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13. ABSTRACT *(Maximum 200 Words)*

Identification of subsurface organic contamination, particularly dense nonaqueous phase liquids (DNAPLs) is one of the highest priorities – and among the most difficult – for remediation of numerous sites, including those of the DOD and DOE. Complex resistivity (CR) is the only geophysical method that has been demonstrated in the laboratory to have high sensitivity to organic compounds, by detecting responses indicative of clay-organic electrochemistry. However, direct detection of organics in the field has been elusive, in part due to the difficulty of obtaining robust measurements at very low contaminant levels in the presence of heterogeneous geological materials and cultural interference (such as metallic utilities and remediation plumbing). This project sought to improve the capability to detect DNAPL by (1) better geophysical imaging of geological pathways that control DNAPL movement and (2) direct detection by detailed comparison of CR lab to field data using this improved imaging. For the first goal, algorithms were developed for the joint tomographic imaging of seismic and resistivity data. The method requires that an empirical relationship can be established between seismic and resistivity; if values are ultimately tied to specific lithologies, then the final tomographic product can be an actual geological cross-section. Because shallow subsurface investigations are now commonly performed using a cone penetrometer (CPT)a new vibratory seismic source was developed to identify sites with clay-organic reactions measurable in the lab from core samples, perform reconnaissance field surveys, and proceed to detailed 2D or 3D cross-hole imaging.

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For the period
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Integrated Geophysical Detection of DNAPL Source Zones

Submitted by

BLACKHAWK GEOSERVICES, INC.
301 B Commercial Rd.
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Project 9820AFL

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1. Summary

Identification of subsurface organic contamination, particularly dense nonaqueous phase liquids (DNAPLs) is one of the highest priorities—and among the most difficult—for remediation of numerous sites, including those of the DOD and DOE. Complex resistivity (CR) is the only geophysical method that has been demonstrated in the laboratory to have high sensitivity to organic compounds, by detecting responses indicative of clay-organic electrochemistry. However, direct detection of organics in the field has been elusive, in part due to the difficulty of obtaining robust measurements at very low contaminant levels in the presence of heterogeneous geological materials and cultural interference (such as metallic utilities and remediation plumbing). This project sought to improve the capability to detect DNAPL by (1) better geophysical imaging of geological pathways that control DNAPL movement and (2) direct detection by detailed comparison of CR lab to field data using this improved imaging. For the first goal, algorithms were developed for the joint tomographic imaging of seismic and resistivity data. The method requires that an empirical relationship can be established between seismic and resistivity; if values are ultimately tied to specific lithologies, then the final tomographic product can be an actual geological cross-section. Because shallow subsurface investigations are now commonly performed using a cone penetrometer (CPT), a new vibratory seismic source was developed for this platform. For the second goal, a multistep CR investigation protocol was developed to identify sites with clay-organic reactions measurable in the lab from core samples, perform reconnaissance field surveys, and proceed to detailed 2D or 3D cross-hole imaging.

Twenty-nine sites were identified over the duration of this project, but all except one were eventually not useable due to potential or measured interference from previously installed infrastructure, spurious natural signals, inadequate clay-organic signatures, or lack of support from site management. The A-014 Outfall at the DOE Savannah River Site (SRS) was ultimately chosen for joint cross-well seismic and complex-resistivity imaging. The seismic-data quality was only fair, because the radiated source waveforms were more narrowband than expected and because of artifacts introduced by incomplete decoupling of the source from the CPT push rods or complications of the radiation pattern. The CR data were also difficult to interpret due to electrode polarization and nonlinearities in the electrodes and/or geology. Although both the seismic and electrical tomography were able to identify major contacts, the data quality and quantity were insufficient to demonstrate the utility of joint tomography in the field. The laboratory CR signatures varied significantly with lithology and duration of DNAPL exposure. Nonetheless, the field study suggested the presence of DNAPL at several locations on the south and west sides of the study area; these predictions are being tested by drilling.

While still a promising tool to identify DNAPL, this project demonstrated that CR is extremely sensitive to site conditions, and the field interpretability of lab data remains difficult. A series of experiments should be devised to separate the effects of electrode material, acquisition system, processing, and geology (particularly nonlinearity). More on-site surveys for DNAPL—perhaps some among the sites initially examined here will still be useful—are necessary to determine the practical utility of the method.

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3. Acknowledgements

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The magnetostrictive seismic source was built and operated by the Sandia National Laboratories: Russ Keefe, Greg Elbring, and Marianne Walck.

Skip Snyder of the Zonge Engineering and Research Organization modified their complex-resistivity acquisition program, supervised lab studies, and carried out field complex-resistivity surveys at Hill AFB and SRS A-014.

Applied Research Associates (ARA) of South Royalton, Vermont, constructed the electrode arrays for both the SRS A&M and A-014 field tests under the supervision of Jim Shinn. The field data for the SRS A&M test were acquired by Sue Conklin, formerly of ARA. Jim Shinn and ARA also built the cone-penetrometer housing for the magnetostrictive seismic source.

Gary Olhoeft, Colorado School of Mines, is Co-Investigator. Prof. Olhoeft and his students, Kathleen McKinley and Bethany Burton, performed laboratory and field nonlinear complex-resistivity (NLCR) measurements and data processing for the SRS A-014 survey. Ryan North contributed to NLCR measurements for some of the other sites.

At Blackhawk, Tom Sprott wrote the joint seismic and resistivity imaging program PARALLAX and Jim Pfeiffer kept both of the SRS field surveys running. Jie Zhang was originally co-PI for this project and wrote an early version of the joint inversion code.

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4. Introduction

Identification of subsurface organic contamination, particularly dense nonaqueous phase liquids (DNAPLs) is one of the highest priorities—and among the most difficult—for remediation of numerous sites, including those of the DOD and DOE. The physical, chemical, and biological properties of DNAPLs render them difficult to detect and remediate and lead to a high risk per unit mass. Separate-phase DNAPL is thought to be distributed in discontinuous stringers and globules and perhaps rarely in lenses or pools (Fig. 4.1) that are difficult to target by drilling alone. Complex resistivity (CR) is the only geophysical method that has been demonstrated in the laboratory (e.g., Sadowski, 1988; Jones, 1997) and the field (Olhoeft and Wardwell, 1998) to have high sensitivity to organic compounds, by detecting responses indicative of clay-organic electrochemistry. However, direct detection of organics in the field has been elusive, in part due to the difficulty of obtaining robust measurements at very low contaminant levels in the presence of heterogeneous geological materials and cultural interference (such as metallic remediation plumbing). Under this contract, Blackhawk Geoservices and its collaborators—particularly the Colorado School of Mines (CSM)—sought to improve the capability to detect DNAPL by (1) better geophysical imaging of geological pathways that control DNAPL movement through joint seismic and electrical tomography and (2) direct detection of DNAPL by detailed comparison of lab to field complex-resistivity data.

Geophysical imaging may be improved by using more than one method, as no single geophysical survey can respond optimally to all possible variations of subsurface properties. In a true *joint inversion* the process of developing an image from field data is iteratively bound between different kinds of surveys. Joint inversion depends on the ability to which subsurface properties can be mapped between different methods. For this project, we developed joint inversion between seismic velocity (P- or S-wave) and electrical resistivity that features an empirical mapping between these quantities using well logs or other a priori data.

The simple, direct-push approach of the cone penetrometer (CPT) has become the tool of choice for sampling, in-situ analysis, and monitoring-well installation where contamination is in unconsolidated materials within a few hundred feet of the surface. For this project, we examined several different ways to perform cross-hole resistivity and seismic experiments using the CPT. Two different styles of vertical electrode arrays (VEA) were installed in separate experiments by

CPT. Because seismic receivers that are most useful for the vadose zone cannot be accommodated in small-bore CPT wells, we developed an approach wherein larger, permanent wells (such as a standard 4" monitoring well) could accommodate the receivers and a seismic source on the CPT could be used to interrogate the surrounding volume. A magnetostrictive seismic source, allowing a programmable transmitted waveform, was built for this project.

The complex-resistivity (CR) method records the frequency-dependent amplitude and phase of the voltage response to a current injected into a material. The amplitude is a measure of energy loss and the phase is a measure of energy storage. The latter can be representative of reversible chemical reactions; clay cation exchange is most relevant here because DNAPL interference with this process can be detected by CR. In contrast to other geophysical methods, CR is most sensitive to the surface area over which chemical reactions occur instead of the volume of the contaminant: the presence of a small quantity of reactive clay (several percent) is sufficient to detect DNAPL in the laboratory at typical concentrations of tens of parts per million (i.e., 10s of μg/g). For volumetric detection without the presence of reactive clay, DNAPL must nearly saturate the pore space and choke off the natural electrical conductivity of the pore fluids. Although other aspects of this project were introduced above, assessment of the CR method was our principal focus.

4. Complex Resistivity

5.1 Overview

In the complex-resistivity method, an electrical current is injected into a material and both the amplitude and phase of the voltage response are measured as a function of frequency. In the system manufactured by Zonge Engineering, a square wave is transmitted and the odd fourier harmonics are recorded, typically from 1/64 Hz to 8 kHz. In the CSM system, a sine wave is transmitted and the response measured directly from a curve fit. The CSM system typically measures 1 mHz to 1 kHz in the field, but equipment exists to go from 1 μHz to 1 MHz. The ratio of the peak-to-peak amplitude of the current and voltage is the magnitude of a transfer function or complex resistance, which is converted to resistivity—a material property—when normalized by the geometry of the current and voltage electrodes. The phase shift between the current and voltage is a measure of the time shift between stimulus and response. Resistivity is a measure of the energy dissipated by the system and the phase shift is a measure of the amount of energy stored in the system. When there is no phase shift, there is no energy stored in the system. Chemical reactions are typical examples of charge (and through charge separation in space, energy) storage processes. Charge separation is also known as electrical polarization (hence the use of the term "induced polarization" or IP). Additionally, if a pure sine wave is used to excite the system and distorted sine wave is the response, then the distortion at each frequency is characterized by the square root of the sum of the squares of the harmonic content in the response sine wave (total harmonic distortion, THD) or from the deconvolved harmonic content between stimulus and response if the stimulus is not a pure sine wave. The THD can also be derived from the even harmonics of a transmitted square wave. If the real and imaginary parts of the complex resistivity as a function of frequency are not related to each other by the Hilbert Transform, then the discrepancy may be used to characterize another, independent characterization of nonlinearity called Hilbert Distortion (HD). Further discussion and details may be found in *Olhoeft* (1979a,b; 1985). Measurement of the THD and HD are the discriminating elements in Nonlinear Complex Resistivity (NLCR) in addition to the resistivity magnitude and phase from linear complex resistivity.

To understand these measurements further, consider two simple circuit elements. An ideal resistor has a voltage response linearly proportional to current without phase shift: energy is dissipated without storage. An ideal capacitor also has a voltage response response proportional to current, but with a 90° phase shift. This phase shift is expressed mathematically as a time derivative, which represents a finite rate of motion, resulting in frequency dependence (which the resistor does not have). Most chemical reactions involve transport motion of charges and charge separation, resulting in both energy dissipation (from charge motion) and storage (from charge separation), thus requiring both resistor- and capacitor-type circuit elements to describe. The real and imaginary parts of the complex resistivity describe the energy dissipation (motion) and storage (separation or polarization) at each frequency.

Chemical reactions require a certain amount of energy to overcome barriers before the reaction may proceed, and they are limited in how fast they can occur by the speed of the reaction itself (kinetics limited) or the speed at which reactants and reaction products can move to and from the site of reaction (diffusion limited). The finite speeds result in frequency dependence, but the barriers result in nonlinearity. Two examples of nonlinearity in circuit elements are a semiconductor diode and an electrochemical Warburg impedance. The diode behaves like a resistor with a threshhold and polarity-asymmetrical exponential nonlinear proportionality between voltage and current, but still independent of frequency. The Warburg impedance has the nonlinear proportionality plus a square-root frequency dependence. The physical embodiment of a Warburg impedance is the interface of water against graphite. Either type of nonlinearity will generate distorted response waveforms and may be characterized by total harmonic distortion as an indicator of nonlinearity. However, the details of the waveforms may be used to derive considerable detail about the chemical reactions (resulting in an electrochemical analytical chemistry technique called cyclic voltammetry). The causes of the Hilbert Distortion nonlinearity are not understood, but are related to the cation exchange process in clay and zeolite minerals (*Olhoeft*, 1979b; 1985; *Jonscher*, 1986). There is no circuit analogue for the Hilbert Distortion. At sufficiently high frequencies (where the chemical reactions can no longer keep up with the driving current rate of change), these nonlinear systems will become linear (*Olhoeft*, 1979b). This transition to linearity usually occurs at frequencies in the kilohertz range.

In summary, a material must exhibit, at a minimum, some frequency dependence (and hence some non-zero phase) to have any chemical activity occurring within it, and some chemistries will also produce characteristic patterns of frequency dependence and nonlinearity that allow the specific chemistry to be identified.

5.2 Instruments and Measurements

5.2.1 Colorado School of Mines

Laboratory measurements of the samples acquired for all of the sites described in this report were performed with equipment and procedures as described in *Olhoeft* (1979a, 1980) and using the fourth generation hardware and software as described in *Jones* (1997). In brief, the samples were placed in teflon sample holders (*Olhoeft*, 1980) with four bright platinum #52 mesh electrodes sandwiched between the three teflon sample sections. Bright platinum is a compromise voltage response electrode material as it is not totally nonpolarizable, but it is easily cleaned and does not itself become contaminated unless sulfur compounds are present. Platinum mesh is used to provide a high surface area. Platinized platinum ("black") electrodes would be more nonpolarizable but their high surface area porous surface is easily contaminated and difficult to clean. Ag-AgCl electrodes are even better nonpolarizable electrodes but also become contaminated, are difficult to clean, and they leak a small amount of chloride solution which can alter clay properties.

A current sine wave was applied to the outer pair of electrodes and the voltage response was measured across the inner pair of electrodes. A pair of phase-locked frequency synthesizers provided the source current and the digitizing trigger to digitize the current and voltage. Current was measured by the digitized voltage across a precision decade resistor in series with the sample. A matrix inversion to fit the waveforms (fundamental sine wave and harmonics) produced the parameterization of amplitudes and phases, and the total harmonic distortion (*Olhoeft*, 1979a). Because a matrix inversion was done, the standard deviation of the fit was also available to go through a derivative error analysis to yield quality indicators as errors in resistance and phase. The geometry of the sample holder was applied to convert the measured resistance into resistivity. A further matrix inversion of the frequency dependence of the real and imaginary parts of the complex resistivity yielded the deviation from the Hilbert Transform to give the Hilbert Distortion nonlinear indicator (*Olhoeft*, 1979b; 1985). The system measured an opened and a shorted sample holder to determine and remove the inductive and capacitative coupling between the wires connecting the measurement system to the sample holder and to remove the input impedance of the system.

Sample holders with and without soil, and at each step of adding distilled water or contaminant (PCE or TCE) were weighed to determine the amounts of materials in the mixtures. Core samples were measured as received as well as after being vacuum dried to determine moisture content, and measured again after rehydration with distilled water. The procedures were as described in *Sadowski* (1988) and *Jones* (1997).

The basic CSM measurement system described for the laboratory measurements was also used for the field measurements to generate the current stimulus, digitize the current and voltage waveforms, and process the data (Fig. 5.1). A Crown DC-300A power amplifier was added to put more current into the ground. The electrodes are connected by triax shielded cables to Intronics IA294 medical instrumentation isolation preamplifiers and thence through twinax shielded cables to the 16-bit digitizer and simultaneous sample-and-hold boards in the computers. The spontaneous polarization (SP) is removed ("bucked out") by a 9-V battery, potentiometer and resistor network just before the preamps. The low-cost preamplifiers isolate and protect the expensive digitizer boards, and they use active driven shields to eliminate capacitative coupling between the cables and maintain $>10^8$ ohm differential and 10^{11} ohm common-mode input impedance all the way out to the electrodes along with passive shielding to minimize powerline and radiofrequency interference. Cable locations and geometries are laid out to minimize inductive coupling. A sixteen-channel system is typically used, with channel 0 recording the voltage across a precision power resistor to measure the current going into the ground, and channels 1 through 15 measuring the voltage across pairs of electrodes at various locations. As many as 6 of these systems have been synchronized to simultaneously measure up to 96 channels (at least one of which has to be the current). Further field examples and details may be found in *Olhoeft and Wardwell* (1998), *Oshetski* (1999), and *Fiore* (1999) and references cited therein. Data are processed to resistance (without geometry) magnitude and phase, and to total harmonic distortion and Hilbert distortion, along with standard deviations and a determination of signal to noise at 60 Hz (as the largest source of noise was the nearby power distribution system).

Before each measurement, the spontaneous voltage is bucked out in all 16 channels. After each measurement, the current amplitude is slowly reduced to zero at 100 Hz, to mimimize the memory relaxation polarization effect of the metal electrodes (much like AC demagnetizing a ferromagnetic metal). If the latter is not done, there appears to be a long term SP drift when an electrode is used as a voltage electrode immediately after using it as a current electrode.

5.2.2. Zonge Engineering

Zonge Engineering also analyzed splits of several core samples from the SRS A-014 site in order for the effect of different measurement systems to be assessed. Isolation amplifiers were added to the standard transmitter-receiver configuration to buffer and electrically isolate the reference voltage and the sample voltage. The samples were placed between two electrode holders containing copper-screen electrodes in a solution of Cu-CuSO_4; galvanic contact between the electrodes and the sample was made through a porous ceramic plate.

Field surveys were contracted to Zonge at Hill AFB and SRS A-014; for the latter, a direct comparison could be made between this commercial system and the custom system of CSM. Also for SRS survey, the standard acquisition program was modified to extend to lower frequency (1/1024 Hz) and to record the even harmonics of the transmitted square wave, in order to evaluate harmonic distortion. The equipment consisted of transmitter and receiver units, switch boxes for transmitter and receiver, power supply (2 x 24-Vdc batteries), and a power booster (Fig. 5.2).

A generalized comparison of the Zonge and CSM systems is given in Table 5.1.

Table 5.1 Laboratory Characterization of Complex-Resistivity Systems.

Parameter	Zonge GDP-32	CSM NLCR
Input Impedance, ohms	1e7	1e8 differential 1e11 common mode
A/D Conversion, bits	16	16
Conversion Time, usec	17	1
Digitization Rate, kHz	37	1000
Frequency Range, Hz	9.8e-4 - 8192 RPIP mode	n/a
	9.8e-4 - 1 TDIP mode	n/a
	1.6e-2 1024 CR mode	1e-6 - 1e4
Waveform	Square	Sine
Frequency Sweep Direction	Low to High	High to Low
System Nonlinearity	not specified	< 0.1% THD, <0.01% Hilbert
Phase Accuracy, mrad	not specified	<0.1
Gain Accuracy	not specified	<0.1%
Output Statistics	partial	Full error and S/N
Time to Measure 1e-3 - 1e3 Hz	several hours	40 minutes
Time Base	Synchronous Clocks	Phase-Locked Clocks

5.3 Tomography

Tomography ("slice picture") is the process of reconstructing spatial variations in a physical property from spatially distributed measurements that depend on that property. Two approaches to complex-resistivity tomography were undertaken for this project. For the first, Dr. William Petrick (Industrial Imaging, Inc., Salt Lake City UT) was contracted to write programs (3D_PLPL and 3D_DPDP) for general, three-dimensional tomographic imaging of CR data. These FORTRAN codes uses file-based I/O but a simple slice-viewer was also included for model assessment. The program operates directly on the complex impedance and therefore will accurately model phases of arbitrary sign and magnitude. However, as a full 3D formulation it proved unwieldy when operating on simple linear surface surveys or on 2D cross-hole data. The problem dimensionality has a much greater effect on electrical imaging than seismic, because current paths are intrinsically three dimensional even in layered media, whereas seismic rays will effectively travel in planes if there is no heterogeneity in the third dimension. Therefore the 3D nature of current flow must be explicitly accounted for even if the geometry is 2D. This is commonly done with a fourier expansion of the third dimension which is much faster than computing the distribution of current and voltage explicitly. Furthermore, a large number of extaneous model blocks must be solved for even if the geometry is 2D and large smoothing is used to enforce a 2D picture in a 3D inversion. For the actual surveys produced during this project, a two-dimensional formulation was adequate and faster and the popular commercial program RES2DINV (Geotomo Software, Malaysia) was used. The full 3D code is outlined here and is described in detail, with source code, in Appendix 11.2 on the CD. The 2D program is also outlined and is provided on the CD; however, a license must be purchased for full functionality.

5.3.1. 3D-PLPL and 3D-DPDP

The two complex-resistivity tomography programs developed under this contract, 3D_PLPL and 3D_DPDP, solve the complex resistivity inversion problem using the nonlinear conjugate gradient method (NLCG). NLCG is described by *Rodi and Mackie* (1999). 3D_PLPL is specifically for the pole-pole array while 3d_DPDP can be used for any array which utilizes bipole receivers (e.g. pole-dipole, dipole-dipole, Wenner, Schlumberger, etc.). The reason for two programs is a significant difference in the details of calculating the Jacobian multiplied by a vector when the derivative operates on a nodal voltage (pole-pole) as opposed to the difference between two nodal voltages (bipole receiver arrays). Both programs permit the combination of surface and borehole electrodes.

Observations input by the user are the received voltage amplitudes (volts), and voltage phases (radians). The objective function is formulated in terms of the logarithm of amplitudes, and the phases, of these observations. The initial guess subsurface conductivities are user supplied in terms of the real and imaginary parts of conductivity. This may seem awkward and, if it becomes a problem, can be easily changed to something the user finds more natural. These inversion algorithms are formulated in terms of the logarithm of subsurface conductivity amplitude (S/m) and phases (radians). Any inconvenience caused by the format of the input pales when considered in the context of the problem being solved.

NLCG offers several advantages over Gauss-Newton (GN) schemes. Important among these are comparatively small storage requirements and the promise of faster execution time. Proper implementations of GN can be made quite stable but NLCG seems inherently so. Both methods start by defining exactly the same objective function, consequently no generality is lost in the ability to apply model constraints in NLCG. The problem with GN is the 3D solution generally requires prohibitive computer resources. The problem with NLCG is slow convergence. Various approaches exist to decrease the resources required for GN and to increase the convergence rate of NLCG. Key to the successful application of NLCG is the definition of an efficient preconditioner.

The preconditioner is an operator which, most importantly, alters the direction of the NLCG search vector to one similar to that obtained with GN. This new search direction should result in increased convergence, in fact convergence approaching quadratic, the same as GN. The quest for an efficient NLCG preconditioner is an active area of research in the inversion development community; the one implemented appears to be superior to the preconditioner described by *Shi* (1998) and *Rodi and Mackie* (1999). Their approach approximates the A^TA component of the preconditioner once at the start of the program and the same preconditioner is then used throughout. Here, the preconditioner similarly generates a value which should be quite a good approximation to the "size" of A^TA but is updated every iteration with virtually no penalty in computation speed or memory useage.

5.3.2. RES2DINV and RES3DINV

The commercial software RES2DINV was used to construct 2D resistivity and phase images from the field data acquired in this project (note that the Hill AFB data were procesed by Zonge Engineering using an in-house code similar to RES2DINV). Version 3.48d included several changes to the program made for this project, including fixing bugs related to cross-hole data and increasing the number of allowed a priori (semi-fixed) zones. The code alternates iterative solutions between the resistivity and phase. Although RES2DINV accepts either time-domain or frequency-domain inputs (chargeability or metal factor vs. percent frequency effect or phase angle, respectively), it was determined empirically that the program cannot model reversed-sense (positive) phases and therefore must internally convert all data to time-domain (causal) form. In contrast, true frequency-domain complex-resistivity codes (such as 3D_PLPL and 3D_DPDP described above) can handle arbitrary positive or negative phase. If all reversed-phase data are due to inductive coupling then they can be rejected and the normal-sense phase data properly inverted with RES2DINV. There are indicators in the lab, however, that reversed phases can occur as a result of clay cation exchange (Olhoeft, 1985).

A companion 3D program, RES3DINV was also acquired with the intent of comparing it to 3D_DPDP. As no data were processed in 3D, however, this has not yet been done.

6. Seismic

6.1. Instruments & Measurements

6.1.1. Sources

Seismic sources operated from ground surface can be as simple as a hammer-and-plate or as complex as large truck-mounted, swept-frequency vibrating platforms. Because much of the search for DNAPL is done with cone penetrometers (CPTs), this project sought to develop a seismic source that could be used in cross-hole surveys deployed by CPTs. From earlier conversations with the Sandia National Laboratories, a magnetostrictive source was identified as promising. During the development and testing of this source, two other sources were investigated.

6.1.1.1. Slide-Hammer Source. This simplest downhole source consists of a clamping shoe and a vertically sliding hammer. By quickly pulling up a cord attached to the hammer, an impulsive, vertically polarized shear wave (SV) is generated. As this is a human-powered source, it becomes more difficult to generate clean waves as the source is deeper and the cord is heavier and longer. Furthermore, the impacts generated are not very strong, so radiated waves can be detected to distances of only 10 m or so. Finally, a small-diameter device that could be accommodated within a CPT would generate even weaker waves. Investigation of hammer sources was subsequently abandoned.

6.1.1.2. Electric-Spark Source. An electric spark in can be generated in saline fluid; the expansion of a gas bubble and its subsequent collapse generates an impulsive P-wave. The method is used extensively in marine seismic exploration and has seen some success in fluid-filled boreholes. For the vadose zone, the fluid must be self contained and so the sparker is encased in a rubber bladder. We acquired such a device from the British Geological Survey and tested it at the SRS A&M Demo Area (see below). We found it very difficult to control and eventually the sparker exploded the bladder, ruining the source. We deemed this source too unreliable and abandoned further investigation.

6.1.1.3. Magnetostrictive Source. Magnetostrictive materials have the interesting property of converting changes in magnetic field into strain. A coil wound around a magnetostrictive rod can then be used to make the rod lengthen and contract at the same frequency as the driving signal. This potentially makes magnetostrictive materials useful as swept-frequency seismic sources. The Sandia National Laboratories previously developed a 4" diameter magnetostrictive seismic source and tested it at the SRS A&M Demo Area. They were subcontracted under this project to develop a source suitable for the CPT, i.e., with a diameter of << 2". Because the magnetostrictive rod is vertically oriented in the borehole, its radiated waveforms should be dominated by vertically polarized (SV) waves.

Preliminary tests of a small magnetostrictive actuator suitable for the CPT (ETREMA Products 110/12-MP) showed a peak force of 45 pounds at a frequency of 900 Hz, using about half the maximum possible activating electrical current. The natural resonance of this sample was strongly peaked (bandwidth ~200 Hz), but it was anticipated that by properly shaping the driving signal (with a near-null at this frequency) the radiated energy spectrum could be flattened. Subsequent bench tests produced approximately 190 pounds of force over the frequency interval 300-1600 Hz, better matched for broadband seismic exploration (Fig. 6.1). Scaling existing 4" magnetostrictive and pneumatic seismic sources to the smaller device indicates signal-to-noise ratios of 10-30 dB can be expected for common vadose-zone conditions like those at SRS.

The device is 8.5" long and 1.9" in diameter (Fig. 6.2). The relatively large diameter implied that a safe fit into CPT casings was not possible, and so a design was formulated to mount the source in the CPT tip. This turns out to be better for seismic coupling as the source will be in good contact with the formation. Applied Research Associates of South Royalton, Vermont, was contracted during the summer of 2000 to build the CPT housing for the magnetostrictive seismic source (Fig. 6.3) and the device was delivered in early November. The CPT housing features a sliding rear sleeve designed to allow the CPT operator to withdraw the push rods by a few inches, thus taking this weight off of the source and providing the necessary seismic decoupling.

Sandia bench- and field-tested the complete device. The field test was performed on 15 November with the PI and an assistant recording the ground signals with a standard seismograph and high-frequency geophones. The source was hand-augered and partially buried by Sandia personnel. Initial stepped-frequency tests showed a strong resonance at ~150 Hz, with overtones. This is likely a vibration mode of the instrument in its housing. Because higher-frequency, broadband signals are desired, the source sweep was reprogrammed to begin at 200 Hz and end at 1 kHz with an 8-second duration. The input spectrum, recorded as the pilot trace (Fig. 6.4) and the output spectrum, recorded 50 ft away (Fig. 6.5), demonstrate that most of the input energy is concentrated between 200 and 700 Hz and that the output energy lies mostly between 200 and 600 Hz. Therefore there is good broadband generation and transmission at frequencies of several hundred Hz. Significant energy is transmitted to the maximum end of the input band at 1 kHz.

Although the test showed that the source was basically working and that energy could be transmitted, the waveforms and spectra are not necessarily those that would be expected in an actual downhole application. This is because the instrument was not completely buried, as it would be in real application. P-waves so generated will travel faster and with less attenuation than the ground-coupled air wave that dominated these results. Due to time constraints a downhole test could not be scheduled and the system was deployed "full up" at the SRS A-014 site in early March, 2001 (see below).

6.1.2. Receivers

A fundamental distinction among seismic receivers is whether they record P-waves only or both P-and S-waves. Hydrophones, responding to variations in fluid pressure alone, are inexpensive to deploy but they record only P-waves in the saturated zone. Wall-clamping sensors are required in the vadose zone and with this effort it is straightforward to record three components of motion, thus enabling the separation of P- and S-waves. Geophones record seismic velocity and accelerometers record acceleration. Because acceleration is the time derivative of velocity, accelerometers typically show higher sensitivity but higher noise also. For this project, we purchased an accelerometer string (model XYZ-44/CG) manufactured by Vibrometric OY, Finland (Fig. 6.6). The unit contains eight 3-component clamping sondes at 2-m spacing. The lead-in cable is 200 m and the unit fits in well diameters from 2.5" to 6". The accelerometer bandwidth is approximately 20 Hz to 6000 Hz.

6.2. Tomography

In traveltime tomography, the total travel time is the integral of slowness (reciprocal of velocity) times the path increment. This is discretized into a sum of block slownesses times the path lengths in each block. The complete traveltime tomography problem may be expressed as **Gm** = **d**, where vector **d** is the travel time for a particular ray path, vector **m** is the slowness in individual blocks, and matrix **G** is the path length for ith ray in jth block. The tomography equation is usually solved iteratively. One iterative technique, back projection, is physically intuitive: the travel-time anomaly, or difference between observed travel time and the travel time of an initial (guessed or uniform) model, is distributed uniformly back along a ray. The changes to slowness in each model block are computed. The process is repeated for additional rays. One can then imagine that zones of low velocity (high slowness) will accumulate excess travel time, and conversely for zones of high velocity.

Three seismic-tomography programs were tested as part of this project. An early version by Jie Zhang was rewritten and incorporated into the PARALLAX joint-inversion software delivered as part of this project. Although PARALLAX has a full graphical user interface (GUI), its focus on joint inversion precluded incorporation of additional functionality found in commercial software (data and model viewing and editing, model analysis). Zhang's subsequent commercial (GeoTomo LLC, Houston TX) programs Tomo+ and Tomo3D were provided gratis to Blackhawk and were used for the Edwards AFB and SRS A-014 surveys. These programs have the additional functionality described above but we found that the inversion quality was sometimes difficult to control. The third program, GEOTOMCG (GeoTom LLC, Apple Valley MN) had broad functionality (including absorption as well as travel-time tomography), was simple to use, and was quite inexpensive. The final seismic results from SRS A-014 were prepared with this program.

7. Joint Seismic and Electrical-Resistivity Tomography

7.1 Principles

Geophysicists will commonly use more than one method to image the subsurface, as no single geophysical survey can respond optimally to all possible variations of subsurface properties. In a *cooperative interpretation*, the geophysicist lays the results of two or more surveys side-by-side and develops a qualitative model that incorporates all results. In a *cooperative inversion*, the quantitative results of one survey may be used to provide boundary conditions for the analysis of another kind of survey. Only in *joint inversion* is the process of developing an image from field data iteratively bound between different kinds of surveys: a partial result is used from the first survey as an initial condition for the second survey. The partial result from the second survey is then fed back to the first survey, etc., until a convergence criterion is reached.

Joint inversions in geophysics are limited by the ability to which subsurface properties can be mapped between different methods. Joint P- and S-wave seismic inversion is relatively straightforward because both of these observables can be related to fundamental elastic parameters. Joint gravity and seismic inversion has been possible on regional scales in the oceanic lithosphere, for example, where temperature variations can be identified as the root cause for changes in the geoid and seismic-wave speed. However, relations between other geophysical parameters are difficult to base directly in physics, especially in the shallow subsurface where heterogeneity is maximized and there are many possible causes. One way to approach joint inversion in this case is by *empirical mapping*, that is, a library of core samples or previous field results is used to catalog parameter variations.

7.2 PARALLAX Software

PARALLAX is a control center developed for this project that can direct forward and inverse modeling of multiple geophysical methods, either singly or jointly. It consists of a graphical user interface (GUI) and a set of programmatic interfaces to geophysical methods such as seismic refraction tomography and complex resistivity, the two methods which it is presently limited to. The term "method" is used to denote a geophysical modeling process such as those just listed.

The basic procedure is to use ground-truth data such as well logs to control the mapping between the two geophysical methods. The ground truth is used to train a neural network. Then, field data is gathered and imported in a form PARALLAX can read. Model grids of a desired density are created and initialized, and the joint inversion is run to produce model estimates. One method produces an estimate and the result is mapped to a starting model for the second method, whose output is in turn mapped back to input to the first method, iteratively.

Complete documentation for PARALLAX, including both a User's Guide and a Quick-Start Guide, is given in Appendix 11.1 on the CD. Here we show the principal features of the model in a synthetic example. A two-dimensional cross-section contains three geological units: a low-resistivity, low-velocity overburden, a low-resistivity, high-velocity bedrock, and a high-resistivity, high-velocity anomaly within the bedrock (perhaps representative of contamination). The seismic and resistivity cross sections produced by joint inversion are shown in Figures 7.1 and 7.2, respectively. Each unit is characterized by a mean and standard deviation in both velocity and resistivity and is constructed by random sampling. The joint inversion is constructed by from empirical correlations established from sparse random sampling of the velocity and resistivity of the study area, as might be expected from coring. These same a priori data can then be used to classify the geology based on the seismic and resistivity images (Fig. 7.3); in this synthetic example, the true geologic cross section is nearly perfectly recovered.

8. Test Sites

8.1 Investigation Protocol

From experience gained previously and through the course of this project, we developed the following investigation protocol using literature reviews of the contaminated site, studies of complex resistivity in the lab, and field tests:

(1) Review site history for kinds of contaminants, remediation history, geology, and hydrology. There are several gates that must be passed here for a successful survey. Although geophysical imaging is intended to provide cross-hole interpolation in the presence of complex geology, certain environments such as fractured bedrock may not be imaged at sufficient resolution to be useful. Sites that have undergone heavy remediation may have extensive infrastructure (metallic wells, pipes, conduits) that could interfere with geophysical surveys. The ability of clays to react may have been inhibited by some remediation techniques. Finally, the interest and support of site management must be gauged. If the site is deemed suitable, proceed to Step 2.

(2) Acquire uncontaminated soil samples from the site. Test response in the laboratory to principal contaminants. If possible, acquire and test naturally contaminated samples also. If soils are nonreactive to DNAPL then CR field studies must be abandoned unless putative thick, saturated source zones can be targeted. The signature of fresh contamination in the lab changes on time scales of hours to days (*Jones*, 1997; *Horton*, 2001); comparison with natural long-term exposure would be helpful. If DNAPL can be detected, proceed to Step 3.

(3) Perform reconnaissance surface complex-resistivity surveys at the site. These are usually inexpensive compared to installation and analysis for cross-hole tomography and therefore can be a cost-effective precursors. Either 2D or 3D imaging can be performed depending on available cost and coverage. Because surface electrode arrays must span distances several times the depth at which lateral variations are to be distinguished, however, the dimensions of the site and accessibility within the site are key constraints on the depth of investigation. Where DNAPL contamination is very shallow, surface surveys may be adequate; otherwise they must be viewed as precursors to cross-hole

surveys, which have higher resolution but more limited spatial coverage. Indeed, if DNAPL is expected to lie only at depth, surface surveys may not be able to detect it at all. Nonetheless, the goal of this step is to determine at minimum expense whether a field response from possible DNAPL can be detected based on laboratory signatures and what site issues will need to be addressed with regard to noise and interferences (especially from buried metallic utilities, pipes and debris).

(4) Perform cross-hole complex-resistivity surveys at the site. This is the culmination of the survey protocol. Useful 3D tomography can be performed only where vertical electrode arrays (VEAs) are densely installed; otherwise imaging must be restricted 2D panels between array pairs. Compare field signatures to expected DNAPL signatures from lab studies.

Twenty-nine sites were investigated for this project. Based on Step 1 of the protocol above, most of these were deemed not suitable due to anticipated difficult site conditions or inadequate management interest (Step 1). The complex-resistivity responses of suites of soil samples from seven sites (SRS A&M, SRS-A014, Tinker AFB, Hill AFB, Kennedy Space Center (KSC), Pinellas STAR Center, and Ft. Lewis) were measured under Step 2; Ft. Lewis alone was rejected for weak response to DNAPL (clean sand and gravel soils with a lack of clay minerals to react). Tinker AFB was subsequently abandoned as site support waned. Surface reconnaissance surveys (Step 3) were carried out at Hill and Pinellas. Hill was attempted in spite of extensive remediation infrastructure added since a prior CR survey (*Olhoeft and Wardwell*, 1998) because DNAPL had been well characterized there, but in fact subsurface imaging from the surface CR survey was very poor because of infrastructure interference. KSC and SRS A&M were rejected when re-examined under Step 1 and the Hill results. At Pinellas, natural organics had a strong CR response that obscured any potential DNAPL signature; these organics were not present in the initial suite of samples analyzed but were discovered in samples delivered after the field test. The SRS A-014 site had some infrastructure and was too small for a surface survey to sense throughout the vadose zone but, because lab tests were positive for DNAPL response and site support was strong, we proceeded to full cross-hole there surveys under Step 4.

In the following sections, more details are given for most of the sites examined; those not discussed are nonetheless listed in Table 8.1.1

8.2 Savannah River Site A&M Demo Area

The Savannah River Site (SRS) A&M Area Integrated Demonstration Site contains numerous experiments for DNAPL detection and remediation over known DNAPL leakage from a process line. Although the site is very cluttered, it is well characterized and was selected for our initial proof-of-concept test in 1998. This early demonstration did not include a field test of complex resistivity, but instead focused on laboratory analyses and joint seismic and electrical-resistivity tomography in the field. The latter is often called "DC resistivity" because it uses only a single low frequency and records amplitude only without regard to phase.

The nonlinear complex-resistivity (NLCR) signatures of 22 core samples from four wells near the SRS A&M area Demo site and settling basin were measured in their uncontaminated, as-delivered, state. From these, two samples were selected that had the largest available mass and were likely to have the extreme CR responses (the best and the worst) based on the presence of the swelling clay smectite, as previously determined by XRD. The smectite-rich sample showed a strong amplitude and phase signature of PCE (the dominant contaminant) at only *10 parts per billion* (Fig. 8.2.1). The entire analysis was repeated to check the validity of this result. The effect saturates by 1 part per million, i.e., all PCE concentrations above 1 ppm have approximately the same CR signature. This may be interpreted as the destruction of clay-solute cation exchange by the organic contaminant (though clay-organic reactions in general are not well understood, they are a hot topic of current study, *Yariv and Cross*, 2001, *Horton*, 2001). An electrochemical relaxation (recognizable as a peak in the phase spectrum and a sigmoidal or Z-shaped decrease in resistivity with frequency, centered on the phase peak) is present in the uncontaminated state that is damped by addition of PCE. The process may be analogous to polymers added in parts per million to adjust the viscosity of drilling muds; these polymers change the electrical size of the mud's clay particles. This CR response is the most sensitive indication of DNAPL ever observed by Co-I Olhoeft and was a principal encouragement in further investigations at SRS. In contrast, the smectite-poor sample showed no reactivity to PCE. These data are given in Appendix 11.3 on CD.

The joint seismic and electrical-resistivity field experiment at the SRS A&M Demo Area was performed on 5-10 October 1998. Two large-diameter wells, separated by 90 ft and previously used for crosshole seismic surveys, were to house the three-component locking geophone and sparker source. The source failed (see above) and so the seismic contingency plan was executed, which consisted of walkaway surface-to-hole hammer shooting to both wells and a standard surface-refraction line. Two VEAs, each with 20 electrodes at 4-ft spacing, were installed by the SCAPS cone-penetrometer truck. Due to surface obstructions (existing wells), the SCAPS could not optimally place the electrode arrays and these ended up only 25 ft apart and relatively near one of the seismic wells. The simple VEA design consisted of 4" long stainless-steel electrodes, each with a wire running to the surface and attached to an insulating stress cable. This configuration had performed well in the saturated zone where the formation collapsed around the VEA when the CPT rods were withdrawn. In the thick vadose zone at SRS, however, the formation did not collapse promptly and so good electrical contact may not have been established for all electrodes.

In spite of these partial equipment failures, we were able to produce a joint seismic and DC-resistivity image that is in good agreement with the cone-penetrometer logs, that is, a silty-clay layer in between more sandy units was readily identified (Fig. 8.2.2).

8.3 Denver Federal Center

Groundwater contamination at The Denver Federal Center originated from the seepage of storage tanks housing chemical by-products of asphalt production. Significant contaminants include DCE, TCA, and TCE. A reactive barrier composed of iron filings was installed to intercept and remediate DNAPL. Previous CR laboratory studies by Prof. Olhoeft and his students indicated that DNAPL was reactive at this site and could be identified and we attempted to establish a field test there because of the trivial mobilization. During the course of this project, however, groundwater sampling indicated that the contaminants had flowed around the reactive barrier and off-site; given the newly increased difficulty of location and access, plans for CR field tests were abandoned.

8.4 Edwards AFB

In May, 1999, we were contacted by Dr. Steven Gorelick of Stanford University to perform seismic surveys in order to determine variations in depth to weathered and unweathered bedrock at a contaminated site at Edwards Air Force Base, California. Dr. Gorelick was a SERDP-sponsored investigator studying DNAPL remediation. We recommended a three-dimensional refraction survey and contributed the costs of data analysis under this SERDP project. Dr. Gorelick also requested a seismic-reflection survey that was paid for separately.

The refraction survey comprised 86 shots (sources) with an average of 118 receivers per shot for a total of 10,190 raypaths. The shots were arranged in lines of 7 for convenience of preliminary 2D interpretation using the Generalized Reciprocal Method (GRM; the bedrock-relief map based on this method was delivered previously). Three-dimensional geometry was achieved by recording 5 parallel lines of receivers for each shot. The in-line and cross-line receiver spacings were approximately 20 ft and 40 ft, respectively. First arrivals were semi-automatically picked using Green Mountain software and data with obvious time or geometrical errors were deleted. The estimated first-arrival accuracy is approximately 1 ms.

Three-dimensional velocity tomography was performed using the Tomo3D software from GeoTomo LLC. Following data reformatting, a surface-topography file is generated, thus ensuring that ground relief is accounted for in the final solution. Ray tracing is performed using a fast graph-theory expansion. The least-squares inversion includes terms both for minimizing data misfit and model roughness; the trade-off between these two terms is controlled by a weight, or regularization parameter, for the second term called "tau." The data misfit is simply the RMS difference between predicted and observed travel times, whereas the model roughness is defined using Tikhonov regularization, i.e., the 3D integral of the square of the spatial curvature of model values (reciprocal velocity, or slowness). The Tikhonov regularization can be spatially anisotropic; a 5:1 horizontal:vertical smoothing ratio was adopted here. The starting model was taken from an approximate 1D refraction solution for the study area: a 30-ft thick overburden with velocity 2000 ft/s overlying bedrock with velocity 11000 ft/s. Solutions were tested as a function of the regularization parameter tau. The best solution is considered to be the one with the optimum trade-off between goodness of fit and model roughness.

The best solution at tau = 0.3 has an rms data misfit of 3.5 ms. Because the tomographic approach produces smooth velocity variations, there is no intrinsic definition of the bedrock interface. Instead, this contact was defined by the velocity isosurface showing minimum misfit with drilling results. Using the locations and bedrock elevations of 10 wells provided to us, the bedrock interface is best defined by a 5100 ft/s velocity, which results in a 4.7 ft RMS misfit with the well data. If the highest and lowest bedrock elevations in the well data are deleted (leaving 8), the same velocity isosurface is chosen but the RMS misfit is just 1.2 ft. As a whole, the western group of wells show bedrock elevations about 3 ft higher than the eastern group. The average elevation difference in the 3D seismic-refraction tomography between these locations is about 2 ft.

The most prominent feature on the interpreted bedrock-elevation map (Fig. 8.4.1) is a bedrock depression or channel that appears to be deepest near the location of the eastern group of wells. The channel continues to be well-defined to the north-northwest and northeast. This structure is robust in that it appeared in most of the trial tomographic solutions; although its absolute relief may be somewhat greater or lesser than depicted due to variations in model smoothing, its overall shape and position are considered to be reliable. The Edwards AFB data are given in Appendix 11.4 on CD.

8.5 Tinker AFB

The full project was approved by the SERDP SAB in the Fall of 1998 but funding was not received until several months later. In the spring and summer of 1999 we were investigating several potential sites for field tests. Blackhawk had previously performed seismic reflection and refraction surveys at Tinker AFB (Oklahoma City OK) to define lateral variations in shallow (30-50 ft) aquitards thought to control migration of DNAPL lost from a former fire-training area. There are some buried utilities, but the area is adjacent to a runway and largely open, so surface electrode arrays of tens to hundreds of feet dimension could be easily accomodated. Soil samples were reactive to TCE in laboratory complex resistivity and so the site was judged suitable for a field test. The initial response from site management was positive but this eroded over the course of the year while we were busy with other sites. In May 2000, follow-on work was abandoned, but this site could still be considered for future investigation. The Tinker AFB data are given in Appendix 11.5 on CD.

8.6 Kennedy Space Center

Extensive DNAPL contamination surrounds the support buildings at Launch Complex 34 at the Kennedy Space Center (KSC) due to the use of solvents for cleaning and preparing rocket components. DNAPL is present at depths of 20-45 ft and a major aquitard is present below 55 ft depth. Remediation demonstrations were being jointly investigated by DOE, Florida State University, and KSC. Soil samples provided by Laymon Gray (FSU) in July 1999 were reactive in laboratory complex resistivity. However, the site surface area available for surface field surveys was insufficient (less than 100 ft dimension). Furthermore, site management was planning an aggressive schedule for remediation demonstrations so that we did not have time to install and test VEAs. The KSC data are given in Appendix 11.6 on CD.

8.7 Pinellas STAR Center

Our work with the DNAPL Consortium at KSC led to the identification of the former DOE Pinellas plant, now called the Pinellas Science, Technology, and Research (STAR) Center, as a possible test site. The DOE Pinellas plant (Fig. 8.7.1) constructed neutron triggers for nuclear weapons from 1956 to 1994. The NE Site was used for disposal of construction and manufacturing waste. A groundwater pump-and-treat operation was begun in 1992 to remove chlorinated solvents and other contaminants. In the mid-90s, several experimental remediation techniques were tested under the Innovative Treatment Remediation Demonstration (ITRDE) program. In 1995, the site was partially excavated for buried drums and debris. A campaign for DNAPL source-zone identification and removal is now underway.

The Pinellas NE site is an open field, with a number of relatively widely spaced monitoring and remediation wells. There are also several utility corridors connecting the wells and the extent to which all previous debris was removed is uncertain (while on site, we were told there were still buried drums and other objects in our study area). Nonetheless, positive DNAPL responses were observed for samples of the confining clay unit (Figs. 8.7.2-8.7.3) received in

August 1999, which encouraged us to commit to a reconnaissance field survey. Of equal importance was good support from site personnel, which also resulted in shared costs between the DOE office managing the site (travel expenses and expendables) and SERDP (salaries for field and analysis work). Our principal contact for the site was Mr. Paul Darr, MACTEC-ERS, Grand Junction, Colorado. The on-site supervisor was Mr. Dave Ingle, DOE; other local contacts were Mr. Barry Rice for the remediation operations and Mr. Hal Koechlein for the geology.

We mobilized a three-man crew on 10/30/99 (we had aborted an earlier opportunity in October due to Hurricane Irene); from 11/1 to 11/ 4 we obtained nearly 300 individual complex-resistivity spectra in 11 experiments at 4 arrays (Figs. 8.7.4-8.7.6). Array 1 was set up in the middle of the field at the greatest possible distance from utility corridors connecting the remediation wells, in order to assess the ambient noise and background signals (standing surface water in the NW portion of the field precluded a background test in this open and apparently contamination-free area). TVOC near Array 1 was recently measured to be <150 ppb (H. Koechlein, pers. comm.)

Laboratory analyses shown in Figures 8.7.2 and 8.7.3 were from south side of Array 2 (SB-35); other samples analyzed were from south-central portion of Array 3 (SB-34) and from center of Array 1 (SB-103). TVOC near Array 1 was recently measured Non-Detect (< 150 ppb).

Quality-check plots generated in the field indicated that good data were being recorded. However, when the calibrated data were subsequently plotted, it became apparent that there was a ubiquitous, strong signal from an unknown source, present on most spectra (e.g., Fig. 8.7.7). This signal is characterized by a high, relatively constant phase (~100 mrad) and high resistivity distortion, often increasing with frequency. Because this effect is seen on most records, regardless of transmitter-receiver spacing or separation, it is likely from one or more shallow sources, probably at depths of no more than 10-20 ft.

These field spectra from Pinellas may be compared to library spectra compiled over time by Prof. Olhoeft. The best matches are to carbonaceous, shalely, silty-sand and to humic matter (Fig. 8.7.8). Evidently some other shallow organic matter is obscuring any potential DNAPL signal, although from the field test alone it is not evident whether that matter naturally occurs in the formation or is some remnant of the former disposal.

In order to test the natural-organics hypothesis, we had 19 samples from the two original soil borings (SB-34, SB-35) and a new boring near the center of Array 1 (SB-103) analyzed for humic acid by the Colorado State University Soil, Water, and Plant Testing Laboratory. One sample had a relatively large amount of humic acid, 7.3%, whereas the other 18 had significantly less humic acid (0.7±0.3%). Laboratory complex-resistivity analyses were also carried out for all of the samples in the new boring. The sample with anomalously high humic acid was from a depth of 16 ft in this new boring, and this sample alone also showed the same resistivity distortion and constant high phase characteristic of the field results and organic materials described above.

Given that only three borings have been analyzed both for humic acid and complex resistivity, we do not know whether the single well in which an obscuring non-NAPL response was observed is representative. At present we can only assume that we were simply unlucky that this organic material was not present in the samples from the original two borings. We hypothesize that elevated levels of decayed organic matter are irregularly distributed as lenses or shoestrings as part of the lagoonal and tidal-flat sedimentary facies associated with overall barrier-island and shoal complexes of the Florida coastline. While these organic concentrations may be irregularly encountered during drilling, the diffuse electrical currents injected by geophysical surveys encompass large volumes and are particularly sensitive to such anomalies. Had the organic response from SB-103 been available before the field test, we would have considered a different array design to focus energy more locally, or a crosshole test arranged to circumvent this material or, more likely, we would have elected not to attempt complex resistivity at this site.

In summary, complex-resistivity analyses of soil samples from the Pinellas NE site indicated that DNAPLs should be detectable as characteristic phase and distortion changes at frequencies below about 0.1 Hz. In the field, however, a strong, ubiquitous, background signature completely obscured any such potential DNAPL signal. In follow-up sampling and laboratory analyses, high levels of humic acid were found to be associated with this signature. We conclude that the signature is natural decayed organic matter associated with coastal sediments and that an irregular distribution of this material is sufficient to dominate a diffuse electrical survey. Other sites containing significant organic matter should be viewed with caution before attempting complex-resistivity surveys. All of the data collected at Pinellas and other supplementary information is given in Appendix 11.7 on CD.

8.8 Other Sites—Y2K

Delays in the second year of our funding interrupted work between December 1999 and March 2000, when the search for demonstration sites was renewed. Most of the sites listed—and rejected—in Table 8.1.1 were reviewed in the spring and summer of 2000. Note that field work at some sites was not carried out because of difficulties in obtaining samples or in dealing with site management; some of these could still be viable targets.

In April 2000 we reviewed information on two locations at Beale AFB (Marysville CA); jet-engine cleaning at the designated Site 10 near the airstrip was the most promising because of a low density of infrastructure, large available surface area, and shallow DNAPL contamination (25-40 ft depth). Regrettably, some site management functions were designated to a national lab whose personnel apparently had a conflict of interest with our investigation, i.e., they were pursuing similar methods and desired all the information about our experiment before we could execute it. When we demurred, they quit responding to our inquiries.

Discussions were begun and literature received from officials at Offutt AFB (Omaha NE) in June 2000. Very shallow (<20-ft depth) TCE contamination resulted from fire training and jet-engine testing. In spite of dense structures, profiles of several hundred feet over suspected source zones appeared viable. However, no samples were available from the site (apparently they were discarded) and no new samples would be provided by site management. They subsequently quit answering emails.

The Tucson Airport has long been a designated Superfund site but much work remains to be done. Several possible locations were identified with DNAPL contamination at depths up to 100 ft, which would require surface electrode arrays up to a few hundred feet dimension. However, there were no samples available for lab study and we would not be permitted to bore through the ramps at the most promising locations to make electrical contact with the ground.

A Remedial Investigation of a chemical waste-disposal area at North Island NAS (San Diego CA) was completed in June 2000 and reviewed by us. Several kinds of DNAPL, notably DCE, DCA, and VC are have been detected discharging into San Diego Bay above a confining unit

~85 ft depth. Additional potential difficulties associated with salt water caused us to reject this site: even larger surface arrays are necessary to achieve penetration into conductive media, which here would have required arrays many hundreds of feet across. Even where natural surfaces could have been accessed, lateral resolution would have been very poor.

An investigation into TCE contamination at the Tow Way Fuel Farm at Roosevelt Roads NAS (Ceiba PR) was completed in February 2000 and subsequently reviewed by us. Unconsolidated fill and marine deposits <10-20 ft thick overlie variably weathered and fractured gabbro. Depth to water is 8-25 ft and the water-bearing zone is only 3-20 ft thick. Due to mobilization costs, possible infrastructure, and complex geology we did not investigate this site further, but the shallow DNAPL and thin water-bearing zone should be considered positive features for possible future investigation.

Several other locations at SRS were considered from May-July 2000. The CMP Pits (chemicals, metals, and pesticides) were considered high priority during the summer of 2000 because the site was spacious (hundreds of feet wide) and had PCE within 50-ft depth. However, an accelerated remediation program there began installing infrastructure before we could perform laboratory experiments and mobilize. The C-BRP and 321-M areas had extensive infrastructure near the putative source zone. The A-014 Outfall was eventually selected for a full cross-hole survey (see below) but at the time was not considered highest priority because of the relatively small size of the site which would restrict the depth of investigation of surface surveys.

8.9 Ft. Lewis

TCE and other VOCs were released from the Ft. Lewis (Seattle WA) East Gate Disposal Yard. A very large groundwater plume formed (0.5 x 2 mi) but the source zones can be constrained to areas several hundred feet across. A glacial outwash gravel with variable thickness (avg. 13 ft) overlies a till that acts partly as a confining layer. Contamination is distributed from 10-40 ft depth. This site was considered to be highly favorable for a surface reconnaissance survey because the available infrastructure-free area is very large compared to the required exploration depth and the water table is very shallow (10 ft), which would improve electrical contact. Unfortunately, lab samples provided by site managers in September 2000 were only weakly reactive with TCE. We interpret this to be due to the lack of reactive clays minerals: the glacial till has been mechanically ground into clay-sized particles, but these lack the high surface area of true clay minerals. These data are given in Appendix 11.8 on CD.

8.9 Hill AFB

By Fall 2000 we had completed the Pinellas survey a year earlier but still had no follow-on site. Prof. Olhoeft suggested a return to Operable Unit 2 at Hill AFB (Ogden UT) where he had previously performed laboratory and limited field studies of the NLCR response to DNAPL (*Olhoeft and Wardwell*, 1998). Laboratory analyses from that study showed that PCE reacted with a bentonite containment wall but not with the native soils, whereas the opposite was found for TCE. A surface survey near the containment wall indeed detected the PCE signature. Note that these measurements were all performed on core "as received" with no added contaminant. While providing an important demonstration of the link between field and lab CR measurements, the signals were very robust because of the large amount of clay in the containment wall and because the wall had inadvertently been installed directly into a DNAPL pool. In spite of concerns about previous and ongoing heavy remediation and associated infrastructure, we decided to perform a broader surface survey.

The site that is presently Hill OU2, formerly contained trenches for chemical disposal, including solvents. The site is located on a small flat part of a steep escarpment to the Weber river valley. Groundwater in perched zones occurs as shallow as 10-ft depth. A clay unit defines a paleochannel at depths of 30-50 ft. DNAPL accumulated in the bottom of the paleochannel, approximately in the middle of OU2. We defined three survey lines approximately perpendicular to the trend of the channel. A dipole-dipole survey geometry was adopted with 20-ft dipoles and a maximum offset of 160 ft (n=6). With this geometry, a depth of investigation of 40-60 ft was expected.

A three-man crew consisting of the PI and two Zonge personnel surveyed these three lines at OU2 on 23-25 October 2000. Shallowly buried stainless-steel mats were used for the transmitters and copper/copper-sulfate electrodes were used for the receivers. As is evident from the complex-resistivity images processed by Zonge Engineering (Figs. 8.9.1 and 8.9.2), strong "cultural coupling" was observed on this site: the metal present in numerous pipelines, conduits, and foundations effectively short-circuited the currents from the source electrodes, preventing the establishment of relatively deep current paths. From the model results, we estimate that the depth of penetration was no more than 10-20 ft, a fraction of what was anticipated. Therefore neither DNAPL nor even the flow-controlling geology at depths >30 ft were detected.

We originally planned to perform back-to-back surveys using both the Zonge and CSM equipment in order to compare these systems, but latter was subsequently abandoned because of the poor results from this survey. The field data from the Hill AFB survey are given in Appendix 11.9 on CD.

8.11 Savannah River Site A-014 Outfall

8.11.1 Overview

The A-014 Outfall at the DOE Savannah River Site (SRS) was ultimately chosen for joint cross-well seismic and complex-resistivity imaging, based on literature review, interviews with site personnel, and site visits on 12 Jul 2000 and 2 Feb 2001. Key factors for the site selection were compact site geometry (characteristic depths to DNAPL and horizontal scales of several tens of feet), low organic content of the soil, a previous indication of a significant CR response at a nearby site, and strong management support. The remediation infrastructure on the site was still of some concern, but it was decided that the surface-based survey—a reconnaissance precursor in our formal DNAPL-investigation protocol—would be skipped due to likely cultural interference. However, the shallow network of pipes and cables was not expected to have a significant effect on the cross-hole data, as all the electrodes and most of the current paths would lie below the utilities and plumbing.

Some 1.4 million pounds of solvents were discharged at the A-014 Outfall of the Savannah River Site (SRS) during the period 1952-1979, after which discharge was stopped (*Jackson et al.*, 1999). The solvents were principally PCE but included some TCE and TCA. Discharge originally occurred from a process sewer directly to a small creek; part of the site was subsequently leveled for a road and a concrete pipe was added to carry the effluent a further 100 ft down the creek bed.

The depth to the water table at the A-014 Site is approximately 120 ft; our studies were restricted to the unsaturated zone to simplify the permitting process for drilling. A pump-and-treat system for remediation of the saturated zone has been in operation since 1985 and a soil-vapor extraction system was installed between 1987 and 1995. However, the locations of source zones in both the unsaturated and/or saturated zones are still unknown. Significant DNAPL contamination (several μg/g or ppm) in the saturated zone has been found above the principal confining zone for the area, the so-called "Green Clay" at elevation 200 ft msl (*Jackson et al.*, 1999; ground-surface elevation at A-014 is ~350 ft, so the corresponding depth to the top of the Green Clay is ~150 ft). This contamination is widely dispersed around and beyond the site, indicating extensive mobility due to groundwater flow. In the unsaturated zone, the Ribbon NAPL Sampler revealed contaminated horizons in well MVE-17 (Fig. 8.11.1) at depths of 11 ft and 22-24 ft (*Jackson et al.*, 1999). Remarkably, another boring within 1 ft of this well made two months earlier showed significant differences in DNAPL distribution: the relatively concentrated contamination near 11 ft was absent, but several hits were recorded between 14 and 20 ft. The zone at 22-24 ft was relatively unchanged. This is likely due to differences in pickup by the ribbon, perhaps at the pore scale: the sum of both holes should probably be considered the "true" distribution of DNAPL (D. Jackson and J. Rossabi, personal communications, 2001). An even more concentrated horizon of DNAPL at 20-22 ft was discovered adjacent to MVE-13, to the northwest of MVE-17 and toward the discharge point.

The Robertson Soil Classification from the cone-penetrometer (CPT) mechanical logs from the holes drilled for electrode installation (Fig. 8.11.2) indicates bedding that is nearly horizontal and laterally contiguous over the area of investigation (less than 100 ft square). Below the heterogeneity in the very near surface, an organic clay is found to a depth of about 20 ft. A 30-ft thick sand is present below, the most massive unit in the study area. A 15-ft thick zone of interbedded coarse- and fine-grained materials exists from 50 to 65 ft depth; there is a distinct thin sand within this unit near 58-ft depth. Another sand body is present from 65 to 80 ft. The underlying fine-grained unit is more laterally heterogeneous than overlying units and unique correlations between the borings cannot be made between 80 and 102 ft, the total depth (TD) of the holes.

This sequence is in good agreement with earlier observations, as expected for such a well-stratified site. The fine-grained units at 50-ft and 80-ft depths correspond to the "300-ft [msl] clay" and "270-ft clay" units described in *Eddy et al.* (1991) and *Jackson et al.* (1999). The latter is also known as the "Tan Clay." The near-surface clay likely corresponds to the "325-ft clay."

The soil-moisture logs showed that the 65-ft sand was the driest unit with 5-10% water and the 20-ft was somewhat wetter with 5-15% water. An infiltration profile was evident in the latter, with higher water contents at shallower depths. The clay units all had higher water contents: 15-20% for the shallow organic clay, 10-15% for the 50-ft clay, and 15-25% for the 80-ft clay.

The electrical resistivity logs from the CPT serve as a guide to expected signatures in the field. It should be noted that the CPT tool operates at 1 kHz whereas most useful CR data is acquired below 10 Hz. As expected, the clay-rich units are less resistive (200-1000 Ω-m) and the sand-rich units are more resistive (2000-5000 Ω-m). The resistivity transition between the shallow organic clay and the 20-ft sand was very gradational, probably due to downward percolation of water across that boundary. The sharpest electrical contrast occurred at both boundaries of the deep sand unit, 65 and 80 ft. The thin sand at ~60 ft was evident in the electrical log.

A suite of archived core samples from the A-014 Outfall was obtained from the Savannah River Technology Center (SRTC) in February, 2001 and analyzed under the SERDP Project. These results are discussed below.

While preparations were underway for the SRS A-014 surveys, we were contacted by Mr. Paul Wang, representing USDOE, to participate in a multi-institution test of CR imaging (also called electrical-impedance tomography or EIT and spectral induced polarization or SIP) for DNAPL at an unspecified site. It was agreed that these follow-on tests could be performed at SRS A-014 because of the strong leveraging with the SERDP project, including the costs of site characterization and electrode installation. Fresh core samples were provided by SRTC in June, 2001, now under the DOE project. These results are also below.

SERDP- and DOE-sponsored complex-resistivitity field surveys were performed on 8-10 March 2001 and 21-27 August 2001 by Zonge Engineering and CSM, respectively. Both surveys were done using vertical electrode arrays (VEAs) installed on 26-27 Feb 2001 (Figs. 8.11.3-8.11.6). Each array had 16 electrodes at 6-ft spacing; the uppermost electrode was placed at approximately 6 ft below ground surface (bgs), so each array spans the vertical interval 6-96 ft bgs. The number of arrays was chosen based on available time and cost for the demonstration.

A maximum horizontal separation of 30-35 ft ensures width-to-height aspect ratios of less than ½, which is commonly selected in electrical-resistivity tomography (ERT) cross-hole surveys. The holes were capped with a sprinkler vault to protect the electrode wires and backfilled with clean play sand.

Surface elevations at the locations of the VEAs differ by less than 15" (Table 8.11.1), a small fraction of the electrode spacing, so no elevation corrections were applied. The spatial pattern of the arrays was designed so that two of the nearest-neighbor panels or cross-sections were approximately perpendicular to the expected direction of contaminant transport (MES-1 to MES-3 and MES-3 to MES-2; see Fig. 8.11.1, Table 8.11.1). The fourth VEA (MES-4) was placed to form an equilateral triangle with two of the others (MES-1, MES-3).

The electrodes were constructed of fine meshes of MP35N, an alloy of 35% Ni, 35% Co, 20% Cr, and 10% Mo. This material was selected for its strong corrosion and cracking resistance to oxidation, sulfides, and salts: corrosion reactions are often observed in complex resistivity spectra near 1 Hz and could introduce artifacts to the desired DNAPL signal. MP35N is used extensively in oil and gas wells, marine saltwater systems, high tensile springs and cables, metal meshes for biofiltration, aerospace structural components, processing chemicals, reactor plants, and the medical industry. Ag-AgCl or Cu-CuCl based nonpolarizable or even elemental lead or platinum electrodes would be better choices for nonpolarizable voltage electrodes, but lead is an environmental contaminant, platinum is too expensive ($24,000 for these arrays), and the metal-metal-chloride combinations leak chlorides and become contaminated (and polarizable) over long deployments. After an extensive study in another project (*Oshetski*, 1999) requiring electrode empacements for up to 200 days, MP35N was found to be the most stable and reproducible, corrosion-resistant compromise. The double-layer capacitance between any metal electrode and water will appear as a polarization that will add a slight frequency dependent phase artifact in the data, but it will not add any nonlinearity until the MP35N corrodes. Nonetheless, the performance of MP35N as an electrode material for this project turned out to be controversial (see below).

8.11.2 Complex Resistivity

8.11.2.1 Laboratory CR. Core samples from MRS-14 (near the Outfall itself, just to the northwest of the study area) at depths of 20, 23, 26, 40, and 48 ft were provided by SRTC in February, 2001. These samples are almost exclusively in the upper sand body. The sampling had been done some time earlier and the stored core was very dry. At CSM, the samples were rehydrated by adding 10 wt% water and their NLCR spectra measured. Trace amounts of PCE (40-80 ppm; average 60 ppm) were then added and the NLCR response measured as a function of time. Most of the uncontaminated samples showed an electrochemical relaxation with a phase peak in the range 0.2-1 Hz that was not significantly affected by adding traces of PCE (Fig. 8.11.7), which could be explained if the relaxation is mechanical, i.e., due to pore size. Furthermore, the reproducibility of this result—in which a sample is mixed, measured, remixed (with PCE), and remeasured—demonstrates that the electromechanical properties of the sample are not changed by handling.

In contrast, the 23-ft sample did not show any relaxation mechanisms in the uncontaminated state, but PCE appeared to introduce a relaxation signature peaking at 0.1-0.2 Hz (Figs. 8.11.8-8.11.9). This suggests that this sample has more clay, enough to inhibit the mechanical relaxation but allowing reaction with PCE to introduce a chemical relaxation. The relative spectral closeness of these presumably different mechanisms could make interpretation of amplitude and phase spectra for PCE ambiguous.

Zonge Engineering also analyzed splits of the 23, 26, and 48-ft core samples in order for the effect of different acquisition systems to be assessed. The sample preparation differed slightly from that at CSM: 20% water and 10 μL of PCE were added to an 18 mL soil sample; this yields ~600 ppm TCE, about ten times that of CSM. However, the Zonge amplitude and phase spectra were generally flat below the resistive-to-capacitative transition at 1-100 Hz, with phases <10 mrad. There may be some weak indications of phase peaks at 0.1-1 Hz, but the flat amplitude spectrum indicates these are not relaxation processes. The 23-ft sample was unchanged by the addition of PCE, whereas resistivity amplitudes decreased by a factor of 2.5 for the 48-ft sample (the effect of contaminant was not tested on the 26-ft sample). This is opposite the CSM results, which showed little difference for all samples except 23 ft. The Zonge team did experiment with the effect of current density and found that nonlinearities began to appear around 2 mA/m^2. It has been noted elsewhere, however, that clay electrochemistry does not have a threshold as do better-studied redox signatures of say, pyrite, and so there may not be an absolute minimum at which nonlinear behavior can be observed. It was not clear from these experiments whether the differences between Zonge and CSM were due to the heterogeneity in the samples, acquisition system, sample preparation, or electrode configuration. THD was also measured but not assessed.

The complex resistivity response is an interfacial effect that occurs at the surfaces of materials. The first batch of samples from SRS had been dry for a long time. Because such drying can alter clay mineral surface properties, a second batch of samples, both larger and fresher than the first group, and preserved with natural water content intact were provided by SRTC in June, 2001, to CSM still sealed in their core barrels. The NLCR responses of these samples were measured by CSM fresh out of the core barrels. These samples focused on the fine-grained units and zones immediately above as likely sites of DNAPL accumulation. A variety of responses were observed (Fig. 8.11.10). The intervals 50-52 and 97-101 ft (Rows 2 and 7 in Fig. 8.11.10) are sandy and contain weak relaxation signatures peaking at 0.1-1 Hz in the uncontaminated samples. This is in good agreement with the previous results, even given that the earlier samples were old. Changes with the addition of PCE were small or erratic in the upper sand (again in reasonable agreement with previous work) but the phase at the lowest frequencies (1-5 mHz) increased dramatically for the lower sand. Amplitudes again did not change much except at the lowest frequencies, suggesting that PCE may have introduced a relaxation below the lowest frequency measured. Note that the increase in phase at the highest frequencies (> 100 Hz) is due to the transition between galvanic and displacement currents.

The sample from the shallow clay (17-21 ft; Row 1 in Fig. 8.11.10) contains a phase peak and amplitude transition near 1 Hz, again indicating a relaxation. With PCE added, the relaxation peak shifts to 0.1 Hz and also increases the phase in the mHz range.

The top of the sand-silt mix, including the thin sand (54-62 ft—the “300-ft clay”; Row 4 in Fig. 8.11.10), is of particular interest as a potential aquitard blocking DNAPL migration. A relaxation may exist at 2 Hz in the uncontaminated sample, but PCE clearly introduces another relaxation at 0.5 Hz. This results in a distinct decrease in phase from 0.5 to 2 Hz; behavior is more erratic at lower frequencies due to the varying positions of phase reversals.

The sand-silt at 52-54 ft and clay-silt mixes at 82-83 ft (Rows 3 and 6, respectively, in Fig. 8.11.10) show similar behavior, most curiously the expansion of a region of reversed phase in the former. Phase ratios between uncontaminated and contaminated samples vary strongly but increase smoothly with decreasing frequency in the deeper sample, because the phase reversal occurs at the same frequency.

In summary, the lab-measured CR response to materials from A-014 varies significantly with lithology in both the uncontaminated and PCE-contaminated states, and therefore there is no single indicator of DNAPL. In general, however, changes in phase are much larger than changes in amplitude and the most common effect is a progressive increase of phase with lower frequency starting below about 10 mHz (the major exception is the 54-62 ft interval, which shows the same phase trend but at ~0.1-1 Hz).

Indicators of PCE were also present in the THD and HD but these were modeled because there is no formalism at present for nonlinear inversion including clay responses. A qualitative discussion of the implications of THD and HD is given below.

8.11.2.2 Zonge CR Field Survey. Zonge Engineering performed a field survey at A-014, again so that we could compare their commercial CR acquisition system with the custom system of CSM. The acquisition pattern was a “skip-1” dipole: Electrodes 1 and 3 in Hole 1 transmit, then 2 and 4, then 3 and 5, etc. Voltage differences from the receiver electrodes in Hole 2 are calculated similarly. This forms dipoles twice as long as the physical spacing, which improves the signal-to-noise. Because the 2-element dipoles are advanced 1 dipole at a time, in principle the image recovered is the same as that in a non-skipping configuration, except the coverage is decreased slightly as there is one less station in both the transmitter and receiver holes. Continued signal-to-noise improvement can be obtained by increasing to a “skip-N” configuration, at the cost of decreased coverage by one electrode per N-value.

The first day’s effort used MES-1 and MES-3 as the transmitter and receiver, respectively. Due to the high resistivity of the borehole annuli, currents of only 3-10 mA were being injected into the ground, which is at the low end of performance for the Zonge system. Substantial SP drift with amplitude of order 100 mV was also observed. At the end of the first day, the boreholes were watered with 7 L each of 100 g/L saltwater solution; this resulted in an increase in current on the second day to 150 mA and a proportionate reduction in the relative SP amplitude. The panels MES-3-1, MES-3-2, MES-3-4, and MES-1-4 (where the first hole was the transmitter and the second the receiver) were subsequently acquired without incident. It was also noticed, however, that the electrodes were strongly polarizing; differences in current injected as a function of sign were as large as a factor of 2.

Data acquisition was slow, about 4 h per 15x15 nonreciprocal dipole panel. Given the resources budgeted, the lowest frequency sampled in the field was 1/64 Hz on three of the panels and 1/16 Hz on the fourth (MES-1-4). More critically, reciprocal data were not obtained. Reciprocity—in which transmitter and receiver dipoles are interchanged—is the most useful measure of electrical data quality. Without reciprocal data, alternative (albeit weaker) measures of data quality were assessed. The Zonge data files report a standard error of the mean resistance but provide no estimate of phase error. The upper and lower 5% (greater than approximately two standard deviations) of both the resistivities and phases were therefore rejected as outliers. Phases with reversed sign within 10 mrad of zero were set to zero; all other reversed-phase data were rejected. This eliminates inductively coupled data at higher frequencies but could also throw out some documented effects at lower frequencies (see *Olhoeft*, 1985, *Jonscher*, 1986). Finally, the data were sorted by transmitter-receiver offset, measured between either the uppermost or lowermost electrode in each dipole. The largest signals are obtained when the transmitter and receiver dipoles are at the same depth and, for the ~30-ft separations of these holes, voltage differences in a homogeneous medium are near zero at separations >25 ft. Therefore only dipole offsets (measured from top to top or bottom to bottom) within 24 ft were retained, and separate solutions performed for those at 0, 12, and 24 ft maximum offset. RES2DINV inversions were performed on resistance (voltage) rather than apparent resistivity, which increases numerical stability and further enforces the influence of nearby observations.

Well-to-well separations were 28, 32, 30, and 34 ft for MES-3-1, MES-3-2, MES-3-4, and MES-1-4, respectively. In order to maintain a regular grid, all panels were modeled as if they were 30 ft apart. The modeled phases are insensitive to the actual separation but the modeled resistivities should be multiplied by a factor of the well separation divided by 30 to approximate the true resistivity. This would result in a maximum difference of 20% (between MES-3-1 and MES-1-4), so this correction has been neglected.

Because of the relatively poor quality of the data, inversion (imaging) parameters were set for maximum smoothness in the result. The maximum damping factors for both resistivity and phase allowed by RES2DINV were used, and a horizontal:vertical smoothing of 4:1 (also the maximum allowed) was enforced. The convergence criterion was 5% change from the last iteration.

Several generalizations can be drawn from the summary of results (Table 8.11.2). For a given well pair and maximum offset, the number of data selected by the preprocessor begins to fall off above ~4 Hz. This is largely due to rejection of reversed (positive) phases, likely because of inductive coupling. The 0-ft maximum-offset images are the most stratified, as expected for so few data with little overlap in the current paths, yet often the errors vary strongly between frequencies. Both of these results indicate there is just not enough data. The 24-ft maximum-offset results begin to show large spatial variance and RMS error, probably because the data are noisy and therefore not self consistent. The 12-ft maximum-offset images (Fig. 8.11.11a-d) appear to be the best compromise between obtaining sufficient path overlap for 2D imaging and achieving moderate error reduction.

The lower sand from 65-80 ft was the most consistently imaged unit due to its high resistivity, followed by the upper sand from 20-50 ft. Both the shallow clay and the middle (50-65 ft or "350-ft") clay are evident from the contrasts with the adjacent sands. The thin sand near 60 ft was not resolved. In spite of the anisotropic smoothing, horizontal contrasts are evident. High phase magnitude is consistently observed at depths of 30-40 ft in MES-3-2; large phases are also seen erratically in other panels at various frequencies, also dominantly in the lower part of the upper sand.

The average resistivity of all panels over all frequencies was ~2400 Ω-m, in reasonable agreement with expectations from the CPT logs.

8.11.2.3 CSM CR Field Survey. At the SRS site, the first attempt was to measure with a dipole-dipole configuration, with the transmitting dipole in hole MES-3 and the receiver dipoles in the other VEAs. However, very small voltage readings indicated that nearly all of the current stayed in the highly conductive borehole annulus, which previous investigators had filled with salt water, and no significant voltage was seen in the other holes until the current was attached to the top and bottom electrodes, spanning the full length of the hole. As this geometry is not useful (a "skip-14" configuration!), another electrode geometry was adopted. This involved running the current between electrodes in two different holes and measuring the voltage response between all the other electrode pairs at common depths between the holes. As there were 16 electrodes in each hole arrray and 16 channels in the measurement system, this mated perfectly. The current was first put in the topmost electrodes with channel 0 monitoring the current by the voltage drop across a resistor in series with the electrodes. Channels 1 through 15 then measured the voltage response in the remaining electrodes. Then the current was moved down one electrode set and the voltage channel moved up into the previous place of the current, and the sequence repeated, cycling through frequencies from 200 Hz down to 2 mHz in a 10, 5, 2, 1 sequence at each location, until all combinations had been measured. Then the whole assembly was moved to another pair of holes. In the CSM use of the four VES arrays, only one bad electrode was encountered (electrode 9 in MES-4 had an intermittant connection). No water or salt were added to the holes as changing water contents and chemistries can alter clay properties, necessitating long re-equilibration times (days). A significant problem at the site during these measurements in August was the fluctuation in the water flow in the outflow caused by the failure and repair of an upstream pump in a remediation facility. This caused a large, slow drift in the SP from streaming potential changes as the outfall flow rates changed by up to 400 gpm. Because of this, we did not record the SP values, and this slowed data acquisition as we were sometimes required to repeat measurements when excessive SP drift caused amplifier clipping.

The CSM acquisition program provides estimates of resistance and phase errors expressed as a percentage and as mrad, respectively. The latter can be converted to a fractional error by dividing by the absolute phase. Because small phases cause high fractional errors, phase cutoffs of 1 and 10 mrad were applied, yielding mean absolute phases of 160 and 130 mrad, respectively, over all panels and frequencies. The corresponding mean phase errors are 37% and 58%, respectively (see Table 3). In contrast, the mean resistivity error was just 0.2%.

Reciprocals provide stronger constraints on data consistency, by computing the relative difference in amplitude and phase between two reciprocal measurements. Considering the normal (negative) phase data only, the 50th percentiles (half of the measurements being better than the stated reciprocity error) for MES-3-1 and MES-3-2 are 5% and 10% at 5 mHz, respectively, but for MES-3-4 and MES-1-4 they are 100% and 500%, respectively (Fig. 8.11.12). The quality of data from the last two wells is significantly poorer than for the first two. All reciprocals improve at 100 mHz but these relative differences persist. The median (over all panels and frequencies) 50th percentile is about 10%. The phases are much worse: the 50th percentiles for MES-3-1 and MES-3-2 are 500 and 1000 mrad, respectively at 5 mHz and lie beyond 1000 mrad for MES-3-4 and MES-1-4. The median 50th percentile over all panels and frequencies also exceeds 1000 mrad. As reciprocals are a measure not only of noise but of system linearity, the poor quality of reciprocals compared to the error on each individual measurement suggests a nonlinear response, which could strongly impact results (see below).

Many different data-processing schemes were attempted in order to select the greatest quantity of high-quality linear data: both of these criteria are necessary to produce good images but they can be mutually exclusive, so selection of an "optimum" trade-off was required. The criteria included:

(1) Selection of the same reciprocal-difference cutoff in both amplitude and phase (10%, 20%, 50%, 100%, 200%...)

(2) Selection of independent reciprocal-difference cutoffs for amplitude and phase.

(3) Selection of amplitude cutoff only (approximately equivalent to a single impedance cutoff when phases are small)

(4) Select amplitude cutoff, compute resistivity section, use as a priori background for different phase data selected from phase cutoff.

The best overall results were obtained using method (2) above, with a maximum difference in reciprocal amplitudes of 30% and a maximum difference in reciprocal phases of 300%. Before selection based on reciprocity, inductively coupled data were eliminated as was done for the Zonge data, by rejecting all positive phases greater than 10 mrad. Furthermore, data with negative-phase magnitude >1000 mrad or amplitude >75 Ω were not used. All parameters for RES2DINV were the same as for the Zonge survey. Table 3 summarizes the results. As mentioned above, linear complex resistivity inversions cannot process the nonlinear indicators THD and HD.

The resistivity images (Figs. 8.11.13a-e) derived from the CSM survey are generally qualitatively similar to those of the Zonge survey; specifically, high-resistivity zones from 20-50 ft and 65-80 ft separated by low-resistivity regions from 0-20 ft and 50-65 ft correspond well to the major sand and clay units, respectively. The cross-hole dipole configuration of the CSM survey tends to laterally stretch anomalies more than the in-hole dipole configuration of the Zonge survey, but again horizontal differences are still apparent. In contrast to the Zonge survey, the highest modeled phases from the CSM survey are in the shallow clay in CSM-3-4 and CSM-1-4, and not in the underlying sand.

There was a quantitative difference in resistivity magnitude: the average value over all panels and frequencies of the CSM survey was 1300 Ω-m, about half of that observed five months earlier in the Zonge survey. The average phase in the CSM survey was also significantly higher than in the Zonge survey. Both of these observations can be explained by increased soil moisture during the CSM survey. Historical rainfall in nearby Augusta GA in the 3-month period preceeding each of the surveys are nearly identical, as was the actual rainfall in the month before. However, actual rainfall on the site was likely different due to the strong spatial variability of summer thunderstorms.

8.11.2.4 Interpretation. As described above, the most common effect of PCE on the SRS A-014 samples as measured in the lab is an increase in phase magnitude at frequencies <10 mHz. In order to quantify this effect in the 2D images from the field surveys, a "Target Index" was constructed (Fig. 8.11.14a-e) as follows:

(1) compute the phase ratio between a test frequency (e.g., 5 mHz) and a reference frequency (e.g., 100 mHz) for all panels of interest—this is similar to a Percent Frequency Effect or PFE commonly used in IP studies.

(2) if the phase at the reference frequency does not exceed the global error for that panel, set the phase ratio to zero.

(3) if phase ratios are greater than a specified cutoff value, reset to the cutoff.

(4) if phases at the test frequency are greater than a specified cutoff value, reset to the cutoff.

(5) compute the mean and standard deviation of the test phase and phase ratio over all panels.

(6) iterate (3)-(5) until the standard deviation is approximately equal to the mean

(7) normalize phases ratios to the mean value observed over all panels

(9) normalize all phases to the mean phase observed over all panels

(9) sum the normalized phase and phase ratio.

(10) divide by the combined error in both the test and reference phases (computed from the sum of variances), normalized to the smallest value.

This algorithm gives approximately equal weight to high phase at the test frequency and high phase ratio between the test and reference frequencies. The selected cutoffs were 5-10 for the phase ratio and ~100 mrad for the test phase. Poorer-quality inversions will reduce the Target Index and higher phase and phase ratio will increase it.

The Target Index for the lowest test frequencies in the Zonge survey shows two large-amplitude, consistent anomalies. One lies in Panel 3-2, stretching from ~45 ft depth near MES-3 to ~30 ft depth at MES-2. The other is in Panel 3-4 at a depth of ~40 ft near MES-3. A very near-surface (<10 ft) anomaly persists in all images of Panel 3-1, but as this is near the edge of coverage it is likely an artifact. A deep anomaly (75 ft) is also evident in the results for Panel 1-4 but is not confirmed at a the lowest test frequency. Another shallow anomaly near MES-4 may also be a coverage artifact. For the ¼ Hz to 4 Hz comparison in the Zonge data, compact anomalies are evident at 40-ft depth in Panel 3-2 and at 55-ft depth in Panel 1-4; correlation is weak between these results and those at lower frequency. A laterally distributed anomaly at depth <10 ft in Panel 3-4 is possibly an edge artifact.

The Target Index for the CSM survey also reveals two large-amplitude, consistent anomalies. Most of the upper clay (<20 ft) in Panel 3-4 is anomalous; the resolution is poor because the upper part of the image is constructed with the single reciprocal pair of cross-hole dipoles at 12 ft and 36 ft. This is of course also cause for great scepticism in interpretation. Panel 3-1 shows a strong, compact anomaly near 50-ft depth close to MES-3; the number of data and coverage are significantly better here. Anomalies in Panel 3-2 are not as consistent but appear from 10-50 ft depths. The general trend is deeper near MES-3 (matching the edge of Panel 3-1) and shallower near MES-2.

Several zones can be identified that show higher indications of PCE, but none has reasonable confidence (Fig. 8.11.15). The large anomaly in the upper sand in Panel 3-2 is striking; however, the apparent transport direction (slope) of DNAPL is opposite expectation, as the anomaly is deeper closer to the source. Although this could be explained by *ad hoc* multiple flowpaths, it could also be an artifact of the coupling or performance of specific electrodes or of local nonlinearity. Nonetheless, this anomaly is the most consistent mapped, not only internally among the Zonge and CSM surveys but between them as well. Anomalies in the bottom of the upper sand are consistent around MES-3 but this could just be a further manifestation of electrode effects. The anomaly in the near-surface clay in Panel 3-4 is a good match to the observed shallow DNAPL at well MVE-17 but, as discussed above, this anomaly is very uncertain due to lack of data.

Six cores to be obtained under DOE sponsorship in late fall, 2001, will test the predictions of this study and those of other investigators at SRS-A014.

8.11.2.5. Conclusions from SRS-A014. Several problems can be identified in these experiments that contributed to apparent poor data quality, and hence poor linearized imaging and poor interpretability.

(1) The play-sand backfill was very resistive, then very conductive when filled with salt water. Electrode coupling may have varied significantly. We recommend that vadose-zone VEAs simply be grouted in the future and that inversion codes account for any annulus of differing conductivity. Grout provides a more stable environment for EIT and does not introduce additional vertical migration pathways. Concrete grout will require a three-month cure before complex resistivity measurements may be made. Bentonite grout may not be used as it will introduce a new strong CR clay mineral signature right at the hole. Cab-O-Sil, a fumed silica food additive that behaves mechanically like bentonite but is nonreactive and cures quickly, should also be explored as a grout material.

(2) In spite of modifications to the acquisition program that allowed frequencies as low as 1 mHz, the measurements using the Zonge system were not extended to sufficiently low frequencies at which the lab data indicate the largest and most consistent changes due to PCE. This was done to save time and money but then possibly failed to provide critical data.

(3) Reciprocals were not acquired in the Zonge survey, another time-and-money shortcut that severely hampered our ability to assess data quality.

(4) Data-quality indicators suggest that a significant nonlinearities were present, which cannot be modeled with existing software. This conclusion follows from a comparison of the error estimates on both individual phases and on reciprocals from the CSM survey. The phase errors are modest (relative errors of tens of percent) but the reciprocal errors are much larger (relative errors of hundreds of percent). As reciprocity is a property of a linear system, we interpret this difference as an indication of system nonlinearity. Electrode memory can be ruled out because the measurements are made from high to low frequencies in order to depolarize the electrodes.

The issue of nonlinearity is most serious in the linearized interpretation done here. The first consideration is whether the nonlinearity arises from the MP35N electrodes or from the formation itself. Electrode nonlinearity is manifested solely as THD whereas clay cation exchange displays both THD and HD. The THD will affect the fitting used to determine the individual phases and so THD influences the phase error. As discussed above, the individual phase errors cannot be considered outstanding but they are far smaller than the reciprocal errors, so the effect of THD and hence electrode nonlinearity must be modest. This is in good agreement with our expectations of the strong corrosion resistance MP35N, because electrode nonlinearity is caused by corrosion. This does not rule out linear polarization (capacitance) effects in the electrodes, which were evident in field during the Zonge survey. Conversely, the large HD observed at SRS A-014 indicates that clay cation exchange is the major source of the nonlinearity.

Using the experimental geometries and source strengths from the Zonge and CSM surveys, current densities in a uniform 1800 Ω-m halfspace are predicted to lie in the range of $\mu A/m^2$ to mA/m^2 (Fig. 8.11.16). This is well below thresholds observed for breakdown nonlinearity in metal electrodes (due to electrolysis of water) or even in pyrite. However, clay cation exchange has not been studied sufficiently to understand the relevant mechanisms, and laboratory data have shown nonlinearity in this range without any apparent threshold (*Olhoeft*, 1979b).

Why has nonlinearity not been considered a major issue previously? First, most shallow-investigation work has been ERT and nonlinearity is much less evident in resistivity than in phase. The popular use of time differences to track fluid flow will further damp the influence of any geological variations. Second, nonlinearity is rare in classical IP for ore detection because sulfides such as pyrite have nonlinear thresholds of order 1 A/m^2, much higher than the ~10 $\mu A/m^2$ levels common in deep exploration. Third, nonlinearity decreases with increasing frequency; in clay analogs, nonlinearity was strong well below 1 Hz but was essentially linear above 10 Hz (*Olhoeft*, 1979b). As most surveys are performed near 1 Hz, nonlinearity could be modest. However, this is not in the range of maximum sensitivity to clay-organic reactions, so either lower sensitivity must be accepted or nonlinear imaging methods developed. This in turn will require a detailed model for the relationship between current and electric field for the materials of interest.

The project also raised several questions that remain unanswered:

(1) How do we translate lab measurements into field tests? That a field response can be predicted from the lab has been one of our central tenets. Yet the lab response of newly contaminated samples was observed to change significantly on time scales of days to months (*Jones*, 1997; *Horton*, 2001)—how long must the sample be allowed to react with PCE before a steady state is reached? What is the effect of changing moisture content over time? What are the relative roles of mechanical vs. chemical mechanisms for relaxation processes? Can nonlinearity be modeled?

(2) Why did the Zonge lab results differ so much from those of CSM?

(3) Why don't the images inverted from the Zonge data show a conductive annulus problem? (in addition to the reasons noted above, is this an imaging resolution issue?) Indeed, why could the Zonge system acquire data at all in an in-hole dipole configuration in the presence of the conductive annuli when CSM could not? It is however, difficult to compare measurements performed in March and August with such a large time separation.

As mentioned above, additional studies including other investigators were funded by DOE to follow up our SERDP funded work at SRS-A014. The key points identified by this group (including ourselves) were:

(1) Electrodes. What is the best material for subsurface electrodes? The strong polarization or capacitance of the MP35N electrodes was noted by most investigators; the other two groups specifically recommended not using this material again. Yet we did not view this as a limiting factor. Any replacement nonpolarizing electrode must not leak fluid and must be corrosion-resistant so that it can be used in long-term monitoring.

(2) VEA completion. What is the best way to install the electrode arrays in the vadose zone? Completion with sand leads to an annulus that is either too resistive or too conductive. Repacking with native soil would ensure an overall impedance match but likely could not be tremmied uniformly back into the borehole. Cement or grout is difficult to impedance

match but otherwise could also lead to annulus problems. As phase is sensitive to different kinds of chemical reactions, care must be taken that fill materials are nonreactive when cured and that sufficient time (months?) be allowed for curing between installation and use of VEAs.

(3) Role of laboratory data. How reliable are the laboratory data as a guide to expected field response? Changes in response are observed on time scales of hours or days in the lab (*Jones*, 1997; *Horton*, 2001); what is the response in the field after years or decades? Can changing moisture levels be isolated as changes in phase magnitude alone without a change in the position of phase peaks or trends? Is the effect of lab disturbance to the original pore geometry minimal, as suggested by the CSM results? Can mechanical versus chemical signatures (differing relaxation processes) be separated—for example, do the broad regions of high phase observed by other investigators simply represent mechanical (pore-geometry) responses of the uncontaminated sand units, as suggested by the lab data?

(4) Optimum frequency band. What is the time (and cost) required to get data most indicative of DNAPL. The lab tests indicated that the strongest changes to PCE occurred at < 10 mHz, i.e., at periods greater than one minute. Acquisition time increases sharply at such low frequencies, especially if multiple periods are transmitted to improve signal-to-noise ratios. Is this essential to identifying DNAPL, or can "standard" frequencies closer to 1 Hz be substituted to improve field efficiency? Or, given the importance of DNAPL detection, must long field tests be accepted?

(5) Nonlinearity. How important is nonlinearity, especially at the low frequencies of optimal DNAPL signature, and how is this partitioned between the electrodes and the ground? Comparison of the individual errors and reciprocals in the CSM data suggest that geological nonlinearity was largely responsible for poor (in a linear sense) data quality, but comparison of responses of copper/copper-sulfate and MP35N responses by another group suggests that electrode effects were dominant. How can the present linear modeling and inversion algorithms be modified to take account of nonlinearity and possibly exploit the added information content therein?

(6) Surface surveys. EIT surveys from the surface provide an inexpensive reconnaissance tool for future detailed investigation, such as VEA installation. Given the small size of

the site and the presence of remediation infrastructure, however, we elected to forego a surface survey. How useful is this approach given reduced depth of investigation and resolution compared to crosshole EIT? How strongly is the data affected by shallow site infrastructure?

These surveys have laid the foundation for future work, perhaps building on our existing knowledge to examine the SRS A-014 Outfall in greater detail. The role of nonlinearity in particular must be better assessed. In these experiments, a few misjudgements in planning and execution, together with possible nonlinearity, resulted in data that is difficult to interpret with normal assumptions and currently available linear complex resistivity commercial hardware and software. If future surveys comparing measurement systems are to be attempted, they must be planned to have the measurements be acquired closer together in time (in this case, surveys were spread out from March through August by a combination of delays while grout in the seismic holes near the VES arrays cured and funding was transferred). All of the complex-resistivity data for SRS A-014 are in Appendix 11.10 on CD.

Table 8.11.1. Borings and Wells for Complex-Resistivity / Seismic-Tomography Experiments

ID	SRS Northing, ft	SRS Easting, ft	Elevation msl, ft
Electrical			
MES-1	101983.9	50052.9	346.8
MES-2	101932.8	50034.7	347.8
MES-3	101964.5	50032.7	346.6
MES-4	101991	50019.6	347.8
Seismic			
MSB-31CC	101983.1	50067.9	346.4
MSS-1	101967	50033	346.6
MSS-2	101932	50031	347.6

Table 8.11.2. Summary of Complex Resistivity Inversions for Zonge Experiment

Well Pair and Max Offset	Frequency, Hz	Number of Data Selected	Number of Iterations	RMS Resistivity Error, %	RMS Phase Error, mrad
MES-3-1					
0 ft	1/64	12	6	1.9	0.8
	1/16	12	7	2.0	0.3
	1/4	12	5	2.5	0.7
	1	13	6	1.8	13
	4	13	5	10	7.
	16	9	6	5	1.9
	48	10	10	0.2	28.
12 ft	1/64	49	5	6.8	1.9
	1/16	49	5	6.8	1.9
	1/4	51	5	5.7	1.2
	1	50	5	4.1	7.7
	4	56	4	7.9	8.1
	16	39	7	3.3	6.6
	48	39	7	2.0	12.3
24 ft	1/64	69	4	28	4.1
	1/16	72	3	35	4.9
	1/4	74	5	25	2.2
	1	74	3	33	9.2
	4	85	4	30	11.
	16	59	3	37	18.
	48	60	5	28	83
MES-3-2					
0 ft	1/64	12	9	0.7	0.4
	1/16	13	10	0.14	0.6
	1/4	12	9	0.71	0.2
	1	14	10	0.03	3.4
	4	10	4	16.	3.6
	16	8	2	30.	13.
	48	8	2	21.	79.
12 ft	1/64	49	5	6.9	5.4
	1/16	54	5	6.6	6.6
	1/4	51	4	7.0	4.8
	1	59	5	7.0	7.0
	4	43	8	1.0	1.6
	16	33	10	0.4	3.2
	48	37	6	2.5	118.
24 ft	1/64	70	6	17.	7.2
	1/16	77	6	16.	11.
	1/4	71	6	16.	5.0

	1	82	4	23.	8.5
	4	60	5	16.	2.4
	16	47	7	13.	9.6
	48	52	7	15.	89.
MES-3-4					
0 ft	1/64	12	10	0.03	10.7
	1/16	12	6	0.07	2.3
	1/4	14	6	3.1	0.42
	1	14	6	0.13	1.7
	4	12	3	16.	3.6
	16	6	6	0.83	14.6
	48	5	2	46.	110.
12 ft	1/64	47	6	7.8	6.4
	1/16	52	5	8.9	2.7
	1/4	57	6	8.2	2.0
	1	59	6	6.6	2.1
	4	50	6	6.8	3.0
	16	50	5	9.0	1.2
	48	46	5	6.1	14.8
24 ft	1/64	64	6	16.	5.9
	1/16	73	4	33.	3.7
	1/4	79	6	23.	2.2
	1	85	5	23.	2.1
	4	67	5	17.	2.7
	16	32	7	13.	2.7
	48	35	5	24.	26.
MES-1-4					
0 ft	1/16	14	5	1.3	0.7
	1/4	14	5	1.3	0.8
	1	14	5	1.3	1.1
	4	14	5	1.3	3.4
	16	9	2	44.	8.1
	48	4	2	21.	2.9
12 ft	1/16	56	8	3.9	1.8
	1/4	59	6	7.0	1.7
	1	58	8	4.8	1.4
	4	57	8	5.1	3.2
	16	37	4	7.0	2.1
	48	46	6	10.8	3.1
24 ft	1/16	77	5	23.	2.2
	1/4	82	5	20.	2.3
	1	81	3	28.	1.9
	4	78	4	25.	21.
	16	48	5	14.	2.5
	48	36	4	22.	2.3

Table 8.11.3. Summary of Complex Resistivity Inversions for CSM Experiment

Well Pair and Max Offset	Frequency, mHz	All Data Resistance Error %	All Data > 1 mrad Phase Error %	All Data > 10 mrad Phase Error %	Number of Data Selected	Number of Iterations	RMS Resistivity Error, %	RMS Phase Error, mrad
MES-3-1								
	2	0.5	60	37	24	5	16.	55.
	5	0.3	70	60	35	6	12.	21.
	10	0.3	57	30	34	10	1.5	38.
	50	0.4	99	91	48	8	2.7	8.8
	100	0.3	55	35	49	9	3.1	41.
MES-3-2								
	2	0.1	31	11	22	4	1.7	54.
	5	0.1	22	15	31	3	19.	23.
	10	0.1	34	22	36	4	5.9	15.
	50	0.1	31	17	42	7	4.8	18.
	100	0.1	31	18	45	6	5.1	5.6
MES-3-4								
	2	0.1	43	28	5	4	18.	49.
	5	0.2	34	18	6	8	0.2	43.
	10	0.2	36	23	11	3	19.	30.
	50	0.4	32	23	25	4	3.6	16.
	100	0.4	107	34	29	4	7.4	16.
MES-1-4								
	2	0.3	71	53	4	5	17.	1.4
	5	0.3	93	42	6	10	0.05	105.
	10	0.3	61	42	12	4	18.	211.
	50	0.2	80	65	20	4	13.	17.
	100	0.2	113	75	16	6	4.2	5.7

8.11.3 Seismic Surveys

Seismic surveys were performed from two temporary borings to a permanent well on 28 Feb to 2 Mar 2001. The seismic source was developed specifically for the SERDP project and consists of a magnetostrictive vibrator in a CPT housing: an initial (dummy) push creates a pilot hole and then the seismic source, slightly wider than the pilot hole, can be snugly inserted to sequentially greater depths. Two 2D panels were surveyed (Fig. 8.11.1); each used the permanent well MSB-31CC for the receivers with source locations at MSS-1 and MSS-2, respectively. Panel 1 (MSS-1 to MSB-31CC) was 38 ft across and Panel 2 (MSS-2 to MSB-31CC) was 62 ft across. The full span of sources and receivers was measured for each panel between 6-ft and 96-ft depth at 6-ft intervals. In practice the source was sequentially pushed to stations at greater depths; at each source station two setups of the 8-sonde receiver string were required to cover the entire borehole. Also, data with the source shallower than 12 ft were not useable to to poor coupling in the fill material. Before acquisition of "production" data, the Sandia field crew attempted to shape a flat spectrum by piecewise inversion of the signal recorded by an accelerometer adjacent to the source within the CPT housing; a flat source spectrum is desirable to produce the sharpest, most impulsive arrivals after deconvolution in order to measure travel times accurately. The swept-frequency (chirp) signal went from 50 Hz to 1 kHz in 8 s, with variable amplitude reflecting the spectral flattening. In addition to the chirp signals transmitted for traveltime tomography, 8-s monofrequency signals at 200 and 600 Hz were transmitted for absorption (attenuation) tomography.

8.11.3.1 Traveltime Tomography. The seismic data were processed using a simple procedure:

1. Truncate first 300 msec of pilot trace (dead time)
2. Bandpass filter pilot trace (Butterworth filter low-cut: 50Hz (36 dB taper) and hi-cut 1000 Hz (72 dB taper)
3. AGC pilot trace (sliding window, 200 msec)
4. Cross-correlate data with pilot trace.
5. Bandpass data.
6. Pick first arrivals.

In contrast to our wishes, the transmitted energy spectrum was not flat but contained several large peaks at 250, 830, and 1600 Hz; the lowest frequency resonance was the largest.

Final tomograms were produced using GEOTOMCG although some preliminary work was done using TOMO+. A 6-ft grid spacing was used; to accommodate a regular grid, Panel 1 was modeled as being 36 ft wide and Panel 2 as 60 ft wide. The relative velocity distortions, which were not corrected, are 6% and 3%, respectively.

Two-dimensional traveltime tomography on Panel 1 using all the picked data (Fig. 8.11.17) shows an unusual number of rays apparently traveling steeply upwards from source to receiver (left to right in the figure), resulting in a general streaking of velocity patterns along the rays and a concentration of high velocity near the shallow receivers. Examination of the average velocity as a function of takeoff angle (Fig. 8.11.18) reveals this pattern to be an artifact: minimum average velocities are nearly constant for takeoff angles greater than about –20°, where takeoff angle is measured from the horizontal between source and receiver and a positive angle is down from the source to receiver. These takeoff angles correspond to configurations where the receiver is 12 ft or less above the source or arbitrarily below. However, the average velocity along a ray increases with increasingly negative takeoff angle, i.e., with the receiver at increasing distances above the source. Note that the few late arrivals in Fig. 8.11.18 that have increasing velocity as a function of takeoff angle are likely P-wave mispicks.

We attempted to eliminate this artifact by editing the data such that the vertical offset between source and receiver was limited. The maximum number of data are retained by eliminating all combinations with the receiver more than 12 ft above the source (Fig. 8.11.19). More stringently, all data with the receiver above the source can be rejected (Fig. 8.11.20). While eliminating the high-velocity artifacts, the latter model obviously overweights the downward traveling rays, resulting in velocity streaking opposite to that above. Another series of models were run in which the receiver offset was limited both above and below the source, to 12 ft (Fig. 8.11.21), 6 ft (Fig. 8.11.22), and finally, zero offset (Fig. 8.11.23). The images become increasingly horizontally smoothed with decreasing offset, as expected. The 6-ft offsets do contain crossing rays and therefore are tomographic, but give the most laterally smoothed image. Lateral variations in velocity could be real but are may not be robust due to the relative poor quality of the traveltime picks.

The same artifacts are evident in the tomographic inversion for all of the data Panel 2; however, the trend is now visible on all angles less than *positive* 10-20° (Fig. 8.11.24). Traveltime tomograms with offsets <12 ft up, <0 ft up, ±12 ft, , ±6 ft, and zero offset are shown in Figures 8.11.25–8.11.29, respectively.

The shallow organic clay (< 20 ft) has the fastest S-wave velocity and was the most clearly resolved on all offset configurations of both panels. The upper sand (20-50 ft) appears to be vertically heterogeneous, with the fastest velocities near 30-36 ft. In contrast, the lower sand (65-80 ft) is among the slowest units, indicating that lithology (as indicated by the CPT) is not the principal control on S-wave velocity. Because the lower sand was drier than the upper sand, we also cannot attribute these differences to moisture (S-wave velocity should increase with decreasing moisture).

Several hypotheses might explain the pattern of artifacts evident in the CPT cross-hole seismic data. We quantitatively tested the hypothesis that the early arrivals when looking from source up to a receiver were due to a head wave along the CPT push rods. The average S-wave velocity of the formation from "pristine" arrivals ~1100 m/s. The S-wave velocity of carbonized steel is ~3200 m/s (using material properties from a simple web search). For Panel 1, the head wave is therefore predicted to exist and be the first arrival at all offsets where the receiver is greater than 14 ft above the source, in excellent agreement with observation. Alternatively, the head wave could be a P-wave (at ~6000 m/s in steel) which then radiates S-waves in the formation. This would lead to a first head-wave arrival at 7-ft vertical offset, still within observational error. Physically this head wave would arise if the seismic source did not decouple sufficiently from the CPT push rods, i.e., the slider mechanism was insufficient. However, the minimum offset at which the head waves appear should increase at greater horizontal separation; i.e., 12 ft and 23 ft for P- and S-waves along the push rods, respectively. Instead, it appears that the trend of increasing apparent velocity with increasingly negative takeoff angle extends to configurations where the receiver is ~12 ft *below* the source (Fig. 8.11.24). It is conceivable that additional reductions in apparent velocity could be due to a second head wave in the well containing the receivers, which was of PVC construction but grouted to the formation.

Alternatively, the problem could lie with the radiation pattern of the source, which was not measured under controlled conditions: the nature of the radiated energy could change as a function of takeoff angle and in particular may not be symmetric for positive and negative angles. The dominant frequency in the picked wavelets was ~250 Hz, which implies a wavelength of ~4 m at an average S-wave velocity of 1100 m/s. The receiver spacing was ~2 m, implying that the data were very near spatial aliasing for near-horizontal cross-hole paths (we had anticipated transmitted frequencies of several hundred hertz, resulting in several points per wavelength). Therefore tracking changes in the received waveform was difficult and some of the picks may have cycle-skipping errors. An erroneous addition of 1 cycle (~4 ms) to travel times of ~10 ms would result in changes in apparent velocity comparable to those observed. As the source radiation pattern likely contains an increasing proportion of energy transmitted as P-waves with increasing takeoff angle, changes in the waveform that could not be tracked accurately could have lead to picking errors that became progressively earlier, resulting in an increase in apparent velocity with source-receiver vertical offset.

The picked travel times and tomographic images are given in Appendix 11.10 on the first CD. The raw seismic data comprise Appendix 11.11 on the second CD.

8.11.3.2 Absorption Tomography. Images of absorption or attenuation can be constructed using standard travel-time tomography programs such as GEOTOMCG. Instead of supplying travel times and solving for velocities, absorption data expressed in dB down from a reference value are supplied and the imaged model parameter is then m/dB (note that the absorptions are given with positive signs and a greater value is a larger absorption). The data must be corrected for geometric spreading and other corrections may be necessary (see below). The simple models given here assume straight-line raypaths without regard to the effect of velocity variations, but in principle a velocity model can be used to determine raypaths and attenuation computed along these rays.

Received amplitudes from the monofrequency transmissions at 200 and 600 Hz and source-receiver offsets limited to ±6 ft were used to construct images of absorption (Fig. 8.11.30). Note that higher values of the model parameter m/dB corresponds to better transmission or lower absorption. The highest absorption is generally found in the shallow clay (<20-ft depth). The horizons with the lowest absorption vary with frequency and panel but appear below 60-ft depth. Again it is difficult to make a direct correlation with moisture content, as the 65-80 ft sand was the driest unit and the fine-grained unit >80 ft was the wettest unit. Attenuation tomography is more difficult than traveltime tomography because of the many factors affecting amplitude, including source repeatability, variable receiver sensitivity, source and receiver coupling, and source radiation pattern. As discussed above, the last may be the greatest source of error.

The derived attenuation data and tomographic images are given in Appendix 11.6 on the first CD. The raw seismic data comprise the second CD.

9. Conclusions

We summarize the successes of the project, the problems encountered, and recommendations. The points listed under each of these categories broadly correlate (i.e., Success 1 is related to Problem 1 and Recommendation 1)

Project successes were:

(1) *Confirmation of earlier indications that small concentrations DNAPL can be robustly identified in the laboratory using complex resistivity.* Concentrations of DNAPL commonly in the tens of parts per million have distinct complex-resistivity signatures; in one remarkable example, DNAPL concentrations of just several tens of parts per billion could be easily recognized.

(2) *Development of an investigation protocol for complex resistivity and application of that protocol to more than two dozen sites.* We inferred that complex resistivity may be very site-specific, and we laid out a general plan on how to proceed from literature review, to laboratory analysis, to surface reconnaissance surveys, and finally to cross-hole surveys. We emphasized the potential strong interference that can result from existing metallic site infrastructure.

(3) *Acquisition and processing of wideband complex-resistivity data.* We acquired laboratory and field data with both the commercial Zonge system with the custom CSM system. We developed a 3D complex-resistivity modeling code and implemented commercial 2D and 3D software as well. We identified key parameters of the DNAPL laboratory signature and applied these to field data.

(4) *Development of the formalism and software for joint geophysical inversion using empirical mappings.* The PARALLAX software written for this project is fully functional for 2D joint seismic and electrical-resistivity tomography. Its modular, object-oriented framework will allow other geophysical methods—including stand-alone commercial programs—to be

incorporated as desired. The probabilistic neural network (PNN) used to determine the empirical relationships between different geophysical data can also function as a stand-alone program for any kind of data mapping (e.g., UXO type vs model or data parameters).

(5) *Integration of complex-resistivity and seismic tools in the cone-penetrometer environment for shallow subsurface investigations.* We built a novel seismic source to be operated during the CPT push. When combined with a permanent well to accommodate seismic receivers, the volume around the permanent can be interrogated as desired by the CPT source. Electrodes were easily emplaced by CPT.

Problems encountered during this project were:

(1) *Unknown usefulness of short-term laboratory measurements of DNAPL response.* Just at the time of this writing, it has been shown that DNAPL responses in the first days to weeks after mixing with standard clays are due to sorptive effects; true chemical reactions are not manifested until months afterward (*Horton*, 2001). Although we observed clear DNAPL signatures, they are not necessarily those that would be observed in the field years or decades after contamination.

(2) *Insufficient number of sites assessed necessary to determine general applicability of complex resistivity for DNAPL detections.* In spite of the large number of sites examined on paper, samples and lab data were obtained for only seven. Only one of these did not show the kind of clay reactivity necessary to potentially identify DNAPL. More examples are needed for robust statistics. We failed to vigorously follow up in obtaining samples from all site managers because the Pinellas, Hill, and SRS sites each in turn looked like our "final" demonstration site. A better approach may have been to simultaneously pursue as many sites as possible. In the field, useful data may have been obtained at only one of three sites. Two sites did provide valuable learning experiences: we found that naturally occurring organics can obscure the potential signature of DNAPL and we confirmed that shallow infrastructure common on sites already undergoing remediation can introduce irrecoverable artifacts. But from what proportion of lab-tested sites, in general, can useful complex-resistivity data be obtained?

(3) *Insufficient data quantity and data-quality indicators (including experiment control) to determine if optimum imaging and DNAPL signatures were being obtained and to understand the role of nonlinearity.* In spite of our attempts in the lab and field, we still do not have a good comparison of the Zonge and CSM complex-resistivity equipment in which all other parameters

are held constant. At SRS-A014, reciprocal electrical measurements (the best indicator of data quality) were acquired for the CSM survey but not the Zonge survey. There are significant differences in the data-quality indicators reported by the different systems: The CSM system gives estimated errors on amplitude and phase and also provides the nonlinear indicators of the Total Harmonic and Hilbert distortions. The standard Zonge system gives the amplitude error only. Although we had the Zonge acquisition program modified to give Total Harmonic distortion, we were unable to use these or the Hilbert data in the field because we are unsure of the origin and effect of nonlinearity (see below). Denser data acquisition may have provided a better statistical framework in which to understand the measurements; at worst the harsh data editing that was applied to both the CSM and Zonge complex-resistivity measurements would have left more data to model. Halving the electrode spacing to 3 ft may have accomplished this goal but would have required four times as long for the CSM survey and eight times as long for the Zonge survey (to obtain reciprocals). Field tests were typically scheduled for three days per method (seismic or electric) in order to minimize time and cost. Part of the reason the number of data were limited is because the lab results led us to believe that DNAPL signatures would be maximized at frequencies much lower (<10 mHz) than commonly acquired during complex-resitivity surveys (~1 Hz). At higher spatial density of low-frequency complex-resistivity measurements with reciprocals, however, one or two weeks each may have been necessary.

The role of nonlinearity is a key outstanding question. We think that the low error on individual electrodes but poor reciprocity between transmitter and receiver points to geological and not electrode nonlinearity, but this is controversial.

(4) *Incomplete demonstration of the utility of joint seismic and electrical tomography.* This was largely a function of the amount of a priori data available for the test at SRS A-014. Although CPT resistivity logs provided abundant data, seismic data were limited to check shots performed from the CPT source at 6-ft vertical separations, which was not enough to establish correlations between velocity and resistivity for each of the five or more major geological units.

(5) *Noise or artifacts introduced by choice of electrodes, well-completion method, and seismic source.* This is the first use to our knowledge of the MP35N alloy for an electrode at an environmental site; although it was known to have superior corrosion resistance optimal for long-term monitoring, time constraints did not allow us to assess its polarizability and nonlinearity in the laboratory prior to installation in the SRS-A014 geology and one or both of

these factors may have substantially degraded the data quality (this assessment was done for a different chemical and mineralogical environment by Oshetski, 1999). The sand backfill to the borings was also chosen to minimize extraneous complex-resistivity responses but resulted in an annulus of resistivity that was either much higher (when emplaced) or much lower (after salt watering) than the formation. The seismic source simply did not perform as expected, radiating energy in too narrow a frequency band to provide sharp arrivals and causing an asymmetry in picked arrivals either due to coupling with the CPT push rods or due to the radiation pattern.

The recommendations from this project are:

(1) *Assess the complex-resistivity response of a site from naturally contaminated core where possible, otherwise measure response of artifically contaminated samples only after many months.* A clear correlation between lab and field responses has been obtained only for Hill AFB in a previous investigation by Co-I Olhoeft; these results were based on comparison of naturally contaminated to uncontaminated core (Olhoeft and Wardwell, 1998). At many sites, however, no contaminated core is available, so long-term lab experiments must be undertaken.

(2) *Acquire core and field data from more sites.* Some of those that were bypassed in this project may still be revisited. The overlapping effects of site geology and clay reactivity, natural organic content, and infrastructure must be deconvolved.

(3) *Acquire better data, understand differences in acquisition systems, and model nonlinear responses if necessary.* Our expectations and those of the community are to spend just several days on a site, but weeks may be required to acquire sufficient complex-resistivity data with reciprocals and other quality indicators, possibly at low frequency. Although this raises the costs and commitments for these surveys, it is still a small investment given the importance of DNAPL detection. Reciprocals should always be acquired and nonlinear indicators should also be interpreted. Nonlinear modeling would be a substantial extra step and would have to be justified by a series of carefully controlled experiments to demonstrate the importance of this effect.

(4) *Acquire sufficient a priori data to constrain joint imaging; investigate other methods with potential for joint imaging.* We have fully functional software to attempt another field demonstration of joint seismic and electrical-resistivity imaging, but we believe that the field test of joint inversion failed because we did not have sufficient quality or quantity of seismic data More check-shot data or a near-continuous CPT log may have provided enough data to correlate

velocity and resistivity; a 1-ft spacing or vertical average may be sufficient. Electromagnetic data could be investigated; EM can be directly inverted with resistivity because they are sensitive to the same physical parameters in a complementary way. Self-potential measurements can also be incorporated into a resistivity inversion, although more a priori parameters must be specified. Electrokinetic experiments—in which the ground is mechanically excited but its electrical response measured—represents a new frontier of geophysical investigation that may quantitatively link seismic and electrical parameters. Ultimately, however, we recommend that the principal focus on DNAPL detection remains complex resistivity, as its sensitivity to the surface area of chemical reactions has been demonstrated to be able to detect small quantities of DNAPL.

(5) *Improve CPT tools.* A nonpolarizing, noncorroding, linear electrode material must be used in subsurface arrays for cross-hole imaging. Based on our current experience with MP35N, prior experience with stainless steel, and the expected limited lifetime of solution-containing electrodes, we recommend platinum. We believe that the high cost of this material will be more than offset by the quality of data obtained. With regard to well completion, we recommend testing fumed silica for rapid, nonreactive curing. If more high-resolution seismic surveys are to be attempted, we recommend searching for a new generation of compact receivers that can be permanently emplaced by CPT. The radiation pattern of the magnetostrictive source must be measured and the CPT decoupling mechanism redesigned if necessary. Most importantly, the material packaging and/or sweep-amplitude envelope must be redesigned to flatten the transmitted spectrum and eliminate strong harmonics. As swept-frequency seismic data are frequently better used in reflection than refraction, reflection tomography should be investigated with this tool. Finally, a CPT tool should be designed to acquire multifrequency complex resistivity data instead of the monofrequency resistivity-only measurements currently made, in order to assess more quickly the utility of complex resistivity on a particular site.

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