

# FIRST BREAK

October 2009 - Issue 10 - Volume 27

## EAGE

EUROPEAN  
ASSOCIATION OF  
GEOSCIENTISTS &  
ENGINEERS

## Reservoir Geoscience and Engineering

*Special Topic*

### ■ Technical Articles

Using automatically generated 3D rose diagrams for correlation of seismic fracture lineaments

Increasing the signal-to-noise ratio using a dual-sensor towed streamer

### ■ EAGE News

Amsterdam workshop reports on carbonate rock physics and geophysics HSE

## Finding bypassed pay in complex channel sands

David Alumbaugh, Michael Wilt, Ping Zhang and Ajay Nalonnil\* of Schlumberger discuss the development of an enhanced crosswell reservoir monitoring acquisition system using electromagnetic with a recent case study from China.

Understanding and predicting fluid movements in the reservoir is the key to successful reservoir management. While oilfields worldwide are becoming more and more mature, operators seek technologies to increase recovery. For example, secondary and tertiary recovery methods have proven to be extremely effective, but at some sacrifice in the understanding of the complex fluid dynamics in the reservoir and how such information can be incorporated into the subsurface reservoir workflow. Until now, reservoir scale imaging and interpretation have relied on geostatistics for petrophysical properties to be populated through the interwell areas.

This paper discusses crosswell electromagnetics (EM), which enables monitoring fluid movements at a reservoir scale by measuring resistivity distribution in between wells. Resistivity variations are seen when changes in porosity (subsidence), saturation (water flooding, bypassed pay), and temperature (steam flooding) occur. While crosswell EM development started two decades ago, it is only today with advances in processing and inversion techniques, and by following rigorous workflows that it is available for oilfield applications on a commercial basis.

### History

The concept of using downhole electromagnetic tools for oilfield applications started in 1985 at the Lawrence Livermore National Laboratory in California. A crosswell EM radar tool used for tunnels detection was modified for that purpose. During the first field test of the system in Kern River field close to Bakersfield, California, the high frequency operation between 50–500 MHz quickly showed its limitations; the frequency was too high to allow penetrations greater than 30 ft in oilfield environments. In late 1986 the system was modified to operate at lower frequencies from 1–5 MHz; subsequent field tests in 1987–88 showed that the frequency would need to be lowered even further for practical use of the technology.

In 1989 things geared up with the launch of a consortium on crosswell research and crosswell EM for reservoir characterization with the US Department of Energy. Schlumberger Doll Research Centre along with several industry leaders joined the consortium led by the Lawrence Livermore and Lawrence Berkeley Laboratories, University of California.

By the end of 1989, a field system was built operating from 1–100 kHz and subsequently tested in Devine, Texas in 1990 and in Richmond, California in 1992 and 1993. To interpret the data, Born Inversion was introduced in 1990 by Dr Zhou of the University of California, followed by Iterative Born Inversion by Dr Alumbaugh in 1992, and then Extended Born by Schlumberger in 1993. In early 1996, the first experiments in steel casing were performed in Lost Hills, California, at the same time Sandia Laboratories was releasing its finite difference inversion code, which is still widely used for other applications.

In 1997 the consortium was reaching its conclusion. At that time EM, a company founded in 1984 as a UC Berkeley spin-off specializing in magnetic sensors and acquisition systems for surface low frequency EM exploration (magnetotellurics), started the development of low frequency EM borehole tools.

A prototype was developed that year. It had three component receivers and was operating at frequencies from 1Hz to 1kHz. More than 40 field experiments were carried out in the USA, Canada, and China. Schlumberger introduced a second generation DeepLook-EM enhanced crosswell reservoir monitoring system and has performed more than 50 surveys worldwide. By following a rigorous survey and interpretation workflow supported by special modelling and processing software, to the method can monitor fluid fronts from water injection, infer flow mechanisms, identify steam chambers, optimize injection and drilling plans, and optimize geomodels which, in summary, is developing new ways of managing the reservoir.

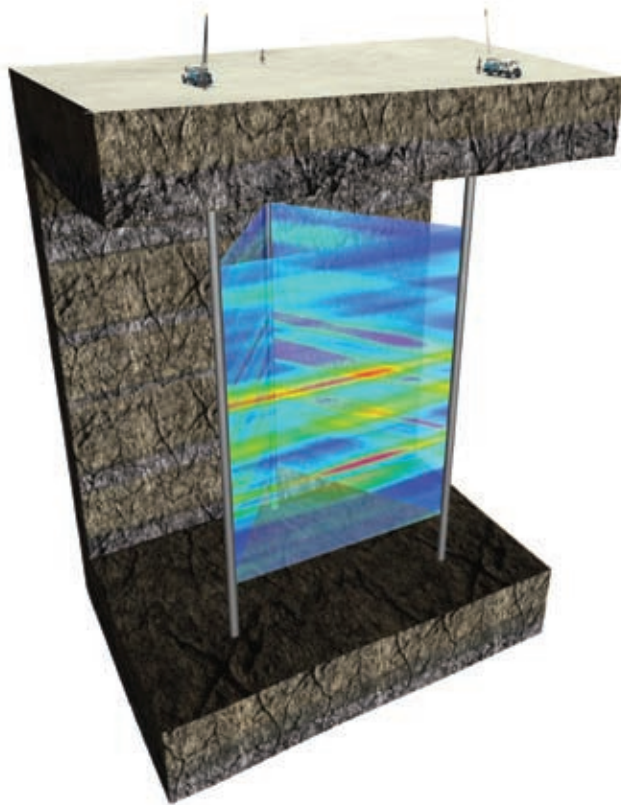
### Measurement principle

The new system directly measures formation resistivity between wells to produce a reservoir-scale resistivity image. The two wells in which the enhanced crosswell reservoir monitoring system transmitter and receiver tools are run can be separated by up to 3280 ft depending on the constraints of the well environments, formations, and resistivity contrasts.

The tools are connected and synchronized by GPS and deployed downhole with standard wireline equipment (Figure 1). 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

\* Corresponding author, E-mail: [ajayn@slb.com](mailto:ajayn@slb.com)

# Reservoir Geoscience and Engineering



**Figure 1** The enhanced crosswell reservoir monitoring acquisition system directly measures the resistivity of a reservoir between wells up to 3280 ft apart.

is achieved. The depths must include positions above, below, and within the layer of interest for an effective tomographic interpretation of the resistivity distribution between the wells. The tools are typically deployed at station spacing of 2–5% of the well spacing.

The 12 ft transmitter antenna is a vertical-axis magnetically permeable core wrapped with several hundred turns of wire and driven to broadcast a continuous sinusoidal signal at frequencies from 5Hz to 1 kHz. The frequency selection depends upon the borehole environment, the well separation, and the formation resistivity. Non-open wells, larger well separation, and low formation resistivity necessitates the use of lower frequencies.

The transmitter generates a magnetic field more than 100,000 times stronger than the source in a normal single well induction logging system. Several interwell distances are possible (Figure 2), but will ultimately depend on modelling and simulation of the scenario and objective. 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.

At the receiver borehole, induction coil receivers detect the total 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 around high permeability magnetic cores. This allows accurate measuring of signals generated by the transmitter. To reduce the logging time, an array of four receiver coils is deployed to simultaneously record the signals.

The system is typically deployed with the receiver sensors stationary in one well while the transmitter moves between the depths of interest in the second well, broadcasting signal continuously. A completed transmitter traverse, or profile, is made for each receiver array position. To reduce the noise, the incoming signals are averaged several hundred times per station. The transmitter logging speed ranges from 2000–5000 ft/hr depending on the amount of averaging and the frequency of operation. After a complete profile is measured, the receivers are then re-positioned and the process is repeated until all desired receiver positions are occupied. A typical crosswell deployment requires roughly 12–30 hours of field recording for a vertical section of 1000 ft.

The logging is done at the transmitter location because at this site the tool is moving during the logging, as opposed to the receiver side where it is stationary. The logging operation is controlled through the logging surface station and a laptop computer. The operation requires a wireline unit and a mast or crane at each well for onshore acquisition, while two offshore cabins are required for offshore surveys.

## Measurement interpretation

The imaging process is based on a data inversion procedure that finds a conductivity model that best fits the data with minimum change to the starting model. This is accomplished via an algorithm that iteratively minimizes the following nonlinear equation:

$$s = \phi_s + \phi_e = \sum_{i=1}^{N_{\text{meas}}} [d_i^{\text{meas}} - d_i^{\text{calc}}(\sigma)]^2 + \lambda \sum_{j=1}^{N_{\text{reg}}} [ \sum_{i=1}^{N_{\text{meas}}} W_{ij} (\sigma_j^{\text{meas}} - \sigma_j^{\text{prior}}) ]^2$$

The first term on the right hand side of the equation represents the *data misfit* term ( $\phi_d$ ) with  $d_i^{\text{meas}}$  representing the measured data,  $d_i^{\text{calc}}(\sigma)$  the numerical data calculated for the current conductivity model ( $s$ ) using the forward modeling algorithm described below, and

$$\sum_{j=1}^{N_{\text{reg}}}$$

DeepLook-EM Interwell Distances		
Transmitter Well	Receiver Well	Well spacing ft [m]
Open hole	Open hole	3,280 [1,000]
Open hole	Steel casing	1,476 [450]
Open hole	Chromium casing	1,640 [500]
Chromium casing	Chromium casing	1,148 [350]

**Figure 2** The system specifications are well completion and inter-well distance dependent, with open hole and fiberglass casing limits being identical.

# Reservoir Geoscience and Engineering

the summation of the square of the difference between the two sets of values over all data points. The second term on the right side ( $\theta_m$ ) is a *model constraint* term that enforces two constraints on the conductivity model. The difference between the image ( $\sigma_j^{image}$ ) and prior or starting ( $\sigma_j^{prior}$ ) models enforces a *model closeness* constraint. That is, the final image is required to be close to the starting model. Choice of an appropriate starting model is crucial to producing realistic resistivity images, and thus this starting model is constructed by incorporating all geologic, geophysical, and petrophysical knowledge of the field area available during the modelling phase of the survey. The second *model smoothness* constraint is applied by multiplying the model perturbation ( $\sigma_j^{image} - \sigma_j^{prior}$ ) by a smoothing matrix ( $W_{ij}$ ). This mathematical operation forces the model perturbation to be smoothly varying in space and eliminates rapid variations that are beyond the resolution of the crosswell imaging technique.

As mentioned, the calculation of the predicted data is accomplished via a forward modelling algorithm. This code solves Maxwell's Equations assuming a two dimensional pixel-based resistivity model, and provides magnetic field values at receiver points generated by magnetic dipole transmitters at specified locations and orientations. The code assumes a rectangular 2D geometry, a 'strike' direction, with the source and sensor positions specified in the code, normally provided by well deviation surveys.

### Survey workflow

It is clear that measuring deeper into the reservoir can only be successful if such complex surveys and interpretations follow a rigorous workflow (Figure 3). Due to the non-unique nature of the inversion process, all information on the reservoir must be gathered and used to guide the inversion to an answer that makes geological sense. This gathering step is done in modelling part of the workflow in Petrel seismic-to-simulation software where all the field data is compiled.

The field model is also used to create through dynamic simulation or by hand, scenarios of possible fluid movements or targets. Those scenarios are used to calculate tool sensitivity for each of them and evaluate resistivity distribution through inversion. This step called simulation ensures suitability of the service to solve a particular problem and predicts what resolution can be expected. It is the optimum way to define clearly the objectives of the survey, minimize operational risks, and gather all information required for data processing and interpretation.

Currently data are processed and interpreted using a 2.5D inversion code developed by Schlumberger Doll Research and the EMI Centre. This code delivers similar or better accuracy than other available codes hundreds of times faster. The resistivity distribution in between wells is

then ready to be imported in static modelling software for integration with other measurements and further static and dynamic interpretation.

### Crosswell EM in the Gudao oilfield

The survey was carried out at the Gudao oilfield in Shandong Province in China. Gudao is an anticline trap located along the Yellow River delta in central China. The field consists of channel and deltaic sands deposited in an ancient flood plain. Large parts of the field are characterized by continuous deltaic sands and other parts by distinct channels, but generally both channel and flood sands are present in each area. The configuration of the sands and the controlling structure is crucial in understanding the ongoing waterflood and in optimizing the oil production strategy.

At present it is estimated that 25% of the reserves in this field has been recovered; another 15% is recoverable with improved reservoir knowledge. Improvement in this knowledge was one of the key goals for the Gudao project. The aim was to provide inter-well resistivity data to help better understand the waterflood dynamics and locate

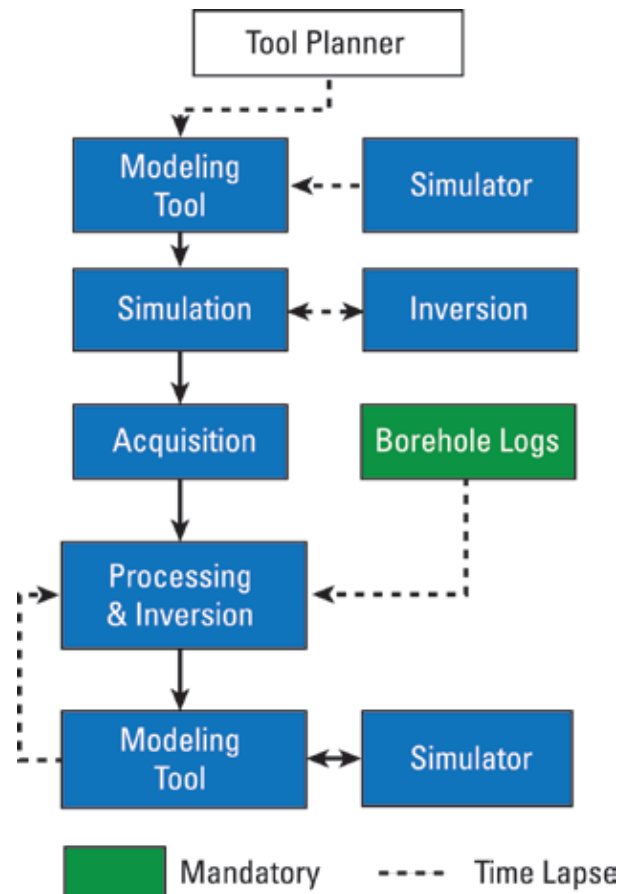


Figure 3 The system's workflow is a model-centric workflow that starts with a geological model to form the basis for data fitting during inversion.

# Reservoir Geoscience and Engineering

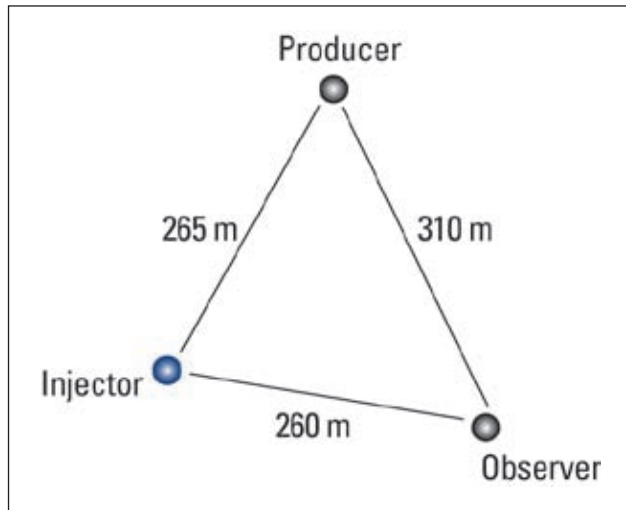


Figure 4 Transmitter and receiver tools were run in pairs of the three wells (three well pairs).

bypassed reserves (thus to provide an improved reservoir definition in this part of the Gudao field).

The project consisted of three separate surveys using three wells (Figure 4). The observer well is a producer (steel-cased), the injector well is a water injector (cased), and the producer well is a newly drilled open-hole producer that was used in the tomography. The wells are located in a mature part of this water-flood. Flooding started in this part of the field in 1985 and has progressed continually since then. The flooding and production is centred in three principal layers. Layers 3 and 4 are well-defined continuous deltaic sands that range in thickness from 4–12 m. Layer 5 is a less continuous layer with heavier oil that has had less success in water flooding operations. At present a cyclic steaming strategy is being used with some success in this layer.

The tomography covered a depth interval of 200 m. Both steel-cased wells were logged with the cased hole formation resistivity tool (CHFR) to account for changes in resistivity at the wellbore during the last 20 years of production and injection. It was crucial for the enhanced crosswell reservoir monitoring system to have recent borehole logs. This measurement is very sensitive to the resistivity near the wellbore and using recent logs in the processing starting model allowed efforts to be concentrated on the resistivity distribution in between the wells and not at the wells.

The resistivity images for the three well pairs are shown in figure 5. Focusing in on the injector-observer panel at the bottom, there is a smooth section consistent with a flat-lying multi-layered section concordant with the well logs at the margins. The low resistivity upper section represents clays and silts. Within this section are thin discontinuous higher resistivity sands (maybe oil-bearing). Note, for

example, the layer at the oil-bearing depth of layers 3, 4, and 5 is associated with continuous high resistivity layers.

Layer 3 is higher in resistivity near the producer well and grades gradually lower towards the injector. The layer thickness stays relatively constant. Layer 4 stays roughly constant in resistivity but seems to thicken gradually from producer to injector. The most interesting part of the image is near location 80 m where the 4–5 layer basal section grades at the producer into a 2–3 layer section. The section also indicates slight stratigraphic thinning in layers 3 and 4 and some variation in the overburden silts and muds at this same lateral position.

Variations in layer resistivity may be associated with saturation and/or water salinity. Clearly the resistivity has fallen from the initial 20–25 m to the present day 8–10 m due to replacement of oil by injected water. As the oil desaturation continues, this trend will persist, but it can be offset by variations in injected water salinity. The injected water supply for this field has changed a number of times, but the salinity is uncertain. This adds an in associating higher oil saturated intervals with a higher resistivity.

The injector-observer section seems to indicate a thickening and increase in formation resistivity in all three layers near the middle of the section from 100–150 m (compare this with the observed thinning in the producer to injector section). It is suspected that these layers vary in thickness continuously throughout this part of the field due to the depositional conditions. The thickness variation

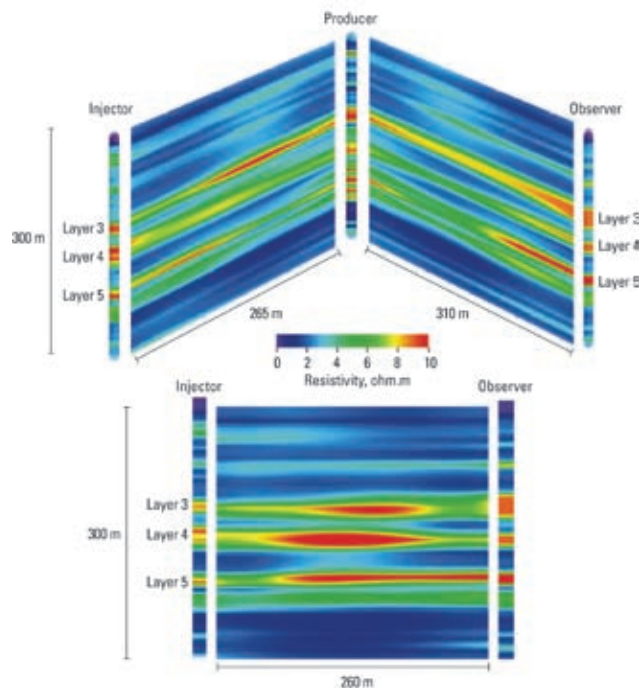
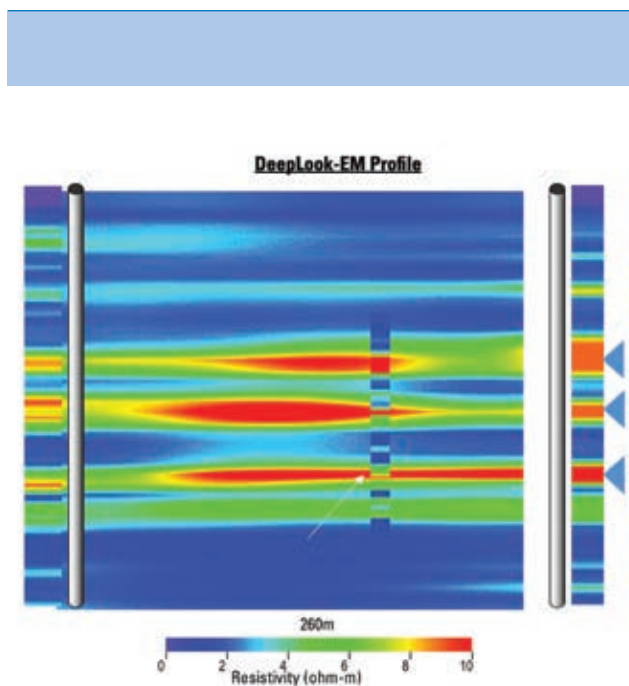


Figure 5 Resistivity images between the three wells show that the three production layers are mostly consistent in thickness and continuity. The high resistivity in layer 5 in the bottom panel indicates bypassed oil.



**Figure 6** Correlation of a high resolution resistivity well log from a nearby producer well and the enhanced crosswell reservoir monitoring system profile showing excellent matches in the three layers of interest.

probably also affects the water flood sweep efficiency and as such it is a worthwhile property to map.

The layers also vary in resistivity, probably due to the water saturation and salinity. It is likely significant bypassed reserves exist in the higher resistivity section. An offset producer well was drilled after the enhanced crosswell reservoir monitoring system, approximately 30 m from the profile between observer and injector and oil was produced from layer 5. This suggested that the higher resistivity in layer 5 represents bypassed oil. Figure 6 shows the correlation of the resistivity log from a nearby producer well with the resistivity section.

### Conclusion

Understanding better reservoir fluid dynamics to improve hydrocarbon recovery is the challenge that oil operators face daily, enhanced crosswell reservoir monitoring system is a new technology that is being added to the list of services to help operators in that sense. Following the rigorous workflow and operational procedures and using processing and interpretation software made the enhanced crosswell reservoir monitoring survey in China Shengli (Gudao) Oil Field a success.

Geologically the sections interrogated were very continuous, showing a coherent thinning in only one of the layers in an area associated with the convergence of the four layers into two. The observed variations in the inter-well resistivity were consistent from section to section although they may represent variations in water salinity as well as oil saturation variations. The enhanced crosswell reservoir monitoring system has helped detect bypassed pay in layer 5, as confirmed by reported production from the field.

Our three **e-Learning** series offer great value...especially when budgets are tight!

### IPIMS

This award-winning, e-Learning system covers all areas of Upstream Petroleum Technology: Geology, Geophysics, Engineering, and Formation Evaluation.

([www.ihrdc.com/eLearning/eage](http://www.ihrdc.com/eLearning/eage))

### Petroleum Online

Just released - a 14-module in-depth overview of the oil and gas industry: Upstream, Midstream, and Downstream.

([www.ihrdc.com/eLearning/eage](http://www.ihrdc.com/eLearning/eage))

### Business Essentials

This e-Learning series covers four key business areas: Finance, Communications, HR Management and Project Management for individuals working in the international oil and gas industry.

([www.ihrdc.com/eLearning/eage](http://www.ihrdc.com/eLearning/eage))

Contact us today to test drive all three e-Learning products.

For complete details  
Email: [ajenks@ihrdc.com](mailto:ajenks@ihrdc.com)  
Tel: 1.617.536.0202



## IHRDC

A Worldwide Leader in Learning and Development for the Oil and Gas Industry