The Impact Of The Values of Cementation Factor and Saturation Exponent In The Calculation Of Water Saturation For Macaé Formation, Campos Basin.

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ABSTRACT

The calculations of water saturation from resistivity logs requires the determination of the cementation factor - m - and saturation exponent - n - used in the Archie's equation.

Researches have shown that the values of the m and n exponents are largely affected by reservoir pressure and temperature conditions, mineralogy, pore throat size distribution, pore geometry, and the wettability condition of the reservoir rock, among other relevant factors. This fact reveals the need to carry out laboratory resistivity measurements in order to obtain representative values of such parameters for a particular reservoir system.

This paper presents the values of m and n exponents measured for the Macaé Formation of the Bonito Field, Campos Basin, Brazil. Formation factors were measured on 50 core samples taken from the main producing zones, under reservoir temperature condition. The calculated values of m exponent ranged from 2.02 to 2.25 depending on the zone. Saturation exponent values were determined on 6 samples, by the centrifuge desaturation method using synthetic formation brine and crude oil. The values of n exponent ranged from 2.40 to 4.24. The high values of the saturation exponents can be related to the oil-wet characteristic of the rock, as revealed by the wettability tests.

A sensitivity analysis was performed in order to investigate the influence of the variation on m and n values in the calculation of the water saturation. The values of m and n exponents measured in this study resulted in a maximum reduction of 12% in the values of ($H.\phi_e.So$), when compared with the previous values calculated considering m=2.0 and n=2.0

INTRODUCTION

The Bonito field is located in the southern region of the Campus Basin, Brazil at water depths between 176 m and 276 m (figure 1). The oil production has been established from the Eocene sandstone of the Carapebus Formation, and from the Albian limestone of the Macaé Formation, while gas production has been established from the Oligocenic sandstone, as shown in figure 2. The reservoir of the Macaé Formation is now in advanced stage of primary exploitation, presenting several depleted production zones.

The carbonate reservoirs of the Macaé Formation are formed mostly by fine-grained limestones deposited in a low-energy environment. This gives a low permeability characteristic to the rock.

The reservoir was divided in two lithofacies. The lithofacies 1 is characterized by the presence of macroporosity and higher permeability values. The capillary pressure characteristic of this lithofacie displays a bi-modal pore-throat size distribution. The average permeability and porosity values are 25.10 mD and 26.20%, respectively.

The lithofacies 2, on the other hand, is characterized by low permeability values with an uniform pore size distribution. It also presented a good correlation between the permeability and porosity values in a log-linear plot. The rock has an average permeability value of 1.5 mD and an average porosity value of 26.70%.

The lithofacies were identified using a discriminant analysis based on the data obtained from logs such as the gamma ray, the sonic, and the resistivity log. The models showed good fitness with a total error of 13.0% for lithofacies 1 and 9.0% for lithofacies 2(1).

Detailed geological characterization studies of this reservoir were conducted in order to define flow unit types, parameters for calculation of water saturation, cutoff of saturation and porosity for calculation of the total meters of oil from porosity and saturation ($H.\phi_e.So$).

Previous calculations lead to water saturation values lower than expected, up to 5 %, in rocks with significant volume of microporosity. This fact brought into the need to investigate the cementation and saturation exponent used in the Archie´s saturation equation in order to obtain more realistic values of the fluids saturations in the Macaé formation.

The main purpose of this paper is to report the values of the cementation (m) and saturation (n) exponents determined for the carbonate reservoir of the Bonito field and discuss the effect of these parameters on the values of the water saturation, calculated using the Archie's equation.

EXPERIMENTAL PROCEDURE

FORMATION FACTORS MEASUREMENTS

A total of 56 carbonate core samples, 3.80 cm in diameter and 4.5 to 5.0 cm long, were taken from the drilling core available for the well 7-B0-5-RJS. The samples were taken from the zones 2, 3, 4, 5, 8 and 9 and were considered to be representative of the two lithofacies of the Macaé formation.

Among those 56 samples, six were selected for resistivity index measurements and the remaining samples were used in the formation factor analysis. This last set of samples were first cleaned in a soxhlet extractor using a single cycle of toluene and methanol to remove their residual fluids, dried at 60° C in a oven for a period of 48 hours, and the gas permeability and porosity were determined. The permeability and porosity values of the samples ranged from 0.67 to 564.0 mD and 19.13% to 35.33% Following the cleaning procedure the samples were saturated in a pressure vessel, with synthetic formation brine, and aged (in brine) for 3 weeks to allow for rock-fluid physico-chemical equilibrium before measuring their resistivity, Ro. The electrical resistivity was determined by the two electrode method, at a frequency of 1000 Hz.

The formation factors, given by equation 1, were determined at ambient and reservoir temperature (80°C). The samples were subjected to 500 psi of confining pressure during the measurements of their resistances, to ensure a perfect electrical contact between the core sample and the electrodes.

$$F = \frac{R_o}{R_w}, \qquad \text{eq.1}$$

RESISTIVITY INDEX (Ir) DETERMINATION

The 6 samples selected for resistivity index analysis were cleaned by injection of toluene followed by chloroform-methanol azeotrope. It is well known that this cleaning procedure is more efficient in extracting the residual fluids from core samples than the conventional soxhlet extraction. So that, it was used in this experiment in order to ensure the removing of all contaminants present in the core that could affect the results. After dried, the samples were saturated with synthetic formation brine and aged.

After the formation factors were measured, the fully saturated samples were placed in a high speed centrifuge to change the saturation to lower levels. The process of centrifugation was repeated at different angular velocities, until the samples achieved the irreducible water saturation (S_{wi}). This saturation condition was achieved at an equivalent capillary pressure of 30 psi, approximately.

The volume of fluid displaced from the sample at a given rotational speed were monitored until no significant variation was observed. At this point the centrifuge was stopped and the sample placed in a core holder for electrical resistivity measurements. The centrifugation of the samples creates an uneven distribution of the fluid along the samples that causes oscillations on the resistivity measurements. The resistivity index, given in the equation 2, was then determined when there was no significant change on the electrical resistance of the partially saturated sample (within error limits). When this equilibrium condition was achieved, an uniform saturation along the core was assumed. The measurements were made at ambient temperature and at 500 psi of confining pressure.

The corresponding saturation levels were calculated on the total volume of fluid expelled from the core at each rotational speed.

$$I = \frac{R_t}{R_o}, \qquad \text{eq. 2}$$

DISCUSSION OF THE RESULTS

The formation factor-porosity relationship is plotted on figure 3, for all data measured at reservoir temperature and at a 500 psi of stress. Both data measured at ambient and at reservoir temperature show a linear trend in a log-log diagram, with a slight difference in the slope of the curve.

The values of the coefficients "a" and "m" were determined for lithofacies 1 and 2 by means of a linear regression using the data measured for each lithofacies. The equation $F = a.\phi^{-m}$ was used as the regression model. The values obtained for the coefficient "a" were 0.91 and 1.05, and 2.25 and 2.09 for the coefficient "m", for lithofacies 1 and 2, respectively. The regression coefficient (R^2) was grater than 0.95 in both cases.

A linear regression was also performed on the whole set of data measured at ambient and reservoir temperature. In this case, also, the values of the coefficient "a" were very close to 1.0, as predicted by Archie's equation for formation factor-porosity relationship. The coefficient "m" assumed a value of 2.22 for data measured at ambient temperature, and a value of 2.18 at reservoir temperature. The slight difference between these values indicates that temperature has no influence on the cementation exponent of the Macaé formation.

The saturation exponent "n" was calculated for each sample, using a linear regression based on the data, (S_w;I_r), measured per sample. The values of the coefficient "n" varies from to zone to zone, for the same lithofacies (see figure 4), as indicated on table 1. Differences in the pore structure can be one of the factor responsible for the variation observed in these values.

The high values determined for the saturation exponent (always grater than two) can be related to the wettability condition of the samples. The interaction between the crude oil and the surface of the sample, rendering it oil-wet, must be taken into account, even considering that they have been performed at laboratory conditions. The influence of the wettability and the reservoir conditions on electrical properties of the reservoir rock has been extensively investigated. The researches(1-7) have shown an increase in the saturation exponent when the wettability of the sample changed towards an oil-wet condition.

Wettability tests were carried out on 5 samples, representatives of the Macaé formation. The wettability was evaluated by the USBM method, at laboratory conditions, after restoring the original wettability condition of the selected sample. To restore the wettability, the samples were cleaned by injection of toluene followed by chloroform-methanol, to make them as water-wet as possible. Following the procedure, the samples were saturated with the reservoir fluids (synthetic formation brine and crude oil) and aged for a month before measuring their wettability. Wettabilities results indicated that the samples were neutral after cleaning (I_w=-0.10). After restoration, the affinity of the samples for oil increased appreciably. The wettability index measured for restored samples was Iw=-0.60, in average.

These results confirm the possibility of the high values of "n" found out in this study to be associated with samples' preference for the oil phase. However, the representativity of these values are still questionable. The main uncertainties come from the fact that the reservoir temperature and pressure conditions were not respected during the resistivity index measurements, nor in the formation factor determination. Another problem to point out is the small number of samples analyzed for lithofacies 2.

To illustrate the impact of the variation on saturation and cementation exponents on the S_w and $H.\phi_e.S_o$ values, some calculations were made using different values of "n" and "m" determined in this study, and comparing them with the results obtained using the classical values of m=2.0 and n=2.0. The Archie's equation (eq. 3), that generally applys well for clean carbonates reservoirs, were used to calculate S_w, assuming a constant value for the coefficient "a" (a=1.0). The results are indicated in table 2, related to the well 7-BO-5-RJS. The variation observed in the values of S_w was up to 93%, when using the values of m=2.18 and n=3.43. In this case, however, a maximum reduction of 12% was observed in the values of $H.\phi_e.S_0$, when compared with the values calculated previously using m=2.0 and n=2.0. The value of n=3.43 used in these calculations corresponds to the arithmetic mean of the values showed on table 1.

$$S_w = \sqrt[n]{\frac{R_w.a}{R_t.\phi^{-m}}}, \qquad \text{eq. 3}$$

These results confirm the importance in determining correct values of the "m" and "n" exponent to accurately predict water saturation for assessing reserves and also the oil-water contact. Therefore, a new study was elaborated in order to obtain accurate values of the saturation exponent, "n", and the cementation factor as well. For this propose a set of 10 sample, representative of the main facies of the Macaé formation, were selected for resistivity index measurements under reservoir conditions, using synthetic formation brine and crude oil. These analysis are been conducting in elsewhere.

CONCLUSIONS

The following conclusions are valid for the investigated production zones of the Macaé formation:

1- The cementation factors determined at reservoir temperature were equal to 2.25 for the lithofacies 1, and 2.09 for the lithofacies 2.
2- The slight difference (1.80%) in the values of the cementation factors determined at ambient and at reservoir temperatures indicates that the temperature has a small influence on this coefficient.
3- The values of the saturation exponent, "n", ranged from 2.40 to 4.24, for the same lithofacies.
4- Wettability tests carried out on restored samples indicate that the rock is preferentially oil-wet. This may explain the high values obtained for the saturation exponent (always grater than 2.0).
5- The values of m=2.18 and n=3.43, measured in this study, resulted in a maximum reduction of 12.0% in the value of $H.\ \phi_e.\ S_0$, in the well 7-BO-5-RJS, when compared with the values previously calculated using m=2.0 and n=2.0.
6- To accurately predict water saturation for reserves evaluation purposes and also the position of the transition zone and oil-water contact it is important to determine correct values of the exponents m and n. This implies that the electrical properties of the reservoir rock must be measured using core samples and fluid system representative of the reservoir, and, also, reproducing the *in-situ* reservoir temperature, effective pressure and wettability conditions.

NOMENCLATURE

S_0, S_w - Oil saturation and brine saturation (%), respectively.

R_o- Resistivity of rock at S_w =100% (Ω.cm).
R_t- Rock resistivity when saturated with water and oil (Ω.cm).
R_w- Resistivity of the brine (Ω.cm).
H- Reservoir thickness
ϕ_e- Effective porosity determined from logs (%).
n- Archie's saturation exponent.
m- cementation factor.
F- Formation Factor.
I_r- Resistivity Index.
I_w- Wettability Index.
H. ϕ_e.S_o- Total oil meters from saturation and porosity.

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TABLE 1 - RESULTS FROM THE RESISTIVITY INDEX MEASUREMENTS: SATURATION EXPONENT VALUES.

LITOFACIES	PRODUCING ZONES	SATURATION EXPONENT, "n"
1	8	3.40
	8	3.40
	8	3.30
	2	2.40
2	4	3.80
	9	4.24

TABLE 2 - VALUES OF S_w AND $H.f_e.S_0$ CALCULATED USING DIFFERENT VALUES OF THE EXPONENTS "n" AND "m" - RESULTS RELATED TO THE WELL 7-BO-5-RJS OF THE BONITO FIELD, CAMPOS BASIN.

	VALUES OF THE COEFFICIENTS "m" AND "n" USED IN THE CALCULATIONS OF Sw AND $H.f_e.S_0$			
PARAMETERS	m=2.00 n=2.00	m=2.18 n=2.00	m=2.00 n=2.40	m=2.18 n=3.43
H (m)	253.00	253.00	253.00	253.00
f_e (%)	26.80	26.80	26.80	26.80
S_w	11.90	13.50	16.70	23.00
$H.f_e.S_0$ (m)	59	57	56	52
Variation in the values of $H.f_e.S_0$ compared with the values calculated using m=2.0, n=2.0	0	3.39	5.08	11.90

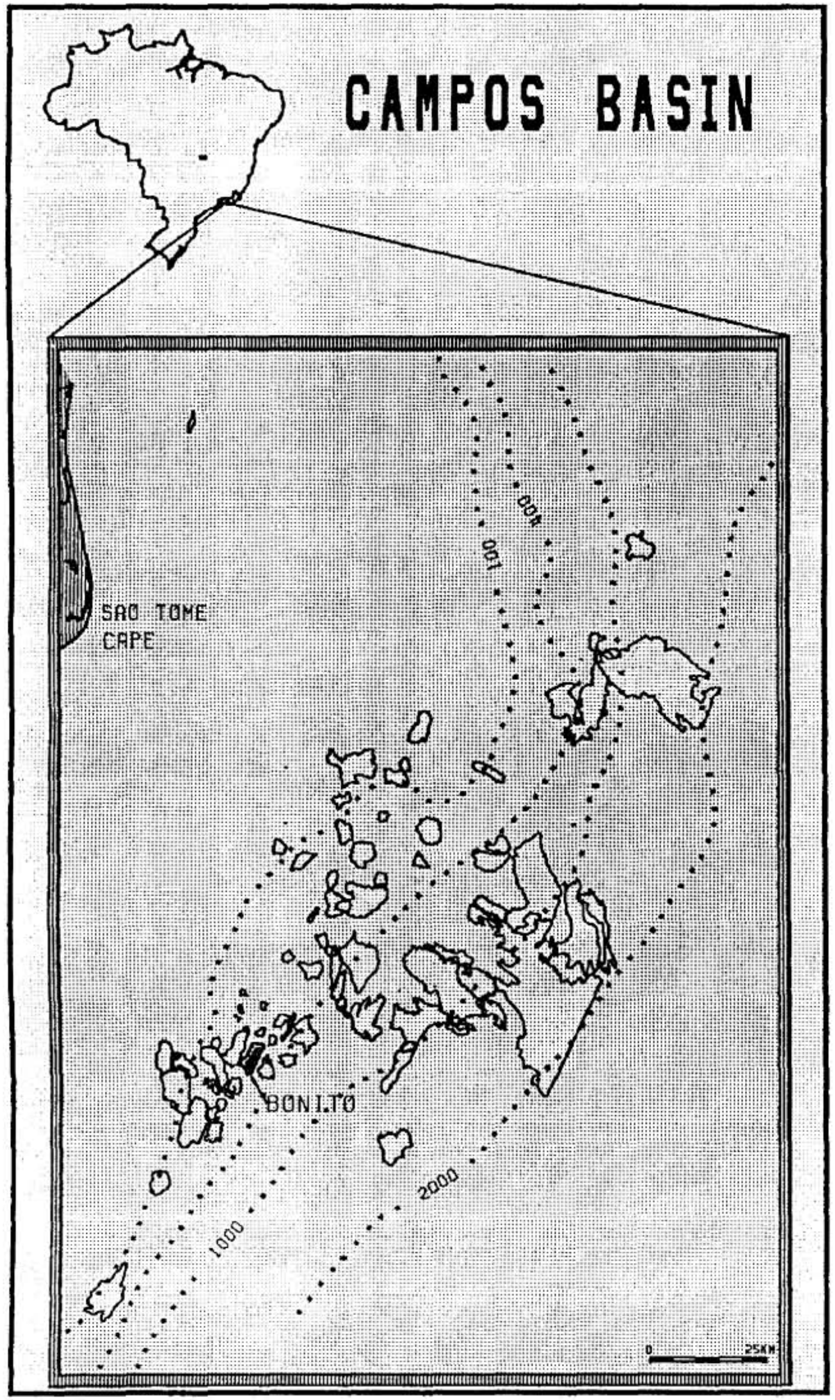

FIG 1 - LOCATION MAP

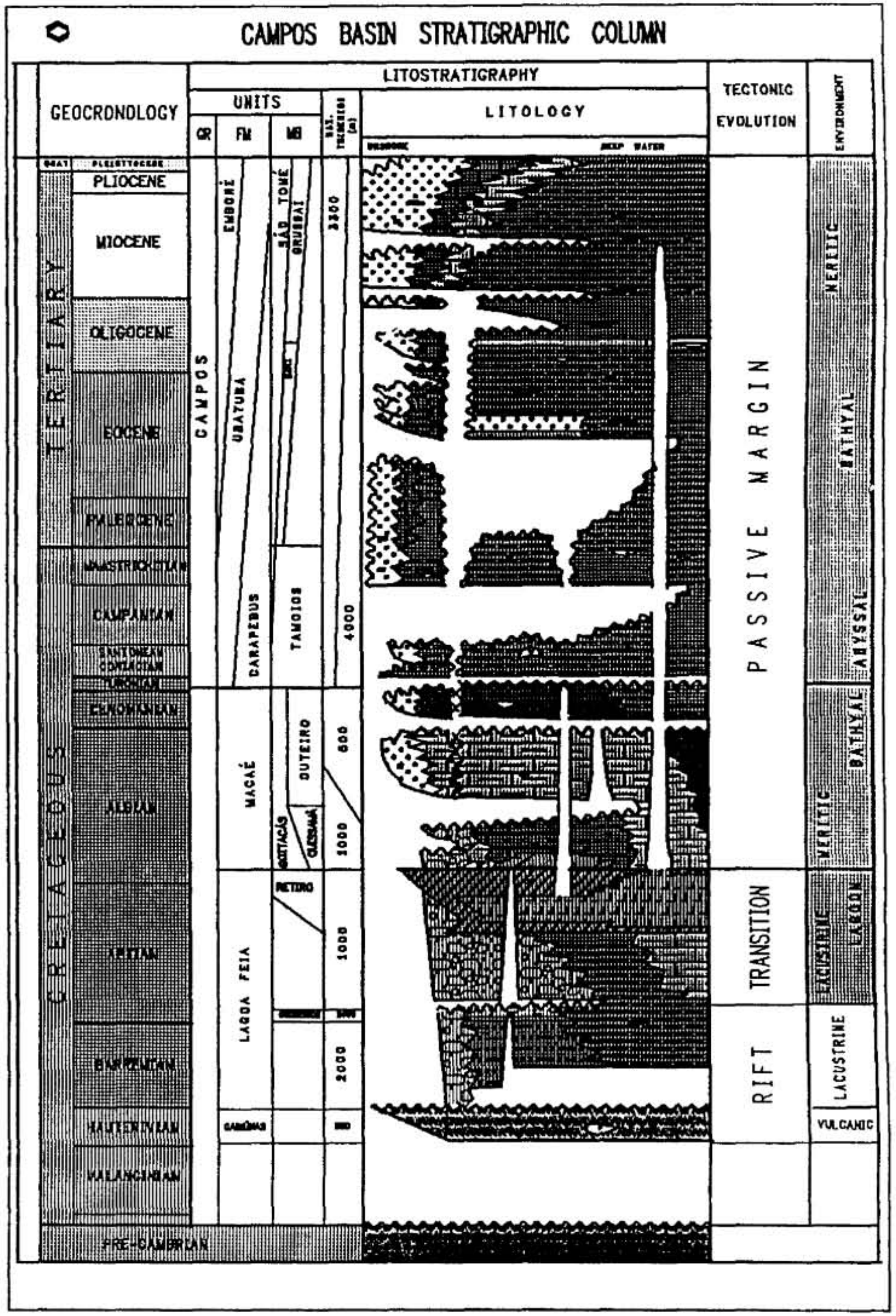

FIG 2 - CAMPOS BASIN STRATIGRAPHIC COLUMN

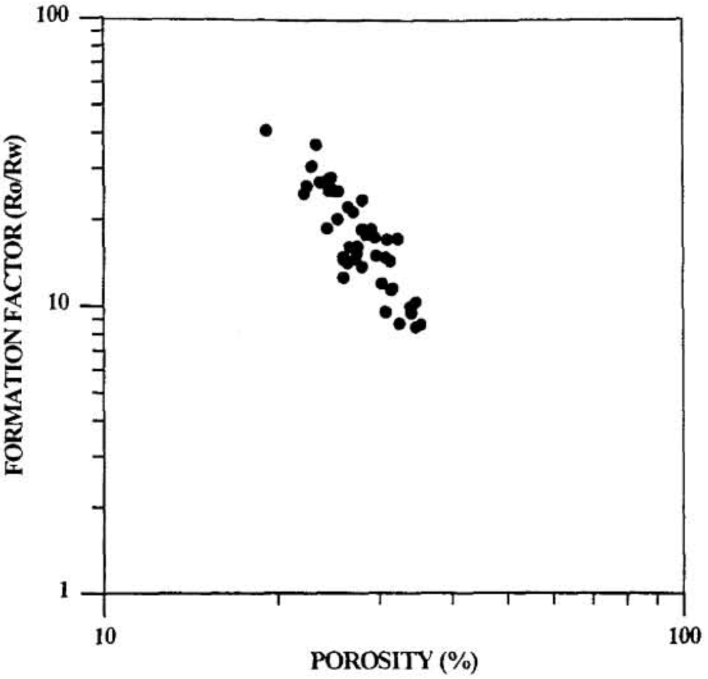

Figure 3: Plot of the Formation Factor *vs* Porosity Relationship for Data Measured at Reservoir Temperature (80°C) and at 500 of Stress.

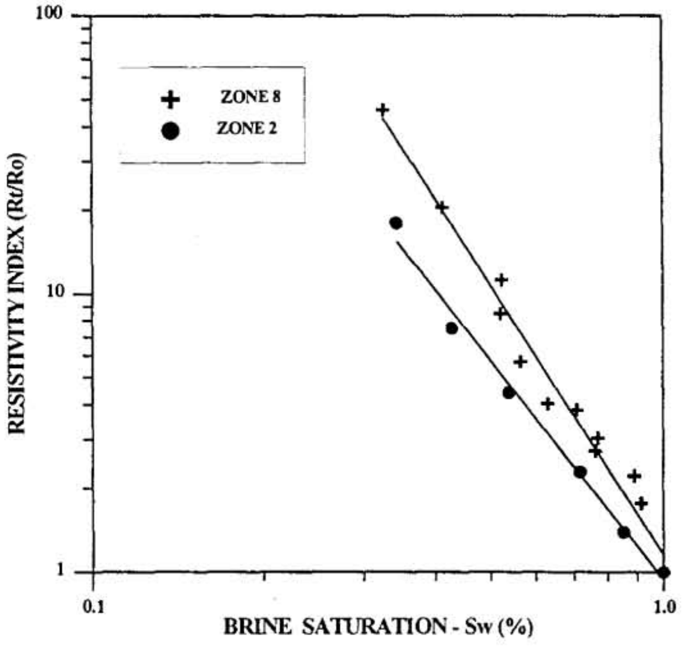

Figure 4: Plot of the Resistivity Index *vs* Brine Saturation Relationship for Data Measured on Samples of The Producing Zones 2 and 8, Lithofacies 1.