Feasibility analysis of surface-to-reservoir electromagnetics for waterflood monitoring

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Summary

We analyze, by means of a synthetic model, the feasibility of detecting the electromagnetic (EM) field variations related to waterflood in a large Saudi Arabian Jurassic reservoir. We utilize a 3D structural reservoir model and derive the geoelectric parameters from careful analysis of well logs acquired at the Saudi Aramco Technology Test Site. The resistivity variations as a result of water flooding are derived using characteristic parameters and injection water salinity of the field. We model a geometry consisting of a radial surface galvanic source and four EM receivers located at the reservoir level. The full EM field is modeled in the time domain and the horizontal and vertical electric field (Ex and Ez) and horizontal crossline magnetic field (dBy/dt) components are interpreted and analyzed. Results indicate that all the modeled fields show substantial variations as a result of water saturation changes with field strength values above the noise level expected for EM sensors. The results will be validated next by modeling more complex and realistic 3D patterns of water saturation in the reservoir, as derived directly from reservoir simulation. Given that one of the modeled components is the vertical electric field, the electrical anisotropy of the overburden is expected to play a significant role in the response and will be taken into consideration in the next round of modeling. Modeling results also suggest that the type of borehole EM sensors currently available in the industry may not be adequate for surface-to-reservoir EM applications.

Introduction

Saudi Arabian reservoirs range from early development to mature conditions. The main oil reservoirs are located in Jurassic carbonate rocks and are typically produced with peripheral water injection using brine for pressure maintenance. Producing wells are progressively turned into injectors when the water front reaches the producers. This reservoir development technique has proven to be very successful over the years allowing very high recovery factors to be reached. Some of the reservoirs have been producing for more than 50 years and optimization of production and monitoring techniques are then required to further enhance the recovery. Fractures in the reservoir generate super permeable zones (super-K) that make the distribution of the water flood irregular. Geophysical methods are therefore the best candidate to infill the information in-between wells and provide feedback to the reservoir simulators. Different geophysical techniques can address the problem with various degrees of efficiency, sensitivity and resolution. In this paper we illustrate the preliminary results of a feasibility analysis carried out using a Jurassic reservoir model and an acquisition geometry involving EM sources located on the surface and receivers located at the reservoir level. This technology is not currently commercialized by any service provider but presents significant possible advantages with respect to maximization of source power and reduction of receiver-side noise.

Parameter sensitivity

Given the characteristics of the reservoir under study, we can compare (Table 1) the expected relative changes of geophysical parameters relative to a baseline of 5% water saturation (Sw).

Sw %	Density % variation	P-velocity % variation	Resistivity % variation
100%	3.1	3.3	99.2
75%	2.3	1.0	98.6
50%	1.5	0.2	97.5
25%	0.7	0.0	92.4
10%	0.2	0.0	67.0

Table 1. Comparison of the relative variation of geophysical parameters for different amounts of water saturation (Sw). Values are normalized relative to a reference Sw=5%.

As expected, the resistivity parameter shows the largest relative variation when compared to density and P-velocity. The amount of change in the resistivity is such that under certain specific conditions, the electromagnetic fields should change enough to be detected. Electromagnetic techniques can therefore be used as an indicator of the presence of water in the reservoir. It should be also noted that the amount of the resistivity variation is highly non-linear, with the greatest changes occurring at low water saturation (e.g. up to 25% Sw).

Geoelectrical model

A 3D model resembling a typical reservoir of the eastern province of Saudi Arabia was used and consisted of a large anticlinal structure. The model has spatial dimensions of 18km by 18km by 2km in x, y, z directions and is surrounded by a large external domain to take into account boundary effects. The hypothetical reservoir is located at 1700m depth with a total thickness of 195m (Figure 1). The geoelectric structure of the overburden is provided by log data acquired at the Saudi Aramco Technology Test Site including both horizontal and vertical resistivity (R_h and R_v respectively). Only the horizontal (R_h) component was used for modeling in the present work. The resistivity of the reservoir is modeled using Archie's law by utilizing realistic parameters such as water resistivity (derived from the salinity content of the injected water), porosity and coefficients: a, m, n, used in production petrophysical analysis. In this first test we assume two water saturation scenarios corresponding to 13% and 50% water saturation. This water saturation range is intermediate as the actual extremes can be as small as 4% Sw or less, to more than 80% Sw. The resistivity values used in the fluid substitution modeling are therefore 55 Ohm.m (13% Sw) or 4 Ohm.m (50% Sw) for the reservoir layer (Figure 1). These theoretical values from Archie's law are consistent with typical values observed in the logs for corresponding water saturations.

Modeling approach

A 3D Finite Element Time-Domain (FETD) EM direct solver of Um et al. (2010) was used in the modeling, which is based on a geometry-conforming unstructured tetrahedral mesh representation of the geologic structure. The acquisition geometry consists of a single source electric dipole 800m in length on the surface oriented along the radial direction with the center of the dipole at a horizontal distance of 2.7km from the borehole. The transient signal modeled consists of a step-off function with a current of 30A. The full EM field is modeled at depth in the reservoir section, as well as above and below the reservoir. This scenario assumes that electric/magnetic receivers could be located either in vertical or horizontal boreholes.

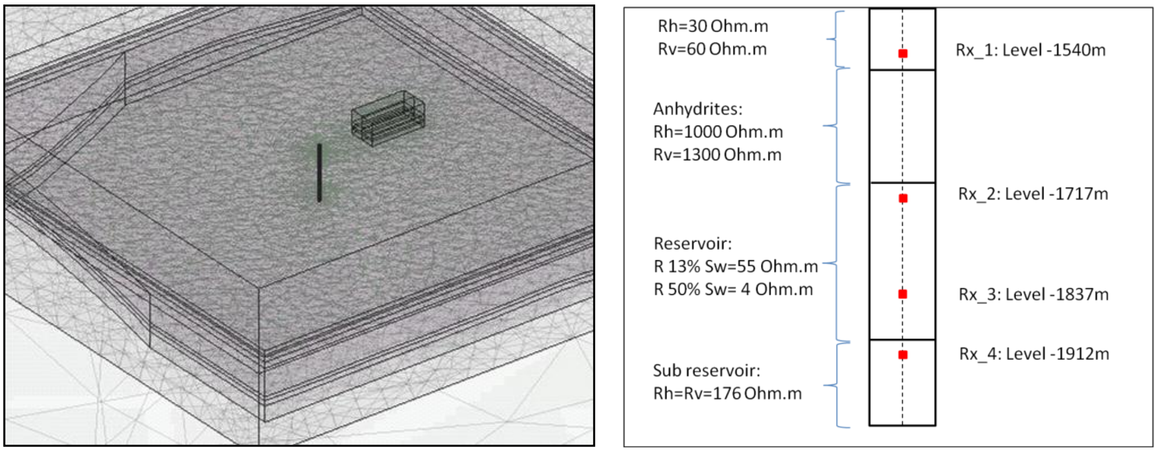

Figure 1. Model sketch with location of the borehole and source position (left) and the deep geoelectric structure and position of the modeled receivers (right). Only the R_h component of the model is used for the current modeling.

Discussion

The acquisition configuration with an electric dipole source oriented in the radial direction from the well generates a radial (i.e., inline) electric field Ex, a vertical electric field Ez and the horizontal magnetic field component (dBy/dt). The dBy/dt is the only (time derivative) magnetic field component present for 1D, 2D and 3D structures that are symmetric relative to the radial direction to the well (Um and Alumbaugh, 2007).

Results (Figure 2) indicate that all the modeled EM components show large sensitivity to the variations of the water saturation in the reservoir. The qualitative behavior of the fields can be analyzed at early times (i.e., almost DC conditions) by considering the EM boundary conditions. The Ex component shows a decay which is consistent with the increased distance from the source. This result is consistent with the continuity condition of the tangential electric fields across two boundaries. Notice the sharp drop of the Ex component across the resistive anhydrite layer above the reservoir zone (i.e., from receiver Rx_1 compared to the others). This sharp drop is further enhanced by the decrease of resistivity in the reservoir layer corresponding to 50% Sw.

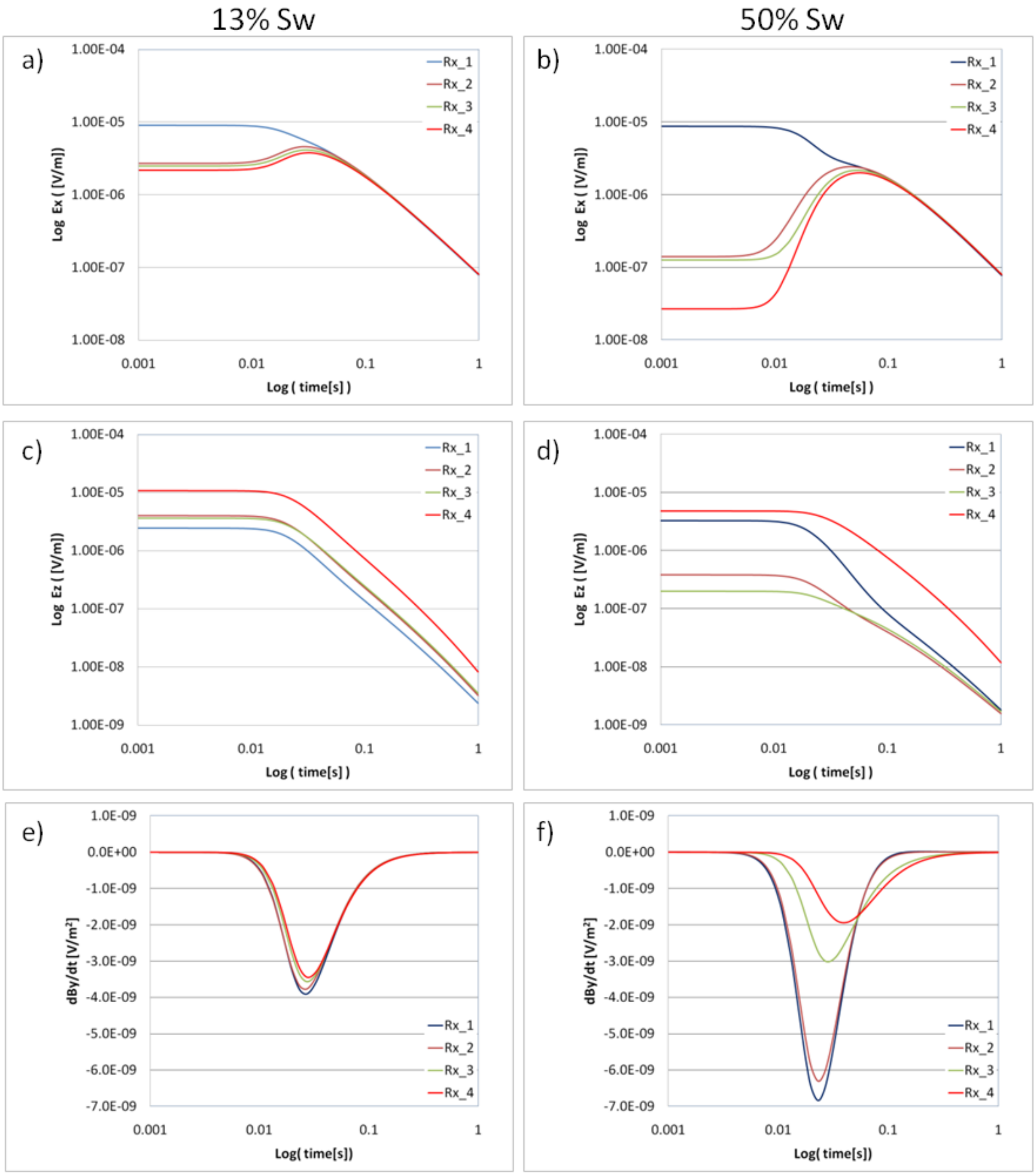

Figure 2. Surface-to-borehole EM field responses: Ex (a-b), Ez (c-d) and dBy/dt (e-f); for the case of 13% water saturation (left column) and 50% water saturation (right column) in the reservoir.

The behavior of the Ez component is less intuitive. Receiver Rx_1 at 1540m depth shows a smaller electric field for 13% Sw relative to other deeper receivers. To explain the phenomenon we have to consider Ohm's law (1) and the EM boundary condition for vertically propagating currents, which imposes continuity of the normal current density at static (i.e., DC) conditions (2). As a consequence, the resulting Ez fields are related to the local resistivity structure (3),

$$\mathbf{J}_i = 1/\rho_i \, \mathbf{E}_i \qquad (1)$$

$$\mathbf{J}_{zi} = \mathbf{J}_{zi+1} \qquad (2)$$

$$\rho_i \mathbf{J}_{zi} = \rho_{i+1} \mathbf{J}_{zi+1} \qquad (3)$$

where **J** is the current density [A/m^2] and ρ is the resistivity [Ohm.m]. The strength of the vertical electric field is controlled by the resistivity of the layer where the receiver is located. In our case (see

Figure 1) at 13% Sw, we have $\rho_4>\rho_2=\rho_3>\rho_1$. As a consequence, the corresponding fields at early times are: $Ez_4>Ez_2>Ez_3>Ez_1$ (Figure 2). Notice that Rx_2 and Rx_3 are both in the reservoir layer and therefore have the same resistivity but $Ez_2>Ez_3$ because Rx_2 is spatially closer to the source. In the case of 50% Sw, the resistivity structure changes to: $\rho_4>\rho_1>\rho_2=\rho_3$. Accordingly, the electric fields are: $Ez_4>Ez_1>Ez_2>Ez_3$ (Figure2). The time derivative of the magnetic field dBy/dt is also displaying a strong response in relation to the water saturation change. This makes the use of magnetic sensors attractive for water flood monitoring purposes. We can further observe that most of the response of the EM fields occurs for times less or equal to 0.1s and are within the expected noise levels of the instrumentation. These observations are consistent with results obtained in a previous 3D simulation study on a similar model (Colombo et al., 2010).

The results obtained so far are quite encouraging, but one should take into consideration that the actual pattern of water saturation in the reservoir is more complex than that modeled here. We should therefore anticipate that for complex 3D distributions of water flooding, the expected responses may be smaller. Moreover, this total field time domain simulation approach shows sensitivity to the model dimensions, as these have effects on the initial values of the electric field for step-off simulations (i.e., DC conditions). The expected error is comprised of a few percent static shifts of the transient EM curves (Sena, 2011, personal communication), however, these errors do not affect the qualitative behavior of the fields. This observation is important for the interpretation of real data.

Conclusions

Results obtained from this 3D modeling exercise (not including the effects of steel casing) indicate that the change in resistivity induced by water-oil substitution (i.e., the waterflood process) produces detectable changes in the EM fields for a configuration of a radial surface galvanic source and receivers located close to, or in the reservoir section. The primary EM field components generated by this geometric configuration are Ex, Ez and dBy/dt, which imposes constraints on the type of EM receivers deployed in a vertical borehole. The only receivers available in the industry, and operating in the frequency band of interest, are vertical magnetometers, measuring the time derivative of the vertical component of the magnetic field (dBz/dt). This component should be minor for a surface-borehole configuration. Additional 3D modelling, which involves the introduction of electrical anisotropy for the overburden, is ongoing and includes 3D resistivity distributions in the reservoir, as derived from the reservoir simulator.

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