Determining the invaded zone diameter in oil reservoirs provoked by mud drilling through geophysical well logs

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Abstract

In a drilling process, muds of different compositions are used, aiming to support the wall and to remove the debris originated by the action of the bit. These muds invade the geological formations and modifies the well surrounding zones, mainly, in terms of porosity and permeability. In the present work, we developed a mathematical approach to determine the invasion diameter, which is different to the methodology developed by SCHLUMBERGER, but utilizing the same well logs: ILD and LLD. Thus, the developed procedure works fast and accuracy, because it considers better the characteristics of the invasion process, specially the *annulus*.

Introduction

After the drilling, geophysical well logs are deployed through the open hole, with the descending of some tools that register physical fields related with petrophysical parameters as porosity, density, etc., which integrate a basic information set in the characterization of oil reservoirs (Anderson, 2001). One of these parameters is the electrical resistivity, which is related with the volumetric characteristics of the rocks that include the matrix and fluids present in the pores, generating, thus, some kind of information that define properties as the fluid saturation, types of fluids, etc. (Borah et al., 1998).

In the measurement of the resistivity, with the purpose to characterize the invasion process (Figure 1), currently the Laterolog Dual (LLD) are very utilized, which use the phenomenon of galvanic conduction into the geologic medium (Baker Hughes, 2002). This system possess two sets of seven electrodes in the same tool, called of LLD (Deep) and LLS (Shallow), which are considered as macro-logs and are recommended for conductive muds with saline base. The same ones aim to investigate great volumes of rock to obtain the resistivity of the virgin zone (R_t). Besides these logs, it exists the micro-logs, as the spherical focused (SFL) and the Micro Spherical Focused (MSFL), both with lesser distances between the electrodes, what fairly diminishes the investigation depth, reaching only the zones near to the borehole wall (R_{xo}) (Chen & Mueller, 1992).

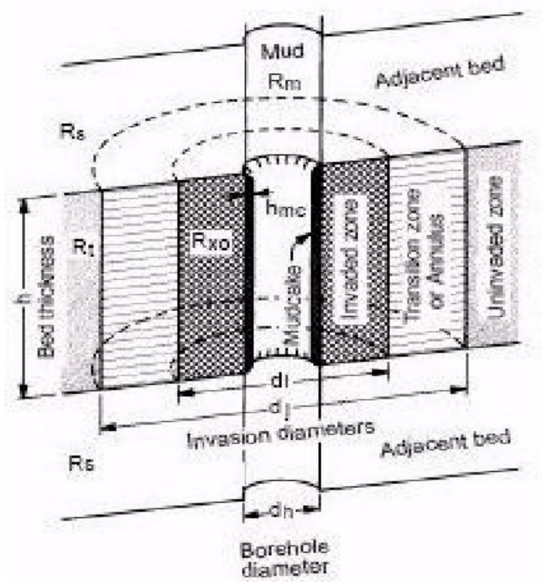

Figure 1. The logging environment (modified from Anderson, 2001).

On the other hand, another kind of log, the Dual Induction (ILD), which functions with the electromagnetic induction phenomenon, was introduced to minimize the mud/well effect existing in the galvanic profile, using as physical principle the inductive electromagnetic coupling between the transmitter, the receiver coils and the rocks (Ellis, 1997). The advantage in use this scheme is that it is not distorted, penetrating, indistinctly, in the mud and rock media. This combination of sensors allows the measuring of the virgin zone resistivity (R_{ILD}), but, when approaching them, it diminishes the radial investigation, permit only to attain average distances. (R_{ILM}). It is coupled, still, to a third combination of coils with lesser investigation depth, the Micro Focused Spherical (R_{MSFL}), allowing the measuring of shallower resistivity. In the same way, the use of the different frequencies in ILD and ILM tools besides the focused ones, provides different volumes and investigation depths, permitting to measure the resistivity of the invaded (R_{XO}) and virgin (R_t) zones, beyond to know D_i, becoming possible the correction of the invasion effect.

Methodology

The knowledge of the invasion is important, and, therefore, our work aimed to find a mathematical expression that we would conduce us to its direct calculation, registering automatically its dimension. In this form, this expression describes, in an appropriate manner, the *Tornado Chart* (SCHLUMBERGER, 1989) and its anomalies, which is a important result with direct applicability in the petroleum industry. Our methodology also uses the LLD and ILD logs, which give us the values of the shallow (R_{xo}), middle (R_{ILM} or R_{LLS}) and deep (R_{ILD} or R_{LLD}) resistivities, which are used to know R_t. Thus, based on the idea of the *Tornado Chart*, we obtain the following functional relationship:

$$\frac{R_t}{R_{LLD}} = f\left(\log\left[\frac{R_{LLD}}{R_{LLS}}, \frac{R_{LLD}}{R_{xo}}\right]\right). \qquad (1)$$

Calling $x = (R_{LLD} / R_{LLS})$ and $y = (R_{LLD} / R_{xo})$ and develop the Equation 1 in the form of a polynomial function, comes to:

$$\frac{R_t}{R_{LLd}} = 1 + D_i, \qquad (2)$$

where,

$$D_i = a_1 x + a_2 x^2 + a_3 xy + a_4 x^2 y + a_5 xy^2 + a_6 x^2 y^2, \qquad (3)$$

which it is defined as the invasion diameter.

The Equation 3 is a polynomial of two degree, which defines the problem of the invasion, because those with higher degrees do not adjust the *Tornado Chart*. In this equation, the number 1 was added, in order to coincide with the *Tornado Chart* and with the observations of *Crain* (1984), which states that, necessarily, the invasion phenomenon must begin its values above 1 on logarithmic scale, setting the work quadrant with physical responses always positive and make as zero the invasion radius at the moment when $x = 0$. In order to obtain the coefficients ($a_1,\ldots,a_6$) of Equation 3, it mounts up the problem in the following matrix system:

$$\begin{bmatrix} \left(\frac{R_t}{R_{LLd}}\right)_1 \\ \left(\frac{R_t}{R_{LLd}}\right)_2 \\ \vdots \\ \left(\frac{R_t}{R_{LLd}}\right)_3 \end{bmatrix} = \begin{bmatrix} 1 & x_1 & x_1^2 & y_1 & y_1^2 \\ 1 & x_2 & x_2^2 & y_2 & y_2^2 \\ \vdots & \vdots & \vdots & \vdots & \vdots \\ 1 & x_6 & x_6^2 & y_6 & y_6^2 \end{bmatrix} * \begin{bmatrix} a_1 \\ a_2 \\ a_3 \\ a_4 \\ a_5 \\ a_6 \end{bmatrix}, \qquad (4)$$

which, briefly, can be expressed in the following linear system:

$$[S] = [A] * [P], \qquad (5)$$

where: **[S]** = vector defined by the log values; **[A]** = matrix defined by *x* and *y* coordinates of the polynomial; **[P]** = vector of polynomial coefficients.

To solve this system, *P* is isolated and A^{-1} is calculated, which is the inverse of matrix A, as follows:

$$[P] = [A]^{-1} * [S], \qquad (6)$$

which is easily calculated using MATLAB (2000), the mathematical engineering software, in which A^{-1} is calculated by the pseudo inverse Moore-Penrose function *pinv*. At the same time, an algorithm was developed to obtain the values of R_t and D_i (Ribeiro, 2007). In practice, if know the *x* and *y* axes in the *Tornado Chart*, it is possible to find the values of R_t / R_{LLD} and D_i. The algorithm described above perfectly adjusts the values of the *Tornado Chart*, both for LLD and ILD.

Results

The developed methodology was applied, firstly, to synthetic data obtained from horizontally layered theoretical models (*Ribeiro*, 2007). With this objective, it was used a three layers simplified model, which facilitates the input of the mineralogical composition of an oil reservoir and its subsequent analysis. The first and third layers are impermeable shales, with small percentages of minerals and with little interstitial water. The second layer, however, is sandstone, which has a varied mineralogical composition (quartz, calcite, dolomite, ilite, caolinite and montmorilonite), where the entire invasion process occurs (Table 1). Figure 2 shows GR (Gamma Ray) log clearly separating the shales and sandstones layers, but the ILD sonde, however, does not show appreciable responses for R_{ILM} and R_{ILD}, which may be due to the model is very conductive (R_{mf}=0.198 e R_m= 0.088 ohm.m) and, for this reason, the electromagnetic energy is unable to penetrate the geological formations. The LLD tool, on the other hand, clearly registers high resistivities values at shallow, medium and deep depths, which is an indication of the presence of hydrocarbons in the reservoir. By comparing the of invasion radius R_i ($R_i = D_i / 2$), in the case of the reservoir, we found that our calculations for the LLD case is closer to synthetic result, leaving the ILD below the estimative and the *Tornado* Chart quite over, around twice.

Regarding real data, we analyzed, initially, a well from Canada for LLD (Figure 3). In this case, GR log shows intervals with high values of up to 100 GAPI (7.600 – 7.800, 8.250 to 8.350 and 8.650 m) related to the presence of shales, with lower values in other ranges, caused by the presence of sands. In relation to resistivity log, we can emphasize the range of depth 7.780 to 7.950, where $R_t > R_{LLM}$, in turn $R_{LLM} > R_{SFL}$, which proves, probably, the use of a conductive mud. The invasion radius has values up to 1,50 m, approximately, in some depths. In the interval 8.350 to 8.450, the situation above related back to repeat, showing that in these depths it exists another potential reservoir. The invasion, in this case, has values around 1,3 m, while in the other intervals its is around 0,75 m.

Table 1. Lithology of the model with 3 layers

LITHOLOGY	SHALE	RESERVOIR	SHALE
QUARTZ	0,20	0,10	0,20
CALCITE	0,05	0,30	0,05
DOLOMITE	0,00	0,05	0,05
ILITE	0,25	0,05	0,20
CAOLINITE	0,15	0,02	0,15
MONTMORILONITE	0,15	0,05	0,15
WATER	0,20	**0,02**	0,20
OIL	0,00	**0,40**	0,00
GÁS	0,00	**0,01**	0,00
TOTAL	1,00	1,00	1,00
SIMULATION: Rmf = 0.198 ohm.m; Rm = 0.088 ohm.m			

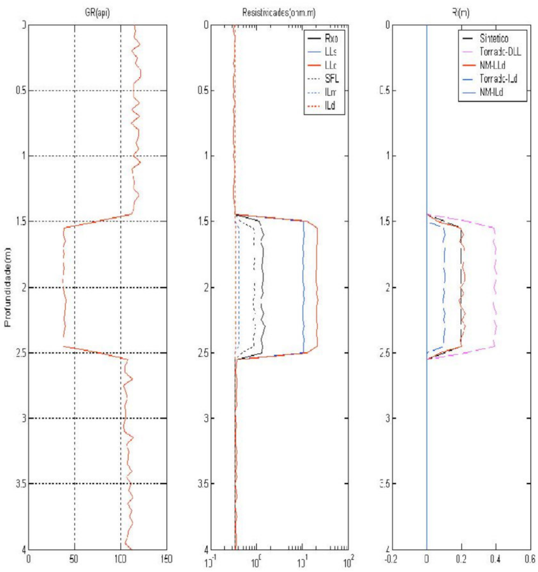

Figure 2. Formation damage profile for the tested model.

Another set of real data provide from a second well from Canada, whose logs for ILD data are shown in Figure 4. GR log, in the interval 1.530 to 1.560 m, presents high values up to 300 GAPI, with low values in other depths. In the same depths, the resistivity log shows high values, as well as at depths around 1.620 m. The disagreeing behavior between GR and resistivity logs shows that in the interval from 1.530 to 1.560 m there may be clayey sandstone. Moreover, the relationship $R_{MSFL} > R_{ILM} > R_{ILD}$ shows, certainly, the use of a resistive oily mud. Regarding invasion track, in the intervals of 1.520, 1.535 and 1.550 m its values are between 1,5 and 2,0 m, which proves the existence of a geological formation with high porosity and permeability, probably sandstone. At the depth of 1.620 m, the invasion is greater, up to 2.0 m. In other ranges, the invasion is less than 1,0 m, showing up very oscillating, may be because the existence of sandstone – shale intercalations, very common in reservoirs.

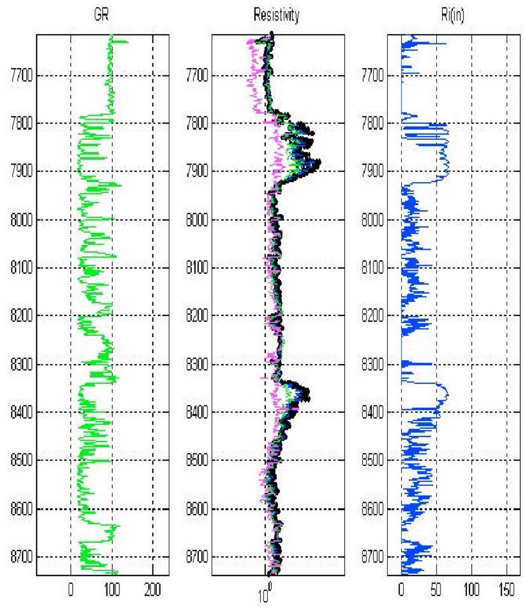

Figure 3. Formation damage profile of the well real data 1 with LLD.

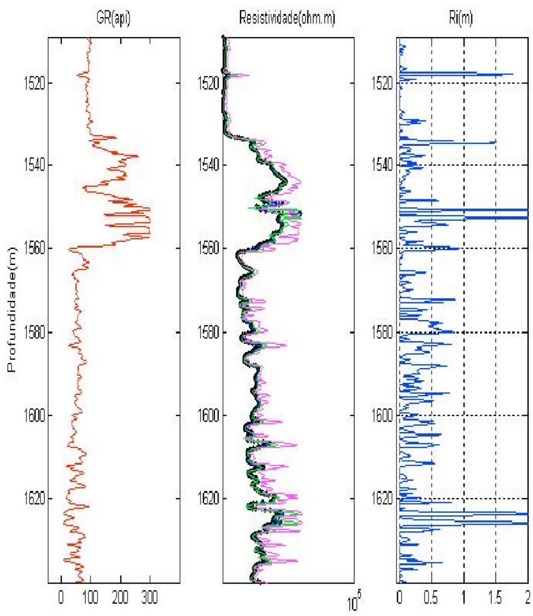

Figure 4. Formation damage profile of the well real data 2 with ILD.

Discussions and Conclusions

The *Tornado Charts* and its based commercial algorithms utilized in environment corrections for geophysical well logs are available long time ago, but, they still are based on simple invasion profile models, generally in delayed graphical processes. In this way, the sophistication of the modern tools is not followed by the improvements in the correction programs of this effect. For this reason, the same ones can, probably, never to be eliminated completely with this kind of approach, but, by the combination of different tool responses and by the forward modeling, better solutions can be reached to prevent interpretation errors. Considering these facts, we develop, in this work, an algorithm to determine the invasion diameter, which is based on a simple polynomial function that calculates this distance from the dual tool resistivities. To accomplish this, we use MATLAB scientific package to develop the programs, which solving the linear system through an inversion process, and, validating the process with synthetic and real data. The results are consistent, with a margin error in the order of 10%, comparing with the theoretical invasion, which is an admittedly reasonable value when it works with experimental data. In conclusion, our process it revealed fast, efficient and exact, because the results are placed graphically in another track besides the other logs, which it facilitates the automatic recognition of the invasion depth provoked by the drilling mud in oil reservoirs.

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References

Anderson B. 2001. Modeling and inversion methods for the interpretation of resistivity logging tool response. PhD Thesis, University of Deft, Holland, 203 p.

Baker Hughes. 2002. Introduction to wireline log analysis, Baker Atlas, 312 p.

Borah, N. M.; Mallick, R. K.; Choudhuri, B. & Rathores, Y. S. 1998. Mud filtrate invasion profile – Its influence on wireline logs and hydrocarbon producibility: a case study. SPE, New Delhi, India.

Chen S.X. & Mueller T.C. 1992. A Simple Approach to Mud-Invasion Correction for Dual Laterolog Resistivities, Oil & Gas. OGR 23962.

Crain, E.R. 1984. The Log Analysis Handbook, Vol. 1, Quantitative Log Analysis Methods.PennWell Books, Tulsa, 684 p.

Ellis, D.V. 1987. Well logging for earth scientist. Elsevier, New York. 532 p.

MATLAB. 1999. MATLAB – The Student Edition, User´s manual. Makron Books, São Paulo, 413 p.

Ribeiro, M. 2007. Geofísica de poço na delimitação do dano à formação produtora de petróleo causado pela invasão da lama de perfuração. MSc. Thesis, LENEP/UENF, Macaé, 92 p. (in portuguese),

SCHLUMBERGER. 1989. Log Interpretation Principles/Applications. SCHLUMBERGER Educational Services, Houston.