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FOSSIL ENERGY

RESERVOIR CHARACTERIZATION AND PROCESS MONITORING WITH EM METHODS

1994 Annual Report

By
Michael Wilt

May 1995

Lawrence Livermore National Laboratory
Livermore, California

Bartlesville Project Office
U. S. DEPARTMENT OF ENERGY
Bartlesville, Oklahoma

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

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Reservoir Characterization and Process Monitoring with EM Methods
Annual Report 1994

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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 secondary recovery processes by providing the electrical resistivity distribution in the region between wells.

Introduction

During the past five years at Lawrence Livermore National Laboratory (LLNL) we have applied the EM induction method to the problem of petroleum reservoir characterization and enhanced oil recovery (EOR) monitoring. The goal is to develop practical tools for determining the electrical resistivity distribution between boreholes at a useful scale for reservoir characterization.

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.

Summary of Results for FY94

During FY94 we conducted our largest field test to date. We applied crosshole and surface-to-borehole EM techniques to reservoir characterization at the Lost Hills #3 oil field making three sets of measurements during the initial phase of the steam drive. From these data we were able to determine the resistivity and configuration of the oil sands, between our observation wells, and provide an image of the subsurface resistivity changes due to the steam drive.

In addition to the steam flood monitoring in FY 94 we also conducted a waterflood experiment at our Richmond Field Station facility using the borehole-to-surface EM technique. For this test we injected a small quantity of saltwater, and applied the EM technique to monitor the progress of the injected plume. Data collection for this experiment is complete but the results are yet to be interpreted. Our preliminary analysis indicates that we were able to detect the saltwater plume and distinguish its orientation. The field data were also observed to be much noisier than corresponding crosshole measurements due to the influence of surface cultural features and external noise.

Finally, a project to understand EM propagation through steel casing was initiated in 1994 through the LBL/LLNL industrial sponsors consortium. The goals of the experiment are to determine the limits and applications for crosswell EM surveys through steel well casing. The work consists of three parts. First, the properties of the casing will be determined from EM measurements. Next, the EM response for segmented steel casing will be determined using numerical and scale models. Finally, a set of crosshole measurements will be made in fiberglass cased boreholes and a second set with steel pipe inserts in the same wells to determine if the casing effect may be easily removed.

Reservoir Characterization and Steam Flood Monitoring at Lost Hills#3

Mobil Exploration and Production Inc. has operated several EOR projects in central California. We are applying EM technology as a pilot test at their Lost Hills#3 field to map the orientation and resistivity of the target oil sands and map the progress of the injected steam using associated resistivity changes. Two fiberglass-cased observation wells (35E and 35W) were drilled along a northeast-southwest profile straddling a steam injector for the combined purposes of crosshole EM surveys and repeated temperature and induction logging (Figure 1). Steam is being injected at depths of 65, 90, and 120 m into upper, middle, and lower members of the Tulare formation which contains heavy oil. The steam plume is expected to develop as an ellipse with the major axis aligned with the natural northwest-southeast fractures.

A cross-section derived from borehole induction resistivity logs shows that the higher resistivity intervals (10-100 ohm-m) typically represent the oil sands; the lower resistivity units (2-10 ohm-m) are confining silts and shales (Figure 2). The target Tulare oil sands extend from depths of 60 to 120 meters in three separate intervals. The upper sand is the thickest and most continuous of the three. It begins at a depth of 60 meters, has a thickness of up to 20 meters it dips gently eastward at about 6 degrees. The middle and lower members are thinner and less continuous. The middle member is 3-6 meters thick and lies at a depth of approximately 90 meters. This unit seems to "pinch-out" near 35W and "water-out" somewhere between 35E and borehole 4034. The lower unit, which lies at a depth of 110 meters, is continuous throughout this portion of the field and dips eastward at about 8 degrees. The water table lies at a depth of 160 meters, or just below the base of the cross-section.

Field Surveys

Crosshole EM data sets were collected in November 1993, April 1994. and late September 1994. Borehole receivers were spaced 4 or 8 meters apart in well 35E and data were collected continuously as the transmitter moved between 130 and 30 meters in borehole 35W. EM data were collected at two frequencies, 5 kHz and 20 kHz, although processing is complete only for the 5 kHz results The error on the crosshole measurements is approximately two percent; we use this figure in estimating data uncertainty during interpretation.

Surface-to-borehole EM data were collected along profile A'-A", using 10-x-10-m surface loop transmitters. The surface loops were spaced at 10- to 20-m intervals, to a maximum distance of 125 m from the receiver borehole, well 35E. For each transmitter, magnetic field data were collected at 6-m intervals at depths from 10 to 140 m using frequencies of 1 and 5 kHz. Individual surface-to-borehole profiles typically required about 1 hour; the collection of 16 profiles on line A-A' required 2 days for both frequencies.

Crosshole EM data were interpreted using a two-dimensional inversion code developed by our CRADA partner at Schlumberger-Doll Research (Torres-Verdin and Habashy, 1993).We use a smoothed version of the induction resistivity logs in boreholes 35W and 35E as a starting guess for the inversion. Surface-to-borehole data were interpreted using one-dimensional models only. Two-dimensional software to interpret these data is under development.

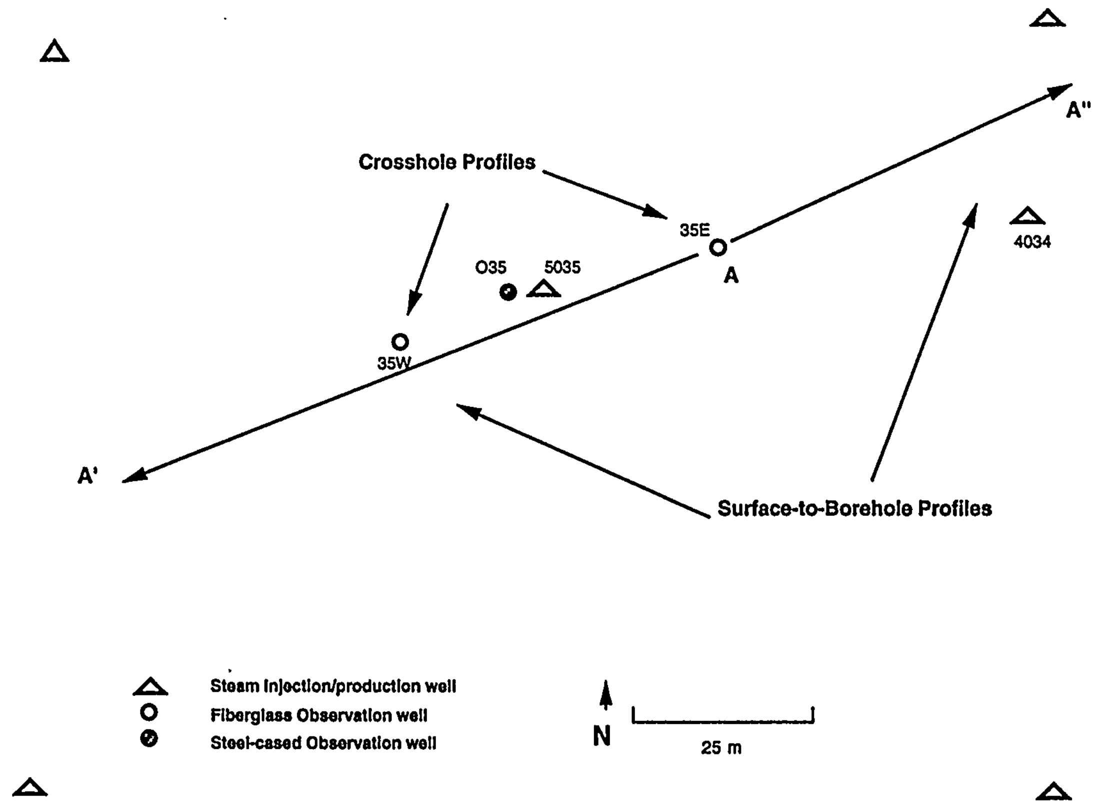


Figure 1. Base map for the EM study at Lost Hills #3.

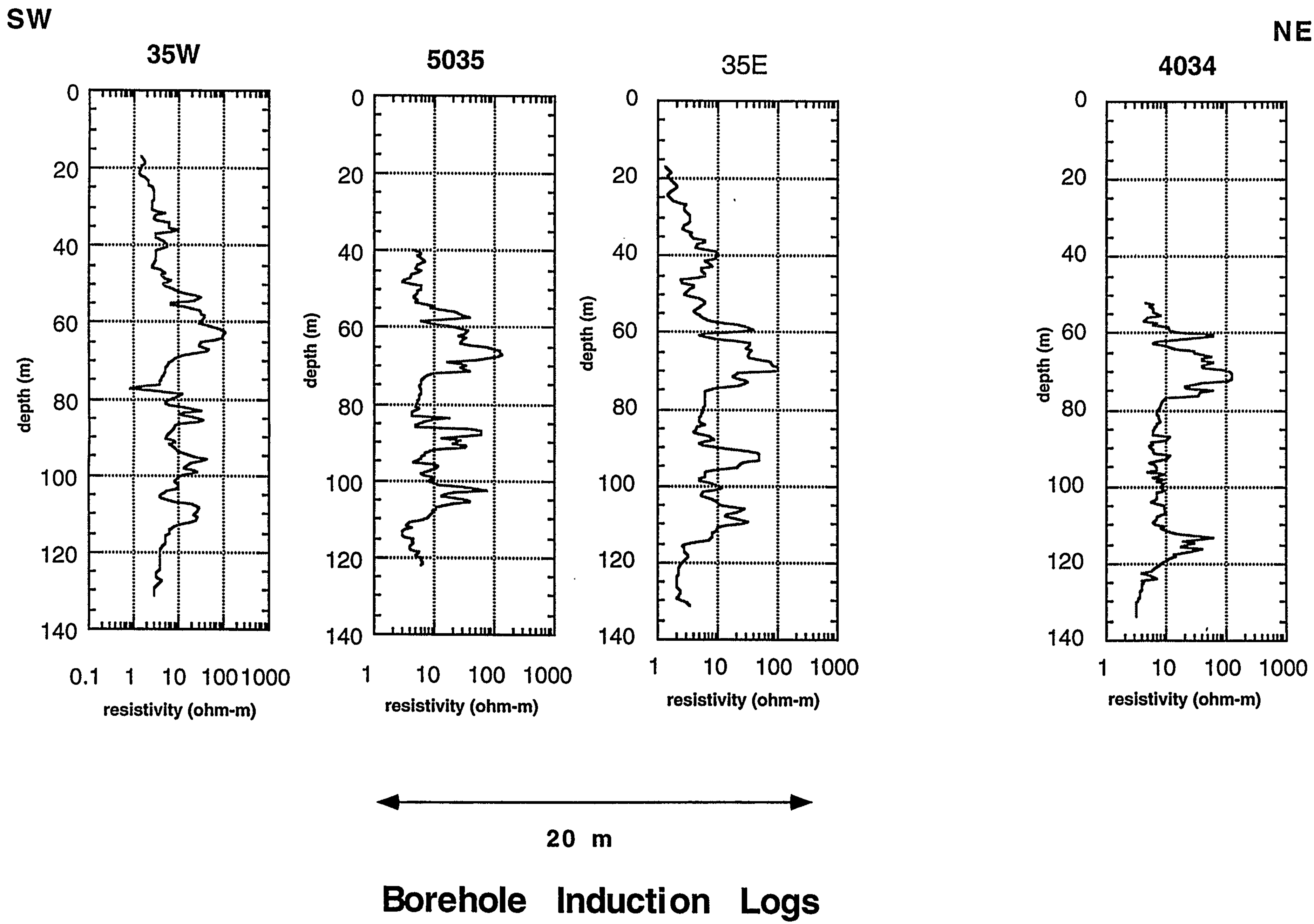


Figure 2. Borehole resisitivity logs from the Lost Hills profile A-A'.

Data Interpretation

We show the subsurface resistivity distribution between boreholes 35E and 35W before steam injection in Figure 3a. The darker section in the images represent higher resistivity zones associated with heavy-oil sands; the lighter areas are lower resistivity silts and confining shale beds of 1-8 ohm-meters, with an average value of 3 ohm-m. The image in Figure 3a indicates that the upper oil sand is a thick unit dipping gently eastward. The middle and lower sands are thinner and more discontinuous between the wells. The images shown in Figure 3b and c are visibly different only at depths below 70 meters. In this portion of the figure the resistivity has decreased significantly due to the steam injection. In all other parts of the image the before and after resistivity values are unchanged.

In Figure 4 we show two difference images made by subtracting the baseline image in 3a from the images in 3b and 3c. The figure shows that the resistivity has decreased by 50 percent or more in the region surrounding the injection hole at depths below 70 meters. The difference images from April and October are quite similar, each showing intense resistivity changes in sub horizontal zones at depths of 90 and 110 meters. The low resistivity zone seems to extend all the way to the observation wells in October, but only part way in April.

Figure 4 indicates that a substantial steam chest has formed in the middle and lower sands and almost none of the steam has gone into the upper oil sand. Since there is considerable steam injection in the upper perforated zone, this implies that there is some connection between the upper and lower oil sands. Perhaps this is due to a connection from the upper to these lower units via natural or man-made fractures. The steam also seems to preferentially flow to the west in the middle Tulare but eastward in the lower Tulare. The westward movement in the middle oil sand is expected since the producing well to the east of 35E was not completed in the middle oil sand due to high water saturation, there is therefore no pressure pull in this direction. The preferential eastward migration in the lower sand is probably due to the better eastward stratigraphic continuity in the lower sand, as evidenced by the borehole induction logs and the crosshole EM baseline images.

Recent temperature logs in borehole 35W and 35E show significant and progressive increases in temperature in the middle (35W) and lower (35E) oil sands but no change in the upper oil sands (Figure 5). These data correlate with the observed resistivity changes and suggest that the resistivity decreases are primarily due to temperature increases. This correlation is supported by earlier field and theoretical studies that also suggest that saturation effects are much smaller than the temperature effects (Mansure and Meldau, 1989; Ranganayaki et. al., 1992).

Water Flood Monitoring with Borehole-to-Surface EM.

In many oil field and environmental problems only one borehole is available for geophysical measurements. In an oil field this may be one of several widely spaced observation wells; in an environmental spill area this may be the initial monitoring well. It is important to make use of this well to determine the electrical resistivity distribution beginning at the wellbore and extending outwards. This may help determine the direction of steam flood migration or the movement of an underground spill. One technique that utilizes a single well is the borehole-to-surface array (BTS), where an EM transmitter is located in the borehole and data are collected on the surface. The method allows for multicomponent measurements along any surface profile; we can therefore focus the subsurface investigation without requiring an additional well. The disadvantage is that the data are less sensitive to the subsurface resistivity than the crosshole array due to the increased source-receiver separation; the array is also more sensitive to the effect of surface geological and cultural noise.

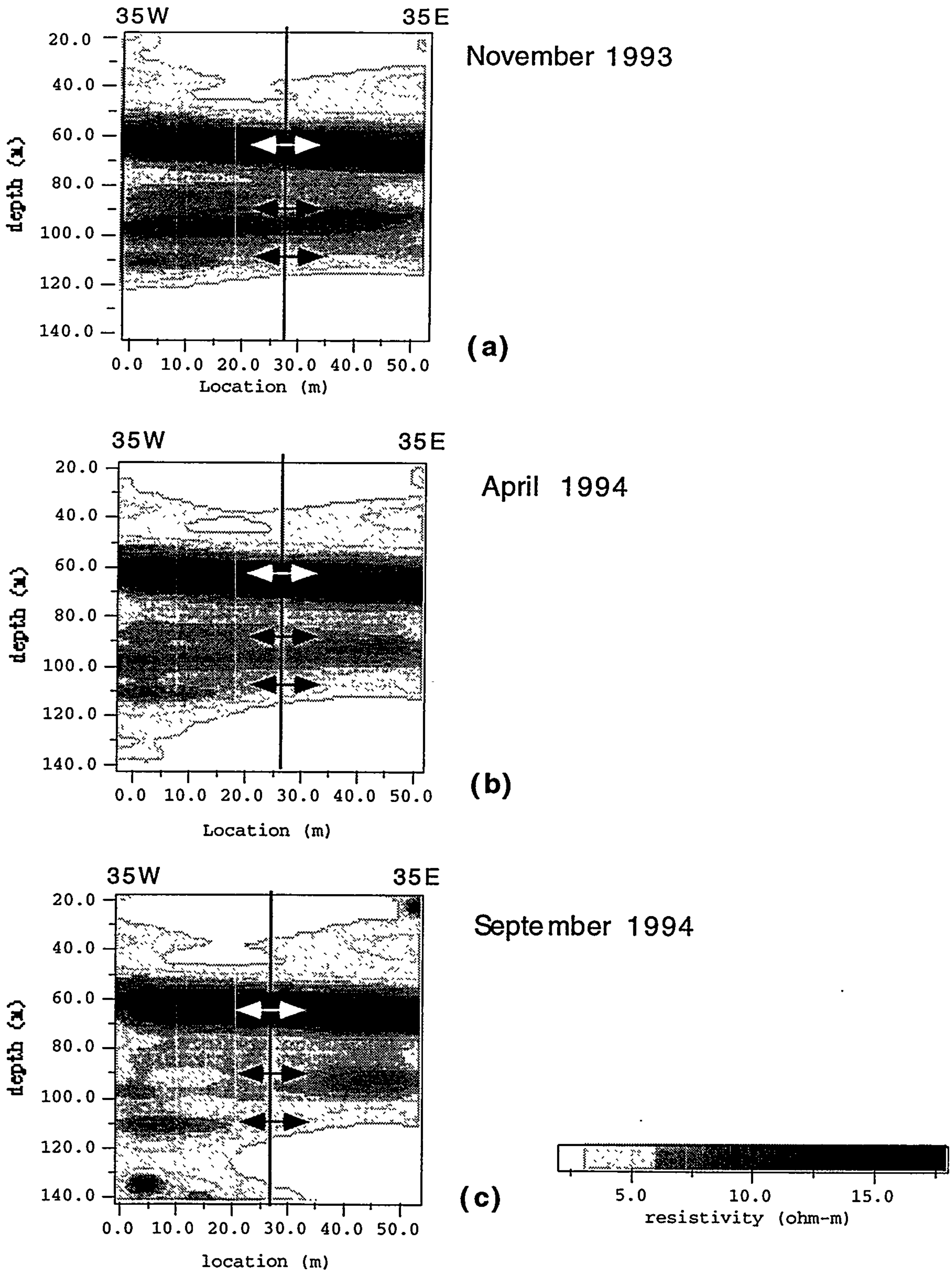


Figure 3 Crosswell resistivity images before and during steam flooding operations at Lost Hills#3.

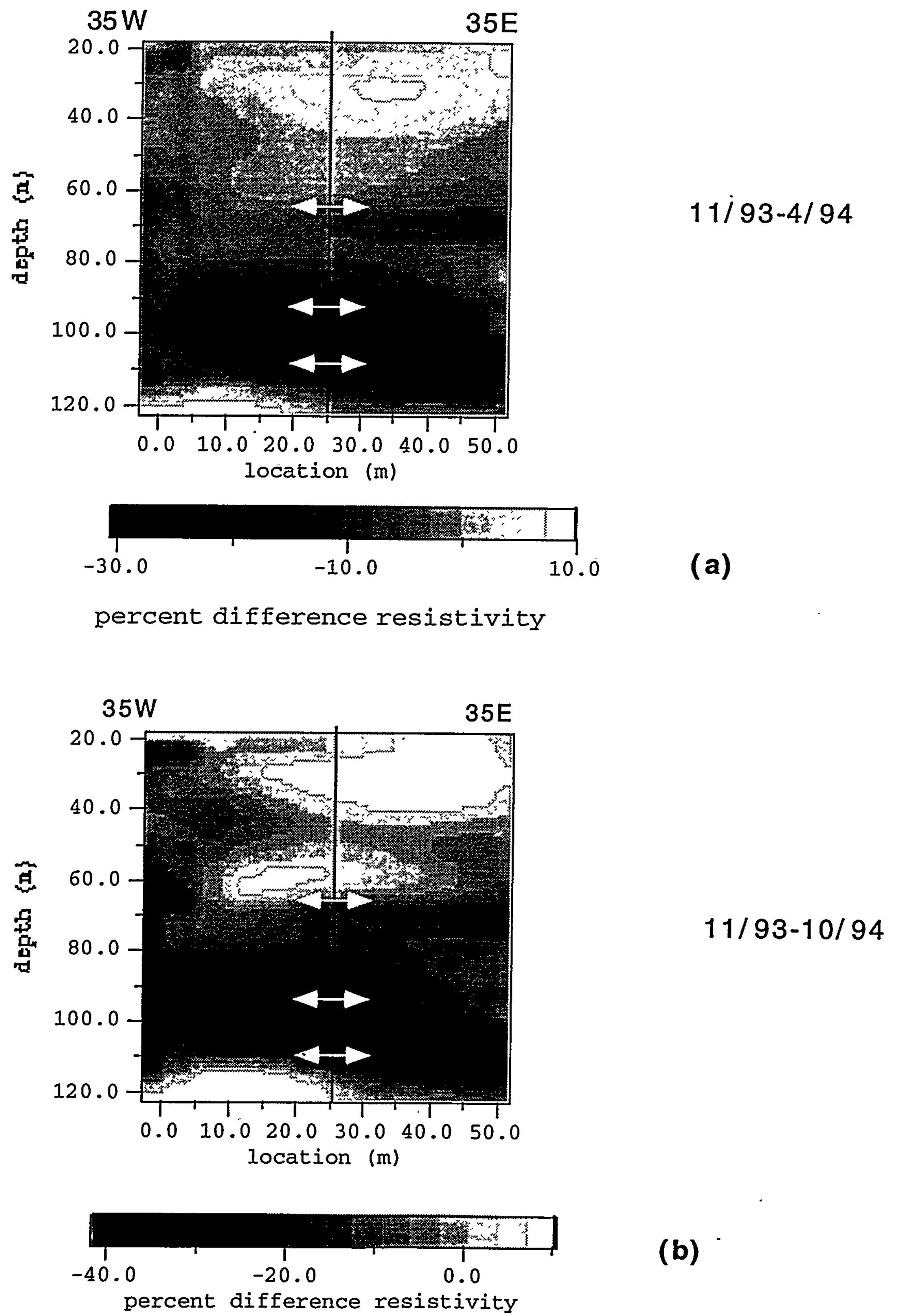


Figure 4 Percent difference resistivity images during the steam flooding operations.

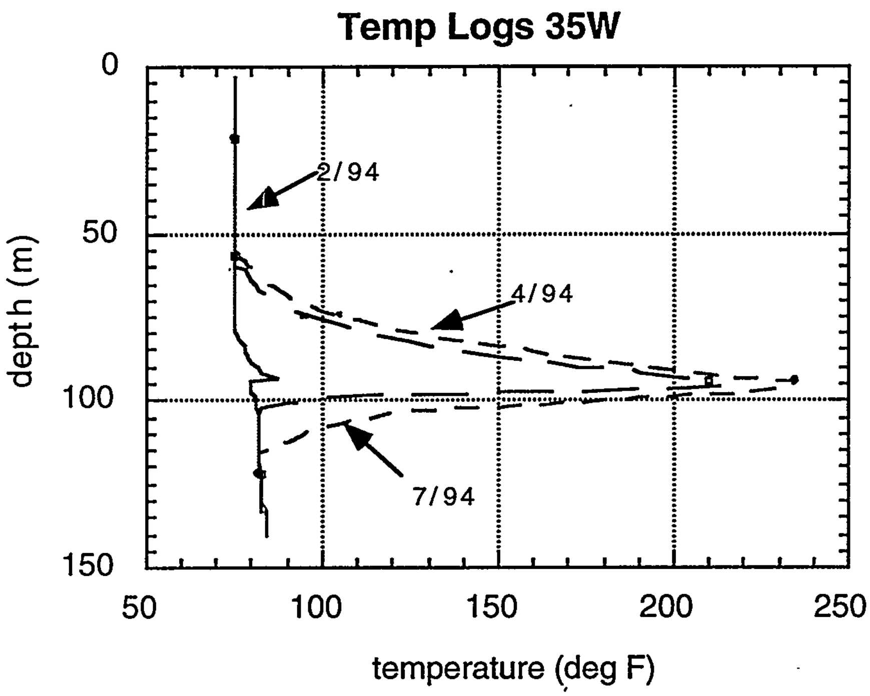


Figure 5 Temperature logs from well 35W during the steam injection process.

To test the applicability of this method to waterflood monitoring we designed a test at our Richmond Field Station facility. This experiment consisted of injecting a slug of salt water into a shallow aquifer and collecting borehole-to-surface EM data before and after injection. We also collected crosshole EM data using boreholes along the same profiles. The crosshole data will be used to supplement the BTS measurements for improved inversion resolution and for comparison with the BTS data. We will apply numerical inversion to both data sets to determine the in-situ resistivity distribution and the direction of salt water migration.

The measurements consist of deploying a borehole transmitter in the injection well and several other observation holes and collecting horizontal and vertical component magnetic fields on the surface on a densely sampled grid (Figure 6). To ensure that measurements were repeatable, a series of temporary stations were established and outfitted with small plastic pipes for placement of the surface magnetic field detectors. A complete survey was done before and after salt water injection. The baseline data for this experiment were collected in late December, 1993 and the salt water was injected immediately afterwards. Post injection data were collected during the last week of December, 1993 and in January, 1994. A final data set was collected in April, after salt water withdrawal.

The data, in general, were of excellent quality. The average repeatability error was one or two percent. The borehole-to-surface EM anomaly, although only half of the size of the crosshole anomaly, was easily discernible, and it is likely that these data can be used for imaging the subsurface plume. Although much of the data was of excellent quality some field results showed affects of obvious cultural and external noise. These persisted even after considerable effort to reduce these effects.

In Figure 7 we show baseline vertical field magnitudes and differences, in percent, between data collected before and after salt water injection. The field data, which are plotted below the surface receivers in Figure 7a, show a smooth continuous amplitude distribution with the field steadily decreasing with distance from the source borehole. The difference plot (Figure 7b) indicates several zones where the field changed after the injection of salt water; the most prominent are the horizontal bands located at a depth of 30 m, between stations 15 and 50 and between stations -45 and -5. Computer modeling shows that these differences are due to the salt water slug. Preliminary indications are that the causative body is a roughly horizontal feature offset slightly to the north of the injection well..

The plot also shows two vertically oriented anomalies; one near the borehole INJ1 and the other at -55. Experience indicates that this type of anomaly is due to a surficial body or some external source of noise. The central anomaly, near the injection borehole, is likely due to residual current leakage in the transmitter tool or the supply cable. Although heroic steps were taken to minimize this leakage some residual current could be measured and this clearly affects data at stations close to the source well. The second anomaly, near -55, is probably due to a grounded metallic fence used in an earlier biological experiment. Although we removed much of this structure prior to measurement, some of the effects remain.

Since the plot in Figure 7b presents the difference in fields, we should expect that the effect of current leakage or a grounded fence would be the same for both surveys and therefore subtract to zero when a difference is taken. This unfortunately was not the case because the near surface resistivity changed (due to rainfall) between the measurement times. It therefore affected the EM coupling to the surface features. This type of variation in geological and cultural noise is the rule, however, and not the exception. It is our challenge to engineer the measurement system to be insensitive to this.

Even with the above effects the data set is of excellent quality and is suitable for inversion. Interpretation of these data is presently underway as part of the Ph.D. thesis for U.C. student

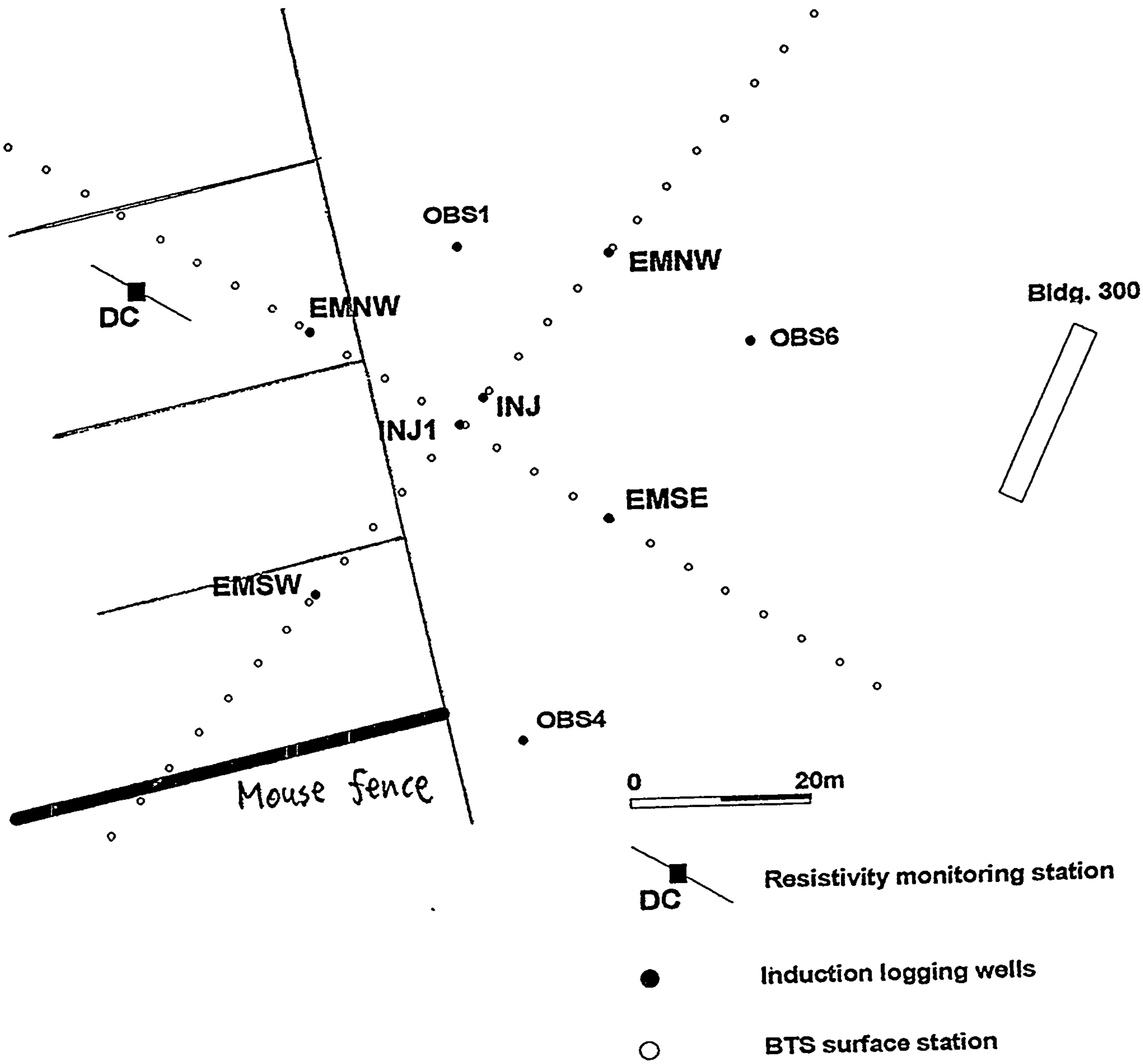
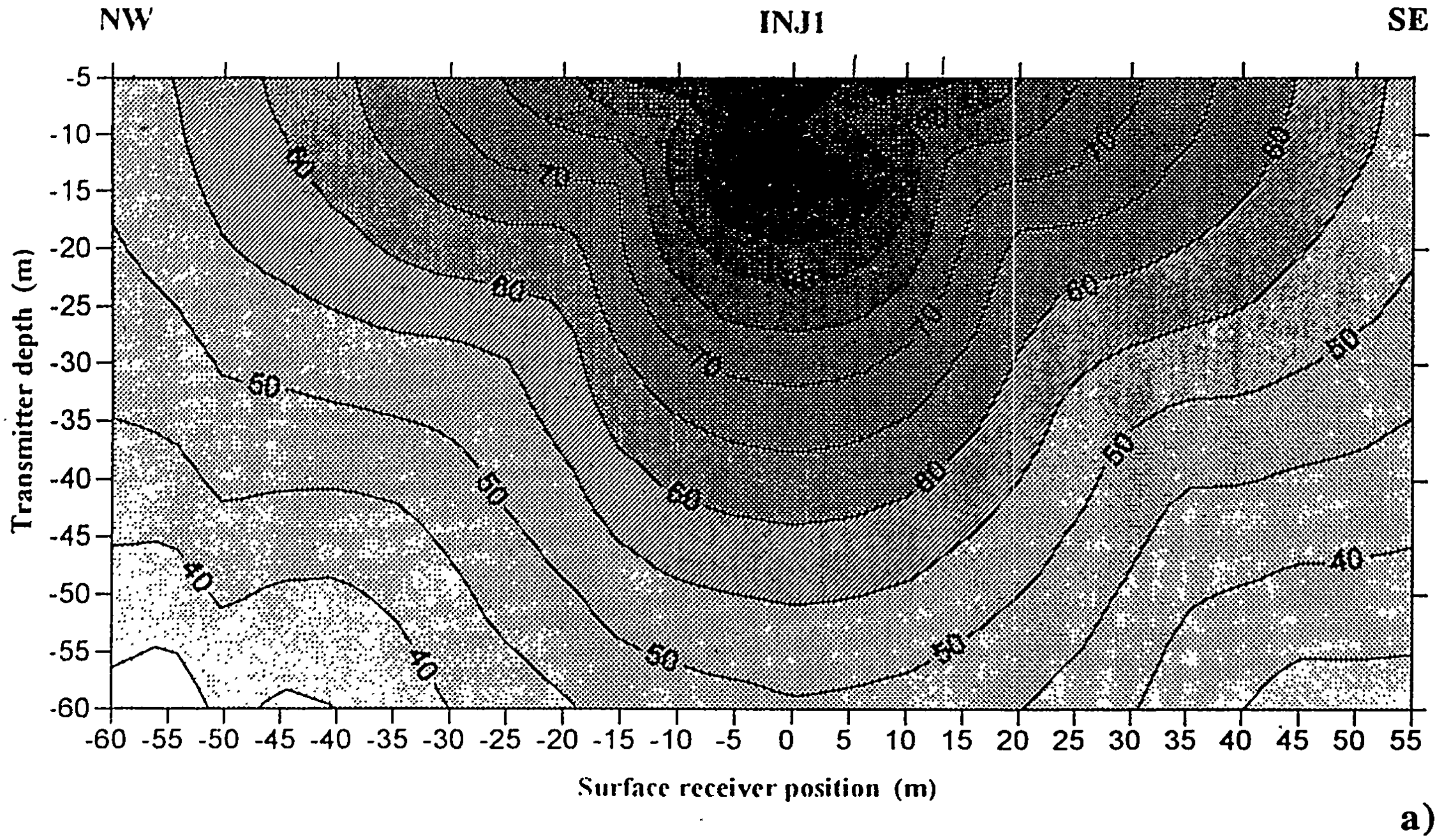


Figure 6. Base map for the Richmond Field Station water flood experiment



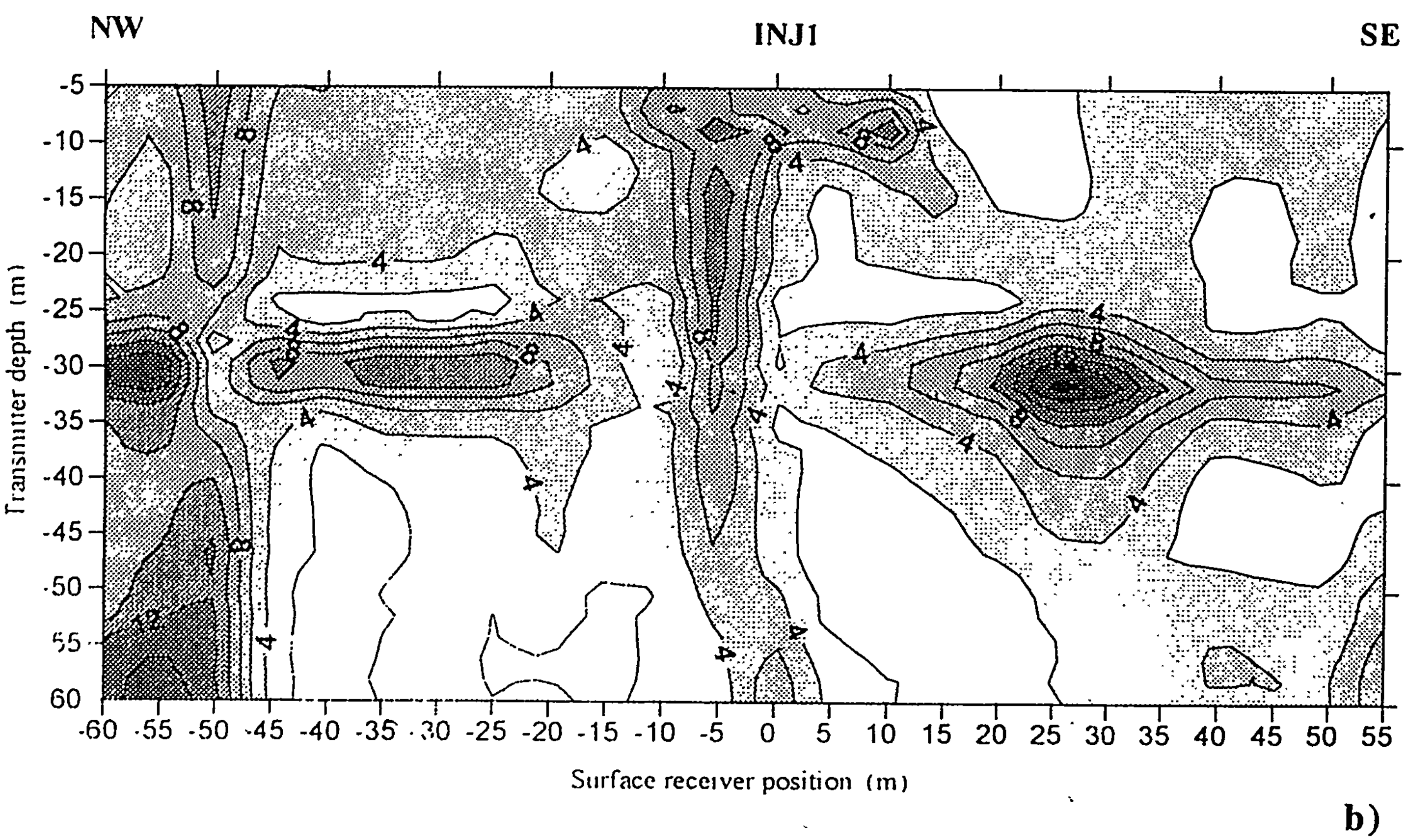


Figure 7a) Borehole-to-Surface EM field data at U.C. Richmond Field Station and **b)** observed percent differences before and after salt water flood for profile NW-SE

Hung-Wen Tseng. He will initially apply some simple two-dimensional models and later interpret the data with a three-dimensional code that he is developing.

EM measurements through steel well-casing

In Figure 8 we show some experimental surface-to-borehole EM data collected at the South Belridge oil field in central California in an observation well. The borehole is steel-cased from the surface to a depth of 150m, but fiberglass cased below this. The data were collected, at a frequency of 540 Hz, using a loop source situated above the measurement borehole (Wilt and Ranganayaki, 1989). The plot shows that amplitude decreases with depth until the receiver reaches a depth of 150m, where it increases by a factor of 1000 as the coil emerges from the steel casing. The plot shows both the problem and promise of working in steel casing. The problem is that the signal is greatly attenuated, especially at high frequencies (Uchida et al, 1992). For example, these field data and associated theoretical results indicate that it will probably not be possible to collect EM data through casing at frequencies much above 1000 Hz; this limits the resolution. However, in spite of the attenuation, the fields are well behaved within the casing and it may be possible to remove the casing effect by a simple arithmetic correction.

A project to understand EM propagation through steel-casing was initiated in 1994 through the LBL/LLNL industrial sponsors consortium. The goals of the experiment are to determine the limits and applications for crosswell EM surveys through steel well casing. The work consists of three parts. First the properties of the steel casing will be determined from EM measurements. Next the fields from a borehole transmitter will be measured through segmented steel casing. Finally a set of crosshole measurements will be made in fiberglass cased boreholes and second set with steel pipe inserts in the same wells to determine if the casing effect may be easily removed.

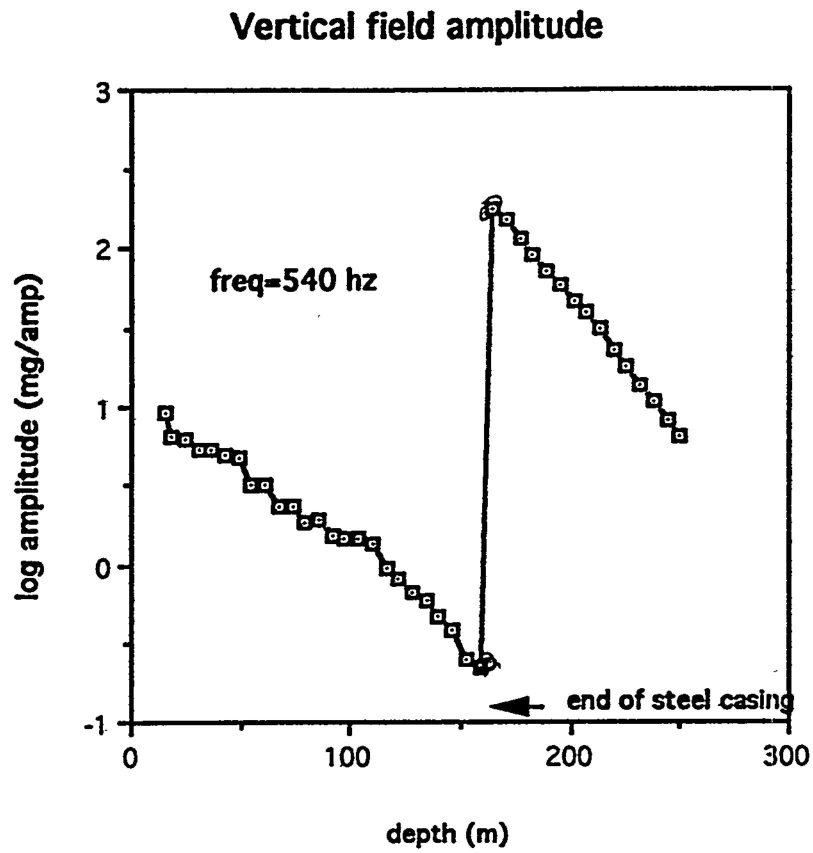
Initial work for this two-year project has begun. The measurements will be the responsibility of U.C. student Bing Wong under the direction of Professor Alex Becker

Plans for FY 95

During FY95 we will deploy some new instrumentation developed over the last several years. The first tool is a borehole transmitter developed as part of a multi-frequency multi-component crosshole system with our CRADA partner, Schlumberger-Doll Research. The system will be finished in February, 1995, with a complete field test at the Shell South Belridge oil field scheduled in March 1995. The second tool under development is a multi-level receiver tool. This devise has up to 6 borehole vertical field receivers separated from each other by 5 meters. This tool, which allows the parallel collection of field data from 4-6 sensors, will dramatically speed up data acquisition and improve overall quality by reducing instrumental drift .

Two major field projects are scheduled for FY 95. The first project is scheduled at the Shell lease at the South Belridge Oil field in central California to monitor steam flood growth and fracture development in the diatomite member of the Monterey formation. This unusual rock has a very high porosity and oil saturation but, due to its structure, very low permeability. Oil is produced by initially creating a fracture and injecting steam to create additional micro fracturing that liberates the oil from the tight structure. The second project involves collection of crosshole EM data in boreholes prior to the installation of steel casing. This test will be done at the Mobil Lost Hills United lease and will utilize the newly completed receiver string to collect crosshole data in 3-4 hours per well pair. Thus we will collect the crosshole EM data in open holes much as wireline logs are routinely collected today.

We are beginning the second year of studies on the propagation of EM field through steel well casing. These initial studies will focus on determining the field behavior in simple analytical



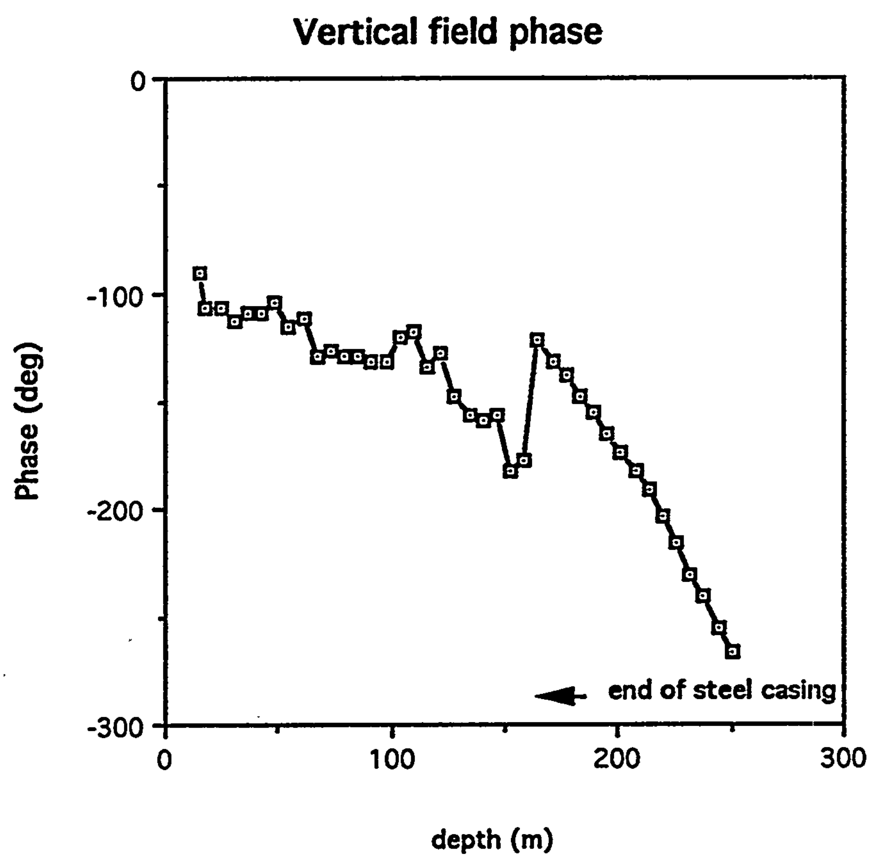


Figure 8 Surface-to-borehole EM data in a partially steel-cased well at the South Belridge oil field.

and scale models. The goals are to determine the casing properties from EM measurements within the pipe. Later this information will be used in separating the EM effects of the pipe from the formation properties that are sought.

Acknowledgments

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References

Mansure, A.J. and Meldau, R.F., 1990, Steam-zone electrical; characteristics for geodiagnostic evaluation of steamflood performance: Soc Pet Eng. Formation Evaluation September 241-247.

Ranganayaki, R.P, Akturk,S.E., and Fryer, S.M., 1990 Formation resisitivity variation due to steam flooding: a log study: **Geophysics**, 57, 488-494.

Torres-Verdin, C., and Habashy T., 1993, An Approach to Nonlinear Inversion with Applications to Cross-Well Tomography. Extended abstracts from the Society of Exploration Geophysicists 1993 annual meeting, Washington DC., pp. 351-354.

Uchida,T., Lee, K.H. and Wilt, M., 1991, Effect of Steel casing on Crosshole EM Measurement, Extended Abstracts Society of Exploration Geophysicists Annual Meeting, Houston Texas.

Wilt, M., and Ranganayaki, R. P. 1990, Surface-to-Borehole Electromagnetic Logging for Enhanced Oil Recovery (EOR) Operations. Extended Abstracts Society of Exploration Geophysicists Annual Meeting, San Fransisco, California. PP 532-534.

Wilt, M.J., Morrison, H.F., Becker, A., and Lee, K.H., 1991, Cross-Borehole and Surface-to-Borehole Electromagnetic Induction for Reservoir Characterization, Fossil Energy report DOE/BC/91002253.

Publications in FY1994:

Wilt, M.J., Alumbaugh, D., Morrison, H.F., Becker, A., and Lee, K.H., and Deszcz-Pan, M. 1993, Crosshole Electromagnetic Imaging for Reservoir Definition and Monitoring, Lawrence Berkeley Laboratory Report LBL-34734 (submitted to *Geophysics*).

Wilt, M.J, Lee, K., Morrion, H.F., Becker, A., Torres-Verdin., C. Alumbaugh, D., and Tseng, H.W., 1995, Crosshole Electromagnetic Tomography--a New Technology for Oil Field Characterization. " The Leading Edge" vol 14 no. 3.

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