Determining the Archie Equation parameters for clean and clayey reservoirs of Campos Basin through an inverse approach

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Abstract

Archie (1942) determined the water saturation in clean sandstones by measuring the electrical resistivity, which is an important parameter in the characterization of hydrocarbon reserves. Later, researchers such as Hossin (1960), Simandoux (1963), Bardon & Pied (1969), Poupon & Leveaux (1971) and Worthington (1985) extended the studies of water saturation for clayey reservoirs. In this work, we used an inverse approach to estimate the Archie parameters in Namorado Oilfield (siliciclastic) and Field A (carbonate) in the Campos Basin. In both reservoirs, the parameters were analyzed using sensitivity analysis, beside correlation and resolution matrices. For Namorado Oilfield, the results showed values for the parameters a = 1; m = 2.4; n = 3.0 and R_W = 0.011 ohm.m, which clearly indicates that it is a no Archie type reservoir formed by arkose sandstone. The sensitivity study indicates that the a and R_W are inversely proportional and a converged to the initial input, with m and n always converged to 2.4 and 3.0. For the water saturation, the results showed a good approximation between the by Archie (1942) estimate and the other authors above mentioned. For Field A, the results were a = 1, m = 3.578, n = 2.3133 and R_W = 0.003 ohm.m. These answers are close to an Archie type reservoir, except for the parameter m, which exhibited a high value. This can be justified by the unconnected pores present in the carbonate reservoir of Field A. The study of the sensitivity of the parameters was made for this indicates that R_W is inversely proportional to a, with m and n converging to fixed values.

Introduction

Campos is a sedimentary basin located along the continental margin of Southeastern Brazil, which has several oilfields (Figure 1). The origin and evolution of this basin are related to the Gondwana breakup and is marked by the fragmentation of South America and Africa plates with the subsequent formation of South Atlantic Ocean. The tectonic-sedimentary evolution of this basin occurred in three phases: rift, post-rift, and drift, that corresponds, respectively, to continental, transitional and marine super sequence. The continental sequence was deposited during the mechanical subsidence from the rift phase and includes the basalts of the Cabiunas Formation and continental sediments of the Lagoa Feia Formation. The transitional sequence is characterized by the evaporites of the Retiro Formation deposited in a period of shallow marine transgression pulses over continental areas and relative tectonic quiescence. The marine sequence marks the commencement of the open marine deposition during thermal subsidence associated with the drift phase. This phase begins with carbonate sedimentation (Macae Group) and grade to a mainly siliciclastic succession (Campos Group) moved by intense halokinesis (Okubo et al., 2016).

In Campos Basin, there are many oilfields with different types of reservoirs. For example, Namorado Oilfield is in the north central portion of the zone of accumulation of hydrocarbons in Campos Basin, 80 km from the northern coast of Rio de Janeiro, at a water depth of between 140 m and 250 m, occupying a 200 km^2 area. This sphere is present divided into four blocks, bounded by normal faults. The main block is in the central - western part of the field and has massive sandstone dominance with the fine texture of thick, low to the moderate selection of grains, low roundness, and sphericity. In the main block, there are adjacent, marginal and secondary blocks, which has little oil. Namorado reservoir consists of turbidite sands interspersed with marl and shale deposited over a carbonate platform ramp. The sandstones are not laminated, containing fine to very fine grained material, but may occur with coarse average grained facies, with a poorly selected clay matrix that includes 3 to 30 % of silt, 1 to 6 % of clay, 11 % of intraclasts of carbonate and 9 % of bioclast. The calcite cementation varies from 1 to 53 % and influences the porosity, which ranges from 1.8 to 32.2% (Guardado et al., 1990).

Regarding carbonate reservoirs in the Campos Basin, these rocks were deposited in an extensive carbonate platform environment, with more than 1500 km of extension along the Campos and Santos Basins (Figure 1). The sedimentary evolution of this platform was conditioned by pre - Albian section structures (Sao Tome Low, internal and external highs, NW and NE lines). The evaporites movement was influenced by the sediment load, substrate slope and reactivation of faults (direction NW/SE), controlling the geometry and distribution of facies. These reservoirs are represented by isolating structures, which correspond to shallow platform carbonate deposits that were formed during a transgressive Lower/Middle Albian regime. They correspond to carbonate sediments deposited in the marine environment with high to moderate energy, represented by hairy packstones to oolitic grainstones (Torrez, 2012). This reservoir has three zones being called, from the youngest to the oldest, as packstone, grainstone and cemented grainstone. The grainstone is considered the reservoir in this oilfield because has the higher values of porosity and permeability (Bruhn et al., 2003).

Method

The functional relationships between the parameterized model, or constructed from the hypotheses, with data that simulate the observed data through a mathematical model is what defines a direct problem. In the case of this work, the water saturation (S_W) equation used to make the inversion is the linearized form of Archie's Equation (1942), in accord to:

$$\log(Sw) = (1/n)(\log(a) + \log(Rw) - \log(Rt) - m\log(\phi)), \quad (1)$$

where Sw is the water saturation (%), Rw is the water formation resistivity (ohm.m), Rt is the measured resistivity (ohm.m), ϕ is the porosity (%) and a, m and n are the parameters of the Archie Equation.

The analysis of S_W for the reservoir was made by inversion of the data with the linearized equation of Archie, using the Tikhonov´s regularization (1963):

$$x = (A^\wedge \mathrm{T}(A) + \lambda I) - A^\wedge T(y), \quad (2)$$

where x is a vector of parameter with dimension p, y is the which is known as the sensitivity or Jacobian matrix (derived from the observations regarding the parameters), λ is the stabilization parameter of the system, I is the identity matrix, 1 is the inverse of the matrix, and T stands for the transposed matrix. One of the good consequences of the inverse process is to do an analysis of the quality of the parameters of the adjustment through statistical studies, using, for example, the correlation and resolution of the parameters.

The Jacobian matrix is the matrix formed by the first order partial derivatives of a function. This matrix is the sensitivity matrix of Tikhonov´s regularization, represented by the term A in Equation 2. Therefore, the terms of this matrix obtained from the partial derivatives of the logarithmic form of the Archie Equation are:

$$\partial a / \partial y = 1/an, \quad (3)$$

$$\partial m / \partial y = -\log\phi / n, \quad (4)$$

$$\partial Rw / \partial y = 1/(nRw), \quad (5)$$

$$\partial n / \partial y = (1/n^\wedge 2)(\log a + \log Rw - \log Rt - m\log\phi). \quad (6)$$

For the inverse process, values of 5 and 0.2 for the stabilization and error parameters were respectively adopted for a maximum of 100 iterations for each test performed.

Results

Figure 2 shows the gamma rays, neutron porosity, density and resistivity logs of a well of Campo Namorado, referring to the depth range of 3030 - 3060 m. This siliciclastic reservoir has as main feature the high porosities, reaching up to 30%, water saturation of 25.86% and permeability greater than 1 Darcy. This same figure shows the same logs referring to Field A, in the depth range of 1800 - 1850 m. This carbonate reservoir has an average porosity of 23.44% and water saturation of 41.26%.

For Namorado Oilfield, these tests take up with an initial input of the Archie parameters, which are presented in Figure 3a. This first test set adopted standard values for m = 2 and n = 2, and changing the values of a and Rw. By subjecting all parameters to the inversion process, using values as a_0 = 0.5, m_0 = 2.0, n_0 = 2.0 and R_{W0}= 0.02, the values for a, m, n and R_W obtained in five interactions are shown in Figure 3b. There is a strong relationship between the initial values and the result obtained after the 100 interactions in each step. In the same figure are presented the standard deviations in each interaction. However, in relation to the parameters m and n, these tended to fixed values (respectively 2.4003 and 3.00001) and at first without a relationship with the value of the initial input of them. However, R_W has a relation inversely proportional to parameter a, since by doubling the initial value a_0, what happened from test 1 to test 2, and the result of R_W was reduced by half. Nevertheless, the initial input value of RW to test 3 did not in any way influence the parameter a, since it proceeded to incline to the value of its initial input. Interactions 4 and 5 corroborate what has already been described, whereby reducing the half to half the final value of R_W has therefore doubled. To confirm the trends, new tests were executed, as depicted in Figure 3c. This time, new initial inputs were used, placing the initial values of a = 1 and R_W = 0.01, leaving m and n to be inverted. Thus, the initial values of the parameters deviate from Archie's standard reservoir values, leading to divergence of the solution. By observing the values of the parameters along the iterations, it was possible to infer what m and n tends to, respectively, 2,4001 and 3,0001; a tends to 1, just to the input value and R_W to 0.0110 ohm.m when a tends to 1. Figure 4a shows the elements of the correlation matrix between the initial values of the Archie parameters and the results that these tended after the iterations. Note that the correlation between a and a_0 is equal to 1, which shows this parameter converges to the initial input. As long as, the correlation between a and R_W is equal to -0.875, which explains the previously perceived inversely proportional relationship between these two parameters. Figure 4b shows the elements of the resolution matrix and shows how well the inversion was solved. The main diagonal is the value 1 in two elements of the matrix, these elements are equivalent to the parameters m and n, indicating that these parameters were well resolved. However, the other elements of the main diagonal, corresponding to a and R_W, indicate that the inversion of these elements has not been well resolved. This can be affirmed by the fact that a and R_W depend on the initial value assigned to a0.

For Field A, the initial values of the Archie parameters for the first tests are shown in Figure 5a. As can be seen, this first test set established the values for m = 2 and n = 2, changing only the values of a and R_W (Figure 5a). The parameters m and n in this test acquired fixed values of, respectively, 3.5780 and 2.3133. While a and R_W varied according to the initial input, specifically the value attributed to a_0. Further tests were performed to verify the behavior of the parameters, however, changing the values of m_0 and n_0 and setting a_0 = 1 and R_{W0} = 0.01 ohm.m, as shown in Figure 5b. The tests showed that m and n assume the values of, respectively, 3.58 and 2.31. The value of m, *although* high, is common between 3 and 4 in carbonates with unconnected pores and old porosity (Lucia, 1983; Focke, 1987). Parameters a and R_W obtained the same relationship that occurred in the Namorado Oilfield. Figure 3c shows the initial values of the next tests, when a and R_W are considered constant in the interactions, making the inversion of m and n. Equally in the Namorado Oilfield, there were very strong deviations from the traditional values of Archie's Equation, leading to a divergence of the answer. The parameter converges in the first input (the correlation of a_0 and a is 1) and R_W is inversely proportional to a (correlation equal - 0.9727), and that m and n are also highly correlated (correlation equal to 0.9987), according to the correlation matrix, shown in Figure 6a. The computation of the Archie parameters was performed with the initial values of a_0 = 1, m_0 = 2, n_0 = 2 and R_{W0} = 0.02, which are standard values used to count the water saturation. This term was adopted and result in a = 1, m = 3.578, n = 2.3133 and R_W = 0.003. Figure 6b shows the elements of the matrix of resolution of the parameters, it is affirmed that the parameters m and n are well solved (value in the main diagonal equal to 1), while a and R_W did not obtain the same success, respectively, 0.4223 and 1.2323).

The inversion of the Namorado Oilfield data allowed to calculate accurate values for m and n, however the values of a and R_W depend on the initial value attributed to a_0. The resistivity of the clay (R_{sh}) used in the calculation was obtained through the resistivity average at a depth of 3010 - 3025 meters, equivalent to a zone of shales above the reservoir. The clay content (V_{sh}) was calculated using the formula of Larionov (1969) equivalent to old and consolidated rocks. For the calculation of water saturation the standard value 1 was adopted for a_0, which consequently results in a equals 1 and R_W at 0.011 ohm.m. For Namorado Oilfield, the water saturation using the models of Archie (1942), Hossin (1960), Simandoux (1963), Bardon & Pied (1969), Poupon & Leveaux (1971) and Worthington (1985) with the standard parameters of Archie and those calculated by inversion is shown in Figure 7a and the curves in Figure 7b. Figure 7c shows the saturation method in this reservoir for the different models, when using Archie's standard parameters and those calculated by inversion. The water saturation of this reservoir measured in the laboratory has a value of 25.86%, close to the value obtained by the inversion for all models tested. For Field A, utilizing the Archie parameters obtained by inversion (a = 1, m = 3.578, n = 2.3133 and R_W = 0.003), it was possible to estimate the water saturation by the Archie Equation. Figure 7d shows the water saturation calculated from the parameters obtained in the inversion and the observed in the logs between 1800 - 1850 m depth. The observed mean water saturation was 41.26% and the calculated by the inversion was 40.26%, which is very close as verified in the curves of Figure 7d. This indicates that the inversion presented a good approximation in the calculation of water saturation.

Conclusions

In this work, the well log data of the clayey turbidite reservoir of the Namorado Oilfield indicated a mean water saturation of 25.86% in the depth range of 3030 - 3060 m. The inverted models of Archie (1942), Hossin (1960), Simandoux (1963), Bardon et al. (1969) and Poupon et al. (1971) presented, respectively, values for this parameter of 23.35, 25.95, 26.22, 27.53 and 22.43, which are close to the log response. In the clay - free carbonate reservoir of Field A, the inversion of the data indicates values of the Archie parameters of a = 1; m = 3.578; n = 2.3133 and Rw = 0.003 ohm.m. The cementation coefficient (m) presented a high value, because it is a carbonate with unconnected pores with a moldic porosity. With the results obtained by the inversion of this field, the water saturation was calculated in the depth range of 1800 - 1850 m, resulted in a saturation of 40.26%, close to the value of 41.26% observed in the log. Thus, in both types of reservoir the process of inversion of the Archie parameters resulted in a good approximation with the values found in the literature.

Acknowledgments

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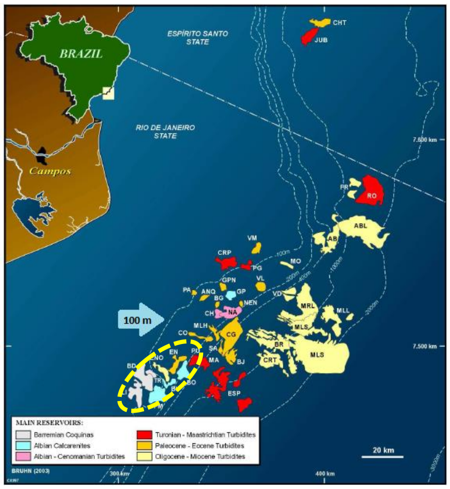


Figure 1. Location of the Campos Basin with their oilfields: Namorado in pink and the carbonate Albian inside the yellow ellipse (Guardado et al., 1990).

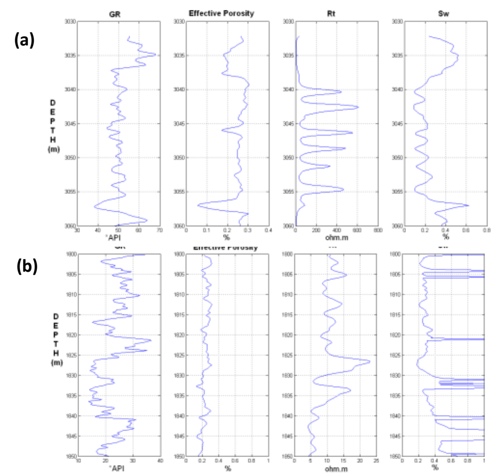


Figure 2. Gamma rays (track 1) and resistivity (track 3) logs of (a) Namorado Oilfield - well Na01 and (b) Field A, as well as effective porosity (track 2) and water saturation (track 4).

(a)

Interaction	a_0	m_0	n_0	R_{w0}
1	1.00	2.00	2.00	0.01
2	2.00	2.00	2.00	0.01
3	1.00	2.00	2.00	0.02
4	0.50	2.00	2.00	0.01
5	0.50	2.00	2.00	0.02

(b)

Interaction	a	m	n	R_w	σ
1	0.9999	2.4003	3.0001	0.0110	4.3054×10^{-5}
2	2.0000	2.4003	3.0001	0.0055	7.2538×10^{-6}
3	1.0001	2.4003	3.0001	0.0110	5.7917×10^{-5}
4	0.4998	2.4003	3.0001	0.0220	2.6894×10^{-4}
5	0.4997	2.4003	3.0001	0.0220	3.3909×10^{-4}

(c)

Interaction	a_0	m_0	n_0	R_{w0}
6	1	4	2	0.01
7	1	3	2	0.01
8	1	1	2	0.01
9	1	2	4	0.01
10	1	2	1	0.01
11	1	2	5	0.01

Figure 3. Namorado Oilfield: (a) Inversion with m_0 and n_0 constants, changing a_0 and R_{w0}. (b) Inversion with all parameters varying, beside standard deviation. (c) Inversion with a a and R_w constants, changing m and n.

(a)

Interaction	a_0	m_0	n_0	R_{W0}
12	1.00	2.00	2.00	0.01
13	2.00	2.00	2.00	0.01
14	3.00	2.00	2.00	0.01
15	1.00	2.00	2.00	0.02
16	1.00	2.00	2.00	0.03
17	2.00	2.00	2.00	0.02

(b)

Interaction	a	m	n	R_W
12	0.9998	3.5780	2.3133	0.0030
13	2.0000	3.5780	2.3133	0.0015
14	3.0000	3.5780	2.3133	0.0009
15	1.0000	3.5780	2.3133	0.0030
16	0.9995	3.5780	2.3133	0.0030
17	1.9990	3.5780	2.3133	0.0015

(c)

Interaction	a_0	m_0	n_0	R_{W0}
18	1	3.0	2.0	0.01
19	1	4.0	2.0	0.01
20	1	2.0	2.0	0.01
21	1	2.0	4.0	0.01
22	1	2.5	2.5	0.01

Figure 5. Field A: (a) Inversion with m_0 and n_0 constants, changing a_0 and R_{w0}. (b) Inversion with all parameters varying. (c) Inversion with a a and R_w constants, changing m and n.

(a)	a_0	m_0	n_0	R_{W0}	a	m	n	R_W
a_0	1	-	-	-	-	-	-	-
m_0	0.3414	1	-	-	-	-	-	-
n_0	-0.02916	-0.02653	1	-	-	-	-	-
R_{W0}	-0.06804	-0.06190	-0.04762	1	-	-	-	-
a	1	0.34134	-0.02910	-0.06777	1	-	-	-
m	$1.81\text{x}10^{-16}$	$1.64\text{x}10^{-16}$	$1.26\text{x}10^{-16}$	$-2.89\text{x}10^{-16}$	$4.53\text{x}10^{-17}$	1	-	-
n	-0.06861	-0.11037	-0.01151	-0.11206	-0.06864	$-4.58\text{x}10^{-12}$	1	-
R_W	-0.87500	-0.22742	-0.02916	-0.06804	-0.87500	$6.43\text{x}10^{-17}$	-0.14767	1

(b)	a	m	n	R_w
a	0.24219	0.85077	-0.44835	-22.05196
m	$2.94\text{x}10^{-15}$	1	$1.80\text{x}10^{-14}$	$3.04\text{x}10^{-13}$
n	$-1.51\text{x}10^{-15}$	$-5.71\text{x}10^{-15}$	1	$-1.49\text{x}10^{-13}$
R_w	0.01746	-0.00715	0.01234	1.58943

Figure 4. Namorado Oilfield: (a) Correlation matrix of the initial values and the results. (b) Elements of the resolution matrix.

(a)	a_0	m_0	n_0	R_{W0}	a	m	n	R_W
a_0	1	-	-	-	-	-	-	-
m_0	0.3244	1	-	-	-	-	-	-
n_0	-0.3244	2.77×10^{-17}	1	-	-	-	-	-
R_{W0}	-0.1842	-0.3244	-0.3244	1	-	-	-	-
a	1	-0.3242	-0.3247	-0.1844	1	-	-	-
m	0.1376	-0.8804	-0.4561	0.1377	0.1373	1	-	-
n	0.1175	-0.8601	-0.4979	0.1175	0.1171	0.9987	1	-
R_W	-0.9727	0.3482	0.3482	0.1475	-0.9727	0.1477	-0.1261	1

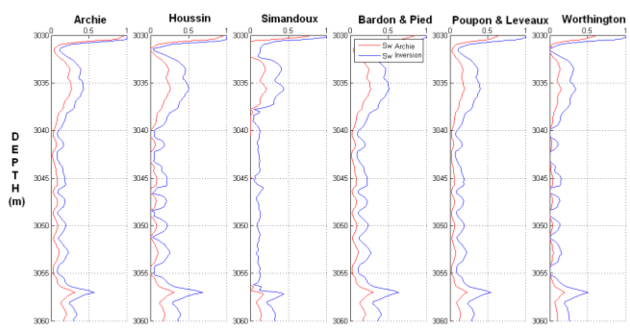
(b)	a	m	n	R_w
a	0.4223	0.6199	0.5887	141.8629
m	1.388×10^{-16}	1	-1.618×10^{-14}	-1.0214×10^{-13}
n	-1.2327×10^{-14}	2.320×10^{-14}	1	-4.45×10^{-12}
R_w	0.0037	0.0045	9.9030×10^{-4}	1.2369

Figure 6. Namorado Oilfield: (a) Correlation matrix of the initial values and the results. (b) Elements of the resolution matrix.

(a)

Method	a	m	n	R_W (ohm.m)
Archie	1.0000	2.0000	2.0000	0.0200
Inversion	1.0000	2.4001	3.0001	0.0110

(b)



(c)

Model/Parameter	*Archie*	*Inversion*
Archie (1942)	0.1254	0.2335
Hossin (1960)	0.1144	0.2595
Simandoux (1963)	0.1056	0.2622
Bardon et al. (1969)	0.1208	0.2753
Poupon et al. (1971)	0.0874	0.2243
Worthington et al. (1985)	0.0585	0.1611

(d)

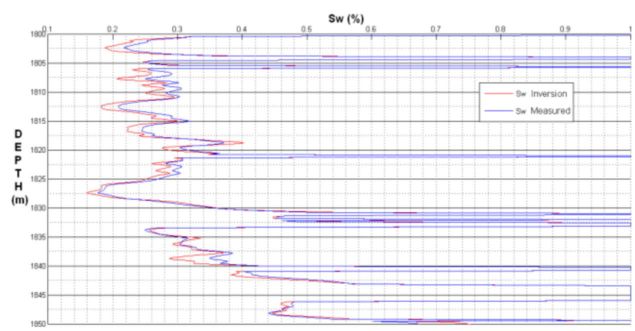


Figure 7. (a) Water saturations for Namorado Oilfield. (b) Standard parameters and calculated by inversion. (c) Average water saturation calculated for Namorado Oilfield according each model. (d) Calculated and observed water saturation in Field A.