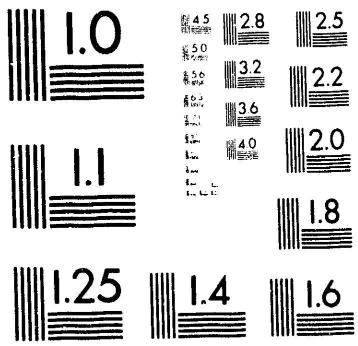
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Monitoring of Thermal Enhanced Oil Recovery Processes with Electromagnetic Methods

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Abstract

Research in applying electromagnetic methods for imaging thermal enhanced oil recovery has progressed significantly during the past eighteen months. Working together with researchers at Lawrence Berkeley Laboratory (LBL) and supported by a group of industrial sponsors we have focused our effort on field system development and doing field surveys connected with EOR operations.

Recent progress at LBL in diffusion tomography has produced the first set of electrical conductivity images from crosshole EM data. A set of crosshole EM data collected in Devine, Texas was inverted with a code developed at LBL. The code was able to reconstruct the prominent conductivity features from this set of data collected in a simple stratified geological environment. The accuracy of the result was verified by comparison with borehole logs.

The success of the crosshole EM method is dependent on continued hardware development. At LLNL we have recently developed a new borehole transmitter more than three times more powerful than our present transmitter and potentially less than half as noisy. The new transmitter generates the oscillating signal internally from dc power supplied from the surface. Because the high level signal is generated only within the transmitter we reduce the surface coupling at the receiver, thereby diminishing the noise.

Field surveys were recently completed at the Lost Hills#3 oil field and at UC Richmond Field station. At Lost Hills, crosshole EM data sets were collected before a new phase of steam injection for EOR and again four months after the onset of steaming. The two data sets were nearly identical suggesting that very little steam had been injected into this borehole. This is in accord with the operators records which indicate injectivity problems with this particular well. At Richmond we conducted a salt water injection monitoring experiment where 50,000 gallons of salt water were injected in a shallow aquifer and crosshole EM data were collected using the injection well and several observation wells. We applied the imaging code to some of the collected data and produced an image showing that the salt water slug has propagated 8-10 m from the injector into the aquifer. This result is partially confirmed by prior calculations and well logging data.

Applying the EM methods to the problem of oil field characterization essentially means extending the borehole resistivity log into the region between wells. Since the resistivity of a sedimentary environment is often directly dependent on the fluids in the rock the knowledge of the resistivity distribution within an oil field can be invaluable for finding missed or bypassed oil or for mapping the overall structure. With small modification the same methods used for mapping EOR process can be readily applied to determining the in-situ resistivity structure. In particular we need to **a)** extend the applicability of the method to steel-cased boreholes **b)** extend the imaging capability to the surface-to-borehole configuration.

Introduction

During past three years at LLNL we have applied the EM induction method to the problem of thermal front tracking during enhanced oil recovery (EOR) operations. In this paper we will briefly describe the progress made during the past eighteen months and discuss the problems remaining to be solved.

Beginning in 1989 we coupled our research program to research efforts at Lawrence Berkeley Laboratory (LBL), the University of California at Berkeley (UCB) and work at Sandia National Lab (SNL). The combined program is partially directed by a consortium of petroleum and service companies who also contribute some financial support. The LLNL program has focused on field system development and on doing field surveys associated with enhanced oil recovery operations. At LBL, UCB and SNL the research is more focused on theoretical and numerical algorithm development.

Since the primary charter of this research is in-field monitoring of oil recovery processes, we focused our efforts at assembling a field system and collecting field data at various sites. At the same time we have supported theoretical and modeling activities at LBL so that our data can be properly interpreted. In this paper we report on progress in the development of numerical modeling codes, discuss present and future improvements to our field system and present the results from two of our field surveys. In addition we will discuss our efforts at directing this research into the characterization of heavy oil fields with electromagnetic methods.

Theoretical Studies--Diffusion Tomography

The interpretation of crosshole EM data is inherently a difficult proposition. The magnetic or electrical dipole source field has three-dimensional characteristics, and in general, so does the medium to be studied. Modeling of electromagnetic fields in an arbitrary three-dimensional medium is a very complex undertaking, typically requiring a supercomputer. Fortunately, for a large class of problems a more simplified geometry can be applied and analysis can be done on a desktop computer.

For example, although the field-wide resisitivity changes associated with an EOR operation are three-dimensional, the resistivity changes around a single injector may be closely approximated by a two-dimensional model with cylindrical symmetry. By collecting crosshole EM data in several planes around an injection well (or nearby temperature observation well) it is reasonable to reconstruct the resistivity distribution around the well during steam injection and thereby infer flowpaths for the steam. Since the resistivity changes due to the fluid injection are quite large and the volume of formation affected is also on a large scale the prospect of imaging such a structure is reasonable.

To map the in-situ structure for many oil fields is also a reasonable proposition. If the structure is simple or smoothly varying one can apply a "Born" approximation which can greatly simplify the mathematics by assuming "weakly" contrasting anomalies. With this approximation smoothly varying two-dimensional structure can be imaged using pairs of boreholes. Note that in these appliocations one must be aware of the limitations of the model and must have some prior knowledge of the medium, such as from borehole logs.

During the past several years we have provided financial support and some technical direction to U.C.B. student David Alumbaugh who under the direction of Dr. H.F. Morrison has developed a scheme for tomographic interpretation of crosshole EM data. The scheme is a further development of the work of Sena and Toksoz (1989) and

Zhou (1989) and makes use of cylindrical symmetry and the "Born" approximation to provide an image of the electrical conductivity between two boreholes.

With the "Born" approximation we assume that ther is no interaction between the conducting bodies located within the background medium. This assumption eliminates a non linearity in the problem making it tenable on a desktop computer. Alumbaugh's contribution is an iterative "Born" inversion scheme whereby an initial approximation to the resistivity distribution between boreholes is obtained with a first-order "Born" algorithm and the image is sharpened during repeated iterations using higher-order Born approximations. In the process the difference between field data and model results is minimized and the EM fields in the anomalous body are more accurately determined.

The new tomographic inversion scheme, developed by Alumbaugh and Morrison (1992), was applied to the data set collected at the Devine, Texas site. The Devine site is in a region of simple flatlying geology and an excellent set of field data was available from an experiment done in 1990 (Wilt et al. 1991). In Figure 1 we show the reconstructed resistivity of the Devine site using the crosshole data. The geology at the Devine site is a series of flat lying and continuous sands, shales and limestones. The EM profiles were measured at depths encompassing a resistive (10 ohm-meter) limestone in less resistive sands and shales. The image in Figure 1 clearly shows the limestone horizon to be a 25 m thick continuous layer. The image also correctly determines the resistivity of all of the significant horizons. There is some distortion in the image due to incomplete and uneven sampling as well as field and numerical noise. In general, however, it does an excellent job at recovering the salient features in the data.

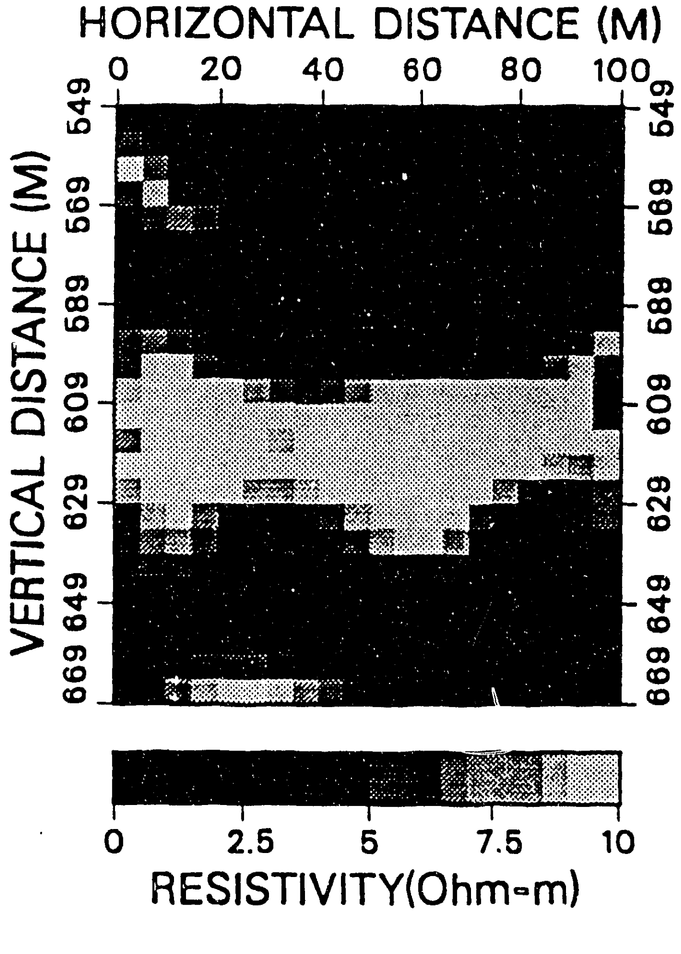


Figure 1 Tomographic Inversion of the EM data in Devine Texas

Instrumentation Development

Recent field measurements have shown that at frequencies above 5 kHz our field system is susceptible to 2-3 percent noise through surface-coupling of the source signal to the receiver. By making use of a design whereby the coil self-oscillates, and only dc power is supplied from the surface, we can eliminate this source of noise. This design was recently tested in field trials and we are quite encouraged by the results. A new high-power borehole transmitter is presently being built using this design and should be ready for testing by October, 1992

In the self-oscillating mode the transmitter consists of a ferrite loop antenna, resonating capacitors, a feedback oscillator-driver, and an FM flux monitor link from transmitter to surface via the supply cable (Figure 2). The driver for the resonant elements is made up of transistor switches arranged in a push-pull bridge. This gives very good efficiency and low heat dissipation. The capacitors series-tune the antenna to the desired operating frequency and the feedback oscillator automatically excites the antenna at the resonant frequency. Note that this frequency may drift as the antenna inductance is affected by changing temperatures or ground loading. The FM link converts the analog of the antenna magnetic flux, derived from a separate winding on the core, to an FM-modulated carrier, transmits the carrier up the supply cable. It then demodulates the signal back to the flux analog at the surface. This provides an estimate of the magnitude and phase of the magnetic dipole for use in data processing. As presently configured, the coil will operate at frequencies from 200 Hz-20 kHz.

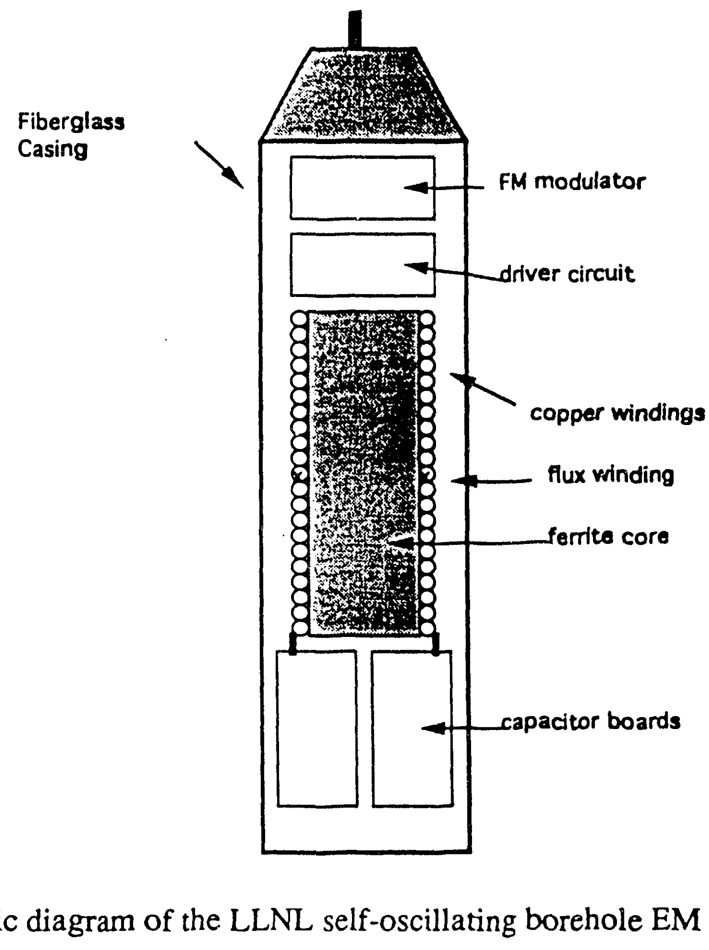


Figure 2 Schematic diagram of the LLNL self-oscillating borehole EM transmitter.

Field Studies

Steam Flood Monitoring at Lost Hills#3 Oil Field

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 R and D. We recently completed a series of cross-borehole EM measurements using these observation wells as part of the steamflood monitoring effort.

Baseline crosshole EM data were collected in September,1991, prior to the onset of steam injection activities. Our measurements included cross-borehole EM using three collinear observation wells spaced 55-125 meters apart. Complete profiles were collected using all possible well combinations at transmitter frequencies from 1.4 kHz (for the largest spacing) to 19kHz for the closest spacing. The data repeat at about the two percent level.

Steam injection activities for Mobil's new pilot began at the Lost Hills#3 oil field on October, 1991. After the first several months the injection wells in the new flood were averaging only about one-tenth the expected rate. Preliminary calculations showed that after four months this early steam plume would have migrated some 10 meters into the formation and change the EM response in the monitoring wells by approximately ten percent in amplitude and five degrees in phase. We decided that this would be sufficient for our system to detect so we deployed the field system in February, 1992 to re-measure the EM profiles collected in observation wells DRL35N and DRL35S.

In Figure 3 we show EM phase profiles measured in October 1991 and February 1992. The profiles are generated using a fixed receiver at a depth of 60 m in one sell while the transmitter move from a depth of 35 to 115 m in the second well. We used a frequency of 10 kHz for each measurement set. The blank portions of the profiles are where the transmitter tool has passed through steel well centralizers, thereby blanking the signal. The figure shows that the two sets of measurements are virtually identical. This was also the case with the eleven other profiles; we therefore observed no significant change after four months of steam injection. After a conference with the field engineer we learned that the injection well monitored was accepting less steam than the other wells in the grid and most likely an insufficient amount to form a steam plume. We would therefore not expect to observe any changes in the resistivity around the well. Measurements in an observation well located some 8 m from the injector, showed no increase in temperature during this period. This is further evidence of thereby confirming this result.

Well stimulation activities at this site are presently underway to improve injectivity. As these activities are completed and the steaming begins again we will return to Lost Hills for another set of measurements, probably in the last quarter of 1992. Although we were not able to provide an image of an EOR flood with these latest measurements, the results are nonetheless very encouraging because the field profiles collected four months apart could be reproduced so closely. If the new measurements (collected after the steam flood has developed) are of equivalent quality, then we can expect to produce some high resolution images of the steam plume.

EM phase Baseline vs Monitoring

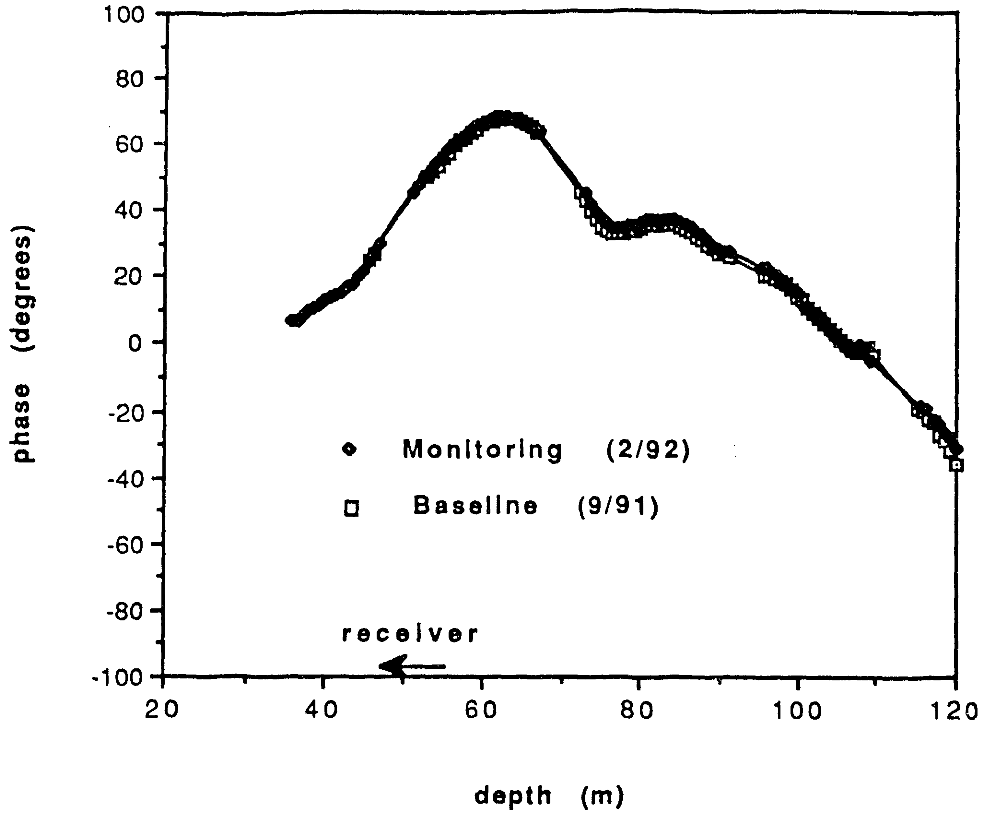


Figure 3 EM field profiles measured at the Lost Hills field four months apart.

Saltwater Injection Monitoring at U.C. Richmond Field Station

A plan view of the Richmond test facility, which lies approximately 7 miles north of the U.C. Berkeley campus and adjacent to the San Fransisco Bay, is given in Figure 4. From April to August, 1992 we used this facility for a saltwater injection monitoring experiment. Using well INJ 1 we injected 50,000 gallons of 1 ohm-meter saltwater into a 3 meter thick aquifer at a depth of 30m. We made a variety of surface and borehole geophysical measurements before, during injection, and after withdrawal of the fluid in an attempt to track the saltwater plume.

The crosshole EM measurements were made using a five well set with the transmitter deployed in the central borehole (INJ1) and the other boreholes (EMNE, EMNW, EMSE and EMSW) used for the receiver tool. This arrangement provides the first-order cylindrical symmetry required by our present imaging code (Alumbaugh and Morrison, 1992). In addition to the expanded crosshole measurements we also collected an expanded set of supporting data. This includes induction resistivity logs in all holes before and after salt water injection, a set of crosshole resistivity measurements (using wells RES1 and RES2), measurements of water conductivity in all the wells before and after injection and a set of water level measurements during the extraction and recovery stages of the experiment.

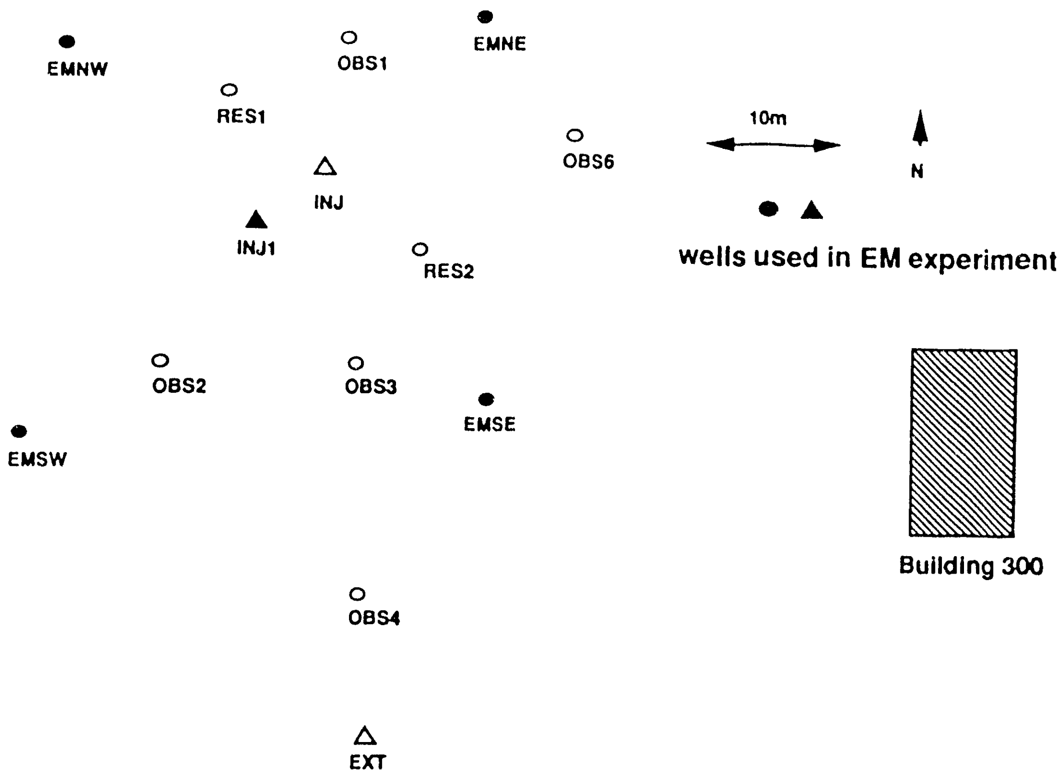


Figure 4 Plan view of the Richmond well field.

In Figure 5 we examine two induction logs from borehole INJ1, the salt water injection well. One of these logs was collected before salt water injection and the other after; the difference between them indicates the change in resistivity around the injection well due to the salt water. The Figure indicates that a zone approximately 8 m thick, from a depth of 23 to 31 meters, has significantly decreased in resistivity due to the salt water injection. A comparison of the logs in the injection interval shows a mirror image, where the higher resistivity sands and gravels before the injection have become the lower resistivity units after the salt water injection. The largest decrease is observed in a 4 meter thick sandy-gravel aquifer at a depth of 26-30 meters. This is the zone where the well is perforated and the rock has decreased in resistivity from 15 ohm-meters to 3.5 ohm meters. Calculations made by A. Mansure from Sandia National Laboratory (Mansure 1991 personal communication) predicted that the salt water should change the formation resistivity to 3 ohm-meters. These calculations were done assuming a rock porosity of 25 percent, clay content of 20 percent and salt water conductivity of 1 S/m.

In Figure 6 we display a tomographic inversion of the crosshole EM data collected at Richmond. Figure 6a shows the reconstructed conductivity section after salt water injection and Figure 6b shows the difference in conductivity before and after injection. The anomalous mass due to the salt water injection is evident at a depth of 25-30 meters and extends 8-10 meters away from the injection well. This is in accord with wireline logging data from boreholes INJ1 and INJ and is likely a good representation on the extent of movement of the salt water plume.

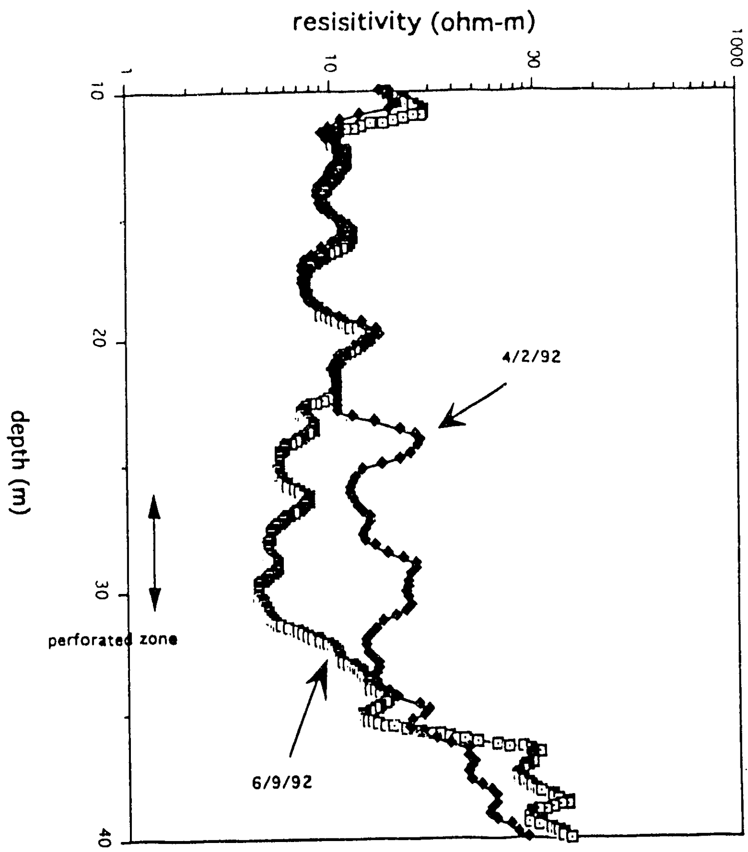
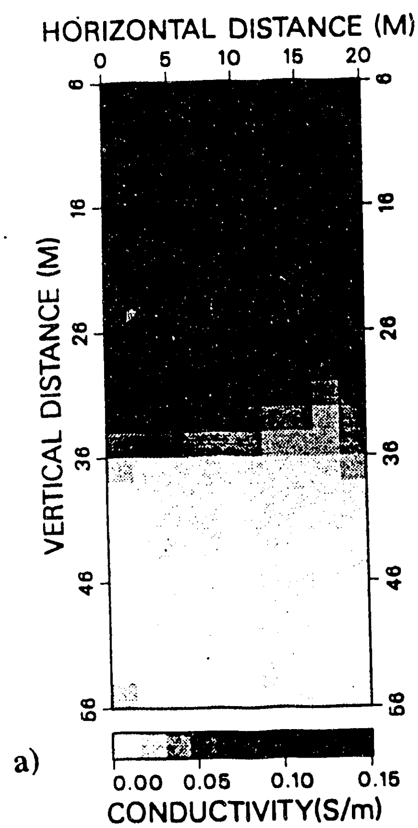


Figure 5 Borehole Induction logs in well INJ1 before and after salt water injection.



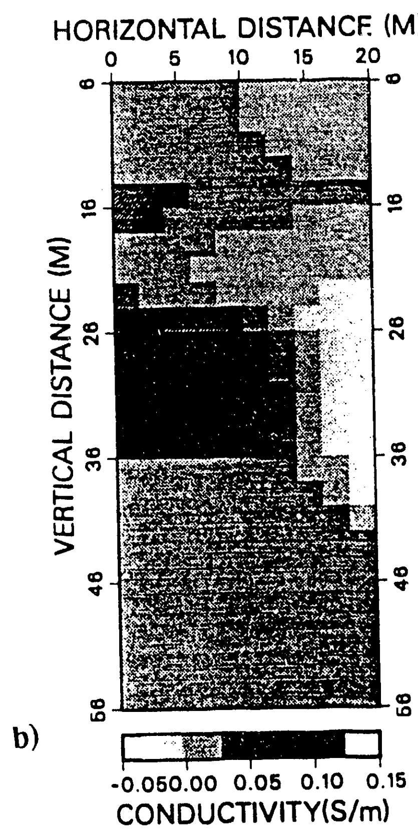


Figure 6 Tomographic inversion of EM profile INJ1-EMNE a) after injection of salt water b) the difference between images before and after injection.

Research Objectives in Heavy Oil Reservoir Characterization

The electrical conductivity of most sedimentary rock is dominantly a function of the fluid type, its saturation and the porosity of the rock. For these reasons resistivity well logs have long been used by reservoir engineers and geologists to distinguish between rock types, map variations in pore fluid and to determine completion intervals in wells. If the electrical resistivity distribution could be obtained throughout the field instead of only in the area immediately surrounding the borehole, the field engineer would have a much improved idea of the distribution of sands and shales as well as the distribution of petroleum fluids in the reservoir. Such a general description is the ultimate goal of this research.

In general, heavy oil (defined here as having API gravity of 10 to 20, inclusive), is chemically less mature than light oil, with a smaller fraction of gas. Although heavy oil deposits often occur in distinct reservoirs it is not uncommon for light and heavy oils to occur in the same reservoir but in different stratigraphic horizons (Miller et al. 1988). There is no particular type for heavy oil reservoirs, but the oil fields being presently exploited have several characteristics in common.

Most heavy oil reservoirs exist at shallow to moderate depths in younger strata. It is presently thought that these reservoirs initially contained lighter oil but that over geological time microorganisms present in the soil consumed the lighter components of the petroleum, leaving behind a heavier residual. Alternatively, the shallow occurrence of heavy oil may be due to upward migration of immature petroleum to strata where the pressure and temperature are insufficient to convert the source fluid to mature light oil. Heavy oil petroleum reservoirs in the central valley of California, for example, occur in the Tertiary and Quaternary sands, mudstones and diatomite shales at depths ranging from 100-3,000 ft with the shallower reservoirs typically containing the heavier oil.

Heavy oil reservoirs in California tend to comprise discontinuous, high permeability lenticular sands separated by impermeable shales. At the South Belridge field, for example, the shallow sands are described as resembling shoestrings (Miller et al. 1988). At Midway-Sunset the sands are described as fingers (Hall et al. 1990). There is also considerable structure overprinted on the central valley reservoirs due to the proximity to the continuously active San Andreas fault system. Reservoirs tend to be complex plunging anticlines with systems of faulting superimposed on the folded structure. To determine such complex structure requires that borehole logs from many wells in a particular field be analyzed. At South Belridge, for example, more than 6,000 wells have been drilled since its discovery in 1911.

Figure 7a is a simplified east-west section across the center of the South Belridge oil field (after Miller et al. 1988). The figure depicts the configuration of oil and water sands and the intervening shales in the upper 1500 ft of section across the central anticlinal structure. We can see that the individual sand bodies are only piecewise continuous and that the oil and water sands are interfingered on the eastern part of the structure. An enlargement of part of the same structure, shown in Figure 7b, indicates that the lower sands are configured in a complex and irregular manner, often abruptly pinching out or only weakly connected to other sands. Typical sand structures at South Belridge are from 150-500 ft wide in cross-section but are often continuous in the northeasterly direction (along strike) for many miles, forming undulating strands (shoestrings). The configuration of individual sand bodies is controlled by the depositional environment and by geological structure. Communication between sand bodies ranges from good to poor, meaning that steam drives, although usually economically successful, bypass much of the oil.

The above cross-sections were assembled largely from wireline logs from the many wells at South Belridge. Wireline logs are extremely effective in selecting sand and shale horizons and are the primary source of data in wellfield stratigraphic correlations. Note that these measurements are reflective only of the region immediately surrounding the borehole. In fact, for most wells the resistivity logs must be corrected for the effects of drilling mud invasion into the formation before they can be used in correlations.

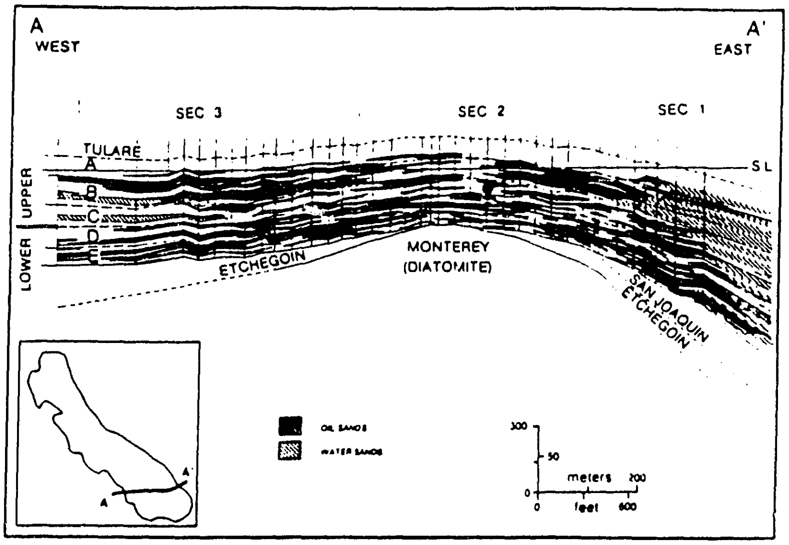


Figure 7a East-west cross-section of the Tulare Sands in the South Belridge Oil Field, San Joaquin county, California.

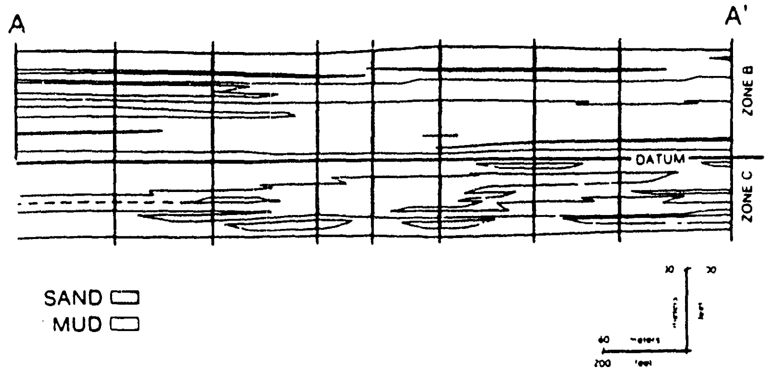


Figure 7b Expanded section of the upper and lower Tulare sands at South Belridge.

One of the goals in this proposed research is to develop technology that extends the borehole log from the region immediately surrounding the well into the formation between wells. With such information the geologist can confidently map the configuration of subsurface beds and better plan his exploration and exploitation strategies. A second goal is to provide the geologist with similar information if he has only a single well to work with. If he had a tool at his disposal to map the configuration of oil sands from a single borehole, the uncertainty would be substantially reduced and production and steam flood patterns could be optimized. This would also reduce the possibility of missed or bypassed oil in developed fields. In the section below we will describe our plans for developing such a tool.

Although the primary focus of this program was to provide tools for EOR monitoring we realized at an early stage that the crosshole EM technique is sufficiently powerful to provide good subsurface resistivity mapping information for reservoir characterization. A small shift in the emphasis could effectively transform the research into reservoir characterization. The following research program is being implemented over the next three years:

For the cross-borehole technique a multi-frequency transmitter is required to take advantage of the high resolution possible. This device would be an extension of the existing LLNL borehole EM source. The new transmitter would switch between a selection of capacitors and alternate windings on the tool to operate at a series of discrete frequencies covering several decades. Computer-controlled switches could be operated from the surface to automatically change frequencies when appropriate. A related improvement is the development of an automatically controlled surface-to-borehole system. Using automatically controlled discrete frequencies the surface-to-borehole system could increase the depth of penetration in a fiberglass-cased borehole from 400 m to more than 1.5 km. We are devloping these hardware advances together with private industry in an effort to reduce the inndividual costs and more effectively transfer the technology.

Development of software concurrent with the hardware development is a critical part of this process. For this we are relying on our close collaboration with LBL and UCB. In particular, we need to improve the discrete frequency imaging codes presently available and apply the recently developed wavefield imaging approach at LBL to field data. Other proposed software developments include the interpretation of EM data through steel well casing and adaptation of imaging codes to the surface-to-borehole configuration.

Field studies need to be done as the hardware and software are developed. We plan to initially use our test facility at Richmond Field Station for prototype testing of both the multi-frequency transmitter and of the surface-to-borehole system. We will also make use of the steel-cased wells at Richmond for a variety of tests. These tests are designed to assess the limitations of measuring through steel casing and to provide data to test interpretation techniques. In addition, we will do additional saltwater injection tests at Richmond to help select optimum techniques for process monitoring. Concurrent with this work at Richmond we will apply several of these techniques to the Lost Hills #3 oil field owned and operated by Mobil. At this facility we have the opportunity to do steam flood monitoring as well as reservoir characterization on a shallow heavy oil reservoir with discontinuous oil sands.

Acknowledgements

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