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Archie's Parameters of a Libyan Carbonate reservoirs: Effect of Porosity Type: Case study.

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ABSTRACT

The water saturation determinations from resistivity logs are based on the famous Archie's equations; $S_w = (\phi^{-m} R_w/R_t)^{1/n}$. The cementation factor, *m* and saturation exponent n, play an important role in S_w calculation. In carbonate formations, generally, *m*=*n*=2 is usually used. However, *m* values between 1.88 and 2.5 have been measured, and also *n* was found to be between 2.11 and 2.78 for a Libyan carbonate reservoir. Inaccurate m and n values would lead to large inaccuracies in the calculated hydrocarbon/water saturations. An experimental study was carried out to measure *m* and *n* for carbonate samples with a wide range of porosity and permeability. Ten samples were collected from a formation having vuggy and interparticle porosity types. The resistivity measurements were performed using the porous plate method with four-electrodes system. Reservoir fluids are simulated using a brine and oil from the formation of interests. As a result of this study, it has been found that the Archie's parameters are functions of pore structures. Samples mainly interparticle or intercrystalline porosity, shows *m* value to be less than or equal 2, while vuggy samples generate higher values of m. The resistivity/saturation correlation is well fitted by the Archie's law except for vuggy samples, where *n* was found to be as high as 2.78. As a sequence, it is recommended that in order to evaluate cementation factor and saturation exponent for carbonates, representative number of samples from each zone or interval porosity type should be used rather than an average of *m* and *n* of the whole formation.

Keywords; Cementation, Saturation, Carbonate, Porosity, Resistivity.

1. INTRODUCTION

Carbonate formations may have several types of porosity which includes interparticle, vuggy, moldic and fracture porosity as classified by Choquette and Pray [1] and discussed by Rieke et al [2]. Many investigators studied the Archie's parameters of carbonate formation with focus on the influence of porosity type (Focke and Munn [3], Nurmi [4], Aguilera [5]). However, as a result of these studies many other approaches were derived such as the empirical approach; Shell formula [6] and Borai correlations [7]. Although these approaches were successful in many cases but do not take into account the fact that the Archie's parameters may vary in the same way as porosity and lithology [8]. The main reason for the challenges in these types of rocks is due to the fact that they originate due to complex biological and chemical processes which contributes to the heterogeneity [9], hence giving rise to intricate reservoir description [10]. The applicability of the Archie equation is limited to strongly water-wet and clean rocks, which is not observed in most carbonate formations [11, 12].

Moreover, the applicability of Archie's equation and therefore, the calculation of *m* and *n* is affected by the pore system that controls electrical resistance through fluid distribution in the pore spaces [13, 14]. A case study in presented in this article to contribute somehow to the carbonate formation evaluation.

2. ARCHIE'S EQUATION

Laboratory core analysis and well logging are the two basic methods used to determine petrophysical properties and a key for calculation of hydrocarbons and therefore for reservoir evaluation. The quantitative interpretation of electrical logs measurements is based on the fact that the formation water conducts electrical current and hydrocarbons do not. The variation of electrical resistivity with depth was first used by the Schlumberger brothers in 1927. Archie [15] observed that the resistivity, R_o of brine-saturated rock samples increased linearly with the brine resistivity, R_w. Archie's first equation is,

$$F = R_o/R_w = 1/\phi^m \qquad (1)$$

Where ϕ is the porosity, F is the formation resistivity factor, and *m* is the cementation exponent (representing the negative slop of F versus ϕ double logarithmic plot). For partially saturated rock samples, Archie introduced a second equation,

$$RI = R_t/R_o \qquad (2)$$

Where RI is the resistivity index and R_t is the resistivity of a rock sample partially saturated with brine. Archie's performed experiments on clean sands and proposed the second equation,

$$IR = 1/S_w^n \qquad (3)$$

Where S_w is the water saturated and *n* is the saturation exponent which is commonly determined by injecting a fluid (gas/oil) into a cleaned, water-saturated rock sample. The sample resistivity R_t is measured at pre-defined steps with decreasing water saturations S_W. A log–log plot of RI versus S_W typically results a straight line with the slope of *n*.

The Archie equation, in fact, is a combination of resistivity index, RI and formation resistivity factor F, which are defined early, and one general Archie's equations can be expressed as follows.

$$S_w = (\phi^{-m} R_w/R_t)^{1/n} \qquad (4)$$

Underlying Archie's equation is the key assumption that resistivity R_t depends only on the porosity, ϕ of a given rock, the water saturation S_w and water resistivity R_w. In order to examine the validity of this assumption, it is essential to investigate the effects of pore structure, fluid mechanism, fluid characteristics, wettability, pressure, temperature, etc. In this study, an intention is paid to the porosity type of carbonates and its effect on Archie's parameters.

3. EXPERIMENTAL WORK

The formation resistivity factor, F, and resistivity Index, RI were measured in the laboratory at ambient conditions for 11/2" diameter for ten carbonate samples. Their physical properties are shown in Table 1.

Table 1. Core samples properties.

Sample no.	ϕ, %	K, mD	G.D. gm/cc
1	20.34	2,37	2.84
2	12.43	3.3	2.84
3	16.2	31	2.86
4	27.92	158	2.86
5	10.84	0.25	2.84
6	37.36	145	2.85
7	11.12	1.46	2.84
8	26.33	3.58	2.84
9	31.21	6.94	2.85
10	13.25	10.3	2.84

These core samples have been collected from a Libya reservoir that located in the Sirte Basin. The samples were cleaned in hot solvents, dried and then mounted in the core holder. All samples were saturated with brine (80,000 ppm). The resistivity measurements were performed using the four-wire method which has the advantage of eliminating end effects. The resistivity for the saturated samples, R_o and brine resistivity, R_w were measured on consecutive days until the results were stabilized. The resistivity index, RI measurements were carried out using the porous plate method, n order to compare it with the continues injection techniques. In this method, the resistivity measurement and desaturation process took place separately. The sample were desaturated simultaneously by placing them on a porous plate in a pressure cell, and gas pressure was applied. The gas (Nitogen) enters the samples from all directions except from the end face. The gas pressure was maintained until no more brine was produced. After capillary equilibrium was reached the gas was then released and the samples removed from the pressure cell and weight measurements were taken as well as resistivity readings. The procedure was repeated for several pressures in the range of 0.5 psi to 180 psi. The desaturated process for each sample typically took 4-5 days to complete. Finally, *m* and n were calculated using the following equations;

$$m = -\log (R_o/R_w) / \log \phi \qquad (5)$$

$$n = -\log (R_t/R_o) / \log S_w \qquad (6)$$

Where, ϕ is the porosity of rock sample (%), R_o is the resistivity of rock fully saturated with brine (Ohm-m), R_t is the resistivity of rock partially saturated with brine (Ohm-m) and R_w is the resistivity of brine (Ohm-m).

4. RESULTS AND DISCUSSIONS

Since early 1940's, many experimental and theoretical investigations have been carried out and a lot of efforts were made to measure and study the effect of various parameters on the saturation and cementation exponent. These parameters that have been investigated includes the wettability type, pore structure complexity, experimental conditions, pressure and temperature effects and have been investigated to study the impact on the Archie cementation and saturation exponents [16-23].

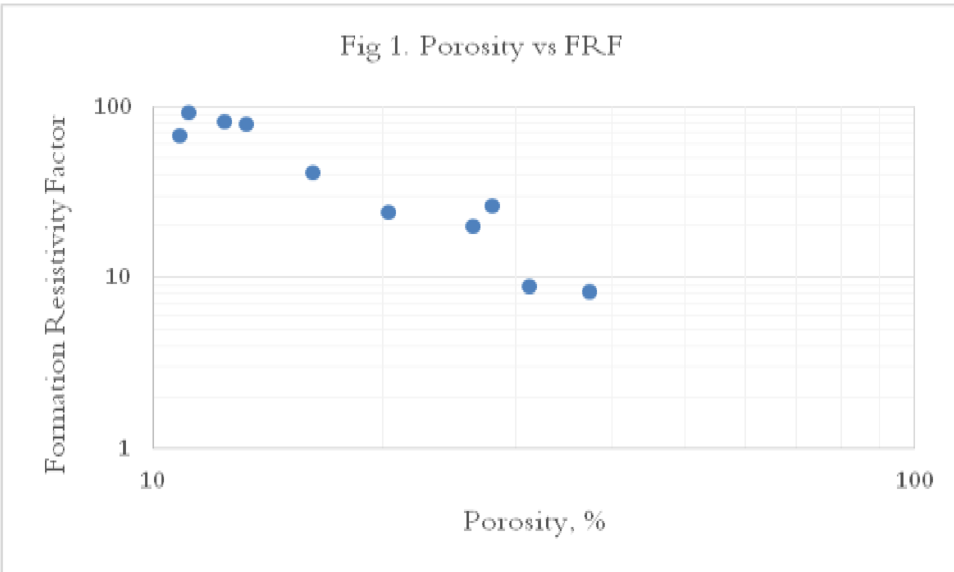

Fig 1. Shows the relation of log F versus log ϕ for all samples.

Table 2. m and n values for all samples

Sample no.	*m* value	*n* value
1	2.01	2.31
2	2.11	2.46
3	2.05	2.11
4	2.5	2.78
5	1.86	2.14
6	2.14	2.48
7	2.06	2.26
8	2.23	2.34
9	1.88	2.51
10	2.17	2.46

Archie's equation obtained for this reservoir by averaging *m* and *n* values was $S_w = (\phi^{-2.1} R_w/R_t)^{1/2.39}$. This cementation factor values were close to each other and ranged from 1.88 to 2.5. However, higher *m* values were found in vuggy samples such as sample 4 and 9 and *m* values were found around 2 for interparticle type porosity (sample 1, 3 and 7). The saturation exponent values were between 2.11 and 2.78. It is observed that high n values were associated with vuggy samples (sample 4, 9 and 10).

Lower *n* values were generated for interparticle porosity type samples (3 and 5). These findings suggest that the assumption of *m*=*n*=2 for carbonates is inaccurate because *m* and *n* depend on a type of porosity which exists in a zone or formation. This assumption would result in a poor reservoir evaluation due to the fact that carbonates are more perplex with regards to pore size distribution, pore geometry and structures, compared to other siliciclastic rocks [24-28].

This assumption is valid for a reservoir with only interparticle or intercrystalline type. The error in water saturation determination could even reach 20% and a decision to consider a zone or formation is dry or productive would be at great risk. Other researchers have developed porosity models to represent the complex nature of carbonate formations but there will always a limitation of these models. According to the triple-porosity model developed in the work a relationship between the total porosity and cementation exponent *m* of the triple-porosity medium composite system with different combinations of fractures and nonconnected vuggy porosity has been developed and obtained [29]. The *m* value of the triple-porosity medium composite system (such as carbonate reservoir varied from 1 to 3.6 [29].

The chemical and biological actions of carbonate rocks cause an irregular salinity distribution of formation water, the tortuous and segmented/partitioned conductive paths, and the apparent nonlinear characteristics [30].

Table 3 shows S_w values calculated and error in it; when *m* and *n* assumed to be constant and they are variable.

Table 3. Sw calculations at different m and n values

Sample no.	*m*=*n*=2	*m*, *n* variable	ΔS_w%
1	24.58	29.9	5
2	51.36	63.86	12.5
3	30.86	34.26	3.4
4	22.86	43.51	20.65
5	58.9	52.72	6.18
6	13.38	20.88	7.5
7	57.41	64.87	7.46
8	24.24	33.96	9.72
9	20.45	19.07	1.4
10	37.74	52	14

The determination of Archie parameters presents a continuous challenge in carbonate reservoir characterisation and formation evaluation due to its inherent complexity in terms of pore structure and pore lithology. In this study and as confirmed by other investigations, an even a small deviation in the two exponents of real reservoirs from their default values will lead to significant errors in the estimated reserves [31]. It has been shown in this study and other investigations that Archie’s parameters must be determined for each reservoir, depending on the rock heterogeneity and other factors such as rock wettability. A careful consideration should be taken in a carbonate reservoir, where the determination of Archie’s parameters is greatly affected by electrical heterogeneity in carbonate rocks. This electrical heterogeneity can be attributed to the complicated grain pattern distribution [32].

5. CONCLUSION

In carbonate reservoir evaluation, the Archie's parameters have a wide variation depending on the pore structure (porosity type). It is concluded that the vuggy samples generate higher *m* and *n* values than the interparticle porosity type samples. it is recommended that in order to evaluate cementation factor and saturation exponent for carbonates, representative number of samples from each zone or interval porosity type should be used rather than an average of *m* and *n* of the whole formation.

Nomenclature

ϕ = the porosity, fraction.
F = the formation resistivity factor.
m = the cementation exponent.
R_o = resistivity of rock 100% saturated with brine, ohm-meter.
RI = the resistivity index.
R_t = the resistivity of a rock sample partially saturated with brine, ohm-meter.
S_w = the water saturation, fraction.
n = the saturation exponent.

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