8th Biennial International Conference
& Exposition on Petroleum Geophysics

"HYDERABAD 2010"

P-101

Feasibility of OWC monitoring from the surface with EM methods

Cyril Schamper *(Sisyph, Univeristy of Paris 6)*, **Baptiste Rondeleux** *and* **Simon Spitz*** *(CGGVeritas)*

Summary

In the last years the possibility of using the electric resistivity as a DHI has strongly raised the interest of the oil and gas exploration community in the EM methodology. But the ability to directly address the nature of the fluids points also to EM in problems related to the reservoir management. This paper discusses some aspects of the feasibility of EM to monitor, from the earth surface, the production related OWC lateral variation in a reservoir. We have chosen this particular subject owing to the large contrast in the electrical properties between hydrocarbons and saline water. Indeed if the spatial variation of a contrast of the order of 1:100 at a depth interesting the oil industry cannot be handled, it is doubtful that EM would be useful when more subtle changes are involved.

Introduction

The controlled source electromagnetic method (CSEM) is often used today in conjunction with seismic data in oil exploration. Since resistivity is closely related to the nature of the fluids, one can expect that resistivity changes induced by changes in the fluid flow in a reservoir can be actually recorded. In this paper we discuss some aspects of the feasibility of monitoring the lateral variation of the oil-water contact inside a reservoir. OWC monitoring might be the most obvious application of time lapse EM, owing to the major resistivity contrast between brine and hydrocarbons.

It is well known that the EM field propagation into the earth does not follow the wave equation. One implication is that the overburden plays a major role: the more conductive the overburden, the less signal reaches the target, leading to a smaller 4D signal. It also follows that 4D EM is more difficult to deal with than 4D seismic because is concerned with amplitude changes rather than with time shifts. It is therefore imperative that experience of fluid substitution should be performed with a 3D code: the utilization of a 2D code, implying that the change is infinite in one direction, would largely over estimate the 4D EM response. The models and inversions discussed in this paper have been obtained using a 3D code that solves the integral Maxwell equations (Schamper et al., 2008) for the anomalous field due to some resistivity anomaly embedded in a "simple" background earth. The integral formulation can be written for any electrical component as following:

$$e_i = e^0_i + \int \sum G^0_{ij}\, \sigma'\, E_j \qquad i, j = x,y,z \quad (1)$$

In this expression e stands for the electric field measured at the surface, 0 for the background electrical distribution, G for the Green tensor components, E for the total electric field inside the anomaly. ' denotes the anomalous distribution of conductivity inside the anomaly and the integration domain is restricted to the volume of that anomaly. The Green tensor components are analytical under the simplified assumption that the background is a layered 1D Earth. The integral equations implementation has the advantage of separating the reservoir, where changes are expected to occur, from the background earth model.

Monitoring the OWC lateral variation is feasible if the induced 4D signal is measurable, if it exceeds the 4D (non repeatable) noise and if the acquired data can be inverted allowing the change in fluids to be correctly positioned in depth. In this paper we present some implications of fluid replacement simulations in terms of signal-to-noise both at acquisition and at the inversion stage.

CGGVeritas, 1 rue Leon Migaux, 91341 Massy, France, simon.spitz@cggveritas.com

EM 4D acquisition: signal and noise

A simplified reservoir is illustrated in Figure 1. The reservoir, at a depth of 1 km, has oil gradually replaced by water. The reservoir is a square box of 4 sq. km., 100 m thick, embedded in an aquifer that extends in all directions. The 3D body and the aquifer are embedded in a uniform earth of 10 Ohm-m. The simulations are made for a resistivity contrast between water and oil of 1:100. The source-receiver geometry is made by a horizontal electric dipole located at the center of a square array of receivers of 25 sq. km. The receiver emits a sinusoidal signal of 1 Hz and both components of the horizontal electric field are recorded.

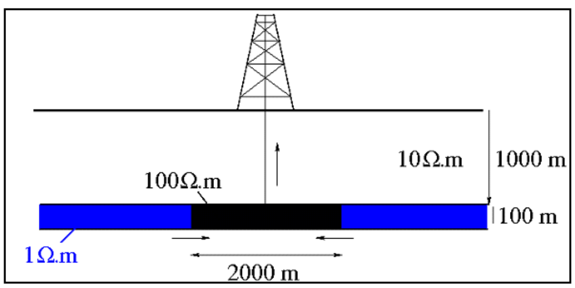

Figure1: A box like reservoir filled with oil and embedded an infinite aquifer.

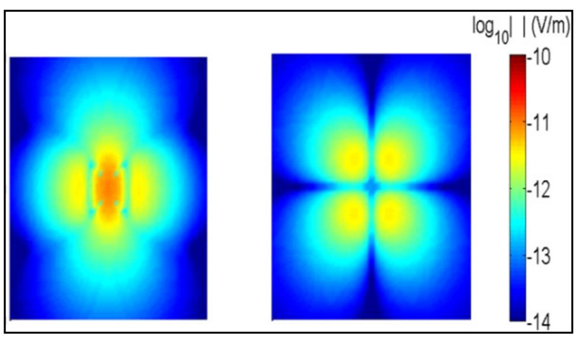

Figure 2: The amplitude of the 4D electric field components at the earth surface corresponding to a 50 m water invasion. DEx is on the left, DEy on the right, with the elementary dipole oriented along x. These amplitudes correspond to unit electric dipoles and a unit source emitting 1 A at 1 Hz.

The amplitudes of the horizontal electric components of the 4D signal measured at the surface corresponding to a reduction of oil to 1.9 x 1.9 sq. km. are shown in Figure 2. The 4D signal is small: operating 100 m electric dipoles as receivers and a dipole electric source of 100 emitting 10 A, the maximum of the 4D signal is of the order of 1 V with most of the amplitudes of the order of 10 µV. The 4D signal would be of course higher for a larger shrinking For a depletion of about 30% (a shrinking to a surface of 1.6x1.6 sq. km.) of the oil filled volume the 4D electric signal would be one order of magnitude higher.

Are such small differences as the ones illustrated in Figure 2 actually measurable in situ? We have acquired passive (non repeatable) electric signals on an array in an industrial site near Paris. Time series of 10 seconds have been recorded in a continuous manner during several weeks. Typical results on 100 m dipoles show that non repeatable noise (i) follows indeed an attenuation law in sqrt(N), N being the number of time series involved in the vertical stack, (ii) is fairly independent of the frequency around 1 Hz and (3) is of the order of 500 nV (on a 100 m dipole) after 2 days. It follows that in order of differences as in Figure 1 to be measurable, it would have been necessary to wait for about 3 months with the actual source – receiver monitoring geometry.

EM 4D inversion: signal and noise.

The extensive use of 3D and 4D seismic is not only due to the high resolution of the seismic method, but also to the fact that seismic data can be processed in time and do not require to be inverted to depth from the onset. This is not the case with EM methods. EM data are notoriously difficult to interpret as they require a non-linear inversion and are most of the time tributary to some a priori resistivity model.

We have chosen to illustrate EM inversion of 4D data for OWC variation in a reservoir offshore. The reservoir, 50 m thick, has a surface of 4 sq. km., is embedded in a homogeneous earth and is located at 1000m below the sea floor. The water column is 1000 m thick. The resistivities are set to 10 Ohm-m for the homogeneous earth and 0.3 Ohm-m for the seawater. Production is achieved by water injection: the extracting well is in the center and two water injectors are located close to the borders. We imagine that 4D EM has been collected at two moments of the life of the field. The first is before production, with the reservoir full with oil. The second is later on, when some water has replaced the oil. The water intrusion is shown in Figure 3.

All the computations have been made assuming the oil filled rock has a resistivity of 100 Ohm-m, while the water filled rock a resistivity of 1 Ohm-m. Forward modeling is carried out by dividing the reservoir into 50m x 50m x 50m cells. The fluid changes are monitored with a permanent installation involving one source and a receiver array. The array is 10km x 10km wide and is located on the sea floor. At each point of the grid of receivers the two orthogonal components of the horizontal electric field are measured with dipoles of unit length. The source is a vertical electric dipole 100 m long, located in the middle of the array with one electrode near the sea bottom and emits a current of 1000 A at 1 Hz.

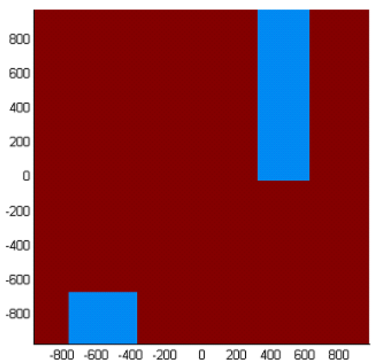

Figure 3: The map of the waterfront in the off shore reservoir: due to structure and inhomogeneous permeability the waterfront is not symmetrical.

The simulation (Figure 5, panel on the left) shows that for such a change in the reservoir the amplitude of the 4D electric field measured on the sea bottom varies between 2 and 6 nV/m for both horizontal components of the electric field (the amplitude of the 4D signal on x and y are similar, due to the central position of the vertical source). Figure 4 illustrates the inversion of the dataset, without any post processing. The 3D inversion has been carried out directly on the 4D data and involved only the reservoir cells: the geo-electrical distribution of the background, the location and the dimension of the reservoir are input parameters. The resistivity is assumed isotropic and constant inside each reservoir cell. Despite the data having been acquired with a single source position and at one single frequency, and despite some numerical noise, the distribution of water in the reservoir is clearly seen.

3D inversion of geophysical data is a non-linear, ill-posed problem. Moreover, the dimensionality of the unknown vector is often much larger than that of the recorded data. Due to the fact that the EM field obeys the heat equation, decreasing the spatial sampling between the sensors does not increase the conditioning of the inversion kernel. It follows that a particular inversion procedure, or a particular conditioning, may lack robustness in presence of coherent noise.

Source for such coherent noise are (among others) errors in the a-priori information. It is perhaps not intuitive, but an extra feature in the background (such as an extra layer) can modify the 4D response of the reservoir even if the electrical properties of that layer do not change with time (Lien and Mannseth, 2007). The explanation is easily obtained starting from (1) and writing the integral equation for a time-lapse experiment:

$$de_i = \int \sum G^0_{ij} \left[\sigma_1' E^{(1)}_j - \sigma_2' E^{(2)}_j\right] \qquad i, j = x,y,z \quad (2).$$

In the expression above dE denotes the difference between the electric fields measured at the surface at two consecutive moments, noted (1) and (2), in the life of a reservoir. As in expression (1), E stands for the total field inside the anomaly. It follows that the 4D EM effect measured at the surface does not depend only on changes inside the reservoir, but also on the background model geo-electrical distribution.

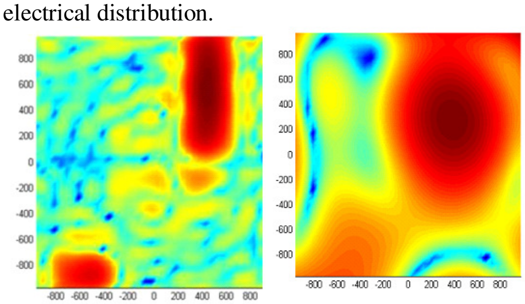

Figure 4. 4D inversion for the OWC in a reservoir off shore without any post processing. The result of the inversion with the correct (homogeneous) background model is displayed on the left. On the right is the result of the inversion when the background model is incorrect, the conductive layer having been ignored.

To experiment the effect of such noise, a 20 m thick conductive layer with resistivity 1Ohm-m has been introduced in the background model, at half distance between the sea bottom and the top of the reservoir (more precisely between 1490 and 1510 m). The amplitude of the 4D signal measured on the sea floor is slightly changed. Figure 5 (on the right) shows that the normalized difference between the 4D signals with and without the conductive

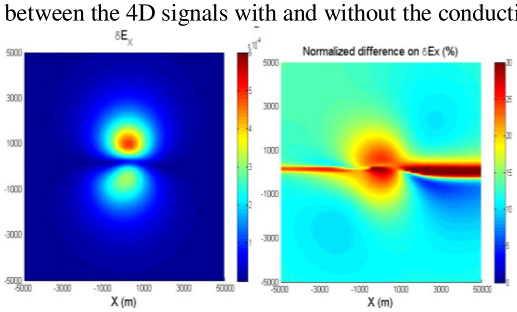

Figure 5. On the left, the amplitude of the Ex component of the 4D signal measured at the sea bottom. The dark red color indicates an amplitude of 6 nV/m. On the right, the normalized difference (in percent) between the amplitudes of the Ex components of the signal measured at the sea bottom with and without the conductive layer in the background. The dark red color indicates a percentage of 30%.

layer is less than 10%, but can reach 30% in the center of the receivers array.

Conclusion

Various theoretical experiments indicate that EM is able to monitor from the surface (or from the water bottom) OWC variations in a deep reservoir. This can be an important application, the resulting image being less local than that obtained with EM cross well tomography. The monitoring geometry considered in this paper is characterized by a single source location that emits a mono frequency signal, the changes in the EM field due to resistivity variation in the reservoir being recorded with electric receivers.

Because 4D variations of the field amplitude are small, the signal-to-noise issue is of utmost importance. For the 4D signal to be above the non-repeatable noise, the acquisition geometry has to be adequate. In that respect the background plays an essential role. If the overburden is conductive leading to a 4D signal smaller (or of the same order of magnitude) than the 4D noise, the source should be placed closer to the reservoir, with important operational consequences. When the recorded 4D signal is larger than the 4D noise (or when signal processing has reduced that noise to an acceptable level) inversion of the data is able to recover the volume of oil replaced by water. However it is doubtful that any regularization might handle the coherent noise due to an insufficient knowledge of the background. EM (or time lapse EM) data cannot be handled alone, but constrained with information from seismic data.

References

Lien M and Mannseth T, 2007, Controlled source electromagnetic data for production monitoring – a sensitivity study: 77 Annual International Meeting, SEG, Expanded Abstracts 502-506.

Schamper, C. Spitz, S. and Tabbagh, A., 2008, Feasibility of EM monitoring in land reservoirs, 71th Annual Conference and Exhibition, EAGE, Extended Abstract, paper 1031.