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Numerical simulation of surface-downhole geoelectrical measurements in order to detect brine plumes

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ABSTRACT

A large amount of hydrocarbon reservoirs in the world are in the secondary recovery stage and improving this step in the exploitation of these reservoirs would greatly benefit the oil industry. Secondary recovery involves injecting brine in some wells in order to maintain reservoir pressure. The injected water moves mainly through the channels with higher permeability of the reservoir rock. The identification of these channels would allow the development of technical strategies to close them. In this context, the ability to detect brine flow pathways after injection is a goal of this work. Given the high electrical conductivity of brine, the use of geoelectrical methods can be useful to detect and monitor flow evolution. The limitations in the application of this method are due to the characteristics of the target: a very conductive fluid is usually contained in paths with dimensions that are much smaller than the depth at which it is located. Therefore, our objective is to overcome these constraints in order to find the strategies required to successfully detect and eventually monitor the movement of brine flowing from injection wells.

In this work, we studied the feasibility of detecting brine in an oil reservoir with surface-downhole electrical measurements. To achieve this, we designed an electrical model of the reservoir from well data and numerically simulated the forward geoelectrical response to determine the conditions under which the anomaly, i.e., the accumulation of brine, can be identified. Our results show that once the initial location of the brine is known, by installing potential electrodes in a single well the direction of brine migration can be determined, even in unfavorable conditions with relatively few surface measurements. In the case of a well equipped with permanent electrodes, this could be an efficient method to monitor the evolution of the brine plume.

1. Introduction

The exploitation of a hydrocarbon reservoir is typically conducted in three successive steps. The first one is primary recovery, when the reservoir pressure is high and hydrocarbon production is achieved through the use of pumps. The second step is secondary recovery, when brine is injected in some of the wells in order to maintain reservoir pressure, and water and oil production is carried out in adjacent production wells. The third step is tertiary recovery, also known as Enhanced Oil Recovery (EOR), when hydrocarbon production requires a more complex production strategy. EOR usually implies the injection of carbon dioxide (CO_2), solvents, and polymers, or the use of thermal methods. Due to its high cost, this phase is implemented when the prices of crude oil are economically favorable.

Most of the world's reservoirs are currently in the advanced primary or secondary recovery stage. Therefore, any optimization strategy that can improve the secondary recovery stage is very important to the oil industry. In the secondary phase, the injected fluid is composed of brine in order to avoid damaging the porosity network of the reservoir. However, due to rock heterogeneities which cause porosity and permeability variations along different volumes in the same layer, and because brine and hydrocarbon have different mobility values, the amount of rock by which either oil or water occupies will vary spatially. Taken together, heterogeneity and mobility could cause inefficiencies for the brine injection if the injected solution bypasses the majority of the oil-filled pores. The identification of high permeability channels allows the development of technical strategies to close them, e.g., by injecting cross-linked polymers to form a gel that will occlude the channel, by modifying the injection pattern, or by drilling a new production well.

Since brine has a high electrical conductivity, geoelectrical methods can be useful to detect and even monitor flow evolution. The limitations in the application of this method lie in the characteristics of the target: a very conductive fluid usually contained in paths whose dimensions are much smaller than the depth at which it is located. Therefore, our objective is to overcome these constraints in order to find the strategies

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required to successfully detect and eventually monitor the movement of brine flowing from the injection wells. In a previous work, Bongiovanni et al. (2013) performed an electrical conductivity study on the detection of brine saturation in an oil reservoir located at depths of 500 to 600 m. For that particular case study, the wells were already in operation and had not been instrumented with permanent electrodes. Different scenarios were numerically simulated and it was found that by placing a few embedded electrodes, each one within the formation at approximate 200 m depth, and laterally separated according to Wenner configuration, the fluid could be detected. Though the work was successful, its application was limited and embedded electrodes far from the injection well were necessary.

Taking into account the above considerations, we now propose to combine sensors on the surface with sensors in the injection well. This methodology has been successfully applied for shallow fluid monitoring (e.g., Rucker et al., 2014) as well as for deeper characterization of a resistive fluid (CO_2) (Schmidt-Hattenberger et al., 2011; Bergmann et al., 2012), but there is no evidence of this method having been used to detect brine for secondary recovery of oil. Therefore, the main objective of the present work is to study the feasibility of detecting brine in an oil reservoir with surface-downhole measurements. To achieve this, we have designed an electrical model of the reservoir from the well data, and numerically simulated the forward geoelectrical response. The modeling was conducted to specifically determine the conditions under which the anomaly, i.e., the accumulation of brine in a volume of small dimensions with respect to its depth, can be identified. The advantage of the method is that the anomaly can be detected with potential electrodes in a single well and its coverage can be mapped effectively by deploying several lines of current electrodes on surface.

2. Background

At shallow depths, monitoring saline fluid migration by means of electrical resistivity tomography (ERT) is a well-established method and valuable information on the spatial variability of solute transport processes can be obtained (e.g., Slater et al., 2000; Perri et al., 2012). The geoelectrical method has received consideration as a tool for permanent monitoring of saline storage reservoirs due to its high sensitivity to compositional pore fluid changes and, therefore, has been the key methodology applied for saline tracer imaging (e.g., Binley et al., 1996).

The sensitivity and resolving power of ERT depend on the type of acquisition methodology. Operating from the ground surface only, although it is a non-invasive methodology, could lead to severe limitations in terms of resolution. Typically, surface ERT can monitor extensive regions but, as its resolution decreases markedly with depth, it tends to be used only for shallow saline tracer systems. The monitoring of tracers in the subsurface via surface ERT has been conducted by Cassiani et al. (2006), Monego et al. (2010) and Robert et al. (2012).

As technical developments allow also the use of downhole electrodes, ERT applications are not constrained strictly to near surface investigations. ERT can also be used to monitor dilution and displacement of a saline tracer plume with electrodes in a borehole, as demonstrated by Slater et al. (2000), Binley et al. (2002) and Wilkinson et al. (2010). Furthermore, it is known that sensitivity and resolution measures show a reasonable capability of imaging saltwater intrusions if surface electrodes are used in combination with a few downhole electrodes. Results of a saline tracer test experiment using both surface and cross-borehole configurations can be found in Kemna et al. (2002), Daily et al. (2004) or Perri et al. (2012).

It is also worth noting that an innovative idea is currently being tested for using ERT to monitor fluid flow using steel well casings as very long electrodes (called LE-ERT: long electrode electrical resistivity tomography). A near-surface application concerning leak detection around a nuclear waste tank, at depths of roughly 10 to 15 m, was conducted by Rucker et al. (2011). More recently, the LE-ERT method was applied in deeper formations (around 100 m) by Ronczka et al. (2013). In the latter work, the authors developed a monitoring system using boreholes as electrodes in order to detect saltwater intrusions that threaten fresh water aquifers.

The problem arises when going to depths exceeding 300 m, as the possibility to detect saline tracer from the surface is practically null and the lateral range of detectability by borehole electrodes is typically limited by their coverage. For example, in Picotti et al. (2013), an electrical resistivity array located in a well was used for monitoring CO_2 migration. The electrical imaging allowed characterizing the distribution of the fluid but the range of lateral penetration was limited by the electrode separation. In the case of monitoring brine in an oil reservoir, this constraint has worse effects. Typically, the porous media containing the hydrocarbon in the reservoir has a thickness of tens of meters. Therefore, the number of electrodes that can be located in the section inside the reservoir is limited and their separation prevents large-scale lateral investigation. This limitation can be partially overcome by using cross-borehole data. Nevertheless, reservoir monitoring at great depths is not straightforward and its success depends on the number and location of the sampling wells. The installation of electrodes deep in a reservoir should be implemented in a cost effective manner during the completion of production/injection wells (Prevedel et al., 2008).

3. Electrical model of the reservoir

A hydrocarbon reservoir contains oil, water, and often a gaseous phase, supported by a geological structure that does not allow these products to escape to the surface. The oil is confined in a porous medium of sedimentary origin, such as sandstone or limestone, with different degrees of consolidation. The reservoir we are modeling is an oil field with a depth of around 500 m, located in the western part of Argentina. The reservoir is currently under secondary recovery operations and we focused our study on an area of approximately 1 km^2, containing six injection wells and eight production wells. The mean distance between the wells is 300 m.

To build the model, we used electrical data acquired from boreholes when drilling, as well as porosity values from rocks belonging mainly to the reservoir together with their geological interpretation. Due to the irregular terrain, the top of the geological formation containing the reservoir is located from approximately 475 to 515 m depth, depending on the location of the wells. Therefore, to assign suitable resistivity values to the reservoir, we used Archie's law (Archie, 1942), which provides the relation between the actual resistivity of a rock and its water content (Bongiovanni et al., 2013):

$$R_t = a\varnothing^{-m} S_w^{-n} R_w \tag{1}$$

where R_w and R_t are the resistivities of the water and of the rock partially filled with water, respectively; $\varnothing$ is the porosity of the rock; S_w is the fraction of the pore volume filled with water; m is the cementation factor; n is the saturation exponent and a is the tortuosity factor. We used the values $a = 0.62$ and $m = 2.15$ as given by the Humble formula for the formation factor suitable for many granular rocks (Telford et al., 1990). To complete the formula, a value of $n = 2$ was also used (Telford et al., 1990). The data obtained from the wells showed that the porosity of the formation lies between 25% and 30% and that the brine concentration was 30,000 ppm. The brine resistivity at 500 m depth with a temperature of around 40 °C is 0.15 $\Omega\cdot$m (Serra, 1984). After the primary and secondary oil extraction, there is about 65% to 75% of oil remaining in the formation. We assumed that the pore space left free is completely occupied by the brine. That is to say, from 25% to 35%, respectively of the pore volume is filled with brine, and S_w takes a value between 0.25 and 0.35. With these values substituted into Archie's law, the formation resistivity takes a value between 14 and 29 $\Omega\cdot$m. We assign an expected value of $\rho = 21$ $\Omega\cdot$m and a thickness of 100 m for the reservoir layer.