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Electrical and Electromagnetic Methods for
Reservoir Description and Process Monitoring

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INTRODUCTION

It is well known that electrical conductivity of rock is closely related to the porosity, hydrologic permeability, saturation, and the type of fluid in it. 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.

At the beginning of FY-91 a coordinated electrical and electromagnetic (EM) geophysical research program for petroleum reservoir characterization and process monitoring was initiated. Parties involved in this program include Lawrence Berkeley Laboratory (LBL), Lawrence Livermore Laboratory (LLNL), Sandia National Laboratory (SNL), and University of California at Berkeley (UCB). The overall objectives of the program were:

- To integrate research funded by DOE for hydrocarbon recovery into a focused effort to demonstrate the technology in the shortest time with the least cost.
- To assure industry acceptance of the technology developed by having industry involvement in the planning, implementation, and funding of the research.
- To focus the research on real world problems that have the potential for solution in the near term with significant energy payoff.

Specific research activities conducted through this integrated effort have been in the following five general areas:

- 1) EM modeling development.
- 2) Data interpretation methods development.
- 3) Hardware and instrumentation development.
- 4) EOR and reservoir characterization.
- 5) Controlled field experiments.

The primary focus of these activities was in the development of reliable inversion and imaging schemes that could yield conductivity distributions from measured electrical and EM field data. The development of accurate forward modeling algorithms and the high-quality scale model experiment are necessarily the early part of the field experiment design and the inversion scheme development for ultimately monitoring the front tracking in existing reservoirs.

At LBL/UCB research has been continued on activities 1), 2), and 5) in FY93, and as described in the next section, some of these research activities have been successfully concluded. These include 1) the development of the wavefield transform algorithm and the subsequent tomographic imaging of electrical conductivity using time-domain EM data, 2) the time-domain scale model experiment whose data have been successfully transformed to the wavefield, and 3) the field experiment at Richmond field station (RFS). The RFS experiment produced high-quality crosswell EM data which have been inverted to reveal the location of a plume of injected salt water and its flow direction.

Especially important to note in this report is that the RFS field experiment has been primarily supported by LBL/UCB industrial sponsors group. There are currently (FY1994) five participants in this group. Each participant provides \$15K per year to support this work which is also partially supported by the Office of Basic Energy Sciences (OBES) and DOE/Fossil Energy.

SUMMARY OF TECHNICAL PROGRESS

• Inversion and imaging of EM data

One of the principal goals of electromagnetic reservoir geophysics is to obtain high-resolution images of subsurface electrical properties. From these images of electrical conductivity and/or permittivity (for this it would require high-frequency EM data), information about reservoir heterogeneity and fluid distribution can be deduced and used to estimate oil field properties such as porosity, fracture orientation, amount of oil present in situ, and improve the design and monitoring of improved oil recovery processes. In this report we describe the following two independent imaging algorithm development. The texts shown here are similar to those appeared in FY91 Annual Report.

a) Iterative Born inversion

The Born inversion method described here is based on the following integral equation for scattered EM fields (Hohmann, 1971).

$$H^S(r_{rx}; r_{tx}) = i\omega\mu \int_{V'} \{ \bar{a}_a(r') - \bar{a}_o \} E(r'; r_{tx}) G_H(r_{rx}, r') dr' \quad (1)$$

where H^S is the measured secondary field at receiver position r_{rx} due to a transmitter at position r_{tx} , $\bar{a}_a$ and $\bar{a}_o$ are the anomalous and background admittivities defined by $\bar{a} = \sigma + i\omega\epsilon$ where σ is the conductivity, ϵ the electric permittivity, E is the total electric field which can be expressed as the sum of the primary and secondary fields, i.e., $E = E^P + E^S$; and G_H is the magnetic field Green's function for the background medium. This equation describes the anomalous fields that arise from the existence of scattering currents in inhomogeneities. The relationship between H^S and $\{ \bar{a}_a(r') - \bar{a}_o \}$ in equation (1) is highly non-linear due to the fact that the electric field E is dependent on the anomalous admittivity. Thus the estimation

of the anomalous conductivity and/or permittivity is a non-linear process requiring extensive computer time and memory which currently allows only the simplest problems to be analyzed.

However, when the medium contains only weak scatterers, i.e., when $\{\bar{a}_a(r') - \bar{a}_0\}$ is small, then a linearized version of (1) ensues through the use of the first order Born approximation in which $E \approx E^P$ (Kong, 1975).

$$H^S(r_{rx}; r_{tx}) = i\omega\mu \int_{\mathcal{V}} \{\bar{a}_a(r') - \bar{a}_0\} E^P(r'; r_{tx}) G_H(r_{rx}, r') dr' \quad (2)$$

This equation now shows linear relationship between H^S and $\{\bar{a}_a(r') - \bar{a}_0\}$. The equation implies that the scattering currents within the inhomogeneities are negligibly small such that coupling between individual scatterers can be neglected. If the background (1-D) electrical properties are known (say from electric logging) then E^P and G_H can be estimated and the anomalous admittivity can be inverted for. This is the formulation used by Zhou (1989) for the line-source problem.

To improve upon the regular Born inversion an iterative Born approximation inversion routine has been developed. The medium is assumed to be cylindrically symmetric about the borehole in which a vertical magnetic dipole is used as the source. Applying the quasi-static approximation and discretizing the cross section into N cells in each of which both the anomalous conductivity and primary electric field are assumed constant (Hohmann, 1971), equation (2) for the first-order Born approximation becomes

$$H^S(r_{rx}; r_{tx}) = i\omega\mu \sum_{j=1}^N \{\sigma_a(r_j) - \sigma_0\} E^P(r_j; r_{tx}) \int_{\mathcal{V}} G_H(r_{rx}, r') dr' \quad (3)$$

where E^P and G_H are the primary electric field and Green's function in a layered earth, respectively. If the background conductivity σ_0 is known, E^P and G_H can be approximated and thus σ_a estimated using a least squares inversion technique.

The iterative process is implemented by first approximating the secondary electric fields at the center of each pixel due to the inhomogeneous conductivity σ_a that was solved for in (3) above. This estimation is accomplished by using the first-order Born approximation for electric fields, i.e.,

$$E_{calc}^S(r_k; r_{tx}) = i\omega\mu \sum_{j=1}^N \{\sigma_a(r_j) - \sigma_0\} E^P(r_j; r_{tx}) \int_{\mathcal{V}} G_E(r_k, r') dr' \quad (4)$$

The second-order Born approximation can then be achieved by using these calculated electric fields in the equation

$$H^S(r_{tx}; r_{tx}) = i\omega\mu \sum_{j=1}^N \{\sigma_a(r_j) - \sigma_o\} [E^P(r_j; r_{tx}) + E_{calc}^S(r_j; r_{tx})] \int_{r'} G_H(r_{tx}, r') dr' \quad (5)$$

Notice that equation (5) is non-linear in $\{\sigma_a(r_j) - \sigma_o\}$. The conductivity is once again estimated using least squares inversion, and equations (4) and (5) are iterated upon until convergence occurs.

The algorithm described here has been used to simulate a steam flooding experiment. Figure 1 shows two conductivity models with essentially four (4) layer background. The one on the left (Model A) has its third layer composed of a number of lateral inhomogeneities, of which the steam (shown in red) is confined to the layer. On the other hand, the one on the right (Model B) shows a model in which the steam has already spilled into the upper layer and started flooding the region. Using the magnetic fields computed in crosswell configuration the conductivity distributions of each of these models have been inverted for and the results are shown in Figure 2. The tomogram clearly shows the locations of steam, either confined in the third layer (Model A) or spilled into the layer above it (Model B), for both models.

In conclusion, the iterative technique shows an increased spatial resolution and appears to be able to handle larger conductivity contrasts compared to the non-iterative Born approximation (Zhou, 1989). The same algorithm has been successfully applied to 2-D inhomogeneities using a line source (Alumbaugh and Morrison, 1993).

b) Development in the wave-field analysis

It has been shown (Lee et al., 1989) that there is a unique mathematical relationship between fields satisfying a diffusion and the corresponding wave equations. The relationship is defined by an integral transform that does not involve space variable r . In this relationship the diffusive field, the magnetic field H for example, is uniquely represented by an integral of a corresponding wave field U weighted by an exponentially damped kernel. One of initial objectives of the research program is to develop methods to calculate wavefields from given data, so that the result can be used for mapping conductivity distributions using wavefield analysis techniques. This fictitious field U would be dispersionless and would have a well defined phase, as well as a group, velocity. The transform equation is written as

$$H(t) = \frac{1}{2\sqrt{\pi t^3}} \int_0^\infty q e^{-\frac{q^2}{4t}} U(q) dq \quad (6)$$

in which the spatial variable r has been omitted because of the reason mentioned above. In this equation the time-domain data, $H(t)$, is on the left hand side and the wave field, $U(q)$, is inside the integral. To construct the wavefield an inverse transform is required, whose process is known to be notoriously unstable.

Over the past few years a numerical algorithm has been developed to obtain the wavefield from the time-domain magnetic field using equation (6). Due to the fact that the time window of the time-domain data is limited, we may not be able to recover full waveform in the transformed domain, however, we have been able to obtain correct traveltime (peak time). Thus obtained traveltimes have been used to construct conductivity image by means of ray tomography. For this purpose an efficient ray tomography algorithm has been developed employing bending rays.

Thus developed algorithm has been tested on a model shown on the left of Figure 3. The model consists of a 10 m wide conductive zone (0.2 S/m) sandwiched between rocks of different conductivity, 0.02 S/m and 0.05 S/m, respectively. The dip angle of the conductive zone is 60 degrees. Using this configuration an array (21 receivers) of magnetic field calculations were made in the receiver hole (on the right), while a vertical magnetic dipole source, located along the borehole to the left of the model, is used to excite the medium. The source is moved down the transmitter hole 10 m at a time. Initially, frequency-domain magnetic fields were computed at the receiver site and inversely Fourier transformed to the time domain. This process produced time-domain magnetic fields in the logarithmic time scale. These fields were then spline interpolated and used as input to equation (6). In our exercise a total of 270 equal-spaced time-domain magnetic fields were used to generate equal number of discrete wavefields in the q domain. The time window used was 10 μ sec ~ 500 μ sec.

The conductivity tomogram shown on the right of Figure 3 clearly copies the conductivity distribution of the original model shown on the left. The number of iterations required to obtain a satisfactory tomogram depends on the conductivity contrast. It took 120 iterations for this model shown in Figure 3. The result shown in Figure 3 is part of the study presented by Lee and Xie (1993) ([Attachment 1](#))

• Time-domain electromagnetic (TEM) scale model

As an integral part of the joint R&D program for petroleum reservoir characterization and process monitoring, we have constructed and conducted a TEM scale model experiment. The scale model study is important because it can be used to simulate reservoir models in a controlled environment. A more immediate objective of developing the scale model is to obtain high-quality (low noise, high bandwidth, high dynamic range) data for the q -domain imaging algorithm (Lee and Xie, 1993) currently under development at LBL. Finally the scale model parameters will be very useful in the design of full scale field instrumentation.

The scale model consists of a 1.2 m diameter, 0.5 m thick, cylindrical graphite block with an electrical conductivity of about 90,000 S/m. The experiments are done on such a scale that 1 cm in the scale model is equivalent to 10 m in real world. The model represents a field environment with an average background resistivity of 11.1 ohm-m (0.09 S/m) so that the transmitted and received wave forms are observed on an identical time scale to that which would be used in a full scale field experiment.

The scale model experiment was started in FY 1991. One of important components in this development is the efficient computer program that can be used to evaluate the effects of the model EM system parameters such as bandwidth and dynamic range on the observed scale model response. The program was written in Math CAD 3.0 and allows the introduction of all technical details such as transmitter moment, inductance and resistance and the receiver capture area as well as its damping and distributed capacitance. Even the effects of cabling parameters can be included. The test geophysical signal for the simulation program is the ideal (theoretical) whole space response. On the hardware side, we are using Geonics EM-47 as the signal generator and for the A/D converter the Analogic 6400 (1 MHz 14 bit) is used. Signal acquisition is controlled by a 486 based PC.

Typical scale model data and their transformed result are described in the following. Figure 4 shows the acquired data in millivolts per unit moment at a sampling rate of one μ s. The transmitter and receiver were located at 8.6 cm below the surface (86 m below the surface of the earth in real world) with its horizontal separation of 5 cm. Data quality seems to be excellent up to 0.5 ms range and then starts to deteriorate. The data have been smoothed (see noise at the late time) and then transformed to wavefields and the results are shown in Figure 5. There are eleven wavefield traces in the figure. The same time-domain data have been used to generate these separate traces, but each trace represents the transformed wavefield using data with different starting time. For example, the wavefield trace on the top represents transformed wavefield using the smoothed time-domain data with its first sample at four (4) μ s. The traveltimes, the fictitious time in q at which the wavefield peaks, changes slowly from one trace to the other, indicating that the transformation is stable. The difference in traveltimes and the corresponding equivalent distance between the experimentally obtained values and the theoretically predicted ones are listed at the lower portion of Figure 5. The result shows that the accuracy can be within 1% if data is collected and used starting from 4 μ s, and 2% if data used is from 6 μ s.

With the successful scale model experiment the next obvious step is to simulate simple 3-D heterogeneities within the graphite scale model. Wood metal or a piece of copper block can be embedded in the graphite block for this purpose. The measurement from this model simulation may then be used to test the imaging code developed in this project.

• Controlled field experiments

As briefly described in the introduction section the controlled field experiment has been largely supported by UCB/LBL-industry consortium. Since 1988, a series of salt water injection experiments has been conducted at RFS to evaluate the use of different geophysical methods for monitoring the injection process and for determining the geometry of the resulting plume. Detailed description of the field experiment was given in FY1992 Annual Report. In addition all important findings from the experiment have been summarized in an LBL report (LBL-34734; Attachment 2), which was subsequently submitted to Geophysics for publication. In this report we describe only the latest part of the experiment.

The latest 1992 experiment employed the cross borehole configuration. After an initial system setup and debugging session, a baseline crosshole EM data set was collected in May, 1992. It consisted of four crosshole profiles with the transmitter in the central well (Figure 6) and the receiver tool deployed in each of the four EM observation holes. Data were collected at a frequency of 18,500 Hz using a transmitter tool spacing of 0.5 m from the surface to a depth of 60 m for each receiver position. Receiver stations were spaced 5 m apart from 5 m to 55 m in each of the four observation holes. Next, a volume of water was pumped into a 100,000 gallon holding pond and mixed with salt until the water conductivity was raised to 1 S/m. The fluid was then injected into the injection well at a rate of 10 gallons per minute for about 4 days. Assuming a porosity of 30 percent, the injected water would sweep a cylindrical space 3 m high and 8 m in radius. We collected a second set of crosshole EM and induction logging data during a four week period in June following the injection.

After the June measurements were made, fluid was pumped out of the injection well until the water conductivity was restored to the background value it had before the experiment began (60 mS/m). The total volume pumped out was 300,000 gallons, about 6 times the amount injected. The pumping began on July 6 at a rate of 20 gallons per minute and it lasted 12 days. Water levels in the wells open to the aquifer were monitored during this period to better understand the hydrology of the site. The water was pumped into a drain that flows into San Francisco Bay. Finally after a two-week period which allowed the water level to recover its original position we attempted to repeat the baseline EM measurements in the NE well. Unfortunately, due to instrument problems data quality was much poorer than in May and this data was not retained. In all, the experiment was conducted over a period of three months.

Data collected from the experiment have been inverted using the iterative Born inversion algorithm described in the previous section. The algorithm assumes a cylindrical symmetry of the conductivity distribution about the transmitter borehole in an otherwise one dimensional earth. Figure 7 shows the images obtained by inverting the pre- and post-injection data collected in the NW well. Although it does not indicate flat lying layers, the pre-injection image does show conductive overburden overlying a more resistive basement. The post-injection image clearly shows a high conductivity anomaly that corresponds to the injection zone at about 35 m depth. Images obtained using other data sets from NE, SE, and SW boreholes reveals no such changes in conductivity. This strongly suggests that the salt water has migrated to the northwest which agrees very well with the results published by Bevc and Morrison (1991).

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Steam Flood Models

Model A

Model B

Figure 1. Models used for simulating steam injection experiment. These models are assumed to be cylindrically symmetric.

Low Frequency (100 Hz) Imaging Results with Model Superimposed

4 Layered Background Model

1% Random Gaussian Noise

Positivity Constraints

Model A

Model B

Figure 2. Inversion results for models shown in Figure 1.

Research in High-Resolution Imaging of Electrical Conductivity

Earth Sciences Division
Lawrence Berkeley Laboratory

- Approach Used -
Diffusion to Wavefield Transform & Traveltime Tomography

**Figure 3. Tomographic imaging of conductivity model
using the wavefield transform method.**

Scale model Data

Figure 4. Time-domain EM data obtained from the scale model

Wavefield $U(q)$

constructed from scale model data

Start sampling time used for transform (μs)	4	6	8
Traveltime obtained from transformed data (q)	0.01675	0.01709	0.01743
Theoretical traveltime (q)	0.01681	0.01681	0.01681
Difference in q (Δq)	- 0.00006	0.00028	0.00062
Equivalent difference in distance (m)	- 0.1833	0.8333	1.8500

Figure 5. Transformed wavefield. Heavy dots indicates the first arrival of the wavefield.

Cross Well EM Tomography

Salt Water Injection Experiment

Richmond Field Station, Richmond CA.

Figure 6. Borehole configuration at Richmond field station.

EMNE Total Field Images

Figure 7. Iterative Born inversion of NW borehole data.