MULTIFREQUENCY CROSSHOLE EM IMAGING FOR RESERVOIR
CHARACTERIZATION

FY 1994 ANNUAL REPORT

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June 1995

Prepared for
U.S. Department of Energy
Assistant Secretary for Fossil Energy

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Introduction

Electrical conductivity of sedimentary rocks is controlled by the porosity, hydraulic permeability, temperature, saturation, and the pore fluid conductivity. These rock parameters play important roles in the development and production of hydrocarbon (petroleum and natural gas) resources. For these reasons, resistivity well logs have long been used by geologists and reservoir engineers in petroleum industries to map variations in pore fluid, to distinguish between rock types, and to determine completion intervals in wells. It is therefore a natural extension to use the electrical conductivity structure to provide additional information about the reservoir. Reservoir simulation and process monitoring rely heavily on the physical characteristics of the reservoir model. At present, numerical codes use point measurements of porosity, permeability, and fluid saturation and extrapolate these data throughout a three-dimensional (3-D) grid. The knowledge of a high-resolution geophysical parameter such as electrical conductivity would aid this extrapolation and improve the reservoir simulation effort. In addition, since conductivity is sensitive to changes in the composition and state of fluids in pores and fractures it becomes an ideal method for monitoring a reservoir process.

Over a period of three years (1991-1993) there was an initial phase of crosshole EM technique development via an informal partnership between LLNL and LBL. The main objective of the technique development was to assure industry to use it on real world problems that have potentials for significant energy payoff. In this partnership researchers at LLNL developed field instrumentation to apply to oil field for monitoring EOR thermal processes. Specifically, a prototype single-frequency instrumentation was developed and with this system we have conducted field surveys in four separate locations. In parallel to the hardware development, theory and software were developed at LBL to interpret these data by providing subsurface images of the electrical conductivity. The software development includes the 2-D iterative Born inversion scheme for inverting axially symmetric conductivity structures, and the Q-domain tomographic imaging algorithm for interpreting general conductivity structures using time-domain data.

In spite of our initial success in developing practical EM techniques, we still had severe instrumentation limitations and shortcomings in interpretation for other than simple structures. The field equipment was designed to work only at a single frequency at a time and the transmitter must be opened to change frequencies. The equipment was also significantly noisier at higher frequencies. Crosshole imaging codes developed using the "Born" approximation are not effective in high contrast environments and can not make use of multifrequency EM data efficiently. For subsurface monitoring, such as a steam flood, these are not major shortcomings. The size of subsurface plumes is large and the information sought by field engineers are more qualitative in nature. For high-resolution

applications, which are more interesting to the oil field developers and reservoir engineers, we need to take full advantage of the resolution inherent in the data. In this case we need to map the configuration of individual oil sands for wide variety of conductivity contrasts and orientations. We need to track steam or water injection fronts with far improved resolution and accuracy, so that connections between individual units can be traced. The development of a high-resolution subsurface conductivity imaging methods would have benefits far beyond the petroleum application. Such techniques would be very useful in environmental applications, mineral and geothermal exploration and for civil engineering applications.

With this as a background we again, at late 1993, proposed a joint LBL and LLNL project to further develop the high-resolution multifrequency EM imaging technology for reservoir characterization. The proposed research consisted of six tasks, and these tasks would be carried out over a period of three years. These tasks are:

- Task 1. Frequency domain- q domain transform -LBL
- Task 2. Collection of a high quality multifrequency crosshole data set -LLNL
- Task 3. Q -domain crosshole imaging of collected data -LBL
- Task 4. Development of prototype multifrequency transmitter -LLNL
- Task 5. 3-D nonlinear inversion -LBL
- Task 6. 3-D field survey to map salt water injection & final report -LBL&LLNL

LBL has partially completed Tasks 1 and 5 at the end of this fiscal year (FY1994) and the progress made for these tasks are summarized in the following.

Summary of technical progress

Task 1. Frequency domain- q domain transform

For most EM applications, the depth of interest requires the use of low frequencies (< 1 MHz). For typical earth materials the conduction current is orders of magnitude greater than the displacement current at these frequencies. The differential equation that describes the behavior of such EM fields is a diffusion equation, and inversion of fields satisfying such a diffusion equation is very difficult except for a few simple models. In spite of many successful magnetotelluric (MT) inversion studies (Jupp and Vozoff, 1977; Sasaki, 1989; deGroot-Hedlin and Constable, 1990; and Smith and Booker, 1991, to list a few) only a few such successful studies have been reported using controlled-source EM methods (Oristaglio and Worthington, 1980; Zhou, 1989; Tripp and Hohmann, 1991; Alumbaugh and Morrison, 1993; Torres-Verdin and Habashy, 1993; and Torres-Verdin and Habashy, 1994). Using the wavefield transform technique Lee and Xie (1993) have shown that diffuse time-domain EM fields can be numerically transformed to wavefields in the fictitious time q (thus called the q -domain), and that a high-resolution conductivity imaging can be obtained in a crosshole configuration. One of the findings in their study was that it was necessary to use 200 to 400 EM field samples over a 1.5 decade time-domain window to obtain reasonably good traveltimes in the wavefields. Often it is not practical to require densely sampled wideband time-

domain data and different methods need to be developed to relax this stringent requirement. The objective of Task 1 is to develop a different numerical procedure for extracting traveltime information using a limited number of data in the frequency-domain.

The wavefield transform involves inversion of the following integral equation (Lee and Xie, 1993). Dropping the dependence in r

$$H(t) = \frac{1}{2\sqrt{\pi t^3}} \int_0^\infty q e^{-\frac{q^2}{4t}} U(q) dq. \quad (1)$$

Here H is the magnetic field and U is the corresponding wavefield. This equation can be easily modified to the frequency (ω) domain by Fourier transform. As a result, we have

$$\tilde{H}(\omega) = \int_0^\infty e^{-\sqrt{i\omega}q} U(q) dq, \quad (2)$$

which can be divided into

$$\text{Re}(\tilde{H}(\omega)) = \int_0^\infty e^{-pq} \cos(pq) U(q) dq, \quad (3)$$

for the real part, and

$$\text{Im}(\tilde{H}(\omega)) = -\int_0^\infty e^{-pq} \sin(pq) U(q) dq, \quad (4)$$

for the imaginary part. Here the relationship $p = \sqrt{\omega/2}$ has been used to simplify the expression. Again these transforms involve ω and q , and is independent from the position vector r . To construct the wavefield $U(q)$ from the frequency-domain magnetic field $\tilde{H}(\omega)$, a numerical procedure has been developed using the trapezoidal integral formula and collocation method. Equations (3) and (4) can be discretized by using the following discrete values of variables of ω and q .

$$\begin{aligned} \omega_1 < \dots < \omega_i < \dots < \omega_{m-1} < \omega_m, \quad \text{and} \\ q_1 < \dots < q_i < \dots < q_{n-1} < q_n. \end{aligned}$$

Here the frequency can be sampled either linearly or logarithmically. Using these discrete variables equations (3) and (4) can be combined together into the following system of linear equations.

$$\mathbf{AU} = \mathbf{H} \quad (5)$$

The solution to this equation is ill-posed, especially when $m < n$, and the method to solve this problem has been described in Lee and Xie (1993).

The numerical methods described above have been successfully tested (Lee *et al*, 1994) using a simple homogeneous whole space of conductivity 0.04 S/m. A crosshole configuration is used here with the transmitter-receiver borehole separation of 50 m. A magnetic dipole source is used in the transmitter hole at $z=0$ m. The transmitter may be moved down if a full tomographic coverage is required. A vertical magnetic field sensor is placed in the receiver hole initially at $z=0$, and is moved down by a 5 m increment to a maximum of $z=100$ m. For the transform of frequency-domain data Figure 1-(a) and -(b) shows the real and imaginary parts of the vertical magnetic fields at 21 receiver position. In each of these traces field values have been normalized by the maximum in that trace. These data have been transformed to wavefields and the results are shown in Figure 1-(c), -(d), -(e), and -(f), using 10 samples, 20 samples, 50 samples, and 100 samples, respectively. The frequency window used is 1.6 decades starting from 5 kHz to 200 kHz. To obtain these results we used equally spaced frequency-domain data (linear). The increment in q used is $\Delta q = 1.05\sqrt{\sigma\mu}$. The maximum q at which the wavefield is calculated is 0.045. The wavefield plotted after this point is simply the continuation of the last data point. The first arrival in q , marked by a heavy dot, corresponds to the maximum amplitude in each trace. These traveltimes data are compared with the theoretically computed traveltimes (distance times the slowness), and the root-mean-square (rms) difference between the theoretical and computed traveltimes are listed under Data 1 in Table 1. Values listed under Δd correspond to the equivalent error in distance. The same numerical procedure has been applied to the data, but at this time the frequency sampling is logarithmic. The error statistics from this exercise is shown under Data 2 in Table 1. Clearly, there is no appreciable difference in the resolution between linear sampling and logarithmic sampling. Within the same frequency window the transform appears to be insensitive to the way the sampling is taken. With 50 to 100 frequency-domain samples, the numerical transform seems to have preserved accurate traveltimes (< one percent in rms). Even with as little as 10 to 20 samples the method is capable of providing reasonably good traveltimes (~ one to two percents in rms).

Data rms Case	Data 1		Data 2	
	Δq	Δd (m)	Δq	Δd (m)
(c)	1.34450e-4	0.5996	1.18387e-4	0.5280
(d)	1.86195e-4	0.8304	1.86195e-4	0.8304
(e)	3.22251e-5	0.1437	3.55617e-5	0.1586
(f)	3.19136e-5	0.1423	3.16136e-5	0.1423

Table 1. Numerical errors in the traveltimes data. Results from the linear sampling are shown under Data 1, and those from the logarithmic sampling under Data 2.

Task 5. 3-D nonlinear inversion

The 3-D inversion scheme developed in this project is based on the integral equation method. The electric and magnetic fields satisfy Maxwell's equation

$$\nabla \times E = -i\omega\mu_b H, \quad (6)$$

$$\nabla \times H = (\sigma + i\omega\epsilon_b)E + J. \quad (7)$$

which can be reduced to the Helmholtz equation

$$\nabla \times \nabla \times E = -i\omega\mu_b(\sigma + i\omega\epsilon_b)E - i\omega\mu_b J. \quad (8)$$

Here J is the electrical current source, ϵ_b is the background dielectric permittivity, and μ_b is the background magnetic permeability. If we further define that σ_b is the background conductivity, equation (8) can be rewritten as

$$\nabla \times \nabla \times E - k_b^2 E = -i\omega\mu_b(\sigma - \sigma_b)E - i\omega\mu_b J, \quad (9)$$

where $k_b^2 = \omega^2\mu_b\epsilon_b - i\omega\mu_b\sigma_b$. Using the Green's function the solution to equation (9) can generally be written as

$$E = E^b - i\omega\mu_b \int_V \tilde{G} \cdot (\sigma - \sigma_b)E dv. \quad (10)$$

The Green's function used in this solution is in fact the solution of

$$\nabla \times \nabla \times \tilde{G} - k_b^2 \tilde{G} = \tilde{I} \delta. \quad (11)$$

The 'anomalous' conductivity $(\sigma - \sigma_b)$ must be confined to a finite region. The background medium is 1-D consisting of either homogeneous or layered earth for which the Green's functions are known.

An immediate application of the integral equation (10) leads to the forward solution of the electric field. In this case the anomalous conductivity is given. The inverse problem can also be addressed using the same integral equation, but it now becomes a nonlinear problem because the electrical conductivity is not known and the electric field is a function of electrical conductivity itself.

Over the past year or so we have developed a 3-D nonlinear inversion scheme for imaging electrical conductivity using the integral equation method and the standard least squares approach. The code has been tested successfully with the crosshole data Mike

Wilt of LLNL collected at Lost Hills Unit #3 in California (Wilt *et al.*, 1994). The transmitter borehole is on the left of the cross section (Figure 2) and the receiver borehole on the right. Each of these boreholes has been occupied by 27 source and receiver positions, respectively. The first data set was taken in November, 1993, just before a steam injection experiment. The injection borehole is located at the center ($x=0$.) with the injection point at the depth of 95 m. In April, 1994, the second data set was collected while the steam injection was continued. It is believed that the steam, by combination of temperature and condensation of saline fluid, would result an increase in electrical conductivity. So, the objective of the EM experiment was to see if we could monitor the subsurface process by observing changes in electrical conductivity that might have been caused by steam injection.

Oil is typically associated with the more permeable sand lenses, so the oil bearing zone is characterized by high electrical resistivity. The inversion of crosshole data taken before the injection is shown on the left in Figure 2, and it clearly shows a dipping sequence of bedding structure. Dark blue zones represent highly resistive oil bearing sand, and yellow to red zones electrically conductive and less permeable shale bedding. The second data set acquired after the steam injection was inverted and the result is shown at the center of Figure 2. The difference in electrical conductivity before and after the injection is shown on the right in terms of percent changes. The result clearly shows a horizontal impermeable barrier at the depth of 80 m. Also, it appears that a major steam chest is developing in the area just below the injection point.

The data base available was not enough to address a 3-D conductivity distribution in this exercise. It was therefore necessary to assume that the structure is 2-D. In addition, we have constrained our inversion with the induction log available in this area. The availability of constraints turns out to be very important, because the inversion without them would not match very well with the resistivity provided by the induction logs.

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Figure 1. Frequency-domain to q -domain transform

3D resistivity inversion using crosshole data

Before Injection, XZ-Plane, Y=-0(m)

After Injection, XZ-Plane, Y=-0(m)

Difference, XZ-Plane, Y=-0(m)

Figure 2. 3-D nonlinear inversion of crosshole EM data collected at the Lost Hills steam injection experiment