Forward modeling of the influences of piston and annulus type models in laterolog responses of carbonate layers in Santos Basin - Brazil

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Abstract

The drilling fluid invasion model is one of the high complexity cases of well logging to be understood. One of the most complex decisions faced is the type of model that will be applied. For this, it is necessary to bring into account the resistivities of the fluid containing the well and the reservoir, as well as the petrophysical properties of the formation. Traditionally, to analyse the resistivities of the virgin zone (Rt) and depth of invasion (di), a step profile model is assumed, which is the simplest model of invasion, since it does not consider the presence of a transition zone or the gravitational effects of fluids. In this work, we studied the response to a piston model of the shallow (LLS) and deep (LLD) laterolog tools and, considering, also, the presence of the annulus. To do this, these responses were simulated utilizing a finite element numerical approach for 2.5D or axial symmetry and, using as a basis for modeling galvanic logs collected in the Santos Basin, Southeast Brazil.

Introduction

During drilling, the drilling fluid is kept at a pressure greater than the geological formation pressure. Due to this pressure difference, there is a trend for the drilling fluid to infiltrate the porous and permeable layers and the solid component to form a thin, impermeable mud cake.

The invasion of the drilling fluid has a significant implication in the log measurements of the well logs, especially in the resistivity ones (Salazar & Torres - Verdin, 2009). Because depending on the depth of the invasion zone, the measured values in the virgin zone undergo changes, making its evaluation difficult. Likewise, the values obtained by the tool are also influenced by the resistivity of the mud filtrate (Rmf) (Akinsete & Adekoya, 2016).

In order to model the resistivity of the non-invaded zone (Rt) and the depth reached by the washed zone (di), the step profile is generally assumed, due to its simplicity and the limited number of independent measurements of radial resistivity. It is recognized, nevertheless, that the invasion may not occur radially, and on that point is no model considered accurate for invasion of the drilling fluid and there are no satisfactory ways of evaluating them in situ.

Thus, the direct modeling of geophysical log responses is extremely significant. In this work, programs that help in the geoelectric modeling of electric tool responses and simulate their effects were used, what mean step and annulus type profiles. These two models are derived from geoelectrical values and the two cases were evaluated with a combination of two electrical tools with different depths of investigation: shallow (LLS) and deep (LLD) laterologs.

Geological Context

The pre-salt covers a total area of approximately 227.000 km^2, which is 800 km long and, in certain regions, 200 km wide. The Santos Sasin is located in this environment, 350 km from the coast (Figure 1). It is bordered to the north by the Cabo Frio High, which separates it from the Campos Basin and to the south by the Florianopolis High, which separates it from the Pelotas Basin (Bruhn et al. 2003).

The petroleum system of the Santos Basin is restricted to the subsalt configuration (pre-salt range), would have as potential generating rocks, black shales rich in organic matter, interspersed with carbonates, deposited in paleo lacustrine environment (formations Itapema and Picarras Guaratiba). Such as reservoirs, carbonates of the Itapema (coquinas) and Barra Velha (microbialites) formations, both of the Guaratiba Group, and may also occur in siliciclastic rocks (Formation Picarras) and fractured basalts (Camboriu Formation). The migration of hydrocarbons generated in the rift section occurred through direct contact between the generating rocks and the reservoir rocks of the rift section. Nevertheless, the presence of an overlapping layer of salt (Ariri Formation) was likely responsible for an almost perfect sealant for this oil system (Papaterra, 2010).

The models used in this work are based on real data from a well of the Santos Basin and the modeling section consists of a sequence of geoelectric layers represented by a layer of salt, carbonate and shale.

Method

One of the most significant factors in this kind of modeling, which is sometimes neglected, is the contrast between the invaded zone (Rxo) and formation resistivities (Rt). Induction measurements respond more easily in conductive formations (Singer & Barber, 1988.), while laterolog measurements respond best to resistive formations (Crary et al., 2001).

Forward Problem

For the geoelectric modeling, a program developed in by Cozzolino (2004) was used for 2.5D geometries using finite element numerical technique.

The semi - analytical solution of the electric potential through Maxwell's Equations (Equations 1 - 4), which relate the electric field to the electric potential generated by a stationary point current sources (Hohmann, 1983).

$$\nabla\times\vec{E}=0, \tag{1}$$

$$\vec{j}=\sigma\,\vec{E}, \tag{2}$$

$$\vec{E}=-\nabla V, \tag{3}$$

$$\nabla\cdot\vec{j}=\frac{I_o\,\delta(r)\delta(z-zr)}{2\pi r}, \tag{4}$$

where E is the electric field, j is the electric current density and V is the electric potential, considering a source of intensity I_O in $(r, z) = (0, z_T)$. By inserting Equations 2 and 3 in Equation 4 obtain:

$$\nabla\cdot(\sigma\nabla V)=-\frac{I_o\,\delta(r)\delta(z-z_T)}{2\pi r}, \tag{5}$$

where σ is the electrical conductivity of the medium.

The differential equation of the scalar electric potential in a cylindrical coordinate system with azimuthal symmetry will look like this:

$$\frac{1}{r}\frac{\partial}{\partial r}\left(r\sigma(r,z)\frac{\partial V}{\partial r}\right)+\frac{\partial}{\partial z}\left(\sigma(r,z)\frac{\partial V}{\partial z}\right)+\frac{\partial}{\partial z}=\frac{I_o\,\delta(r)\delta(z-zr)}{2\pi r}, \tag{6}$$

being the potential V is the desired solution and subject to the boundary conditions,

$$[V(r,z)]_{r+|z|\rightarrow\infty}\rightarrow 0. \tag{7}$$

Regarding the invasion models, it will be considered a piston - type geometry, and later the model of annulus. In both cases the bearing of the mud cake will not be counted in the modeling, since it is an impermeable element and of little thickness.

a) Piston Type

In the piston type or step profile (Figure 2), the mud filtrate is idealized as a cylinder around the hole. For this model, it is not considering the presence of a transition zone between the resistivity of the flushed or washed zone (Rxo) and the virgin or uninvaded zone (Rt). The radius of the well to be modeled has a length of 0.1 m.

According to Crary et al. (2001), in high resistivity formations, as many induction as electrical logs are necessary for accurate formations evaluations. There are many wells drilled where R < Rt in the zones of interest containing hydrocarbons. In these cases, the interpretation of laterologs is more adequate. This is likewise true for wells where Rmf ≤ Rw, ensuring that Rxo ≤ Rt at all intervals.

In the piston model, used in this work, the resistivities vary from 1 to 2000 ohm-m over 36 layers. In each layer was simulated invasion of the drilling fluid. The depths of invasion vary from 0.1 to 0.45 m in the upper log range, and these depths were scaled based on the value of the porosities of the layers and the adjustment of the responses of the simulated values with the actual data. Thus, Figure 3 shows the responses to the piston type model, where the green line represents the LLS response, in black the LLD, and for comparison purposes the actual data used as reference for direct modeling were plotted in red. In the piston model, as there is no annulus presence, there was an adjustment in the curves in comparison to the real data. It is possible to verify a departure from the two responses (LLS and LLD) only at the high and low peaks of the resistivity curve. In these models is included the invasion of the drilling fluid according to the porosity of each layer. The depths on the vertical axis are referential.

b) Annulus Type

A large discrepancy between the salinity of the water and the drilling mud is responsible for the presence of a ring of low resistivity near the well wall. The annulus develops when the mud cake has not yet been constituted and the rate of invasion is high (Figure 3). Thus, most of the oil will be displaced in its upper part in a short period of time, and simultaneously miscible displacement of the original brine by the mud filtrate, with higher resistivity (Carrasco & Carrasquilla, 2011).

This ring suppresses the sensitivity of the tool measuring currents. The modeling of the process of invasion of filtered mud is the only possible way to estimate the saturation of hydrocarbons in situ from electric logs. It is also found that laterolog measurements are only marginally affected by the comportment of a low resistivity ring (Torres - Verdín et al., 2004).

The annulus model used in this work has resistivity values ranging from 1 to 1000 ohm-m over 48 layers. In the lower layers, the modeling includes the transition zone, the oil-water contact and the water zone, a washed zone and later the annulus.

Results

Figure 4 shows the responses for the forward modeling of the piston type model, when a good fit is achieved. The green line means the response of the LLS, the black is the LLD and red the real data to be fitting. Figure 5, on the other hand, shows a rough representation of 10 layers for the 36 simulated layers, with their respective (average) values of resistivities. The invasion is shown in brown color and the virgin formation in green. The thickness of the layers is not considered.

Figure 6 displays the responses for the direct modeling of the annulus type model, when a good fit is reached. The green line signifies the response of the LLS, black is the LLD and red the real data to be matched. In the figure, it is verified that the upper part of the log, where there is no annulus presence, the curves coincide, while in the lower part, where the transition to water begins, the responses start to have a slight distance between them. The aquifer represented here is 27.5 meters thick. It is confirmed that the annulus has a strong influence in the responses of the logs, requiring a more careful adjustment in the modeling. Figure 7 shows an approximate representation of the distribution of layers and resistivities, when a good fit is reached in the presence of the annulus. The invasion is shown in brown color, annulus in blue and the virgin formation in green. The thickness of the layers is not considered. The actual model consists of 47 layers, but only the top 10 are presented in the figure, with the values of the resistivities being also approximated.

Conclusions

In this work, the forward modeling of the resistive deep lateral (LLS) and deep (LLD) logs were done in a satisfactory manner. The responses show that it is possible to model with a good fit with the piston model and no presence of the annulus. However, in its presence, it was evident that there is a departure in the log responses. It shows that its presence influences the log responses, which implies that it must be considered when the oil reserves are estimated in the reservoir.

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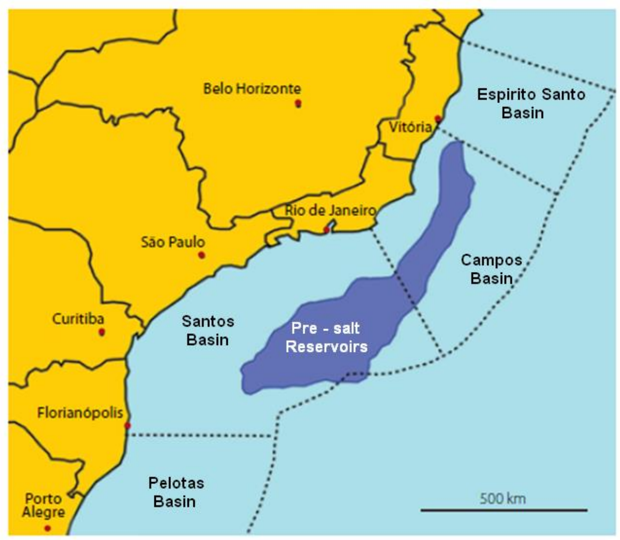

Figure 1. Pre - salt location map in Santos Basin (modified from Papaterra, 2010, apud Riccomini et al., 2012).

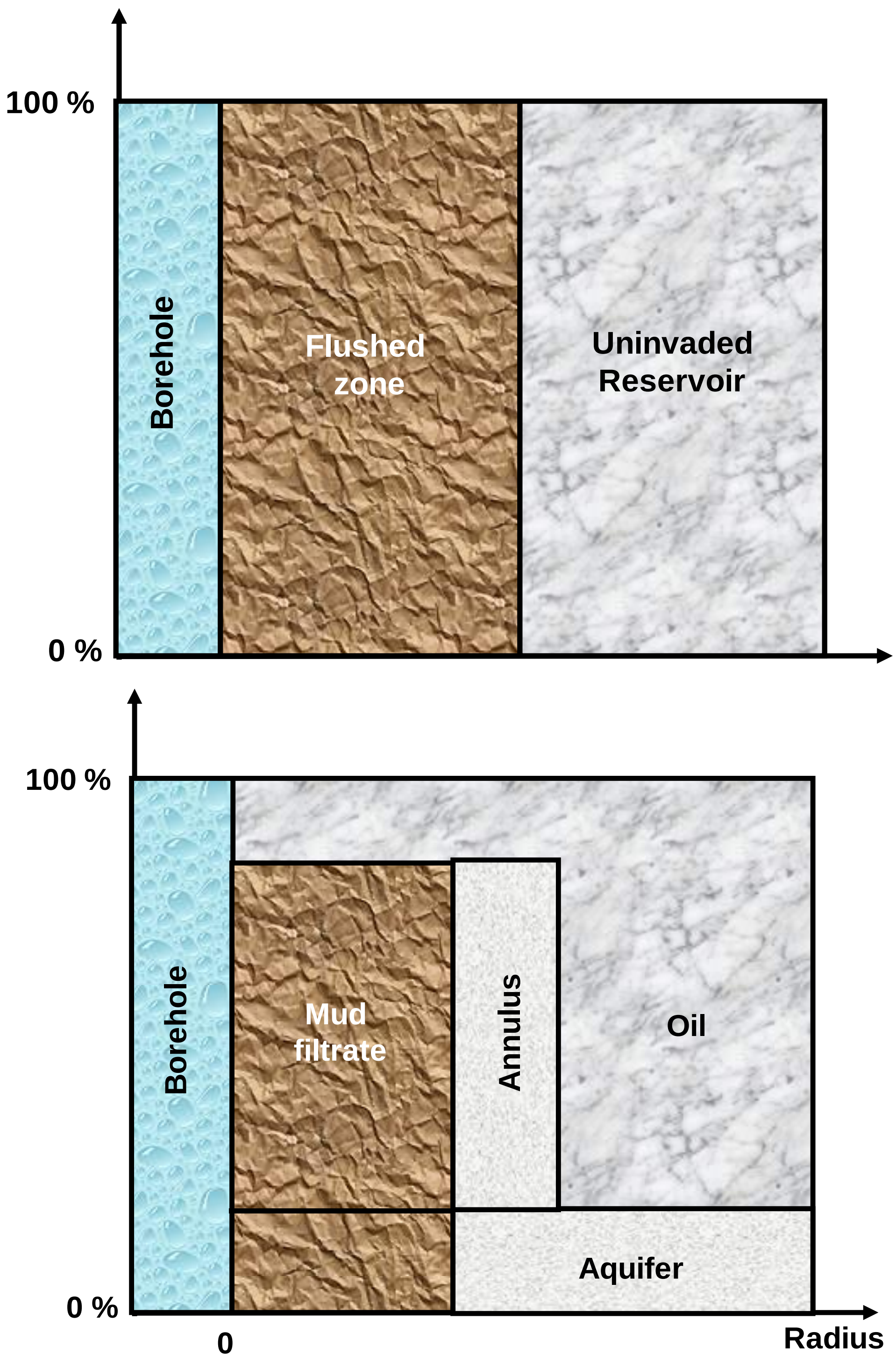

Figure 3. Annulus type model (modified by Singer and Barber, 1988, apud Carrasco & Carrasquilla 2011).

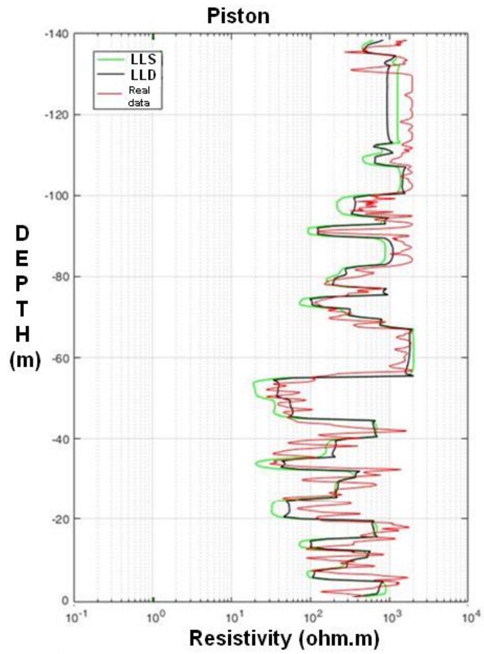

Figure 4. LLS and LLD responses for the piston - type model.

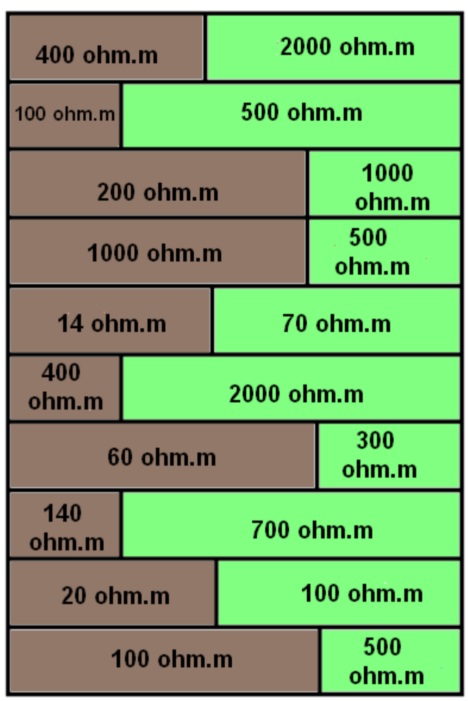

Figure 5. Approximately distribution of layers in the piston type model after a good fit with forward modeling. The invasion is shown in brown color and the virgin formation in green. The thickness of the layers is not considered.

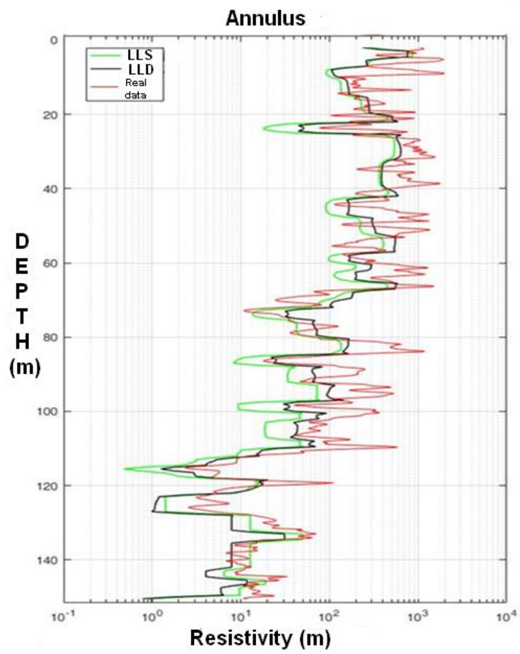

Figure 6. Responses of LLS and LLD tools for the annulus type model.

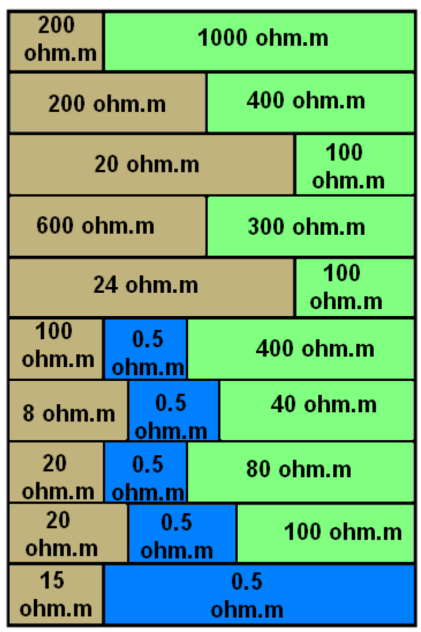

Figure 7. Approximately distribution of layers in the annulus type model after a good fit with forward modeling. The invasion is shown in brown color, annulus in blue and the virgin formation in green. The thickness of the layers is not considered.