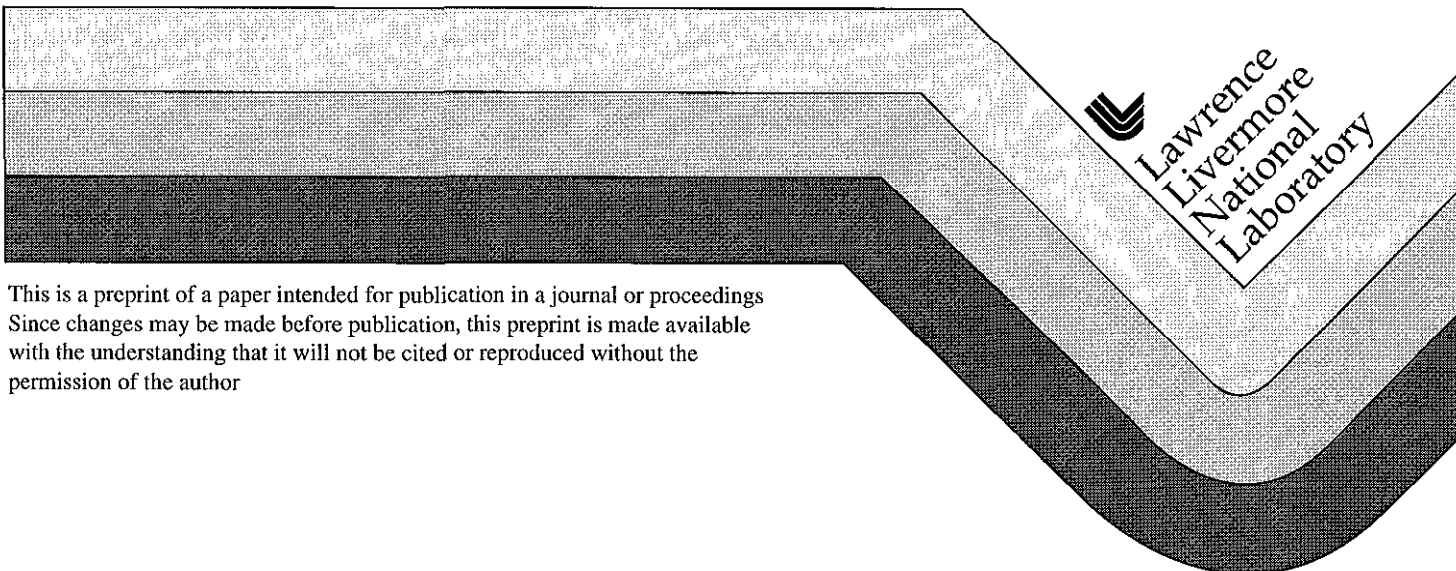


Surface and Borehole Electromagnetic Imaging of Conducting Contaminant Plumes

James G. Berryman

This paper was prepared for submittal to the
Environmental Management Sciences Program Workshop
Rosemont, IL
July 27-30, 1998

July 1998



This is a preprint of a paper intended for publication in a journal or proceedings. Since changes may be made before publication, this preprint is made available with the understanding that it will not be cited or reproduced without the permission of the author.

DISCLAIMER

This document was prepared as an account of work sponsored by an agency of the United States Government. Neither the United States Government nor the University of California nor any of their employees, makes any warranty, express or implied, or assumes any legal liability or responsibility for the accuracy, completeness, or usefulness of any information, apparatus, product, or process disclosed, or represents that its use would not infringe privately owned rights. Reference herein to any specific commercial product, process, or service by trade name, trademark, manufacturer, or otherwise, does not necessarily constitute or imply its endorsement, recommendation, or favoring by the United States Government or the University of California. The views and opinions of authors expressed herein do not necessarily state or reflect those of the United States Government or the University of California, and shall not be used for advertising or product endorsement purposes.

Report on EMSP Project #55011:

Surface and Borehole Electromagnetic Imaging of Conducting Contaminant Plumes

Principal Investigator

James G Berryman

Lawrence Livermore National Laboratory

P O Box 808 L-200

Livermore, CA 94551-9900

E-mail berryman1@llnl.gov

Telephone 925-423-2905; FAX: 925-423-6907

Abstract

Electromagnetic induction tomography is a promising new tool for imaging electrical conductivity variations in the earth. The EM source field is produced by induction coil (magnetic dipole) transmitters deployed at the surface or in boreholes. Vertical and horizontal component magnetic field detectors are deployed in other boreholes or on the surface. Sources and receivers are typically deployed in a configuration surrounding the region of interest. The goal of this procedure is to image electrical conductivity variations in the earth, much as x-ray tomography is used to image density variations through cross-sections of the body. Although such EM field techniques have been developed and applied, the algorithms for inverting the magnetic field data to produce the desired images of electrical conductivity have not kept pace. One of the main reasons for the lag in the algorithm development has been the fact that the magnetic induction problem is inherently three dimensional; other imaging methods such as x-ray and seismic can make use of two-dimensional approximations that are not too far from reality, but we do not have this luxury in EM induction tomography. In addition, previous field experiments were conducted at controlled test sites that typically do not have much external noise or extensive surface clutter problems often associated with environmental sites. To use the same field techniques in environments more typical of cleanup sites requires a new set of data processing tools to remove the effects of both noise and clutter. The goal of this project is to join theory and experiment to produce enhanced images of electrically conducting fluids underground, allowing better localization of contaminants and improved planning strategies for the subsequent remediation efforts. After explaining the physical context in more detail, this report will summarize the progress made in the first 18 months of this project: (1) on code development and (2) on field tests of these methods. We conclude with a brief statement of the research directions for the remainder of this three year project.

Report on EMSP Project #55011:

**Surface and Borehole Electromagnetic Imaging of
Conducting Contaminant Plumes**

Principal Investigator
James G Berryman
Lawrence Livermore National Laboratory
P O Box 808 L-200
Livermore, CA 94551-9900
E-mail berryman1@llnl.gov
Telephone 925-423-2905, FAX 925-423-6907

Co-Investigators, LLNL
H Michael Buettner, Nathan J Champagne II, J Brian Grant, Robert M. Sharpe

Co-Investigators, Stanford University, Department of Mathematics
Oliver Dorn, George Papanicolaou

Project Structure

Forward Modeling	Field Experiments	Data Inversion
Earth Model/EM Code	Instrumentation	Data Comparison
Predicted Fields	Collected Field Data	Underground Image

Hyperlinks to Contents.

Abstract
Introduction
Code Development
Field Work
Future Research
Acknowledgments
References

Introduction to the Physical Problem

Electromagnetic induction tomography is a promising new tool for imaging electrical conductivity variations in the earth (Wilt *et al.*, 1995a,b). The source field is a magnetic field generated by currents in wire coils. This source field is normally produced in one borehole, while the received signals are the measured small changes in magnetic field in another, distant borehole; however, the method may also be used successfully in combination with surface sources and receivers. The goal of this procedure is to image electrical conductivity variations in the earth, much as x-ray tomography is used to image density variations through cross-sections of the body. Although field techniques have been developed and applied to collection of such EM data, the algorithms for inverting the magnetic field data to produce the desired images of electrical conductivity have not kept pace. The current state of the art in electromagnetic data inversion (Alumbaugh and Morrison, 1995a,b) is based on the Born/Rytov approximation (requiring a low contrast assumption), even though it is known that conductivity variations range over several orders of magnitude and therefore require nonlinear analysis. The goal of this project is therefore to join theory and experiment to produce enhanced images of electrically conducting fluids underground, allowing better localization of contaminants and improved planning strategies for the subsequent remediation efforts.

Electromagnetic induction logging has long been used in the petroleum and environmental industry to measure the electrical conductivity in the region immediately surrounding the borehole. This data, which is used to estimate pore fluid saturations near the well, is very sensitive to variations in rock pore fluid. Mapping surface variation of conductivity has also been found to be a very sensitive indicator of zones of higher salinity and acidity in many shallow environmental studies.

Recent research at LLNL (Newmark and Wilt, 1992; Wilt and Schenkel, 1992; Tseng *et al.*, 1995; Berryman, 1997) has developed instrumentation and software to deploy EM induction technology in crosshole and surface-to-borehole configurations, thereby extending the conductivity information to the region between boreholes. This results in a determination of subsurface conductivity at a much higher resolution than can be achieved with surface techniques and much greater penetration than can be achieved with radar technology.

Although other technologies, such as ERT (Berryman and Kohn, 1990; Dailey *et al.*, 1992; Ramirez *et al.*, 1993; Borcea, 1996; Borcea *et al.*, 1996), can produce electrical conductivity images at a useful spatial scale, the advantage of the electromagnetic induction technology is that we can make use of existing monitoring wells and the surface to do imaging. Since signals are transmitted and received inductively, we do not need to make ground contact (no ground penetrating electrodes); the technology is

therefore relatively noninvasive. There is also the important potential advantage that multiple frequencies can be employed to improve the imaging capability for electromagnetic induction tomography; this feature is simply not available with ERT imaging since the inversion methods used to date are inherently based on the DC (zero frequency) limit of the pertinent equations.

We have had good success deploying the EM induction technology in petroleum applications for field characterization and steam flood monitoring, but it has yet to be used in noisy urban areas where we are often unable to drill holes or do anything invasive. The targets for imaging in environmental problems are significantly more variable than in the petroleum production environment, ranging from highly resistive DNAPLs and petroleum products to highly conducting acidic brines.

In this report, we summarize the progress made in the first 18 months of this project: (1) on code development and (2) on field tests of these methods. We conclude with a brief statement of the research directions for the remainder of this three year project.

Progress in Code Development

The summary presented in this section describes collaborative work done by Nathan J. Champagne II, J. Brian Grant, Robert M. Sharpe, and H. Michael Buettner, all of the Lawrence Livermore National Laboratory.

Since the transmitters in our field experiments are induction coils with alternating current at a fixed frequency (typically in the range 1-10 kHz), our basic numerical problem is to solve Maxwell's equations in the frequency domain. Because of the practical frequency range (< 1 MHz), it is *adequate* to ignore displacement currents in the formulation as is typically done by other researchers, but it is *not essential* to do so in the particular implementation that we have chosen. We have used the finite-difference frequency-domain formulation of Beilenhoff *et al.* (1992) and the anisotropic PML (perfectly matched layer) approach (Berenger, 1994) to boundary conditions of Wu *et al.* (1997) to deal with the fact that the computations must be done in a finite domain even though the real problem is effectively of infinite domain. The resulting formulas for the forward solver reduce to a problem of the form

$$(1) \quad \mathbf{A}x = y,$$

where \mathbf{A} is a non-Hermitian matrix with real values off the diagonal and complex values along its diagonal (Smith, 1996a,b). The matrix \mathbf{A} may be either symmetric or nonsymmetric depending on details of the boundary conditions chosen (*i.e.*, the particular PML used in the application). Equation (1) must be solved for the vector x (which

represents field quantities such as electric and magnetic fields) with the vector y determined by the boundary conditions and transmitter location. There are many choices of forward solver for this system [see for example Saad (1996)], but not many of these have been thoroughly tested for the type of matrix encountered in our problem. We found the stability characteristics of the standard Bi-CG algorithm for solving (1) to be quite inadequate (in terms of reliability and uniform accuracy) for this application and have chosen to use an alternative developed by van der Vorst (1992) for such situations called Bi-CGSTAB. We have found the stability characteristics of this solver to be entirely adequate for our application.

Considerable effort was devoted to finding good test cases for validating our new 3-D EM code. The *Proceedings of the International Symposium of Three-Dimensional Electromagnetics* which took place on October 4-6, 1995 at Schlumberger-Doll Research, contained a useful test problem in the contribution "Quasi-Linear Approximation in 3D Electromagnetic Modeling" by Zhdanov and Feng (1995) in which a $20\text{m} \times 10\text{m} \times 10\text{m}$ conducting body is buried in a resistive half-space and excited by a wire loop transmitter. Our new code produced good agreement with the results of Zhdanov and Feng, and also with that from an older code, EM3d, from the University of Utah.

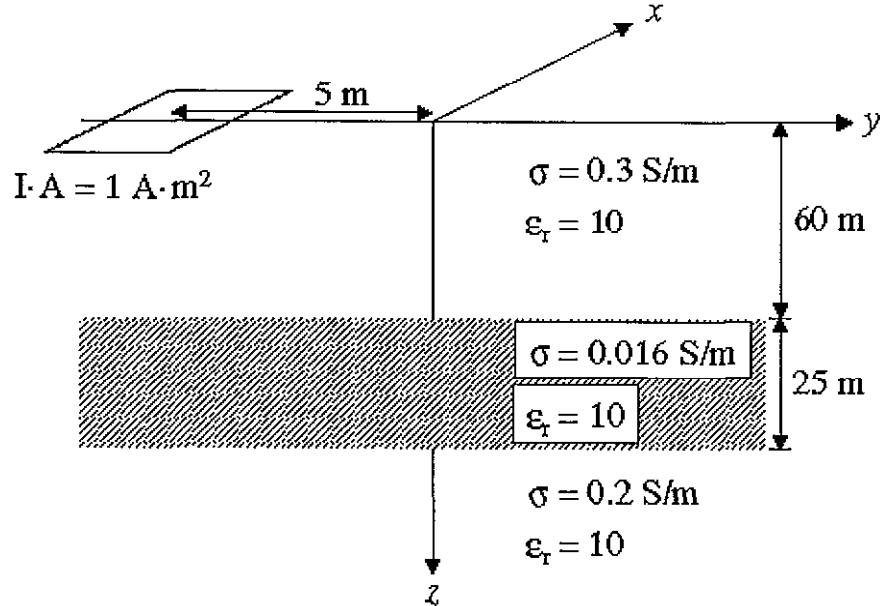


Figure 1. Current loop in a layered conducting medium.

To demonstrate further the accuracy of the new code (called FDFD for finite-difference/Fourier-domain), we have tested various cases against results found in the literature. One example (see Figure 1) is for receivers down a borehole in a layered medium with air above the free surface, a 60m thick layer with conductivity = 0.3 S/m, a 25m thick layer with conductivity = 0.016 S/m, and a 60m layer with conductivity = 0.2 S/m at the bottom of the model, with appropriately designed PML absorbing layers on all six sides of the domain. Relative permittivity of all three earth layers is constant and assumed to equal 10.0. The frequency of the excitation is $f = 1$ kHz with the transmitter located at the free surface with an offset of 5m from the borehole. The finite difference representation was chosen so the unit spacing in the earth model was 2.5m, with 50 cells \times 50 cells in the xy direction, and 10 layers of PML on all four sides. In the vertical direction, there were 68 cells in the earth model, 10 cells in the air above the free surface, and 10 more cells above and below for the PML layers. All PML cells are 10m thick in the directions away from the earth model. The overall problem is then approximately $70 \times 70 \times 100 \approx 500,000$ cells. The computations were performed on a DEC Alpha 8400 Model 5/4400, and required approximately 2 hours of CPU time, including about 2000 iterations to achieve the desired convergence. This computation was serial and required about 500 MB of memory. In Figure 2 the results of the code calculations for the magnetic field magnitude and phase are compared to results for the same model obtained using the code EM1D based on a semianalytical formula for such layered models and developed by Ki-Ha Lee at LBNL. The observed agreement is excellent.

FDFD is written in Fortran 90 and is designed to be easily parallelizable, but we have not yet tested this feature of the code. We anticipate an improvement in execution time when the parallel features are invoked, but otherwise we expect the performance to be the same on the same computer platform.

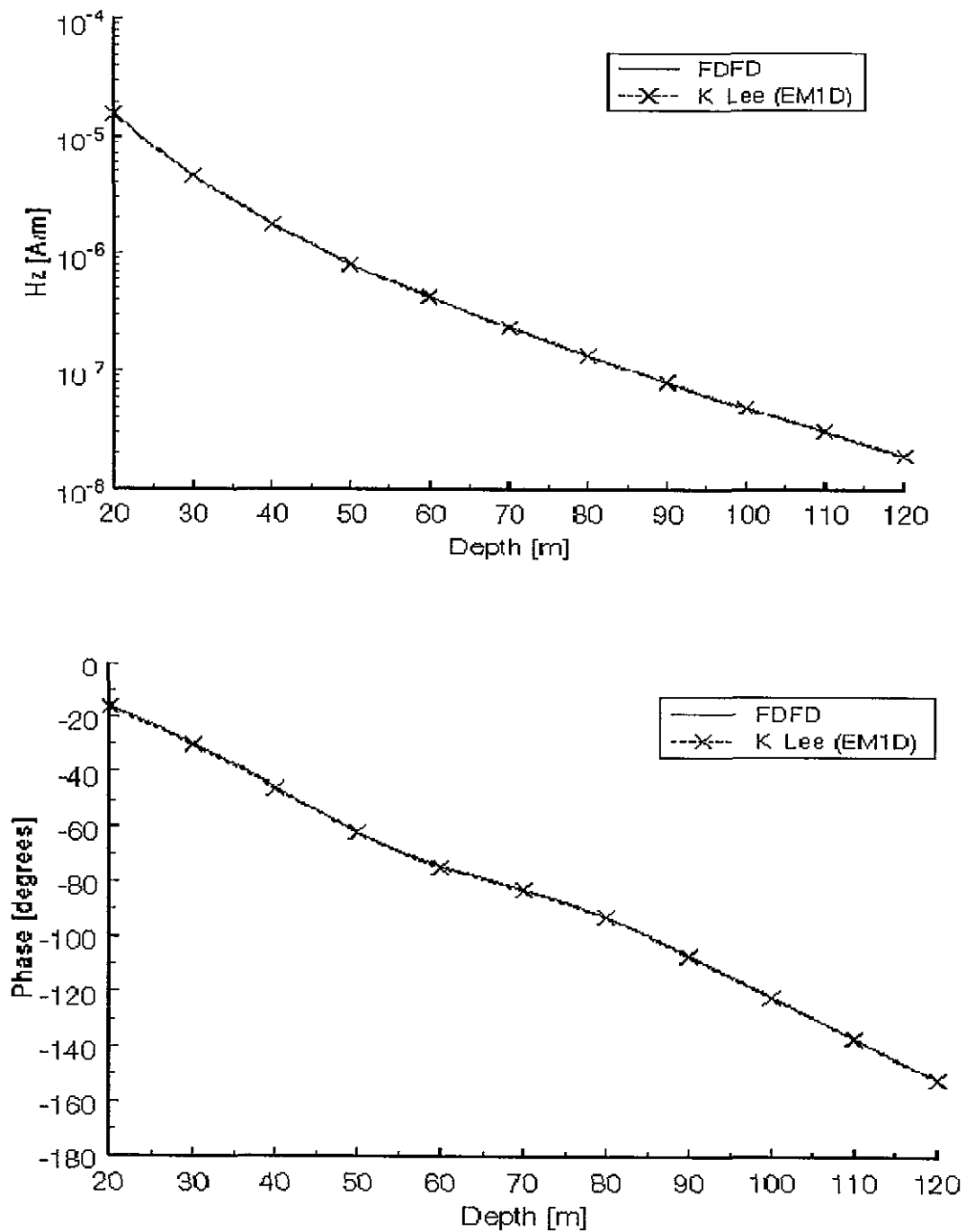


Figure 2: Comparison of computed magnitude and phase of magnetic field in a layered model to semianalytic results of Ki-Ha Lee (LBNL).

The summary presented in this section describes collaborative work done by H. Michael Buettner, Clifford Shenkel, and Michael J. Wilt.

Experimental, field, and related work

Planning took place to improve the EM data acquisition system. Improvements include: 1) additional data channels, 2) faster, more reliable software, 3) purchase and testing of 3 new magnetometers for hole to surface imaging work, 4) securing a larger, newer, more reliable, safer data acquisition vehicle, and 5) a larger, newer, more reliable, safer boom/logging truck. The new system should allow us to collect better quality data more rapidly and reliably. Items 1, 3, 4, and 5 have been accomplished.



Field Probes



Instrumentation



Survey Line

Experimental work at Lost Hills, CA

During the week of April 7, we collected borehole to surface EM data for a shallow steam injection which is underway at Mobil Oil's Lost Hills-3 field in San Joaquin Valley [see Wilt *et al.* (1996) for site details]. This is an interesting case because it can be viewed as an analog of a shallow environmental remediation using steam injection. Surface magnetic field data (vertical and radial fields, magnitude and phase) were collected at 18 receiver stations along two profiles which ran radially from the EM transmitter well from 5 m to 120 m. The data at each surface station were collected while the EM transmitter was raised slowly from a depth of 120 m to a final depth of 20 m. As part of this experiment, a calibration of the EM transmitter was also performed.

Magnetic field data from Lost Hills are displayed in Figure 3. This includes both vertical and horizontal magnitude and phase data along the North profile and along the West profile.

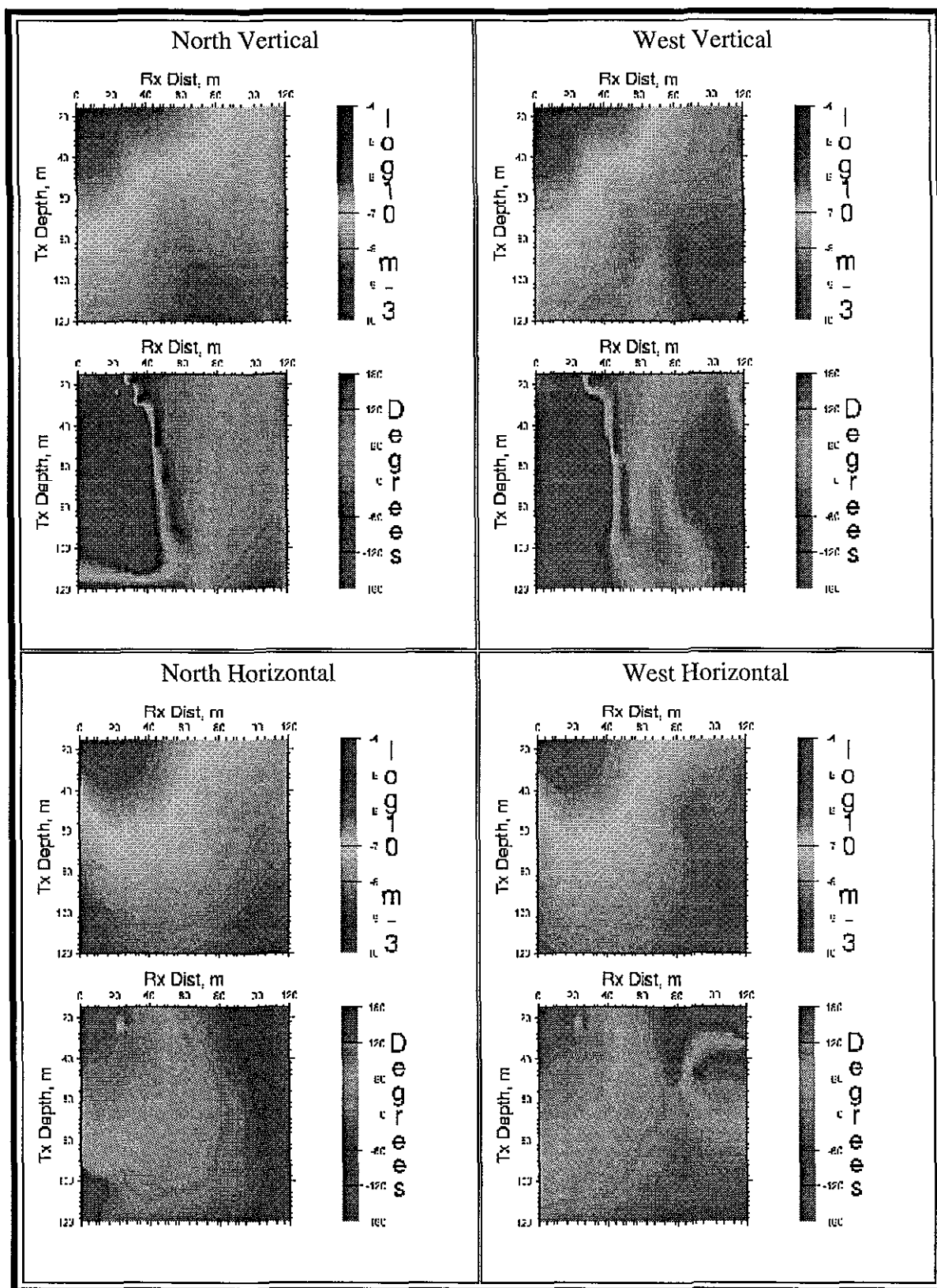
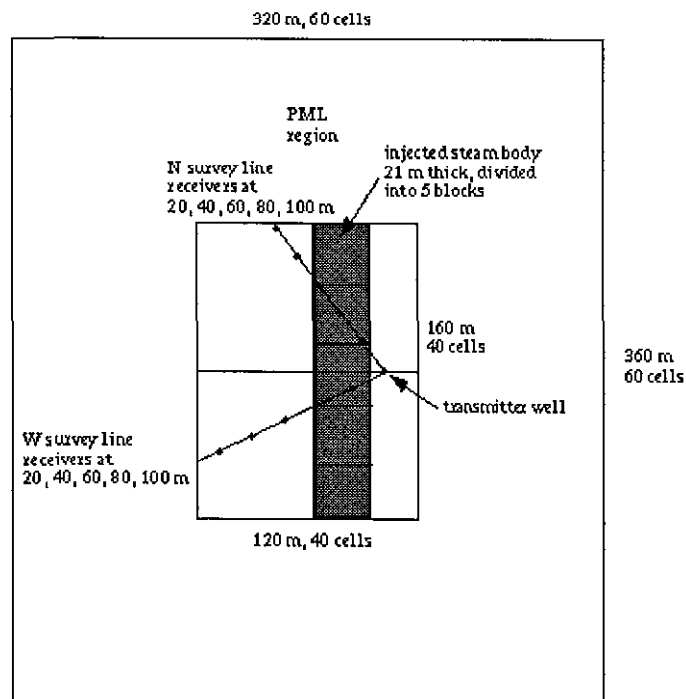


Figure 3. *Magnetic field magnitude and phase data for vertical and horizontal receivers*

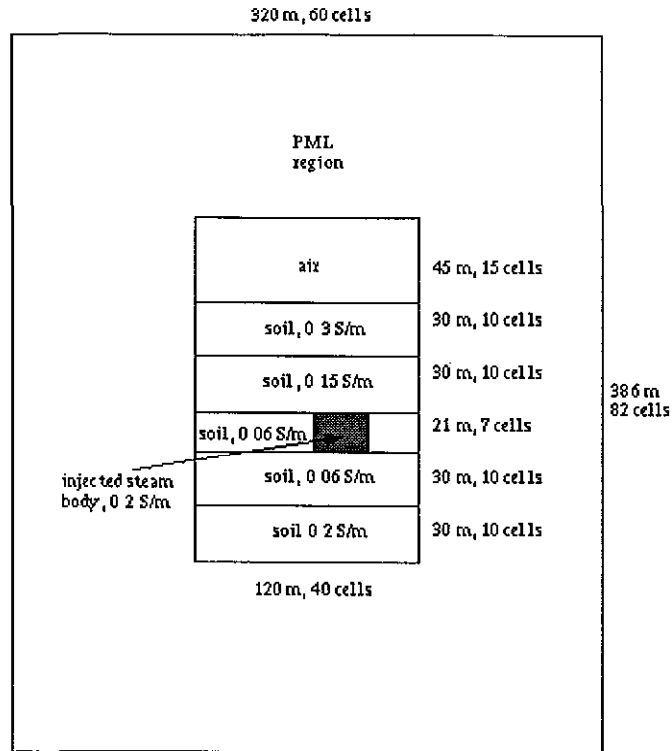
along the North and the West profiles at Lost Hills, CA.

The data from this experiment have not been completely analyzed as yet, primarily because good interpretation tools have not been available. Some simple 1-D modeling has been done to confirm that the expected conductivity change in the steam zone should produce an anomaly large enough to detect in the measured data when comparing the pre-steam to the post-steam conditions. Results of this test were positive.



Plan view of problem space and PML regions for fdtd forward modeling

Figure 4a.



Sectional view of problem space and
PML regions for fdtd forward modeling

Figure 4b.

In addition, some 3-D forward modeling has been done in which the steam zone is modeled as a single inhomogeneous layer with two outer segments having one conductivity value and an inner segment (in the vicinity of the borehole) having a higher conductivity more typical of the steam zone (the red zone in Figures 4a and 4b). Because steam injection is directional, this inhomogeneous layer consists of three strips oriented along the direction of the steam injection. The resulting magnetic field distributions are therefore not azimuthally symmetric with respect to the borehole, and this lack of symmetry is qualitatively confirmed in the field data. Some of these data together with the modeling comparisons are shown in Figures 5 and 6. There are two sets of modeling results shown in each figure: For one set, all five of the red blocks in Figure 4a are assumed to hold steam, whereas in the other set only the three central red blocks are assumed to hold steam. We find in most cases that these curves are largely indistinguishable in the regions of the measurements but become more distinguishable at greater depths.

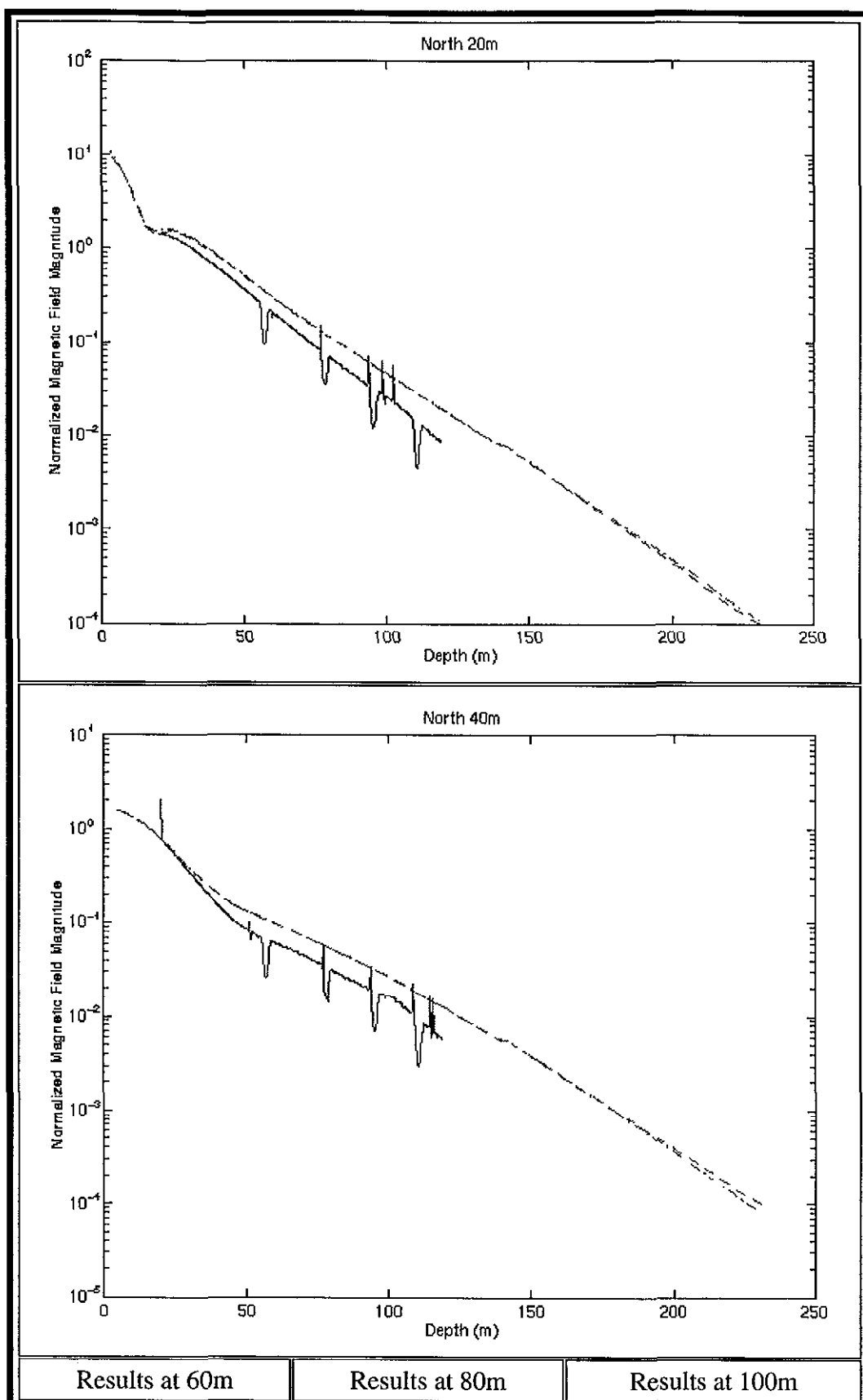
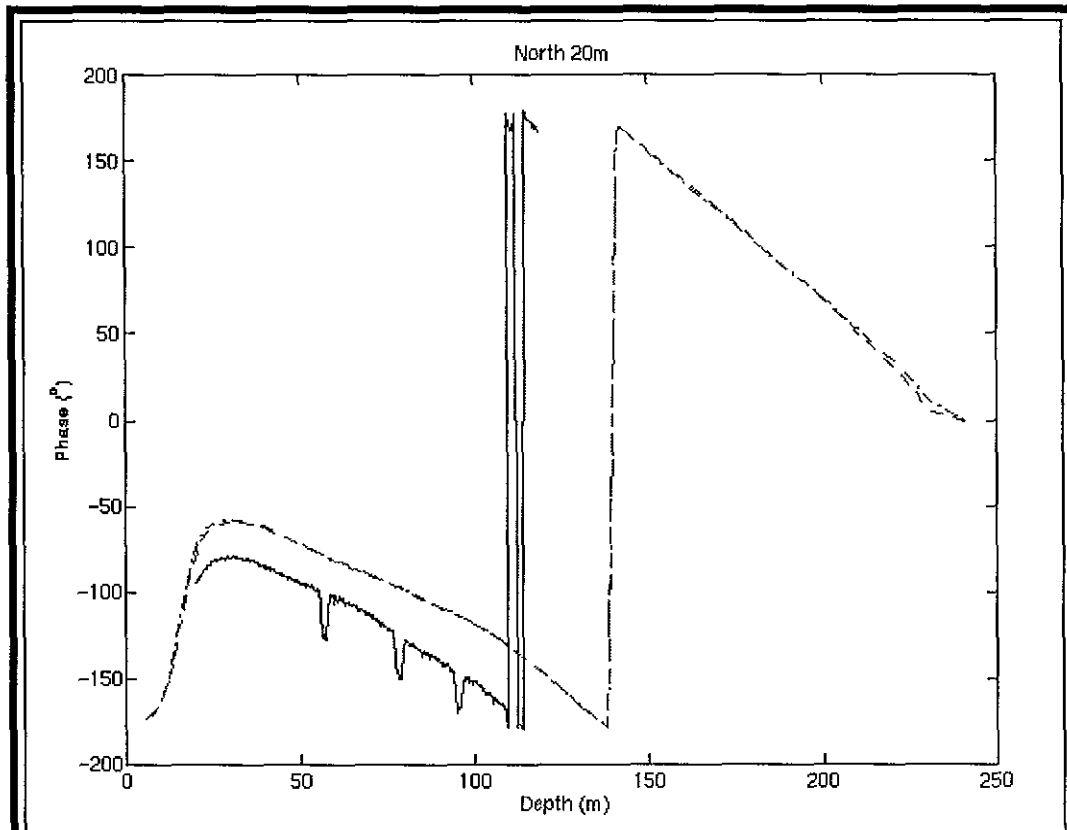


Figure 5. Showing the comparisons between measured magnetic field magnitude along the North profile (blue curves) and synthetic results for the 3D model shown in Figure 4 (red and green curves, see text for distinction between these two). Receivers for the subset of the data shown were at 20, 40, 60, 80, 100m from the transmitting borehole.

Results for West survey.



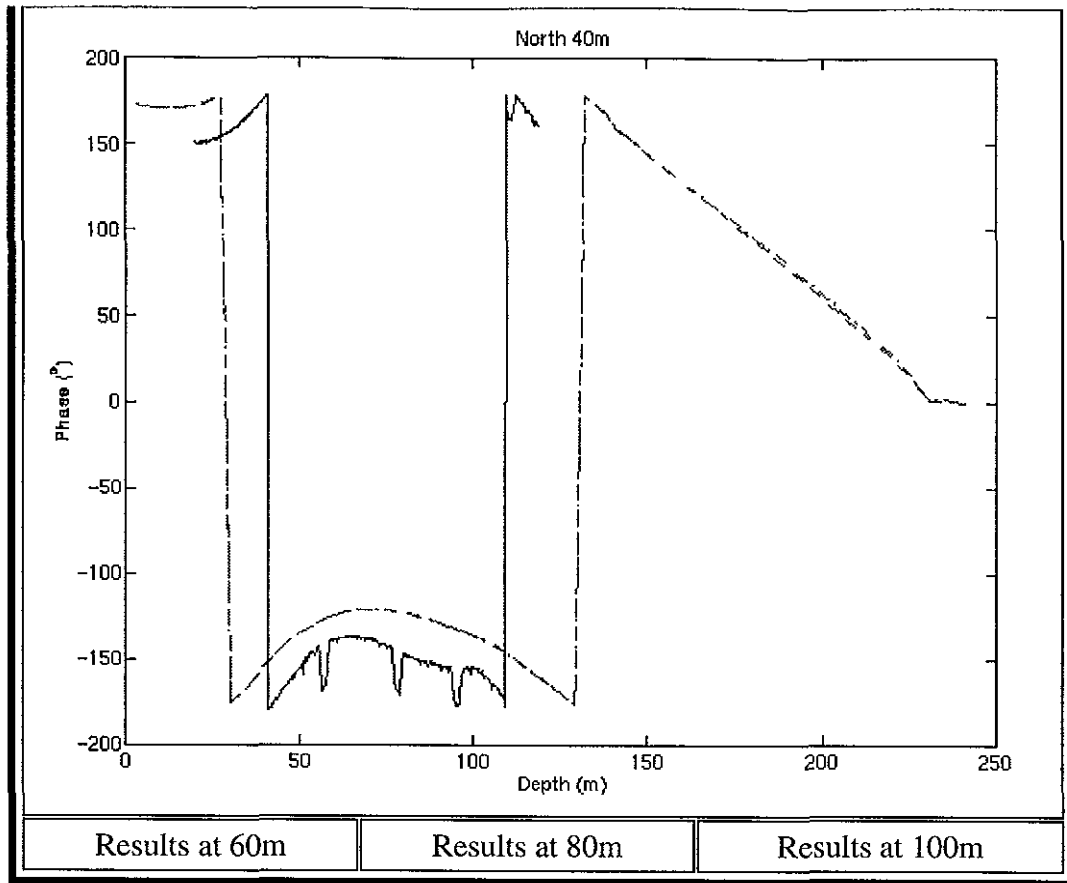


Figure 6. Showing the comparisons between measured magnetic field phase along the North profile (blue curve) and synthetic results for the 3D model shown in Figure 4 (red and green curves, see the text for distinction between these two). Receivers for the subset of the data shown were at 20, 40, 60, 80, 100m from the transmitting borehole.
Results for West survey.

During this effort, we also worked on the problem of removing cultural effects (*e.g.*, fences, pipes, etc.) from EM data. This involved a survey of the literature and discussions with M. Wilt and W. Daily. The only approach found to be effective thus far involves spatial filtering of the raw magnetic field data. That is, the rapid spatial variations need to be filtered out before interpretation begins. More sophisticated means of doing this filtering will be developed later in conjunction with the development of our inversion codes.

Directions of Research in the Remainder of the Three Year Project

We will continue to test and improve the forward modeling capability developed in the

first year of the project. At the same time a new approach to the inverse problem of electromagnetics is being developed, in collaboration with Dr. Oliver Dorn and Prof. George Papanicolaou at Stanford University, based on the so-called “adjoint technique.” This method has the very useful property that the inverse problem can be solved approximately by making two uses of the same forward modeling code we have already developed. Using a somewhat oversimplified description of our technique, the updates to the electrical conductivity will be obtained by first making one pass through the code using the latest best guess of the nature of the conducting medium, and then another pass with the adjoint operator (which for this problem is just the conjugate transpose of the operator \mathbf{A}) applied to the differences in computed and measured data. Then the results of these two calculations are combined to determine updates to the original conductivity model. The resulting procedure is iterative and can be applied successively to parts of the data, *e.g.*, data associated with one transmitter location can be used to update the model before other transmitter locations are considered. Use of data reciprocity can greatly improve the efficiency of this process by taking advantage of the fact that we actually have significantly fewer locations for receivers than for transmitters (*e.g.*, at Lost Hills, we had 36 surface receiver locations and about 500 borehole transmitter locations, so reciprocity reduces the number of required forward calculations from 500 to 36). Thus, the number of forward and adjoint calculations can be limited to that of the number of receivers by resorting the data into receiver gathers, as is often done for convenience in seismic reflection survey analysis.

Further fields tests are planned for the remainder of the second and third years as well. There is one field site at present which may present a good opportunity for field testing our system. That site is the Southern California Edison pole yard at Visalia, CA, which is contaminated with creosote. The site is currently under steam remediation and is being monitored using ERT (electrical resistance tomography). Other sites may become available as well.

EM induction data were collected at the LLNL main site recently by a group from UC Berkeley, and these data are available to us. This is not an active remediation site, but it does have some of the elements of interest to us. For example, it has some organic contamination, soils typical of the Western United States, and monitoring wells for both EM induction and ERT.

We would also like to conduct a calibration for our EM transmitter coils at a highly-resistive site if such a site can be found where the experiment can be done for a reasonable cost.

Acknowledgments

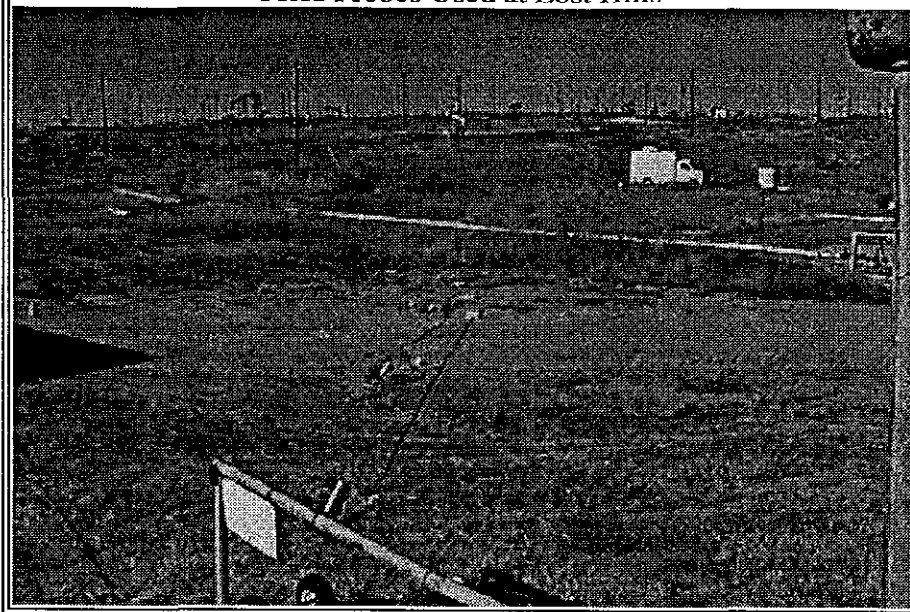
Work performed under the auspices of the U.S. Department of Energy by the Lawrence Livermore National Laboratory under contract No. W-7405-ENG-48, with support provided specifically by the Environmental Management Science Program.

References

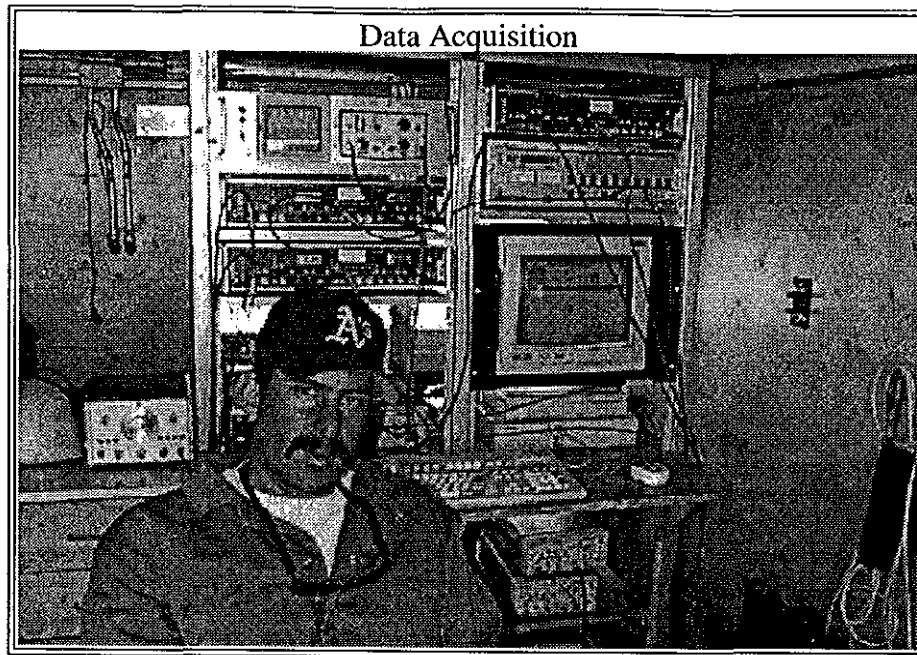
- Alumbaugh, D L, and H F Morrison, 1995a, Monitoring subsurface changes over time with cross-well electromagnetic tomography, *Geophysical Prospecting* **43**, 873-902
- Alumbaugh, D. L., and H F. Morrison, 1995b, Theoretical and practical considerations for crosswell electromagnetic tomography assuming cylindrical geometry, *Geophysics* **60**, 846-870
- Beilenhoff, K , W. Heinrich, and H L Hartnagel, 1992, Improved finite-difference formulation in frequency domain for three-dimensional scattering problems, *IEEE Trans Microwave Theory Tech* **40**, 540-546
- Berenger, J. P , 1994, A perfectly matched layer for the absorption of electromagnetic waves, *J Computational Phys* **114**, 185-200
- Berryman, J G , 1997, Challenges for computational physics in underground imaging of electrically conducting contaminant plumes, invited talk P2 03 in special session on Geological Phenomena at the *International Conference on Computational Physics*, American Physical Society, Division of Computational Physics, Santa Cruz, California, August 25-29, 1997
- Berryman, J. G , and R V Kohn, 1990, Variational constraints for electrical impedance tomography, *Phys Rev Lett* **65**, 325-328
- Borcea, L , 1996, *Direct and Inverse Problems for Transport in High Contrast Media*, Ph D. thesis, Stanford University, May, 1996
- Borcea, L., J G Berryman, and G C Papanicolaou, 1996, High contrast impedance tomography, *Inverse Problems* **12**, 835-858
- Daily, W D , A Ramirez, D LaBrecque, and J Nitao, 1992, Electrical resistivity tomography of vadose water movement, *Water Resources Res* **28**, 1429-1442
- Kuzuoglu, M , and R Mittra, 1996, Frequency dependence of the constitutive parameters of causal perfectly matched anisotropic absorbers, *IEEE Microwave Guided Wave Lett* **6**, 447-449
- Newmark, R L , and M J Wilt, 1992, Monitoring underground steam injection using geophysical logs, in *Dynamic Underground Stripping Demonstration Project - Interim Engineering Report*, edited by R L Newmark, LLNL UCRL-ID-110064, April, 1992, pp 343-372.
- Ramirez, A , W D Daily, D LaBrecque, E Owen, and D Chesnut, 1993, Monitoring an underground steam injection process using electrical resistance tomography, *Water Resources Res* **29**, 73-87
- Saad, Y., 1996, *Iterative Methods for Sparse Linear Systems*, PWS Publishing, Boston

- Smith, J T , 1996a, Conservative modeling of 3-D electromagnetic fields: Part I Properties and error analysis, *Geophysics* **61**, 1308-1318.
- Smith, J T , 1996b, Conservative modeling of 3-D electromagnetic fields: Part II Biconjugate gradient solution and an accelerator, *Geophysics* **61**, 1319-1324
- Tseng, H.-W , A Becker, and M J. Wilt, 1995, A borehole-to-surface electromagnetic survey, *Society of Exploration Geophysicists Expanded Abstracts*, Proceedings of the International Exposition and Sixty-Fifth Annual Meeting, Houston, Texas, October 8-13, 1995, pp 246-249
- van der Vorst, H A , 1992, Bi-CGSTAB: A fast and smoothly converging variant of Bi-CG for the solution of non-symmetric linear systems, *SIAM J Sci Stat Comput* **12**, 631-644
- Wilt, W J., D. L. Alumbaugh, H. F. Morrison, A. Becker, K. H. Lee, and M. Deszcz-Pan, 1995a, Crosswell electromagnetic tomography: System design considerations and field results, *Geophysics* **60**, 871-885
- Wilt, M , H F Morrison, A Becker, H.-W. Tseng, K. H. Lee, C. Torres-Verdin, and D. Alumbaugh, 1995b, Crosshole electromagnetic tomography: A new technology for oil field characterization, *The Leading Edge* **14**, March, 1995, pp 173-177
- Wilt, M J , and C. Schenkel, 1992, Cross-borehole electromagnetic induction at the Dynamic Underground Stripping clean site, in *Dynamic Underground Stripping Demonstration Project - Interim Engineering Report*, edited by R. L. Newmark, LLNL UCRL-ID-110064, April, 1992, pp 407-425
- Wilt, M J , C. Schenkel, M. Wiat cher, I. Lambert, C. Torres-Verdin, and H.-W. Tseng, 1996, Crosshole EM for oil field characterization and EOR monitoring. Field examples from Lost Hills, California, LLNL UCRL-ID-123893, July 16, 1996
- Wu, J Y , D. M. Kingsland, J. F. Lee, and R. Lee, 1997, A comparison of anisotropic PML to Berenger's PML and its application to the finite-element method for EM scattering, *IEEE Trans Antennas Prop* **45**, 40-50
- Zhdanov, M S , and S. Feng, 1995, Quasi-linear approximation in 3D electromagnetic modeling, in *Proceedings of the International Symposium of Three-Dimensional Electromagnetics*, October 4-6, 1995, Schlumberger-Doll Research Ridgefield, Connecticut, edited by M. Oristaglio and B. Spies, pp 251-257
-

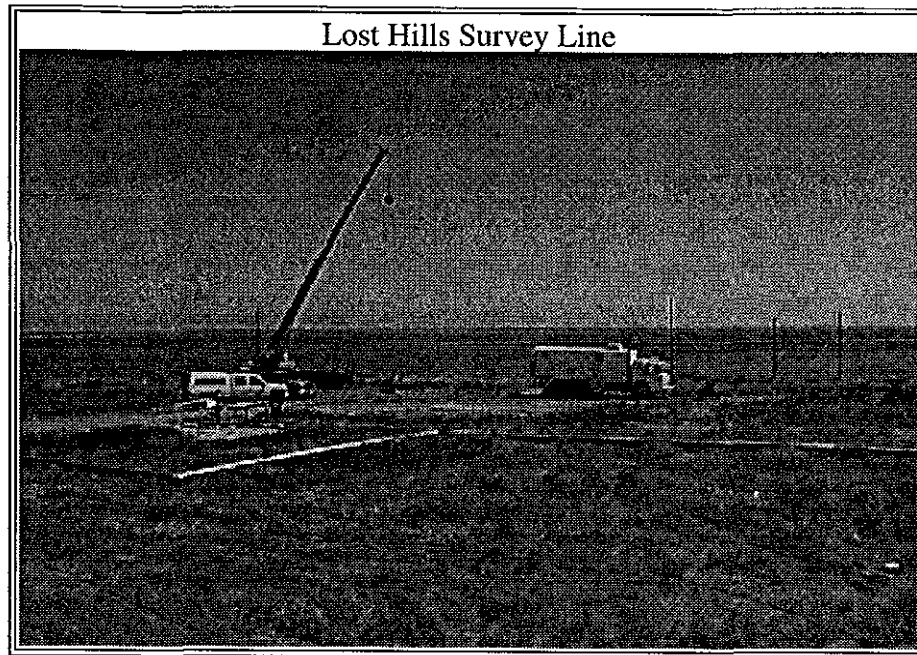
Field Probes Used at Lost Hills



Looking out along the West survey line from the transmitter well, radial magnetic field probes can be seen at 5, 10, 15, and 20 m



Operator and some of the data acquisition equipment in the instrumentation van (not shown in other pictures) for the field measurements used at Lost Hills, CA



West survey line looking back toward the transmitter well The winch and logging truck is on the right and the boom truck is positioned above the transmitter well

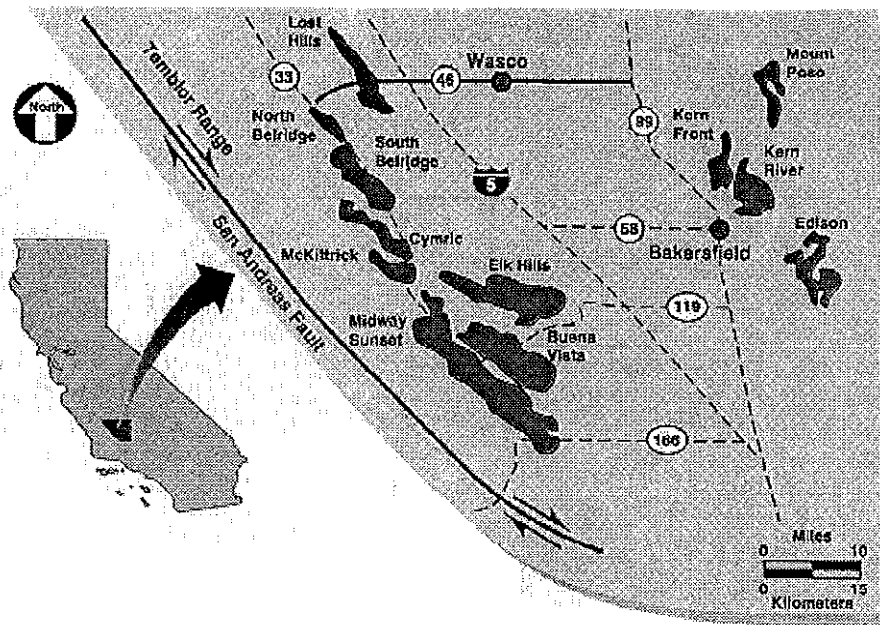
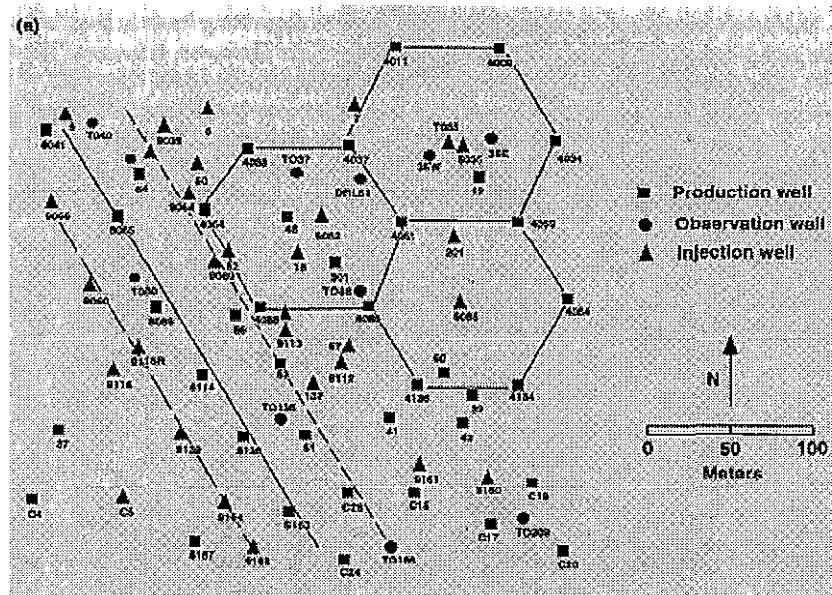
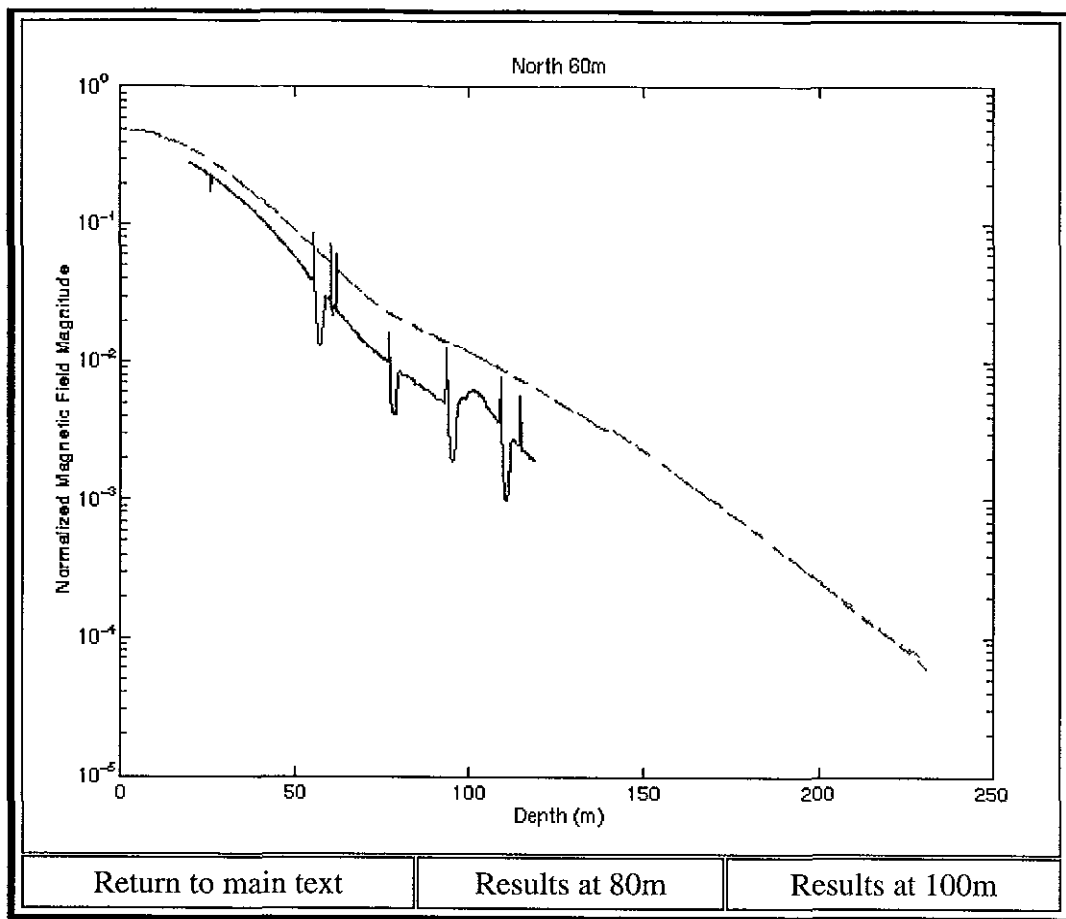


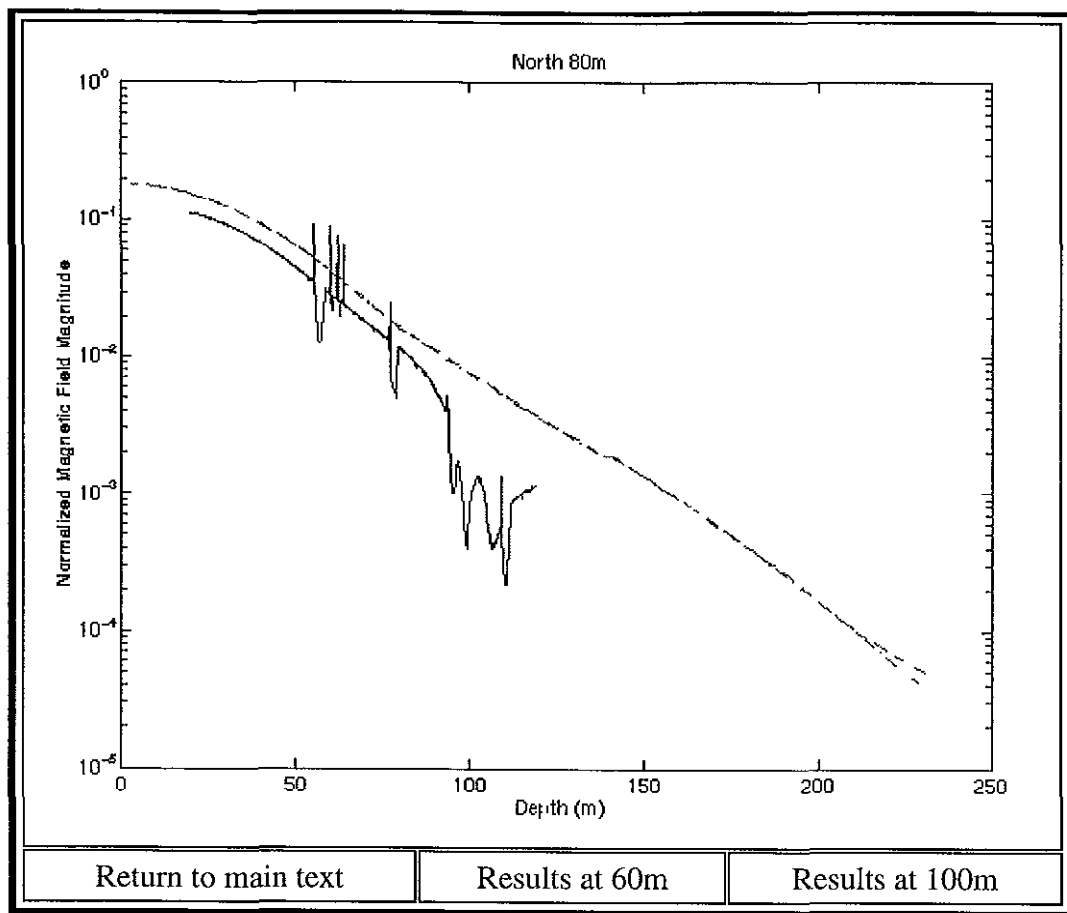
Figure 1. Site location map for the Lost Hills oil field.

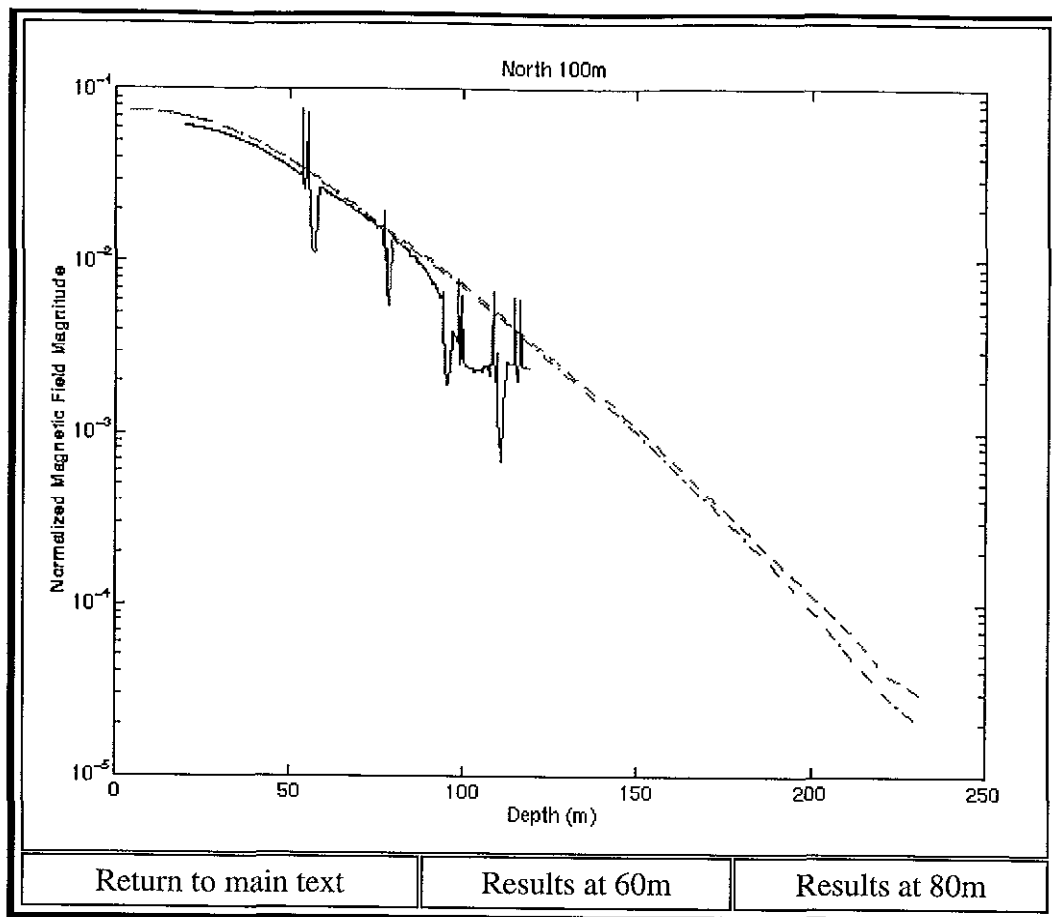


Site map for Lost Hills 3T steamflood.

EM field experiments were performed in the vicinity of injector #5035.







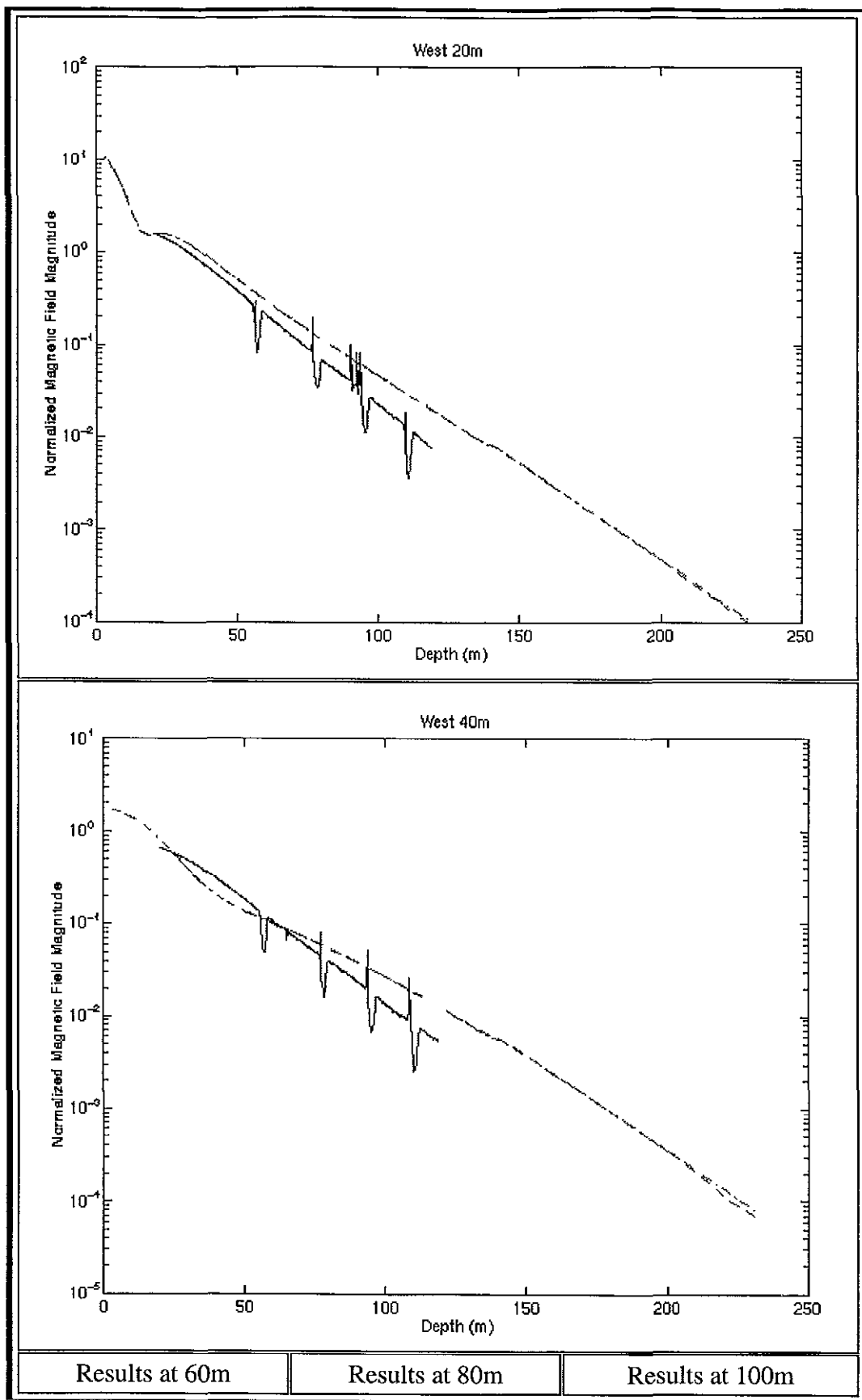
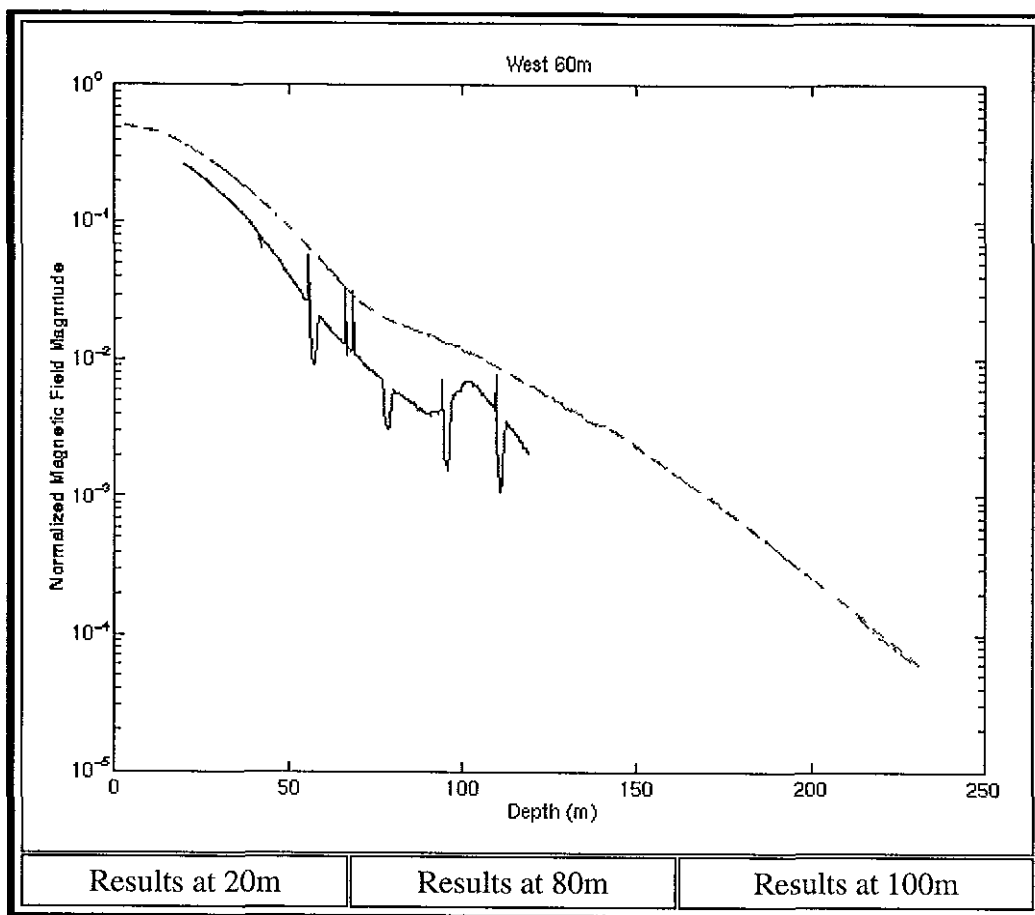
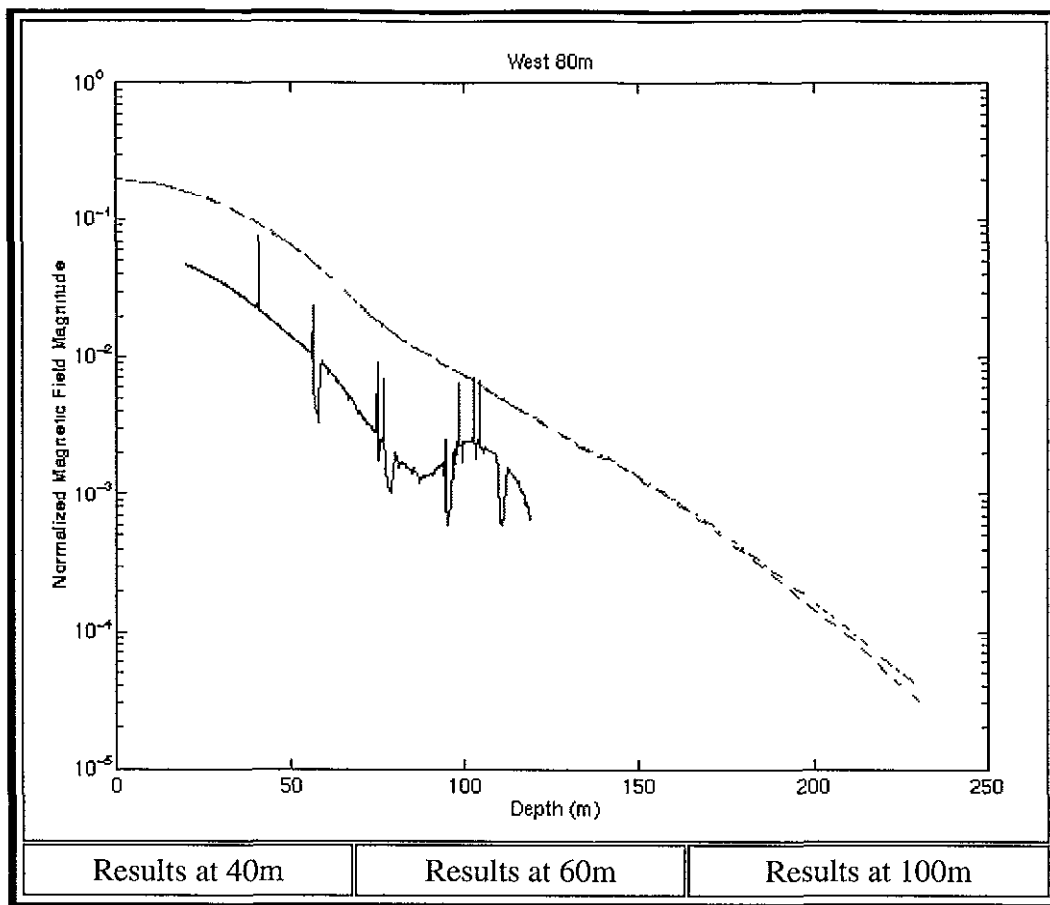
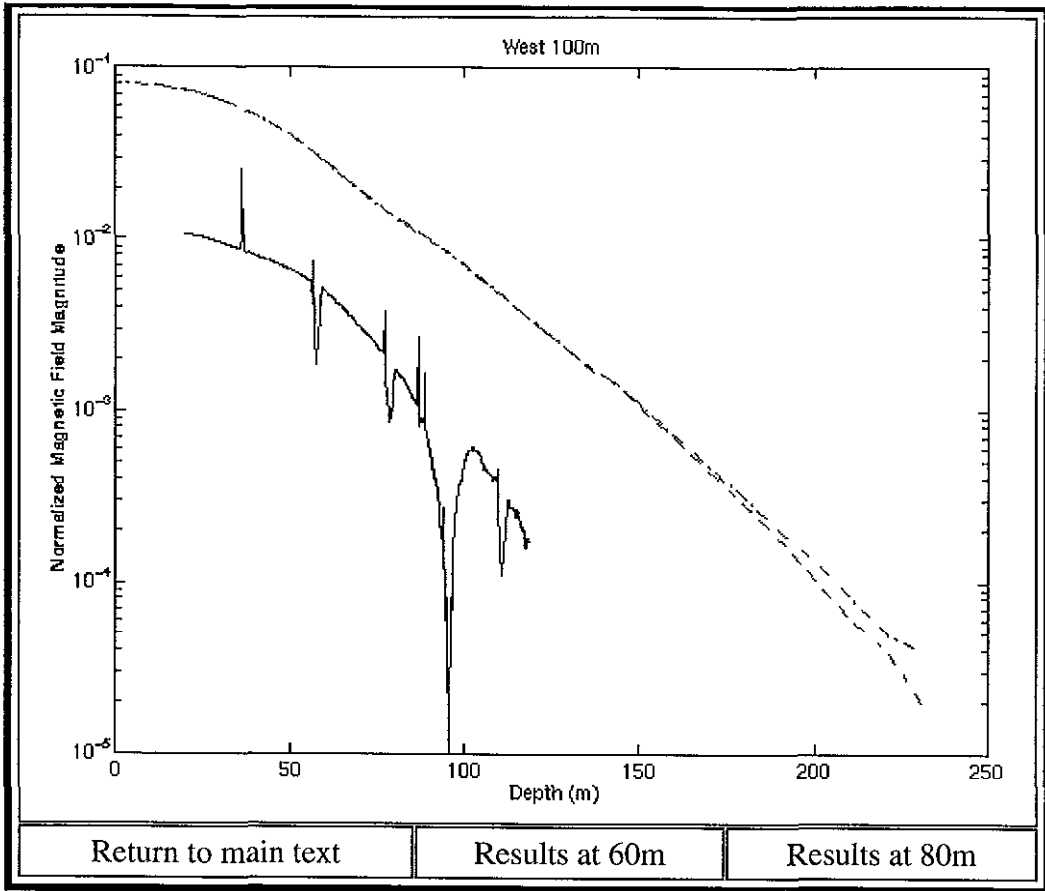


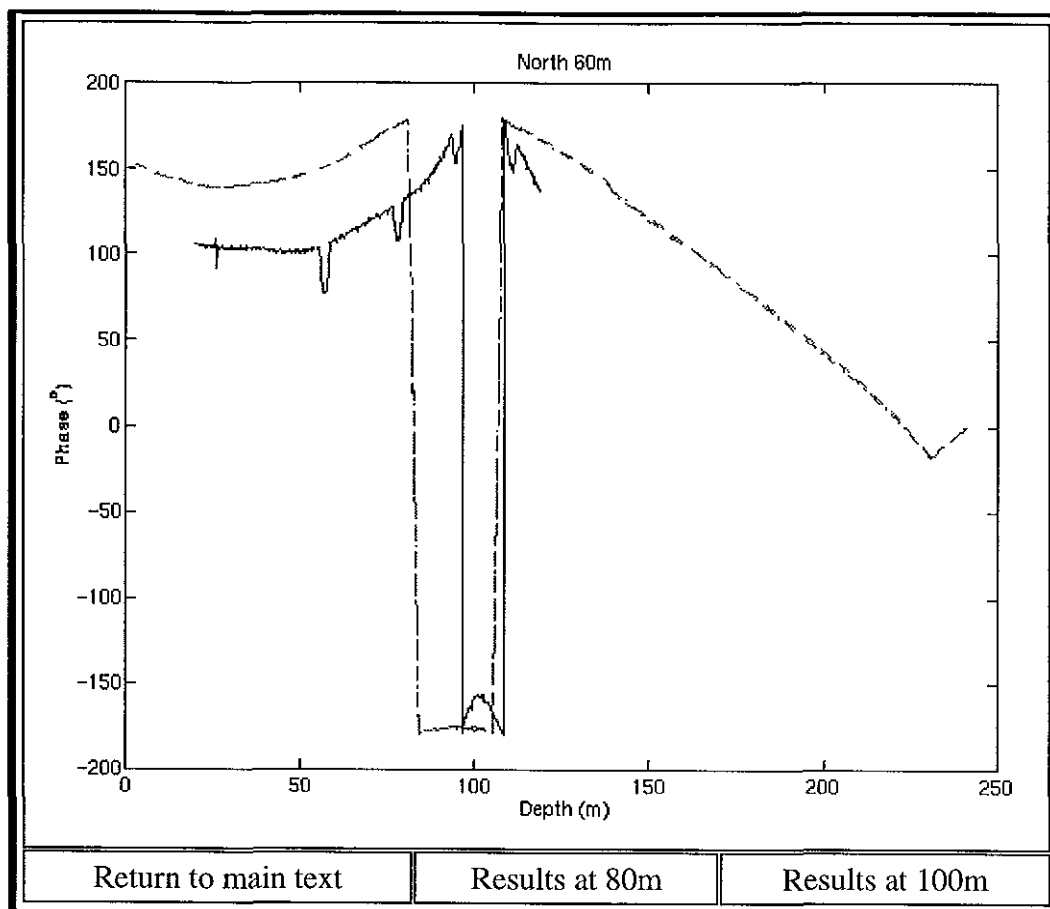
Figure 5b. *Showing the comparisons between measured magnetic field magnitude along the West profile (blue curve) and synthetic results for the 3D model shown in Figure 4 (red and green curves, see text for distinction between these two). Receivers for the subset of the data shown were at 20, 40, 60, 80, 100m from the transmitting borehole.*

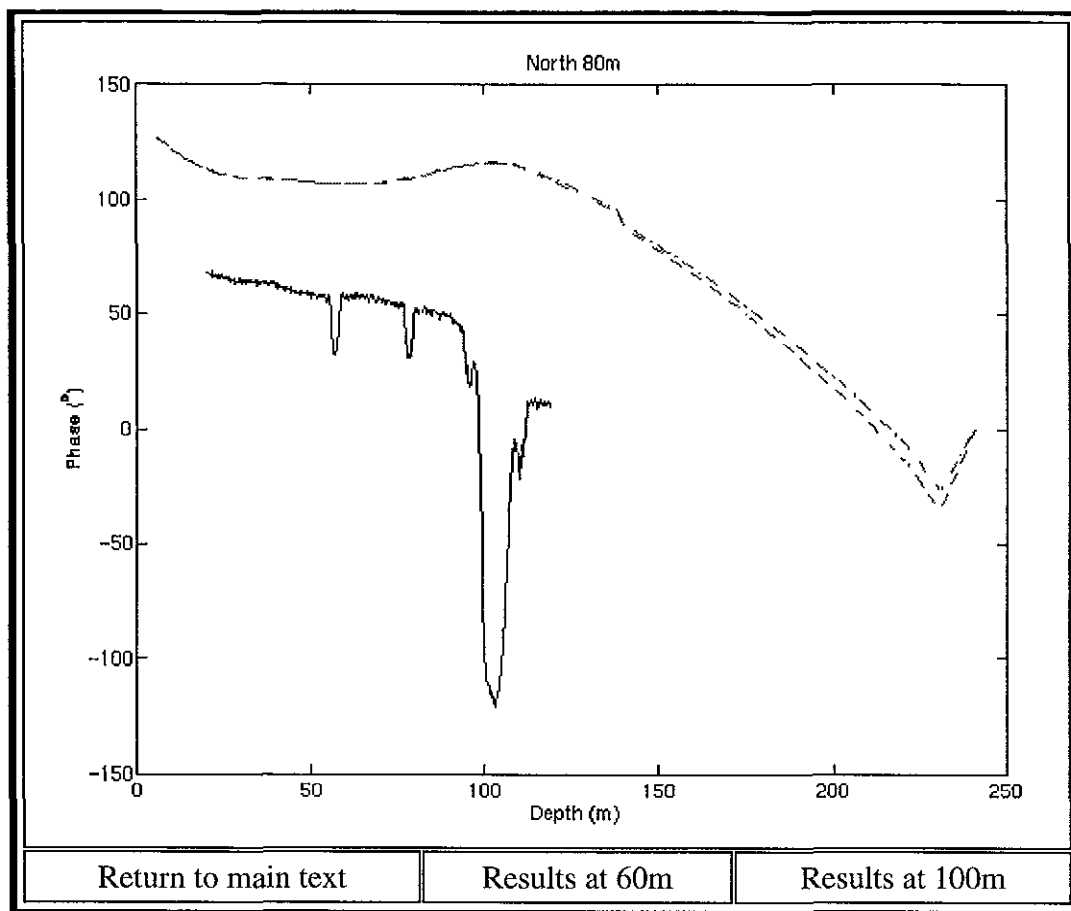
Return to North survey.

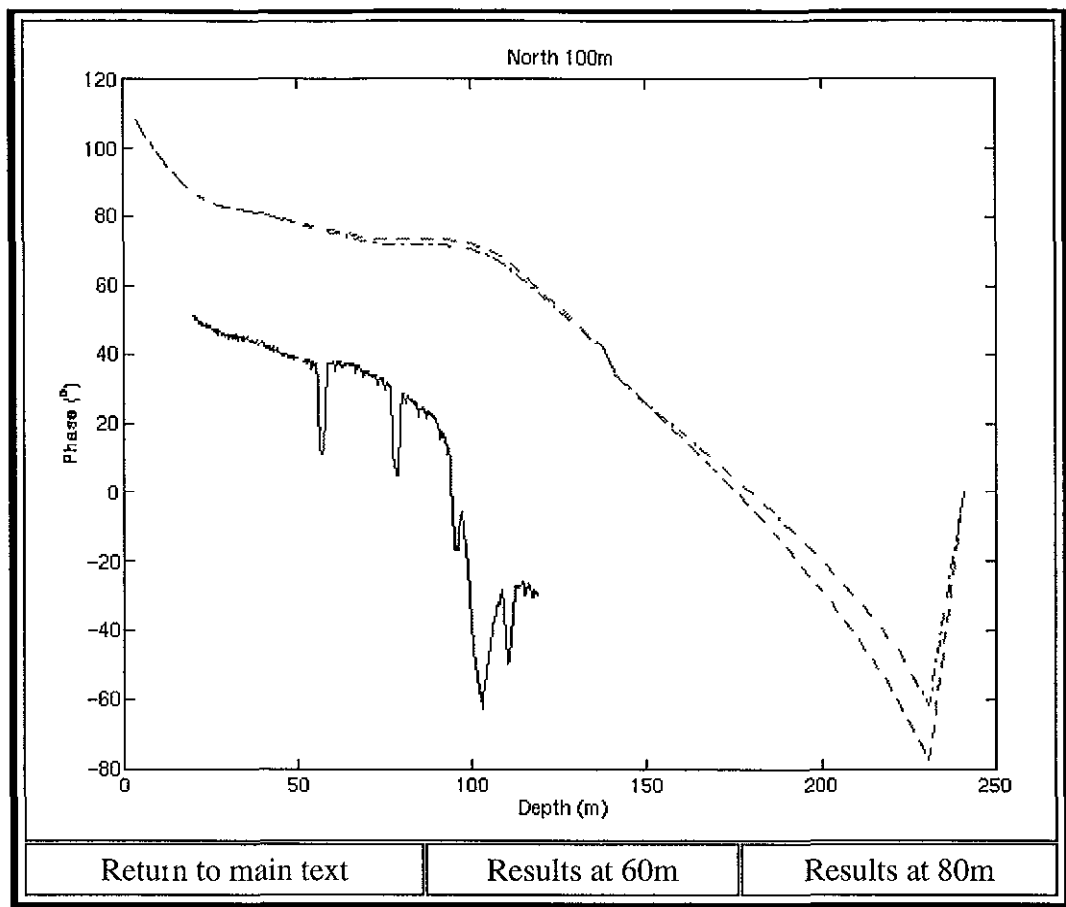


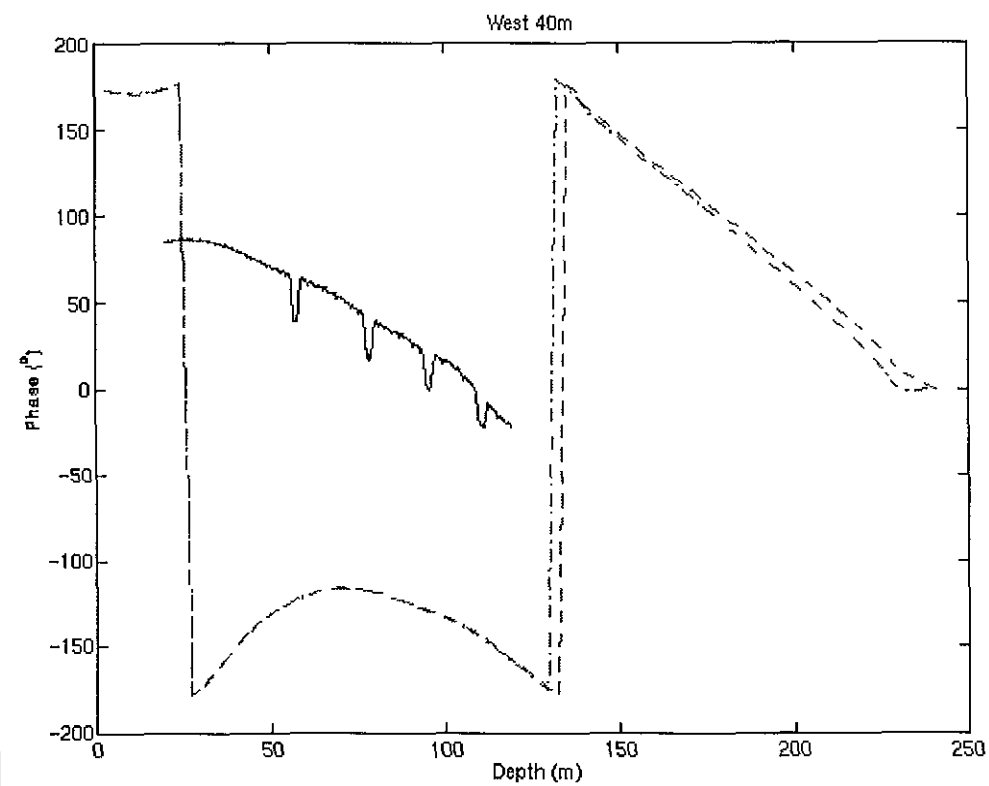
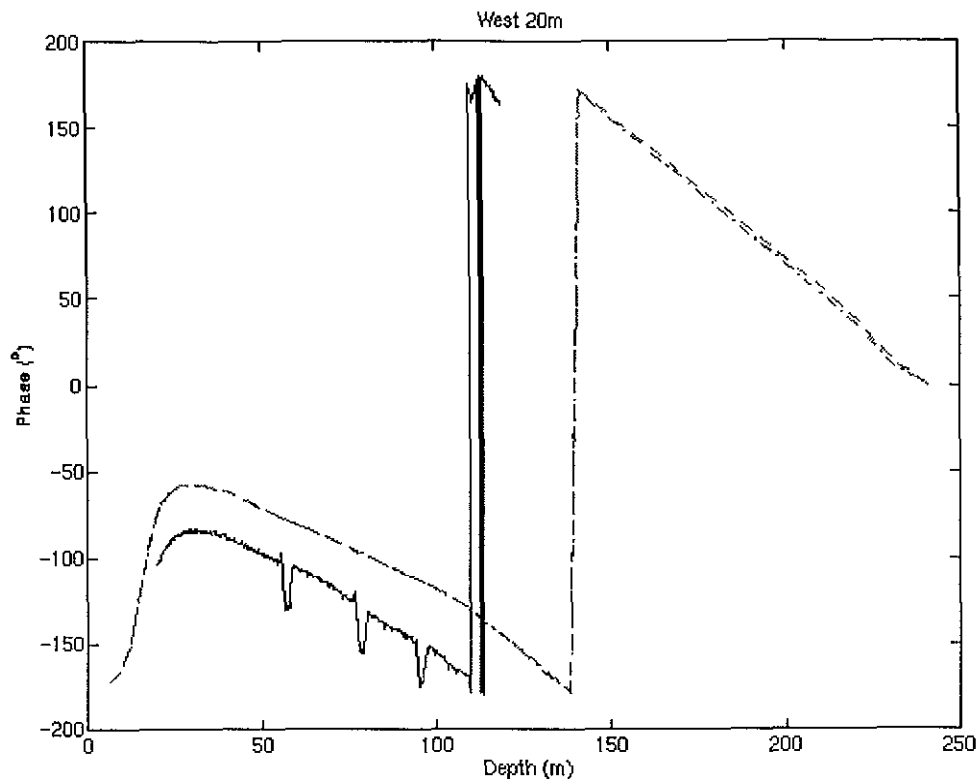








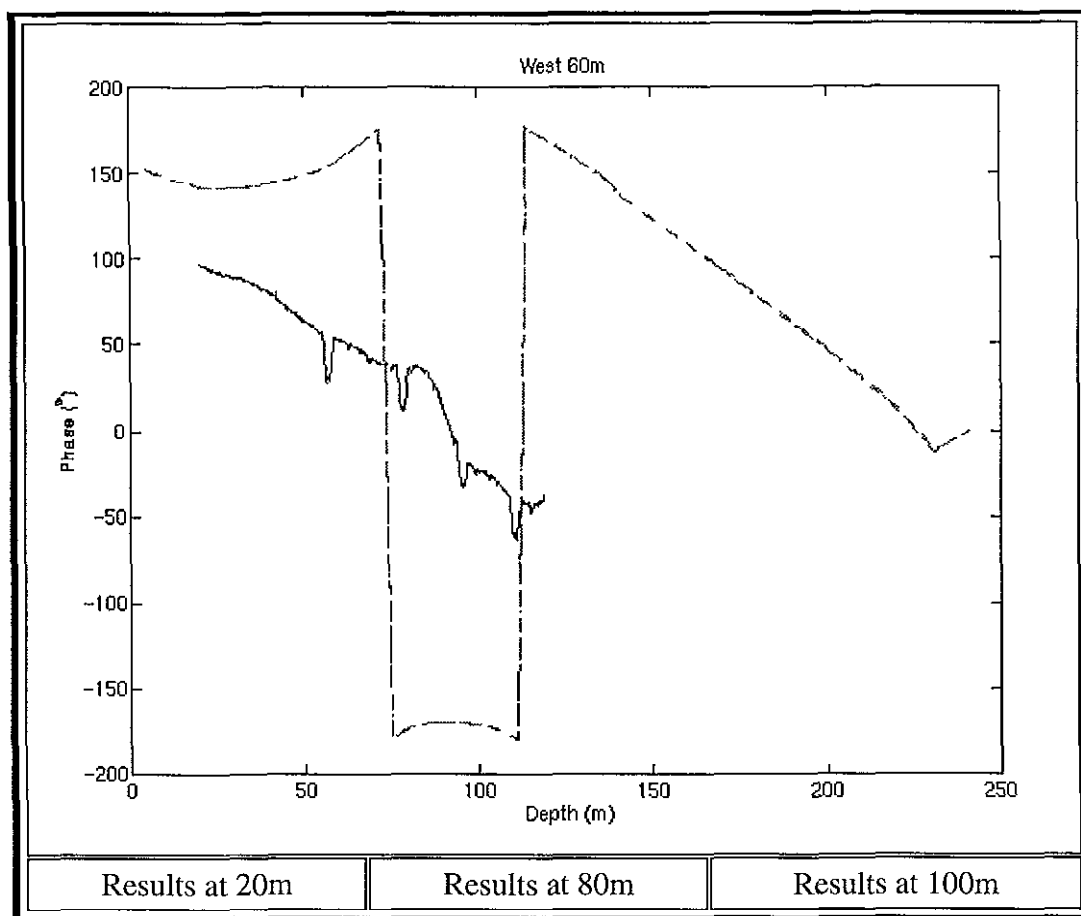


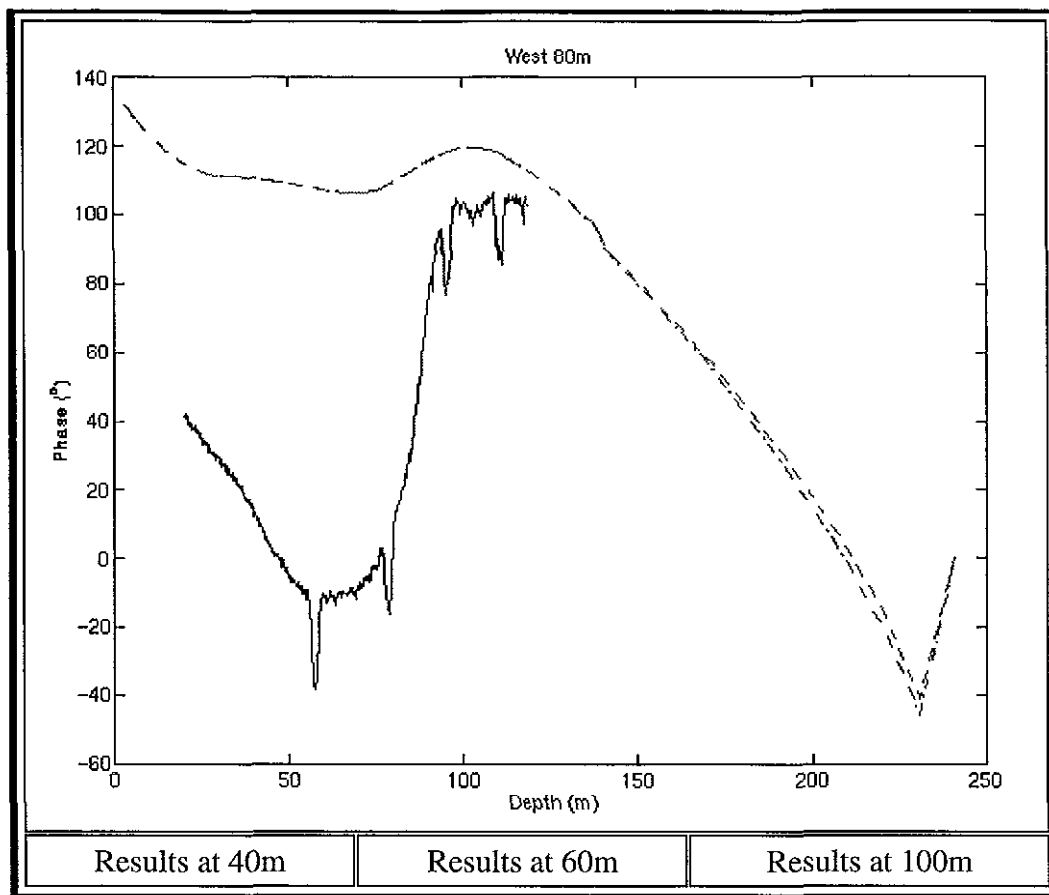


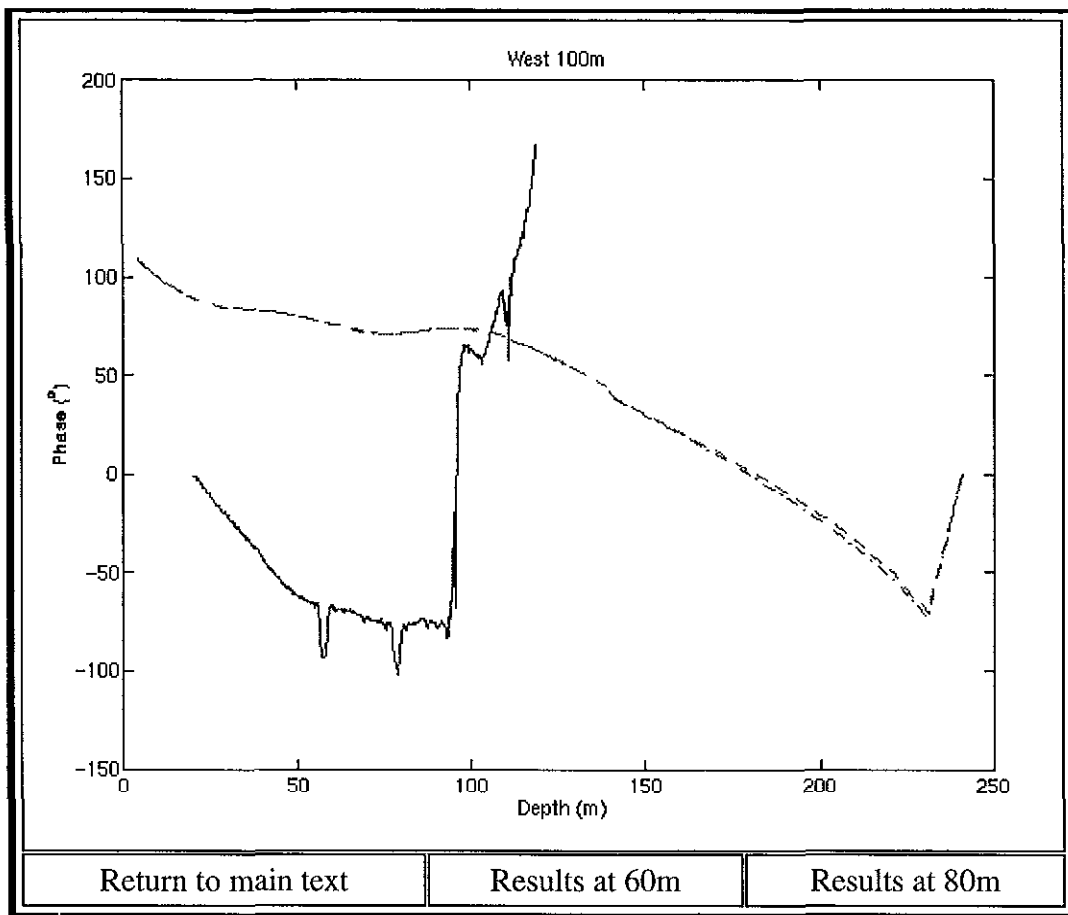
Results at 60m	Results at 80m	Results at 100m
----------------	----------------	-----------------

Figure 6b. *Showing the comparisons between measured magnetic field phase along the West profile (blue curve) and synthetic results for the 3D model shown in Figure 4 (red and green curves, see text for distinction between these two) Receivers for the subset of the data shown were at 20, 40, 60, 80, 100m from the transmitting borehole.*

Return to North survey.







Technical Information Department • Lawrence Livermore National Laboratory
University of California • Livermore, California 94551

