Using Crosshole Electromagnetics (EM) for Reservoir Characterization and Waterflood Monitoring
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Abstract

The crosshole EM technique provides an image analogous to a smoothed two-dimensional induction resistivity log. Inductive EM sources are placed in one well and magnetic field receivers in a second well, up to a km away. Sources and receivers are positioned above within and below the depth interval of interest, and we image the resistivity of the interwell volume to fit the collected data. Data may be collected in open and/or steel-cased boreholes, although steel casing reduces this range. The resolution of images is roughly 5 percent of the well spacing.

The technique has been used for more than 5 years in imaging thermal oil recovery operations, but more recently for reservoir characterization and water flood imaging. The resistivity contrast between salt water saturated zones and oil and gas pay zones usually provides an excellent signal for the EM data and makes the imaging of the water flood fairly straightforward.

In this paper we provide a technology overview and then show a case history where the EM resistivity images have defined the initial water saturation distribution, and have tracked changes over a two-year period due to water flooding in a fracture dominated southern California reservoir. We further describe simulations for crosshole EM imaging in carbonates for a WAG (water alternating gas) process where the technique is used for initial site characterization and to monitor saturation changes during the injection.

Introduction

With the advent of crosshole seismic technology in the 1980's a new generation of high-resolution geophysical tools has become available for reservoir characterization and process monitoring. The chief improvement over other methods is simply that the tools are deployed in boreholes, enabling the measurements to take place much closer to the region of interest.

Beginning in 1990 researchers began development of a low frequency crosshole EM technology (3). The crosshole EM induction system can be thought of as an extension of the borehole induction logs into the region between wells. The system, in fact, operates very similar to single well logging tools but with the transmitter and receiver tools deployed in separate boreholes.

Figure 1 provides an excellent illustration of why field developers should consider collecting EM in addition to seismic data. Here we plot seismic velocity and electrical resistivity as a function of porosity, water saturation and temperature in water flooded sandstone cores. The plots indicate a high sensitivity of the electrical resistivity to variations in reservoir conditions, and a smaller sensitivity of seismic velocity to the same reservoir variations. Typically, the resistivity varies up to an order of magnitude over the range of typical reservoir conditions whereas the seismic velocities vary by no more than 10 to 20 percent. The contrast is most pronounced in Figure 1b where the seismic data indicate a very small change due to fluid saturation whereas the electrical data are greatly affected.

This above plot is not surprising considering the physics. Seismic waves are predominantly supported by the rock matrix and variations due to pore fluids are secondary effects. EM-induced currents primarily flow in the pore fluids; therefore, electrical property variations of these fluids have a large effect on EM data. The combination of the two techniques thereby allows high definition of both the rock matrix and pore fluids.
In this paper we briefly discuss the crosswell EM technology, describe the field apparatus and interpretation procedure and then show a field example. Finally we apply a computer simulation to illustrate the application of this technique to Permian basin geology.

Overview of Crosswell EM Technology

A crosshole EM field system consists of a transmitter tool deployed in one well and a receiver tool deployed in a second well located up to 1 km from the source well. The tools are connected with surface wire telemetry and deployed with standard wireline equipment. By positioning both the transmitter and receiver tools at various levels above, below and within the zone of interest, we can collect sufficient data for a tomographic interpretation of the resistivity distribution between the wells. The tools are typically deployed at depth intervals equal to five percent of the well spacing, which is also roughly equal to the image resolution.

Modern field instrumentation uses downhole electronics and computers for signal generation and data acquisition. This results in very accurate and efficient data collection while still using standard wireline equipment. Surface equipment consists of a small station to supply power and communication with the tool and a laptop computer to control the acquisition and log the data.

The transmitter antenna is a vertical-axis magnetic core wrapped with several hundred turns of wire and tuned to broadcast a sinusoidal signal at frequencies from 10 Hz to 2 kHz. Note that this produces a magnetic field more than 10,000 times stronger than the source of a normal 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 in proportion to the electrical resistivity of the rock where they flow.

At the receiver borehole we use induction coil receivers to 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 around high permeability magnetic cores; this allows us to accurately measure signals generated by our transmitter up to 1 km away.

The system is typically deployed with the receiver sensors stationary in one well and the transmitter moving in the second well. Data is collected in profiles where the transmitter moves at a rate of 5 m/minute between the depths of interest, broadcasting signal continuously. The receivers are then repositioned and the process is repeated. A typical crosswell deployment requires roughly 24 hours of field recording for a vertical section of 300 m. Data is typically collected at a one percent error level or less.

The EM data are interpreted by computer modeling in which the interwell formation is divided into two-dimensional, square blocks 1 to 5 meters on a side. We apply a two dimensional inversion based on a finite difference forward code (1). Each block is assigned an electrical resistivity value, estimated from the borehole resistivity logs (if available). The inversion code then modifies the resistivity of these blocks until the calculated and measured EM data agree to within the measurement error. This process usually requires several hours per data set on a fast computer workstation to produce a detailed image of the underground strata. The resolution of the images is roughly 5 percent of the well spacing.

Case History: Waterflood Monitoring with Crosswell EM at the Lost Hills Oil Field

The Lost Hills oil field is located at the western margin of the San Joaquin basin in Kern County, California, Figure 2. Production is concentrated in the Pliocene and Miocene Etchegoin and Reef Ridge formations, which combined account for reserves in excess of 1 billion barrels within a 300 m thick reservoir. The principal reservoir rock is a diatomite shale characterized very low matrix permeability (0.1 to 20 mdarcies) but high porosity and oil saturation (2). Fluid flow is dominated by the network of natural and induced fractures.

Most recovery operations at Lost Hills use induced fractures for better reservoir contact and waterflood for pressure maintenance. Both production and injection wells are fractured in up to three intervals within the 300 m production interval. Oil recovery operations have been characterized by low flow rates and inefficient sweep in spite of efforts to optimize the flood. Operators have struggled with methods to improve production, control local subsidence and well failure and improve recovery, which presently runs less than 10 percent.

The Ellis lease lies at the southern margin of the Lost Hills field (Figure 2). As part of an effort to address the above issues a small pilot was established in 1996 at the northeast corner of the lease, Figure 3. Within the pilot several induced fracturing, water injection and production options were tested and production and injection closely monitored. In particular the operators did extensive reservoir characterization using logs, cores and simulation. They also tested line and staggered grid injection and production geometries and used tracers, downhole spinners and repeat logs to assess the progress of the water flood.

As part of the monitoring effort 2 fiberglass-cased observation wells were installed to measure resistivity changes associated with the water injection. In 1997 and 1998 we made a series of crosshole EM measurements using these wells to track the movement of injected water in this largely fracture dominated reservoir. We also wished to image the in-place conditions prior to the water flood.
EM Surveys

Crosshole data were collected in observation wells OB1-9 and OB 2-10 in April 1997 and September 1998 (Figure 3). The crosshole EM data covered depths from 700 to 850m and each data set consisted of 20-25 measurement profiles corresponding to a single receiver depth and a series of transmitter depths. Receivers are spaced 4 to 8 m apart within this depth interval with the most closely spaced points located within the upper reservoir at depths from 700-750m. Note that the receivers are spaced by roughly 5 percent of the well spacing.

Collected data were interpreted with a two dimensional inverse code described above. The data fit required the initial structure to incorporate the 15-degree formation dip for an acceptable fit. The final fit of observed and calculated data was better than one percent at Ellis, which is unusually close.

The interpretation of the crosswell EM resistivity data follows the same principles as single well induction log interpretation. That is the resistivity is interpreted in terms of formation porosity, clay content and fluid saturation. In this case the formation and injected water are good electrical conductors whereas the formation oil is an insulator. We therefore feel that the biggest influence of the resistivity is the fluid saturation. For example regions of high water saturation would typically indicate relatively low resistivity and higher resistivity zones may indicate higher oil saturations.

Figure 4a shows the baseline cross-section made between the two wells in 1997, near the onset of water flooding. The pixel size for this image is 3 m; the resolution ranges from 3 to 6m.

The dominant feature of the image is a 50m layer centered at 725m, dipping 15 degrees, with a resistivity of 1.5-2 ohm-m. This is the chief oil bearing zone within the Etchegoin formation at this lease. At the base of the layer the higher resistivity zone is fairly continuous but at the top of the layer the higher resistivity seems to grade into a lower resistivity towards the middle of the section. We expect that the lower resistivity at the image center is due to oil production in well 223-9, which is located between the two observation wells used in the tomography (Figure 3). Because of the mobility difference between oil and water we suspect that oil production results in a net decrease in the electrical resistivity in the vicinity of the wellbore which creates a lower resistivity “ghost” that likely marks the region of oil depletion.

Note that the image shows several stairstep features from the left to the right. These are artifacts present from the initial model. The stairsteps are used in the starting model to take account of the dipping structure in the rectangular coordinates of the modeling code. Some residual of this initial model remains in the final image.

Below the upper zone there are several minor higher resistivity streaks between 750 and 800m, perhaps representing higher oil saturation zones or higher resistivity silicified shale layers. These streaks are only piecewise continuous. At the base of the section the resistivity is substantially lower corresponding to lower oil situations.

In Figure 4b we show the image derived after the September, 1998 survey. Clearly, the 1998 image is substantially different from the baseline data, especially in the upper producing zone. The resistivity of the upper producing zone has undergone some major changes as the result of the water injection and continued production in well 223-9. Near well OB2-10 the resistivity has decreased dramatically due to the water flood, with most of the changes occurring near the base of the layer. This low resistivity zone is confined to the upper productive zone and extends to no more than 15m from the well. Near well OB 1-9 the resistivity has decreased broadly throughout the upper layer with the major changes also occurring at the base of the layer, at a depth near 750m. The section also shows significant resistivity decreases above and below this horizon. This suggests that water is probably contacting the lower parts of the reservoir, but more slowly.

In Figure 4c we plot the differences in resistivity between the two sections; this type of display tends to amplify the regions that have changed due to the water flood. We see a large part of the cross-section showing substantial resistivity change during the 18 months of field monitoring. For example there is an almost forty percent resistivity decrease at the base of the upper reservoir unit, adjacent to observation well OB2-10. This accounts for a virtual complete replacement of the oil phase with the injected salt water. Note that region of greatest change is aligned with the induced fracture in well 534-9. The second large feature is a broad region of decreased resistivity extending from well OB1-9 about 30m towards OB 2-10. In this zone the resistivity has decreased from 5 to 25 percent, with most of the change concentrated in the upper reservoir section.

Notice also that about halfway between the wells the resistivity has actually increased during the 18 months between data sets. There are two potential explanations for this behavior. First it is possible that the water flood has displaced significant oil towards the center of the image, this would increase the resistivity due to higher oil saturation. Alternatively, the resistivity increase could be due to production induced porosity reduction near well 223-9. We favor the second explanation, as it is more consistent with the known behavior in this field near production wells and also consistent with our model of flow in a low permeability reservoir.

By referring to the site map in Figure 3 we can explain some the dynamics of this water flood. For example we note that water injector 534-9 lies south and west of well OB 2-10 with the induced fracture direction (NE) roughly in-line with the
observation well. The large resistivity decrease observed within the production horizon near OB9 is likely due to injected water from 123-9 traveling along the induced and natural fracture network. The operator reports that some of this water is produced in production well 133-10, which is also roughly in line. Near well OB 1-9 we observed a broad resistivity decrease. Again referring to the figure we believe that water injected from well 123-9 is traveling towards producer 223-9 primarily through the matrix of the upper formation, with smaller flow at depths below this. This section of the water flood seems to be working according to design. That is the injected water is displacing oil within the formation matrix, not simply the fractures.

The resistivity images shown above have revealed that the flow at Lost Hills is quite dynamic, and that much of the subsurface flow can be monitored with crosshole EM. We feel that tracking the resistivity changes over time is an excellent means for understanding the reservoir dynamics in this field, and thereby optimizing the oil recovery process.

Simulation of a WAG Process in the Permian Basin

The example above clearly indicates that the crosshole EM technique provides valuable information in a California waterflood, using closely spaced fiberglass cased observation wells. It is not at all clear that it would be equally effective for widely spaced steel-cased wells and a CO₂ flood in the Permian basin. For this reason we have done a numerical simulation to test the sensitivity of crosswell EM to CO₂ flooding in Permian basin conditions.

We chose the model displayed in Figure 5 for the simulation. Here we assume that the wells are spaced by 550m, they are all cased with steel and that we are monitoring either a water or CO₂ injection process. We assume that the CO₂ has increased the resistivity, in a 50 m wide slug, from 500 ohm-m to more than 2000 ohm-m and the salt water has decreased it in the same region to 50 ohm-m. The model and variation are based on logs supplied from the Vacuum field in eastern New Mexico. We further assume that the steel well casing attenuates the signal by a factor of 100 as compared to open hole transmission. This factor is in accord with published data for steel pipe (4).

The simulation is far less favorable than the California example shown above. The large well spacing reduces the signal amplitude, the presence of steel well casing forces us to use lower frequencies and to further process the collected data to account for casing effects. Note that the 100 Hz employed for this case is less sensitive to formation effects than the 1000 Hz data from the previous example but the higher frequency would be unable to penetrate the steel casing.

We show some results of the simulation for cases 1 and 2 using a simple line plot, Figure 6. Here we plot the field amplitudes for the baseline and flooding cases using a single receiver situated in the flooded interval with multiple transmitter positions that span the zone of interest. The adjoining plot shows the difference in field level between the three cases and the noise level of the field system employed in the previous example.

From the figure, it is clear that the conditions for this example strain the limits of the present generation of hardware. Although existing field systems could easily measure the signals we would be unable to distinguish between native and CO₂ flooded rock. The effect of the CO₂ is less than 0.5 percent of the total field signal, which is smaller than can be practically measured with existing hardware. Note that CO₂ is an insulating fluid; thereby it is less visible with EM especially when injected in a higher resistivity oil bearing formation.

The water flood is more tractable case. Here the changes are roughly 10 percent of the signal and twice as large as the system noise level. It is therefore feasible to track injected water following a CO₂ flood but probably not the CO₂ flood itself. Note that only part of the anomaly is visible in the waterflood example. The effect of this partial view would be to provide a lower resolution image of the flood.

From this example, we expect that tracking a CO₂ flood in native formation would be very difficult under these conditions. A much more feasible example however would be tracking the introduction of CO₂ into a previously waterflooded formation. Here the resistivity contrast is much larger and the signal would be as large as the waterflood example shown above.

References


Figure 1. Resistivity and P-wave velocity for laboratory sandstone cores as a function of porosity, saturation, and temperature.
Figure 2. Location map for the major oil fields in California’s San Joaquin Valley.

Figure 3. Site map for the Ellis pilot at southern Lost Hills.
Figure 4a). Two dimensional resistivity image for the baseline EM data b) two dimensional resistivity image for the monitoring EM data c) percent resistivity difference between Figures 4a and 4b.
Figure 5

Figure 6. Calculated EM field for the models shown in Figure 5. The upper plot shows the field levels, the lower plot gives the field differences for the three cases. Note the predicted system noise level at the base of the plot.