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**Geophysical Data Fusion
For Subsurface Imaging
Phase I**

Topical Report

**Pieter Hoekstra
James Vandergraft
Mark Blohm
David Porter**

August 1993

Work Performed Under Contract No.: DE-AC21-92MC29106

**For
U.S. Department of Energy
Office of Environmental Restoration and Waste Management
Morgantown Energy Technology Center
Morgantown, West Virginia**

**By
Coleman Research Corporation
Columbia, Maryland**

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9891 Broken Land Parkway, Suite 200
Columbia, Maryland 21045**

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Abstract

A geophysical data fusion methodology is under development to combine data from complementary geophysical sensors and incorporate geophysical understanding to obtain three dimensional images of the subsurface. The research reported here is the first phase of a three phase project. The project focuses on the characterization of thin clay lenses (aquitards) in a highly stratified sand and clay coastal geology to depths of up to 300 feet. The sensor suite used in this work includes time-domain electromagnetic induction (TDEM) and near surface seismic techniques. During this first phase of the project, enhancements to the acquisition and processing of TDEM data were studied, by use of simulated data, to assess improvements for the detection of thin clay layers. Secondly, studies were made of the use of compressional wave and shear wave seismic reflection data by using state-of-the-art high frequency vibrator technology. Finally, a newly developed processing technique, called "data fusion", was implemented to process the geophysical data, and to incorporate a mathematical model of the subsurface strata. Examples are given of the results when applied to real seismic data collected at Hanford, WA, and for simulated data based on the geology of the Savannah River Site.

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1 Executive Summary

A sensor fusion methodology has been developed that leverages the synergism between dissimilar geophysical sensors and explicitly incorporates geophysical understanding to obtain the best possible 3D image of the subsurface. A DOE (OTD) Workshop on Non-intrusive Geophysics, held in Dallas, TX, in August, 1991, cited data fusion (integration) as the highest ranking technology for development. Related to this need, Coleman Research Corporation (CRC) is developing a software package for use in a workstation to process multiple geophysical sensor data with sufficient fusion automation to be accessible to scientists and engineers with minimal training in fusion technology.

The research described in this Topical Report was conducted under the first phase of a proposed three phase project. The project focuses on the characterization of thin clay lenses (aquitards) in a highly stratified sand and clay coastal geology to depths of up to 300 feet. The chosen sensor suite includes time-domain electromagnetic induction (TDEM) and near surface seismic exploration techniques, with four important improvements:

- The use of high frequency seismic sources to enhance identification of thin clay strata.
- Shear wave as well as conventional compression wave seismic surveys to provide additional geologic detail.
- Improved algorithms for differential processing of TDEM data.
- The use of out-of-loop horizontal magnetic field TDEM processing techniques to increase sensitivity to geologic strata.

A newly developed processing technique, which we call "data fusion", will be used to process the geophysical data, and to incorporate a mathematical model of the subsurface strata. Finally, to provide the most advanced capability for the three dimensional display and modeling of the fused data, and for varied quantitative analyses by the user, the latest release of the Earth Vision software package by Dynamic Graphics is used.

This first phase of the project resulted in new processing techniques for TDEM data which, together with the acquisition of more parameters than is common in present practice, improves the sensitivity of TDEM for detecting thin clay lenses. Furthermore, studies were made into the use of compressional wave and shear wave seismic reflection and refraction data, produced by using state-of-the-art high frequency vibrator technology, to further delineate the clay layers. Finally, sensor data fusion technology was developed to simultaneously invert TDEM and seismic data, while incorporating a geophysical model of the subsurface. Tests of these new methodologies, using simulated data, indicate that the stated goals of detecting and mapping three foot thick clay layers at depths of up to 300 feet should be achievable.

2 Introduction

The purpose of this report is to describe the progress that was made during the first phase of a three phase project. The long- range goal of the project is to integrate geophysical data derived from multiple sensors to characterize hazardous waste sites by the delineation of contaminant plumes and by the identification of thin clay layers and geological discontinuities. During this first phase, emphasis was placed on three activities: the development of improved methods for measuring and processing time domain electromagnetic (TDEM) data, the evaluation of newly available seismic vibrators for use in the data collection activities of Phases II and III, and the development of data fusion algorithms for processing the data.

During Phase II of this project, the improved measuring and processing techniques, the use of improved seismic vibrators, and the enhanced data fusion methodology will be tested with data collected from a selected site at the Savannah River Site. Phase III will expand the demonstration to other sites. Also, the geophysical data fusion methodology will be enhanced to provide a fully automated computational flow and the advances in fusion and sensor technology will be incorporated into the final software package.

2.1 Relevance to DOE's Mission

The mission of DOE's Office of Environmental Restoration and Waste Management (EM) is to clean up the inventory of inactive DOE sites and facilities by the year 2019. The goal of the EM Office of Technology Development (OTD) is to advance and deliver technologies that can make environmental restoration and waste management operations more efficient and less costly. Significant volumes of hazardous wastes (containing organic and/or metal chemicals and mixed wastes) have been generated by the DOE weapons production complex. At some facilities, hazardous waste streams were routinely disposed into the ground by means of infiltration cribs (Hanford), trenches (Oak Ridge, Savannah River) or ponds (Rocky Flats). In other places, contaminants were introduced into soils and ground water through leaks from tanks and process piping, or from burial grounds and storage areas.

Once introduced into the subsurface, a complex interplay of physical, geochemical and biological forces govern the release, transport and fate of chemical substances. Site characterization is the process that identifies the distribution of contaminants, and all the critical subsurface features influencing contaminant behavior and migration. The most expensive component of site characterization is drilling and chemical analysis on soil and rock samples. Development of non-intrusive (geophysical sensors) that reduce the drilling and sampling costs have been identified by DOE as a critical technology need.

2.2 Objectives of Research Project

Effective site characterization requires that many relevant geologic, hydrogeologic and biological properties of the subsurface be evaluated. A parameter that often directly influences

chemical processes, ground water flow, contaminant transport, and biological activities is the lateral and vertical distribution of clays.

The objective of the research and development under this contract is to improve non-invasive methods for detecting clay lenses. The percentage of clays in soils influences most physical properties that have an impact on environmental restoration and waste management. For example, the percentage of clays determine hydraulic permeability and the rate of contaminant migration, absorption of radioactive elements, and interaction with organic compounds. Therefore, improvements in non-invasive mapping of clays in the subsurface will result in better:

- characterization of contaminated sites,
- prediction of pathways of contaminant migration,
- assessment of risk of contaminants to public health if contaminants reach water supplies,
- design of remedial action and evaluation of alternative action.

The distribution of clays in the subsurface can occur in many forms depending on the depositional environment. Figure 2.1 shows some distributions commonly encountered.

Clay lenses may be interbedded as thin lenses in a coarse grained soil matrix (Figure 2.1 a) and an important objective would be to map their distribution, or an individual clay lens may pinch out, as in Figure 2.1 b.

2.3 Geophysical Methods

All geophysical methods exploit differences in physical properties between the strata to be mapped and the surrounding soils and rocks. Three physical properties often allow differentiation of clays:

- Natural gamma ray emissivity. Clays often have a higher content of Thorium (Th) and Potassium (K) than sands and gravels. However, because of rapid attenuation, natural gamma ray emissivity measurements cannot be exploited remotely from the surface. It is an effective tool to map clays in borehole geophysical logging.
- Electrical resistivity (or the inverse conductivity). Electrical conductivity of the subsurface can be mapped remotely from the surface.
- Seismic compression and shear wave velocities and impedances. This method also can be implemented from the surface.

a) Single clay layer in sand section

b) Discontinuity in single clay layer

c) Multiple clay layers schematic

Clay Sand

a)

ELEVATION IN FEET
360
350
340
330
320
310
300
290
280
270
260
250
240
230
220
210
200
190

b)

Figure 2.1: a) Occurances of Clay Lenses in a Coarse Grained Matrix (Schematic). b) Pinching Out of a Clay Strata (Collierville, TN)

2.4 Technical Approach to Research

The lateral and vertical distribution of clays can be determined by intrusive and non-intrusive (geophysical) methods. Intrusive methods have the advantage that they are direct and give unambiguous answers. Their limitations are that they are a point measurement, are expensive, have the risk of cross contaminating aquifers, and can expose personnel to safety hazards. Surface geophysical methods have the advantage that they are of low cost, have no risk of cross-contaminating aquifers and present minimum exposure to personnel. They have the disadvantage of being an indirect measurement that requires calibration and verification.

The trade-off between intrusive and non-intrusive methods, therefore, often consists of extensive low-cost geophysical surveys, verified and calibrated at optimum locations by intrusive tests. This approach leads to continuity in subsurface information at a high level of confidence.

2.5 Distinguishing Features of the Research

The detail in the lateral and vertical distribution of clays required for effective design and costing of remediation is far greater than information commonly collected in conventional geotechnology. The underlying concepts of the research and development of this contract are that one geophysical method cannot produce a breakthrough in the detection of clay lenses, but that use of multiple sensors, and integration (fusion) of multiple sensor data, intrusive as well as non-intrusive, can produce significant improvements. The essence of our approach, therefore, is to acquire multiple sets of geophysical data over the same area and integrate (fuse) the results to produce a consistent image of the subsurface.

2.6 Breadth of Application of the Technology

Effective and proven methods for determining the lateral and vertical distribution of clays also have a wide range of applications at many other DOE sites. Clays are known to determine the movement of contaminants at the Savannah River Site, and at Fernald clays have a major impact on the effectiveness of soil washing as a remediation technology to remove uranium contamination from soils. In addition, the improvement in time domain electromagnetics and high resolution seismics being developed and tested under this program have applications at DOE sites beyond just the detection of clay lenses. The same technologies can be applied to the detection of sandstone stringers within the claystone at Rocky Flats, caliche layers at Hanford and depth to bedrock and fracture within the bedrock at Oak Ridge.

2.7 Sensor Data Fusion

Our fundamental sensor fusion approach combines data from complimentary sensors with explicit geophysical understanding to form a subsurface image. Information contained in the

data is directly combined with physical information to form the best image. Figure 2.2 gives a good example of the output from this approach. Here, seismic reflection and refraction data are fused with lithology data from wells, together with an autoregressive model of the spatial variation of layer depths and seismic velocities. In this figure, surface construction is shown by white outlines, well locations are indicated by squares that have long tails into the subsurface, and the four lines along which the seismic measurements were taken are clearly indicated. The figure shows the detection of two layer interfaces. The first is at approximately nine meters depth, the second begins at about 32 meters at the far left of the figure. The two-toned band from five meters to eleven meters is the “one standard deviation” (1-sigma) uncertainty in the estimate of this first layer interface. Similarly, the two-toned band from, approximately, 29 to 38 meters is the 1-sigma uncertainty in the estimate of the interface between the second and third layers. The lateral shading is an indication of the changes in seismic velocity within the second layer, keyed to the display on the left in meters per second. The vertical shading is to emphasize the changes in depth with location. The “bump” in the center of the lower layer is called an “erosional high”, and was previously undetected. The purpose of this exercise was to map this lower layer, which is composed of a hard material called “caliche”. This layer acts as a barrier to prevent contaminants from reaching the ground water.

The physical motivation for sensor fusion is that different sensors for subsurface imaging depend on different physical principles, and hence measure different physical properties of the subsurface. For example, seismic sensors respond to bulk and shear moduli differences in the subsurface layers, whereas electromagnetic sensors measure differences in electrical properties, such as resistivity. If the subsurface layers can be defined by *both* of these properties, then the fusion process reinforces these sensor measurements and produces a more reliable image. An important aspect of our fusion process is that the combining of physical information with sensor information provides a delineation of the geology that is much more accurate than could be obtained from sensor information alone. For example, the geological understanding that subsurface material properties often vary slowly in space provides the basis for spatial smoothing that produces a more realistic image.

2.8 Fusion to Enhance Geophysical Understanding

Sensor data is fused so as to avoid information loss, while at the same time avoiding problems of dealing with raw data. For example, raw seismic reflection data from the geophone traces is not fed directly into the fusion process. Instead, standard seismic preprocessing is used to obtain time of travel data that can be more easily interpreted by the fusion processor. Seismic data processing has been done in the past by experts who used a variety of ad-hoc manipulation techniques, combined with years of experience and a solid background in geophysical sciences. In order to use seismic data as part of the data fusion process, it was necessary to develop new computational techniques that would attempt to meet the requirements of these experts, but through a much more highly automated process.

An important aspect of sensor fusion is that it can use information from one sensor to improve the estimates produced by another sensor. For example, seismic refraction data can

Reflection and Borehole Data Locations

Figure 2.2: Fused Geological Layer Depths and Seismic Velocity Field at Hanford 200 West

provide good estimates for the velocity of the seismic signal within the subsurface regions. Processed seismic *reflection* data, however, consists of times-of-travel of the seismic signal between the source and the reflective target. If the velocity in a formation is known, then the depths to the reflective layers can be determined. The fusion process automatically combines the velocity information from the refraction data with the time-of-travel data from the reflection sensors to estimate the depths of the subsurface layers.

2.9 Site Selection to Reduce Cost of Intrusive Tests

Intrusive testing is the most expensive component of site characterization. For this reason, we propose that the data acquisition for Phase II be performed at the Savannah River Site (SRS) since extensive drilling and cone penetrometer surveys are available at several locations within SRS. Conducting the work at SRS requires no further intrusive testing beyond the available test holes.

2.10 Technical Approach and Outline of Report

The technical approach used in this project to improve the detection of clay lenses is proceeding along three paths:

1. Improving the sensitivity of time domain electromagnetic (TDEM) measurements by acquisition of more parameters of the electromagnetic field than is common in present practice, and by new processing techniques.
2. Acquiring compressional wave and shear wave seismic reflection data by using state-of-the-art high frequency vibrator technology over the same section as TDEM data and combining the interpretation of both data sets.
3. Developing sensor data fusion for simultaneous inversion of TDEM and seismic data sets, while incorporating a geophysical model of the subsurface.

Section 3 of this report documents the research, algorithm development and results of the feasibility studies to improve the TDEM methods. Section 4 describes the seismic analysis performed, and Section 5 discusses the sensor fusion technology. Section 6 describes the selection of test sites at the Savannah River Site for the field testing of Phases II and III.

3 Electromagnetic and Electrical Methods

3.1 Basis for Electrical Resistivity Mapping

Clay lenses can often be differentiated from coarser grained soils by electrical resistivity (the inverse of conductivity). Figure 3.3 shows a typical relationship between soil types of the Unified Soil Classification System and conductivity.

Figure 3.3: Soil Types versus Electrical Resistivity

Figure 3.4: Schematic Illustration of Cloud of Ions Surrounding Negatively Charged Clay Particles

In non-saline soils, the main parameter determining electrical resistivity is clay content and types of clays. The reason is that the dominant electrical charge carrier in non-saline soils are the exchangeable ions surrounding the clay mineral lattices. Because clay minerals carry a negative electrical charge, a “cloud” of ions surrounds the mineral particles to maintain electrical neutrality. See Figure 3.4. These ions conduct electricity in clay soils and cause the clays to have higher conductivity than sands and gravels.

Thus, from a measurement of the geoelectric section the presence or absence of clays can be inferred. Recognizing clay lenses in an interbedded sequence of sands and clays is particularly effective when the geoelectric section is derived from borehole electromagnetic induction logs, because such a log can resolve the geoelectric section in great detail. See Figure 3.5 for an example of this effect.

In saline soils the electrical current carried by dissolved ions in ground water may dominate the electrical current caused by ions absorbed in clay particles. However, distinguishing between sands and clays is often feasible because of differences in porosity. Saline ground water, however, is not known to occur at shallow depths at DOE sites.

Measuring the geoelectric section remotely from the surface cannot provide the same detail as sections obtained from geophysical borehole logging. The objectives of the research and feasibility analyses performed in this project are to determine what the resolution of surface electrical and electromagnetic methods is, how the resolution can be improved, and whether these methods can be used to map clay lenses.

Figure 3.5: Example of Electromagnetic Induction and Lithologic Log Showing Correlation Between Clays and Electrical Resistivity

3.2 Electrical and Electromagnetic Technologies

There are a number of electrical and electromagnetic methods in common use in geoelectric prospecting for determining, from the surface, the geoelectric section of the subsurface. These methods differ in lateral and vertical resolution, sensitivity to ambient and geologic noise, and in practical aspects of surveying. Sensitivity to geologic noise is highest for methods that measure electric fields (direct current resistivity mapping techniques) compared to methods that measure magnetic fields. In the exploration depth range from about 15 feet to 7,500 feet, time domain electromagnetic (TDEM) has advantages over alternative methods because of its high sensitivity to the geoelectric section, low sensitivity to geologic noise, and good lateral resolution. Therefore, to evaluate the detection of clay layers, the TDEM method was selected for further development to enhance its capability for detecting these clay lenses.

The TDEM method has been employed for approximately ten years for geoelectric exploration. Most of the applications were for the mapping of deep, large geologic structures. To map thin clay lenses and subtle features in the distribution of clays, improvements in the resolution of TDEM data acquisition and processing are required. In this report on Phase I, the feasibility of improving resolution by horizontal field measurements and differential processing is evaluated. Before discussing these improvements in more detail, we give a short summary of current TDEM technologies.

3.2.1 Overview of Currents Methods in Time Domain Electromagnetics

TDEM is a controlled source EM method (Kaufman and Keller, 1983) with two common types of sources usually employed; (i) grounded line sources with magnetic dipole receivers offset from the line, and (ii) non-grounded square transmitter loops with magnetic dipole receivers positioned in the center and at positions offset from the center. Two types of transmitter and receiver geometries are illustrated in Figure 3.6.

The most common receivers employed are multi-turn air coils and the effective areas of the receivers vary from 100 m^2 to 10^5 m^2 (Hoekstra and Blohm, 1990). The receivers with large effective area are often seismic cables laid out over the ground surface, but coils with effective area of 1000 m^2 and less are wound on a rigid mandrel. With these latter coils, both vertical and horizontal components of the field can be measured.

A common system waveform of TDEM signals is shown in Figure 3.7. The current driven through the transmitter loop is a half-duty cycle waveform and a steady current is terminated by a linear ramp. The ramp time depends on peak current and the dimensions of transmitter loops, and is about 2 to 50 microseconds for exploration depths to 300 feet.

It has been shown (Kaufman and Keller, 1983) that the sensitivity of the electromotive forces (emf's) to the geoelectric section change with time. Figure 3.8 shows emf_z as a function of time in the center of the transmitter loop. At time corresponding to "early stage", emf_z is proportional to ground conductivity, σ , whereas, at late stage emf_z is proportional to $\sigma^{3/2}$. It is therefore advantageous to have the range of measurements mainly in "late stage" because of the high sensitivity to the geoelectric section. The onset of "late stage" is

Figure 3.6: Transmitter (Tx) and Receiver (Rx) Arrays Used in Time Domain Electromagnetics (TDEM)

Figure 3.7: System Waveforms in TDEM

defined by :

$$\frac{\mathfrak{S}}{r} > 16$$

where $\mathfrak{S} = \sqrt{2\pi\rho t}10^{-7}$ and

- r = transmitter-receiver separation
- ρ = resistivity
- t = time of measurement

Figure 3.9 shows the relation between onset of "late stage" and transmitter loop size. The concept of "late stage" is used in subsequent sections to discuss improvements in TDEM under this program.

Present practice of TDEM interpretation consists of inversion by one-dimensional (1-D) algorithms. At each receiver station, a 1-D geoelectric profile is derived, and typically a 2-D geoelectric cross-section is constructed from a series of 1-D profiles. The inversion algorithms used are those initially published by Inman (1975) using a forward solution taken from Anderson (1973). Thus, TDEM is a controlled source EM method with distances between transmitter and receiver approximately the same as the effective exploration depth.

3.2.2 Horizontal Field Measurements Applied to Clay Lens Detection

Figure 3.10 shows the behavior of the electromotive force due to the horizontal magnetic field emf_x and the vertical magnetic field emf_z on a line through the center of a 100 meter by 100 meter transmitter loop for ground with a uniform resistivity of 100 ohm-m. For

Figure 3.8: Behavior of Time Derivative of Vertical Component of Magnetic Field as a Function of Time

Figure 3.9: Relation Between Onset of Late Stage and Electrical Resistivity and Transmitter Loop Size

transmitter loops of different dimensions and for horizontally stratified ground or ground of different resistivity, the trends are similar.

Characteristics of the vertical field are:

- Emf_z is a maximum in the center of the transmitter loop.
- With increasing distance from the loop, emf_z decays and eventually crosses through zero.

Characteristics of the horizontal field are:

- Emf_x is zero in the center of the loop.
- With increasing distance from the loop, emf_x increases to a maximum then decreases and crosses through zero.

For the same time gates, the maximum amplitude of emf_x is less than the maximum amplitude of emf_z . At the present time the common mode of TDEM surveying consists of making measurements of the vertical field, emf_z , in the center of a non-grounded loop. There are several reasons for this preferred procedure, such as:

Figure 3.10: Behavior of emf_z and emf_x on a Profile Through the Center of a Square Transmitter Loop

- The plotting point of the measurement is well defined, because the induced current is concentric about the center.
- The distance between the transmitter and receiver is minimized, helping lateral resolution.
- Ambient electrical noise is less for the vertical component, and emf_z is a maximum in the center. The signal-to-noise ratio is therefore optimal for emf_z in the center.
- Survey requirements to locate the center are minimal, because the field is relatively flat in the center.

There is, however, one important incentive for investigating measurements of emf_x , and that is its higher sensitivity to the geoelectric section over a certain time range. It has been shown (Kaufman and Keller et. al., 1983) that in late stage, the vertical field, emf_z , is related to conductivity of the geoelectric section and time of measurement by:

$$emf_z \propto K \frac{\sigma^{3/2}}{t^{2.5}}$$

and for the horizontal field, emf_x , we have:

$$emf_x \propto K \frac{\sigma^2}{t^3}$$

where σ is ground conductivity and t is time after current turn-off. It was this increased sensitivity of emf_x to the geoelectric section; $\sigma^{3/2}$ versus σ^2 that was the impetus for developing horizontal field measurements for this investigation. However, there are also some disadvantages to horizontal field measurements, such as:

- Emf_x is of lower amplitude and decays faster with time. Figure 3.11 compares the amplitudes of emf_z and emf_x as a function of time. At early time (10^{-2} milliseconds) emf_x is about a factor 3 less than emf_z , but because emf_x decays faster with time, it is an order of magnitude less than emf_z at later times. However, lower amplitudes for emf_x are only significant if noise exceeds signal. Our computations show that a sufficient signal-to-noise ratio could be maintained for the time range required for 300 foot maximum effective exploration depth. Some equipment modifications would need to be implemented, however.
- Emf_x is zero in the center of the transmitter loop and measurements must, therefore, be made outside the loops. This will require careful surveying to locate receiver positions.

Despite these disadvantages of emf_x measurements, the increased sensitivity was considered the overriding incentive for developing methods to detect thin clay layers. To implement the measurements and interpretations of emf_x the following research and development was performed:

Figure 3.11: Comparison of Amplitude of emf_z and emf_x as a function of time

- Forward modeling algorithms for horizontally stratified ground were developed and tested.
- Inversion algorithms to derive the geoelectric sections were developed and tested.
- Feasibility investigations of signal-to-noise and sensitivity were made.

3.2.3 New Results About the Horizontal Field

The results of the development of the algorithms and feasibility investigations for the horizontal field are summarized next.

Figure 3.12 shows the results of a sensitivity analysis for both the vertical and horizontal components of the TDEM field. For this analysis, the system parameters of the Geonics EM47 were used. The Figure shows (on the bottom) the geoelectric section with a clay layer (10 ohm-m) buried at a depth of 300 feet in clean sands (500 ohm-m). These values are representative of those encountered at the Savannah River Site. Sensitivity analyses were run for three cases where the thickness of the clay varied from 1 ft. to 10 ft. The upper part of Figure 3.12 shows the percentage difference versus time between the fields calculated for the geoelectric sections with and without the clay layer. On these graphs, data are only shown for the time range over which signal exceeds noise. Percentage differences of 5% or greater are believed to allow detection of the clay layers and this threshold value is also shown on the graphs. The graphs show that for all three cases, differences above the threshold occur for both components and thus the presence of the clay will be evident in the data. The horizontal component shows a larger percentage difference than the vertical component in each case. However, the time range over which signal exceeds noise will be shorter for the horizontal field. For a 1 ft. thick clay layer, about 2/3 to 3/4 of the available time gates show differences greater than 5% for the two field components. For the case of the 10 ft. thick clay layer, all of the available time gates show differences of 5% or greater for the two field components.

In summary, feasibility investigations of TDEM measurements to detect clay layers show that, in principle, detection of a 1 ft. clay layer at 300 ft. depth embedded within sands is feasible. Horizontal field measurements to that depth can be implemented with minor equipment modifications, and will further assist detection of clay layers. The significant progress achieved under this contract is the development and testing of algorithms for inversions of horizontal field data.

The limitations of implementing the detection of clay layers will almost entirely be determined by geologic noise, such as multiple clay layers, inhomogeneities in the sands, and variation in composition of the clays. The extent to which these noise sources can be handled must be determined from field tests.

3.2.4 New Processing Procedures for Electromagnetic Fields

Measurements of emf_x represent an additional data set not commonly collected to derive the geoelectric section from which clay layers can be inferred. To assist further in the detection

Figure 3.12: Results of Sensitivity Analysis for emf_z and emf_x for Detection of Clay Layers

of clay layers, new processing procedures for the data were investigated. One such technique which shows special promise is *differential processing*.

In differential processing, a differential emf (Δemf) from measurements at two different times is defined by:

$$\Delta EMF = EMF(t_1) - (t_2/t_1)^n EMF(t_2)$$

where $EMF(t_1)$ and $EMF(t_2)$ are emf's measured at times t_1 and t_2 respectively, and n is a constant. This constant was selected as 2.5 after a number of investigations by Soviet geophysicists because it can be shown that, over a wide range of time measurements, the field over ground with uniform resistivity decays as $t^{-2.5}$ for emf_z . Perturbations in this behavior will be due to deviations from uniform ground, such as the presence of clay layers within resistive sands.

The Soviet geophysicists performed differential processing on emf_z for the objective of detecting a highly conductive brine layer within resistive host rock. They proved the following advantages for this processing technique:

- A better sensitivity to the presence of and conductance of a thin brine layer.
- The time range of maximum sensitivity shifted to earlier time where there is a higher signal-to-noise-ratio.

Under this project, algorithms for differential processing for forward modeling of emf_z were developed and feasibility investigations were performed. In our computations, the approach followed by the Soviets was used, based on the behavior of emf_z over a thin conductive layer, such as clay, in a resistive host, such as sand. Since this section approximates the situation at Savannah River, this seemed an appropriate line of investigation. A quantity S_q was defined by

$$S_q = S_n \frac{\rho_a}{\rho_1}$$

where ρ_a is the apparent resistivity at time t , and ρ_1 is the resistivity of the resistive half-space (sand), and

$$S_n = \frac{16\pi\rho_1 t_1^3}{Mku^3(1 - \sqrt{t_1/t_2})}$$

with M the moment of the transmitter loop, k is a constant related to the transmitter-to-receiver distance, and u is magnetic susceptibility. Figure 3.13 shows values for S_q for ground with and without a clay layer at a depth of 300 ft. (see bottom of figure). The clay layer is varied in thickness from 0.1ft. to 5 ft.

These results show:

- There are very large differences in S_q , up to a factor of 1,000, between geoelectric sections with and without a clay layer.
- The part of the curve that is diagnostic of the clay layer (minimum) occurs at early time, at which point the signal to noise ratio is high.

Figure 3.13: Result of Computing S_q for Geoelectric Sections With and Without Clay Layer

In summary, differential processing is a highly sensitive procedure for recognizing a conductive layer, such as clay, within a homogeneous, resistive, ground. The effectiveness of this transformation will largely depend on geologic noise, such as multiple clay layers and variations in the resistivity of the sands. Since it is a processing method that requires no additional data collection, it will be tested on the data to be acquired during Phase II at Savannah River. Under Phase I, the algorithms to compute the differential processing quantities were developed and completely tested. If field data suggest this method to be valuable for recognizing clay layers, inversion routines will be developed in Phase II.

4 Seismic Methods

4.1 Introduction to Seismic Theory as Applied to Geophysical Exploration

The application of seismic waves is one of the most commonly used geophysical tools. Seismic (or sound) waves yield information by refraction and reflection at the interfaces between media of different physical properties. Geophysical surveys involving seismic methods provide depths to different lithologic units as well as physical properties of the units.

Seismic methods use sources (either impulsive or vibrational) to generate sound waves. Receivers (hydrophones or geophones) are used to record the particle motion caused by the sound waves. These sources generate many types of waves which are propagated through the earth. For example, compressional, shear, surface waves (ground roll), tube wave (in boreholes) are all generated by the seismic source. However, for exploration and environmental studies, compressional and shear waves are of primary concern. The following discussion is therefore limited to these wave types and their uses.

The compressional wave (referred to as P-wave) is a compression- dilation event where particle motion is in the direction of wave propagation, as shown in Figure 4.14 (after Brown, 1981). P-waves are the most commonly used wave type. This is due to the ease with which they are generated and recorded compared to other signals.

The shear wave (referred to as S-wave) is a transverse event with particle motion at some predetermined, transverse orientation to the wave propagation direction. Shear waves undergo a phenomenon known as shear wave birefringence upon entering a heterogeneous medium. As shown in Figure 4.15, the shear waves split into two signatures, S_v and S_h , with polarization directions mutually perpendicular but traveling the same path. Common causes of splitting include fracturing, layering and preferential particle orientation or alignment. Shear wave splitting has received much attention from the oil and gas industry for mapping regions of fractured rock and preferential flow through them (Lynn and Thompson, 1990 and Crampin, Lynn and Booth, 1989). The technique has also been used to measure the degree of transverse isotropy in particle orientation for shallow clay sequences (Bates, 1991).

Figure 4.14: Schematic Presentation of Particle Motion of Compressional and Shear Waves (after Brown, 1981)

Figure 4.15: Ideal Model of Shear Wave Passage at Some Angle Through a Transversely Isotropic Medium with Vertical Symmetry Axis. S_h is the Faster Split Shear Wave, S_v the slower.

4.2 Seismic Wave Propagation

In seismic surveys, sound waves are generated at a source location and subsequent particle motion as a function of time is recorded at receiver locations. Time measurements are used to infer acoustic velocity of the medium through which the wave has passed. Acoustic velocity of a medium is related to a number of physical properties, such as: density, consolidation, compaction, elastic properties of the soil/rock, and properties of the fluid.

Compressional wave velocity is a function of density (density is related to porosity of the material and individual densities of the soil grains and fluid), bulk and shear moduli of the medium, bulk modulus of the fluid, and percent fluid saturation. Compressional waves are sensitive to percent saturation within the media and somewhat to fluid type. As a result, they are readily effected by boundaries, such as at the water table and between unconsolidated material and bedrock, and are less sensitive to boundaries between sands and shales within unconsolidated sediments.

Shear wave velocity is only a function of solid density and the shear modulus (or rigidity) of the medium. Shear wave velocity is essentially independent of fluid type and degree of saturation. Shear waves are thus more effected at sand-clay interfaces within unconsolidated sediments than are compressional waves.

There has been significant research in using compressional and shear wave velocity ratios as a method of lithology discrimination (e.g. Tatham 1982, Byun et. al. 1989). This method typically involves establishing an empirical relationship between velocity ratio and clay content within unconsolidated sediments. The empirical relationship is valid only on a site-to-site basis. Figure 4.16 shows a summary of factors influencing seismic velocity ratios.

4.3 Current Methods of Seismic Exploration as Applied to the Savannah River Site Geology

Two features of wave propagation are used in the majority of seismic surveys: refraction and reflection. Both of these methods rely on the laws of reflection and transmission at an interface between two media. These laws state that in the case of oblique incidence of plane waves on a plane boundary, an incident wave produces both reflected and transmitted waves (see Figure 4.17). This phenomena is required to satisfy boundary conditions for non-normal incident plane waves at an interface.

Equation 1 in Figure 4.17 is Snell's law of refraction (after Sengbush, 1983). Snell's law gives the angles of reflection and transmission as a function of the incident angle and wave velocities. In practice, two criteria must be met to observe an interface with seismic refraction:

1. There must be a significant velocity contrast across the interface of interest.
2. The interface must correspond to the upper boundary of a layer that has sufficient thickness. The layer thickness required to observe the refracted event depends on the velocity of the mass on either side of the boundary.

Figure 4.16: Summary of Factors Influencing Compressional and Shear Wave Velocities.

Figure 4.17: Geometry of Incident Reflected and Refracted Seismic Waves

The amplitude or strength of the reflection at an interface is a function of the density and velocity of both media. The reflection coefficient, R , is given by the following:

$$R = \frac{\rho_2 V_2 - \rho_1 V_1}{\rho_2 V_2 + \rho_1 V_1}$$

For a reflection event to be observed seismically, the acoustic impedance contrast must be significant, and the thickness of the layer must be approximately 1/8 to 1/4 of the dominant wavelength.

Another aspect of the seismic waves that must be considered is mode conversion. For a compressional wave incident at a plane boundary, a compressional wave is both reflected and transmitted (as described above). Also, a vertically-polarized shear wave is both reflected and transmitted due to the incident compressional wave. For a vertically-polarized shear wave incident on a plane boundary, vertically-polarized shear waves as well as compressional waves will be produced. However, with a horizontally-polarized shear wave, no mode conversion is experienced in isotropic media. Mode conversion phenomena exist to satisfy boundary conditions (conservation of energy) of elastic waves incident on plane boundaries. For more detail on mode converted seismic waves refer to White (1983).

A refracted seismic wave, governed by Snell's law, is a function of velocities and incident angle only. Seismic refraction surveys, which record only the first arrival times, are only used to solve for depths and velocities of geologic layers. Seismic reflection surveys record reflections as a function of time. To model or understand a seismic reflection survey, densities and velocities of the media must be known.

The "simplified" geologic section at Savannah River Site consists of a thin clay layer in a relatively homogeneous sand sequence as depicted in Figure 4.18.

		VELOCITY (FT/SEC)	
		P-WAVE	S-WAVE
SAND	▽ Unsaturated	800-2200	250-1500
	Saturated	2500-5500	250-2000
CLAY		2500-6000	1000-2000
SAND		2500-5500	1000-2000

Figure 4.18: Schematic Geologic Section at Savannah River Site, with Seismic Velocities

The range of P-wave and S-wave velocities expected for this section are also shown on this Figure. In this section, relatively minor density changes are expected and thus the main P-wave reflection and refraction events (velocity changes) are expected from the water table. In contrast, for the S-wave the major velocity change is expected at the clay layer and thus a reflection event is expected from this boundary. As mentioned earlier, there will be no S-wave event associated with the water table.

Commonly, shallow reflection surveys only include P-wave data acquisition. In some instances, S-wave reflection is acquired but almost never are full multi-component data sets acquired in a similar manner to some of the oil and gas exploration studies. State-of-the-art software for processing shallow reflection data is inadequate to fully account for the information contained in multi-component data sets. In particular, static problems with velocity differences between split shear and compressional waves can become major mistakes in interpreted reflection profiles. During Phase I, some aspects of this situation were addressed with algorithm and program development packages using continuous refraction profiling interpretation method. The resulting software and field methodology will be tested in Phase II.

4.4 Seismic Research in Phase 1

Based on the preceeding discussion, the principle seismic method recommended for detection of thin clay layers in this research is seismic reflection, and in particular, S-wave reflection. As previously stated, the ability to detect a clay layer using reflection techniques with either P-waves or S-waves is dependent on two factors:

1. Frequency content of the recorded seismic signal. In general the broader the frequency band to shorter wavelength the better the resolution of thin layers.

2. Sufficient impedance (product of density and velocity) contrast between the clay and the surrounding material.

The first parameter is the only one which is under the control of the geophysicist, and thus is one of the primary research objectives in this PRDA.

When a layer thickness is less than one-fourth of the seismic wavelength, then its thickness cannot be resolved. However, it has been shown (Reference 5) that given a sufficient acoustic impedance contrast, information about a layer that is one-twentieth of the wavelength can be inferred from the amplitude of the reflection. Given these constraints and a typical unconsolidated, saturated sediment P-wave velocity of 6,000 ft/s, and S-wave velocities of 2,000 ft/s then the frequencies required to resolve a 3 ft thick layer are:

	1/4 Wavelength	1/20 Wavelength
P-wave	500 Hz	100 Hz
S-wave	166 Hz	33 Hz

It is important to note that for a given wavelength an S-wave will have a higher resolution due to its slower velocity compared to a P-wave. P-wave impedance (product of velocity and density) contrasts between clays and sandy aquifers are generally not very high, however S-wave *velocity* contrasts between sands and clays can be up to 2 to 1. This would be a sufficient contrast to use the 1/20 of a wavelength criteria.

To increase the frequency content of seismic sources, development of experimental high frequency vibratory sources were recommended as part of Phase 1 of this PRDA. Since submitting the Management Plan, several significant vibrator developments were made by commercial companies (OYO Corporation and IVI Inc.) which have in essence solved this problem. These developments include:

- The development of a portable electrodynamic vibrator which operates in the frequency range of 20 to 1500 Hz, and a larger P and S-wave vibrator operating between 10 and 550 Hz.
- A compact PC-based vibrator control and data acquisition system.
- Software for preliminary data processing in the field.

These systems are currently being field tested by OYO Corporation with CRC participation and additional tests prior to any field work are also recommended in Phase II.

The use of explosives and "shaped" charges to increase the frequency content of sources (particularly S-wave) was also considered in this Phase of work. Because of the potential environmental impacts at the SRS and the recent advances in vibratory sources, these methods were not considered as viable options.

The correct interpretation of surface seismic data is highly dependent on the quality and quantity of borehole information available along the surface profiles. For a complete

model of subsurface conditions, borehole geologic and geophysical information is used to generate synthetic seismograms to compare to actual surface data. A number of commercially available programs were evaluated to determine:

1. The utility for modeling shallow data.
2. The ease of use of each package.
3. The applicability to the particular objectives at SRS.

These software packages will be used to model the borehole data across the proposed field acquisition site to produce synthetic seismograms in Phase II. The synthetics will be used for initial field planning, testing, final interpretation and also in the analysis of seismic resolution for thin bed mapping.

5 Fusion Technology

5.1 Site Models

In order to incorporate site specific information into the fusion algorithm, a so-called "layered cake" model is assumed to be a good approximation to the subsurface structure.

Hanford Site Model To test the fusion of real seismic data, collected at the Hanford Site, a three layer model was used; an upper layer, called the "Hanford Coarse", a middle layer, the "Hanford Fine", and a hard impermeable layer, called the "caliche" layer. These layers were chosen because the interfaces between them seem to provide good seismic reflectors. The states to be estimated included the seismic velocity in all three layers, and the depths to the interfaces between the Hanford coarse and fine, and between the Hanford fine and the caliche. A macroscopic trend was defined by a two-dimensional quadratic polynomial for both the layer depths and the seismic velocities. The fine variations of these parameters were defined by a two-dimensional spatial autoregressive model, similar to a "kriging" model as used by geophysicists. (A kriging model is a least squares estimate obtained by fitting depth data to a low order polynomial.) The area of interest for this test was 480 meters by 840 meters around three cribs. For the numerical computations, a grid of evenly spaced points was overlaid on this area, with grid spacing of 40 meters.

Thus, the grid had 22 rows and 13 columns. At each grid point, two layer depths and three seismic velocities were estimated. In addition, the six polynomial coefficients that define the macroscopic trends in the depths and velocities were estimated from the data. This give a total of 1,460 states to be estimated. Figure 2.2 shows the result of applying our fusion methodology to seismic and borehole data with this site model.

Savannah River Site Model To test the fusion in a geology similar to what will be found at the Savannah River Site, a model of a three foot thick clay layer embedded in a resistive host at a depth of about 300 feet was assumed. The region of interest is 150 meters by 450 meters. The grid spacing was 50 meters, laid out in four columns and ten rows. See Figure 5.19 for a complete description of the grid. Also shown on this figure is the locations of all the measurements. The notation used on this figure is as follows:

- ◇ denotes a grid point,
- + denotes a TDEM measurement point,
- denotes a refraction measurement point,
- × denotes a reflection measurement point.

At each of the 40 grid points, 6 parameters were estimated; 2 depths, 3 resistivities, and 1 seismic velocity. In addition, a quadratic polynomial was used to model the macroscopic trend in depths and velocities. Figure 5.23 shows the fused results of simulated time domain electromagnetic and seismic data with this site model. This figure is discussed in detail in Section 5.4 below.

5.2 Sensor Models

To test the ability of the fusion methodology to handle seismic and TDEM data, simple but realistic models were used.

Seismic Models: For seismic refraction, a simplified ray-tracing model was used to track the signal through the upper layers. In both the Hanford and Savannah River models, there was considerable lateral variation in the seismic signal velocity, whereas the layer boundaries were fairly smooth. This allowed for a great simplification in the ray-tracing algorithm. The layer giving the first time-of-arrival was assumed to define the reflective surface. Figure 5.20 shows the seismic velocities that were used for the Savannah River simulation. The curves represent the velocities in the upper layer, above the clay. The four colors denote different velocities along the four columns, as defined in Figure 5.19. The straight lines are the velocities in the clay layer (constant at 1,000 meters/sec) and in the sand layer below the clay (constant at 600 m/s).

For seismic reflection data, common midpoint gathers were used to give two-way transit time to each layer of interest. Figure 5.21 shows an example of a simulated reflection data set that was generated to test the fusion methodology, whereas Figure 5.22 is a refraction data set.

Time Domain Electromagnetic Model To generate and to process simulated TDEM data, the TEMIX code, written by Interpretex, Inc. of Golden, CO. was used. This code has been used within the geophysical industry for some time, and is considered to be reliable and accurate.

Figure 5.19: Layout of measurements and grid locations for Savannah River Site Simulation

Figure 5.20: Seismic Velocities Used to Generate Simulated Data

Figure 5.21: S-Wave Reflection Measurements (Simulated Data Set)

Figure 5.22: S-Wave Refraction Measurements (Simulated Data Set)

5.3 Computational Considerations

The fusion is done by stacking the measurement models together with the site model equations, and formulating a non-linear least squares problem, which must be solved by an iterative algorithm. For this Phase I effort, a simple Gauss-Newton algorithm was used to solve the least squares problem. This worked well in all cases, with convergence occurring in 15 to 20 iterations. Limited experimentation with starting values for the iterative scheme indicates that there is a well defined global minimum for the least squares cost function.

5.4 Fusion Results

Figure 2.2 shows the fusion of real seismic data with well log data from the Hanford 200 West Area. This seismic data was gathered by CRC for another related project. Since the algorithms to process this data were needed for the current project, it was appropriate to test the algorithms by trying them on real data that was collected under very controlled and well understood conditions. Four lines of seismic reflection and refraction data were collected. Each line was processed separately to check for consistency, then all of the data was processed together to obtain the three dimensional view shown in Figure 2.2. With this verification that the algorithms for processing the seismic data worked correctly, attention was turned to the Savannah River simulation.

For the Savannah River geology, TDEM data alone was used to estimate the depth and thickness of the clay layer, and the resistivity of both layers. However, equivalence problems limited the accuracy with which these parameters could be estimated from the TDEM data alone. That is, the inversion of TDEM data to produce estimates of depth to the clay layer and its thickness produced a wide range of possible estimates, any of which could explain the data. On the other hand, seismic data alone cannot estimate the thickness of the clay layer because it is not possible to detect reflections from the bottom of this thin layer. However, when the fusion methodology was used to combine TDEM with seismic data, using the site model as described earlier, the results were remarkable. Figure 5.23 gives a three-dimensional view of the output from the fusion.

The bottom of the chair cut view is the estimate of the clay layer. Above and below that estimate are the "one standard deviations" away from the estimates of the top and bottom of the clay. Note that, as expected, the estimate of the bottom of the layer has a larger uncertainty. The "true" value for the depth to the top of the clay, as used in the simulation, was 91.4 meters. This is well within the one standard deviation from the estimate. The variations in shading laterally show the changes in seismic velocity. The lateral shading is keyed to the display on the left of this figure, which gives seismic velocities in meters per second. The estimates shown track the truth model very well, with velocities ranging from 1,500 meters/sec. down to 500 m/s, then back to 2,400 m/s toward the rear of the chair cut view.

These results were obtained after 20 iterations of the Gauss-Newton algorithm, with total run-time on a SUN IPX Workstation of about 30 hours. There were 16,860 measurements processed to estimate the 320 parameters.

Figure 5.23: Savannah River Site Estimates of Depth and Seismic Velocity from Fusion Methodology

6 Site Selection

One requirement of the Phase I activities was to recommend a potential field survey site for geophysical data acquisition. The main site selection criteria were:

- Significant clay strata occur interbedded in sands (mapping of these strata is the project's objective).
- Absence of culture (power lines, metal structures, etc.). This criteria is important because one of the proposed methods (time domain electromagnetics) is highly sensitive to these features.
- Relevance of site to DOE environmental restoration activities.
- Access and availability of ground truth (e.g. borehole data).

On March 18 and 19 the Savannah River Site (SRS) was visited for the purpose of test site evaluation. Personnel of the Environmental Services Group at SRS made site specific information available and discussed the relevance of several sites to environmental restoration programs. From these sites, the area in the vicinity of Basin M was selected for future field surveys.

The general area proposed for field survey is shown in Figure 6.24. In this area, chlorinated solvents have been detected in the subsurface. The solvents (trichlorethylene (TCE) and tetrachlorethylene (PCE), are immiscible in water and tend to form a dense nonaqueous phase liquid (DNAPL) that can migrate downward through the vadose zone and into the groundwater. The migration path is influenced by the site geology (e.g. clay layers) hydrology and the physical/chemical characteristics of the solvents.

A Hydrostatigraphic Chart for the study area is shown in Figure 6.25. It is reported that the only known occurrence of organic contamination in the form of DNAPL's are within the formations above the "green clay" confining layer which splits the Steed Pond aquifer into the M-Area and Lost Lake aquifers. Below the "green clay" organic contamination exists in the aqueous phase. In the study area there are differing interpretations of the extent of the "green clay". This is likely due to the fact that the "green clay" is thin and discontinuous across the area. One interpretation of the distribution of the "green clay" is shown on Figure 6.26, and the organic plume distribution is outlined in Figure 6.27.

The exploration objectives of the surface geophysical surveys at this site are to attempt to group the distribution of the "green clay" and other clay strata which influence the distribution of contaminants.

Two potential areas for the geophysical study are indicated on Figure 6.27. These lines lie within the organic plume detected in the aquifer, and line 1 also crosses an inferred structural low in the "green clay" which may control DNAPL migration.

An analysis of the inferred structural low in the green clay serves several purposes:

Figure 6.24: General Site Location map of the Savannah River Site

Figure 6.25: Hydrostratigraphic Chart for A and M Area

Figure 6.26: Structure Contour of Green Clay (After Radland et al, 1992)

Figure 6.27: Generalized Plume of TCE in Parts per Billion in Tertiary Aquifers

- It may confirm or refute the existence of the structure. The structural low is inferred from widely spaced borehole and cone penetrometer data.
- It can help determine the ultimate accuracy of mapping the depth to clay layers with combined geophysical methods and data fusion.

At the Savannah River Site, even slight (e.g. several feet) depressions or structural lows in clay layers can form pockets in which DNAPL's will pool. Geophysical methods which can detect these pockets from the surface could replace or supplement costly invasive methods such as drilling or cone penetrometer tests.

The proposed lines were selected to utilize road and trail access, and also because they are removed from cultural noise sources which are present in this area. The selection of test lines along roads and away from cultural noise sources is desirable for the following reasons:

- At this time, the optimum seismic source (vibrator) is truck or trailer mounted. Off-road travel with vehicles is discouraged at the Savannah River Plant and permits must be obtained to cut brush or trees. Therefore, it is logistically simpler to use existing roads at the site for Phase II work.
- For the purpose of testing new TDEM and fusion algorithms, the highest possible data quality is desirable. This can best be achieved by avoiding cultural noise sources.

The data acquired in Phases II will be evaluated to determine what effects cultural noise will have. If subsequent surveys are performed at the Savannah River Site, it may be necessary to establish trails in areas of interest if roads are not available.

In this general area, more than 20 cone penetrometer tests and more than 20 boreholes are available to provide ground truth.

It is felt that the site selected at SRS adequately satisfies all of the selection criteria. Although geologic ground truth is plentiful at this site, several different interpretations of the distribution of the "green clay" have been made by researchers.

7 Conclusions

This report has described some preliminary results of on-going research into the use of non-invasive techniques for mapping thin clay layers. The research so far indicates that the improvements in TDEM and seismic technology, together with the use of sensor data fusion, can indeed accomplish the desired goals.

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A APPENDIX: Related Projects

In this Appendix, we give a short description of related DOE projects in which CRC is involved.

A.1 Fusion Workstation

Under the joint support of DOE (EM-50) and DOD, CRC is developing a Fusion Workstation that will demonstrate the effectiveness of data fusion in providing a cost-effective method for high quality subsurface characterization of DOE sites, specifically the Hanford West 200 site. Cost savings are realized by using the Fusion Workstation to process data from non-invasive sensors to provide a low cost yet high quality solution to site characterization problems.

The major application of this effort is to demonstrate the capabilities of this new fusion technology for mapping the caliche layer by using seismic data together with an autoregressive model of depth and seismic velocity changes.

A.2 Non-intrusive Characterization and Sensing of Buried Objects

The purpose of this project is to demonstrate that significant improvements can be made in the information content and level of confidence about buried waste, extracted from surface measurements with non-invasive geophysical methods. The demonstration is supported by, and will be performed at, the Idaho National Engineering Laboratory (INEL).

A.3 Fracture Detection, Mapping and Analysis of Naturally Fractured Gas Reservoirs using Seismic Technology

Under this DOE supported project, CRC will acquire approximately six to twelve miles of 9-component surface compressional and shear wave reflection data over a producing naturally fractured gas reservoir. The use of three sources and three-component geophones results in a matrix of nine recorded datasets. In addition to the surface reflection data, a 9-component VSP survey will be acquired for interpretation purposes by entering an existing drill hole. Static corrections will be applied to the survey data. For compressional wave reflection surveys, procedures for static corrections are well developed, but they are less developed for shear wave reflection processing. To understand and apply shear wave static corrections, a seismic 3- component refraction survey will also be run over the survey lines.

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