New approach to calculate the mud invasion in reservoirs using well logs

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Abstract

In the drilling process, the mud invades the formations and modifies the surrounding zones of the well, mainly, in terms of the physical properties of the rocks, such as porosity and permeability. The identification of this formation damage is important, mainly in the reservoir characterization. In this sense, many years ago, Schlumberger developed a way to determine the mud invasion diameter using the Tornado Chart, which is utilized until today in oil industry, essentially using well logs. Later, with the objective to improve the determination of the invasion diameter, Crain used mathematical equations to calculate this value, making corrections of Schlumberger´s methodology. In this work, on the other hand, we propose a polynomial mathematical method to determine the invasion diameter, which is different to the methodology developed by Schlumberger and Crain, but also utilizing the same resistivity logs. Thus, the procedure developed in this work it was shown fast and accuracy, because it considers better the characteristics of the invasion process, showing yet the results in the form of a log beside the tracks of the another logs measured in the well, resulting a more efficient visualization.

Introduction

The drilling of a well, the mud has the function to carry the generated debris up to the surface, besides to lubricate the bit and keep stables the wall of the borehole through the exerted hydrostatic pressure (Machado, 2002). An intervention like this also prevents the invasion of hydrocarbons into the well, which can cause accidents in the surface structures. This created condition provokes the mud go inside the geological formation, causing an invasion the starts in the wall of the well in a mudcake way, that if constitutes in a sealing agent. From the mudcake, the concentration of the particles of the mud decreases with distance inside the reservoir, forming an intermediate zone invaded by of the mud filtrate, which is subdivided in invaded zones and of transition. From this moment, reaches the deep uninvaded zone, where the oil, the gas and the formation water are located (El-Wazzer & Ad Haggag, 1999). In this zone, can happen a displacement or a mixture of the fluids, which is known as invasion diameter D_i (Figure 1).

After drilling, open hole well logs are performed descending several tools that record physical fields, which are related to petrophysical parameters such as density, porosity, clay volume, etc. These parameters include a set of fundamental information on the petroleum reservoir characterization (Anderson, 2001).

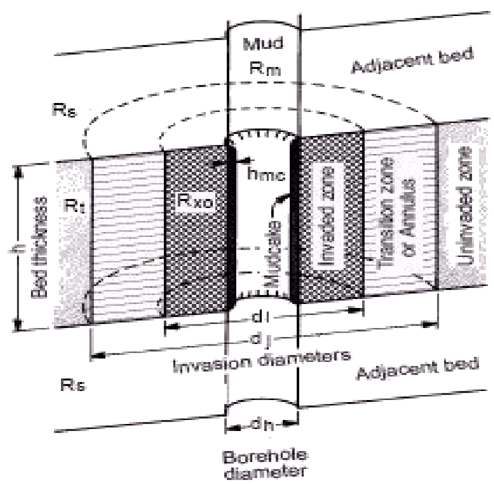

Figure 1. The logging environment (modified from Anderson, 2001).

One of is the electrical resistivity, which is related to the volumetric characteristics of rocks that comprise the matrix and the fluids present in the pores, generating, thus, information that defines properties such as saturation and fluid types, etc. (Borah et al. 1998).

Currently, in order to map the invasion process, the resistivity measurements are performed using the Dual LateroLog (DLL) tool, which uses the galvanic phenomenon to drive a DC current through the geological media (Baker Hughes, 2002). This system has two sets of seven electrodes in the same tool called LLd (deep) and LLs (shallow), which are considered macro logs and are recommended to be used with conductive water base mud (Figure 2). These tools aim to investigate large volume of rock to obtain the virgin zone resistivity (Rt). Alongside these profiles, there are micro spherical focused (SFL) and micro cylindrical focused (MCFL) logs, which have shorter distances between electrodes that reduce significantly the investigation radio, recording only the resistivity Rxo of the zones close to borehole wall (Chen & Mueller, 1992).

Another log used in the resistivity measurements is the Dual Induction Log (DIL), which uses the physical principle of the inductive electromagnetic coupling between the coils and the geological formations, being introduced to minimize the mud effect existing in galvanic log. The advantage of using this device is that it doesn´t distort the electric field, penetrating indistinctly in the mud - rock environment, especially when resistive oil base mud are used (Figure 3).

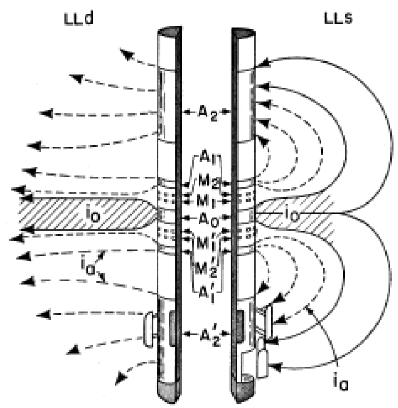

Figure 2. Schematic diagram of the Dual Laterolog electrode configuration and current patterns (modified from Anderson, 2001).

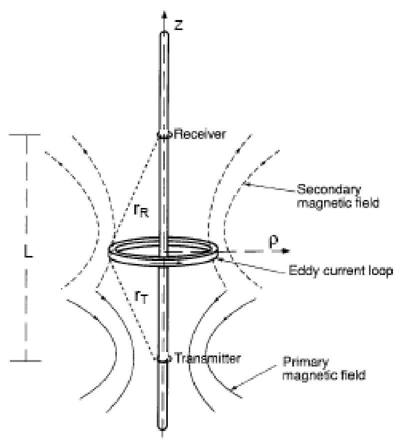

Figure 3. Basic two-coil induction sonde showing electromagnetic field patterns and the coordinate system used for computing response functions (modified from Anderson, 2001).

This combination of sensors allows measuring the resistivity of the virgin zone (RILd), but, when the distance between them is decreased, the investigation radius is reduced to reach average distances (RILm). Together with these two tools, there is the MCFL, which explores even more shallow measuring the shallow resistivity (RMCFL) using electrodes. The use of different frequencies in the ILd and ILm tools, beside the focused one, provides different depths and volumes of investigation, allowing thus to measure the resistivity of the invaded (Rxo) and virgin (Rt) zones, obtaining also Di, which makes possible to correct the invasion effect (Singer & Ellis, 2008).

To correct the effects of invasion on oil producing formations, Schlumberger (1989) developed the Tornado Chart, in order to measure Rt and Di, measuring the shallow, medium and deep resistivities. This chart uses the ratios RLLd/RLLs and RLLd/RFSL, RILm/ RILd and RMCFL/ RILd of the tools DLL and DIL, respectively. These ratios represent the x and y axes, with all its values read directly on the chart at different intervals. Nowadays, most of the environmental corrections of commercial softwares to interpret well logs contains modules based on these charts. However, there are two basic types of radial resistivity profiles of invasion that are considered in Tornado Chart, when resistivities of the invaded zones are considered (Figure 4).

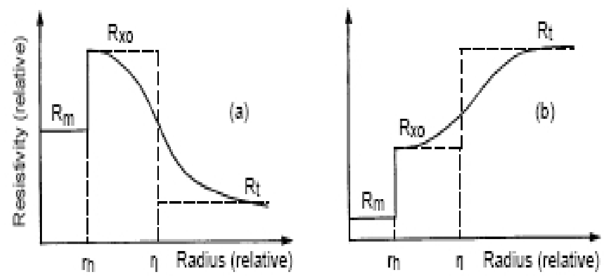

Figure 4. Radial resistivity profiles encountered in formations drilled with resistive (a), or conductive mud (b). Solid lines denote the actual shape of the resistivity profile and dashed lines denote the step profile approximation often used for modeling invasion effect (modified from Anderson, 2001).

In this figure, the (a) profile corresponds to the cases where Rxo> Rt, as that the (b) profile is typical of formations which have Rxo <Rt. However, there are variations in points outside the boundaries of the charts, which are considered as Tornado "anomalous", especially when a transition exists between the invaded and the virgin zone, known as the annulus. The annulus has generally a low resistivity Ran (Ran <Rt <Rxo), because it is a mixture of mud filtrate, formation water, salt and oil. Its location is important because, when it is detected, is certain the presence of oil in the reservoir (Figures 5). However, different situations may occur when it inverts Rt <Ran <Rxo, especially with the use of oil base muds (Semmelbeck & Holditch, 1988).

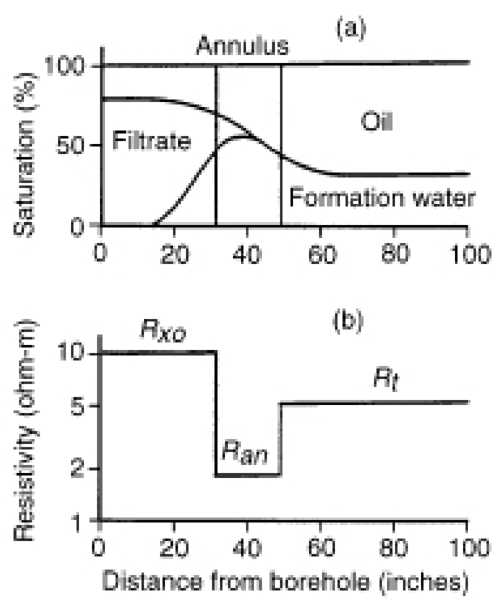

Figure 5. Saturation (a) and resistivity (b) profiles for a representative. Example of annulus invasion (modified from Anderson, 2001).

By studying the effects of the invasion of drilling mud, Crain (1984) showed that when the ratios between the shallow and deep resistivity are outside the range of the selected Tornado Chart, it is possible that the chosen chart is not appropriate. It found, however, that these charts are useful only in the washed area, but they show conflicting results on virgin area, where the oil and the annulus zone are. Worse still, the invasion inside the oil or gas zones usually creates data set which falls out the Tornado Chart, and thus, corrections are not made, though they are needed.

Methodology

It is evident that knowledge of Di is important in the characterization and the production operations of the reservoirs. Thus, the main objective of our work was to find a direct way to calculate it, registering automatically the damage provoked by mud invasion. In the process, we find a mathematical expression that describes adequately the Tornado Chart and anomalous values do not contemplate in it, as indicated by Crain (1984).

The methodology uses the DDL and DIL tools, which provide us the values of shallow (MCFL or SFL), medium (ILM or LLs) and deep (ILD or LLD) resistivities and allows to obtain the Rt, Rxo, and Di values. Thus, starting from the idea of the Tornado Chart for DLL log, we obtain the following functional relationship:

$$\frac{R_t}{R_{LLd}} = f\left(\log\left[\frac{R_{LLd}}{R_{LLs}}, \frac{R_{LLd}}{R_{SFL}}\right]\right). \quad (1)$$

Calling x = R_{LLd}/R_{LLs} and y = R_{LLd}/R_{SFL} and developing Equation (1) in form of a bicubic polynomial function, we obtain:

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

where:

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

is defined as the invasion diameter, where $a_1 \ldots\ldots a_6$ are coefficients.

Equation (3) is a two degree polynomial that describes the problem of invasion, because those with greater degrees not adjust the Tornado Chart. In Equation (2) was added the number 1 with the purpose to coincide with the Tornado Chart and with the observations of Crain (1984). This author asserts that, obligatorily, the phenomenon of invasion must begin their amounts over 1 in a logarithmic scale, defining the work quadrant with physical answers always positive and making zero the diameter of invasion at the time when *x* is equal to zero. With the objective of obtain the coefficients of Equation (3), it is organized the problem in a matrix form, that, in short, may be expressed in the following linear system:

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

where:
[S] = vector defined the values of the profiles,
[A] = matrix defined by the coordinates x and y of the polynomial,
[P] = coefficient vector.
P can be solved for this system in the form:

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

expression that is easily solved to calculate $\boldsymbol{A^{-1}}$, which was calculated by the pseudo inverse function of Moore - Penrose (MATLAB, 2012).

To obtain R_t, R_o and D_i values in the form of logs along the well, we developed an algorithm to calculate those parameters using the MATLAB (2012) code. This program considers the mineralogical composition and fluids present in the layers, calculating gamma rays (GR), resistivity (DLL e DIL), density (RHOB), neutronic (NPHI) and transit time (Vp e Vs) logs. From a practical, if we know the x and y axes in the Tornado Chart is possible find the values of R_t/R_{LLd}, R_{xo}/R_{LLd} and the D_i. The previous algorithm describes perfectly all values of Tornado Chart, for both DLL as DIL tools, and, yet, values that are outside of the envelope of these charts. On the other hand, the same procedure can be adopted for the DIL log, considering R_t/R_{ILd} on the left side of Equation 1, with x = R_{ILm}/R_{ILd} and y = R_{MSFL}/R_{LLd}.

Results

The methodology proposal was used, firstly, with synthetic data derivatives from a theoretical model of horizontal layers (Crain, 1984). For this, it was used a simplified model of three layers, which facilitates the input of the mineralogical composition of an oil reservoir and its subsequent analysis (Figure 6). The first and third layers are impermeable shales, with small percentages of minerals and with low interstitial water. The second layer, however, is a sandstone that has a diversified mineralogical composition (quartz, calcite, dolomite, illite, kaolinite and montmorillonite), where it happens the invasion process (Table 1). In Figure 7, it is observed that GR log clearly separates the shale and of sandstone layers. ILD tool does not show significant differences for RILm and RILd, which is justified by the fact of the mud be very conductive, what does the electromagnetic energy to decay and to be unable to penetrate into the formation. The DLL tool, on the other hand, clearly reads the values of RSFL, RLLs and RLLd resistivities, this last with high value, what is an indication of the presence of hydrocarbons in the reservoir. Comparing the results of the invasion radius Ri (Ri=Di/2) in the reservoir, we verified that our methodology for the DLL case is close of Crain (1984) result, staying the DIL below the estimation and Tornado Chart much above.

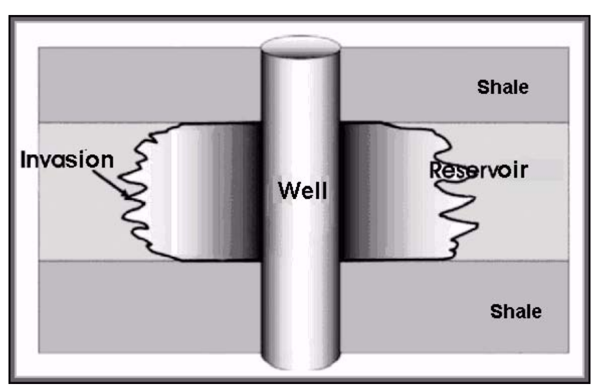

Figure 6. Reservoir model with three layers.

Table 1. Lithology of the model 1 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
R_{mf} = 0.198 ohm.m; R_m = 0.088 ohm.m			

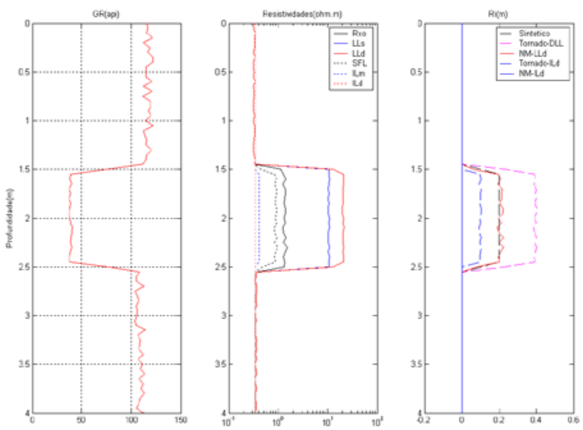

Figure 7. Formation damage profile of the model 1.

To apply our technique the real data, we selected an example from Ellis & Singer (2008, Chapter 5, page 111), that shows typical logs for DLL tool in a hypothetic reservoir, with RSFL, RLLs and RLLd resistivity values. For the studied depth (36.5 m), we have the following values to RLLd = 2.000 ohm.m*,* RLLs = 1.200 ohm.m and RSFL = 70 ohm.m*.* When we plot the values of RLLd /RLLs and RLLd/RSFL ratios for all the log in the Tornado Chart (Figure 8)*,* we observe that a large part of points are outside of the chart, that confirm the Crain's affirmations (1984).

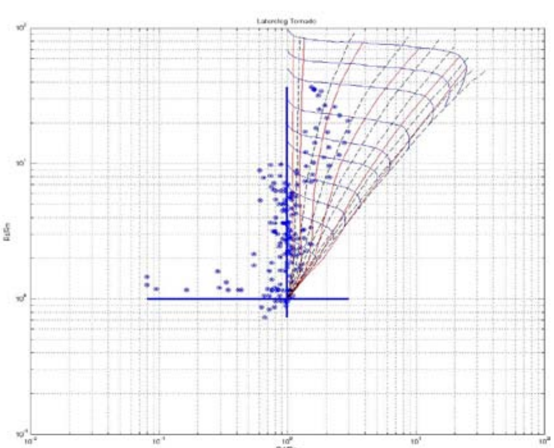

Figure 8. Tornado Chart for laterolog.

In that example, the GR log on track 1 indicates a clean zone, in other words, it is a sandy reservoir of moderate porosity, with aquifer and hydrocarbons zones. The aquifer appears in the bottom part of the curve, in this case with low resistivity values and no separation between RSFL and RILd. The zone of hydrocarbons is given by high resistivity values in the curve above the 12.470 feet depth, but, 20 feet below of this zone, the values are high in water zone, which indicates a small amount of hydrocarbons or changes in porosity. For this example, the corrections of the invasion with the Tornado Chart, having the values of Rxo, Rt and Di, by which values can be found utilizing the profiles RILd, RILs and RSFL*,* considering that this last read correspond to Rxo values. In this figure, in depth of 12.435 feet, it is observed the following:

$$\frac{R_{LLd}}{R_{LLs}} = 2, \text{ and, } \frac{R_{LLd}}{R_{SFL}} = 30, \qquad (7)$$

which indicates an moderate invasion. In the utilized Tornado Chart (Dual Laterolog – Rxo Device, Rxo/Rm = 50), the intersection of the two ratios of Equation (7) indicates the following relationship:

$$\frac{R_t}{R_{LLd}} = 1.28, \text{ and } \frac{R_t}{R_{xo}} = 40. \qquad (8)$$

In the same Tornado Chart it is observed that the diameter of invasion has a value of 30 inches (0,70 m) and that in the lower zone, between 12.455–12.466 feet, the readings of RSFL and RILd stay overlapped, indicating this that the invasion is small and not is necessary a correction. In Figure 9, we can observe the Rt values at the second track, with values of 2.000 ohm.m for the studied depth, which coincides with Ellis & Singer (2008) values. In the last track, the invasion diameter (red) is very close of the calculated value of Crain (1984) algorithm.

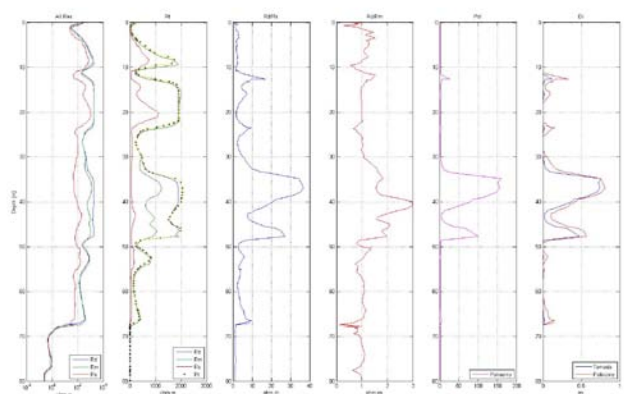

Figure 9. Results obtained for laterolog.

In the case of induction log, we selected an example of Engler (2011), for the depth of 30 m, with the following values for RILd = 10 ohm.m*,* RILm = 14 ohm.m and RMCFL = 90 ohm.m*.* When we plotted the values of RMCFL /RILd *and* RILm /RILd ratios for all the log versus the Tornado Chart, we observed again that there is points outside of envelope (Figure 10). In this case, in the studied depth, we observed the following values:

$$\frac{R_{MSFL}}{R_{ILd}} = 9, \text{ and, } \frac{R_{ILm}}{R_{ILd}} = 1.4, \qquad (9)$$

starting by Tornado Chart (Induction, Rxo/Rm = 20), we obtain:

$$\frac{R_t}{R_{LLd}} = 0.89, \text{ and, } \frac{R_{xo}}{R_t} = 14, \qquad (10)$$

that results in:

$$R_t = 8.9 \text{ ohm.m}, \; R_{xo} = 144 \text{ ohm.m} \text{ and } D_i = 1.14 \text{ m}. \quad (11)$$

In Figure 11 can we observe that values obtained by our methodology agree with these values, observing in the last track that the value of Di in this depth is 1 m and the values of Rt on the second track.

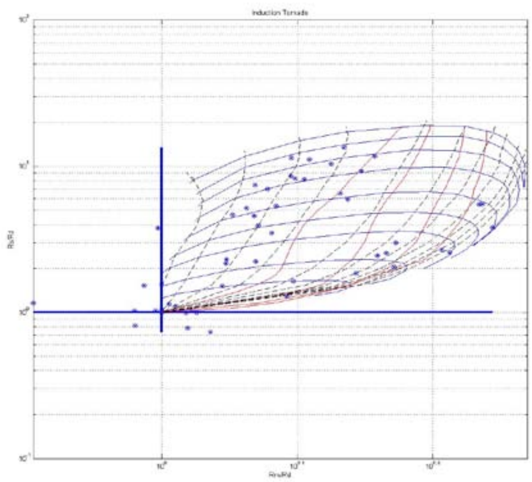

Figure 10. Tornado Chart for induction.

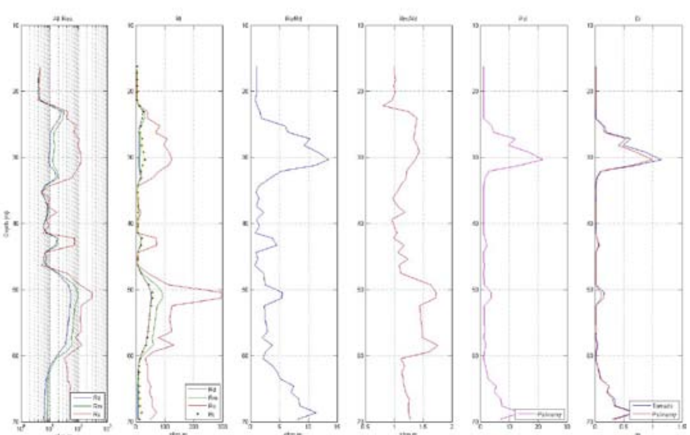

Figure 11. Results obtained for induction

Conclusions

The charts and the algorithms used in environmental corrections for geophysical logging tools are long time available, but, they are even based in a simple invasion concept that utilizes graphic processes of determining. Thus, the sophistication of modern tools is not accompanied by the best programs of correction the effects on the logs. It is concluded that these can, probably, never be completely eliminated, but by combination of various tool responses and of forward modeling a better solution can be achieved, avoiding the erroneous interpretations. Due to those factors, in our work we developed an algorithm for automatically determining Rxo, Rt and Di, which is based on utilization of a bicubic polynomial that calculates those parameters starting from of the resistivity of DLL e DIL tools, solving a linear system across an inversion process. The same was implemented in MATLAB code and validated with synthetic models and real data logs from the literature. In conclusion, the results presented are consistent, with a small error, showing that our process is automatic, fast, efficient and accurate. Moreover, the invasion is shown in the form of one more log placed beside of other well logs, which facilitates the visual recognition of the extent of the invasion of drilling mud in the reservoirs.

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