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**RESERVOIR CHARACTERIZATION AND PROCESS
MONITORING WITH EM METHODS**

1993 Annual Report

**by
Michael Wilt**

September 1994

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

**Thomas B. Reid, Project Manager
Bartlesville Project Office
P.O. Box 1398
Bartlesville, OK 74005**

**Prepared by
Lawrence Livermore National Laboratory
Livermore, CA 94551**

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Reservoir Characterization and Process Monitoring with EM Methods

Annual Report 1993

Contract No. FEW6038

BPO contact: Tom Reid

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Principle Investigator: Michael Wilt
Lawrence Livermore National Laboratory

Objective:

To apply surface and borehole EM methods for oil-field characterization and process monitoring. We wish to improve the knowledge of oil field structure and recovery processes by providing the electrical resistivity distribution in the region between wells.

Introduction

During past four years at Lawrence Livermore National Laboratory (LLNL) we have applied the EM induction method to the problem of thermal front tracking during EOR operations. During this past year we have also turned our attention to the larger, but related, problem of petroleum reservoir characterization.

As in this past this research is a collaborative effort. The main focus of our activities at LLNL is hardware development, field measurement and geological interpretation of the results. We are therefore dependent on others for theoretical and software development, geological information and the availability of sites to test our field systems. Our closest collaborators are Lawrence Berkeley Laboratory (LBL) for theory and software development, Schlumberger-Doll Research (SDR) for hardware and software development and Mobil Exploration and Production for field site access and geological information. This interdependency serves to make our research dollars stretch further and allows us to complete the tasks in a timely manner.

In this annual report we discuss the progress in the development of numerical modeling codes, describe improvements to our field system and present some field results.

Summary of Results for FY93

In December 1992 LLNL signed a Cooperative Research and Development Agreement (CRADA) with Schlumberger-Doll Research for the development of a new generation of instrumentation for crosshole and surface-to-borehole EM. The goal of the three year agreement is to develop a commercially viable prototype instrument for oil field characterization and process monitoring. SDR will develop a new borehole receiver, LLNL will develop the corresponding borehole transmitter and both parties will participate in software development and field testing activities.

During the first year of this agreement we developed a new transmitter as a prototype to the system outlined in the CRADA. This tool was tested in field surveys in FY93 and provided much superior performance compared to our older transmitter.

Concurrent with the hardware development there has been a rapid development of software for interpreting the field measurements. Codes were developed at Lawrence Berkeley Lab, Sandia National Lab, the University of Houston and Schlumberger-Doll Research. Several of these appear to be effective for interpreting field data in rather complex geological environments. We are presently testing the most promising of these.

Among the stated goals for FY 93 was the development of the surface-to-borehole method for subsurface imaging in relatively shallow oil fields. With this method a single borehole is utilized, in combination with the surface, to provide an image of the electrical resistivity variations extending outwards from the well. During FY93 we collected some field data at Richmond field Station and the Lost Hills oil field, investigated repeatability and noise problems and interpreted the results.

Instrumentation Development

LLNL/SDR CRADA

In December 1992 a Cooperative Research and Development Agreement (CRADA) was negotiated with Schlumberger-Doll Research (SDR) for the development of a new generation of instrumentation for crosshole and surface-to-borehole EM. The agreement consist of three parts 1) instrumentation development 2) companion software development and 3) field validation of the hardware and software. The goal of the three year agreement is to develop a commercially viable prototype instrument for oil field characterization and process monitoring.

Under the agreement SDR will develop a multicomponent borehole receiver and LLNL will develop the companion multi-frequency transmitter. This proposed system is a major upgrade from the single-frequency, single-component system presently in-use at LLNL. It is designed to provide much higher resolution and more accurate subsurface images than is possible using our present system. The schedule calls for system design and prototype development during the first year with serious construction activities and testing to occur in year 2. The final year is reserved for field surveys.

The multi-frequency multi-component data to be provided by our new system requires a new generation of interpretation software to take advantage of the improved frequency and spatial data coverage. Software is presently under development both at Schlumberger-Doll Research and Lawrence Livermore Lab (in collaboration with LBL) that takes advantage of this additional coverage to produce higher resolution images.

Field test of new Borehole Transmitter

In FY93 we developed a new analog transmitter and are presently using it for field measurements. This tool was built to test some of the concepts outlined in the LLNL/SDR CRADA; it was designed as a prototype to the more sophisticated tool to be built for the CRADA. It is equally powerful to the upcoming tool but far simpler in design.

The new borehole transmitter is a significant departure from our previous source. With the new source the transmitted signal is developed downhole, instead of at the surface, and only dc power is supplied from the surface. This design eliminates many ground loop paths and thereby reduces noise and measurement drift. The new design also allows us to develop an automatic switching system, using computer-controlled relays, to control the transmission frequency.

In Figure 1 we show some sample field data using our new transmitter and also give the repeatability error for the system. The plots demonstrate a repeatability error of less than one-half percent in amplitude and less than one-half degree in phase. This significant improvement over our older system can be attributed to the improvements in design. The recent field test also allows us to calculate the noise floor of our system. We determined that the noise is approximately 5-10 fempto-Teslas, approximately four times smaller than our older source but still 10 times larger than the sensitivity limit of the receiver. This implies that further improvement is possible.

The new tool is considerably more powerful than our previous source due to the inclusion of a solid ferrite core in the design. (The older transmitter used a segmented ferrite core). At an operating current of 10 amperes the tool provides a peak moment of about 700 A-m², or about 3 times higher than our older source. The testing did reveal a shortcoming when operating in the presence of metal. Large metallic objects (such as steel well casing) serve to de-tune the oscillator and the transmitter will not function. This is unimportant in plastic or fiberglass lined wells but in steel-cased wells we must operate with the old transmitter.

The new transmitter to be developed under the CRADA will be similar, in the analog portion, to the present source. The differences are that the source controls, switching, phase synchronization and depth control will all be digital and controlled by surface and borehole computers.

Theoretical Advances/ Software Development

A series of new codes have been developed or are under development in FY93 that should dramatically improve imaging capabilities with crosshole and surface-to-hole EM. Three dimensional codes are under development by Newman of Sandia National Laboratory and Lee of LBL; two dimensional codes have been developed by Shin of the University of Houston and Torres-Verdin of SDR. All of these have promise for helping interpret field data. At LLNL we are providing the modelers with field data sets to test these codes.

One of these new imaging codes to interpret crosshole EM induction data was developed by Drs. Torres-Verdin and Habashy of SDR (Torres and Habashy, 1993). This code assumes a two-dimensional rectangular earth geometry and an arbitrary resistivity distribution within the image plane. The code is a significant advance over previous codes due to its flexibility, speed and ability to handle high-contrast anomalies and irregular geology; it is an ideal tool for imaging in a plane between two boreholes.

In Figure 2 we show a conductivity image, using this code, of the crosshole EM data set collected in Devine, Texas in 1990. As described in Wilt et al. (1993) the strata at Devine are flatlying and continuous, and the crosshole data set is of excellent quality. Figure 2 also shows the borehole induction log to the left of the image for comparison purposes.

The image faithfully reconstructs the resistivity structure with significant error only at the top and bottom of the image plane, where the spatial coverage is incomplete for imaging. There are minor errors in the absolute value of the conductivities and some small artifacts, but, in general, the code does a good job of reconstructing the conductivity distribution between the boreholes. We are presently applying this code to field data sets collected at Lost Hills and will soon test it with surface-to-borehole data from Richmond Field Station.

a)

b)

Figure 1 Field trials with new borehole transmitters. The upper plots depict a field data profile; the lower give the repeatability for this profile.

Figure 2 Interpretation of crosshole EM data collected in Devine, Texas with the 2 1/2 d inversion code developed at SDR. The borehole induction log is shown on the left.

Field Studies--Surface-to-Borehole Method

At field sites where only one borehole is available for geophysical activities the surface-to-borehole method can be an effective tool for imaging the subsurface in the vicinity of the well. By placing a receiver in the well and sources on the surface (or vice versa) the subsurface can be imaged along profiles emanating from the borehole. This technique will not provide as detailed an interpretation as the crosshole measurements, but it offers a dramatic improvement over surface techniques.

Much of our field activity in FY 93 focused on collecting data and estimating error for the surface-to-borehole technique and on modifying computer codes to interpret these data. We collected high density STB data sets at the Lost Hills #3 site and at Richmond field station. In these surveys we collected data at frequencies from 1-10 kHz, evaluated short and long term error, and applied existing interpretation algorithms to the data. The results were then compared to the crosshole interpretation and to the known geology.

Activities at Lost Hills #3

In August, 1991 two observation wells were drilled at the Lost Hills #3 oil field for the purpose of monitoring a new steam flood that commenced in October 1991. The wells, which straddle a steam injector, were drilled for geophysical observation of the steam injection pilot operated by Mobil Exploration and Production. Steam injection activities began in this portion of the field in January 1992 but it wasn't until September 1993 that Mobil was able to inject steam into the area we are monitoring (Figure 3).

Figure 3 Base map for the EM activities at the Lost Hills field site.

Surface-to-borehole profiles were collected at the Lost Hills site in May, 1993. Each profile consists of a surface transmitter loop, broadcasting a monochromatic 1 kHz signal, and a series of induction coil receivers in borehole DRL35S spaced at 6 m intervals from the surface to a depth of 150 m. A separate profile was made for each of the eight surface transmitters extending westward from borehole DRL35S to DRL61, a distance of 125m. The data set consists of 8 profiles each including of 22 measurements. In Figure 4 we display these data in pseudo-section form.

Due to the greater source-receiver separations and the noisier environment on the surface these data is somewhat noisier than crosshole measurements. We found that short term errors average from 1-3 percent and longer term errors (several months) can be as high as 10 percent. These higher errors are due to a combination of changing surface conditions (i.e. due to rainfall) and changes in the level of local cultural noise. As we gain more experience these errors should decrease.

The surface-to-borehole data were interpreted by applying a one-dimensional (layered) modeling code developed by Schenkel to the individual profiles (Wilt and Schenkel, 1992). We assumed that the resistivity distribution consisted of 12 ten-meter thick layers each with a resistivity of 5 ohm-meters. The computer then is free to change the resistivity of the layers until the model-generated results fit the observed data. The computer code was usually able to fit the profiles to within five percent. For all of the profiles the inversions indicate the presence of two separate resistive layers at depths below 50 meters. These layers represent the oil sands which are the targets for upcoming EOR steam flood activities.

We can form a resistivity cross section by plotting the layered section derived from the one-dimensional inversions for each sounding beneath the position of the surface loop transmitters. The layered models are then pieced-together along the profile to form a quasi-two dimensional model of the earth along the profile (Figure 5). For a smoothly varying section, such as Lost Hills, this model is probably a good first guess for a two-dimensional structure. We will test this assertion in the near future when Dr. Kiha Lee of LBL applies his two-dimensional code to the Lost Hills data set.

The pseudo-section shown in Figure 5 accurately reflects the configuration of the upper two oil sands at Lost Hills as known from the borehole induction logs. It shows that the sands form two distinct, gently dipping resistive units in a low resistivity background. The resistive units are known to correspond to coarse-grained oil sands whereas the low resistivity rocks are finer grained clays and silts.

Surface-to-Borehole Field Experiment at U.C. Richmond Field Station

As part of the May, 1993 semi-annual meeting with the industrial sponsors of LBL/LLNL electromagnetic research a field plan was proposed for additional work at the UC Richmond field station. This work will consist of a saltwater injection monitoring experiment applying a variation of the borehole-to-surface technique. The experimental plan calls for high density multi-station and multi-component surface measurements along two crossing profiles over the injection borehole.

For this experiment the field system was modified so that four channels of surface data will be measured simultaneously. This allows for the determination of magnetic field gradients in addition to the fields themselves. We plan to measure both the vertical magnetic field and the radially directed horizontal field components. Recent theoretical work at UC Berkeley has shown that using multicomponent magnetic fields and field gradients can

Figure 4 Surface-to-borehole EM data collected along profile A-A' at Lost Hills

markedly improve the resolution of subsurface features. Crosshole EM measurements will also be collected so that the borehole-to-surface and crosshole methods can be compared for the same experiment.

The experimental data was collected in the fall, 1993. This data will be interpreted in 1994 using software developed by UC student Ocean Tseng as part of his Ph.D. thesis.

Figure 5 Layered model inversion of data from Figure 4.

Plans for FY 94

During FY94 we will see the program will move at a significantly faster pace. Results from field projects in steam flood monitoring and reservoir characterization at Lost Hills will be available and preliminary results will be published. We will likely see resistivity changes at Lost Hills due to the steam flood activities. Interpreting these data will provide a good test of our field system and software.

Construction on the LLNL/SDR field system should be complete by August, 1994 and the initial field test will likely occur next fall. The initial field test will most likely be at the University of Oklahoma Gypsy facility where good reservoir characterization data is available and a good quality crosshole seismic data set may be used for comparison.

In FY94 the LBL/LLNL EM consortium will turn its attention to operations in steel cased wells. If research in this area is successful several new tools will be added to our arsenal and the scope of applications for EM techniques will expand considerably.

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Milestones FY93

During FY93 two students supported by the project graduated from the University of California with Ph.D. degrees. They are David Alumbaugh--presently employed as a postdoctoral researcher at Sandia National Laboratories and Maria Deszcz-Pan, soon to begin a staff scientist job at the U.S Geological Survey.

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