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Electrical Tortuosity Index: A New Approach for Identifying Rock Typing to Enhance Reservoir Characterization Using Well-Log Data of Uncored Wells

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Cite This: *ACS Omega* 2023, 8, 19509−19522

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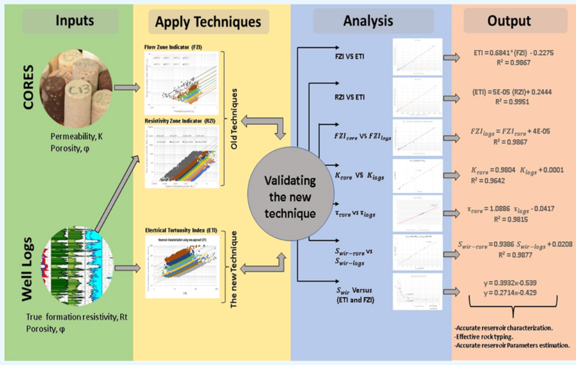
ABSTRACT: The world is gradually moving toward a severe energy crisis, with an ever-increasing demand for energy overstepping its supply. Therefore, the energy crisis in the world has shed important light on the need for enhanced oil recovery to provide an affordable energy supply. Inaccurate reservoir characterization may lead to the failure of enhanced oil recovery projects. Thus, the accurate establishment of reservoir characterization techniques is required to successfully plan and execute the enhanced oil recovery projects. The main objective of this research is to obtain an accurate approach that can be used to estimate rock types, flow zone indicators, permeability, tortuosity, and irreducible water saturation for uncored wells based on electrical rock properties that were obtained from only logging tools. The new technique is obtained by modifying the Resistivity Zone Index (RZI) equation that was presented by Shahat et al. by taking the tortuosity factor into consideration. When true formation resistivity (R_t) and inverse porosity ($1/\Phi$) are correlated on a log−log scale, unit slope parallel straight lines are produced, where each line represents a distinct electrical flow unit (EFU). Each line's intercept with the *y*-axis at $1/\Phi = 1$ yields a unique parameter specified as the Electrical Tortuosity Index (ETI). The proposed approach was validated successfully by testing it on log data from 21 logged wells and comparing it to the Amaefule technique, which was applied to 1135 core samples taken from the same reservoir. Electrical Tortuosity Index (ETI) values show marked accuracy for representing reservoir compared with Flow Zone Indicator (FZI) values obtained by the Amaefule technique and Resistivity Zone Index (RZI) values obtained by the Shahat et al. technique, with correlation coefficients of determination (R^2) values equal to 0.98 and 0.99, respectively. Hence, by using the new technique, the Flow Zone Indicator, permeability, tortuosity, and irreducible water saturation were estimated and then compared with the obtained results from the core analysis, which showed a great match with the R^2-values of 0.98, 0.96, 0.98, and 0.99, respectively.



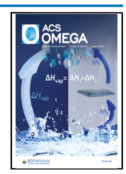
1. INTRODUCTION

A successful field development plan (FDP) requires an accurate estimation of rock properties. Thus, reservoir characterization is essential for decreasing uncertainty, quantitatively assigning reservoir properties, and recognizing geological information.[1] Besides, reservoir characterization is very important in dealing with reservoir rock and enhanced hydrocarbon recovery techniques.[2−5] Reservoir characterization provides critical data that is necessary for creating models that accurately predict production outcomes, including the areal sweep efficiency for different injection patterns and water saturation.[6,7] Therefore, the development of artificial neural network models is dependent on the accuracy of the reservoir characterization process, highlighting the essential role it plays in improving oil recovery.

The goal of reservoir characterization is to determine how many hydraulic flow units (HFUs) we have and what are the properties of each HFU. According to Amaefule et al.,[8] the hydraulic flow unit (HFU) is defined as a representative elementary volume of the total reservoir's rock having internally consistent geological and petrophysical properties. In addition, the concept of hydraulic flow unit (HFU) is frequently used to characterize a reservoir's rock.[8−12] Several petrophysical parameters are considered very important to achieve an accurate reservoir characterization, e.g., pore throat size, capillary pressure, and pore shape and arrangement.[13−15]

The fluid flow through the porous medium is controlled by the geometrical microscale of the reservoir rock. The relation between permeability (k) and porosity (Φ_e) is introduced by the Kozeny−Carman equation, which assumes a porous medium as a bundle of capillary tubes. The Kozeny−Carman

Received: February 11, 2023
Accepted: May 9, 2023
Published: May 24, 2023



concept is used to enhance reservoir characterization and permeability estimation[16,17]

$$K = \Phi_e \times \frac{r_{mh}^2}{F_S \times \tau} \tag{1}$$

where r_{mh} is the mean hydraulic unit radius, F_S is the shape factor, which equals 2 for a circular tube, and τ is the hydraulic tortuosity.

Besides, they related the surface grain volume with porosity, pore radius, and mean hydraulic unit radius by the following equation

$$S_{gv} = \frac{2}{r} \times \left(\frac{\Phi_e}{1 - \Phi_e}\right) = \frac{1}{r_{mh}}\left(\frac{\Phi_e}{1 - \Phi_e}\right) \tag{2}$$

where S_{gv} is the specific surface area per unit grain volume (in μm^{-1})

Thus, a generalized form of the Kozeny–Carman equation is frequently given by

$$K = \frac{\Phi_e^3}{(1 - \Phi_e)^2} \times \left[\frac{1}{F_S \times S_{gv}^2 \times \tau}\right] \tag{3}$$

Amaefule et al.[8] introduced a new technique to characterize reservoir rock using core data based on modifying the Kozeny–Carman equation, in which the mean hydraulic radius concept is used. A new term "Flow Zone Indicator" (FZI) was developed, which considered a unique value for each hydraulic flow unit. FZI can be achieved by plotting the reservoir quality index (RQI) versus the normalized porosity (Φ_N), where a linear parallel line is obtained with unity slopes and the intercept represents the Flow Zone Indicator (FZI). The newly introduced technique showed great success on clastic reservoir rock fields in Southeast Asia, Texas, West Africa, and South America. Moreover, it was applicable in carbonate reservoir rock fields in West Texas and Canada. They concluded that the Flow Zone Indicator technique is considered effective in reservoir characterization and determining the number of HFU

$$K = 1014 \times (\mathrm{FZI})^2 \times \left(\frac{\Phi_e^3}{(1 - \Phi_e)^2}\right) \tag{4}$$

Besides, they also introduced a correlation that relates the value of Flow Zone Indicator (FZI) with irreducible water saturation (S_{wir}) as follows

$$S_{wir} = 1 - \left[\frac{1}{a + b \times \mathrm{FZI}^{-C}}\right] \tag{5}$$

where $a = 1.12$, $b = 0.5634$, and $c = 1.44$.

Furthermore, many other researchers presented extensive studies to enhance reservoir characterization by predicting the petrophysical properties, e.g., reservoir quality index (RQI), permeability, and FZI of unlogged wells.[11,12,18−34] That is based on the hydraulic flow unit concept and many modified versions of the Kozeny–Carman equation. Al-Ajmi and Holditch[12] introduced a new technique to enhance reservoir characterization from well logs. A new equation is introduced to predict the values of the Flow Zone Indicator for each hydraulic flow unit. This study was applied to the central Arabian sandstone reservoir rock. FZI is predicted by the following equation

$$\mathrm{FZI}_j^{pre} = \theta^{*-1}[\Phi_1^*(\ln\_\mathrm{GR}_j) + \Phi_2^*(\ln\_R_{d/s_j}) + \Phi_3^*(\Phi_{ej}) + \Phi_4^*(\mathrm{Zone}_j)] \tag{6}$$

where FZI_j^{pre} is the predicted FZI value for a given well log. GR_j is γ-ray. R_{d/s_j} is the deep-to-shallow resistivity ratio. Φ_{ej} is the effective porosity. Zone_j is the zone indicator.

They concluded that the results of permeability obtained by using the new technique showed success in estimating FZI by comparing it with core analysis.

Nooruddin and Hossain[21] worked on a new technique to enhance reservoir characterization and accurately estimate permeability in uncored wells. The main idea of the technique is to reduce the assumptions and limitations in the Kozeny–Carman model for the accurate determination of hydraulic flow units. The concept of Flow Zone Indicator and RQI that were introduced by Amaefule et al. was modified. The proposed study was tested on carbonate reservoir rock with high heterogeneity in the Middle East. They concluded that the new technique resulted in better reservoir characterization and an improvement in hydraulic flow unit determination.

Izadi and Ghalambor[22] worked on a new approach to enhance the accuracy of determining hydraulic flow unit (HFU) and permeability estimation. The new techniques are based on using both Poiseuille and Darcy equations. Applicability was tested on 17 samples of Berea sandstone reservoir rock. Results showed excellent prediction for the petrophysical properties of reservoir rock, which helped in enhancing reservoir characterization

$$\mathrm{MRQI} = \left[\frac{\Phi_e}{1 - \Phi_e}\right] \times \left[\frac{1}{S_{gv} \times \tau \times \sqrt{F_s}}\right] \times (1 - S_{wir})^2 \tag{7}$$

where MRQI is the modified reservoir quality index (in μm). $\left[\frac{1}{S_{gv} \times \tau \times \sqrt{F_s}}\right]$ is the Flow Zone Indicator, FZI (in μm). $\left[\frac{\Phi_e}{1 - \Phi_e}\right]$ is the normalized porosity, ΦN, which can be defined as the ratio of pore volume to grain volume (ratio). K is the permeability (in md). S_{wir} is the irreducible water saturation (fraction of pore volume). τ is the hydraulic tortuosity (dimensionless). F_s is the shape factor (dimensionless).

Abedini et al.[35] presented the relation between many reservoir rock parameters. According to the findings, the following equation can be obtained for the same radius of a tortuous capillary tube bundle

$$\sqrt{k/\Phi_e} = \frac{r}{\sqrt{8\tau}} \tag{8}$$

where $\sqrt{k/\Phi_e}$ is the reservoir quality index (in μm). τ is the hydraulic tortuosity (dimensionless). r is the pore throat radius (in μm).

Aguilar et al.[25] introduced a new technique for accurate reservoir characterization based on the concept of the hydraulic flow unit (HFU). In the Venezuelan Eocene, permeability was accurately predicted, and the hydraulic flow unit (HFU) was determined on sandstone reservoir rock. Attia et al.[36] demonstrated that reservoir characterization is critical for secondary and enhanced oil recovery projects. The main goal of the research was to use reservoir characterization to identify productive zones and the barriers of the reservoir. This study was applied by using the traditional methods in reservoir

https://doi.org/10.1021/acsomega.3c00904
ACS Omega 2023, 8, 19509−19522

characterization such as the Winland R35 methods, discrete rock type (DRT), and Flow Zone Indicator (FZI). A static reservoir characterization model was built by applying the reservoir characterization methods to four wells to identify the flow units and the rock types. Results showed effective improvements in determining flow zones and rock types; moreover, potential productive zones and barriers could be identified. They concluded that the study allowed for a more accurate descriptive reservoir model with a good image that can be used to simulate reservoir rock more accurately. Abdallah et al.[23] studied the concept of hydraulic flow units and how to enhance reservoir characterization in uncored wells. A correlation was presented between the FZI values calculated from the core analysis and those obtained from well logs, and then permeability was predicted. The study was implemented on shaley sandstone reservoir rock in Berkine Basin (Algerian Sahara). The result showed that the prediction of permeability was successful. Shahat et al.[10] concluded that accurate reservoir characterization can be obtained by a new approach to rock typing using well-log data. A log−log correlation between true formation resistivity (R_t) and the square of normalized porosity (Φ_N^2) is established to yield parallel straight lines (each representing a distinct electrical flow unit (EFU), the intercept of which at (Φ_N^2) gives a unique parameter specified as the Resistivity Zone Index (RZI). The validity of the proposed model is tested using log data obtained from 21 logged wells and 1135 core samples. RZI values (calculated for each EFU) demonstrate remarkable accuracy in representing the reservoir. The equation for the Resistivity Zone Index can be written as follows

$$R_T = [{\Phi_N}^2] \times [\text{RZI}] \tag{9}$$

Defining the Resistivity Zone Index RZI $(\Omega\cdot\text{m}) = \left[\frac{I_r \times R_w}{k \times F_S \times {S_{gv}}^2}\right]$ and $\Phi_N = \frac{\Phi_e}{1 - \Phi_e}$

In the Archie equation,[37] the tortuosity factor is a very important parameter to calculate the formation resistivity factor. Hydraulic tortuosity is defined as the ratio of the actual traveled length (L_a) to the system straight length (L).[38−40] According to Attia,[41] many studies on tortuosity have been conducted, including the following.

Perkins et al.[42] demonstrated that the formation resistivity factor (F_r), tortuosity (τ), and porosity (Φ_e) for a fully brine-saturated sandstone reservoir rock are related to the following equation

$$F_r = \tau^2/\Phi_e \tag{10}$$

David[29] indicated that there is a difference between tortuosity values for hydraulic and electrical paths. Furthermore, the tortuosity values for the hydraulic path are considered much greater than the obtained values of the tortuosity for the electrical path. Zhang and Knackstedt[34] investigated the fluid flow and electrical conductivity in random porous three-dimensional. The results showed that the hydraulic tortuosity is far greater than the electrical tortuosity. Tiab and Donaldson[43] presented the new relationship between tortuosity and porosity as follows

$$\tau = \left[1 + \frac{\Phi_{\text{trapped}}}{\Phi_{\text{channel}}}\right] = \left[1 + \frac{\Phi - \Phi^m}{\Phi^m}\right] \tag{11}$$

Koponen et al.[44] defined tortuosity as a specific transportation mechanism. Obviously, it is a physical quantity that is not uniquely defined. They constructed an empirical equation between porosity and tortuosity as follows

$$\tau = 0.8 \times [1 - \Phi] + 1 \tag{12}$$

Olny et al.[45] presented a new technique for indirectly estimating the tortuosity and characteristic lengths of porous materials using acoustical measurements. The technique is based on the relationship between the tortuosity of a material and the acoustic properties of the fluid inside it. By analyzing the transmission and reflection of acoustic waves in the material, the viscous characteristic length and thermal characteristic length of the material can be estimated, which, in turn, can be used to estimate the tortuosity, where the viscous characteristic length is a measure of the resistance to flow due to viscous forces within the porous material. The thermal characteristic length, on the other hand, is a measure of the resistance to heat transfer within the porous material.

Fellah et al.[46] introduced a new technique to measure the tortuosity and porosity of reservoir rock. The proposed technique is based on transient ultrasonic wave propagation in a rigid frame of porous material, which is considered a homogeneous isotropic slab. Porosity and tortuosity are measured for packed glass beds in pore space.

More recently, Bo-Ming and Jian-Hua[47] formulated a simple geometric model for the tortuosity of flow path in a porous medium using simple square geometry in two dimensions based on the assumption that some particles in a porous medium are overlapped and others are not. The developed model is expressed as a function of porosity, and it contains no empirical constants. Tang et al.[48] simulated the relationship between tortuosity and porosity using cubic particles with the assumption that the porous medium is homogeneous. However, rocks frequently deviate from homogeneity and cubic particles may not be abundant in situ.

The objective of this paper is to introduce a new equation for more accurate reservoir characterization using well-log data. Efficient reservoir characterization leads to time and money savings. The main advantage of the new technique is that it can be applied using only the data gathered from only logging tools in the field. In this approach, characterization is achieved based on a new index called the "Electrical Tortuosity Index, ETI". The new index is built on modifying the discussed Resistivity Zone Index equation that was introduced by Shahat et al. to enhance reservoir characterization. Moreover, new equations are developed to calculate Flow Zone Indicator, permeability, tortuosity, and irreducible water saturation from well logs. The results obtained by the new technique were compared with those previously published techniques and showed a great match. Therefore, the new technique is considered reliable to be used for reservoir characterization from well-log data in case no core data is available.

2. DATA AND METHODOLOGY

2.1. Data Description. In this study, the core and log data were gathered from the oil field in Algeria. The main reservoirs in the area belong to Cambrian−Ordovician sandstones, which are of fluvial to shallow marine environments, with most of the discoveries being structurally controlled where previously described anticlines and faults form the main structural traps. The seal in these traps is represented by Triassic shale and salt. This oil field consists of 21 wells. 15 out of 21 wells were

https://doi.org/10.1021/acsomega.3c00904
ACS Omega 2023, 8, 19509−19522

cored, whereas all 21 wells were logged. 1133 actual core data sets were collected from 15 oil wells. Core data includes porosity (Φ) and permeability (K). 33598 data points were obtained from well-logging data. Well-logging data includes neutron porosity (Φ_{Log}) and true resistivity of the formation (R_t). As shown in Table 1, the statistical analysis is accomplished by specifying the values of mean, median, mode, minimum, maximum, and dispersion parameters like standard error, standard deviation, kurtosis, and skewness. According to Table 1, the core porosity ranges from 0.32 to 17.3%, the core permeability ranges from 0 to 246.78 MD, the log porosity ranges from 0.01 to 22.5%, and the true resistivity of the formation ranges from 0.16 to 2231.15 Ω·m.

Table 1. Statistical Description of Data Used in This Study

	core data		log data	
	K, MD	Φ, %	R_t, Ω·m	Φ, %
mean	2.58	6.82	70.04	7.22
standard error	0.34	0.08	1.28	0.02
median	0.14	6.86	10.56	6.93
mode	0.01	7.1	2000	5.97
standard deviation	11.51	2.81	234.88	4.07
sample variance	132.42	7.9	55169.6	16.53
kurtosis	222.25	0.51	26.22	10.67
skewness	12.89	0.15	5.07	2.22
range	246.78	16.98	2230.99	22.5
minimum	0	0.32	0.16	0.01
maximum	246.78	17.3	2231.15	22.5
count	1133	1133	33,598	33,598

2.2. New Approach Development. Accurate determination of rock parameters is considered very important for accurate reservoir characterization. Several techniques have been developed over the years to describe reservoir rock and divide it into distinct hydraulic flow units. The concept of the hydraulic flow unit has been studied extensively to characterize reservoir rock.

The new technique is obtained by modifying the Resistivity Zone Index (RZI) equation that was presented by Shahat et al.[10] by considering the tortuosity factor. For the same radius of the tortuous capillary tube bundle, the relation between porosity (Φ_e), permeability (k), tortuosity (τ), and pore throat radius (r) can be obtained by using eq 8 and then squaring both sides to be as follows

$$k/\Phi_e = \frac{r^2}{8\tau} \tag{13}$$

Then, rearranging eq 13 to be on the form

$$\frac{1}{r^2} = \frac{\Phi_e}{k \times 8\tau} \tag{14}$$

The effective porosity (Φ_e) is related to the mean hydraulic radius (r_{mh}) and the surface area per unit grain volume (S_{gv}) by eq 2. Squaring both sides of eq 2 results in

$$S_{gv}{}^2 = \frac{4 \times \Phi_e^2}{r^2(1-\Phi_e)^2} \tag{15}$$

Substituting variables of eq 14 in eq 15, then rearranging to obtain the following equation

$$S_{gv}{}^2 = \left[\frac{4 \times \Phi_e^2}{r^2(1-\Phi_e)^2}\right] = \left[\frac{4 \times \Phi_e^2}{(1-\Phi_e)^2} \times \frac{\Phi_e}{k \times 8\tau}\right] = \left[\frac{4 \times \Phi_e^3}{(1-\Phi_e)^2} \times \frac{1}{k \times 8\tau}\right] \tag{16}$$

Resistivity Zone Index (RZI) is related to the square of normalized porosity (Φ_N^2) and true formation resistivity (R_t) to form eq 9 introduced by Shahat et al.[10] By substituting eq 16 into the Shahat et al. equation, the obtained relationship will be as follows

$$R_T = \left[\frac{\Phi_e^2}{(1-\Phi_e)^2}\right] \times \left[\frac{I_r \times R_w}{k \times F_S}\right] \times \left[\frac{(1-\Phi_e)^2 \times k \times 8\tau}{4 \times \Phi_e^3}\right] \tag{17}$$

where I_r (= R_t/R_0) is the resistivity index (dimensionless), R_0 is the formation resistivity at a 100% water saturation (Ω·m), R_t is the true formation resistivity (Ω·m), and R_w is the formation water resistivity (Ω·m).

Equation 17 is rearranged and simplified to yield the following resulting form of eq 18, which describes the relation between true formation resistivity, porosity, and many reservoir parameters. Noting that F_S is the shape factor, which equals 2 for the circular tube as mentioned in Amaefule et al.[8]

$$R_T = \left[\frac{(1-\Phi_e)^2 \times \Phi_e^2}{(1-\Phi_e)^2 \times \Phi_e^3}\right] \times \left[\frac{k}{k}\right] \times \left[\frac{I_r \times R_w \times 8\tau}{F_S \times 4}\right] \tag{18}$$

The developed equation of the new technique is obtained by finding the relation between true formation resistivity (R_t), inverse porosity $\left(\frac{1}{\Phi_e}\right)$, and Electrical Tortuosity Index (ETI). Simplifying eq 18 and substituting with $F_S = 2$, the following equation is obtained

$$R_T = \left[\frac{1}{\Phi_e}\right] \times [I_r \times R_w \times \tau] \tag{19}$$

The final form of the developed equation used in the new technique to characterize reservoir rock from well logs can be obtained by defining Electrical Tortuosity Index (ETI = $I_r \times R_w \times \tau$), where, and taking the logarithm of both sides of eq 19 gives

$$\log(R_t) = \log\left(\frac{1}{\Phi_e}\right) + \log[\mathrm{ETI}] \tag{20}$$

where where R_t is the formation true resistivity obtained from deep resistivity logs (in Ω·m). Φ_e is the effective porosity. ETI (Ω·m) = I_r (dimensionless) × R_w (Ω·m) × τ (dimensionless).

On a log–log plot of true formation resistivity (R_t) versus the inverse of porosity $\left(\frac{1}{\Phi_e}\right)$, samples with similar Electrical Tortuosity Index (ETI) values will lie on a unit slope straight line. On the other hand, samples with different Electrical Tortuosity Index (ETI) values will lie on other unit slope parallel lines. The value of the Electrical Tortuosity Index (ETI) can be obtained from the intercept of each unit slope parallel straight line at $\frac{1}{\Phi_e} = 1$. Electrical Tortuosity Index (ETI) is considered a constant unique value for each electrical flow unit (EFU).

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ACS Omega 2023, 8, 19509−19522

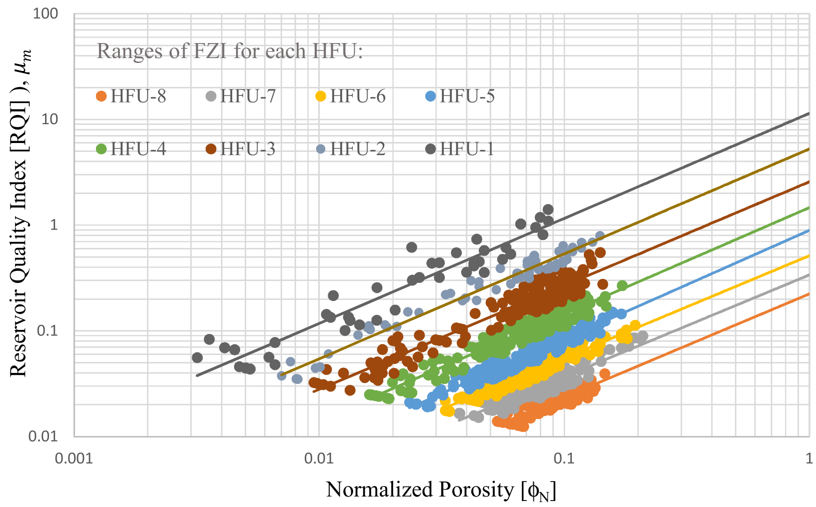

Figure 1. Reservoir Quality Index (RQI) versus normalized porosity (Φ_N) for all wells using core data by applying the Amaefule et al. technique.

3. RESULTS AND DISCUSSION

3.1. Model Verifications and Well-Log Data Analysis.

Accurate determination of rock parameters is considered very important for accurate reservoir characterization. Many techniques are used through the past years to describe reservoir rock and to split it into individual unique hydraulic flow units. The concept of hydraulic flow unit is most widely studied to characterize reservoir rock.

Table 2. Flow Zone Indicator Values Were Obtained at Various Hydraulic Flow Units (HFUs) Using the Amaefule et al. (1993) Technique

(HFU) Amaefule	empirical equation	coefficient of determination (R^2)	FZI
HFU-1	$RQI = 11.411[\Phi_N]^{0.99}$	0.9172	11.411
HFU-2	$RQI = 5.2539[\Phi_N]^{0.99}$	0.9685	5.2539
HFU-3	$RQI = 2.571[\Phi_N]^{0.98}$	0.8900	2.5710
HFU-4	$RQI = 1.4648[\Phi_N]^{1.01}$	0.9147	1.4648
HFU-5	$RQI = 0.8928[\Phi_N]^{1.03}$	0.9222	0.8928
HFU-6	$RQI = 0.5139[\Phi_N]^{0.97}$	0.9280	0.5139
HFU-7	$RQI = 0.3384[\Phi_N]^{0.96}$	0.8561	0.3384
HFU-8	$RQI = 0.2236[\Phi_N]^{0.98}$	0.7479	0.2236

Table 3. Summary of the Results Obtained by the Resistivity Zone Index Technique Introduced by Shahat et al

electrical flow units (EFUs)	empirical correlation between R_T and $[\Phi_N^2]$	correlation coefficient (R^2)	RZI
EFU-1	$R_t = 146{,}553[\Phi_N^2]^{0.9351}$	0.9606	146,553
EFU-2	$R_t = 54{,}386[\Phi_N^2]^{0.9699}$	0.9613	54,386
EFU-3	$R_t = 14{,}999[\Phi_N^2]^{0.9511}$	0.9282	14,999
EFU-4	$R_t = 6488.1[\Phi_N^2]^{0.9762}$	0.9355	6488.1
EFU-5	$R_t = 2470[\Phi_N^2]^{0.9574}$	0.8822	2470
EFU-6	$R_t = 1185.2[\Phi_N^2]^{0.9632}$	0.9033	1185.2
EFU-7	$R_t = 583.59\ [\Phi_N^2]^{0.9565}$	0.8958	583.59
EFU-8	$R_t = 213.97[\Phi_N^2]^{0.9011}$	0.773	213.97

In this paper, the concept of electrical flow unit (EFU) will be applied to characterize reservoir rock by using well-logging data obtained from 21 logged wells in oil fields. First, conventional reservoir characterization will be applied to reservoir rock such as the Flow Zone Indicator (FZI) technique introduced by Amaefule et al.[8] and the Resistivity

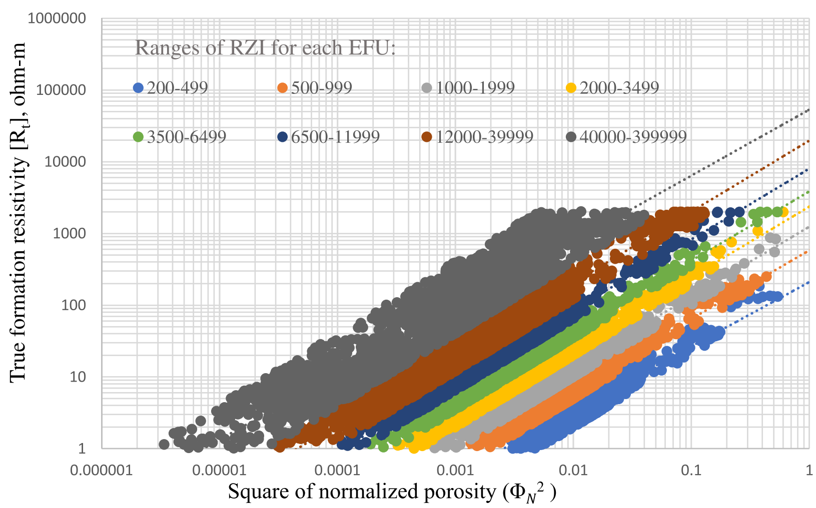

Figure 2. True formation resistivity (R_t) versus square of normalized porosity (Φ_N^2) for all wells using log data by applying the Shahat et al. technique.

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ACS Omega 2023, 8, 19509−19522

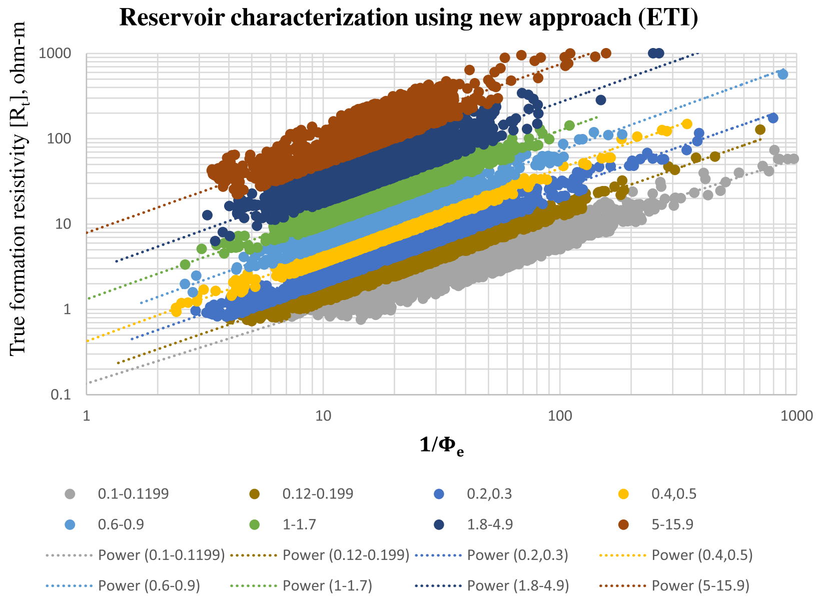

Figure 3. True formation resistivity (R_t) is plotted against the inverse of porosity ($1/\Phi$) for all wells using log data by applying the new approach (ETI).

Table 4. Summary of Results Obtained by the New Approach (ETI)

electrical flow units (EFUs)	equation	R^2	ETI = intercept with $\frac{1}{\Phi_e} = 1$
EFU-1	$R_t = 7.9054\left[\frac{1}{\Phi_e}\right]^{0.9874}$	0.7509	7.9054
EFU-2	$R_t = 2.7392\left[\frac{1}{\Phi_e}\right]^{0.9944}$	0.653	2.7392
EFU-3	$R_t = 1.3206\left[\frac{1}{\Phi_e}\right]^{0.988}$	0.8027	1.3206
EFU-4	$R_t = 0.6963\left[\frac{1}{\Phi_e}\right]^{1.0085}$	0.8328	0.6963
EFU-5	$R_t = 0.4235\left[\frac{1}{\Phi_e}\right]^{1.0129}$	0.9063	0.4235
EFU-6	$R_t = 0.2931\left[\frac{1}{\Phi_e}\right]^{0.9733}$	0.9205	0.2931
EFU-7	$R_t = 0.175\left[\frac{1}{\Phi_e}\right]^{0.9655}$	0.9569	0.175
EFU-8	$R_t = 0.1354\left[\frac{1}{\Phi_e}\right]^{0.877}$	0.9068	0.1354

Zone Index (RZI) technique introduced by Shahat et al.[10] Second, the introduced new technique of Electrical Tortuosity Index (ETI) will be applied to characterize the same reservoir rock by using only logging data. Furthermore, data will be analyzed and the relations between the different indicators are established.

The application of the new approach of Electrical Tortuosity Index (ETI) allows the division of reservoir rock into different rock types with distinct electrical flow units (EFUs), each one has a unique value of Electrical Tortuosity Index (ETI). Moreover, permeability and tortuosity can be estimated from the values of the Electrical Tortuosity Index (ETI) for each rock type.

3.1.1. Applying Conventional Reservoir Characterization Techniques. Conventional techniques are applied to be considered as a reference to evaluate our new technique for more accurate results to characterize reservoir rock, applying the very known reservoir characterization technique based on Flow Zone Indicator, FZI, from core data, which is established by Amaefule et al.[8] The concept of Flow Zone Indicator, FZI, is built on modifying the Kozeny−Carman equation to find a new equation that has a unique value "Flow Zone Indicator" (FZI) for each hydraulic flow unit, HFU. Reservoir Quality Index (RQI) is plotted versus the normalized porosity (Φ_N) on a log−log scale for 1135 core samples, which results in linear parallel lines with unity slopes as shown in Figure 1. Flow Zone Indicator (FZI) value is the intercept at the value of normalized porosity equal to 1 for each hydraulic flow unit, HFU. Table 2 summarizes the data obtained by applying reservoir characterization by the Amaefule technique. Results showed that reservoir rock contains eight unique different rock types (hydraulic flow unit, HFU), and each one has a distinct Flow Zone Indicator (FZI) value.

Another conventional reservoir characterization technique is applied, which depends on the Resistivity Zone Index (RZI) that was published by Shahat et al.[10] The RZI technique is based on modifying the Kozeny−Carman equation, taking into consideration data obtained from logging tools. The Resistivity Zone Index technique using eq 9 is applied to characterize reservoir rock by using log data, and true formation resistivity (R_t) versus square of normalized porosity (Φ_N^2) on a log−log scale is plotted, which yields eight different electrical flow units represented by eight parallel straight lines as shown in Figure 2. Each electrical flow unit has a unique value at the intercept ($\Phi_N^2 = 1$) called Resistivity Zone Index (RZI). The model is applied to log data obtained from 21 logged wells, and the results are summarized in Table 3.

Summarizing conventional techniques have been successfully applied on the described reservoir rock by using log data obtained from 21 logged wells and 1135 core samples to validate the new approach. The Amaefule technique was applied to characterize reservoir rock by using the 1135 core samples as shown in Figure 1. On the other hand, the Resistivity Zone Index (RZI) technique was applied to characterize reservoir rock by using the 21 logged wells as shown in Figure 2. Both techniques of reservoir character-

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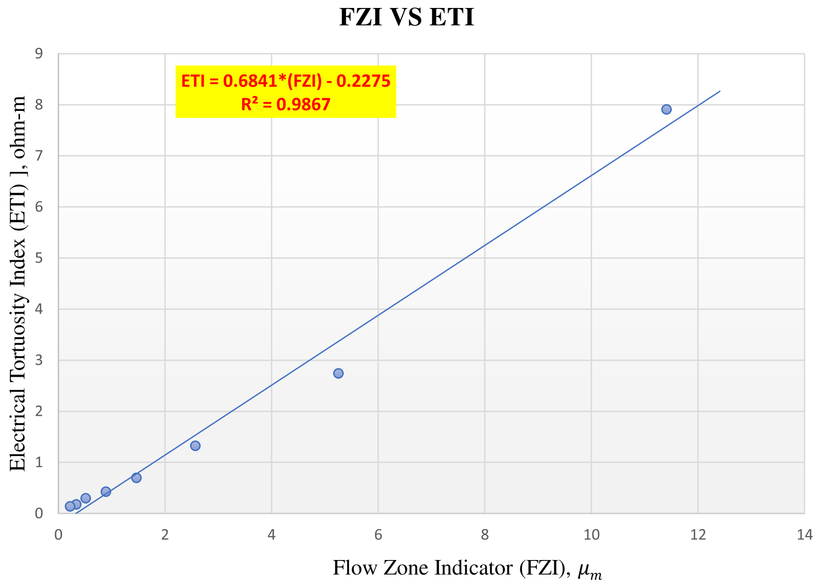

Figure 4. Flow Zone Indicator (FZI) by applying the Amaefule technique versus Electrical Tortuosity Index (ETI) by the new approach.

Table 5. Summary of Values Obtained by the Amaefule Technique and ETI Technique by the Current Study

hydraulic flow units	flow zone indicator (FZI) by Amaefule et al.	electrical tortuosity index (ETI) by the new technique
HFU-1	11.411	7.9054
HFU-2	5.2539	2.7392
HFU-3	2.571	1.3206
HFU-4	1.4648	0.6963
HFU-5	0.8928	0.4235
HFU-6	0.5139	0.2931
HFU-7	0.3384	0.175
HFU-8	0.2236	0.1354

Table 6. Relation between the RZI Technique by Shahat et al. and ETI in the Current Study

hydraulic flow units	resistivity zone index (RZI) by Shahat et al.	electrical tortuosity index (ETI) by current study
HFU-1	146,553	7.9054
HFU-2	54,386	2.7392
HFU-3	14,999	1.3206
HFU-4	6488.1	0.6963
HFU-5	2470	0.4235
HFU-6	1185.2	0.2931
HFU-7	583.59	0.175
HFU-8	213.97	0.1354

ization gave the same predicted number of rock type. Results of the Amaefule technique showed that reservoir rock contains eight unique different rock types (hydraulic flow unit, HFU), each one has a distinct Flow Zone Indicator (FZI) value as shown in Figure 1. Results of the RZI technique showed eight different electrical flow units represented by eight parallel straight lines as shown in Figure 2.

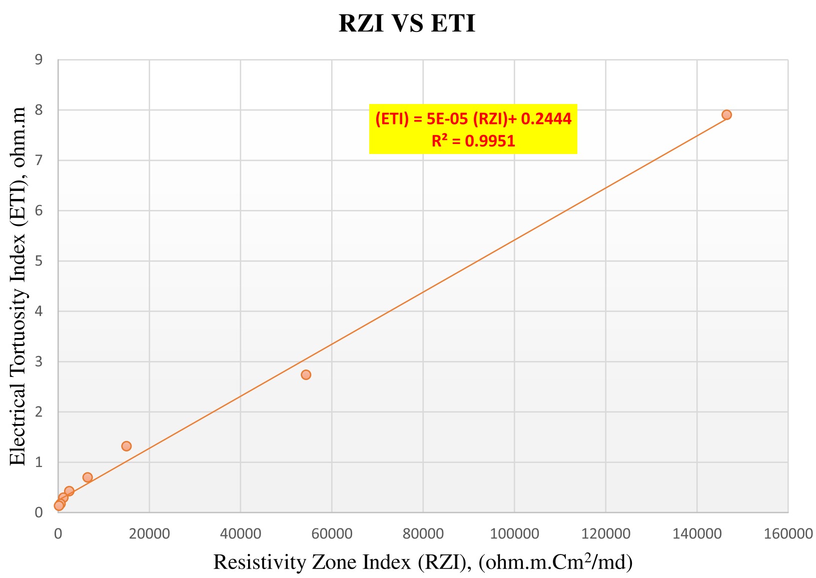

Figure 5. Resistivity Zone Index (RZI) by applying the Shahat et al. technique versus Electrical Tortuosity Index (ETI) by the new approach.

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Table 7. Relation between FZI by the Amaefule Technique and FZI by a New Approach Using Equation 21

hydraulic flow units	FZI_{core} by Amaefule technique from core	FZI_{logs} by current study from logs
HFU-1	11.411	11.8884
HFU-2	5.2539	4.3366
HFU-3	2.571	2.2629
HFU-4	1.4648	1.3503
HFU-5	0.8928	0.9516
HFU-6	0.5139	0.761
HFU-7	0.3384	0.5883
HFU-8	0.2236	0.5304

3.1.2. Applying the New Technique to Characterize Reservoir Rock from Well Logs. The new technique is based on modifying the Resistivity Zone Index (RZI) approach that is introduced by Shahat et al.[10] The final form of the newly released equation relates the true formation resistivity R_t with inverse porosity $(1/\Phi)$ as shown in eq 20. The new technique is validated by applying the new approach to log data obtained from 21 logged wells and by plotting true formation resistivity (R_t) on the y-axis versus the inverse of porosity $\left(\frac{1}{\Phi_e}\right)$ on the x-axis on the log–log scale as shown in Figure 3.

Results showed eight distinct electrical flow units (EFUs) described by eight parallel straight lines as shown in Figure 3. Each electrical flow unit (EFU) has a unique representative value at the intercept $\left(\frac{1}{\Phi_e} = 1\right)$ called Electrical Tortuosity Index (ETI). Based on the new approach, Electrical Tortuosity Index (ETI) can be defined as ($\mathrm{ETI} = I_r \times R_w \times \tau$). Table 4 summarizes the results obtained by applying the new technique showing Electrical Tortuosity Index (ETI) values.

Comparing the number of electrical flow units (EFUs) obtained by the new technique with results obtained from conventional reservoir characterization methods showed a great match with the same number of rock types for each technique. This represents the accuracy of the new technique to characterize reservoir rock by using the Electrical Tortuosity Index approach from well-logging data.

3.1.3. Relations between the New Technique and the Conventional Reservoir Characterization Techniques. The Electrical Tortuosity Index (ETI) technique was validated by comparing it with the conventional reservoir characterization techniques. First, the results of Flow Zone Indicator (FZI) (obtained from core data analysis) on the x-axis versus the results of Electrical Tortuosity Index (ETI) (obtained by the new technique from logging data) on the y-axis are plotted as shown in Figure 4. The relation between Flow Zone Indicator (FZI) and Electrical Tortuosity Index (ETI) showed a great linear correlation with a coefficient of determination R^2 = 0.9867. Table 5 summarizes the whole values of the Flow Zone Indicator (FZI) obtained by applying the Amaefule technique and values of the Electrical Tortuosity Index (ETI) obtained by using eq 20 introduced in this study.

Second, the relation between Resistivity Zone Index (RZI) and Electrical Tortuosity Index (ETI) is established by plotting the results of the Resistivity Zone Index (RZI) (obtained from log data analysis) on the x-axis versus results obtained by the new technique (from logging data) on the y-axis as shown in Figure 5. The relation between Resistivity Zone Index (RZI) and Electrical Tortuosity Index (ETI) showed an excellent linear correlation with a high coefficient of determination R^2 = 0.9951. Table 6 summarizes the whole values of the Resistivity Zone Index (RZI) obtained by applying the technique introduced by Shahat et al. and the values of the Electrical Tortuosity Index (ETI) obtained by using the new approach. The relation between the introduced new technique and the used conventional techniques is very good with high values of coefficient of determination. Therefore, we can depend on the new technique to characterize reservoir rock from only well-logging data instead of core analysis to save time and money.

3.2. Applying the New Technique for Flow Zone Indicator Estimation. Researchers proposed many studies to

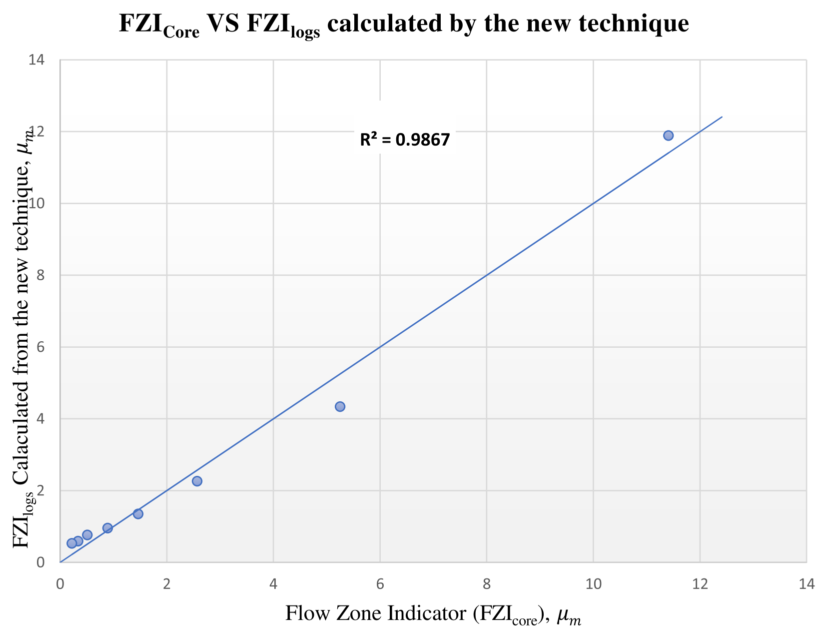

Figure 6. Relation between Flow Zone Indicator (FZI) by applying the Amaefule technique versus Flow Zone Indicator (FZI) by using Electrical Tortuosity Index (ETI) obtained by the new technique.

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Table 8. Summary of Results for Average Permeability Obtained from the Amaefule Technique and That Calculated by Equation 22 by Using ETI

hydraulic flow units	FZI Amaefule core	Φ_{avg}	calculated K_{avg} from core by FZI	ETI new tech. logs	Φ_{avg}	calculated K_{avg} from log by ETI
HFU-1	11.411	0.0292	3.4946	7.9054	0.0292	3.79326
HFU-2	5.2539	0.0551	5.2494	2.7392	0.0551	3.57649
HFU-3	2.571	0.0653	2.1411	1.3206	0.0653	1.65881
HFU-4	1.4648	0.0674	0.7685	0.6963	0.0674	0.65321
HFU-5	0.8928	0.0684	0.2982	0.4235	0.0684	0.33881
HFU-6	0.5139	0.0686	0.0997	0.2931	0.0686	0.21870
HFU-7	0.3384	0.0756	0.0587	0.175	0.0756	0.17748
HFU-8	0.2236	0.0827	0.0341	0.1354	0.0827	0.19207

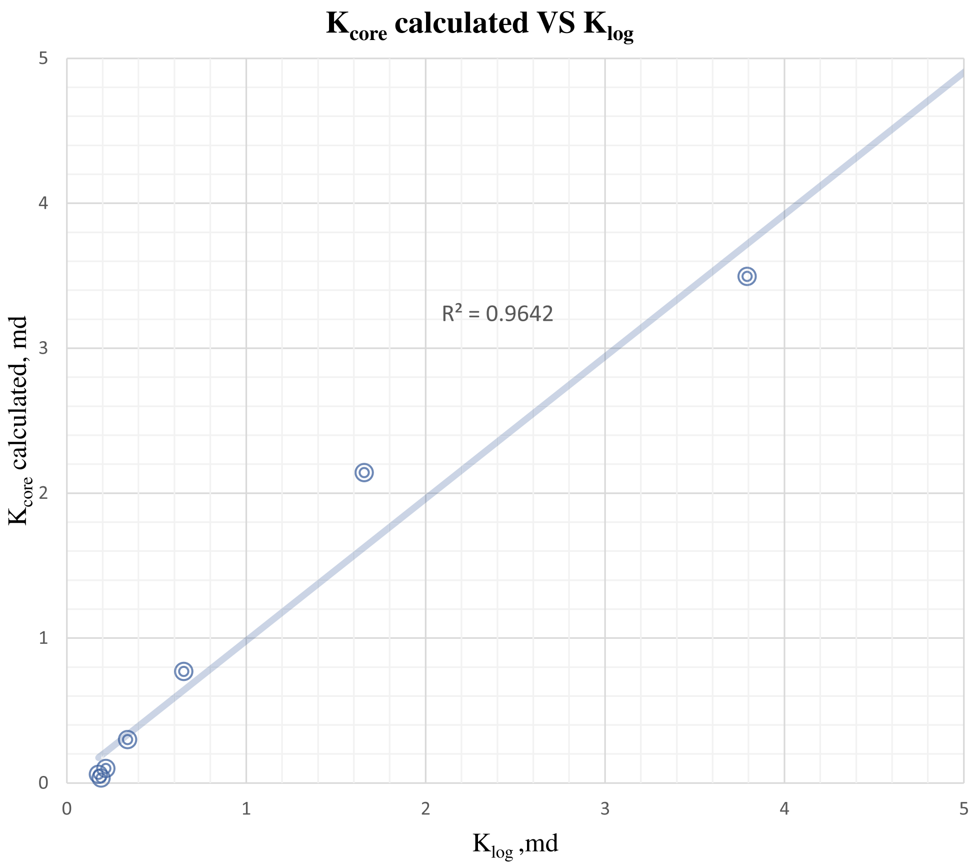

Figure 7. Relation between permeability (K) calculated by using the Amaefule equation eq 4 versus permeability (K) obtained by using eq 22.

Table 9. Core and Log Data Were Taken from Attia et al. for the Validation of the New Technique

	core data		log data		
core no.	Φ_{core}	τ_{core}	R_t	I_r	Φ_{log}
21	0.207	3.84	17.2	9.25	0.19
23	0.191	4.35	15.08	6.61	0.18
24	0.192	4.26	28.16	12.6	0.176
30	0.186	3.78	15.3	7.58	0.173
31	0.187	4.71	20.1	7.99	0.173
32	0.181	4.04	12.2	5.47	0.17
33	0.182	3.82	17.5	8.33	0.17
34	0.192	4.48	18.23	7.82	0.176

Table 10. Result Summary of Tortuosity Calculations by Using the New Technique ETI on Berea Sandstone

	new technique			Attia et al.	
sample	$1/\Phi_{log}$	ETI	τ_{log}	τ_{core}	error %
21	5.26	3.27	3.534	3.84	8
23	5.55	2.71	4.104	4.35	5.7
24	5.68	4.95	3.9072	4.26	8.3
30	5.78	2.66	3.5119	3.78	7.1
31	5.78	3.48	4.3596	4.71	7.4
32	5.88	2.07	3.791	4.04	6.2
33	5.88	2.97	3.57	3.82	6.5
34	5.68	3.21	4.1008	4.48	8.5

enhance reservoir characterization based on using the concept of hydraulic flow unit (HFU) by using porosity, permeability, and Flow Zone Indicator (FZI) of reservoir rock. Therefore, in this paper, a new correlation (eq 21) is introduced by using the new technique to estimate the values of Flow Zone Indicator from logging data (FZI_{logs}) depending on the correlation obtained from FZI versus ETI as shown in Figure 4

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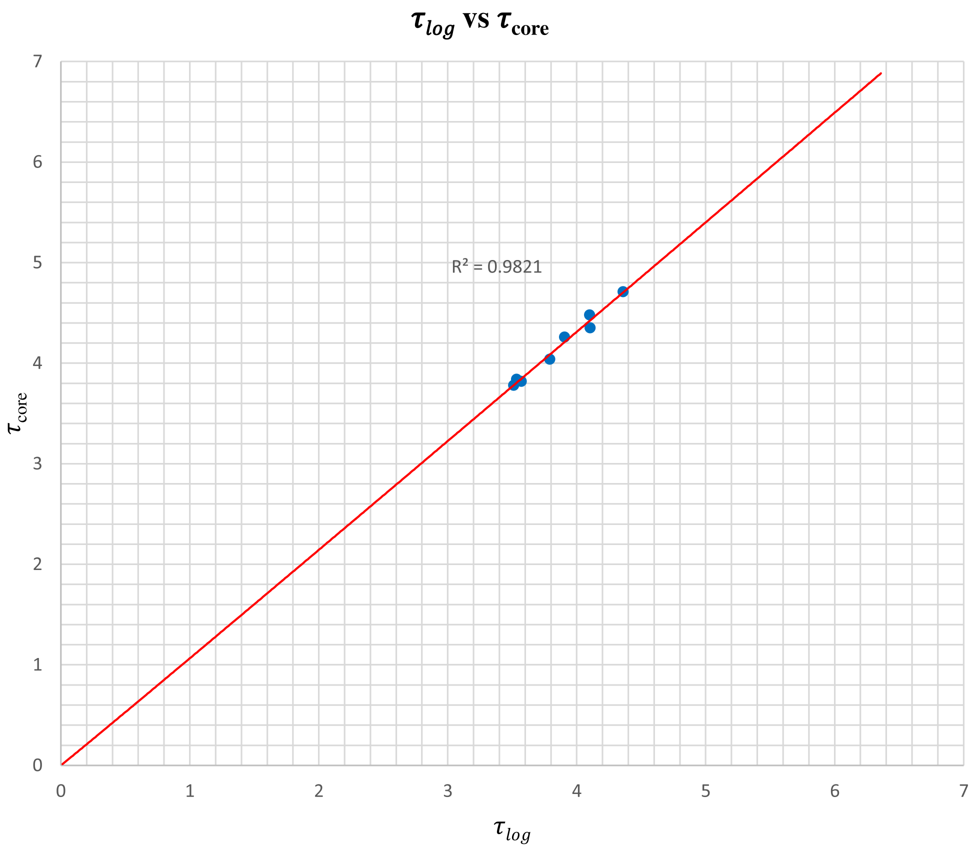

Figure 8. Relation between the values of tortuosity taken from core analysis τ_{core} versus tortuosity obtained by the new technique τ_{log}.

Table 11. Summary of Obtained Values of $S_{wir\text{-}core}$ and $S_{wi\text{-}logs}$ for Each Electrical Flow Unit (EFU)

FHU	core		logs		
	FZI_{core}	$S_{wir\text{-}core}$	ETI	FZI_{logs}	$S_{wir\text{-}logs}$
EFU-1	11.411	0.12042673	7.9054	11.8884	0.119
EFU-2	5.2539	0.146524695	2.7392	4.3366	0.158
EFU-3	2.571	0.209257269	1.3206	2.2629	0.227
EFU-4	1.4648	0.308034713	0.6963	1.3503	0.326
EFU-5	0.8928	0.439251856	0.4235	0.9516	0.420
EFU-6	0.5139	0.613816001	0.2931	0.761	0.488
EFU-7	0.3384	0.736971291	0.175	0.5883	0.570
EFU-8	0.2236	0.833070246	0.1354	0.5304	0.603

$$FZI_{logs} = \frac{(ETI + 0.2275)}{0.6841} \quad (21)$$

By using eq 21, we can calculate the values of the Flow Zone Indicator estimated from well logs (FZI_{logs}) by the new technique. Table 7 summarizes the values of the Flow Zone Indicator estimated from core analysis by the Amaefule technique and values of the Flow Zone Indicator estimated from well logs FZI_{logs} obtained by applying the current study. On the log–log plot, Flow Zone Indicator estimated from well logs FZI_{logs} is plotted on the y-axis, and Flow Zone Indicator (FZI) estimated from the core analysis is plotted on the x-axis as shown in Figure 6. The relation between FZI and FZI_{logs} showed an excellent match with a high coefficient of determination R^2 = 0.9867.

3.3. Applying the New Technique for Permeability Estimation. The accuracy and efficiency of reservoir rock characterization vary by many reservoir rock parameters but are mostly affected by reservoir rock permeability. As a sequence, a lot of researchers studied how to estimate reservoir rock permeability for enhancing reservoir characterization. In this paper, a new correlation eq 22 is introduced to estimate reservoir rock permeability from well-logging data. By substituting with eq 21 in eq 4, the developed new equation can be used to calculate permeability by using the value of the Electrical Tortuosity Index (ETI)

$$K = 2166.7(ETI + 0.2275)^2\left(\frac{\Phi^3}{(1 - \Phi)^2}\right) \quad (22)$$

Table 8 summarizes permeability results calculated by the Amaefule technique using eq 4 from core data and that calculated by eq 22 using the new technique (ETI) from log data. The permeability values obtained by the new technique (ETI) are validated by comparing them with permeability data obtained by applying the Amaefule technique. Figure 7 shows a cross plot of K_{core} values calculated from cores using the Amaefule technique and K_{log} values calculated from logs using the new approach (ETI), which shows a good match with a high coefficient of determination R^2 = 0.9642. Results showed that the proposed new technique by Electrical Tortuosity Index (ETI) can be applied to estimate reservoir rock permeability from only well-log data, which reflects enhancement of reservoir characterization.

3.4. Applying the New Technique to Calculate the Tortuosity Factor. In the Archie formula, the tortuosity factor is a very important parameter in reservoir characterization; it is defined as "the ratio of actual traveled length L_a to the system straight length L". Therefore, researchers released many studies for estimating tortuosity factor to enhance

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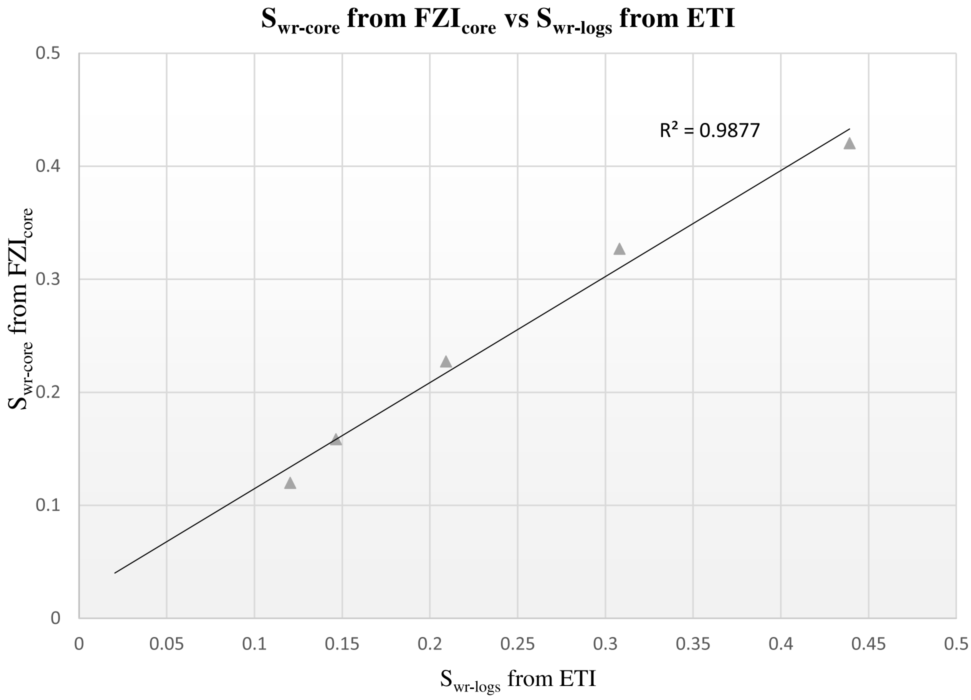

Figure 9. Relation between the values of $S_{wr-core}$ calculated from core data versus $S_{wr-logs}$ calculated by using logging data by applying the new technique.

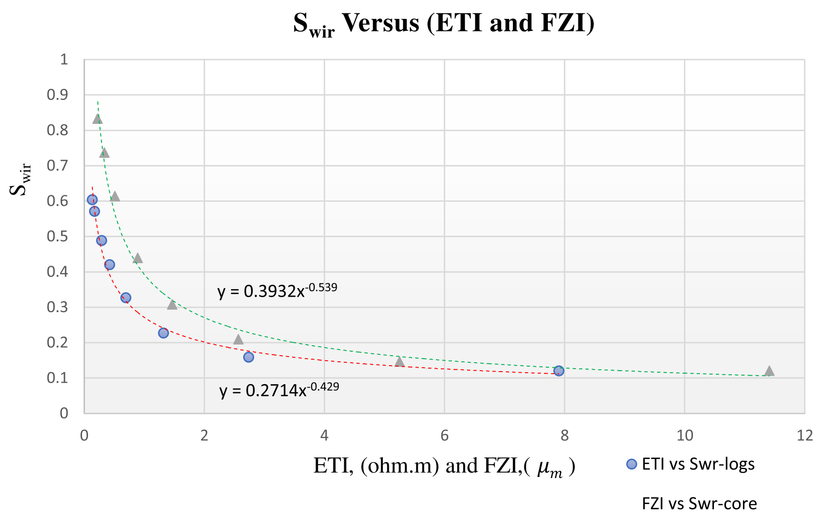

Figure 10. Relation between the values of $S_{wr-core}$ calculated from core data versus FZI_{core} calculated by using the Amaefule technique, and the relation between values of S_{wr-log} calculated from log data versus ETI calculated by applying the new technique.

reservoir characterization. In this paper, a new correlation is introduced to estimate the tortuosity factor from only well-logging data by using Electrical Tortuosity Index (ETI). The generalized form of the new equation can be obtained by rearranging eq 20 to give the following form

$$\tau = \frac{\text{ETI}}{R_w \times I_r} \tag{23}$$

where $I_r = R_t/R_O$ is the resistivity index and R_w is the formation water resistivity.

The newly proposed technique was validated using eight data sets of core and log data obtained from Attia et al.[49] as shown in Table 9. The Electrical Tortuosity Index (ETI) approach is applied to calculate Tortuosity (τ) by using eq 23 for Berea Sandstone. Then, the results of the new technique are compared with data obtained from core analysis for Berea Sandstone as demonstrated in Table 10. Data of tortuosity factor calculated by the new technique from logging data (τ_{log}) is plotted on the x-axis versus tortuosity factor from core calculations (τ_{actual}) as shown in Figure 8. The relation between τ_{log} and τ_{actual} that is drawn in Figure 8 shows an excellent match with a very high coefficient of determination, which approaches 0.98.

The new technique showed high accuracy in estimating the values of the tortuosity factor for more than one type of reservoir rock. Therefore, Electrical Tortuosity Index (ETI) values are validated to be used for determining reservoir rock properties and detecting how many rock types we have.

3.5. Applying the New Technique to Calculate Irreducible Water Saturation.

The estimation of initial

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hydrocarbon reserves is critical during field development planning. Accurately determining irreducible water saturation (S_{wir}) is one of the requirements. Irreducible water saturation plays an important role in reservoir evaluation and productivity prediction and also has a significant effect on residual oil saturation (S_{or}) after the displacement process, which is the goal of enhanced oil recovery. Moreover, determining irreducible water saturation is necessary in order to obtain the correct value of the maximum effective permeability to oil, which is commonly used as a reference value when building representative relative permeability relationships.[50] A new equation is introduced to calculate irreducible water saturation from well logs ($S_{wir\text{-}logs}$) by substituting with eq 21 in eq 5, and the obtained relationship will be as follows

$$S_{wir-logs} = 1 - \left[a + b \times \left(\frac{\text{ETI} + 0.2275}{0.6841} \right)^{-C} \right]^{-1} \quad (24)$$

where a = 1.12, b = 0.5634, and c = 1.44.

Table 11 summarizes $S_{wir\text{-}logs}$ results calculated by Electrical Tortuosity Index (ETI) by the new technique using eq 24 from log data and $S_{wir\text{-}core}$ calculated by using Flow Zone Indicator (FZI) values obtained from the Amaefule technique using eq 5 from core data.

The $S_{wir\text{-}logs}$ values obtained by the new technique (ETI) are validated by comparing them with $S_{wir\text{-}core}$ values obtained by applying the Amaefule technique. $S_{wir\text{-}core}$ on the y-axis versus $S_{wir\text{-}logs}$ on the x-axis is plotted, as shown in Figure 9, which shows an excellent match with a high coefficient of determination R^2 = 0.99. Results showed that the proposed new technique by Electrical Tortuosity Index (ETI) can be applied to estimate the irreducible water saturation S_{wir} from only well-log data.

The relation between $S_{wir\text{-}core}$ and FZI_{core} is achieved by plotting $S_{wir\text{-}core}$ on the y-axis versus FZI_{core} on the x-axis. Also, the relation between $S_{wir\text{-}logs}$ and ETI is achieved by plotting $S_{wir\text{-}logs}$ on the y-axis versus ETI on the x-axis, as shown in Figure 10.

4. CONCLUSIONS

- Reservoir characterization has led to successful field development plans to minimize inaccurate petrophysical data and uncertainty, which leads to saving time and money. In this research, a new technique is introduced to characterize reservoir rock based on data gathered from logging tools only for characterizing the uncored wells.
- The new technique was achieved by modifying the Resistivity Zone Index (RZI) equation that was presented by Shahat et al. by taking into consideration the tortuosity factor parameter. The new technique was applied by plotting true formation resistivity (R_t) versus the inverse of porosity ($1/\Phi$) on the log–log scale, which yielded unit slope parallel straight lines (each represents a distinct electrical flow unit (EFU). The intercept of each line with a y-axis at $1/\Phi = 1$ gave a unique parameter specified as the "Electrical Tortuosity Index" (ETI) for each electrical flow unit (EFU).
- Validation of the proposed technique was tested on log data obtained from 21 logged wells and 1135 core samples. Results showed that the number of distinct electrical flow units determined by the new technique from well logs agreed with the conventional reservoir characterization techniques.
- Moreover, by using the new technique, tortuosity factor τ, permeability K, and S_{wr} were estimated from only well-log data and then compared with the results measured from core analysis, which showed a great match with the average correlation coefficients of about 0.98. Then, empirical correlations were developed to calculate tortuosity, permeability, and S_{wr} from log data and can be applied to uncored wells.
- We concluded that the newly introduced approach showed great results in characterizing reservoir rock from data obtained from logging tools for cored and uncored wells.

ASSOCIATED CONTENT

Supporting Information

The Supporting Information is available free of charge at https://pubs.acs.org/doi/10.1021/acsomega.3c00904.

Plots of depth logs versus variables used in this study, such as porosity and true formation resistivity for some of the wells (PDF)

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Notes

The authors declare no competing financial interest.

ACKNOWLEDGMENTS

The authors thank the British University in Egypt for supporting them with software and open access to the electronic library.

NOMENCLATURE

Symbols and Abbreviations

EFU electrical flow unit
HFU hydraulic flow unit
ETI electrical tortuosity index, Ω·m
F_r formation resistivity factor, dimensionless

F_s shape factor (= 2 for a circular tube), dimensionless
I_r R_t/R_o, dimensionless
k permeability, md
RQI reservoir quality index, μm
FZI flow zone index, μm
R_o formation resistivity at 100% water saturation (aquifer), Ω·m
RZI resistivity zone index, Ω·m.cm^2/md
R_w formation water resistivity, Ω·m
r pore throat radius (μm)
r_{mh} mean hydraulic unit radius, μm
R_t true formation resistivity, Ω·m
R_{35} effective pore throat radius at 35%, microns
S_{wir} irreducible water saturation, fractional pore volume
S_{gv} specific surface area per unit grain volume, μm^{-1}
S_w water saturation, fractional pore volume
Φ_N normalized porosity, pore-volume-to-grain-volume ratio
Φ_e effective porosity, fraction
τ hydraulic tortuosity, dimensionless

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https://doi.org/10.1021/acsomega.3c00904
ACS Omega 2023, 8, 19509−19522