / \delta m = 2/n \sum\sum \left(S_{wij} - h_{ij}\right) h_{ij} \ln \phi_{ij} = 0 \quad \text{(2-17)}$$

$$F3 = \delta\varepsilon / \delta n = -2/na \sum\sum \left(S_{wij} - h_{ij}\right) h_{ij} = 0 \quad \text{(2-18)}$$

Where S_{wij} (water saturation) is the *ith* measurements on the core *J* and $h_{ij} = \left(aR_w / \phi_j{}^m R_{tij}\right)^{1/n}$ is the calculated water saturation using assumed values of Archie's parameters. The Equ. 2-16 to 2-18 is nonlinear. Therefore, a numerical solution can be obtained by linearzing *F1, F2* and *F3* about some point near the true solution. The linearization is accomplished by expanding the functions in a first order Taylor series. So

the function; *F1, F2* and *F3* become

$$F1(a_k, m_k, n_k) + \delta F1/\delta a(a_{k+1} - a_k) + \delta F1/\delta m(m_{k+1} - m_k) + \delta F1/\delta n(n_{k+1} - n_k) = 0 \text{ .... (2-19)}$$

$$F2(a_k, m_k, n_k) + \delta F2/\delta a(a_{k+1} - a_k) + \delta F2/\delta m(m_{k+1} - m_k) + \delta F2/\delta n(n_{k+1} - n_k) = 0 \text{ ... (2-20)}$$

$$F3(a_k, m_k, n_k) + \delta F3/\delta a(a_{k+1} - a_k) + \delta F3/\delta m(m_{k+1} - m_k) + \delta F3/\delta n(n_{k+1} - n_k) = 0 \text{ ... (2-21)}$$

The above equations can be solved to calculate $a_{k+1}, m_{k+1} and .. n_{k+1}$ by arranging the previous three equations in the form.

$$\begin{bmatrix} a_{k+1} \\ m_{k+1} \\ n_{k+1} \end{bmatrix} = \begin{bmatrix} a_k \\ m_k \\ n_k \end{bmatrix} - \begin{bmatrix} \delta F1/\delta a ..... \delta F1/\delta m ..... \delta F1/\delta n \\ \delta F2/\delta a ..... \delta F2/\delta m ..... \delta F2/\delta n \\ \delta F3/\delta a ..... \delta F3/\delta m ..... \delta F3/\delta n \end{bmatrix}^{-1} * \begin{bmatrix} F1(a_k, m_k, n_k) \\ F2(a_k, m_k, n_k) \\ F3(a_k, m_k, n_k) \end{bmatrix} \text{..... (2-22)}$$

When *a*=1 at the case one the above equations can be solved to calculate $m_{k+1} and .. n_{k+1}$ by arranging the previous two equations in the form.

$$\begin{bmatrix} m_{k+1} \\ n_{k+1} \end{bmatrix} = \begin{bmatrix} m_k \\ n_k \end{bmatrix} - \begin{bmatrix} \delta F1/\delta a ..... \delta F1/\delta m ..... \delta F1/\delta n \\ \delta F2/\delta a ..... \delta F2/\delta m ..... \delta F2/\delta n \end{bmatrix}^{-1} * \begin{bmatrix} F1(a_k, m_k, n_k) \\ F2(a_k, m_k, n_k) \end{bmatrix} \text{..... (2-23)}$$

Assumptions and Limitations:

1- Require more than one data core to calculate *n* and *m* when *a* is assumed to unity.
2- Require two or more than data core to calculate *a, n* and *m*.

3- Equation will not converge since the matrix of partial derivatives is singular.

Maute et al. (1992) used both techniques conventional and CAPE methods to determine the Archie's parameters (*m, n, a*) in order to calculate water saturation. They found that the results of the CAPE analysis method in computed water saturations agree well with core-measured whereas the results of the conventional method are not agree well. This means that the conventional method minimizes the error in nonphysical quantities. Whereas, CAPE provides a natural and physically meaningful method of "averaging" Archie's parameters. Finally, they show that the Archie constant "*a*" is a weak-fitting parameter, with no physical significance, that can generally be set to unity.

Assumptions and Limitations:

1. The cores follow Archie's law acceptably well.
2. The core samples represent the zone.
3. Most of the clean sandstones should work well but dirty sandstones may deviate significantly from Archie's equation.
4. Carbonate samples should work if they don't contain any vogues or shale.
5. The collection of core samples accurately represents the zone.

2.3.3 Three –Dimension (3D) Method:

The conventional method to obtain a, m, n has many disadvantages as represented by the comments discussed before. The CAPE method is an excellent way for *a, m* and *n*

determination but the complexity of the mathematical treatments of the equations and the time consumed for obtaining these parameters by this method hinder many log analysts from using this method. As a result, Hamada et al. (2002) proposed the 3-D technique to calculate Archie's parameters

Methodology:

By taking the logarithm of the two sides of equation (2-7) we get:

$$n\log S_w = \log a + \log R_w - m\log Ø - \log R_t \quad \text{…….....…....….. (2-24)}$$

and rearranging the previous equation in the form:

$$\log R_w / R_t = -\log a + m\log Ø + n\log S_w \quad \text{……..…..…….. (2-25)}$$

The left hand side of the previous equation may be treated as the dependent variable and the right hand term which includes porosity and water saturation is the independent variable.

We can consider this equation as a plane in three dimensional (3D) space of coordinate *x*, *y* and *z*. where;

$x = \log Ø$,

$y = \log S_w$

$z = log\ R_w / R_t$

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.

One may try to solve the problem graphically, but the error resulting will be greater than if we use the analytical method. The three dimensional regression analysis technique is used for obtaining a, m and n simultaneously as follows:

For a given set of data for a core sample, we can obtain an equivalent set of variables *x, y* and *z*. Equation 2-25 will take the following form for i measurement points:

$$Zi = - A + m\ Xi + n\ Yi \quad \text{(2-26)}$$

By normalizing Equ. 2-26 for *N* reading, we can have the following three simultaneous equations

$$\Sigma\ Zi = - NA + m\ \Sigma Yi + n\ \Sigma Yi \quad \text{(2-27)}$$

$$\Sigma Zi\ Xi = -A\ \Sigma Xi + m\Sigma Xi2 + n\ \Sigma Yi\ Xi \quad \text{(2-28)}$$

$$\Sigma ZiYi = -A\Sigma\ Yi + m\Sigma XiYi + n\Sigma Yi2 \quad \text{(2-29)}$$

Where *A* is equal to log *a*.

For an accurate determination Archie's parameter, a computer program is developed which uses the resistivity data for all the cores in order to get an average value for Archie's parameter. The flow chart for the steps used in this program is illustrated in Fig. and the results of this program are illustrated in the Table.

Assumptions:

First, the 3D method assumes that Archie's formula is applicable to the examined core samples representing the zone of interest. For shaly sand, 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 method. The second assumption might be satisfied, as it is concerned with the accuracy of laboratory measurements under reservoir conditions.

2.4 Error Analysis of Archie's Parameters Determination Techniques

Statistical and graphical error analyses were used to check the accuracy and performance of these methods developed in the study.

2.4.1 Statistical Error Analysis:

The accuracy of these methods relative to the actual or measured values is determined by using various statistical means. The criteria used in this study were average percent relative error, average absolute error, minimum/maximum absolute and relative error, the

root mean square error, standard deviation, and the correlation coefficient.

2.4.1.1 Average Percent Relative Error:

It is an indication of the relative deviation in percent from the measured values and given by:

$$E_r = \frac{\sum_{i=1}^{i=n_d} E_i}{n_d} \quad \text{…….....……. (2-30)}$$

E_i is the relative deviation in percent of an estimated value from a measured value and it is defined by:

$$E_i = \left[\frac{X_{\exp} - X_{est}}{X_{\exp}}\right] * 100 \quad \text{…….....…..….. (2-31)}$$

where

X_{exp} represent the experimental values.

X_{est} represent the estimated values.

E_r is an indication of the relative deviation in percent from the experimental values. The lower the value of E_r, the more equally distributed is the errors between positive and negative values.

2.4.1.2 Average Absolute Error:

It is defined as:

$$E_a = \frac{\sum_{i=1}^{i=n} E_{abs}}{n_d} \quad \text{.....} \quad (2\text{-}32)$$

$$E_{abs} = \left| X_{exp} - X_{est} \right| \quad \text{.....} \quad (2\text{-}33)$$

and indicates the absolute deviation, in percent, from the experimental values.

A lower value implies a better method.

2.4.1.3 Minimum/Maximum Absolute Error:

After calculating the absolute error and the absolute percent relative error for each data point, E_i .i = 1, 2,…., nd , both the maximum and minimum values were scanned to determine the range of error for each method.

$$E_{\max} = \max\left|E_i\right|$$

$$E_{\min} = \min\left|E_i\right| \quad \text{.....} \quad (2\text{-}34)$$

The lower the value of maximum absolute or relative error is the higher the accuracy of the method.

2.4.1.4 Root Mean Square Error

$$RMS = \sqrt{\left(\frac{E_{abs}}{n_d}\right)^2} \quad \text{..... (2-35)}$$

The lower the value of root mean square error (*RMS*) is the higher the accuracy of the method.

2.4.1.5 Standard Deviation:

Standard deviation of the errors, *S*, is a reflection of the dispersion of errors around the mean and a measure of the quality of the fit. It is expressed as the positive square root of the variance.

$$S = \sqrt{\left(\frac{\sum_{i=1}^{i=n_d} \left| X_{exp} - X_{est} \right|}{n_d - 1}\right)} \quad \text{..... (2-36)}$$

A lower value of standard deviation means a smaller degree of scatter and a better quality of fit.

2.4.1.6 The Correlation Coefficient:

The correlation coefficient, *r*, represents the degree of success in reducing the standard

deviation by regression analysis.

$$r = \sqrt{\left(1 - \frac{\sum_{i=1}^{n_d} \left(x_{\exp} - x_{est}\right)_i^2}{\sum_{i=1}^{n_d} \left(x_{\exp} - \bar{x}\right)_i^2}\right)}$$

where

$$\bar{x} = \frac{\sum_{i=1}^{n_d} \left(x_{\exp}\right)_i}{n_d} \qquad \text{…….....……. (2-37)}$$

The correlation coefficient lies between 0 and 1. A value of 1 indicates a perfect correlation whereas a value of 0 implies no correlation at all among the given independent variables. The larger of the value of *r*, the greater is the reduction in the sum of squares of the errors, and the stronger is the relationship between the independent and the dependent variables.

CHAPTER 3

STATEMENT OF THE PROBLEM

3.1 Significance of this study

A lot of work has been done in the laboratory using core-resistivity and conventional method in the determination of Archie's parameters and water saturation in sandstone reservoir. Limited work have done to determine the Archie's parameters and water saturation in carbonate reservoir using conventional, CAPE and 3-D methods.

Major hydrocarbon formation in the Middle East is carbonate rocks that need more evaluation studies. So this study is done experimentally using carbonate core samples. Moreover, evaluation of water saturation is very important either in early life of reservoir or during development stage to calculate an oil reserve.

This work seeks to get an accurate Archie's parameters and consequently better evaluation of water saturation in the carbonate rock using above techniques.

3.2 Problem Statement

The conventional techniques are generally accompanied by some assumptions and limitations that can affect the calculation of Archie's parameters. In addition, the difficulty to apply this technique in carbonate rock to get formation parameters (*a, m, n*).

For this reason, the CAPE and 3-D techniques were applied and the results were compared with conventional method in order to get the most accurate technique to calculate the Archie's parameters.

3.3 Objectives

The objectives of this study are: 1) Conducting laboratory experiment to determine electrical properties of core plugs, 2) Using an appropriate algorithm to calculate Archie's parameters and a corresponding water saturation values by different techniques, 3) analyzing and discussing experimental result in order to get the most accurate technique.

3.4 Methodology

The approach to be adopted in this study was experimental. Carbonate plugs were selected, prepared, cleaned and dried. Then, their dimensions, dry weight, and porosity were measured. Cores were then saturated with brine .The cores were then de-saturated by the application of constantly increasing capillary pressure using nitrogen and crude in a porous plate cell.

Two-and four-pole resistivities, temperature, confining pressure, pore pressure, and produced brine were monitored and recorded using data acquisition system. Electrical measurements were taken until resistivity and desaturation equilibriums were reached at

each capillary pressure step.

All resistivity measurements were corrected for a reservoir temperature of 80°C during data processing. After temperature equilibrium, the confining pressure was raised to 2500 psi and the brine expelled from each sample was measured. After initial electrical measurements, desaturation was performed stepwise from 0 to 120 psi pore pressure. Although four-pole resistivities were used for determining the electrical parameters, two-pole resistivities were also recorded for monitoring the contact problems that might have occurred.

Three techniques, (Conventional, CAPE and 3-D) were used to calculate Archie's parameters and corresponding water saturation using brine resistivity (R_w), cores resistivity (R_t), porosity and measured water saturation. The accuracy analysis between calculated and measured water saturation values was applied in order to select the best technique.

CHAPTER 4

EXPERIMENTAL PROCEDURES

4.1 Sample Selection and Preparation

Core samples used in this study have different range of porosity and permeability.

4.1.1 Sample selection

A total of 44 plug samples were received from three wells. Seventeen core samples are from well A, fifteen core samples from well B, and twelve core samples from well C. These core samples had different ranges of porosity and permeability. These samples are a carbonate core samples (limestone and dolomite) and some have vugs.

4.1.2 Trimming of core plugs

The core plug samples were trimmed to ensure plane and parallel surfaces at both ends. Rough edges in the core plugs were made even using gypsum.

4.1.3 Sample Cleaning and Drying

The core samples were cleaned using toluene for 12 -16 hours to remove residual oil and then cleaned for 8-10 hours in methanol alcohol to remove salt from the pores. The core samples were dried in an oven for 24 hours under vacuum and the dry weight of the core samples were recorded.

4.2. Measurement of Porosity and Permeability

Porosity and permeability at ambient (500 psi) and stressed (2500 psi) conditions were measured for each core samples using an overburden permeameter porosimeter (OPP 610).

4.3 Brine Preparation

4.3.1 Preparation of Brine

The salt type and amount used in preparation of synthetic brine are listed in table 4.1. The brine was kept covered during the preparation and afterwards to ensure that water did not evaporate and the salinity of brine which (76,339 ppm) did not change.

Table 4-1 Composition of the synthetic brine used in the electrical tests

Salt Type	**Solids (g/l)**
NaCl	47.726
$CaCl_2$.	23.996
$MgCl_2 . 6H_2O$	6.670
Na_2SO_4	0.804
$NaHCOl_3$	0.143
Total dissolved	79.339

4.3.2 Measurement of Brine Resistivity

Brine resistivity was measured using a Dresser Fann resistivity meter. Since brine resistivity is highly sensitive to change in temperature and since the lab temperature was not uniform, the temperature and resistivity were measured over a period of about 5 minutes and stable values of resistivity were recorded to equal 0.2 ohm.m at 72 ^{o}F. Care was also taken to ensure that the electrodes of the resistivity cell were cleaned with sand-paper before use as they are prone to oxidation. This brine resistivity is converted to reservoir temperature 80 ^{o}C by using the relation below:

$$R_2 = R_1 (T_1+21.5) / (T_2+21.5) \quad \text{…….....……..} \quad (4\text{-}1)$$

Where:

R_1, R_2: are the resistivities of brine in different condition.

T_1, T_2: are the temperatures of brine in different condition

4.4. Sample Saturation and Preservation

The dried core samples were vacuumed in a cylindrical cell for about 4 hours. After sufficient vacuuming, the samples were saturated with brine. Then a pressure of 2000 psi was applied to ensure complete saturation of small pores. The weight of the saturated core samples is recorded. The core samples were then loaded to electrical cart cells or kept preserved inside vacuum cylinder.

4.5 Bulk and Pore Volume Calculation

The bulk volume was calculated from the dimensions of core samples (diameter, *D*, and length, *L*) whereas the pore volume (*PV*) was calculated from the deference between saturated weight and dry weight divided by density of saturated fluid (brine).

$$\text{Bulk Volume} = \pi (D/2)^2 * L \quad (5\text{-}2)$$

PV (cc) = (Saturated Weight (g) – Dry Weight (g))/ Density of brine (g/cc)

4.6 Porous plate de-saturation

4.6.1. System Description

The ER2005 Electrical Resistivity Test System consists of five components**, Figure 4-1**: Pressure Control Cart, Test Cell Cart, Lift Assist, Electronics Rack and Work Station. There is a lift assist that is mounted to the top of the Test Cell Cart. Each of these system components is described in the paragraphs below.

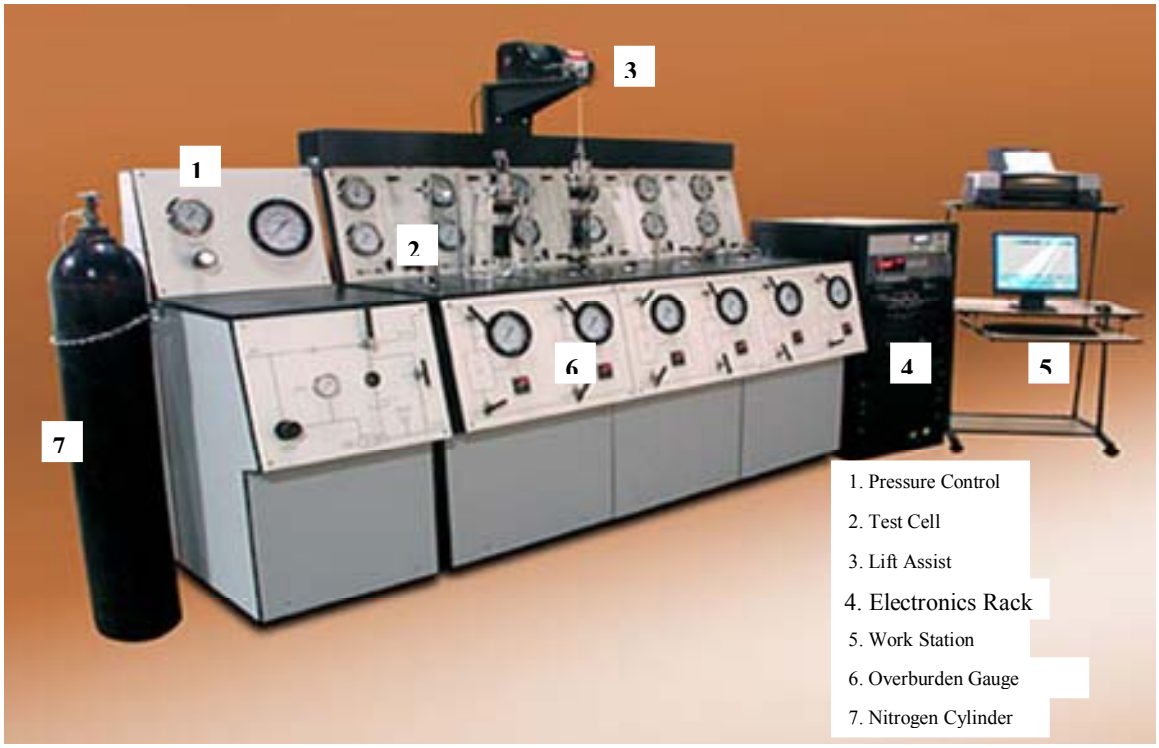

Figure 4-1 ER2005 Electrical Resistivity Test System

4.6.1.1 Pressure Control Cart

The Pressure Control Cart provides confining pressure and desaturation pressure to the cells in the Test Cell Cart. The Pressure Control Cart includes a valve panel, located on the front of the cart, below the work surface and a gauge panel, located above and behind the work surface.

The schematic silk screened on the valve panel indicates the confining pressure control components that are located in the Pressure Control Cart. This includes a reservoir that stores the heat transfer fluid that provides confining pressure to the test cells and a high pressure pump that generates the confining pressure.

The high pressure pump is air-driven. The air pressure regulator on this panel, label "Drive Pressure Regulator" controls the air pressure to the high pressure pump, and hence the confining pressure generated by the pump. The "Drain" valve allows the output from the high pressure pump to be returned directly back to the reservoir. The three-way valve labeled "Vent" determines whether the vent line returning from the test cells is connected to the reservoir, or to the air supply for air-assisted draining of the test cells. A flow site allows the operator to observe flow returning to the reservoir,

4.6.1.2 Test Cell Cart

The test cell cart contains the six test cell (**Figure 4-2**) in which core samples are tested for electrical resistivity properties.

Five of these test cells have a 3.5 inch inside diameter, for testing core samples up to 1.5 inches in diameter. Above and behind the work surface that supports the test cells is located a series of desaturation pressure control panels. Below and in front of the work surface is a series of test cell pressure/temperature control panels.

The desaturation pressure control panels contain two pressure gauges for each test cell. These two pressure gauges indicate the nitrogen pressure on the upstream side of the sample in the test cell. One pressure gauge has a range of 0-200 psi. The second gauge has a range of 0-15 psi for accurate indication of the pressure in lower ranges. An isolation valve allows the lower pressure gauge to be isolated from the system when higher desaturation pressures are applied. A reference volume is located behind the desaturation pressure control panel.

Appropriate valves are located on the panel. Bulkhead connections are located on the panel as well to allow the desaturation pressure to be connected to the test cell.

The test pressure/temperature control panel indicates a temperature controller to control the temperature of the test as well as the necessary valves to isolate pressure inside the test cell. A separate pressure gauge for each test cell indicates the inside the test cell. **Figure 4-3** shows Test cell pressure and temperature control panel.

Figure 4-2 Test cells cart

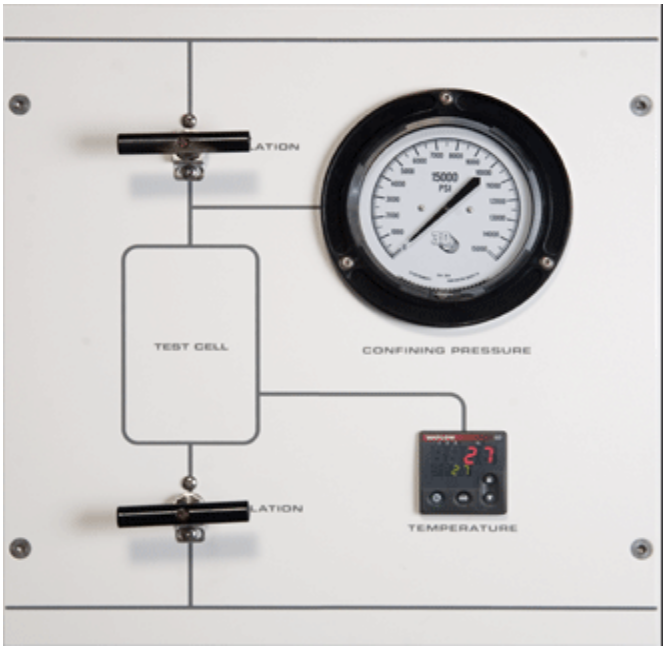

Figure 4-3 Test cell pressure and temperature control panel

4.6.1.3. Lift Assist

The lift assist is mounted along the top of the test cell cart. This consists of trolley-mounted winch that can be moved to a position above each test cell along the length of the test cell cart. Winch controls allow the electric winch to be used to raise or lower the upper plug assembly from the test cell.

4.6.1.4. Electronics Rack (ER)

System electronics are rack mounted in the electronics rack. The following components are mounted in this rack:

- Arbitrary Waveform Generator, whose function is to provide the AC current to the core sample for electrical resistivity measurements
- Digital Analyzing Voltmeter for measuring phase and amplitude of the voltage at various points through the core sample, to allow electrical resistivity to be measured
- ER-8 Switch Box to provide the necessary switching functions between test cells, and measurement points on the test sample
- Signal conditioning for the pressure transducers and thermocouples in the system
- System computer
- Uninterruptible power supply(UPS)

4.6.1.5. Work Station

Work station provides a place for the operator to work. The monitor, keyboard, mouse, and printer connected to the computer are located on the work station.

4.6.2 Operational Procedure of Test Cart

Operational procedures are listed in the order that they would normally be carried out in a complete test procedure.

- Sample Stack Assembly(**Figure 4-4**)
- Installing Sample Stack into the Test Cell
- Filling the Test Cell
- Heating the Test Cell
- Pressurizing the Test Cell
- Applying Desaturation Pressure
- Measuring Displaced Pore Fluid
- Removing Desaturation Pressure
- De-Pressurizing the Test Cell
- Draining the Test Cell
- Removing the Upper Plug Assembly

Figure 4-4 Sample stack assembly attached to upper plug assembly in the test cell

4.6.3 Experimental Set Up

1) Before a test can be started, an entry must be made in each field on the screen

- In the field labeled project, rock type, porosity, and permeability, anything can be entered. These entries are not used by the program, but are saved in the data file for use as desired in data reduction.
- The text entered in the sample ID field is displayed in the corresponding box on the Test Data Screen.
- The values, entered in the R_w and associated temperature, are used to calculate R_w at the test temperature, and F2-3.

- Length, Diameter, and Electrode spacing must all be entered in cm, and are used in the calculations for the four ER values.
- Frequency is the signal frequency at which the ER measurement is made.
- Acquisition period is the time between automatic ER measurements.
- File is the bath and file name for the data file where test data will be saved.

2) A total of 44 core samples were tested. Electrical tests were conducted using a set-up which has four test vessel assemblies (hydrostatic cells and upper plug assemblies) that allow the simultaneous testing of four samples under elevated pressure and temperature.

3) Two and four-pole resistivities, temperature, confining pressure, pore pressure, and brine displacement are monitored continuously and recorded by a computer attached to the system.

4) A rubber sleeve used for jacketing the core plug contains imbedded electrodes for resistivity measurements. The electrical resistivity stack includes a sample and end caps clamped tightly in the rubber sleeve.

5) The outlet end cap holds a porous plate. Desaturation is accomplished using the porous plate method by applying pore pressure in steps. Arab-D crude oil was used to displace the brine. Electrical measurements were taken continuously until resistivity and desaturation equilibriums were reached at each step.

6) The brine saturated samples were mounted in resistivity stacks and the temperature was raised to 70 ℃ while the confining pressure was kept at 500 psi.

7) All resistivity measurements were corrected for a reservoir temperature of 80 °C during data processing. After temperature equilibrium, the confining pressure was raised to 2500 psi and the brine expelled from each sample was measured.

8) After initial electrical measurements, desaturation was performed stepwise from 0 to 120 psi pore pressure. Although four-pole resistivities were used for determining the electrical parameters, two-pole resistivities were also recorded for monitoring the contact problems that might have occurred.

CHAPTER 5

RESULTS AND DISCUSSION

In this study three methods (Conventional, CAPE, 3D Method) are presented to calculate the Archie's parameters as it is extremely important in petrophysical interpretation that accurate water saturation needs good values of Archie's parameters.

5.1 Basic Core Measurements:

5.1.1 Measurement of Porosity and Permeability

The results of Lithology, porosity and permeability at (2500 psi) of 44 core samples were reported in **Tables 5-1, 5-2, and 5-3**.

Table 5-1 Lithology, porosity and permeability at (2500 psi)of 17 core samples, well A

Sample No	Lithology	Porosity (%)	Permeability (mD)
A1	Foram Grainstone	0.17	18.68
A2	Foram Grainstone	0.22	31.66
A3	Dolomatic Skeletal Packstone	0.15	1.82
A4	Dolomatic Skeletal Grainstone	0.19	16.61
A5	Skeletal Peloidal Grainstone	0.22	15.17
A6	Mic Peloidal Grainstone	0.25	45.48
A7	Mic Skeletal Peloidal Grainstone	0.26	48.55
A8	Dolomatic Skeletal Peloidal Packstone	0.18	5.74
A9	Dolomatic Skeletal Peloidal Packstone	0.16	2.35
A10	Dolomite	0.18	502.25
A11	Calc Dolomite	0.15	14.59
A12	Skeletal Peloidal Grainstone	0.19	613.05
A13	Mic Skeletal Peloidal Grainstone	0.18	74.59
A14	Dolomite	0.14	81.93
A15	Dolomite	0.16	127.45
A16	Intcl Grainstone	0.10	119.47
A17	Intcl Grainstone	0.10	95.70

Table 5-2 Lithology, porosity and permeability at (2500 psi) of 15 core samples, well B

Sample No	Lithology	Porosity (%)	Permeability (mD)
B1	Peloidal foraminiferal grainstone	0.17	210.13
B2	Peloidal foraminiferal grainstone	0.18	93.48
B3	Peloidal foraminiferal grainstone	0.13	24.91
B4	Peloidal sponge spicule packstone	0.21	12.79
B5	Peloidal skeletal grain dominated packstone	0.16	10.34
B6	Peloidal foraminiferal grainstone	0.21	78.61
B7	Peloidal foraminiferal grainstone	0.18	17.63
B8	Peloidal skeletal grain dominated packstone	0.20	12.81
B9	Dolomitic peloidal skeletal packstone	0.15	11.44
B10	Dolomite	0.11	10.38
B11	Peloidal skeletal wackestone	0.12	19.12
B12	Peloidal intraclastic skeletal grainstone	0.19	248.55
B13	Dolomite	0.11	49.54
B14	Dolomitic peloidal skeletal packstone	0.07	0.39
B15	Peloidal domal stromatoporoid wackestone	0.22	13.28

Table 5-3 Lithology, porosity and permeability at (2500 psi) of 12 core samples, well C

Sample No	Lithology	Porosity (%)	Permeability (mD)
C1	Coated grain oolitic skeletal grainstone	0.16	54.51
C2	Peloidal oolitic foraminiferal echinoidal grainstone	0.21	62.16
C3	Peloidal skeletal grainstone/grain dominated packstone	0.18	27.18
C4	Peloidal foraminiferal grain dominated packstone	0.19	9.24
C5	Peloidal foraminiferal Clypeina grain dominated packstone	0.21	14.70
C6	Peloidal skeletal wackestone	0.19	8.04
C7	Dolomitic peloidal domal stromatoporoid wackestone	0.22	27.45
C8	Dolomite	0.18	11.77
C9	Dolomitic peloidal skeletal packstone/grain dominated packstone	0.13	2.22
C10	Peloidal Clypenia packstone/grain dominated packstone	0.25	23.25
C11	Peloidal foraminiferal grainstone	0.26	10.24
C12	Peloidal domal stromatoporoid bivalve grainstone	0.12	14.11

5.1.2 Bulk and Pore volume Calculation

Bulk volume and pore volume of core plugs are listed in **Table 5-4**.

Table 5-4 Bulk and pore volumes for Well A, B and C

Well No.	Sample No.	Bulk Volume	Pore Volume	Well No.	Sample No	Bulk Volume	Pore Volume	Well No.	Sample No.	Bulk Volume	Pore Volume
Well A	A1	50.163	8.47	Well B	B1	51.82	8.918	Well C	C1	52.62	8.30
	A2	47.056	11.19		B2	50.31	9.051		C2	52.38	10.55
	A3	49.786	8.07		B3	51.25	6.670		C3	51.93	9.60
	A4	52.877	10.95		B4	51.55	7.647		C4	53.01	9.92
	A5	49.960	11.76		B5	52.27	8.368		C5	52.13	10.48
	A6	46.254	11.92		B6	52.46	10.218		C6	52.80	9.52
	A7	47.997	13.25		B7	52.69	8.880		C7	52.78	11.71
	A8	55.786	10.61		B8	52.23	9.753		C8	52.41	4.75
	A9	50.669	8.75		B9	51.93	7.723		C9	52.93	6.17
	A10	47.290	8.89		B10	51.05	5.285		C10	51.43	9.45
	A11	55.608	8.80		B11	52.97	6.262		C11	52.36	6.17
	A12	50.173	9.93		B12	52.53	10.161		C12	53.08	5.83
	A13	45.546	8.80		B13	52.29	5.664				
	A14	54.697	8.53		B14	52.33	3.292				
	A15	48.569	7.93		B15	53.67	4.602				
	A16	47.882	4.71								
	A17	50.517	5.44								

5.2 Electrical Measurements

A total of forty four core samples were tested for electrical properties. All resistivity measurements and corresponding water saturation of well A, B, and C are shown in **Tables 5-5, 5-6,** and 5-**7** respectively.

Table 5-5 Electrical measurements of core plugs, well A

Sample A1			Sample A2			Sample A3			Sample A4			Sample A5			Sample A6		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	2.28	1.00	1.00	0.50	1.00	1.00	0.83	1.00	1.00	1.67	1.00	1.00	0.58	1.00	1.00	0.52	1.00
0.84	2.81	1.23	1.00	0.78	1.56	0.71	1.49	1.80	0.97	1.72	1.03	0.79	0.89	1.53	0.90	0.75	1.44
0.83	2.90	1.27	0.94	0.81	1.62	0.71	1.63	1.96	0.94	1.73	1.04	0.78	0.90	1.55	0.83	0.91	1.75
0.81	3.21	1.41	0.86	1.00	2.00	0.70	1.69	2.04	0.90	1.79	1.07	0.75	0.96	1.66	0.62	1.67	3.21
0.62	7.60	3.33	0.36	5.61	11.22	0.69	1.69	2.04	0.79	2.30	1.38	0.57	1.74	3.00	0.54	2.42	4.65
0.45	21.69	9.51	0.28	9.11	18.22	0.56	2.41	2.90	0.61	4.56	2.73	0.51	2.33	4.02	0.46	3.61	6.94
0.28	33.35	14.63	0.21	17.42	34.84	0.43	4.00	4.82	0.33	14.23	8.52	0.41	3.19	5.50	0.38	6.54	12.58
0.22	56.16	24.63	0.15	30.26	60.52	0.31	7.86	9.47	0.20	37.75	22.60	0.32	5.87	10.12	0.29	14.74	28.35
0.20	67.11	29.43	0.13	40.15	80.30	0.21	15.72	18.94	0.15	82.17	49.20	0.18	14.58	25.14	0.25	27.24	52.38
0.18	82.17	36.04															
Sample A7			**Sample A8**			**Sample A9**			**Sample A10**			**Sample A11**			**Sample A12**		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	0.44	1.00	1.00	2.10	1.00	1.00	0.95	1.00	1.00	1.86	1.00	1.00	1.39	1.00	1.00	1.09	1.00
0.87	0.88	2.00	0.96	2.30	1.10	0.95	1.09	1.14	0.69	5.41	2.91	0.96	1.40	1.01	0.59	2.42	2.22
0.81	1.00	2.27	0.94	2.33	1.11	0.92	1.16	1.22	0.53	11.03	5.93	0.94	1.43	1.03	0.35	8.36	7.67
0.66	0.99	2.25	0.88	2.41	1.15	0.89	1.19	1.25	0.22	54.22	29.15	0.85	1.81	1.30	0.31	11.55	10.60
0.53	2.21	5.02	0.59	4.79	2.28	0.79	1.63	1.71	0.14	144.3	77.59	0.64	3.38	2.43	0.29	14.59	13.39
0.44	3.77	8.57	0.36	11.75	5.60	0.58	2.92	3.06	0.12	198.3	106.63	0.40	12.40	8.92	0.26	18.92	17.36
0.35	7.18	16.32	0.18	43.91	20.91	0.24	17.06	17.88	0.11	252.4	135.70	0.25	15.49	11.14	0.24	22.37	20.52
0.26	16.49	37.48	0.13	82.85	39.45	0.15	42.59	44.64	0.10	297.4	159.94	0.23	18.70	13.45	0.22	26.99	24.76
0.20	32.16	73.09	0.12	109.4	52.13	0.09	83.04	87.04	0.09	333.5	179.33	0.16	37.86	27.24	0.20	30.74	28.20
Sample A13			**Sample A14**			**Sample A15**			**Sample A16**			**Sample A17**					
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*			
1.00	2.63	1.00	1.00	3.96	1.00	1.00	2.72	1.00	1.00	6.60	1.00	1.00	7.35	1.00			
0.86	4.41	1.68	0.70	8.65	2.18	0.91	3.12	1.15	0.78	9.57	1.45	0.87	9.17	1.25			
0.71	8.01	3.05	0.35	45.87	11.58	0.80	3.79	1.39	0.44	31.16	4.72	0.56	21.57	2.93			
0.64	10.06	3.83	0.29	57.16	14.43	0.66	6.04	2.22	0.35	56.80	8.61	0.47	32.93	4.48			
0.50	14.44	5.49	0.26	61.56	15.55	0.59	9.84	3.62	0.30	90.91	13.77	0.41	45.73	6.22			
0.42	18.92	7.19	0.24	68.92	17.40	0.21	78.69	28.93	0.21	142.8	21.65	0.36	58.47	7.96			
0.36	24.90	9.47	0.22	74.62	18.84	0.19	94.54	34.76	0.17	252.4	38.24	0.31	78.43	10.67			
0.29	32.33	12.29	0.19	82.56	20.85	0.17	101.8	37.43	0.16	288.4	43.71	0.28	99.16	13.49			
0.23	55.89	21.25	0.17	88.68	22.39	0.14	123.2	45.28	0.15	324.5	49.17	0.26	109.4	14.90			
						0.14	133.9	49.22									

Table 5-6 Electrical measurements of core plugs, well B

Sample B1			Sample B2			Sample B3			Sample B4			Sample B5		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	0.83	1.00	1.00	0.58	1.00	1.00	4.66	1.00	1.00	0.88	1.00	1.00	1.12	1.00
0.71	1.49	1.80	0.79	0.89	1.53	0.63	27.66	5.94	0.95	1.09	1.24	0.90	1.46	1.30
0.71	1.63	1.96	0.78	0.90	1.55	0.53	54.83	11.77	0.92	1.16	1.32	0.65	4.51	4.03
0.70	1.69	2.04	0.75	0.96	1.66	0.44	167.91	36.04	0.89	1.19	1.35	0.51	7.48	6.68
0.69	1.69	2.04	0.57	1.74	3.00	0.39	299.44	64.28	0.79	1.63	1.85	0.43	11.21	10.01
0.56	2.41	2.90	0.51	2.33	4.02	0.19	477.78	102.56	0.58	2.92	3.32	0.41	12.91	11.53
0.43	4.00	4.82	0.41	3.19	5.50	0.14	675.06	144.91	0.24	17.06	19.39	0.35	18.82	16.80
0.31	7.86	9.47	0.32	5.87	10.12	0.11	771.22	165.55	0.15	42.59	48.40	0.30	22.54	20.13
0.21	15.72	18.94	0.18	14.58	25.14				0.11	83.04	94.36	0.13	64.71	57.78
Sample B6			**Sample B7**			**Sample B8**			**Sample B9**			**Sample B10**		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	1.12	1.00	1.00	0.61	1.00	1.00	2.19	1.00	1.00	2.88	1.00	1.00	6.11	1.00
0.89	1.29	1.15	0.90	0.75	1.23	0.49	8.53	3.89	0.36	271.78	94.21	0.84	12.26	2.01
0.85	1.73	1.54	0.82	0.91	1.49	0.25	39.76	18.15	0.29	497.00	172.29	0.77	14.60	2.39
0.66	2.86	2.55	0.62	1.67	2.74	0.19	90.52	41.32	0.23	641.64	222.43	0.60	23.54	3.85
0.60	3.52	3.14	0.54	2.42	3.97	0.14	148.33	67.71	0.18	844.08	292.60	0.49	42.44	6.94
0.50	5.26	4.70	0.46	3.61	5.92	0.12	222.27	101.47	0.16	1110.62	385.00	0.38	48.58	7.95
0.44	7.66	6.84	0.38	6.54	10.72	0.11	253.98	115.94	0.16	1240.20	429.92	0.24	49.37	8.08
0.29	14.08	12.57	0.29	14.74	24.16	0.10	260.00	118.69	0.16	1544.29	535.33	0.17	50.84	8.32
0.16	44.92	40.11	0.22	27.24	44.66									
Sample B11			**Sample B12**			**Sample B13**			**Sample B14**			**Sample B15**		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	3.07	1.00	1.00	2.23	1.00	1.00	5.90	1.00	1.00	19.94	1.00	1.00	2.87	1.00
0.93	9.50	3.09	0.67	3.16	1.42	0.69	10.31	1.75	0.76	38.37	1.92	0.71	11.61	4.05
0.88	10.61	3.45	0.35	11.73	5.27	0.56	19.87	3.36	0.69	68.29	3.42	0.43	19.94	6.96
0.79	13.40	4.36	0.26	17.11	7.68	0.47	31.46	5.33	0.58	103.75	5.20	0.35	27.29	9.52
0.71	19.87	6.46	0.23	52.23	23.46	0.45	38.67	6.55	0.32	184.08	9.23	0.33	36.28	12.65
0.53	44.85	14.59	0.16	199.70	89.69	0.43	47.16	7.99	0.27	268.34	13.46	0.27	45.74	15.96
0.43	102.31	33.28	0.14	351.26	157.75	0.35	61.63	10.44	0.27	372.52	18.68	0.25	55.62	19.40
0.21	141.18	45.93	0.13	376.51	169.09	0.27	63.53	10.76	0.26	380.53	19.08	0.24	66.39	23.16

Table 5-7 Electrical measurements of core plugs, well C

Sample C1			Sample C2			Sample C3			Sample C4		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	3.61	1.00	1.00	1.61	1.00	1.00	2.10	1.00	1.00	1.74	1.00
1.00	3.73	1.03	0.83	2.31	1.43	0.71	3.71	1.77	0.83	2.48	1.42
0.94	4.25	1.18	0.68	3.11	1.93	0.71	4.98	2.37	0.50	7.83	4.50
0.86	5.11	1.42	0.52	4.32	2.68	0.70	6.12	2.91	0.44	10.93	6.28
0.36	20.45	5.66	0.45	5.98	3.71	0.69	7.65	3.64	0.27	30.33	17.43
0.28	37.64	10.43	0.29	11.78	7.32	0.56	8.11	3.86	0.19	77.18	44.36
0.21	50.61	14.02	0.18	34.78	21.60	0.43	10.43	4.97	0.10	142.57	81.94
0.15	77.53	21.48				0.31	16.32	7.77	0.09	147.10	84.55
0.10	98.75	27.35				0.21	23.22	11.06			
Sample C5			**Sample C6**			**Sample C7**			**Sample C8**		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	2.00	1.00	1.00	2.31	1.00	1.00	3.16	1.00	1.00	1.91	1.00
0.79	1.65	1.65	0.84	2.87	1.24	0.86	4.88	1.54	0.89	2.50	1.31
0.78	1.98	1.98	0.80	3.11	1.35	0.86	4.88	1.54	0.88	2.71	1.42
0.75	2.00	2.00	0.72	3.87	1.68	0.67	6.75	2.13	0.74	3.67	1.92
0.57	2.51	2.51	0.70	4.12	1.78	0.28	10.27	3.25	0.51	6.71	3.51
0.51	2.98	2.98	0.61	5.66	2.45	0.25	17.93	5.67	0.41	9.89	5.18
0.41	4.62	4.62	0.51	5.98	2.59	0.21	23.73	7.50	0.37	15.17	7.94
0.32	7.12	7.12	0.19	26.22	11.35	0.21	29.19	9.22	0.29	25.66	13.43
0.18	17.54	17.54	0.16	38.11	16.50				0.18	41.65	21.81
Sample C9			**Sample C10**			**Sample C11**			**Sample C12**		
Sw	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*	*Sw*	*Rt*	*RI*
1.00	3.81	1.00	1.00	0.98	1.00	1.00	1.01	1.00	1.00	3.99	1.00
0.93	7.22	1.90	0.90	1.15	1.17	0.87	1.12	1.11	0.84	9.21	2.31
0.87	7.25	1.90	0.83	1.43	1.46	0.81	1.28	1.27	0.65	15.76	3.95
0.82	8.41	2.21	0.62	1.92	1.96	0.66	1.67	1.65	0.59	23.89	5.99
0.72	11.20	2.94	0.54	2.76	2.82	0.53	2.42	2.40	0.45	30.89	7.74
0.43	41.71	10.95	0.46	3.41	3.48	0.44	3.61	3.57	0.37	41.66	10.44
0.29	72.02	18.90	0.38	5.32	5.43	0.35	6.54	6.48	0.28	59.58	14.93
0.24	100.05	26.26	0.29	7.21	7.36	0.26	14.74	14.59	0.19	126.67	31.75
			0.25	14.58	14.88	0.20	27.24	26.97	1.00	3.99	1.00

5.3 Determination of Archie's Parameters

Three well examples are given to calculate the Archie's parameters by the four techniques: 1) conventional technique, 2) core Archie parameter estimation (CAPE) technique with "*a*" equal one 3) core Archie parameter estimation (CAPE) technique with *a* not equal one and 4) three dimension (3D) technique. Then, the comparison and analysis among the four techniques have done in order to predict an accurate and physically meaningful way to get Archie's parameters *a, m* and *n* for given core samples of each well individually. 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 by applying the different techniques. Finally, the previous steps were repeated by considering all core samples of three wells as one studied section and the results were reported.

5.3.1 Results and Analysis of Well A

The electrical data produced experimentally of well A are summarized in **Table 5-5**. The data are used to calculate the Archie's parameters by applying the four techniques. Then, the data analysis is done between measured and calculated water saturation using Archie's parameters that calculated from each technique.

5.3.1.1 Conventional Method

5.3.1.1.1 Conventional Determination of *a* and *m*

In the conventional method, there is concepts either fixed the value of "*a*" to be one or the value of "*a*" is not equal to one. In this study, we used the concept when "*a*" is varied.

The practical application of the relation $F = f(Ø)$ for a particular rock type is best accomplish by evaluating the cementation factor "*m*" and the formation factor coefficient "*a*" using laboratory measured values of the formation factor and the porosity. Each rock type has its characteristic formation factor versus porosity relationship. The porosity has already been determined and the resistivity (R_o) of the core at 100 percent brine saturation was measured for each core samples and the resistivity of simulated formation brine (R_w) is 0.090 ohm.m at reservoir condition. The formation resistivity factor F is determined for each core sample using the definition $F = R_o/R_w$.

Table 5-8 summarized the porosity and formation factor values for 17 core samples. The data on **Table 5-8** is used to plot of log F vs. log Ø. This plot should give a liner trend, where m represents the slope of this trend and the intercept at Ø=1 gives the value coefficient a. **Figure 5-1** shows that cementation factor of well A, m=1.68, is determined from the slope of the plotted points, while tortousity factor (a=1.02) is given from the intercept of the line. Note that in this plot only points of $S_w = 1.0$ are used.

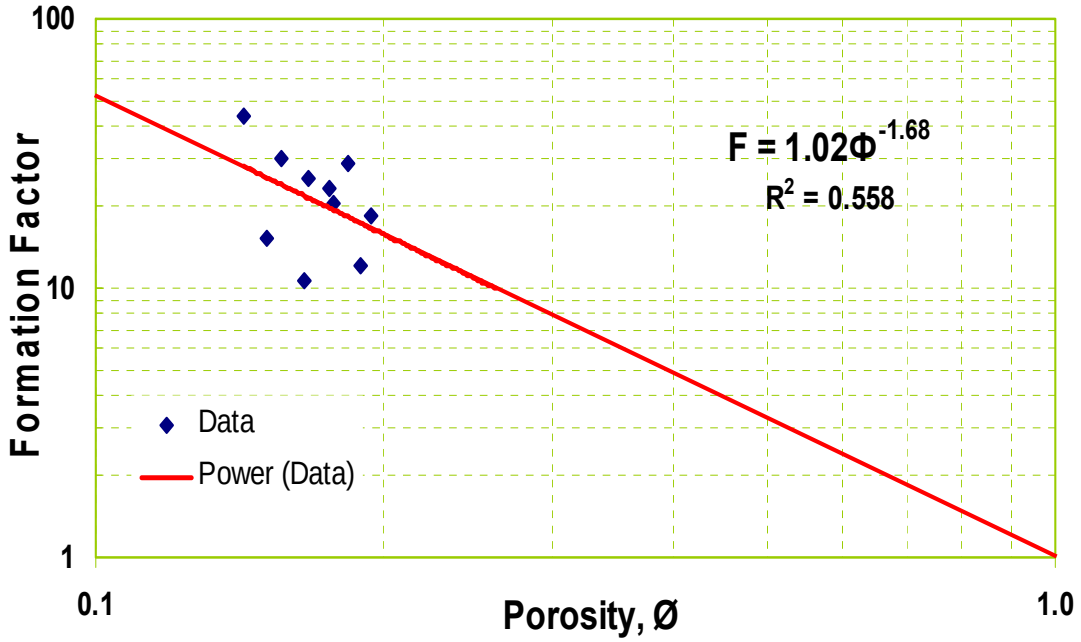

Figure 5-1 Formation factor vs. porosity from Well A

Table 5-8 Porosity and formation factor values for 17 core samples (Well A)

	Sample No.	Porosity, $Ø$	Resistivity (R_o)	Formation Factor, F
	A1	0.17	2.28	25.33
	A2	0.22	0.50	5.56
	A3	0.15	0.83	9.22
	A4	0.19	1.67	18.56
	A5	0.22	0.58	6.44
	A6	0.25	0.52	5.78
	A7	0.26	0.44	4.89
	A8	0.18	2.10	23.33
	A9	0.16	0.95	10.56
	A10	0.18	1.86	20.67
	A11	0.15	1.39	15.44
	A12	0.19	1.09	12.11
	A13	0.18	2.63	29.22
	A14	0.14	3.96	44.00
	A15	0.16	2.72	30.22
	A16	0.10	6.60	73.33
	A17	0.10	7.35	81.67

5.3.1.1.2 Conventional Determination of *n*

The saturation exponent "*n*" estimated using the second law of Archie's equation that relates the rock resistivity partially saturated with water to the rock resistivity 100% saturated with water.

The laboratory measured *RI* and S_w points for seventeen core samples from well A are shown in **Tables 5-5.**

Saturation exponents (*n*) were determined from the logarithmic plot of resistivity index *RI* versus brine saturation, S_w, for cores taken from well A. These plots and results are shown in **Figures 5-2 to 5-4**. **Table 5-9** shows water exponent values (*n*) of Well A varies from 1.80 to 2.73 and the average is about 2.06 for all core samples. **Table 5-10** shows water saturation exponent values of well A core plugs.

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.

Table 5-9 Water saturation exponent of well A core plugs

Core No.	A1	A2	A3	A4	A5	A6	A7	A8	A9
n	2.15	2.01	1.88	1.98	1.93	2.73	2.59	1.8	1.92
Core No.	A10	A11	A12	A13	A14	A15	A16	A17	Average
n	2.09	1.83	2.17	1.93	1.83	2.04	2.06	2.05	2.06

Table 5-10 Archie's parameters (*m, n, a*) values of the well A

a	**1.02**
m	1.68
n	*2.06*

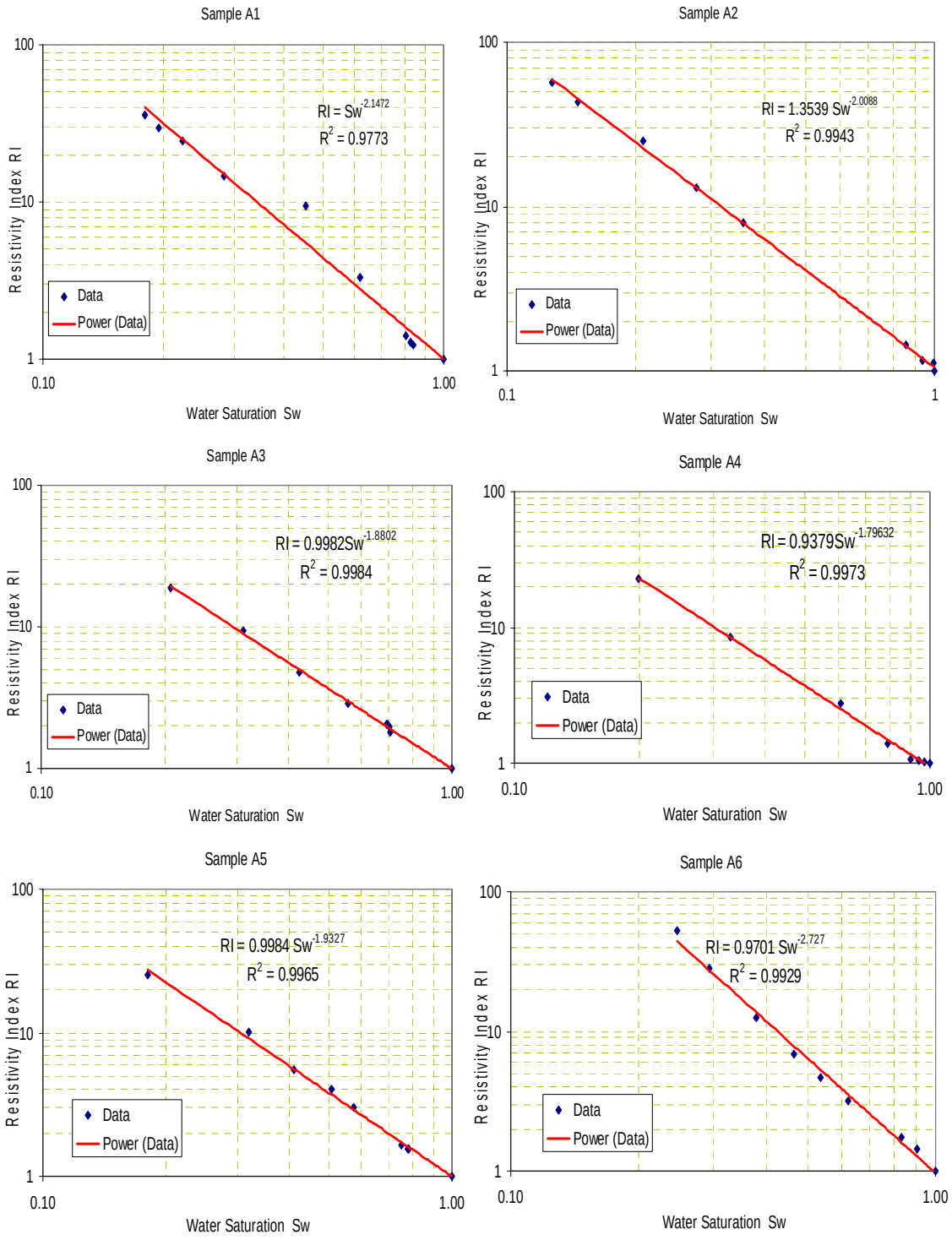

Figure 5-2 Resistivity vs. water saturation for core samples A1, A2, A3, A4, A5, and A6

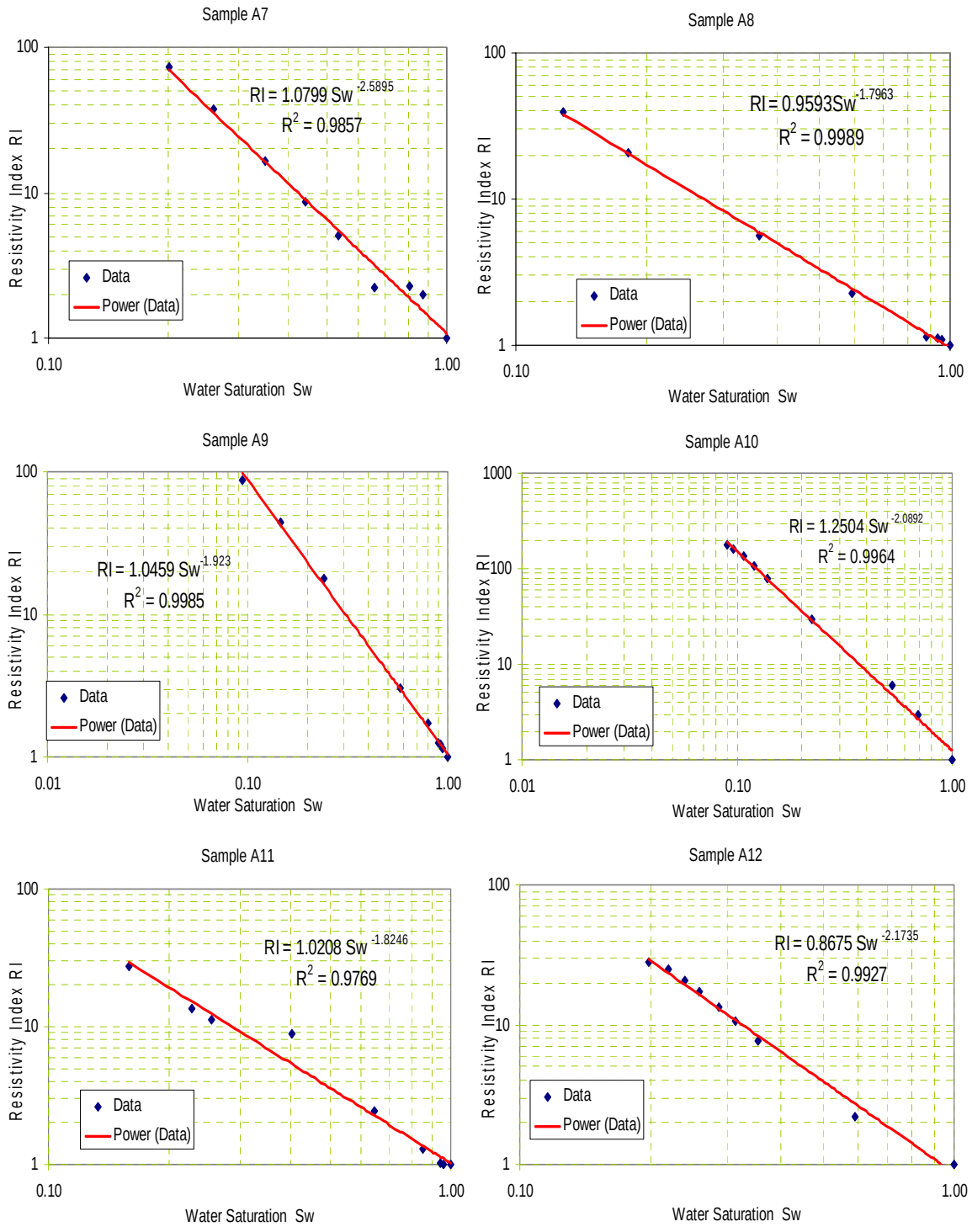

Figure 5-3 Resistivity vs. water saturation for core samples A7, A8, A9, A10, A11, and A12

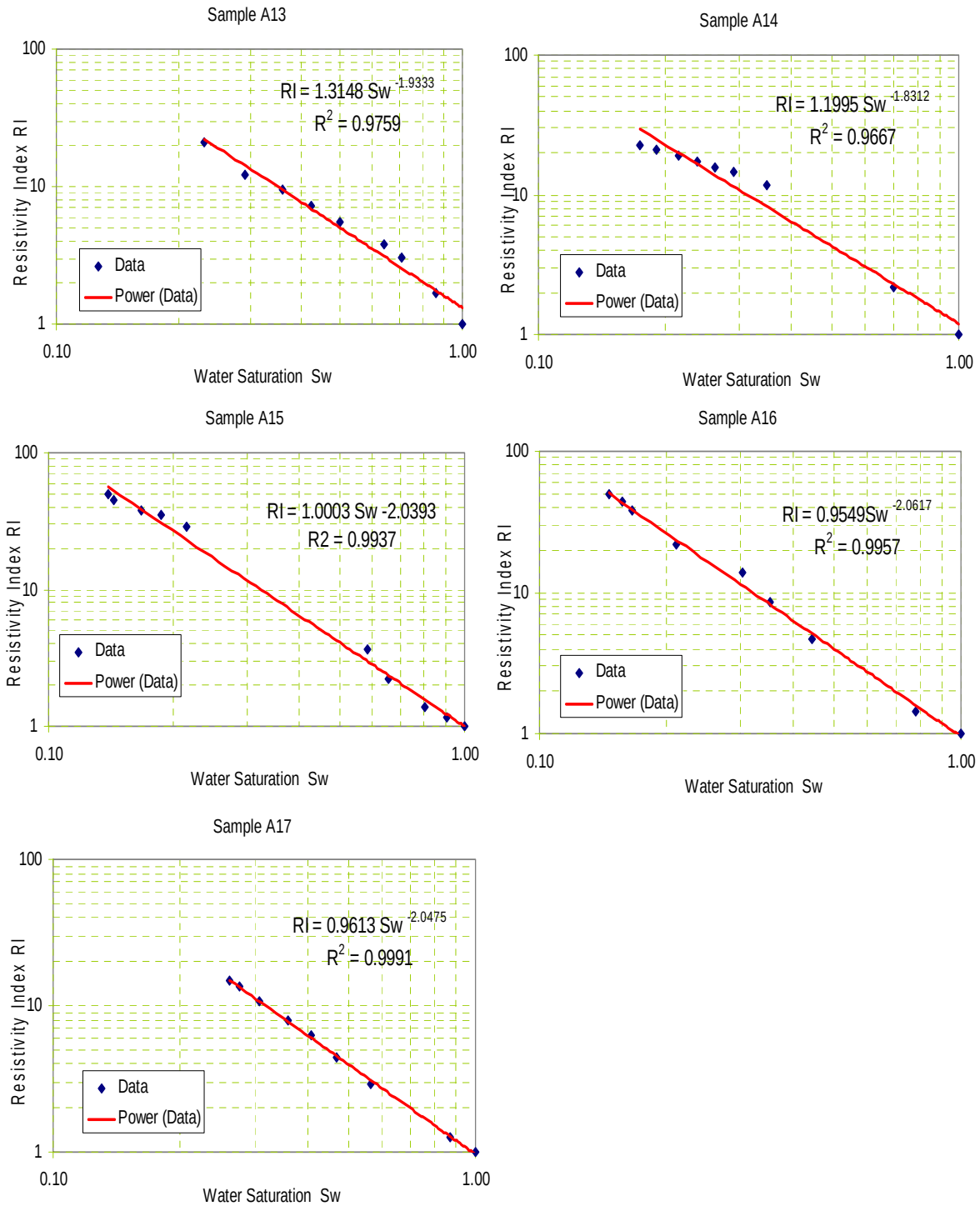

Figure 5-4 Resistivity vs. water saturation for core samples A13, A14, A15, A16, and A17

5.3.1.2 Core Archie Parameters Estimation (CAPE)

The idea of this technique is to determine the Archie's parameters by minimizing the mean-square error between the measured and the computed saturations using the Archie's equation. There are two separate cases to be considered.

A computer program is developed to solve the mathematical equations related to CAPE method in order to determine *a, m,* and *n*. The program is designed to obtain Archie's parameters in case of a=1 and $a \neq 1.0$. The flow charts of these methods are shown in **Figure 5-5 and 5-6. Table 5-11** illustrates values of Archie's parameters as calculated from the program of both types of CAPE method.

Table 5-11 Archie's parameters calculated using the two CAPE methods

	CAPE (1, *m, n*)	**CAPE (*a, m, n*)**
a	1.00	0.28
m	1.62	2.29
n	2.16	2.15

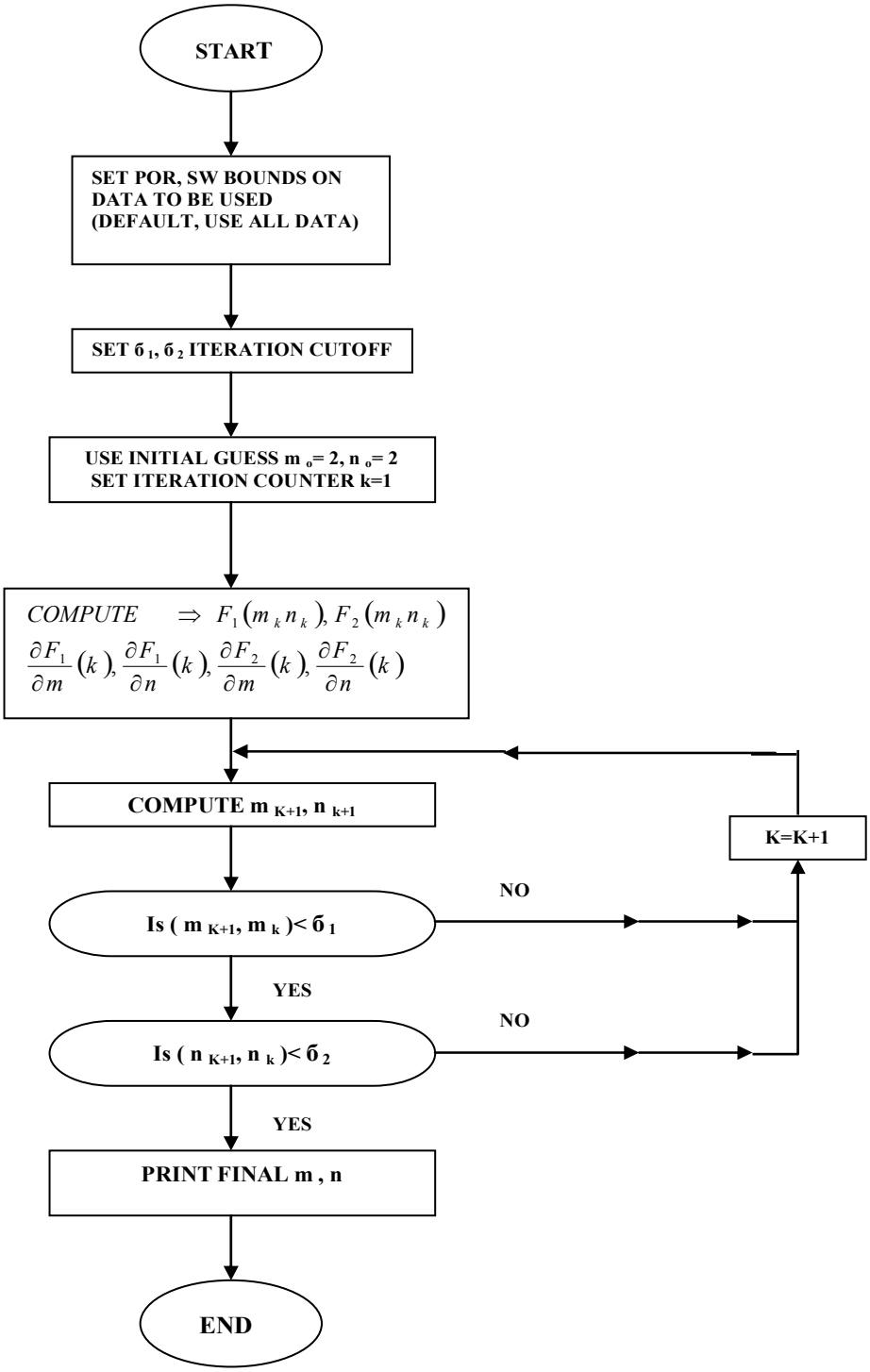

Figure 5-5 Flow chart to compute m and *n* with CAPE (1, *m, n*) technique

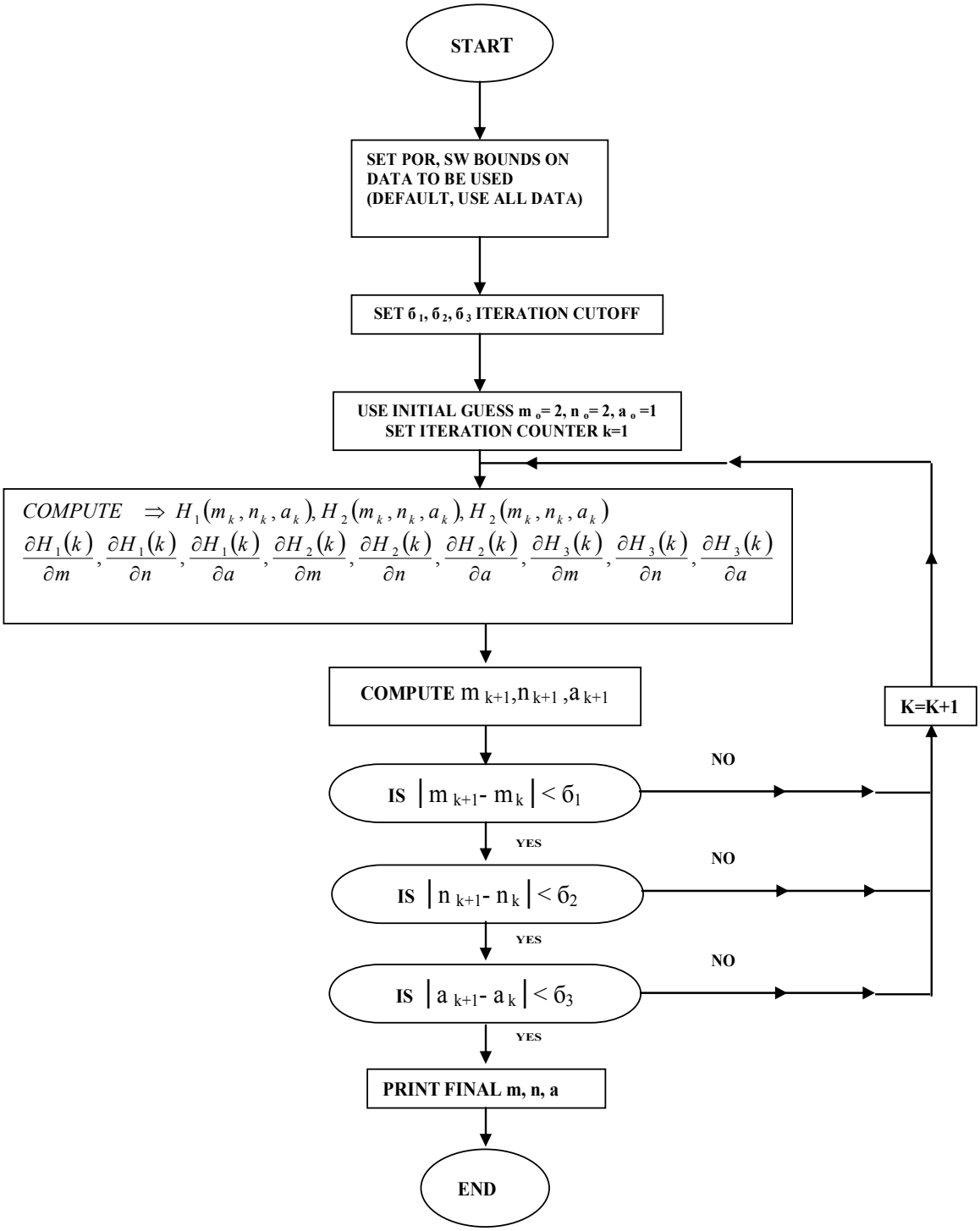

Figure 5-6 Flow chart to compute a, m, and n with CAPE (*a, m, n*) Technique

6.3.1.3 3-D Method

The solution of Equations **2-27** to **2-29** provide 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. For accurate determination Archie's parameters, a computer program is developed which uses the resistivity data for all the cores in order to get an average value for Archie's parameters. The flow chart for the steps used in this program is illustrated in **Figure 5-7** and the results of this program are illustrated in **Table 5-12**.

Table 5-12 Archie's parameters values calculated with the 3D methods

a	**0.28**
m	2.34
n	2.11

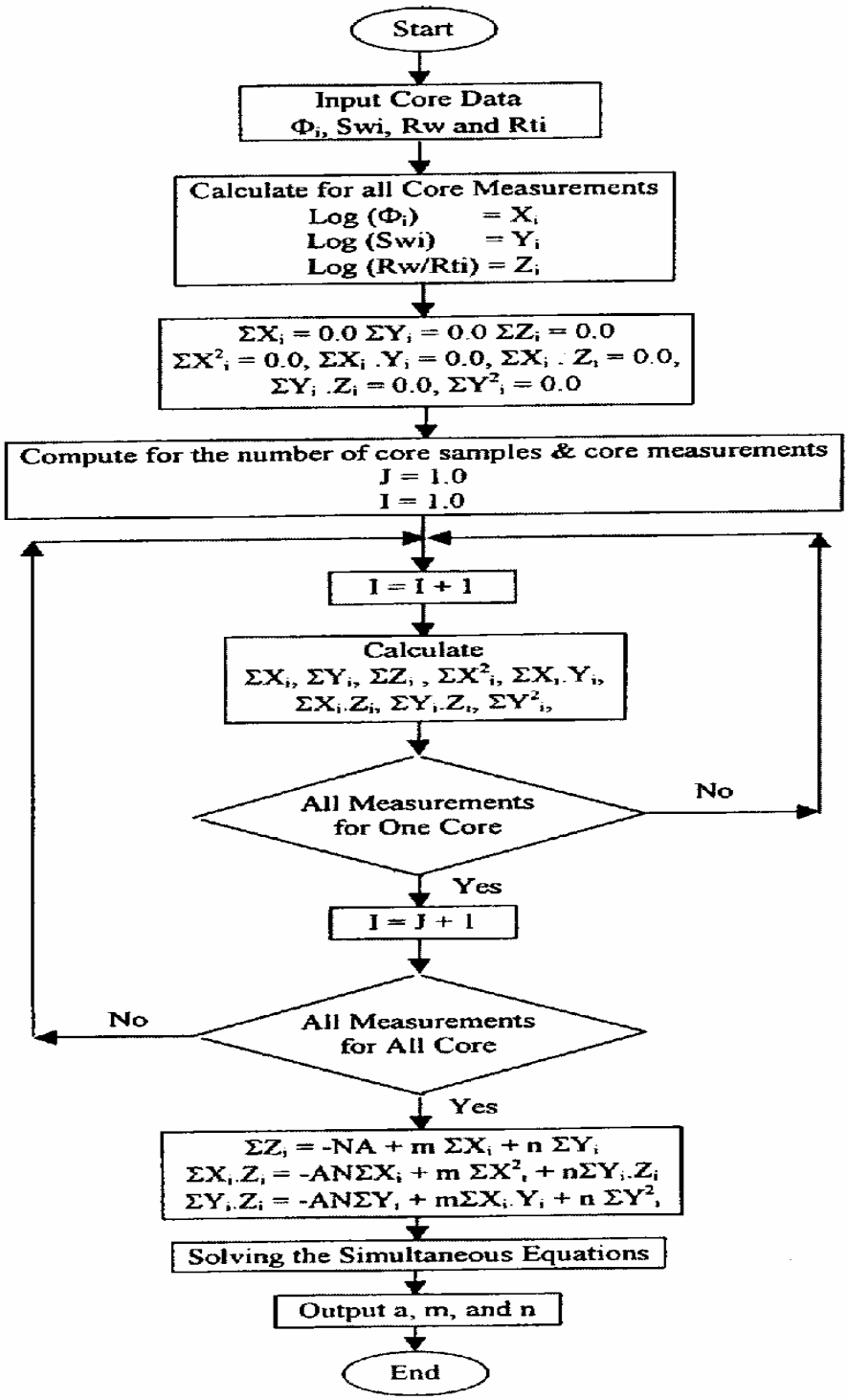

Figure 5-7 Flow chart to compute Archie's parameters with 3-D Technique

5.7.1.4 Comparison of the Methods Used for Archie's Parameters Determination

Table 5-13 shows the typical results of Archie's parameters for the carbonate cores taken from well A by the four discussed methods.

Table 5-13 Comparison of Archie's parameters estimation methods for well A core plugs

	Conventional	**CAPE (1, *m*, *n*)**	**CAPE (*a*, *m*, *n*)**	**3-D Method**
a	1.02	1.00	0.28	0.28
m	1.68	1.62	2.29	2.34
n	2.06	2.16	2.15	2.11

The water saturation values were determined by using the Archie's parameters of each techniques as well as brine resistivity (R_w), cores resistivity (R_t), and porosity. Then, the accuracy analysis between calculated and measured water saturation values was applied in order to get the best technique.

The results of the accuracy analysis were illustrated in **Table 5-14** and **Figure 5-8**. this results show us how the saturation error decreases as we go from the case of 1) Conventional method, 2) Core Archie parameter estimation (CAPE) with a fixed at unity, 3) 3D method and 4) core Archie parameter estimation (CAPE) without a fixed at unity on well A.

Table 5-14 Accuracy analysis of the different techniques on well A

	Conventional		CAPE (1,*m*,*n*)		CAPE (*a, m, n*)		3D Method	
	Abs Error	Rel. Error %	Abs Error	Rel. Error %	Abs Error	Rel. Error %	Abs Error	Rel. Error %
Max. Error	**0.69**	**74.93**	**0.44**	**78.74**	**0.44**	**76.30**	**0.50**	**80.13**
Min. Error	**2.2E-03**	**0.62**	**1.5E-03**	**0.97**	**1.0E-05**	**0.00**	**3.5E-03**	**0.84**
Average Error	**0.14**	**25.14**	**0.12**	**22.30**	**0.10**	**19.19**	**0.10**	**19.64**
Standard Deviation	**0.14**	**17.71**	**0.10**	**15.39**	**0.09**	**14.87**	**0.10**	**16.00**
***RMS* Error**	**0.19**		**0.15**		**0.13**		**0.14**	
Correlation Factor	**0.90**		**0.91**		**0.92**		**0.92**	

The advantage of this comparison is to show how to select the proper technique which gives the minimum error of water saturation and to show us the effect of using the values of Archie's parameters of different techniques on water saturation. **Figures 5-9, 5-10, 5-11, 5-12** and **5-13** show the profile of average water saturation of each core samples with their relative error. This comparison clearly shows how the relative error decreases from the case of 1) Conventional method, 2) Core Archie parameter estimation (CAPE) with "*a*" fixed at unity, 3) 3D method and 4) core Archie parameter estimation (CAPE) without a fixed at unity. **Table 5-15** shows the standard deviation and correlation factor values of each technique that also confirm this result in well A. A big contrast between the result of conventional technique and other techniques was observed.

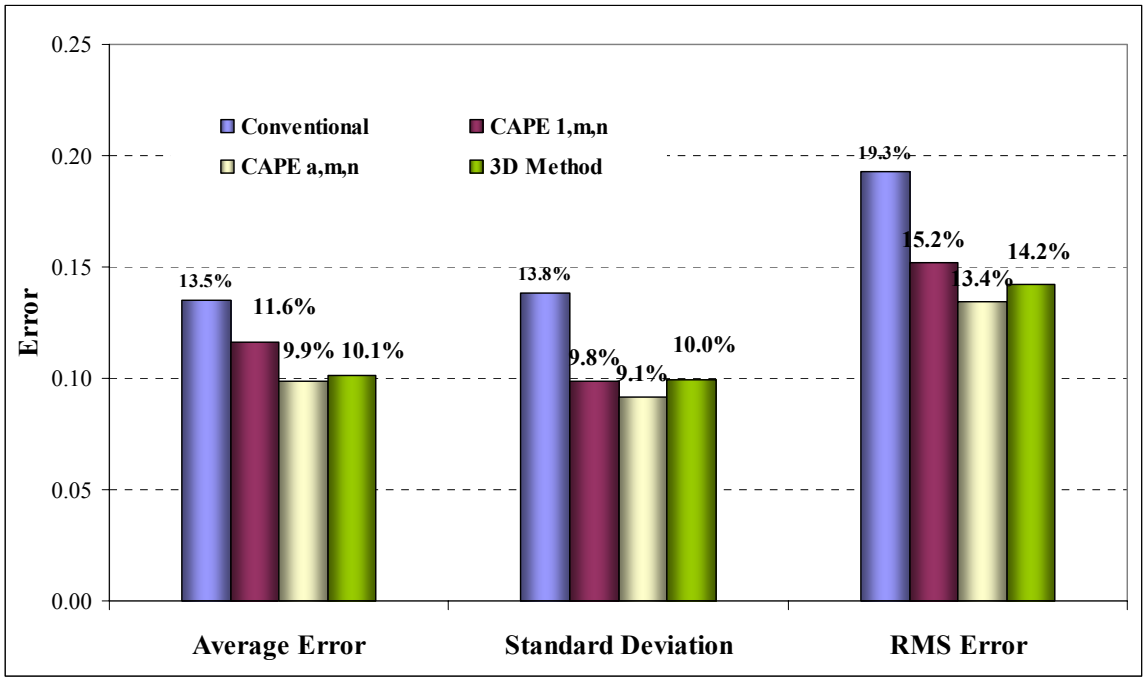

Figure 5-8 Accuracy analysis of the different techniques of well A core plug

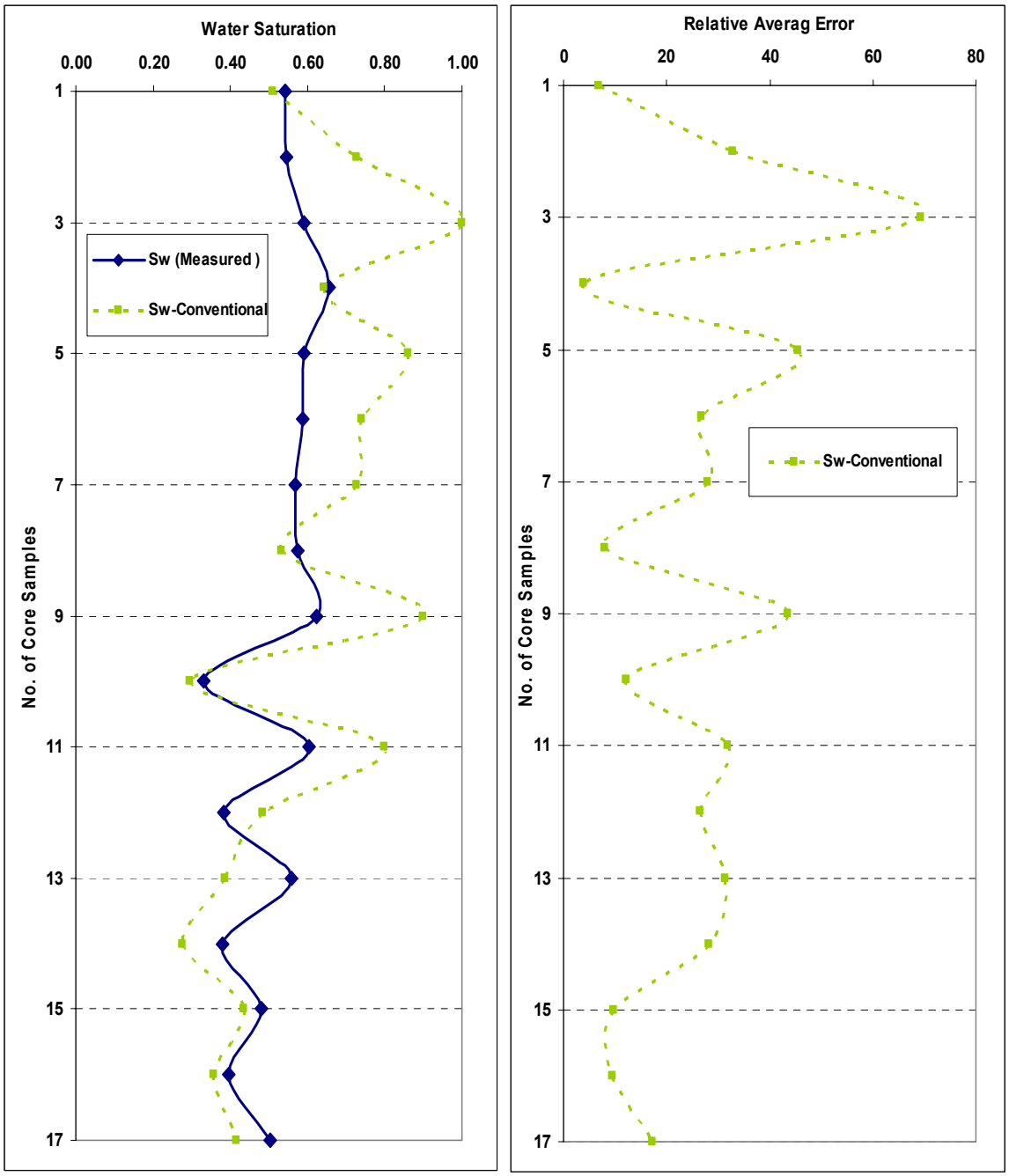

Figure 5-9 Comparison between measured and estimated water saturation using conventional technique

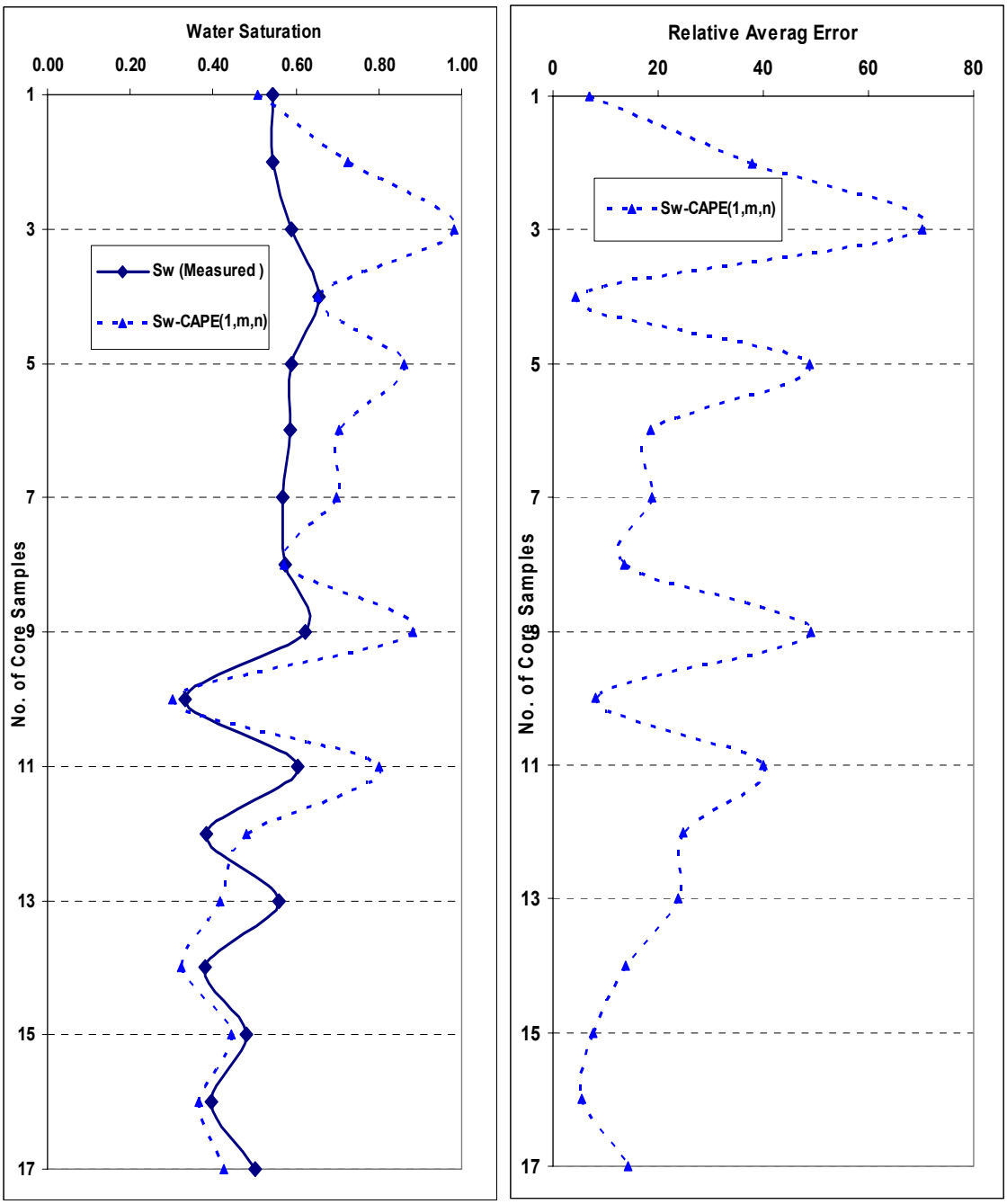

Figure 5-10 Comparison between measured and estimated water saturation using CAPE (1, *m*, *n*) method

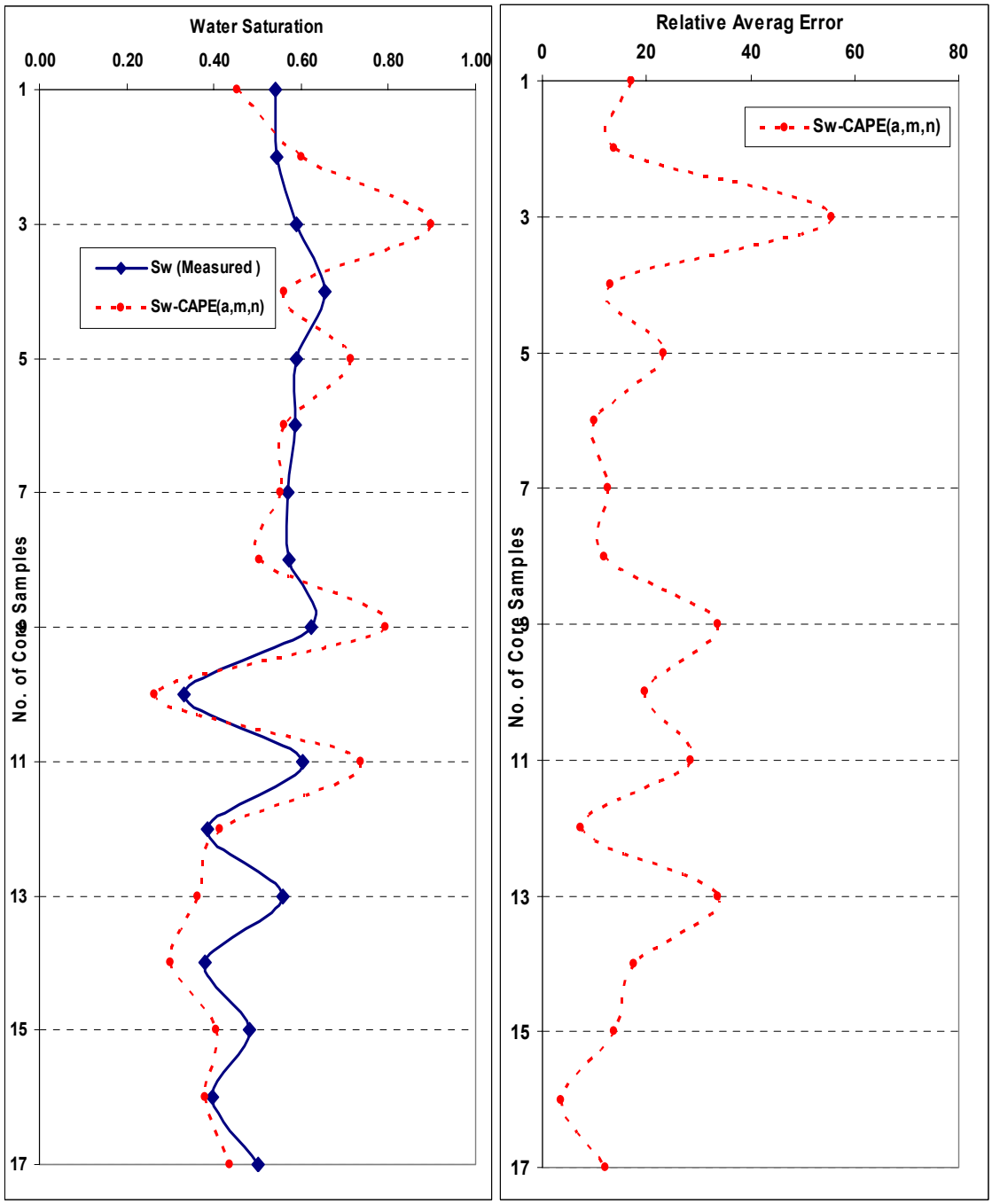

Figure 5-11 Comparison between measured and estimated water saturation using CAPE (*a, m, n*) method

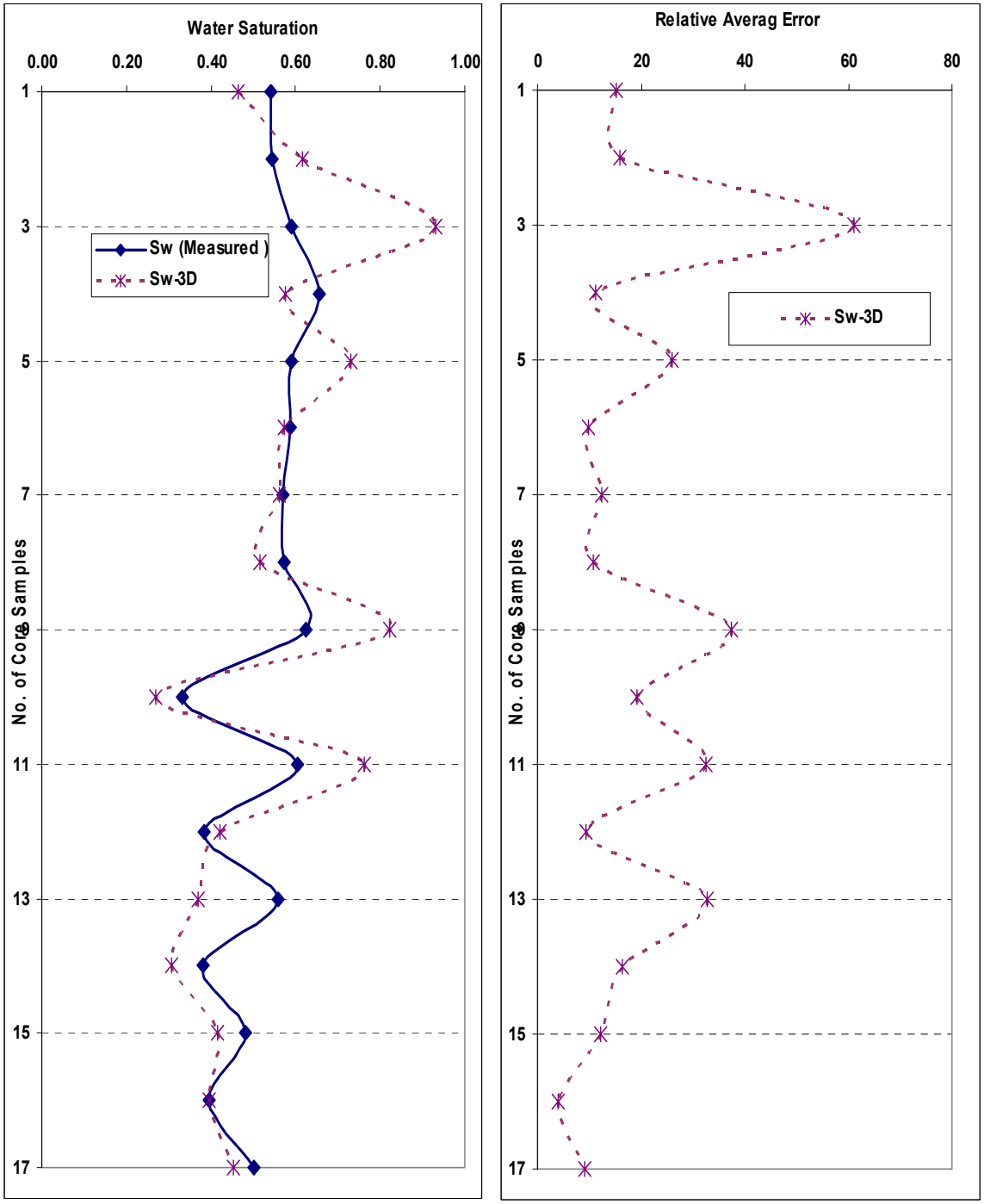

Figure 5-12 Comparison between measured and estimated water saturation using 3-D method

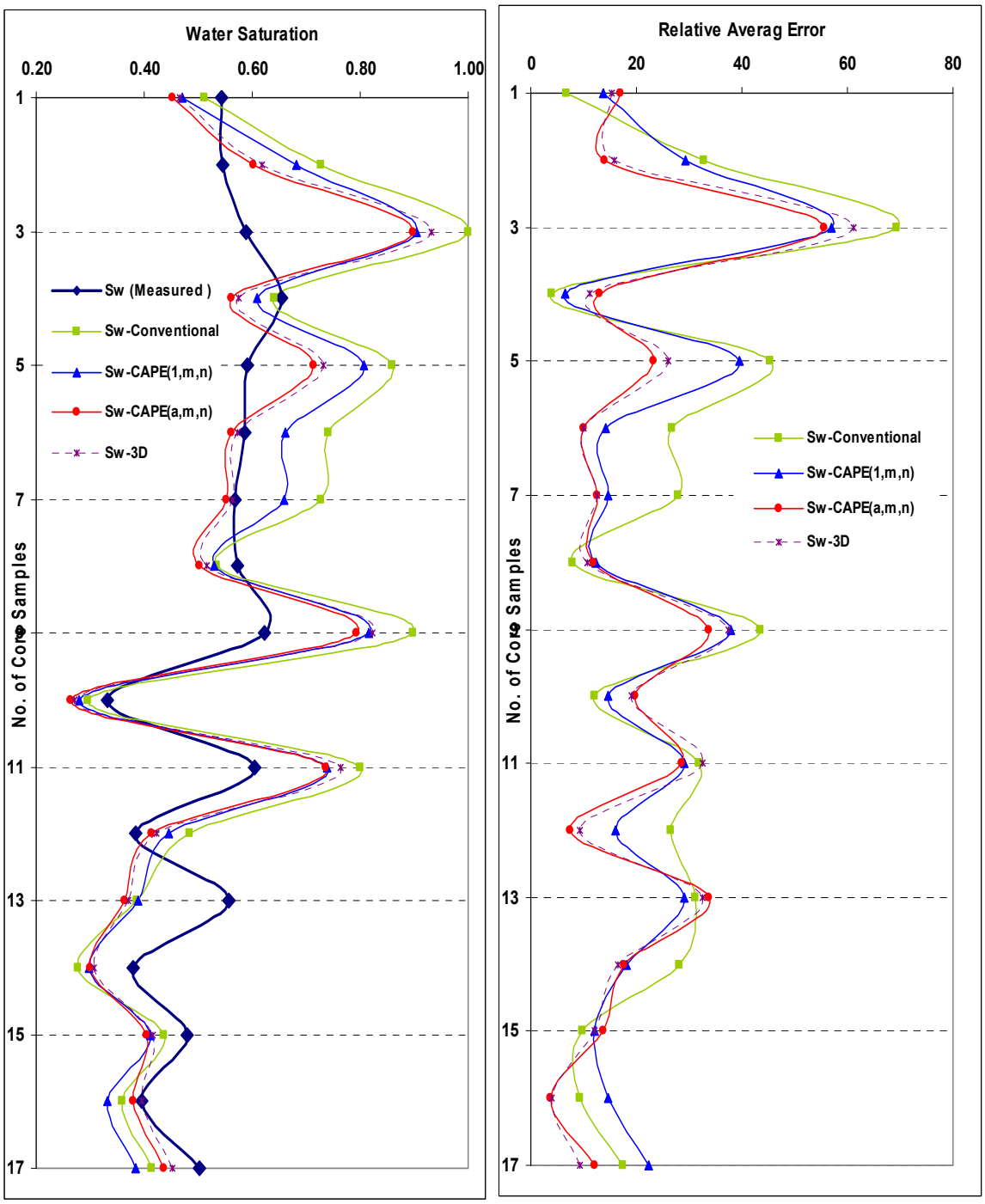

Figure 5-13 Comparison between measured and estimated water saturation using all method

5.3.2 Results and Analysis of Well B

5.3.2.1 Conventional Method

5.3.2.1.1 Conventional Determination of *a* and *m*

The data on **Table 5-15** was used to plot formation factor versus porosity. This plot gives a liner trend, where *m* represents the slope of this trend and the intercept at Ø=1 gives the coefficient "*a*". **Figure 5-14** shows that Cementation factor of well B core plugs, *m*=1.60, is determined from the slope of the plotted points, while tortousity factor 1.98 is given from the intercept of the line. Note that in this plot only points of S_w = 1.0 are used.

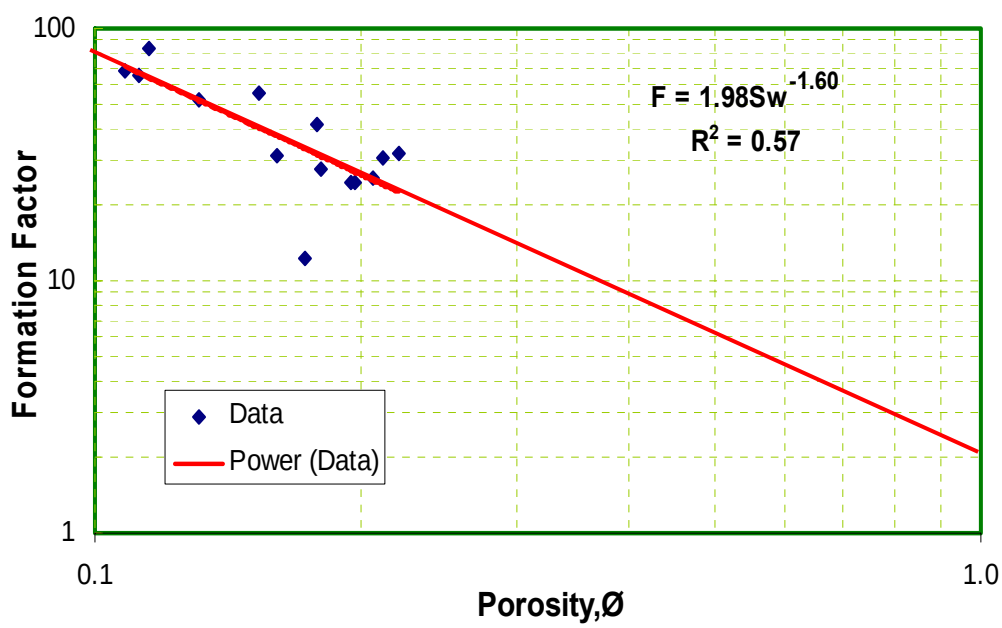

Figure 5-14 Formation factor vs. porosity from Well B core plugs

Table 5-15 Formation factor and porosity of the well B core plugs

	Sample No.	Porosity, Ø	Formation Factor, *F*
Well B	B1	0.17	12.22
	B2	0.18	27.65
	B3	0.13	51.76
	B4	0.21	30.96
	B5	0.16	31.15
	B6	0.21	25.74
	B7	0.18	41.67
	B8	0.20	24.34
	B9	0.15	55.56
	B10	0.11	67.91
	B11	0.12	83.44
	B12	0.19	24.74
	B13	0.11	65.61
	B14	0.07	222.42
	B15	0.22	31.97

5.3.2.1.2 Conventional Determination of *n*

The laboratory measured *RI* and S_w points for fifteen core samples for well B that is shown in **Table 5-6.** The data is plotted on log-log paper and least-squares fit of Log (*RI*) vs. Log (S_w) is made for each core samples. The water exponent "*n*" is obtained from the negative of the slope of the least squares fit. This procedure was repeated for all core samples.

The results of plotting fifteen core samples are shown in **Figure 5-15 to Figure 5-17**. **Table 5-16** shows water exponent values (*n*) of each core sample of well B that varies from 1.10 to 2.57 and the average is about 2.01 for all core samples. **Table 5-17** shows Archie's parameters (*m, n, a*) values of the well B.

Table 5-16 Water saturation exponent for well B core plugs

Core No.	B1	B2	B3	B4	B5	B6	B7	B8
n	1.88	1.93	2.10	2.01	2.05	2.03	2.57	2.18
Core No.	B9	B10	B11	B12	B13	B14	B15	Average
n	2.06	1.10	2.08	2.35	2.07	1.83	1.94	2.01

Table 5-17 Archie's parameters (*m, n, a*) values of the well B

a	**1.98**
n	2.01
m	1.60

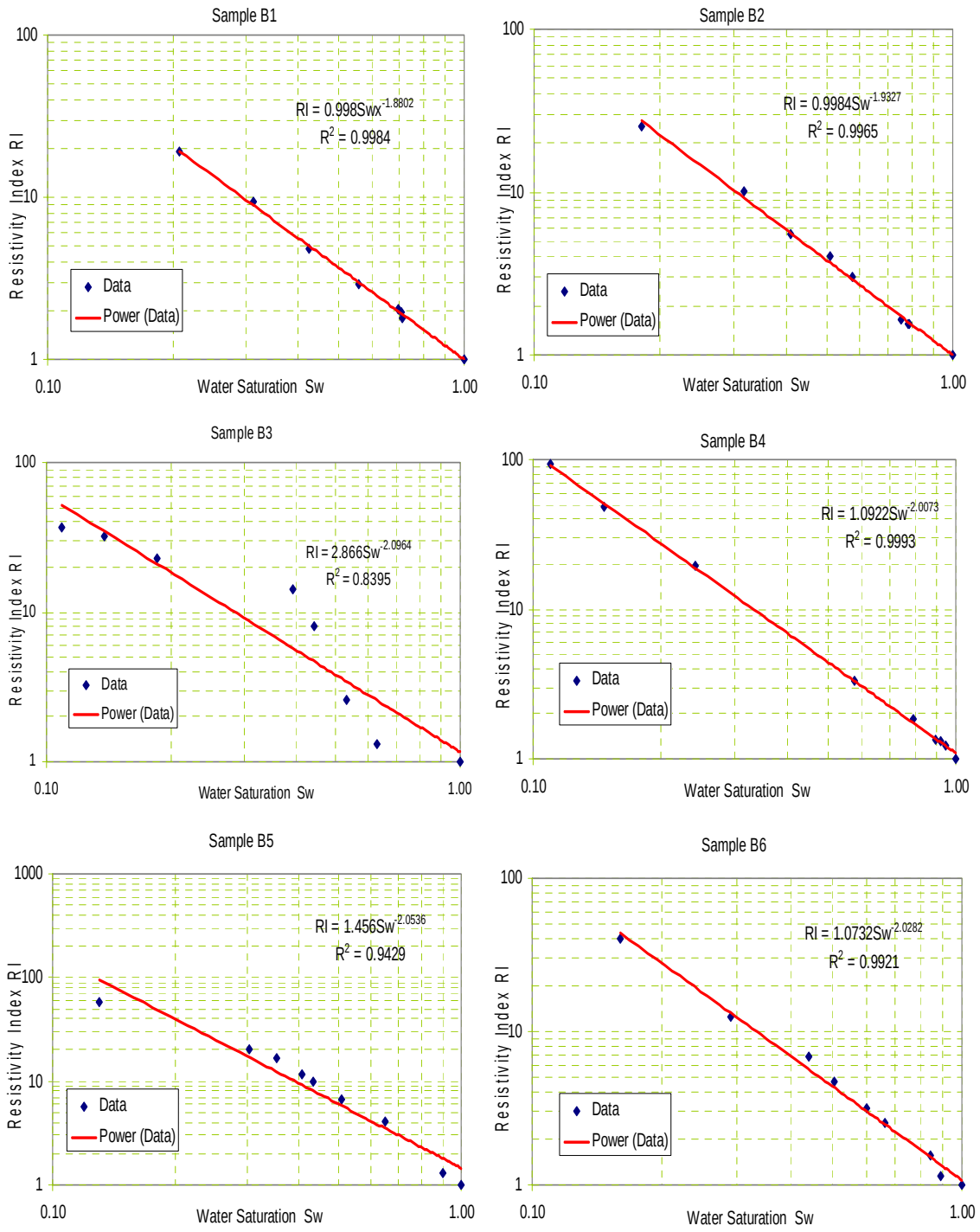

Figure 5-15 Resistivity vs. water saturation for core samples B1, B2, B3, B4, B5, and B6

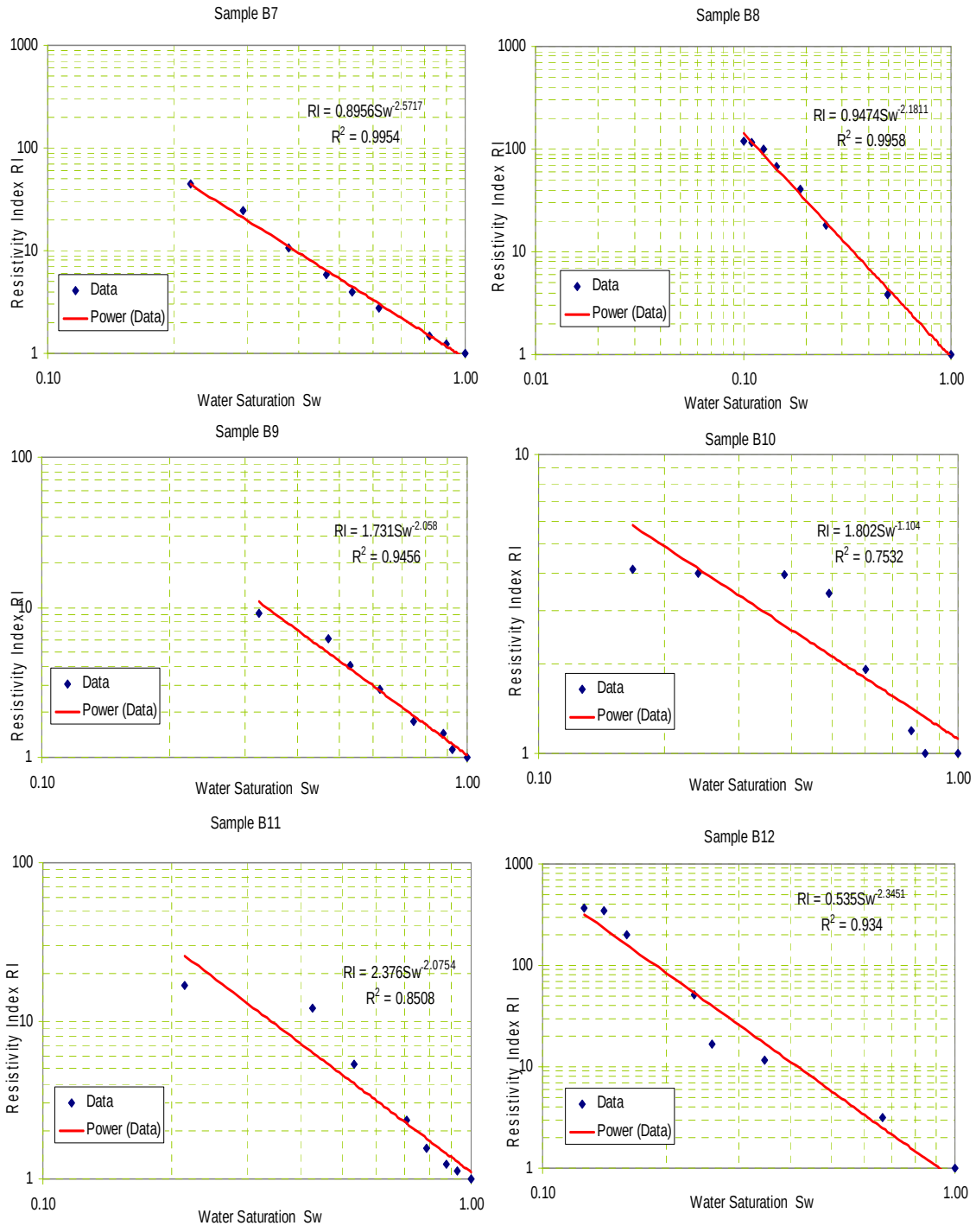

Figure 5-16 Resistivity vs. water saturation for core samples of B7, B8, B9, B10, B11, and B12

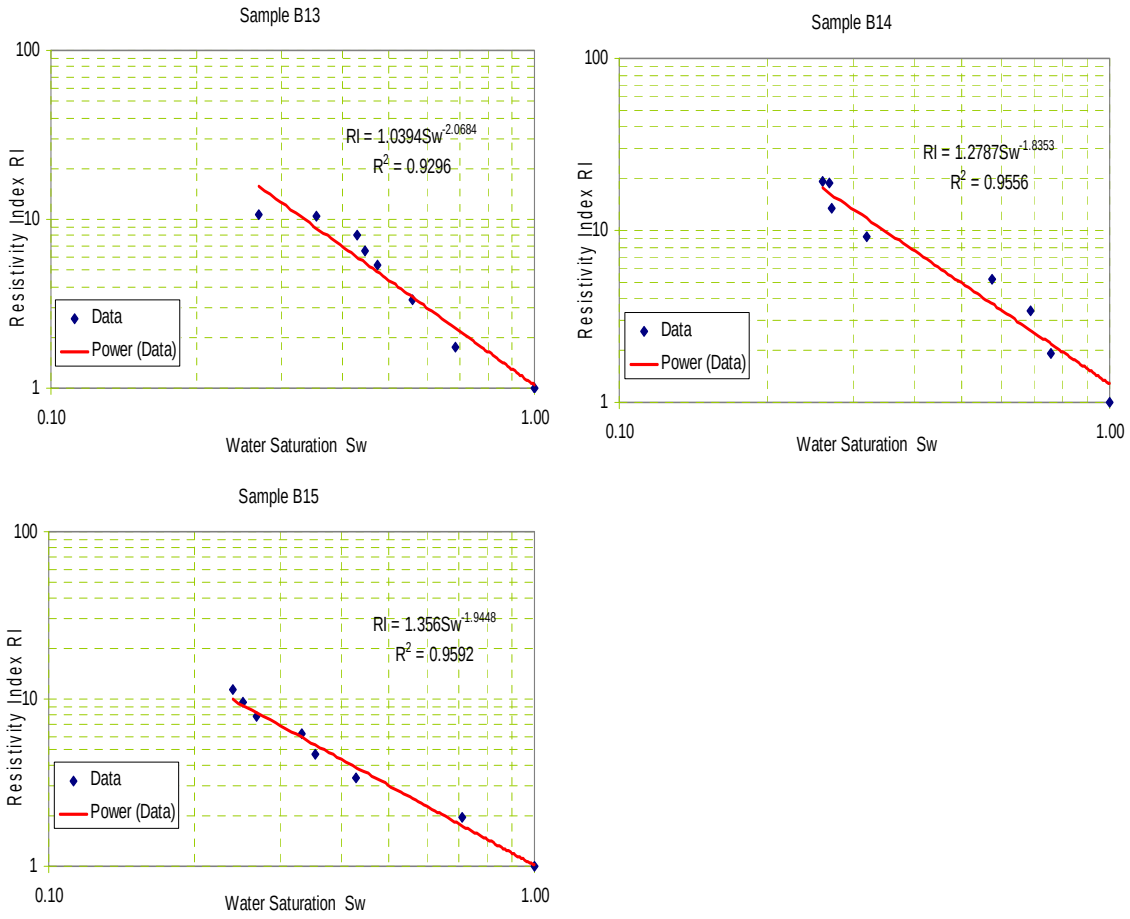

Figure 5-17 Resistivity vs. water saturation for core samples B13, B14, and B15

5.3.2.2 Core Archie Parameters Estimation

To minimize the error between the measured and calculated water saturation in laboratory, the partial derivative of the error with respect to Archie's parameters should be equal to zero.

All data of fifteen core samples (S_w, RI, R_w and Ø) are used as input data. A computer program is developed in this study to solve the mathematical equations that related to CAPE method in order to determine *a, m,* and *n*. The program is designed to obtain Archie's parameters in case of a=1.0 and $a \neq 1.0$. **Table 5-18** shows values of Archie's parameters values as the results of matlab program using the two CAPE methods.

Table 5-18 Archie's parameters values calculated using the two CAPE methods

	CAPE (1, *m*, *n*)	**CAPE (*a*, *m*, *n*)**
a	1.00	0.25
m	1.82	2.40
n	2.59	2.46

5.3.2.3 3-D Method

A computer program is developed in this method to solve these mathematical Eqs. 2-27 to 2-29 in order to determine *a, m,* and *n*. **Table 5-19** shows *a, m,* and *n* values calculated with the three dimensional- regression method.

Table 5-19 Archie's parameters values calculated with the 3-D methods

a	**0.14**
m	2.78
n	2.28

5.3.2.4 Comparison of the Methods Used for Archie's Parameters Determination

Table 5-20 shows the typical results of Archie's parameters for the carbonate cores taken from well B by using the four discussed methods.

Table 5-20 Comparison of Archie's parameters estimation methods well B.

	Conventional	**CAPE (1, *m*, *n*)**	**CAPE (*a*, *m*, *n*)**	**3-D Method**
a	1.98	1.00	0.25	0.14
m	1.60	1.82	2.40	2.78
n	2.01	2.59	2.46	2.28

The water saturation values were determined by using the Archie's parameters of each techniques as well as brine resistivity (R_w), cores resistivity (R_t), and porosity. Then, the accuracy analysis between calculated and measured water saturation values was applied in order to get the best technique.

The results of the accuracy analysis were illustrated in **Table 5-21** and **Figure 5-18**. This results show us how the saturation error decreases as we go from the case of

1) Conventional method, 2) Core Archie parameter estimation (CAPE) with "*a*" fixed at unity, 3) 3D method and 4) Core Archie parameter estimation (CAPE) without *"a*" fixed at unity on well A.

Table 5-21 Accuracy analysis of the different techniques on well B

	Conventional		CAPE (1, *m, n*)		CAPE (*a, m ,n*)		3D Method	
	Abs Error	Rel. Error %	Abs Error	Rel. Error%	Abs Error	Rel. Error%	Abs Error	Rel. Error %
Max.	1.25	134.38	0.62	158.80	0.43	127.75	0.50	135.50
Min.	6 E-04	1E-01	8 E-05	5 E-02	1 E-05	1E-03	2E-03	2 E-01
Average	0.25	44.82	0.18	35.98	0.14	27.20	0.14	27.93
Standard Deviation	0.26	35.68	0.16	32.42	0.12	23.19	0.13	23.29
RMS Error	0.36		0.24		0.18		0.19	
Correlation Factor	0.77		0.81		0.83		0.84	

The advantage of this comparison is to show how to select the proper technique which gives the minimum error of water saturation and to show us the effect of using the values of Archie's parameters of different techniques on water saturation.

Figures 5-19, 5-20, 5-21, 5-22 and **5-23** show the profile of average water saturation of each core samples with their relative error. This comparison clearly shows how the relative error decreases from the case of 1) Conventional method, 2) Core Archie

parameter estimation (CAPE) with "*a*" fixed at unity, 3) 3D method and 4) core Archie parameter estimation (CAPE) without "*a*" fixed at unity. **Table 5-21** shows the standard deviation and correlation factor values of each technique that also confirm this result in well A. A big contrast between the result of conventional technique and other techniques was observed.

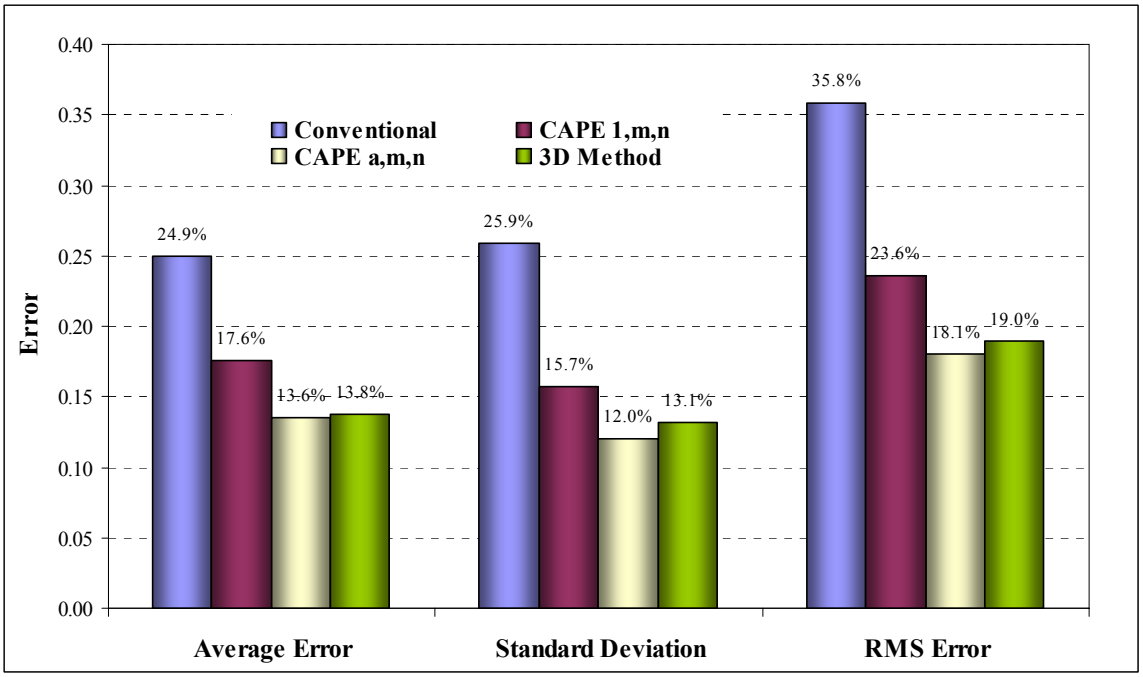

Figure 5-18 Accuracy analysis of the different techniques of well B core plugs

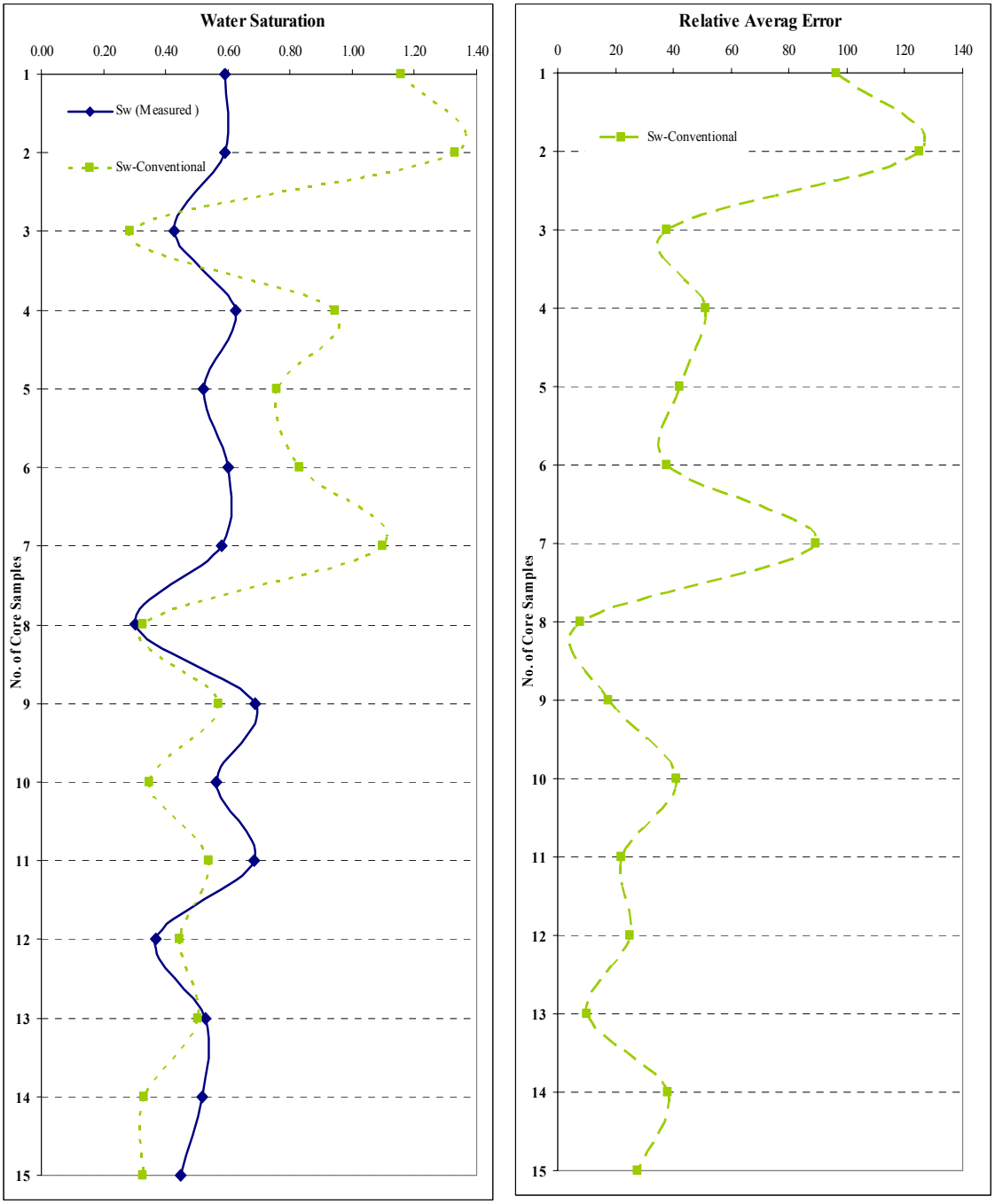

Figure 5-19 Comparison between measured and estimated water saturation using conventional technique

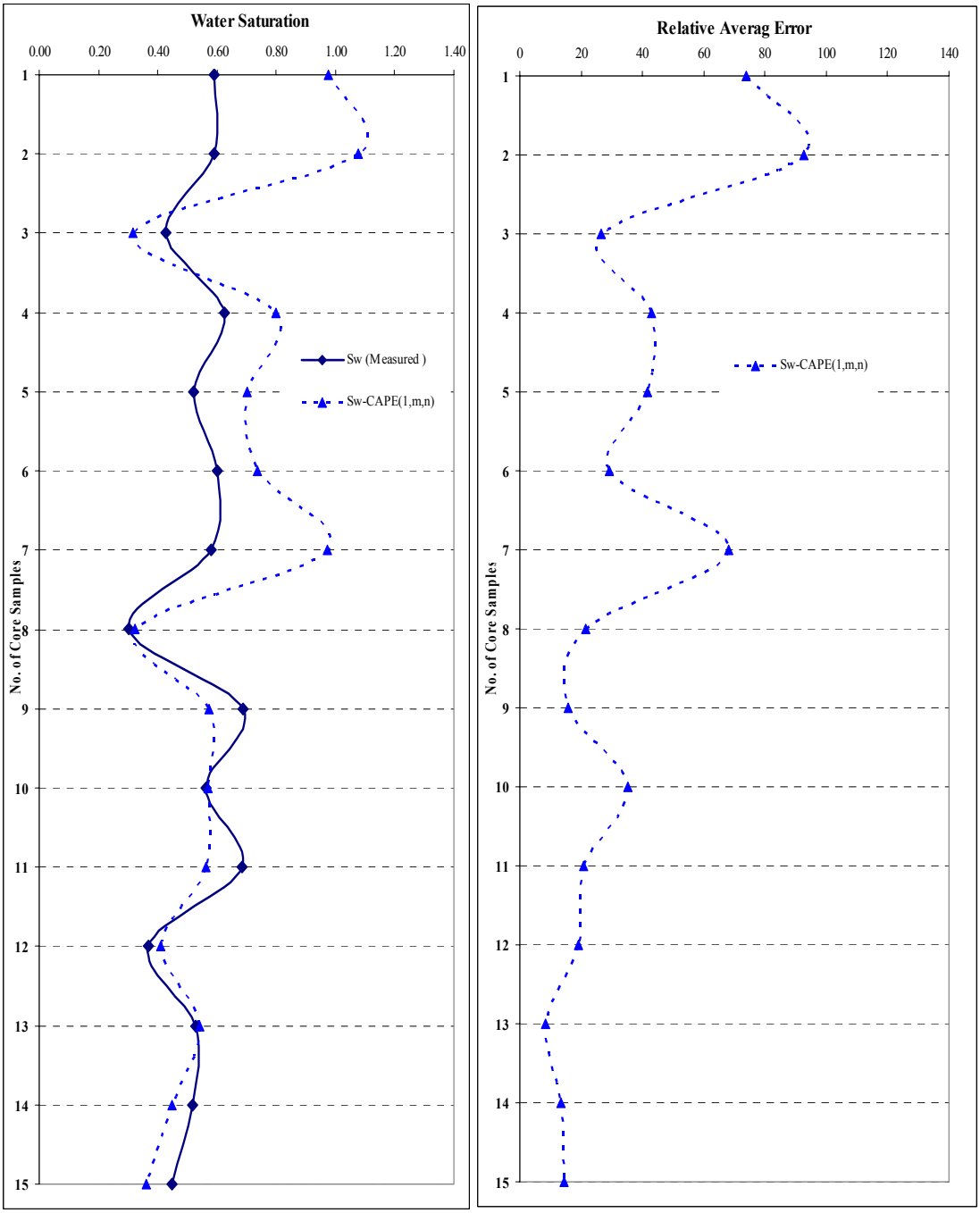

Figure 5-20 Comparison between measured and estimated water saturation using CAPE (1, *m, n*) method

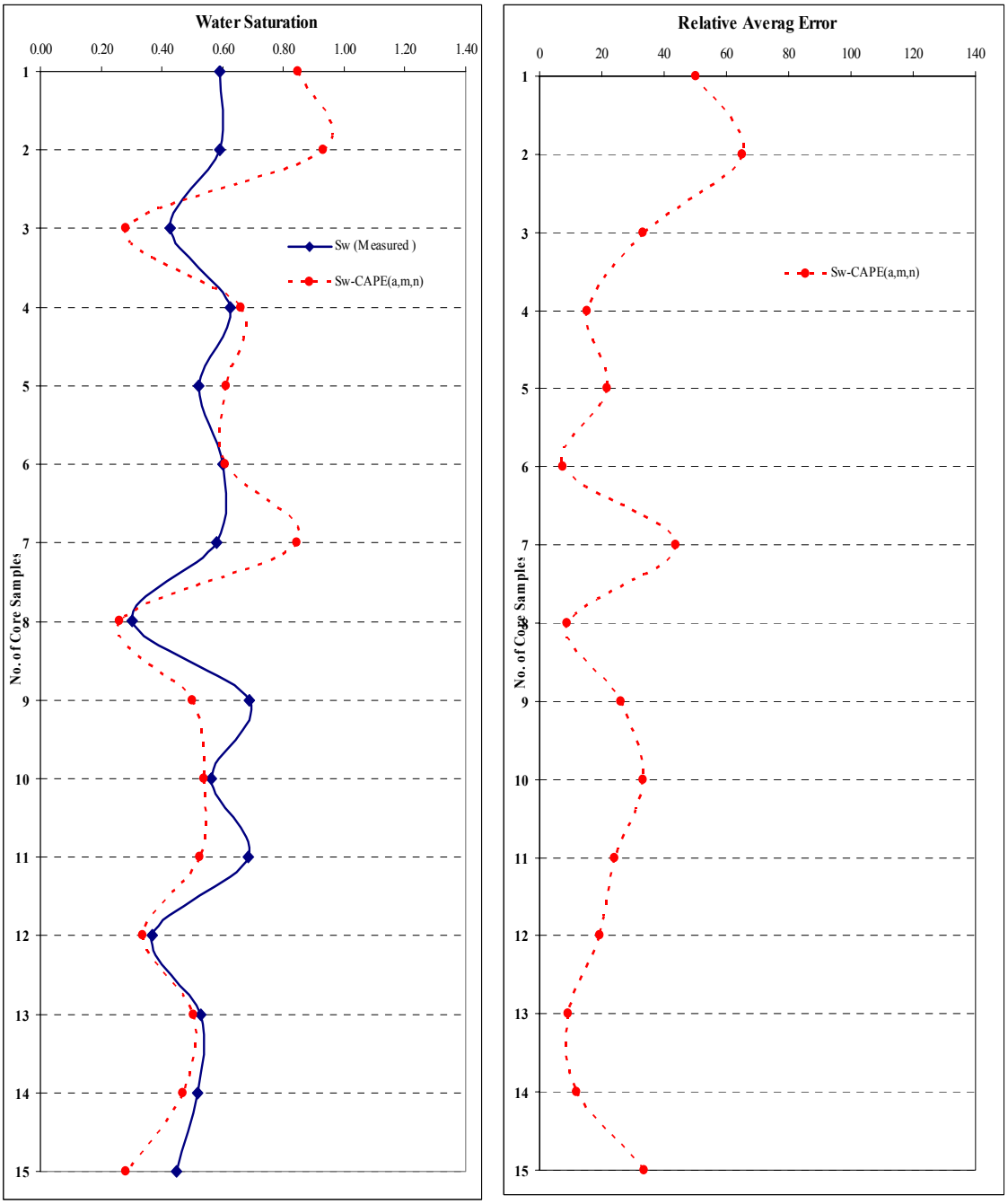

Figure 5-21 Comparison between measured and estimated water saturation using CAPE (*a, m, n*) method

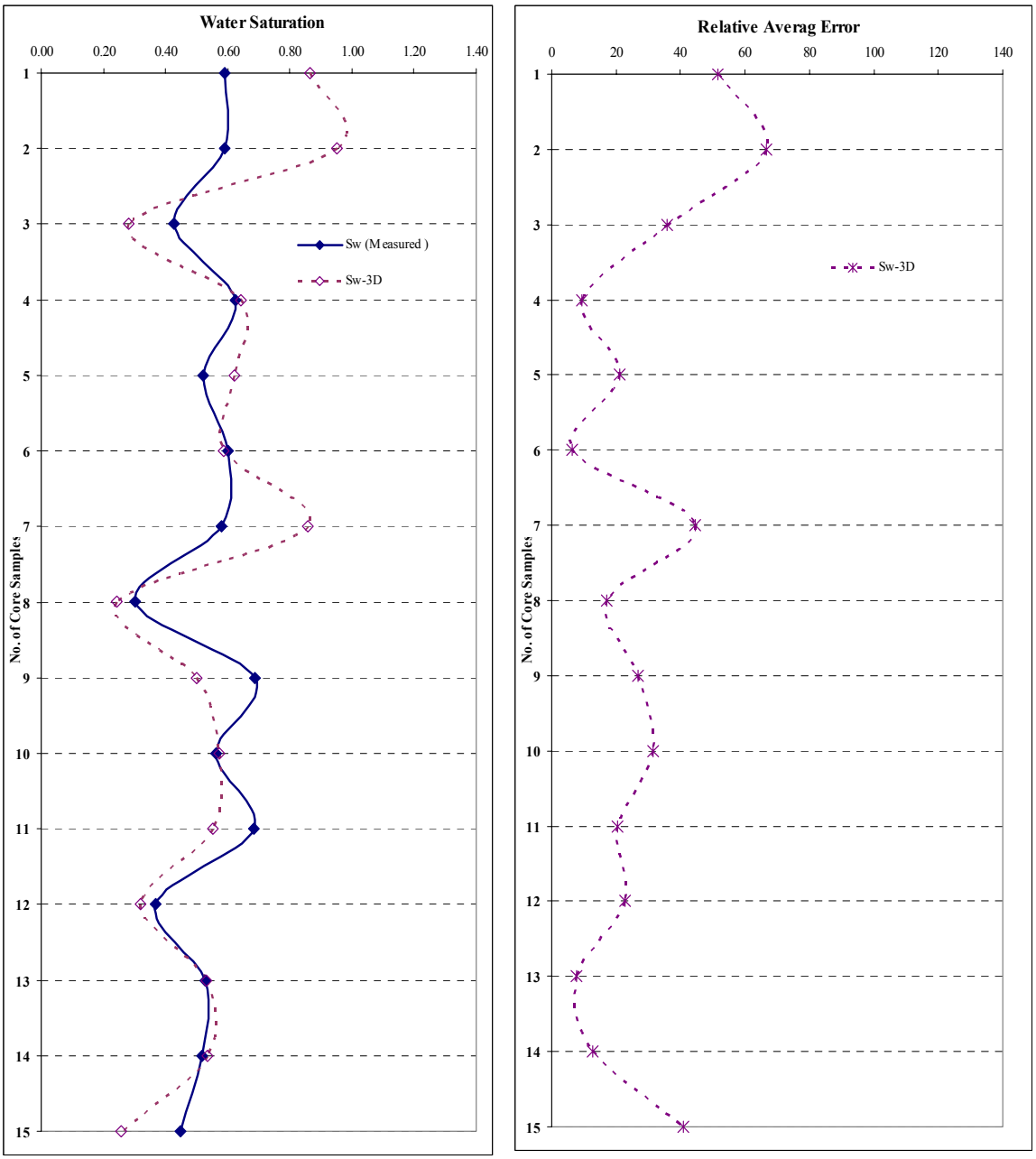

Figure 5-22 Comparison between measured and estimated water saturation using 3-D technique

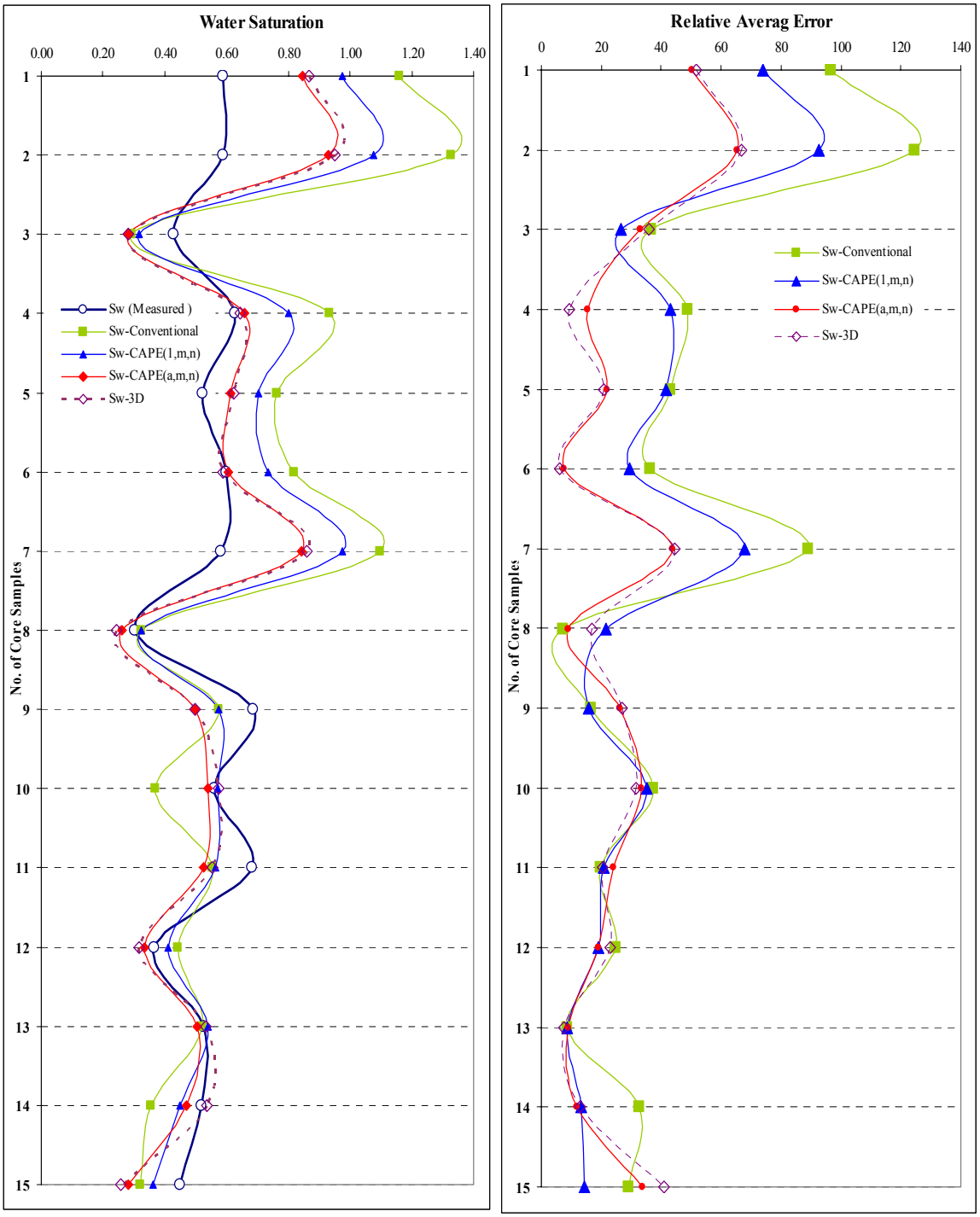

Figure 5-23 Comparison between measured and estimated water saturation using all techniques

5.3.3 Results and Analysis of Well C

5.3.3.1 Conventional Method

5.3.3.1.1 Conventional Determination of a and m

The data in **Table 5-22** were used to plot of log *F* vs. log Ø. This plot should give a liner trend, where *m* represents the slope of this trend and the intercept at Ø=1 gives the coefficient *a*. **Figure 5-24** shows that Cementation factor of well C, *m*=1.55, is determined from the slope of the plotted points, while tortousity factor 1.84 is given from the intercept of the line.

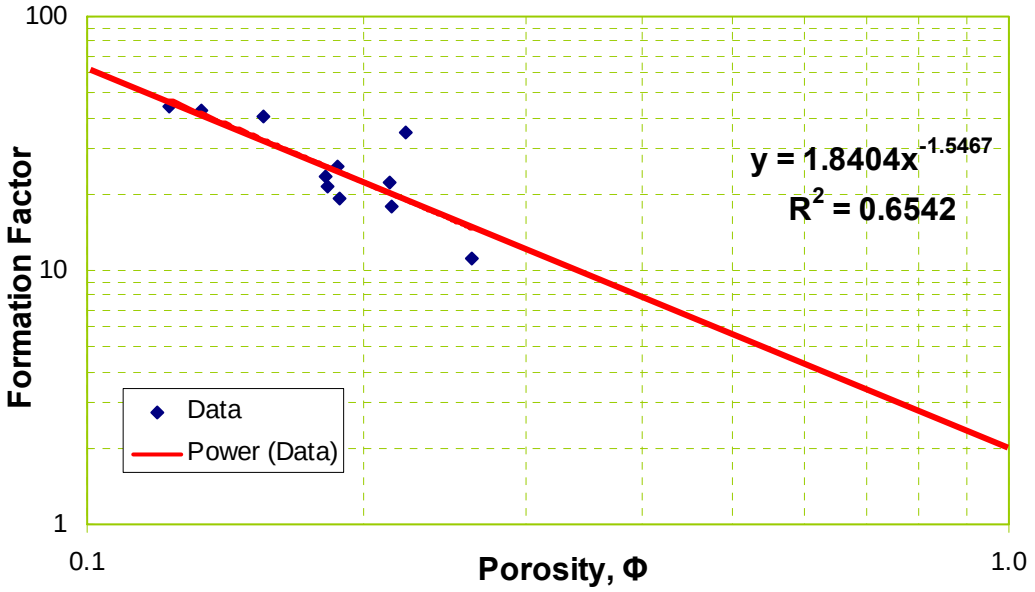

Figure 5-24 Formation factor vs. porosity from Well C core plugs

Table 5-22 Formation factor and porosity of well C core plugs

	Sample No.	Porosity, Ø	Formation Factor, *F*
Well C	C1	0.16	40.11
	C2	0.21	17.89
	C3	0.18	23.33
	C4	0.19	19.33
	C5	0.21	22.22
	C6	0.19	25.67
	C7	0.22	35.16
	C8	0.18	21.22
	C9	0.13	42.33
	C10	0.25	10.89
	C11	0.26	11.11
	C12	0.12	44.33

5.7.3.1.1 Conventional Determination of *n*

Saturation exponent *n* were determined from the logarithmic plot of resistivity index *RI* versus brine saturation, S_w, for cores taken from well C. The results of plotting twelve core samples are shown in **Figure 5-25 and Figure 5-26**. **Table 5-23** shows water exponent values (*n*) of Well C varies from 1.14 to 2.17 and the average is about 1.84 for all core samples. **Table 5-24** shows the Archie's parameters (*m, n, a*) values of well C.

Table 5-23 Water saturation exponent of well C

Core No.	***n***
C1	1.53
C2	1.73
C3	2.1
C4	1.88
C5	1.40
C6	1.49
C7	1.14
C8	1.84
C9	2.17
C10	1.80
C11	2.11
C12	1.89
Average	1.76

Table 5-24 Archie's parameters (*m, n, a*) values of the well C

a	**1.84**
n	1.76
m	1.55

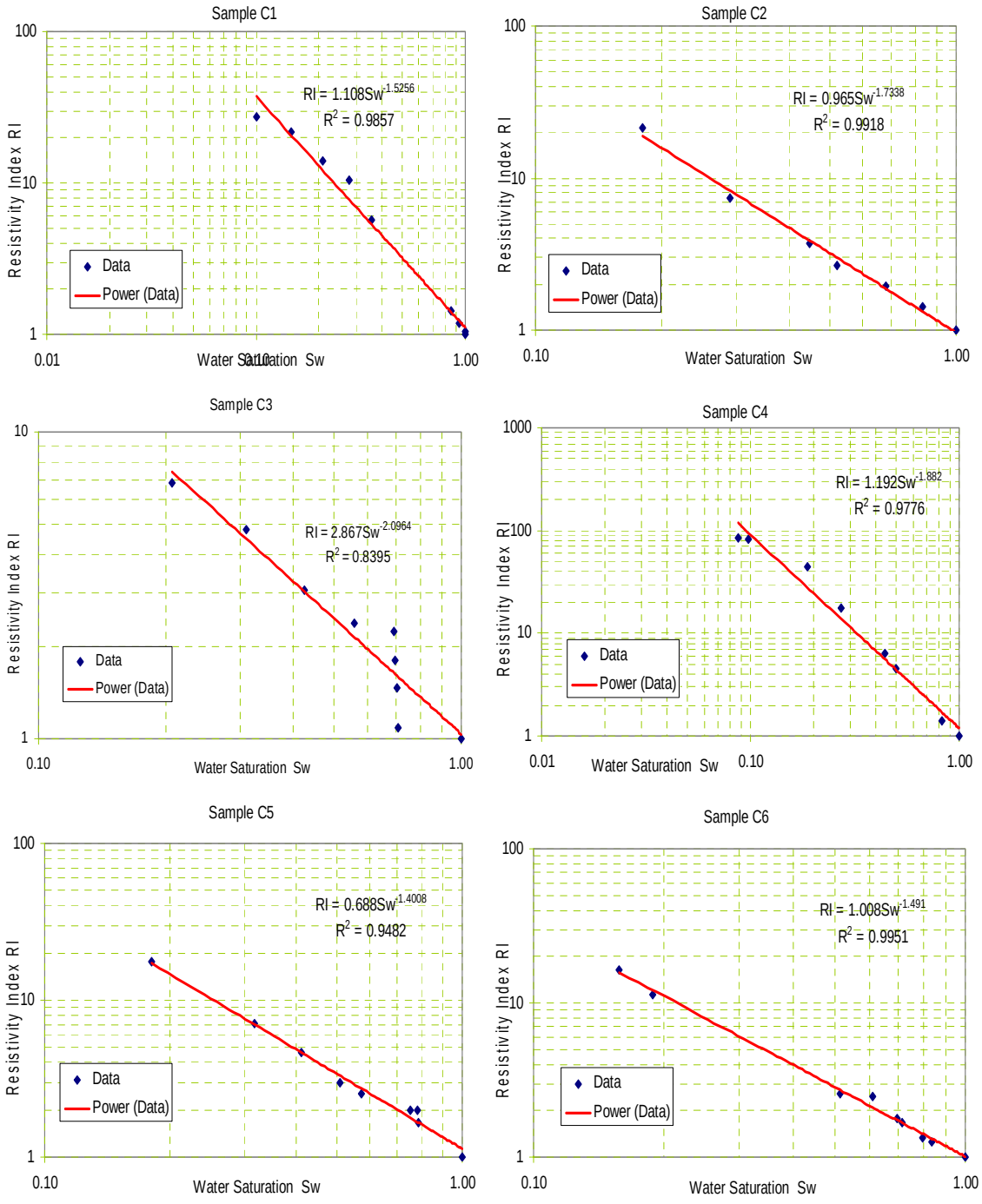

Figure 5-25 Resistivity vs. water saturation for core samples C1, C2, C3, C4, C5, and C6

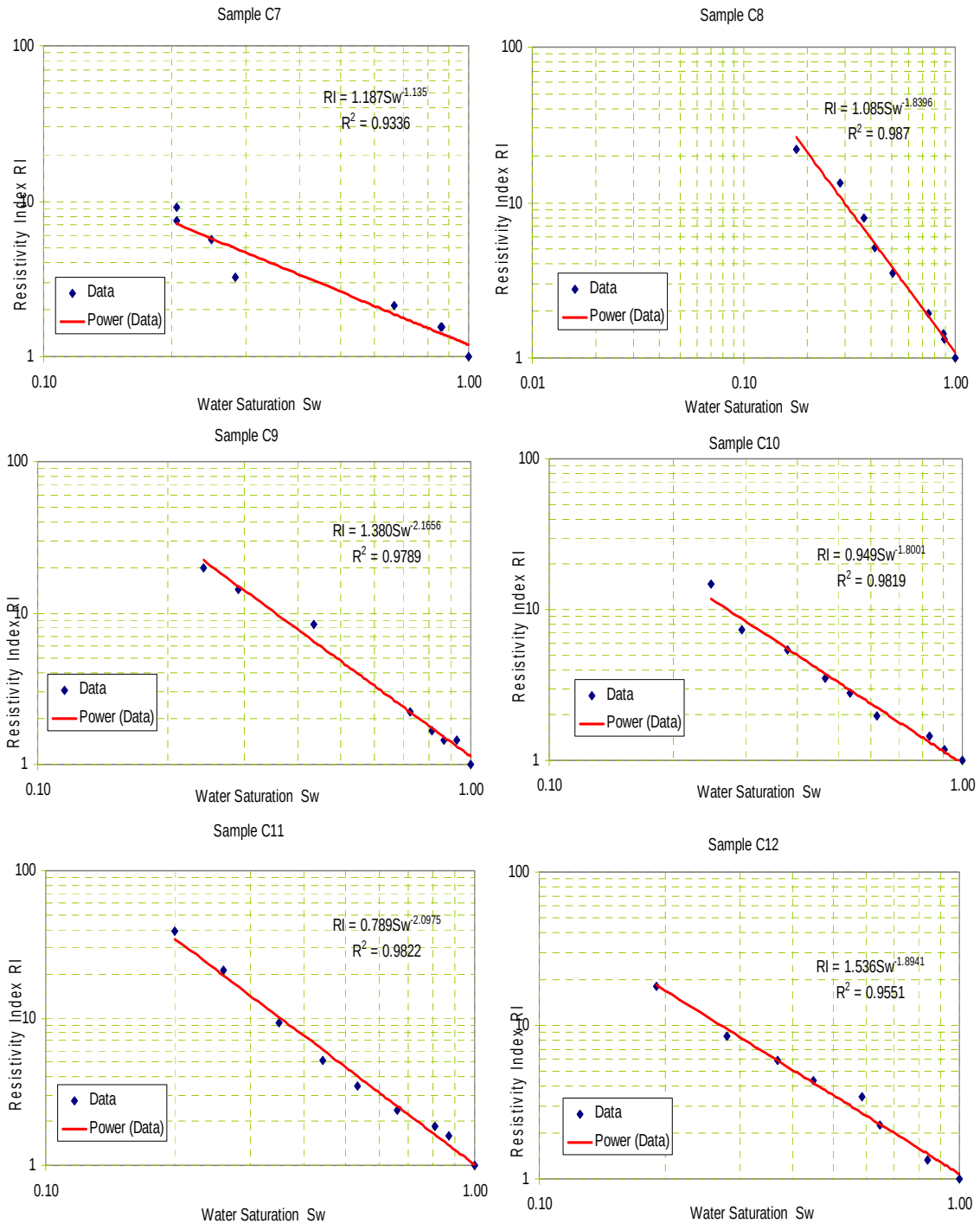

Figure 5-26 Resistivity vs. water saturation for core samples C7, C8, C9, C10, and C11

5.3.3.2 Core Archie Parameters Estimation

A computer program is developed in this study to solve the mathematical equations treatments that related to CAPE method in order to *a, m,* and *n* determination. The program is designed to obtain Archie's parameters in the case of a=1.0 and $a \neq 1.0$. **Table 5-25** shows values of Archie's parameters values as the results of Matlab program using the two CAPE methods.

Table 5-25 Archie's parameters values calculated using the two CAPE methods

	CAPE (1, *m*, *n*)	**CAPE (*a*, *m*, *n*)**
a	1.00	0.33
m	1.79	2.57
n	2.04	1.84

5.3.3.3 3-D Method

Table 5-26 shows *a, m,* and *n* values calculated with the three dimensional-regression method.

In this method, the error in the water saturation value should be kept a minimum, because water saturation quantity is desired and physically meaningful quantity. Here, standard resistivity measurements on core samples is used to determine Archie's parameters *a, m* and *n*.

Table 5-26 Archie's parameters values calculated with the 3D methods

a	**0.30**
m	2.65
n	1.70

5.3.3.4 Comparison of the Methods Used for Archie's Parameters Determination

Table 5-27 shows the typical results of Archie's parameters for the carbonate cores taken from well B by using the four discussed methods.

Table 5-27 Comparison of Archie's parameters estimation methods well B

	Conventional	**CAPE (1,*m*,*n*)**	**CAPE (*a*, *m*, *n*)**	**3-D Method**
a	1.84	1.00	0.33	0.30
m	1.76	1.79	2.57	2.65
n	1.55	2.04	1.84	1.70

From **Table 5-28** below, it is be noted that the saturated error decreases as we go from the case of 1) Conventional method, 2) Core Archie parameter estimation (CAPE) with *a* fixed at unity, 3) 3D method and 4) core Archie parameter estimation (CAPE) without *a* fixed at unity on well C.

Table 5-28 Accuracy analysis of the different techniques on well C

	Conventional		CAPE (1, *m, n*)		CAPE (*a, m, n*)		3D Method	
	Abs Error	Rel. Error %	Abs Error	Rel. Error %	Abs Error	Rel. Error %	Abs Error	Rel. Error %
Max.	0.465	59.71	0.34	65.91	0.35	63.08	0.39	46.85
Min.	0.001	0.48	0.001	0.098	0.001	0.085	0.001	0.31
Average	0.106	19.14	0.08	16.31	0.06	12.92	0.068	12.85
Standard Deviation	0.096	13.94	0.07	13.58	0.07	12.61	0.083	11.87
RMS Error	0.14		0.12		0.099		0.107	
Correlation Factor	0.89		0.93		0.944		0.941	

Figure 5-27 and Table 5-28 also show the standard deviation and correlation factor that confirm the saturated error in well C. A big contrast between the result of conventional method and other techniques was observed.

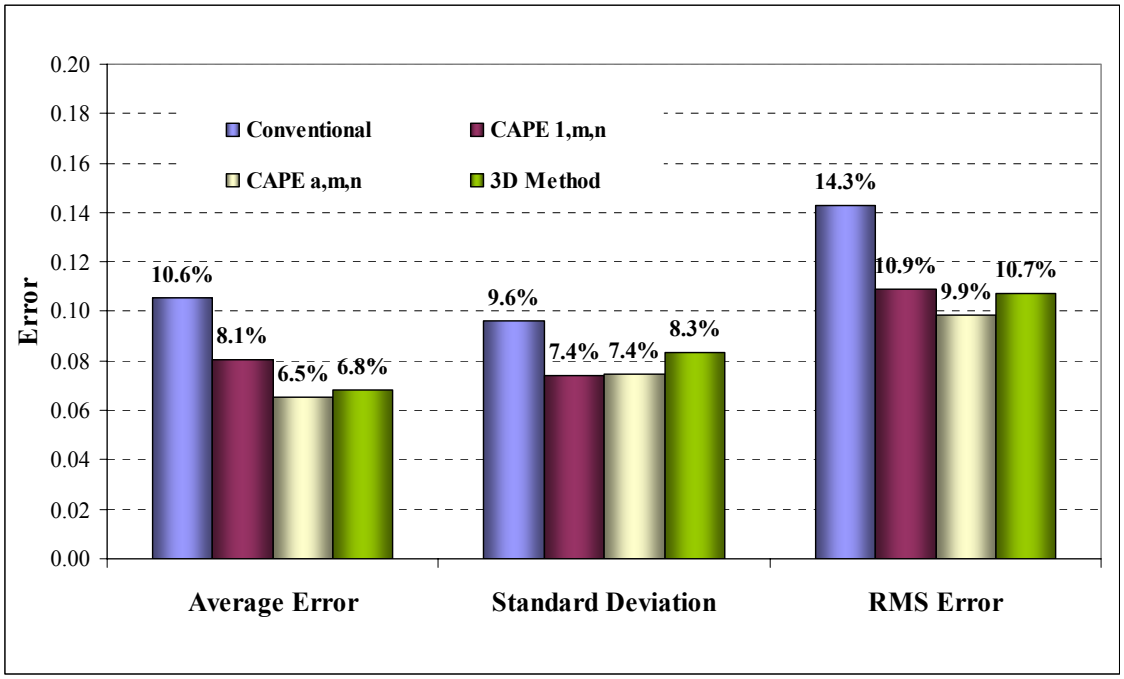

Figure 5-27 Accuracy analysis of the different techniques of well B

Figure 5-28, 5-29, 5-30, 5-31, and 5-32 show the profile of average water saturation error of each core samples with their relative error. This comparison show us clearly how the relative error decreases from the case of 1) Conventional method, 2) Core Archie parameter estimation (CAPE) with "*a*" fixed at unity, 3) 3D method and 4) Core Archie parameter estimation (CAPE) without "*a*" fixed at unity.

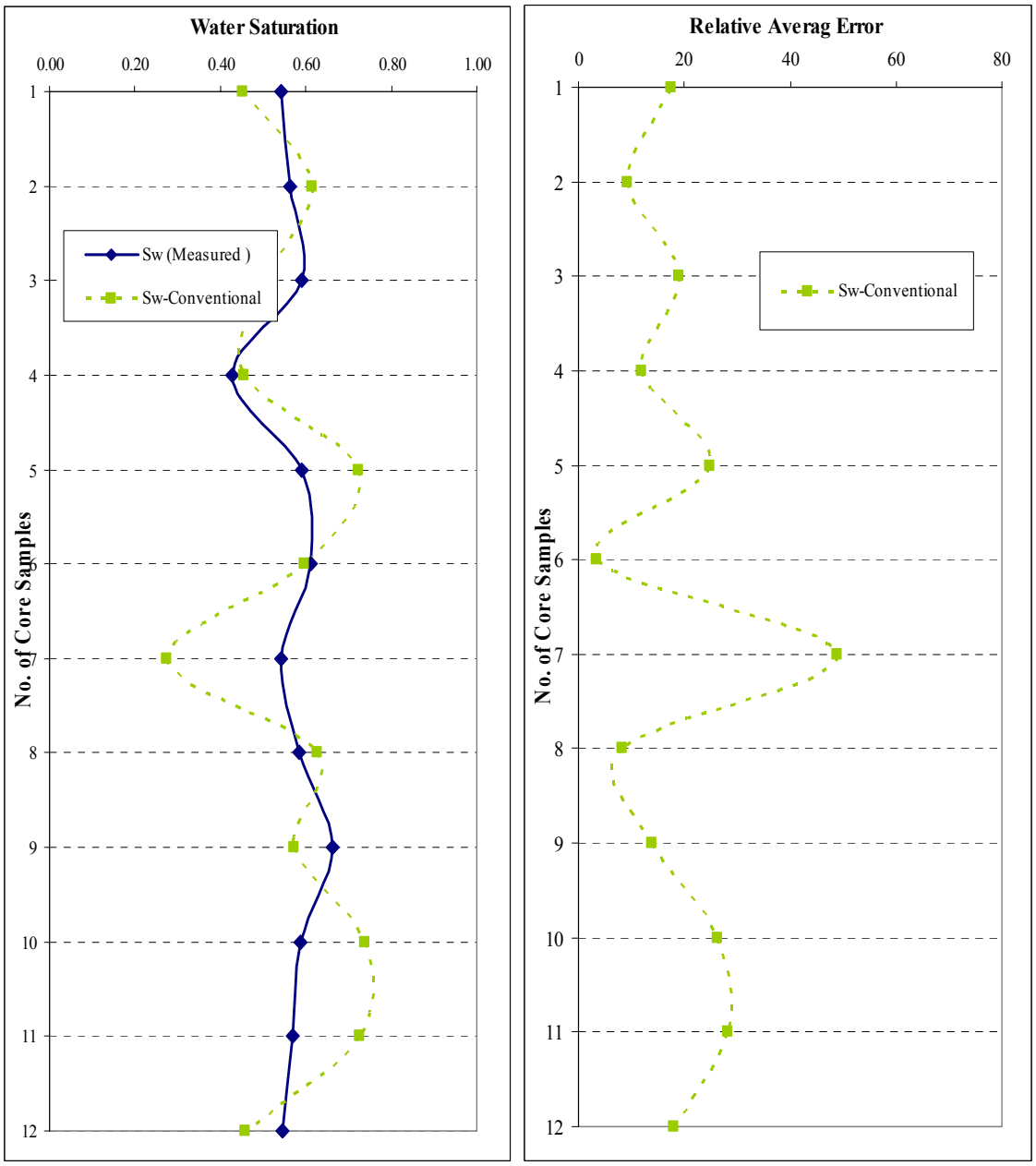

Figure 5-28 Comparison between measured and estimated water saturation using conventional technique

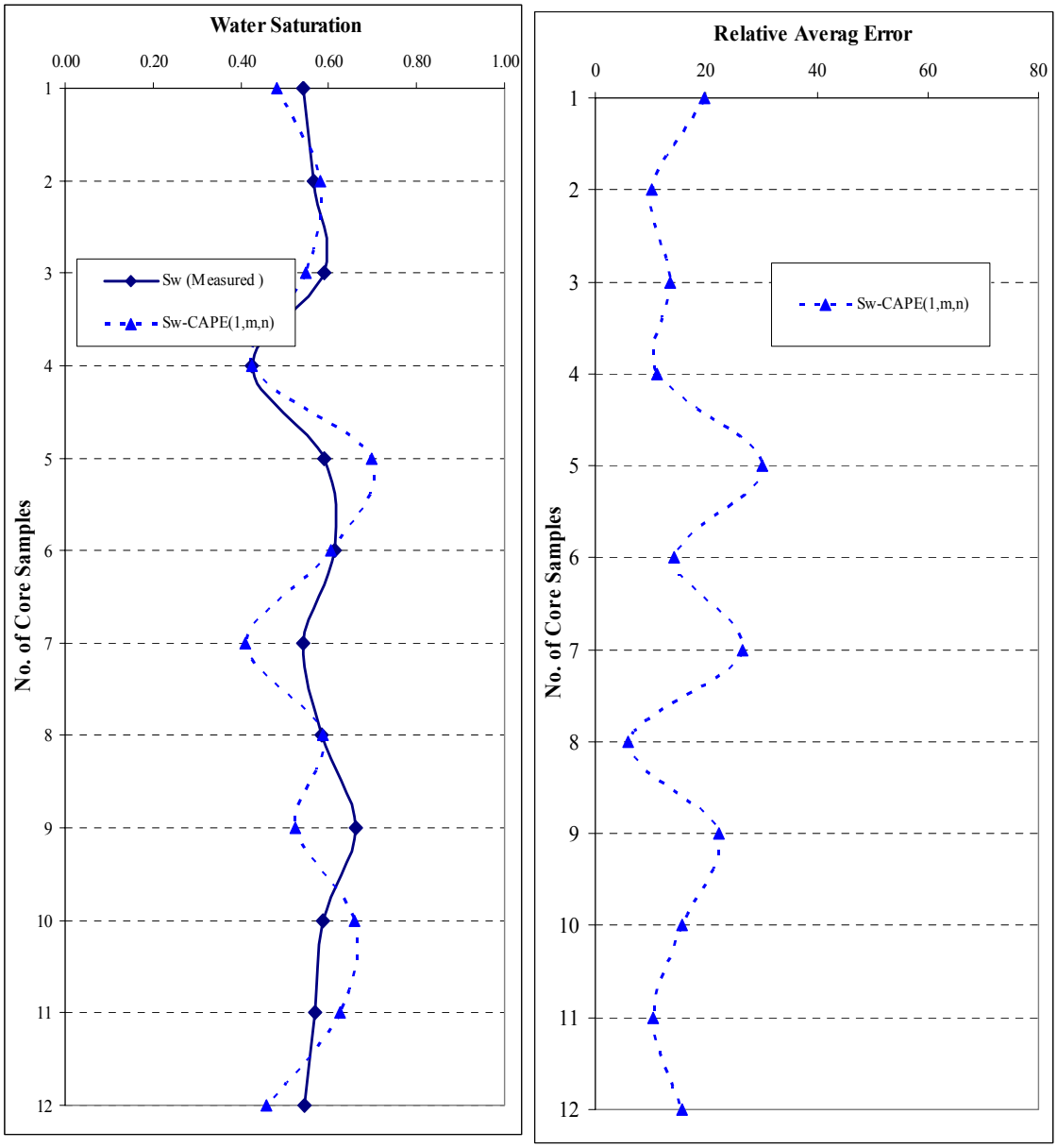

Figure 5-29 Comparison between measured and estimated water saturation using CAPE (1, *m, n*) method

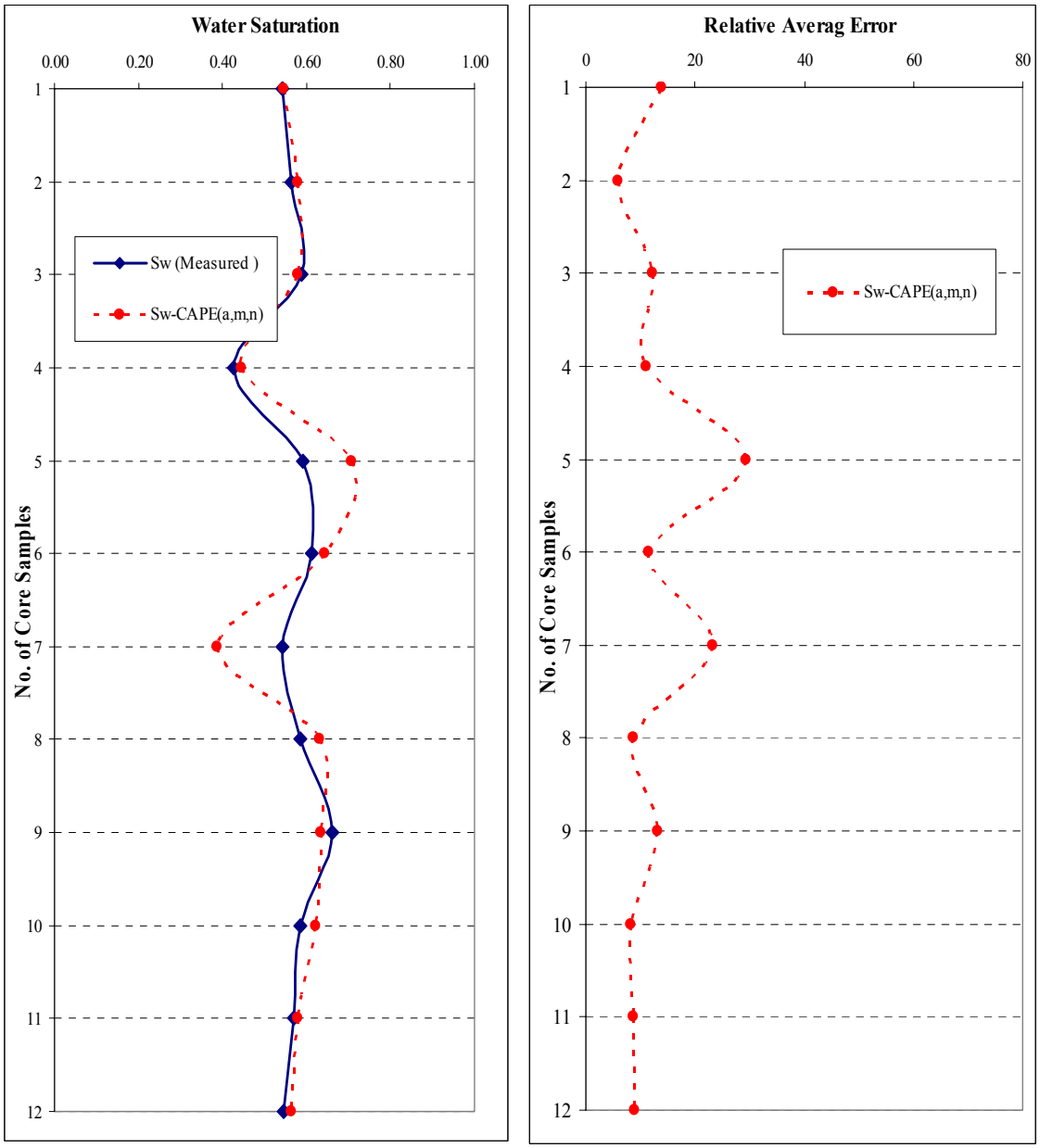

Figure 5-30 Comparison between measured and estimated water saturation using CAPE (*a, m, n*) method

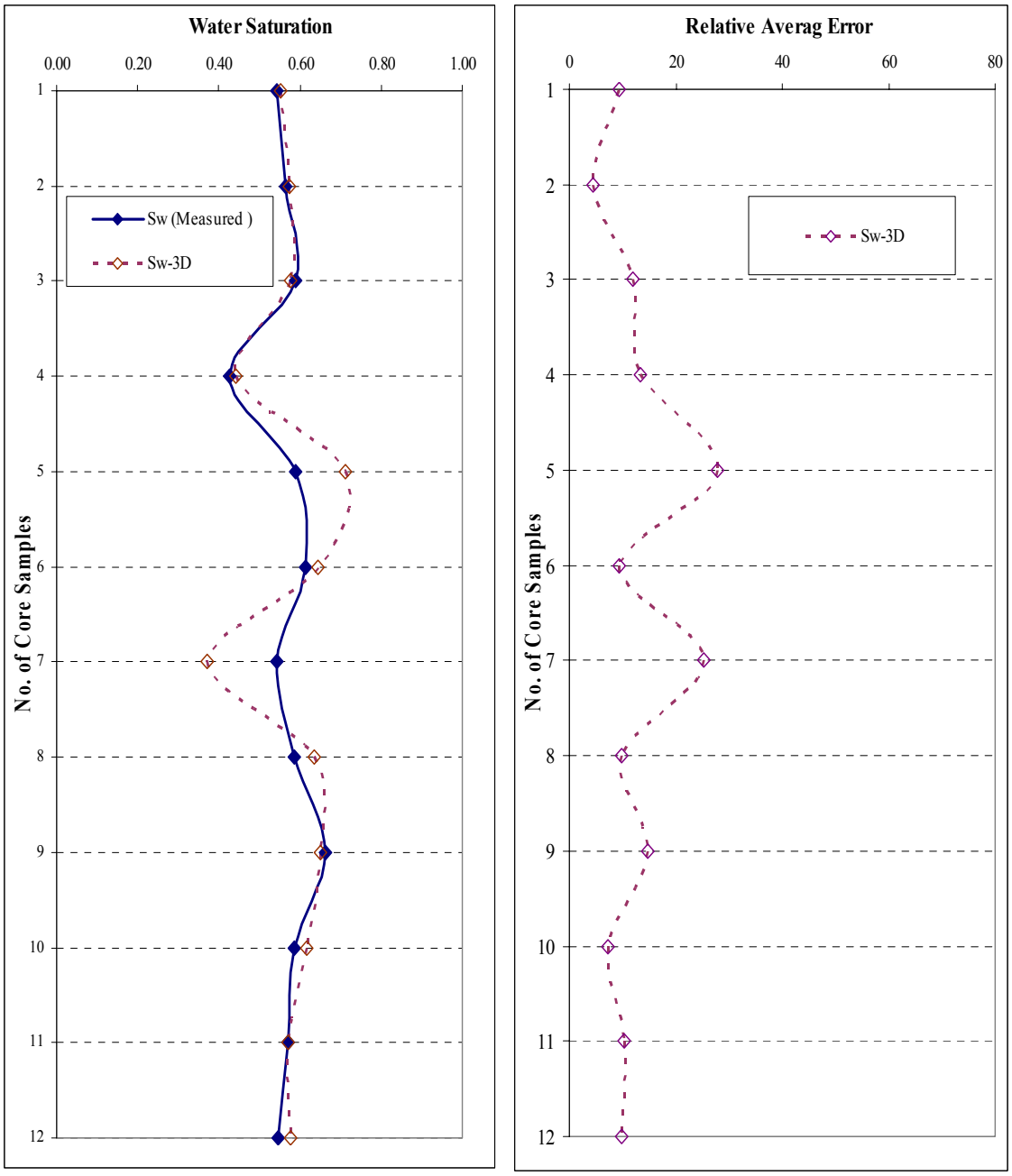

Figure 5-31 Comparison between measured and estimated water saturation using 3-D technique

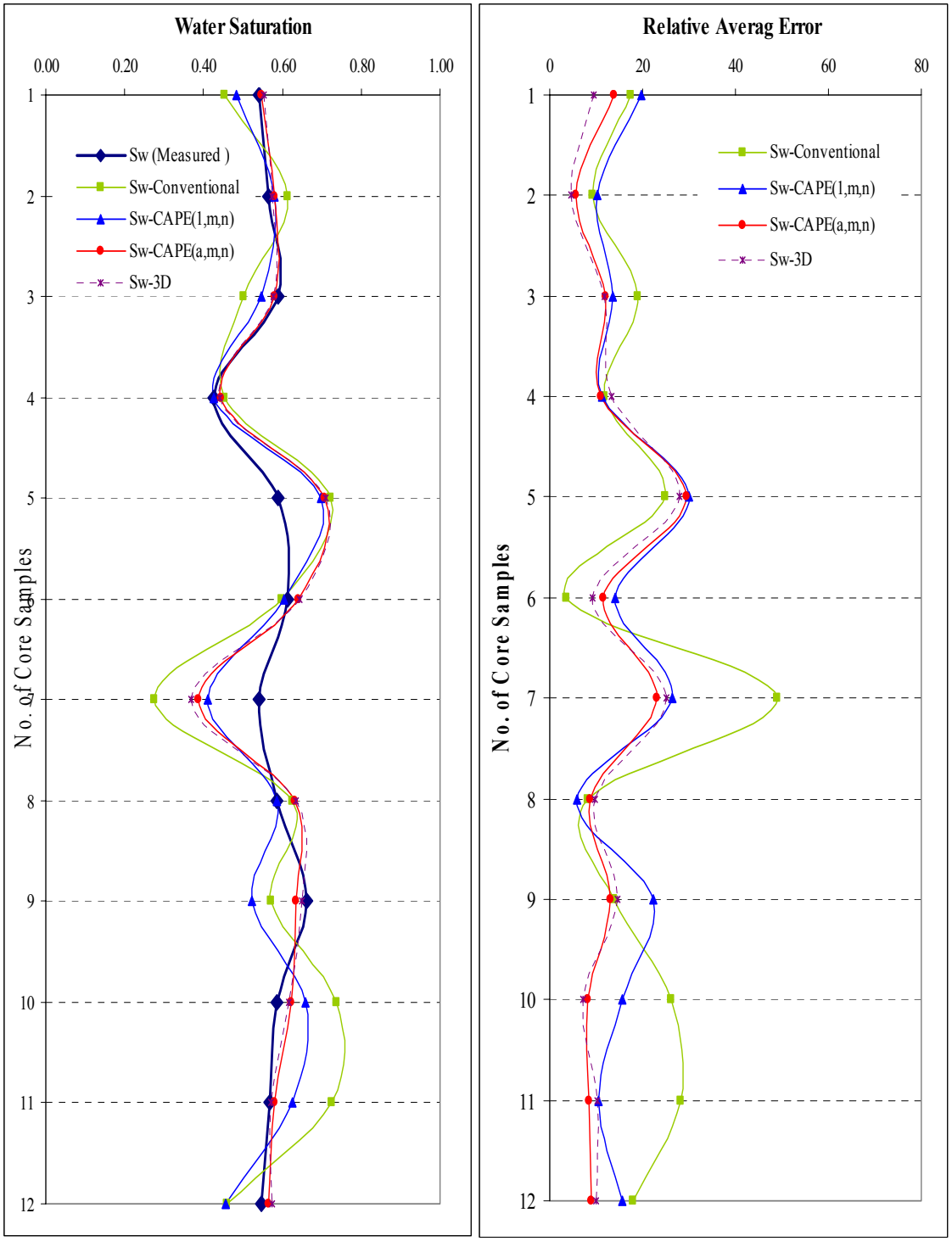

Figure 5-32 Comparison between measured and estimated water saturation using all techniques

5.3.4 Results and Analysis of Well A, B and C

5.3.4.1 Conventional Method

5.3.4.1.1 Conventional Determination of *a* and *m*

If we consider the three wells are the same lithologies. Then, we can use all data in **Table 5-8, Table 5-15** and **Table 5-22** to plot of log *F* vs. log Ø. This plot should give a liner trend, where *m* represents the slope of this trend and the intercept at Ø=1 gives the coefficient a. **Figure 5-33** shows that Cementation factor *m*=1.56, is determined from the slope of the plotted points, while tortousity factor 1.68 is given from the intercept of the line.

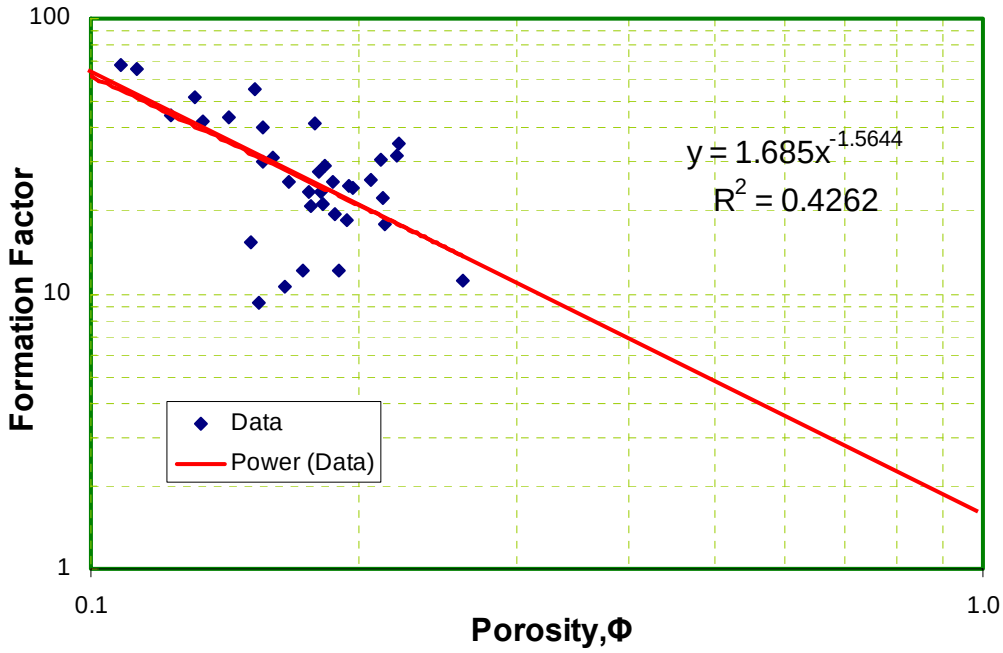

Figure 5-33 Formation factor vs. porosity from Wells A, B, and C core plugs

5.3.4.1.2 Conventional Determination of *n*

Saturation exponent *n* was determined from the logarithmic plot of resistivity index *RI* versus brine saturation, S_w, for cores taken from well A, B and C. This plot should give a liner trend, where *n* represents the slope of this trend. The results of plotting forty four core samples are shown in **Figure 5-34** shows water exponent value (*n*) is about 2.05 for all core samples.

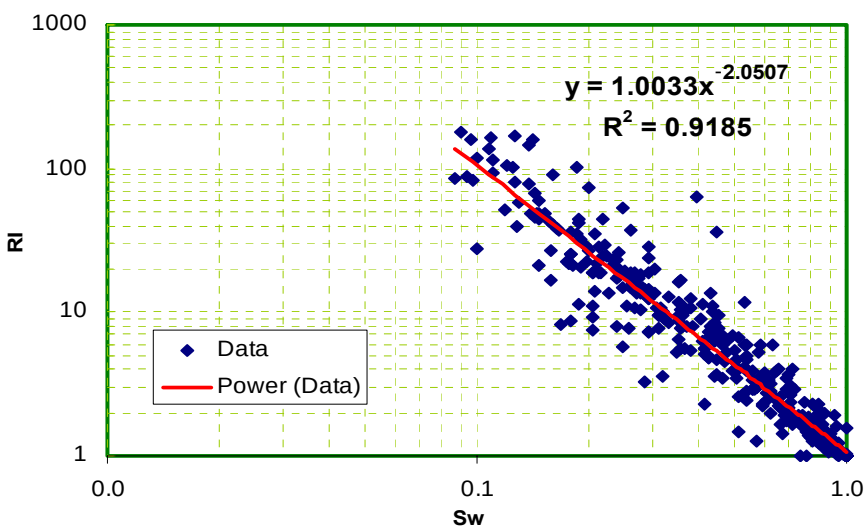

Figure 5-34 Water saturation exponent of well A, B and C core plugs

Table 5-29 Archie's parameters (*m, n, a*) values of the well A, B and C

a	**1.68**
m	1.56
n	2.05

5.3.4.2 Core Archie Parameters Estimation

Table 5-30 shows values of Archie's parameters values as the results of matlab program using the two CAPE methods.

Table 5-30 Archie's parameters values calculated using the two CAPE methods

	CAPE (1, *m*, *n*)	**CAPE (*a*, *m*, *n*)**
a	1.00	0.10
m	1.49	2.78
n	2.53	2.38

5.3.4.3 3-D Method

Table 5-31 shows *a, m,* and *n* values calculated with the three dimensional- regression method.

Table 5-31 Archie's parameters values calculated with the 3D methods

a	**0.24**
m	2.55
n	2.04

5.3.4.4 Comparison of the Methods Used for Archie's Parameters Determination

Table 5-32 shows the typical results of Archie's parameters for the carbonate cores taken from all wells by the four discussed methods.

Table 5-32 Comparison of Archie's parameters estimation methods well A, B and C

	Conventional	**CAPE (1, *m* ,*n*)**	**CAPE (*a*, *m*, *n*)**	**3-D Method**
a	1.68	1.00	0.10	0.24
m	1.56	1.49	2.78	2.55
n	2.05	2.53	2.38	2.04

The results of the accuracy analysis were illustrated in **Table 5-33** and **Figure 5-35**. this results show us how the water saturation error decreases as we go from the case of 1) Conventional method, 2) Core Archie parameter estimation (CAPE) with "*a*" fixed at unity, 3) 3D method and 4) core Archie parameter estimation (CAPE) without "*a*" fixed at unity.

Figures 5-36, 5-37, 5-38, 5-39 and **5-40** draw the profile of average water saturation of each core samples with their relative error. This comparison explain that the relative error decreases from the case of 1) Conventional method, 2) Core Archie parameter estimation (CAPE) with "*a*" fixed at unity, 3) 3D method and 4) core Archie parameter estimation (CAPE) without "*a*" fixed at unity.

Table 5-33 Accuracy analysis of the different techniques on well A, B and C

	Conventional		CAPE (1,m,n)		CAPE (a, m, n)		3D Method	
	Abs Error	Rel. Error %	Abs Error	Rel. Error %	Abs Error	Rel. Error %	Abs Error	Rel. Error %
Max.	1.03	112.12	0.42	107.27	0.50	113.00	0.72	113.83
Min.	3E-05	2.6E-02	5 E-05	1.2E-02	6 E-05	3.3E-02	3 E-04	1E-01
Average	0.18	31.81	0.12	24.00	0.12	21.85	0.12	22.97
Standard Deviation	0.19	26.54	0.10	18.33	0.10	16.17	0.14	21.54
RMS Error	0.26		0.16		0.15		0.18	
Correlation Factor	0.83		0.86		0.87		0.86	

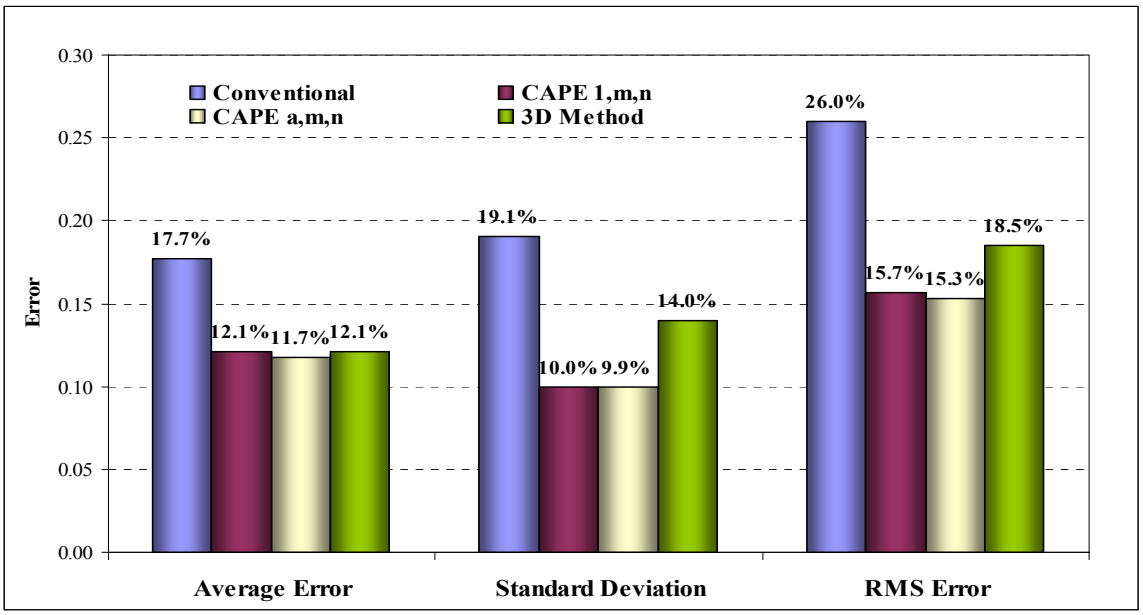

Figure 5-35 Accuracy analysis for different techniques on wells; A, B, and C core plugs

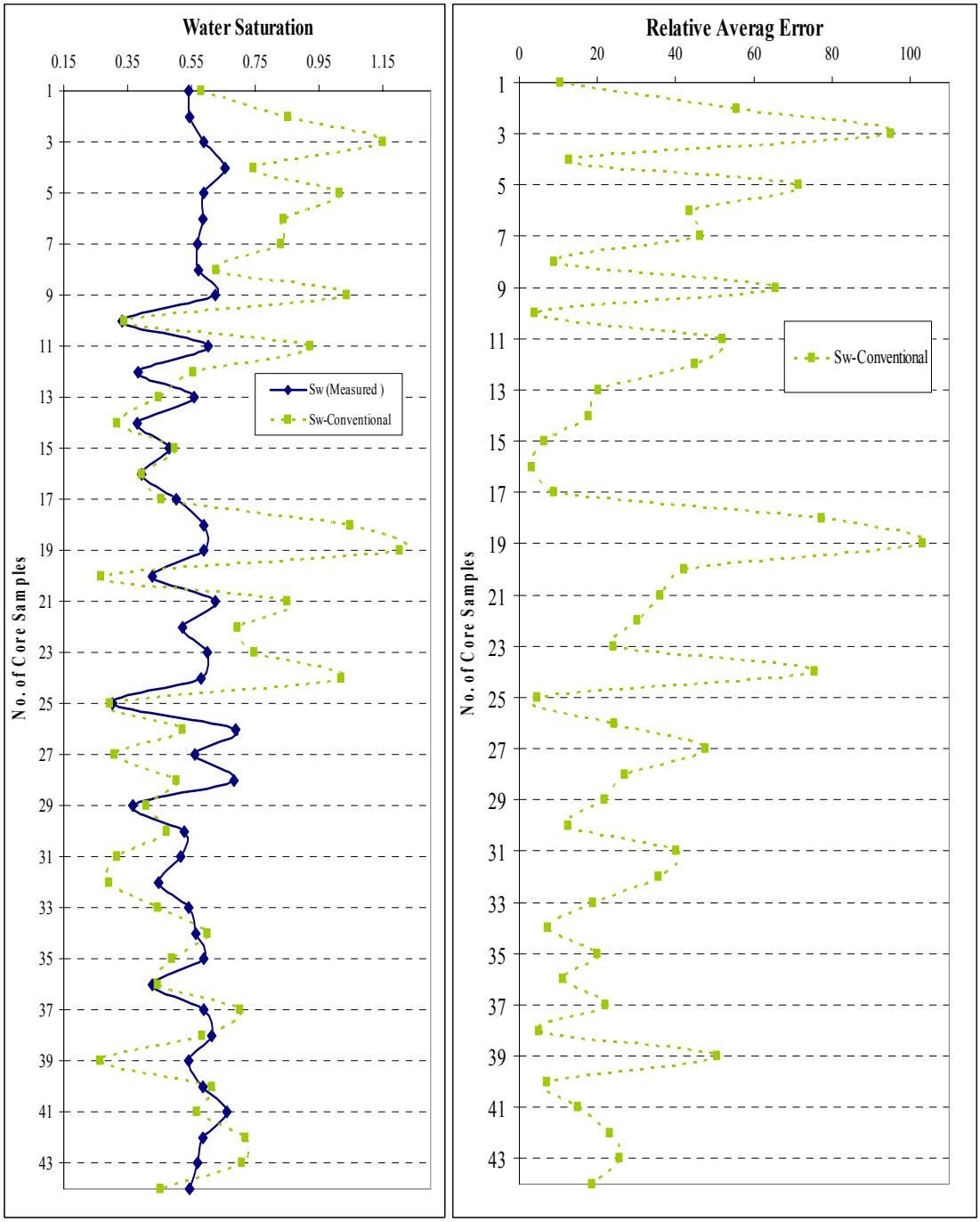

Figure 5-36 Comparison between measured and estimated water saturation using conventional technique

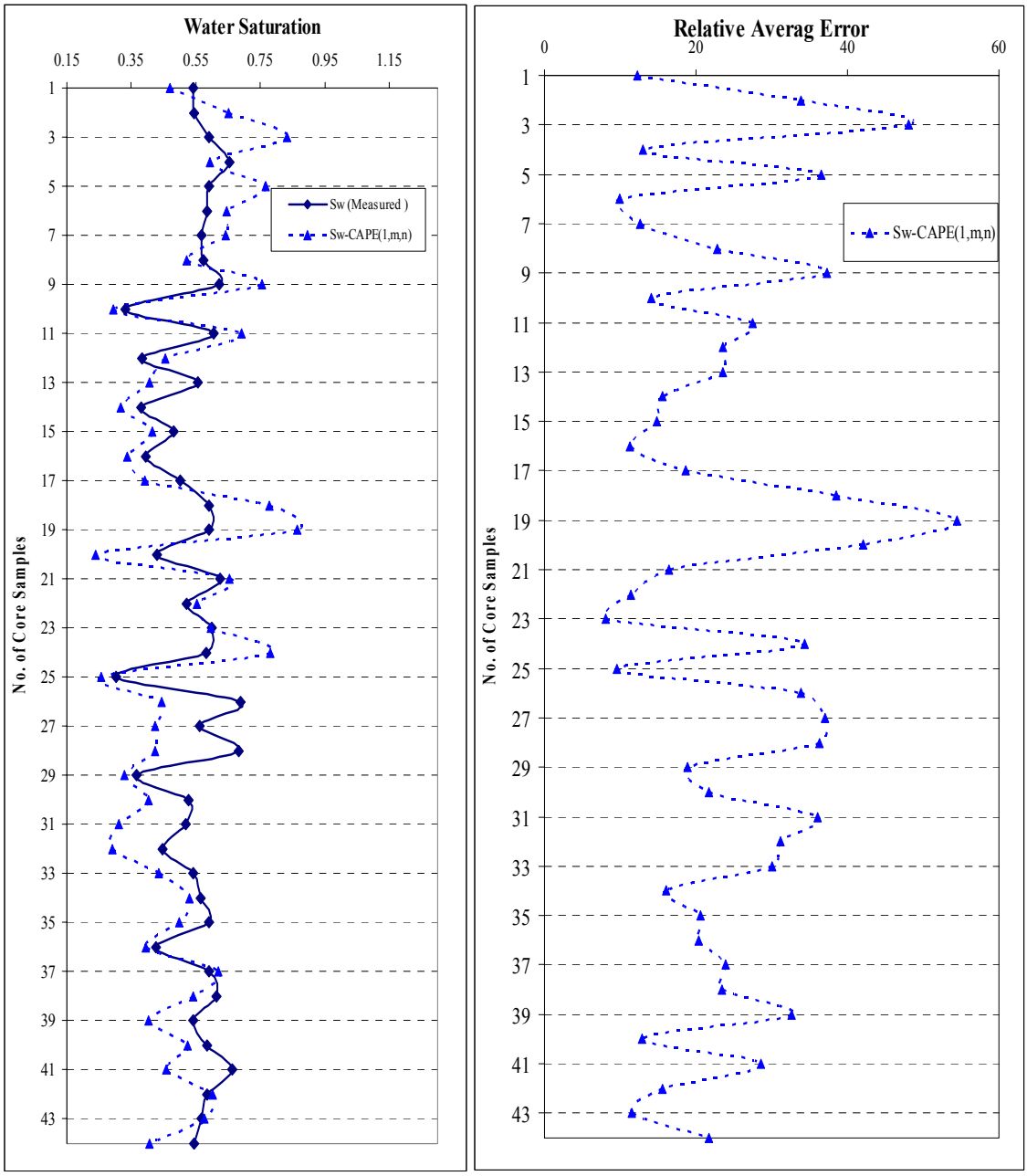

Figure 5-37 Comparison between measured and estimated water saturation using CAPE (1, *m, n*) method

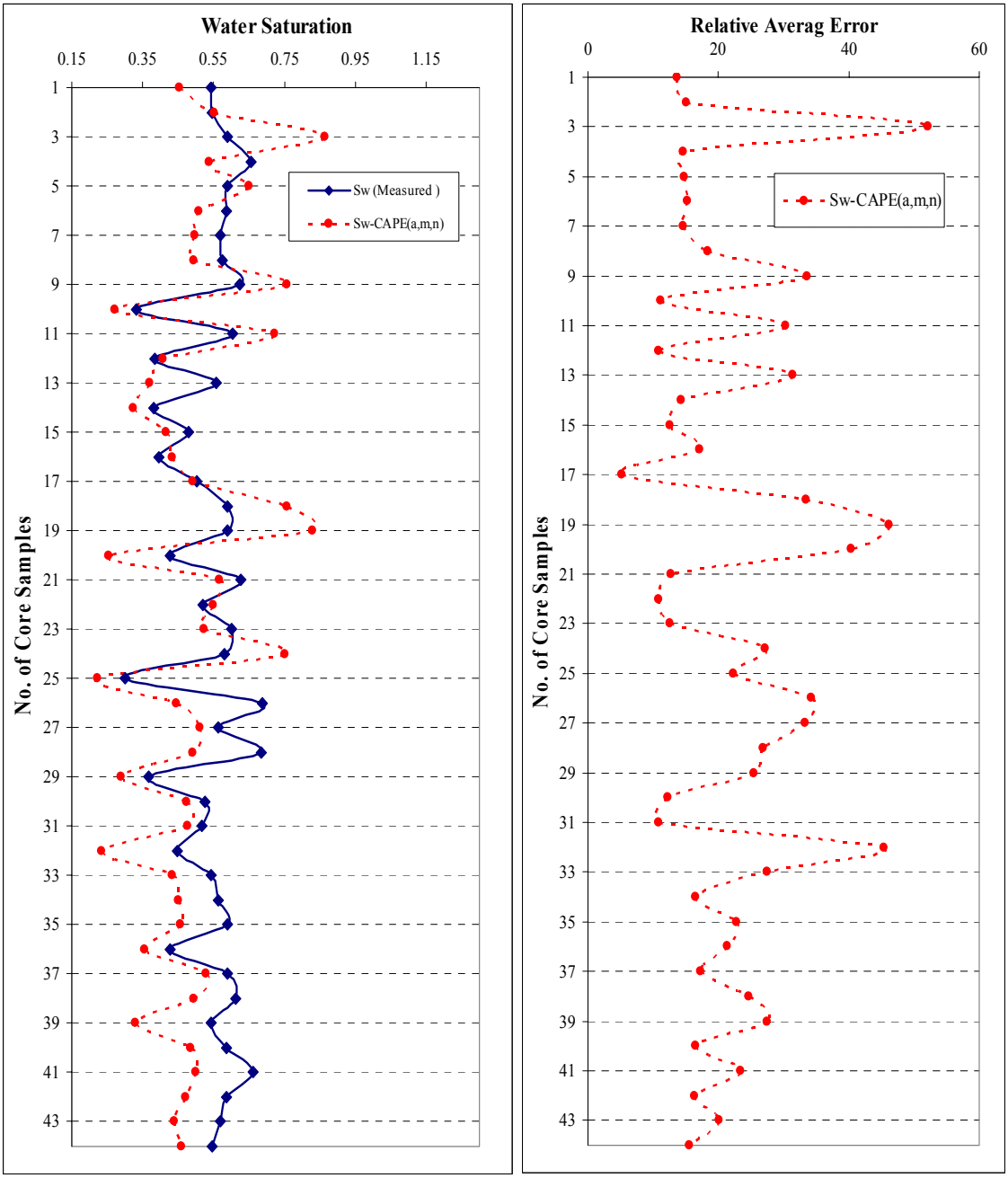

Figure 5-38 Comparison between measured and estimated water saturation using CAPE (*a, m, n*) method

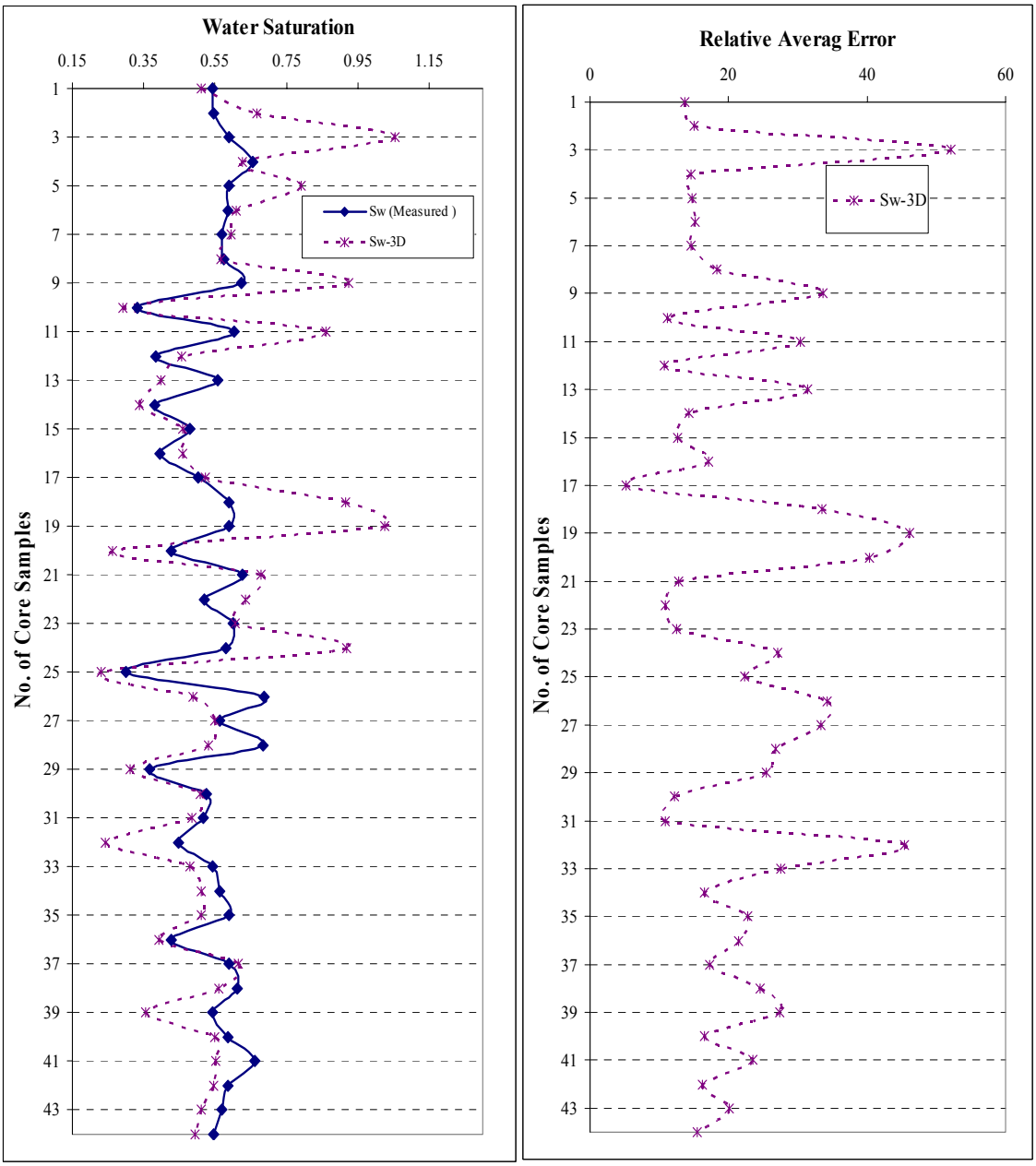

Figure 5-39 Comparison between measured and estimated water saturation using 3-D technique

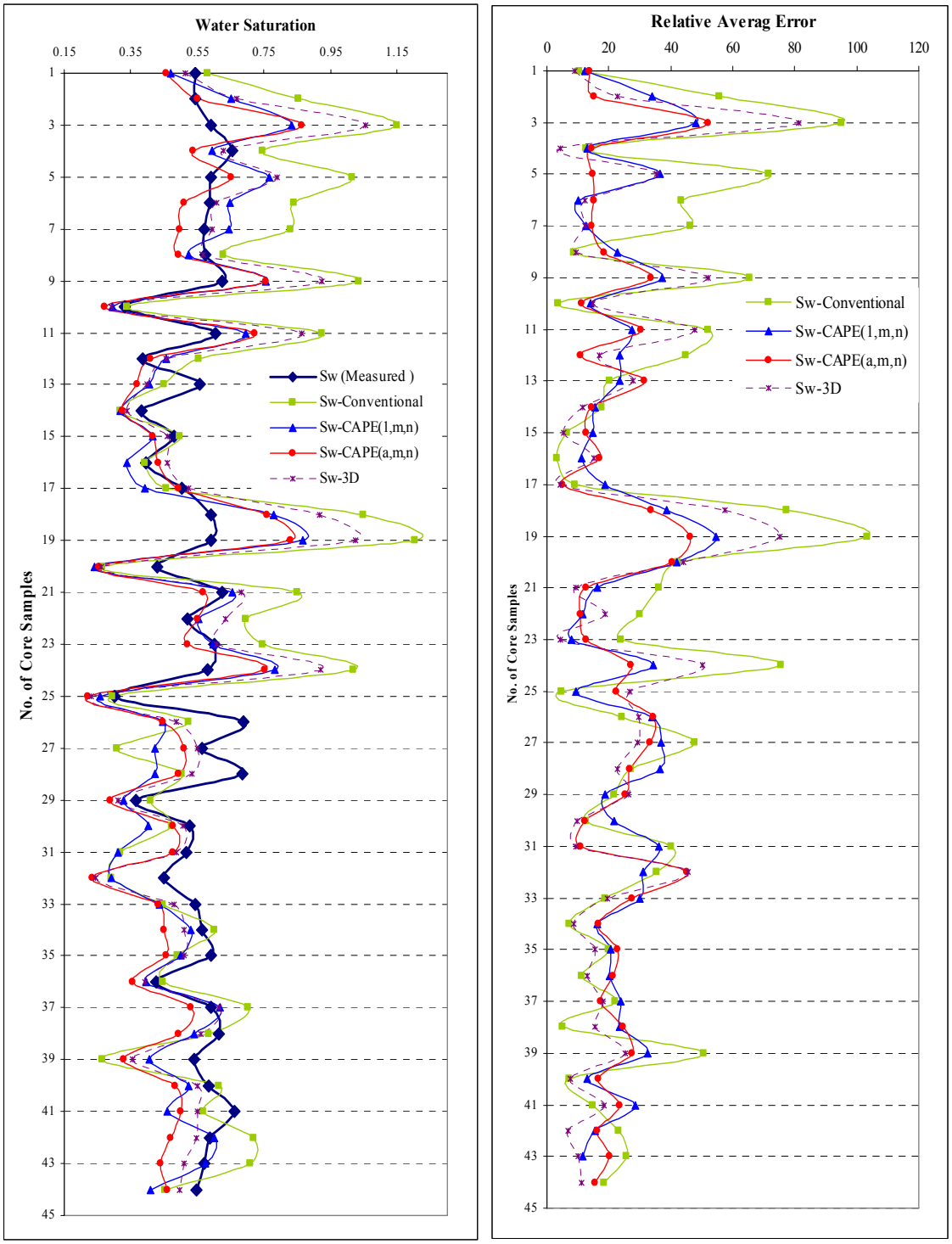

Figure 5-40 Comparison between measured and estimated water saturation using all techniques

CONCLUSIONS

From the analysis of the different determination techniques of Archie's parameters on carbonate reservoirs rock samples, the following conclusions can be drawn.

1. Conventional technique optimizes the two functions F vs. Ø and R_t vs. S_w rather than water saturation values in the determination of Archie's parameters.

2. Unlike the conventional method which ignores the values of S_w <1.0 in the determination of a and m, the 3-D and CAPE use all the data of S_w points.

3. 3-D and CAPE methods provide simultaneously the values of Archie's parameters from the standard resistivity measurements on core samples.

4. CAPE yields improved values of Archie's parameters (*a, m, n*) from standard resistivity measurements on core samples.

5. CAPE and 3-D give values of Archie's parameters that minimize the error in the desired quantity of water saturation.

6. 3-D and CAPE methods provide a proper method of averaging n and m values from related cores or wells by using all the data in the algorithm simultaneously.

7. CAPE (*a, m, n*) method provides the lowest absolute relative error but the CAPE (1, *m, n*) and 3-D methods are still faster.

8. For applications where the highest possible accuracy in hydrocarbon saturation is required, it is recommended to use the 3-D method, unless, there are adverse conditions as mentioned in thesis.

9. Error analysis of water saturation values increases on going from CAPE to 3-D and conventional techniques.

10. Standard deviation and correlation factor showed that CAPE (with, *a*, variable) is the best one while conventional is the worst technique.

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