Interwell fluid mapping using multiscale data sets: An application of crosswell electromagnetics (EM) from Brazil

Rudolfo Beer*, Jorge Luiz Sena de Queiroz, Paulo Roberto Alves Netto (Petrobras), Laurence Reynolds*, Ajay Nalonnil*, David Alumbaugh, Ping Zhang and Sebastian Thum, Schlumberger

This paper was prepared for presentation during the 11th International Congress of the Brazilian Geophysical Society held in Salvador, Brazil, August 24-28, 2009.

Abstract

Crosswell resistivity interpretation combines the results of log processing for near-well parameterization and well-to-well results for setting the general structure away from the wells. Data processing and interpretation required to image and understand interwell resistivity is significantly different than summing the two ends of the crosswell scale spectrum - log scale and surface scale. The results need to be robust on a reservoir scale. By integrating multiple data sets the non-uniqueness of the inversion result required to image the resistivity is reduced.

Additional multi-scale data bring the possibility of translating the reservoir scale resistivity model to the reservoir engineering domain in order to calculate apparent water saturation and to enable fluid and seismo-facies modeling. This paper presents a description of the method and the workflows. The benefit of employing apriori data to construct geologically reasonable starting models as well as the need for appropriate upscaling, gridding and model population is discussed. A case study illustrates the importance of the multi scale approach to deliver a geologically and geophysically representative model and demonstrates the impact of constraints on the final resolution.

Introduction

While oil fields worldwide are becoming increasingly mature, operators are seeking additional technologies to help achieve further recovery and extend efficiencies. Secondary and tertiary recovery methods, as well as infill drilling programs, have proven to be extremely effective but at the cost of complex fluid dynamics in the reservoir, which are rarely well understood. Methods for enhancing the understanding of and predicting these fluid movements will play an increasingly important role in successful reservoir management strategies.

Resistivity variations in the subsurface can occur due to changes in porosity (subsidence), saturation (water flooding, bypassed pay) or temperature (steam injection).

In Crosswell electromagnetics (EM), the principle of electromagnetic induction is used to provide an image of the resistivity distribution between wells via tomographic inversion. The resistivity map can be used to monitor fluid movements on a reservoir scale,

While crosswell EM development for the oilfield started two decades ago, it is only today, with the advent of sufficient advances in processing and inversion techniques, as well as the development of relevant workflows, that meaningful oilfield applications using this technology, are becoming available

Method

Resistivity response to reservoir conditions

The contrast between a resistive background and a conductive body is the basis for detecting changes in certain petrophysical parameters in the reservoir.

Figure 1 highlights the response of resistivity (in red) and seismic P-wave velocity (in green) to variations in saturation, porosity, and temperature in the same sand core sample.

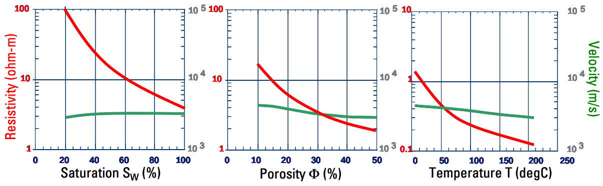

Figure 1: Resistivity response to changes in the reservoir

The seismic velocity measurement is more influenced by the formation rock properties and structure, while the resistivity measurement, is more sensitive to the actual formation fluids and associated detail. Both measurements are complementary.

In terms of depth of investigation and vertical resolution, crosswell EM fills the current measurement gap between logs and surface to surface measurements

The fact that the resistivity parameter is particularly sensitive to fluid saturation and temperature effects (independent of salinity) allows for its applications in both water and steam front monitoring. Both of these are much used enhanced oil recovery techniques.

Physics

The crosswell transmitter generates a magnetic field that is more than 100,000 times stronger than the source in a normal single well induction logging system.

The transmitter signal induces electrical currents to flow in the formation between the wells. These currents, in-turn, generate a secondary magnetic field related to the electrical resistivity of the rock where they flow (Figure 2).

At the receiver borehole, induction coil receivers detect the magnetic field generated by the transmitter (primary field) as well as the magnetic field from the induced currents (secondary field). The detection coils are extremely sensitive devices, consisting of many thousands of turns of wire around high permeability magnetic cores; this allows accurate measurement of the signals generated by the transmitter.

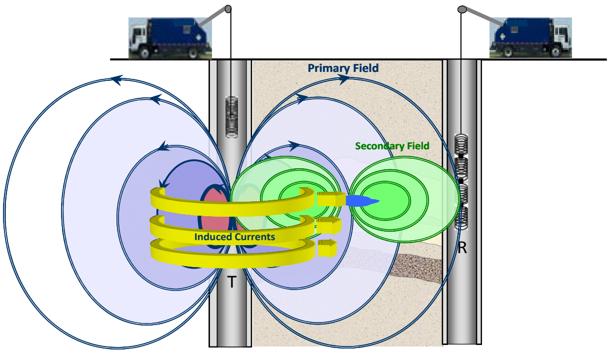

Figure 2: Crosswell EM acquisition system

Acquisition

The acquisition system consists of a transmitter tool deployed in one well and a receiver tool deployed in a second well located up to 1000m from the source well. The maximum interwell distance achievable is determined through modeling and simulation of the scenario.

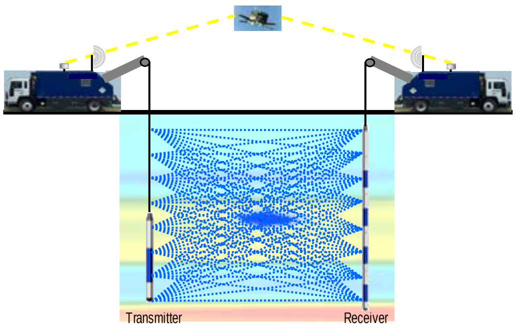

Figure 3: Crosswell EM acquisition system

The tools are connected and synchronized by GPS and deployed downhole with standard wireline equipment (Figure 3). By positioning both the transmitter and receiver tools over a logging interval roughly equal to or greater than the well spacing, adequate coverage for tomographic imaging is achieved. Effective tomographic interpretation of the resistivity distribution between the wells, requires the logging interval to include positions above, below, and across the zone of interest. The result is a physical measurement between the wells that is sensitive to fluids and structure in the subsurface and does not dependent on interpolation and/or geostatistical derivation.

Workflow

The complexity of the survey design, acquisition and interpretation means that a successful deep reading EM measurement across the reservoir is only possible if a rigorous workflow is followed (Figure 4).

Due to the non-unique nature of the inversion process, information from as many sources as possible on the reservoir must be used to guide the inversion to an answer that makes geological sense.

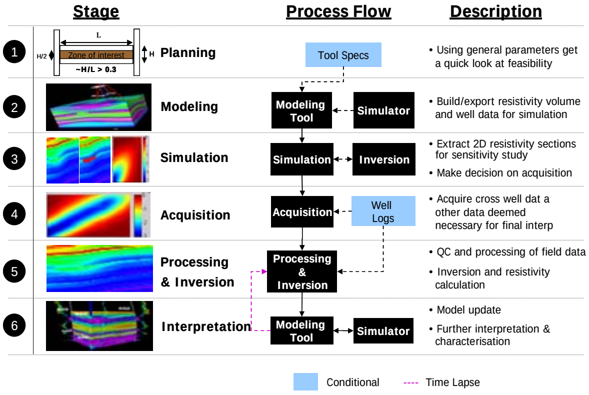

Figure 4: Crosswell EM workflow

The key steps in the Crosswell EM workflow, including the planning, acquisition and processing phases, can be described as follows:

In Step 1 – Planning - basic reservoir parameters and the proposed well geometries are used to determine project feasibility.

In Step 2 – Modeling – field data are compiled. Starting from an established reservoir or geological model or based on new offset well logs a 3D formation resistivity model is built up.

In Step 3 – Simulation - scenarios of possible fluid movements or targets are created through dynamic simulation or by hand. Using sensitivity analysis the survey sensitivity to each of these scenarios is simulated, through forward modeling, and the resulting resistivity distribution evaluated through inversion. This iterative step ensures suitability of the service to solve a particular problem and predicts what resolution can be expected, while optimizing the well spacing and the operational frequency. At the same time clear survey objectives are established helping to minimize operational risks while identifying the need for any additional information which may be required for completion of the data processing and interpretation phases.

In Step 4 – Acquisition - the EM surveys are acquired using the parameters established in the previous step. Tests to validate the recommended acquisition frequency in the actual environment and geometry are made as part of each survey, Other wireline logs or data necessary for the final interpretation may also be acquired at this stage.

Once the crosswell EM field data are acquired they are quality controlled (QC'd).

In Step 5 – Inversion – the 2D field data is processed via tomographic inversion to obtain a final RT map. In this step the inversion process starts with a resistivity model, derived from prior knowledge of the field area (in Step 2). Using a forward EM code the inversion calculates the model response in the 2D survey section and then adjusts the model parameters until the observed and calculated data fit within a specified tolerance.

The inversion process is based on Newton's method for estimating the value of a function from its value at a nearby location. That is, if you know the value of a function for a given model and its first derivative (sensitivity function) you can estimate the value of that function at a nearby position. By applying this sensitivity function to each point and iterating, the data misfit between old and new points can be reduced and a complete, new and theoretically more accurate model can be built up. If the new value of a point is very different to the original value then the first derivative alone is not adequate to guide the inversion. It is therefore essential that the initial model be somewhat close to the final model, unless the eventual misfit can be geologically explained.

In Step 6 – Interpretation - the inverted 2D resistivity distribution sections between well pairs are then ready to be imported to the static model. Maps from pairs with different geometries are combined to build up a 3D resistivity cube and integrated with the other available measurements.

From here, integration with, and further interpretation of the static and dynamic reservoir and geological models are then possible,

Case Study

Several crosswell EM projects have been completed in various geological, structural and production environments worldwide to date, with results showing good delineation of fluid boundaries in the formation as a result of water or steam injection.

The Case Study of the processing workflow included here refers to a crosswell EM survey comprising 8 profile "well pairs" from onshore Brazil, where the objective was to locate hydrocarbons left behind after several years of peripheral water flooding.

Data Integration to Produce a 'Starting Model'

To reduce the non-uniqueness and improve resolution of the crosswell image, data from multiple sources (wireline logs, core lithology and seismic) were integrated to construct a 3D resistivity starting model (Step 2) in preparation for the inversion process. This provided an apriori model that is more representative of reality than a uniform starting model. The generation of the final apriori model consists of three steps:

Step 1 - Geological Model Building

The first step in the generation of the starting model is to construct a geological model that incorporates known structural features such as stratigraphic interfaces and faults. This step can employ any type of geologic / geophysical / petrophysical data that are available.

Figure 5 shows how the surface seismic data (A) is used to guide the dip of the interfaces, creating faults (B) and horizons (one shown in blue - C). Well logs, such as the GR curve in white (D) help define the top/bottom of various stratigraphic intervals. The result is a structural framework consisting of a number of zones which represent the regions between the seismic-picked horizons.

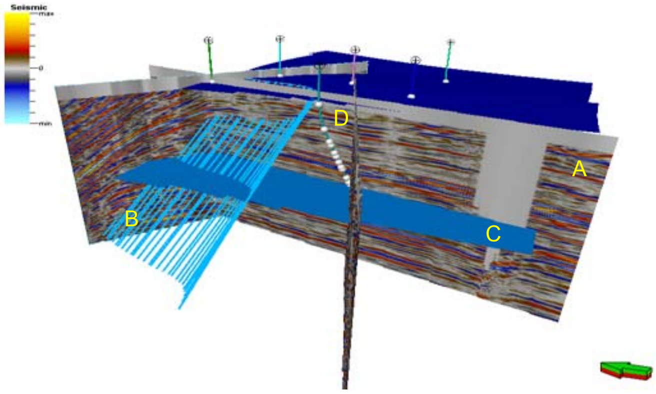

Figure 5: Using well logs and seismic to define zones and structural framework

These zones, with the inherent resolution of the seismic data, are used to guide the population of the model with resistivity values from the logs. Sub-zones or layers are generated to ensure that the main log variations are captured and to match the scale of the crosswell measurement.

Step 2 - Resistivity Log Upscaling

The upscaling of well logs such as resistivity and porosity and the subsequent interpolation between wells is required to populate the property model. The resistivity logs are first upscaled from their normal sampling interval (usually one measurement every 6 inches) to an interval that is comparable to that of the crosswell EM vertical resolution. The latter is considered to be on the scale of the receiver sampling interval which is generally 2.5m to 5m along the borehole. (Figure 6).

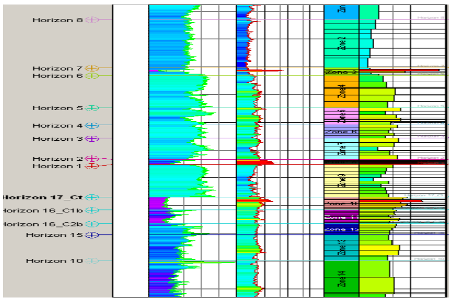

Figure 6: Log upscaling stages . Wireline logs on the left with final coarser upscaled logs at reservoir scale on the right.

Step 3 - 3D Model Population

The last step to produce a good starting model is to interpolate the upscaled logs, created in the previous step, between the wells, to produce a 3D distribution of the property (Figure 7) from which, in turn, a 2D cross-sections can be extracted for the inversion process. At this point, if appropriate geostatistical parameters (defining the variogram in x,y and z planes) are available then these can be used. Otherwise, simpler interpolation / extrapolation techniques can be employed.

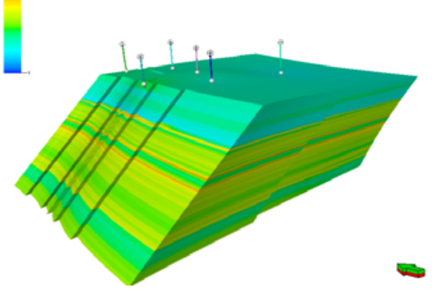

Figure 7: Populated start model of resistivity in 3D

Results

Crosswell EM Inversion with and without constraints

Using a starting model constrained along the wellbore with wireline logs and other near wellbore information, a guide inversion provides results with the best-achievable resolution and imaging clarity required to monitor fluid saturations in the target area. Typically, the inversion results of crosswell EM data using a uniform starting model (without any constraints), are dominated by the raw spatial resolution of the cross well measurement, while data inverted against a constrained model allows the measured data to be guided within real bounds (Figure 8).

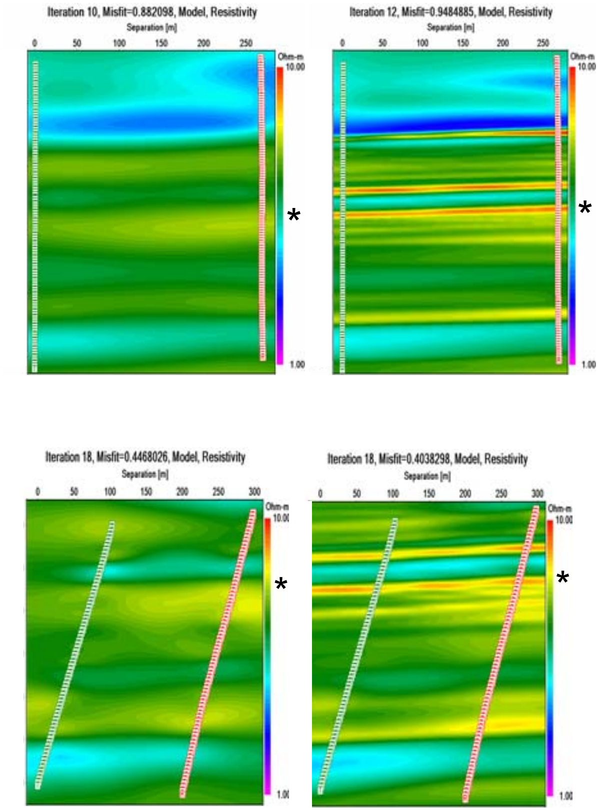

Figure 8: Inversion based on uniform starting model (left) compared with constrained start model inversion (right) for 2 well pairs. (Reservoir indicated at *)

Figure 8 shows the results from two of the 8 well pairs. The resistivity is scaled from 1 ohmm (cold colours) to 10 ohmm (warm colours). On the left, for both pairs, is the inversion based on a 5 Ωm uniform starting model with no constraints (other than those imposed by the regularization within the inversion algorithm (Abubakar et al., 2008)). Conductive zones are shales and sands while the resistors are the hydrocarbon bearing sands. The right side of Figure 8, for both pairs, shows the inversion result that employs the geologically and petrophysically constrained starting model.
Note that although the images show similar overall features, the constrained model results provide the higher spatial resolution required for interpretation.

Standard QC practice involves comparing inversion results from the uniform model with results from the constrained model for each well pair to ensure that the scale of the measurement is in the right range, both in terms of property value and structural trend.

Post-Resistivity Interpretation

The final product provided by the crosswell EM survey is a resistivity image such as shown in the right panels of Figure 8.

Several options for post inversion interpretation exist in the modeling domain, including the determination of new properties.

Importing the actual 2D crosswell resistivity images back into the geological or reservoir model allows for an improved way of correlating the different scales of data between the log interpolation and the coarser scale seismic, helping to better define the lateral and vertical variations of resistivity (Figure 9). At the same time it allows trend analysis and correlation of the resistivity property to highlight potential seismic bright spots directly in the depth domain.

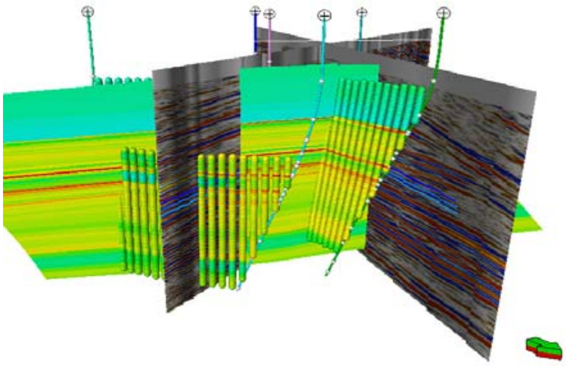

Figure 9: Inversion profiles imported into model domain with an interpolated log resistivity intersection, tops and seismic sections

Visualisation of the results in 3D (Figure 10) clearly show resistivity features associated with known production and injection patterns in the field to date, as well as suggested structural information. A sweep of higher resistivity to the centre of the survey area in the reservoir is clearly shown. This demonstrates the power of the 3D resistivity mapping technique using multiple well pairs.
The inter profile distance for the 2D EM survey is similar to a 2D seismic survey in which seismic is also interpolated between the profile and extrapolated to the limits of the model (cube).

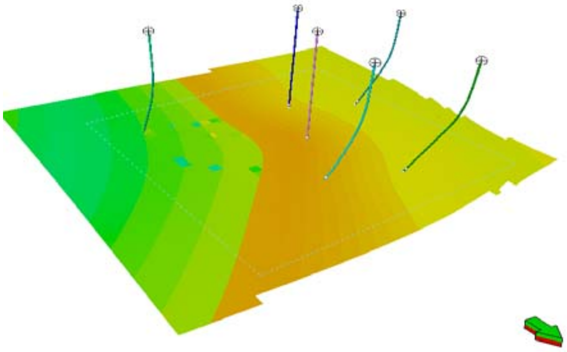

Figure 10: 3D visualization in reservoir scale shows the areal trend of the crosswell EM data using a depth slice (potential sweep trend shows a sweep of higher resistivity to the centre of the survey area in the reservoir)

Next Steps

The natural extension of this multi scale data integration exercise involves the derivation of apparent saturation distribution in the interwell space for a clastic environment.

Under this approach, formation evaluation studies are currently under way and water resistivity maps of the inter well flooded area are being built. Assisted by the geological and petrophysical information already acquired, the inverted cross-well resistivity panels constitute the basis for obtaining a fluid volume distribution.

Estimates of the distribution of two fluids, oil and water can then be derived using resistivity and porosity information through appropriate water saturation equations along each 2D section, and then propagated in 3D across the reservoir.

Additional data transforms will be required to highlight and integrate existing reservoir heterogeneities in the results.

The development of the apparent water saturation model is a key step in the construction of accurate static and dynamic reservoir models, which, in turn, will provide the basis for dynamic modeling workflows. In addition to providing value as standalone snapshots of the reservoir fluid distribution, time lapse cross well EM surveys will play an essential role here.

Conclusions

Crosswell EM imaging is a technology that demonstrates great promise for enhancing the understanding of reservoir flow mechanisms and provides the necessary information to optimize the monitoring strategies critical to sustaining mature oilfields.

However, the nature of the measured scale of the crosswell EM data, between traditional logs and seismic scales, shows that without constraints and controlled upscaling from log to reservoir to seismic, the resulting images will not be of interpretable use.

This paper has illustrated how multi-scale data sets can be integrated to provide apriori-constraints to the crosswell inversion process resulting in higher resolution images that are consistent with other available data.

Current focus is now on data integration procedures beyond the inversion stage to provide spatial and temporal distributions of reservoir parameters that are ultimately more valuable to reservoir engineers and asset managers than resistivity alone.

Acknowledgments

The authors are thankful to Schlumberger and Petrobras for their support in publishing this paper.

References

1. Beer*, R., M. de Aguiar Almeida, G. Sotomayor, E. Leite, J. Queiroz, M. Carige, L. Reynolds, A. Nalonnil [2008], Resistivity Imaging the Earth Between Wells: an Application of the Crosswell EM Technique, D. João Field, Reconcavo Basin. Brasil Onshore, Salvador-Bahia, Brasil, October 2008
2. Abubakar, A., T. Habashy, V. Druskin, L. Knizhnerman, and D. Alumbaugh, 2008, Two-and-half dimensional forward and inverse modeling for the interpretation of low-frequency electromagnetic measurements: Geophysics, In Press.
3. The Leading Edge, March 1995: Crosshole electromagnetic tomography: A new technology for oil field characterization, Michael Wilt, Kiha Lee/ Lawrence Livermore National Laboratory, HF Morrison, Alex Becker and Hung-Wen Tseng/ UC-Berkeley, David Alumbaugh/ Sandia National Laboratory, Carlos Torres-Verdin/ Schlumberger Doll Research
4. SPE 59529 (2000), Using Crosshole Electromagnetics (EM) for Reservoir Characterization and Waterflood Monitoring, Tadeusz Patzek/ UC Berkeley, Michael Wilt/ Electromagnetic Instruments Inc. and GM Hoversten/ Lawrence Berkeley National Laboratory
5. SPE SA-55 (2004) Crosswell Electromagnetic Surveys for Monitoring Large-Scale Reservoir-Saturation Changes, Martin G. Lüling, Kamal Babour, Tarek M. Habashy, Edward Nichols, Michael J. Wilt, Ping Zhang, Schlumberger