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GEOPHYSICAL DATA FUSION FOR SUBSURFACE IMAGING

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DISCLAIMER

P9 Geophysical Data Fusion for Subsurface Imaging

1. CONTRACT INFORMATION

Contract Number	AC21-92MC29106
Contractor	Coleman Research Corporation 9891 Broken Land Parkway, Suite 200 Columbia, Maryland 21046 (301)621-8600
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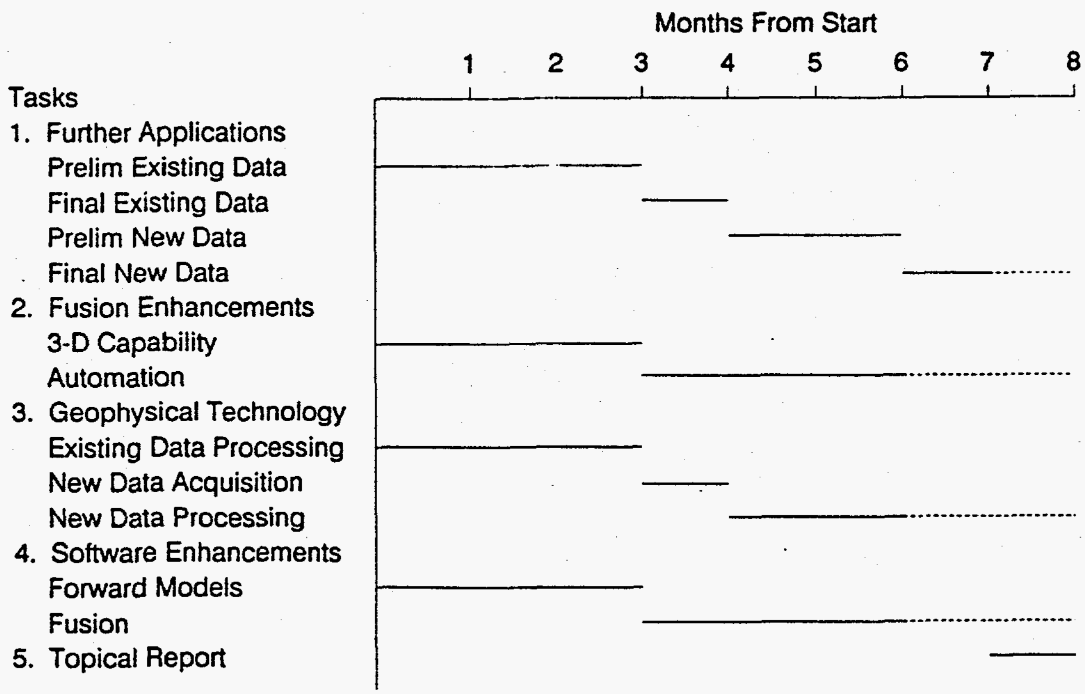
METC Project Manager	Vijendra P. Kothari
Period of Performance	October 1, 1992 to March 31, 1995
Schedule and Milestones	

FY95 Program Schedule



2. OBJECTIVES

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 an 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.

3. BACKGROUND INFORMATION

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 emmisivity. Clays often have a higher content of Thorium (Th) and Potassium (K) than sands and gravels. However, because of rapid attenuation, natural gamma ray emmisivity 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 can also be implemented from the surface.

The geophysical methods employed in Phase II to map clay layers were Time Domain Electromagnetics (TDEM) and Seismic Reflection (using both P and S waves). The reasons for selecting these methods is detailed in the Phase I report. In general terms, the main reasons are:

1.) Both methods measure parameters (resistivity in TDEM, velocity in Seismic Reflection) that are sensitive to physical property changes between sand and clays.
2.) Both methods have exploration depth capabilities that can meet or exceed the 300 ft. exploration depth requirement.
3.) Both methods are capable of vertical and lateral resolution (mapping accuracy) of geologic layers which are significant for Environmental restoration activities.
4.) Both methods are non-intrusive.

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. The 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, 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.

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 the 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.

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 seismic 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.

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 images 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

4. PROJECT DESCRIPTION

The A&M area of the Savannah River Site was selected for the Phase II data acquisition. A detailed view of the geophysical survey line (line 1) showing nearby boreholes and landmarks is given in Figure 4.1. The main site selection criteria used to select the A&M area were:

1.) Site has known clay layers and geologic (borehole) control.
2.) The distribution of clays at site controls ground water flow/contaminant migration.
3.) The geologic/hydrologic data base was made available for correlating with the surface geophysics.

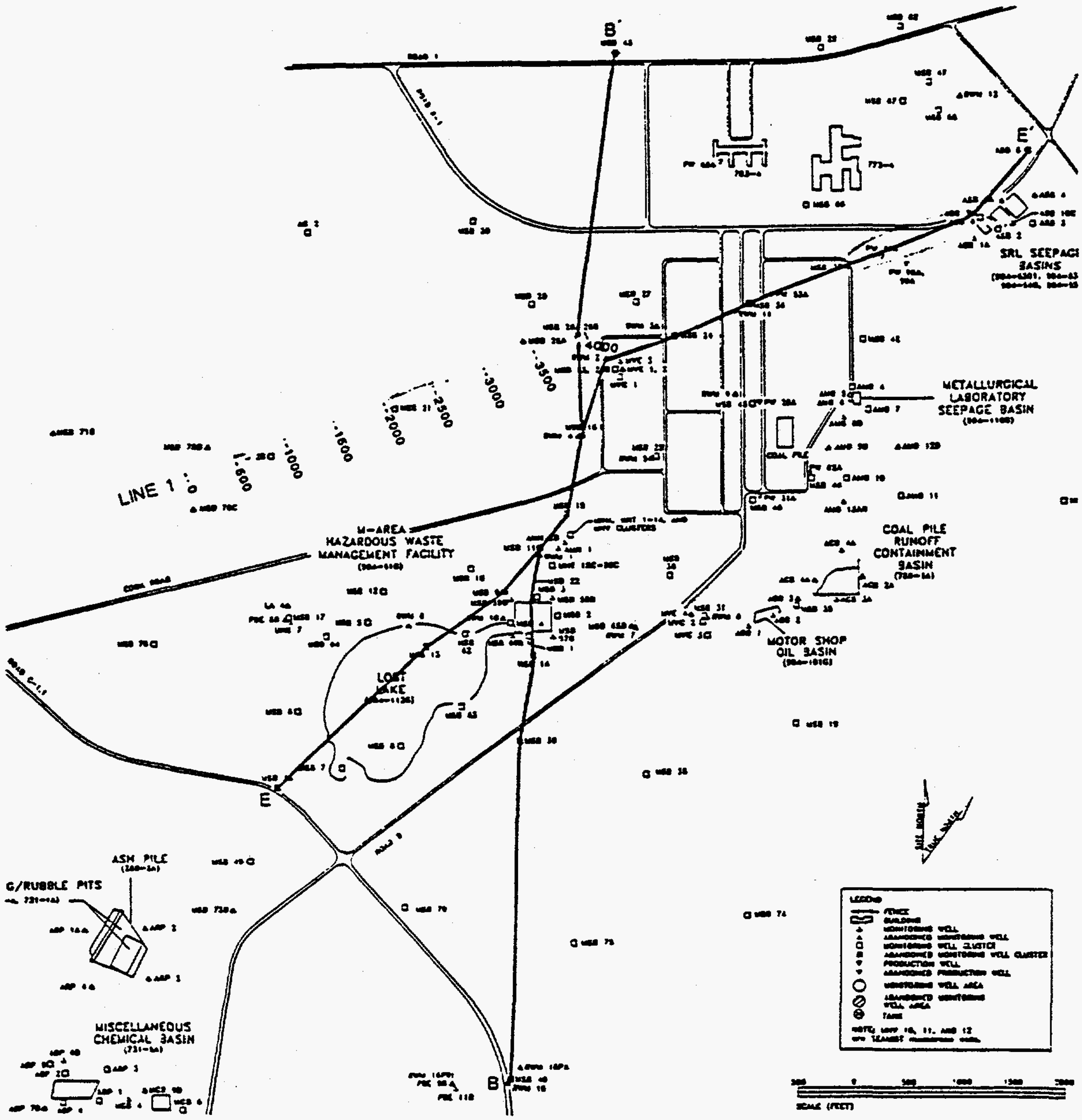


Figure 4.1. Location of Geophysical Survey (Line 1 - Yellow) and Hydrogeologic Sections (Red). A&M Area Savannah River Site

Another important criteria for selecting the specific location of line 1 for the geophysical survey was the absence of cultural features which would affect the geophysical data. Cultural features defined in this manner would be powerlines, fences, buried metallic objects, etc., for TDEM surveys, and vibrating noise sources (such as drill rigs, compressors etc.) for the seismic surveys. Also, near surface soil disturbances often cause a deterioration in the quality of the seismic data. Line 1 was selected to avoid as much as possible these cultural features.

The hydrostatigraphic chart of the A&M area (Reference Westinghouse Savannah River Company, 1992a) is shown in Figure 4.2. This chart shows multiple clay confining zones in the A&M area, with pinch-outs and discontinuities inferred towards the northern part of the A&M area.

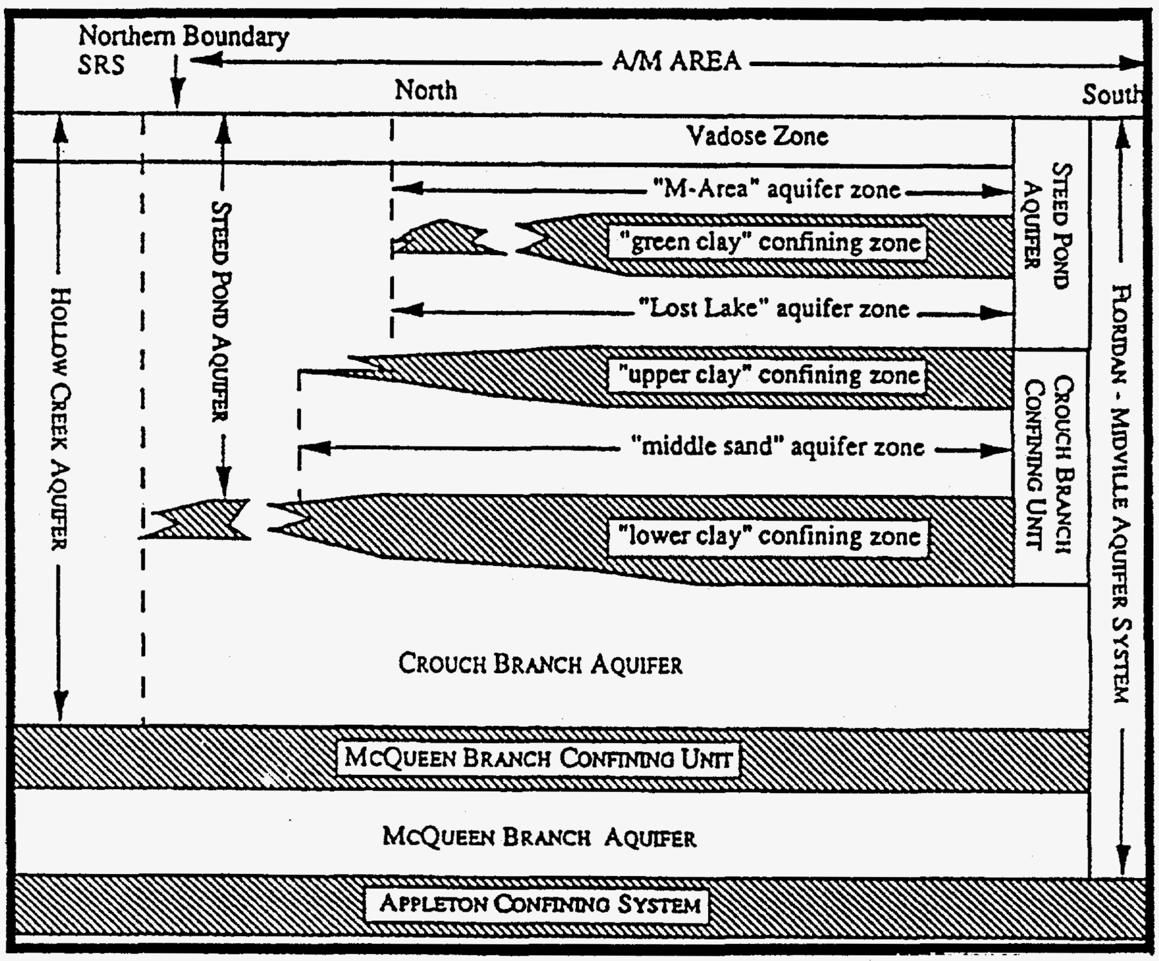


Figure 4.2. Hydrostratigraphic Chart for the A&M Area (From WSRC-TR-92-355)

Two hydrogeologic cross-sections (B-B' and E-E') were created from borehole information in the A&M area (U.S. EPA Publication 9355.4-05A., February 1992) as shown on Figure 4.3 (reference figure 1.2 for position). These sections show the concentration of the contaminant 1,1,2-trichloroethylene (TCE) in parts per billion (ppb) in ground water and the position of the Ellenton clay at a depth of about 180 to 250 feet. Clean up goals in this area are to reduce TCE levels to 5 ppb. In the A&M area, the Ellenton formation is reported to vary in thickness from 32 to 95 feet and is composed of two major clay layers separated by a poorly sorted sand.

The Ellenton clay is reported to be one of the dominant barriers to downward contaminant flow in the A&M area. Section B-B' shows that the Ellenton clay is an effective barrier to TCE migration into deeper aquifers. Section E-E' shows that the TCE contamination has migrated below the Ellenton clay (between wells MSB-37 and ASB-8) to the deeper aquifers. Concentrations of TCE below the Ellenton clay are 1980 ppb in well MSB-37.

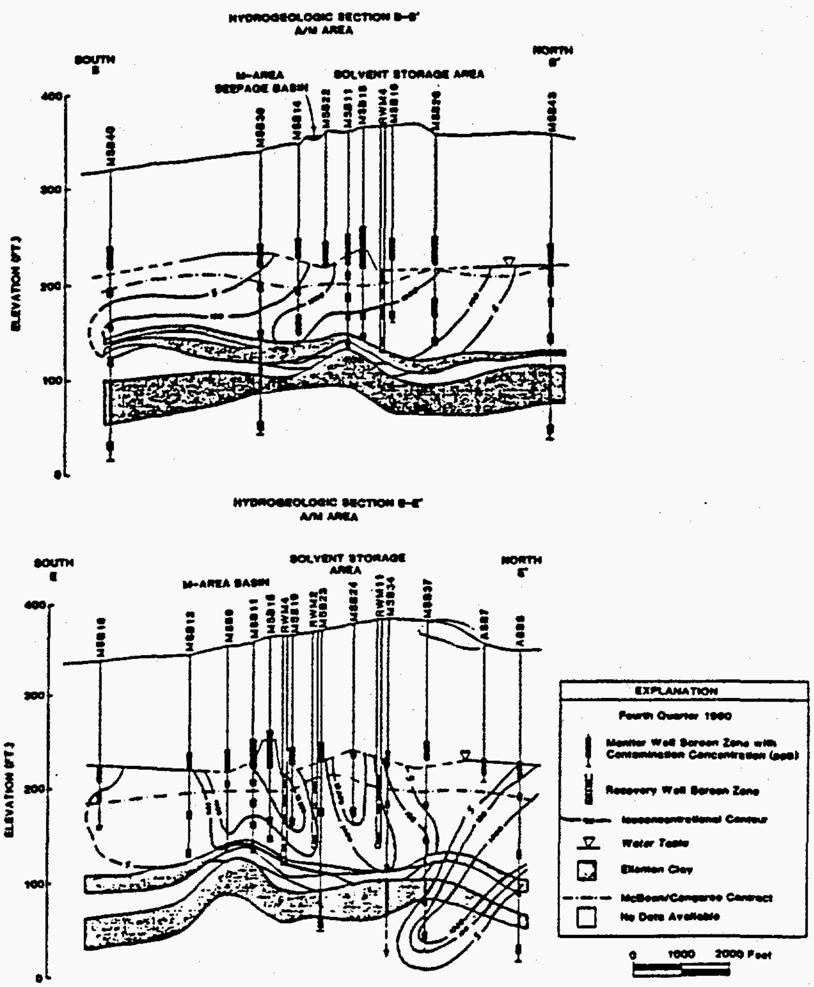


Figure 4.3. TCE Concentration Along Cross Sections B-B' And E-E'. A&M Area, Savannah River Site. Source: U.S. DOE, 1991. (Redrawn From Original)

Several scenarios can be used to explain this occurrence. One scenario is that the Ellenton clay may be discontinuous between the two wells, which allows contaminants to migrate downward. Even though there are a substantial number of boreholes in the area, this scenario cannot be confirmed by the intrusive borehole testing. This hydrogeologic section clearly illustrates the role surface geophysical surveys can play in mapping clay layers and extrapolate continuity (or discontinuity) of clays and other geologic units between boreholes.

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 geological model of the subsurface.

5. TDEM RESULTS (1-D INVERSIONS)

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 forward solutions taken from Anderson (1973) for the vertical field, and those developed for this research for the horizontal field. For all inversions, the minimum number of layers necessary to adequately fit the data were used (i.e. a significant improvement in error between model and data was not achieved by adding additional layers). All of the parameters of the geoelectric section (resistivities and thickness) were allowed to vary freely in the inversions. The interpretation of the geoelectric parameters into geologic/lithologic units was accomplished by assigning characteristic resistivity ranges to lithologic units. Information from a nearby borehole geophysical log was used to guide this correlation. Five separate measurement stations (resulting in 9 soundings), were obtained for each transmitter loop. In standard production TDEM surveys, often only the central loop measurement is taken. To evaluate the data taken in this survey with 1-D inversions, five separate geoelectric sections were created, being:

1.) One geoelectric section for central loop vertical field.
2.) Two geoelectric sections for out of loop horizontal fields (one for each of the offset distances, 120 and 180 feet).
3.) Two geoelectric sections for out of loop vertical fields (one for each of the offset distances, 120 and 180 feet).

The geoelectric cross-section and geologic interpretation for the central loop TDEM measurements (vertical field) is given in Figure 5.1. This figure shows that for most of the line a three layered section was interpreted. The upper layer with resistivity ranging from 500 to 1500 ohm-m is

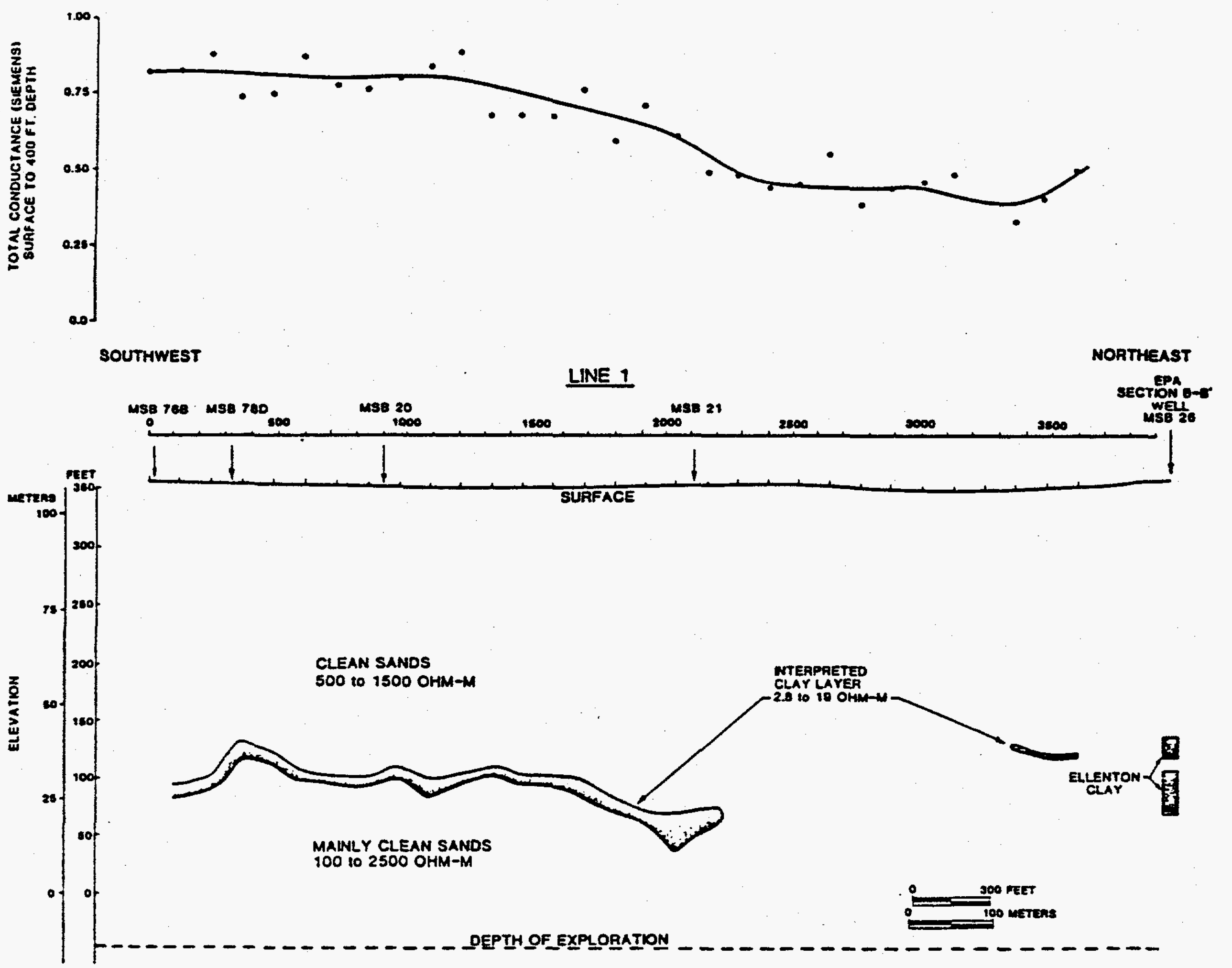


Figure 5.1. Geoelectric Cross Section, Line 1. A&M Area, Savannah River Site Central Loop, Vertical Field Measurements

interpreted as clean sands. A thin (3 to 10 meter) and conductive (2.8 to 19 ohm-m) layer at a depth of about 70 meters (230 ft) is interpreted as a clay. This clay interpreted from the TDEM data corresponds to the Ellenton Clay described in U.S. EPA report 9355.4-055A and illustrated in Figure 4.3 (Section 1.8). In the central loop inversion this layer is absent between station 2280 and 3240. The basal layer in the section with resistivity ranging between 100 and 2500 ohm-m is interpreted as mainly clean sands. Thus, the interpretation of the central loop TDEM data infers a discontinuity or pinch-out of the Ellenton Clay between stations 2280 and 3240.

The TDEM soundings are highly sensitive to the conductance (ratio of thickness and resistivity) of layers within the geoelectric section. In this geoelectric section, the layer with the highest conductance is the clay layer, and so graphs of conductance will illustrate changes or discontinuities in the clay. Figure 5.1 shows a graph of the total conductance of all layers to a depth of about 400 feet (122 meters) which is the approximate exploration depth of the soundings.

This graph shows that over the section of the line where the clay is interpreted to exist, conductance values of greater than 0.5 Siemens are computed. Conductance values less than 0.5 Siemens correspond to the section of the line where the clay was interpreted to be discontinuous (or missing).

An example of the geoelectric sections obtained from inversion of out of loop measurements is given in Figure 5.2 for the vertical field, 180 feet offset measurements. The other out of loop geoelectric sections display similar attributes.

This section shows a similar geologic interpretation as that obtained from central loop measurements (e.g. a thin clay layer at a depth of 70 meters is resolved). However, the clay layer is interpreted to be continuous across the line. A plot of total conductance (to a depth of 400 feet) is also shown in Figure 5.2. The total conductance plot is similar to that obtained with the central loop data and indicates a change in clay layer parameters (decreased conductance) over the section from stations 1920 to 3360.

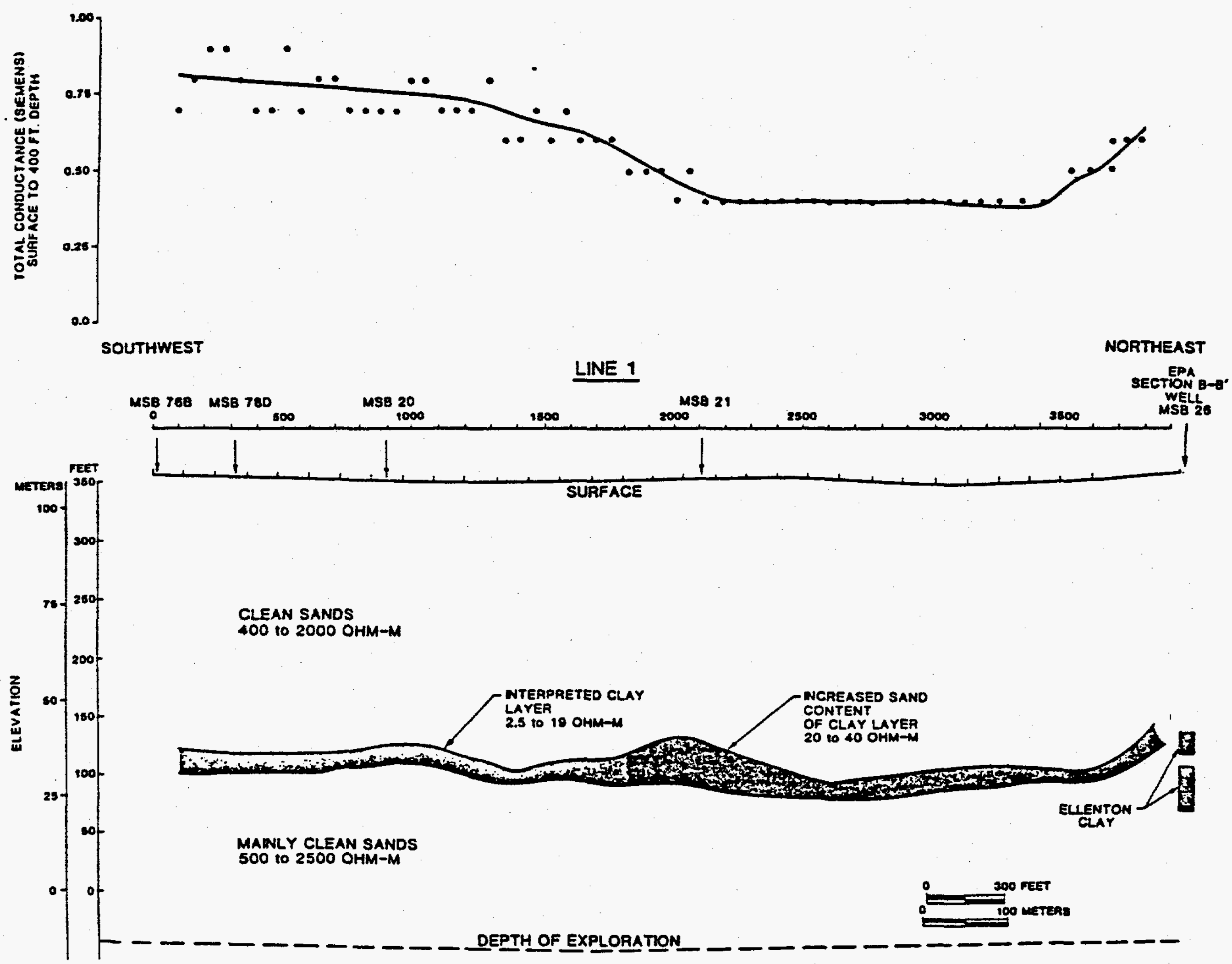


Figure 5.2. Geoelectric Cross Section, Line 1. A&M Area, Savannah River Site Out Of Loop, Vertical Field Measurements

Examination of the individual inversion results reveals that the clay layer resistivity increases over this section. The increase in resistivity over this interval is likely caused by a change in the composition of the clay, perhaps due to an increase in sand within the clay unit.

In this survey, the data quality of out of loop, vertical field TDEM measurements was better than the central loop (vertical field) measurements. Based on past experience, this phenomenon is unusual. Possible causes for the lower quality Central loop measurements are:

- direct coupling of the primary field with the receiver electronics, or
- Induced Polarization effects. Both of these effects will cause a deterioration of the quality of Central Loop measurements but not out of loop measurements. Direct coupling effects are most prominent in highly resistive geoelectric sections, such as that encountered in the A&M area, and thus are expected to be the reason for the phenomenon.

6. DATA FUSION RESULTS

This section describes the fusion of the geophysical survey data to produce an estimate of the A&M site lithology along the survey line. Along line 1 in the A&M area, three measurement types of TDEM (vertical field-central loop, and vertical and horizontal field-out of loop) and two measurement types of seismic data (P and S wave) were collected.

The TDEM survey methods used by CRC resulted in the collection of eight times the amount of data typically collected in a TDEM survey. A new vibratory seismic source was used, resulting in the recording of 16 times more data than is typically recorded in a seismic survey. At present, CRC has not completed the preparation of the seismic data as required for use in data fusion. Therefore, this report will only describe the data fusion of the three different types of TDEM data.

6.1 Description of TDEM Data

The three types of TDEM data collected in the A&M area are:

- Central loop, vertical field (26 soundings),
- Out of loop, vertical field (124 soundings)
- Out of loop, horizontal field (116 soundings)

In routine, production type TDEM surveys, 33 central loop TDEM soundings would be measured along the A&M line 1. This was done, and in addition, 264 out of loop soundings were taken along line 1. After elimination of soundings that were corrupted by nearby power lines and metal culverts, 26 central loop and 240 out of loop soundings were used in the data fusion. As will be discussed in the following sections, this additional data was useful in resolving a thin clay layer about 70 meters below the surface.

6.2 Definition of Data Fusion

Data Fusion, as developed and applied under this PRDA, involves the joint inversion of spatially distributed measurement data under spatial continuity restraints to obtain an estimate of the lithology of the area. This concept is illustrated in Figure 6.1. The measurements may be from different sensors and/or from one or more modes of the same sensor. The fusion estimate is obtained by using an a priori, layered model of the earth which can be derived, for example, from traditional 1-D inversion/interpretation methods. Next, the sensor forwards models are used to generate anticipated measurement values.

The differences between the actual and anticipated measurements are used by a constrained nonlinear least squares estimator to update the layered earth parameters. This step is repeated until the estimator converges. The fusion results are used to generate a 3-D visualization of the estimated survey area lithology.

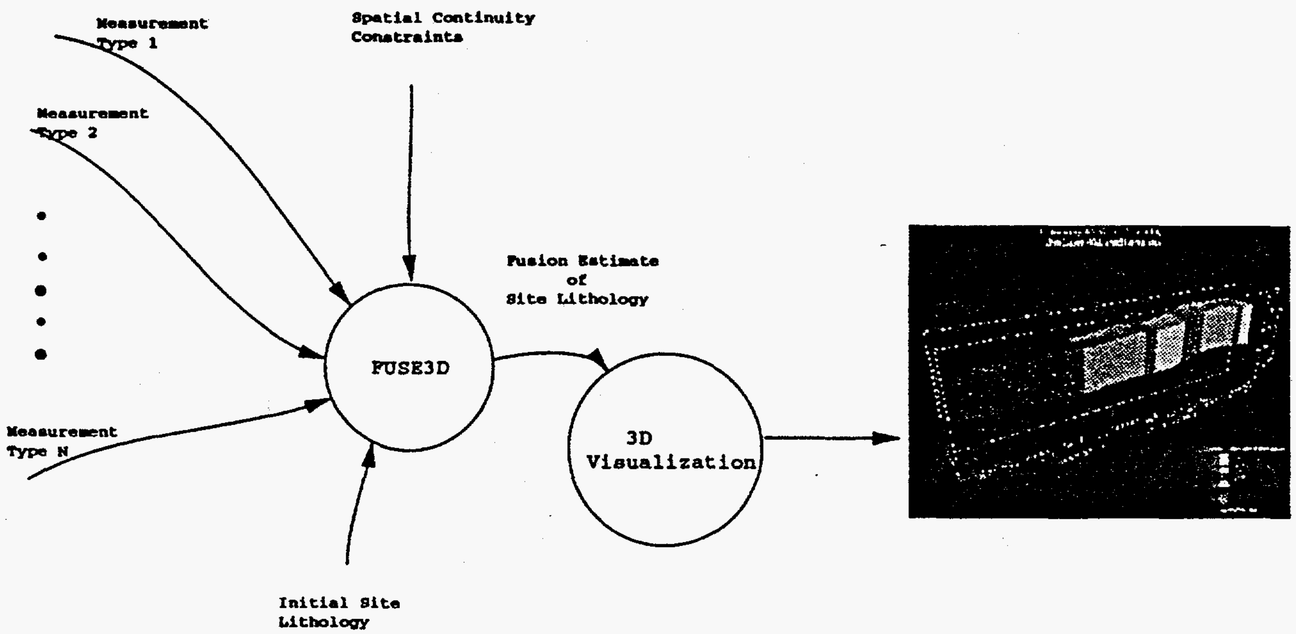


Figure 6.1. Concept Of Data Fusion

The fusion methodology is more fully described in a paper by Porter (1993). CRC has been granted a patent (US Patent 07/974,405), on the Data Fusion Workstation.

6.3 Preprocessing of TDEM Survey Data

The largest part of the survey data processing effort occurs prior to the data fusion. The data flow diagram in Figure 6.2 shows how the TDEM data is prepared. The survey team uses a digital data logger and manual notebook to produce a quality assured data set of individual soundings. For each sounding, a log-log plot of the measurement value vs. timegate is generated. These plots are reviewed to assess data consistency within a sounding. A 1-D TDEM inversion is performed on the individual soundings as a further quality control check.

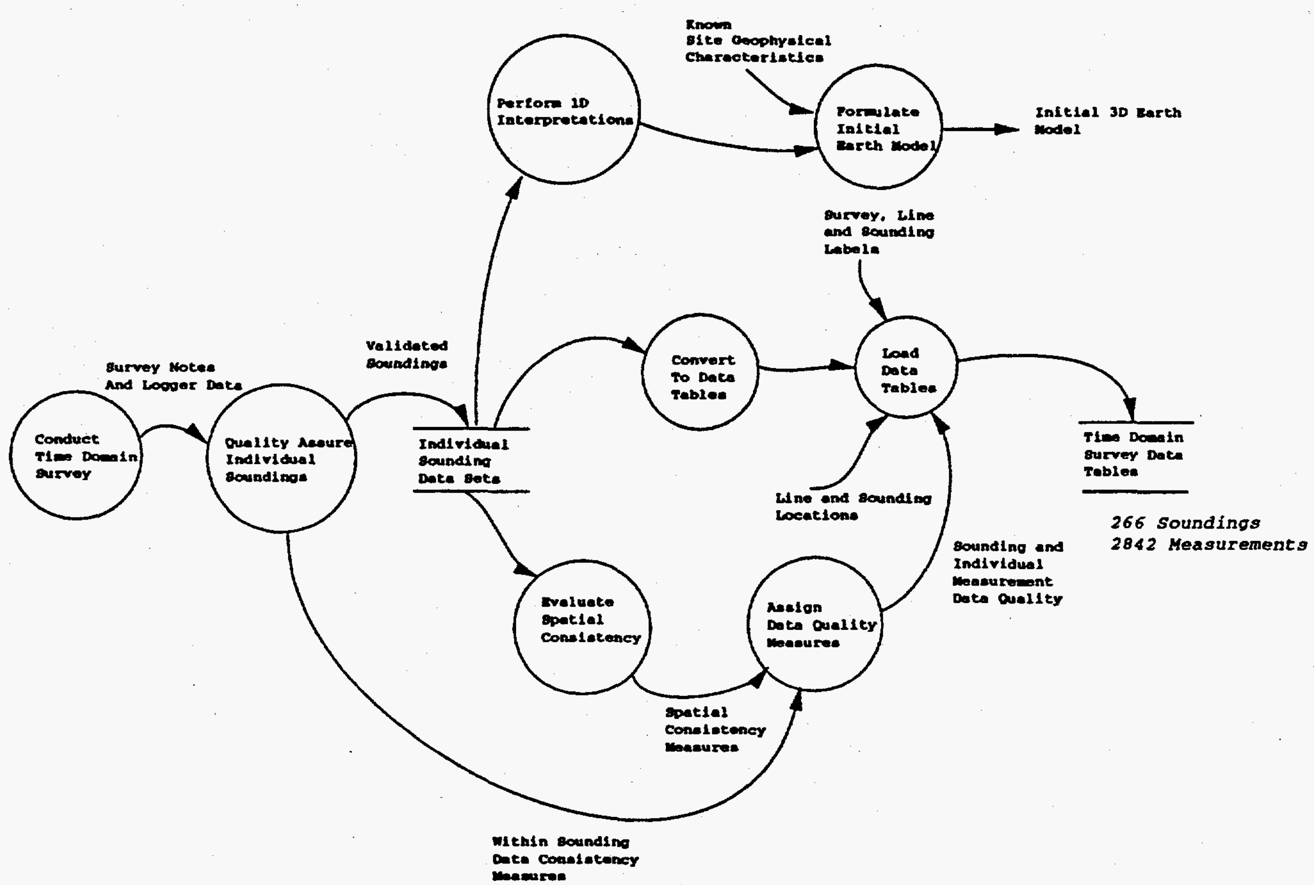


Figure 6.2. Time Domain ElectromagneticSurvey Data Preprocessing

The spatial consistency of the data is evaluated for each measurement type by plotting the measurement value vs. sounding distance from the line origin for each timegate. These plots will identify individual soundings that are inconsistent with adjacent soundings of the same type.

The results of the individual sounding consistency checks are used to assign a data quality index to each individual data point. The quality index is a number between zero and one, with zero being useless data, and one being perfect data.

After the data quality assessment procedures are completed, the measurements data is converted to a tabular format loaded to a set of INGRES tables. During this conversion step, x and y positions values are computed for each sounding. Typically thesounding data files, as received from the survey team, may only contain the distance of each sounding from the line origin. The location and orientation of the survey line in an x-y frame is than manually picked off a survey map. In this survey, the locations of points on the line was established in the Savannah River Site Coordinate System.

6.4 Time Domain Data Fusion

The Line 1 time domain data fusion was accomplished in two phases as illustrated in Figure 6.3. During the first phase, 26 central loop soundings were used to obtain a preliminary solution that was consistent with existing information about the A&M site geology and the 1-D TDEM inversion/interpretation results. After each fusion iteration, the estimates and residual plots were reviewed to identify possible inconsistencies. The spatial continuity parameters were then revised for the next iteration. This process took about four days.

During the second phase, all 266 soundings were used with an initial earth model and continuity constraints from the phase one solution. The 240 out of loop soundings were not subjected to the same degree of quality assurance checking as the central loop soundings. For this reason, a robust reweighting procedure was used to automatically exclude individual outlying measurements. The fusion estimator was initialized with the phase one solution and all 266 soundings processed with measurement initial weightings derived from the computed measurement sigma values. After the estimator converged, Tukey's bisquare weight (Mosteller and Tukey 1977) was used to adjust the measurement sigmas. The adjustment is a function of the absolute value of the measurement residual. For measurements with small residuals, there is no corresponding adjustment to the measurement sigma. For measurements with very large residuals, the measurement sigmas is multiplied by 1.0×10^6, which effectively excludes that measurement from the fusion estimation process. For measurements having intermediate residual values, the measurement sigma was adjusted as a function of the residual magnitude. After adjustment of the measurement sigmas, the fusion estimator was executed again to obtain the robust estimate of site geoelectric parameters. The second phase was completed in two days, including the programming of the utilities for processing the measurement residual files to adjust the measurement sigmas and prepare revised TDEM measurement data files for input to the next fusion iteration.

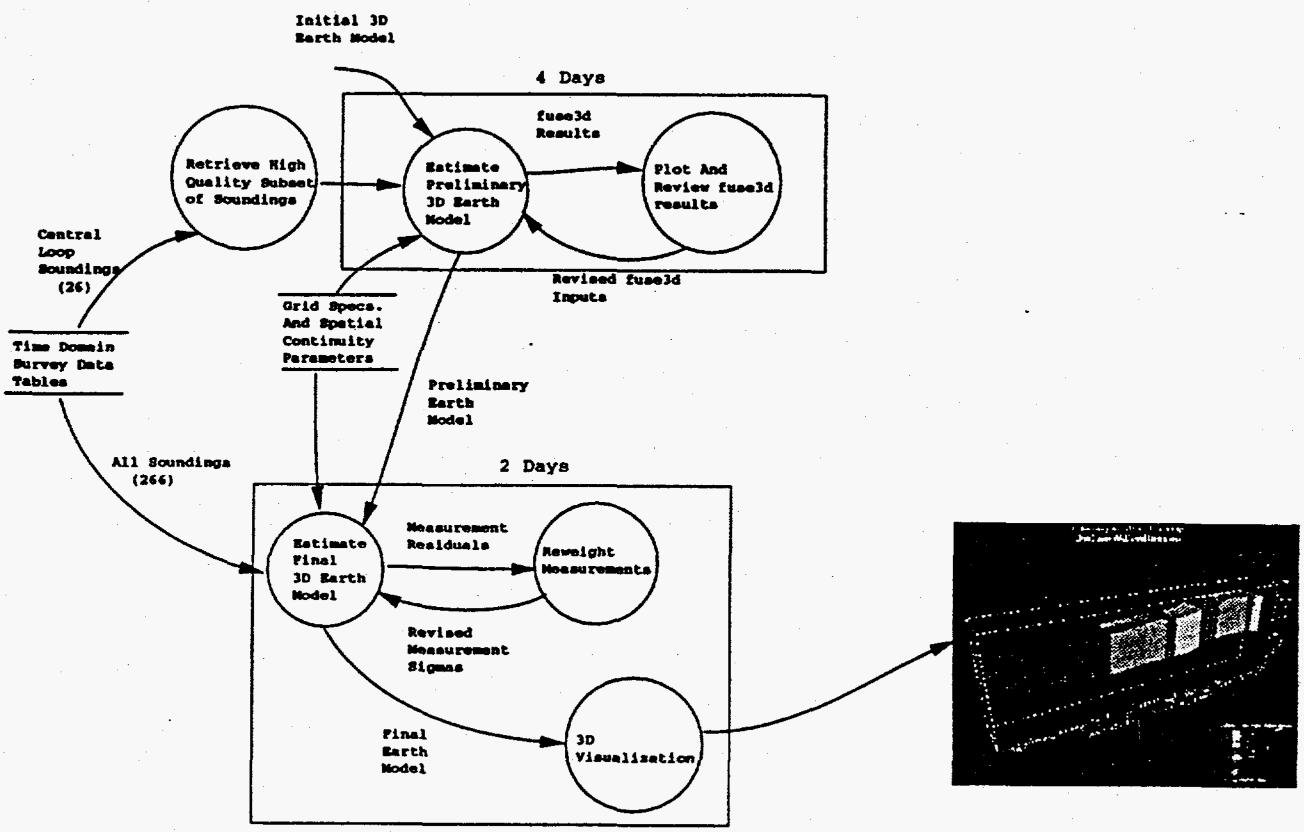


Figure 6.3. Time Domain Data Fusion For Savannah River A&M Line 1

6.5 TDEM Data Fusion Results

The TDEM data fusion results for the A&M Line 1 are presented in Figure 6.4. The clay layer depth and thickness were constrained to be relatively constant and the clay layer resistivity was allowed to be highly variable. This resistivity shows a significant increase at the end of the line. The geologic interpretation of these results is that either the clay layer has a break in this interval or the clay composition changes.

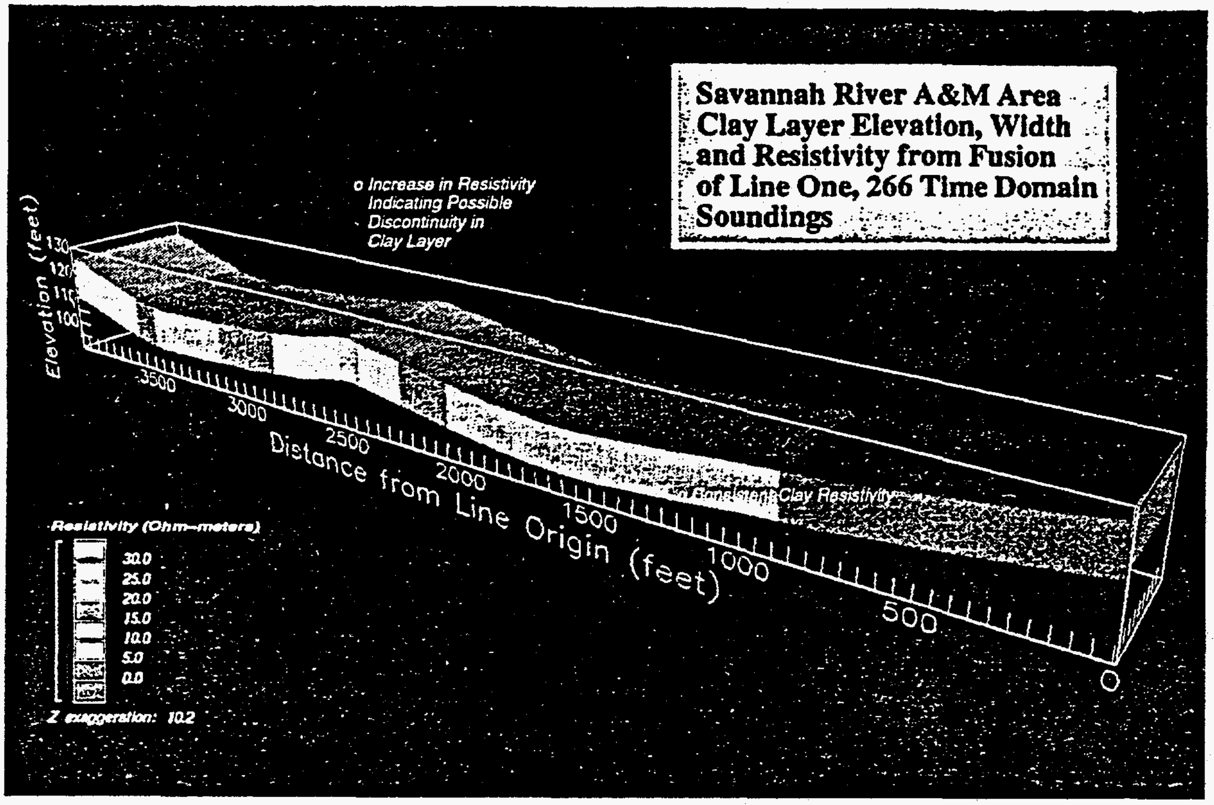


Figure 6.4 TDEM Data Fusion Results

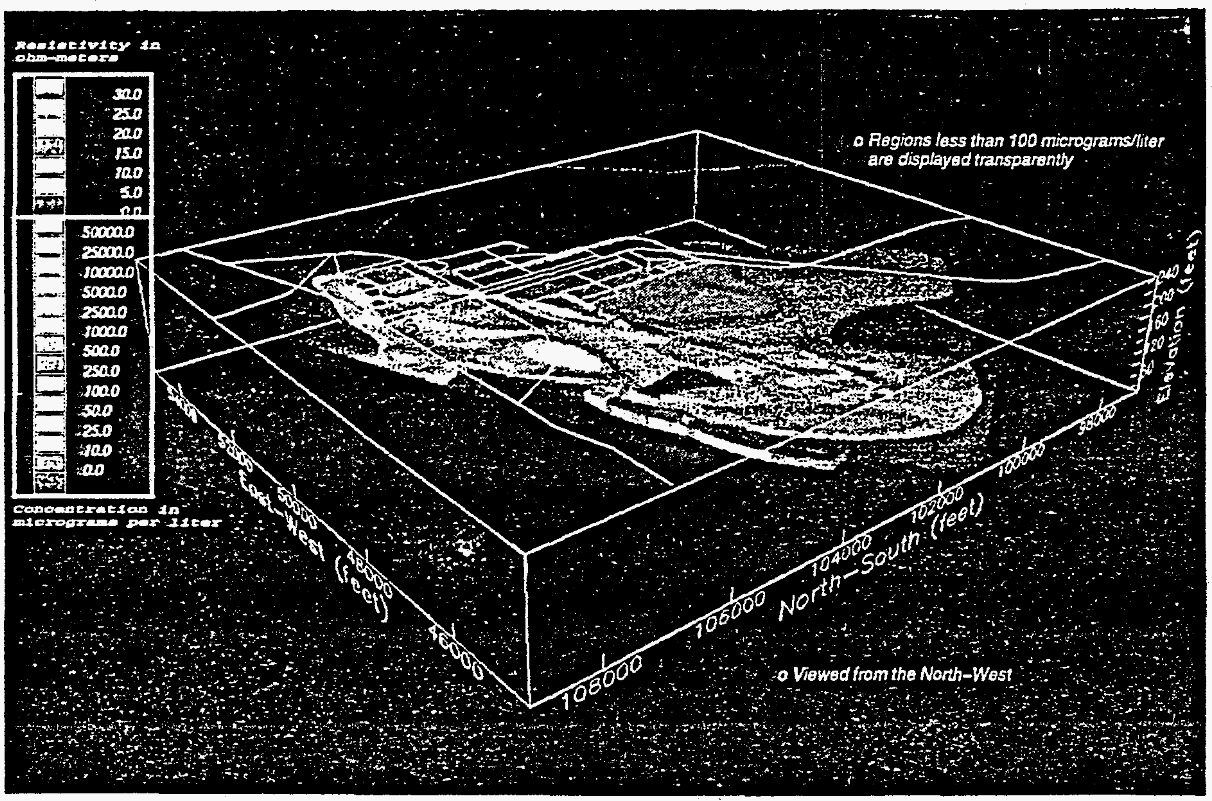


Figure 6.5. Intrepreted Clay Relative To TCE Plume

Figure 6.5 is a 3-D visualization of the fusion estimates of thin clay layer depth, width (thickness) and resistivity along Line 1. Figure 6.5 places this in the context of the entire A&M area. The TCE contaminant plume was provided by Carol Eddy-Dilek at the Savannah River Site.

6.6 Benefits of Data Fusion

Over the past three years, CRC has worked with data from several different DOE sites and demonstrated the benefits that are to be derived from the application of statistical data fusion, as implemented by CRC, to DOE site characterization problems. Working with PNL at the 200 West area of the Hanford Site, CRC conducted a seismic reflection and refraction survey and used the data fusion software to refine the characterization of a caliche layer approximately 38 meters below the surface. The use of data fusion permitted CRC to process high density seismic refraction data that current practice seismic methods cannot handle. The resultant 3-D estimate of caliche layer depth was in agreement with existing well logs, provided more interpolation between wells, and extended into areas where there were no wells.

At the Savannah River Site A&M area, CRC conducted TDEM and seismic surveys along a single line. Fusion of the high-density TDEM data has identified a confining clay layer about 70 meters below the surface and a zone where clay composition changes or a discontinuity exists. This zone appears to be small enough that it is not present at nearby wells.

From these examples and other applications, CRC has identified the following benefits to the use of data fusion for site characterization:

- *Increased Staff Productivity* -- CRC has been able to jointly process eight to ten times more site-characterization data than could be processed using current geophysical data reduction methods,

- *Increased Confidence in Characterization* -- by processing a larger volume of data and by using statistically rigorous physically valid methods for obtaining estimates which incorporate data from wells, geophysical sensors and a priori site geology, CRC has demonstrated that a significant increase in confidence of characterization can be achieved,

- *Improved Visualization and Interpretation* -- the data fusion output is a set of grids that can be directly utilized by commercial 3-D visualization tools (e.g. earthVision, from Dynamic Graphics, Inc., 1015 Atlantic Avenue, Alameda, California, 94501). The resulting 3-D images have been essential to CRC for communicating the significance of characterization results to our clients and their management,

- *Improved Reproducibility of Results* -- using the same fusion software, and the same survey data, analysts can accurately verify each others results. For example, PNL was able to use the fusion software to process the seismic data from the Hanford 200 West area and get the same results that CRC had previously published.

7. FUTURE WORK

Phase III work will expand upon the survey coverage obtained in this Phase II of this project at the Savannah River Site, and include improvements in geophysical sensor and fusion technologies. The Phase II acceptance criteria satisfied in preparation for Phase III are described below.

Technical Acceptance Criteria -- Phase II:

- Recommend locations for monitor wells, showing reduced need for monitor wells and reduced cost overall.

The geoelectric section derived from the TDEM in the A&M area illustrates how surface geophysics (in conjunction with all other geologic and hydrogeologic data) can be used to select drill holes and monitoring well locations, and how information from these intrusive tests can be extrapolated. The geoelectric sections indicate a region of discontinuity or composition change in the Ellenton Clay, which can have a major impact on the local hydrology and contaminant migration patterns. Drill holes or monitoring wells would be placed in this region of the clay layer, and the information from the drill hole extrapolated over the extent of the region observed in the surface geophysical data. Likely, another drill hole or monitoring well would be placed in areas with geophysical signatures where the clay is inferred to be present, so that information from these intrusive tests can be extrapolated over the entire area with similar geophysical structures. The seismic reflection, still being processed, will further amplify continuity, discontinuities, and offsets in the clay.

- Identify thin (1-3' thick) clay layers and geologic discontinuities.

A conductive layer was detected with TDEM in the A&M area at a depth of about 70 meters. This layer, which was about 5 meters (16') thick, was correlated with the Ellenton Clay. Over a portion of the survey line the TDEM data infers a lithologic change or discontinuity in this clay. An evaluation was made using synthetic data (forward models) to determine the minimum clay layer thickness which could be detected at a depth of 300 feet (91.4 meters), using the geoelectric parameters typical of the A&M area. This evaluation shows that clay layers of relativity low resistivity (< 30 ohm-m) and with a thickness of 3 feet, are expected to be detectable.

The seismic shear wave data indicate that with the parameters used in this survey, good reflectors with thicknesses of less than 3 feet can be resolved at depths of 300 feet.

- Show advances in seismic technology to improve subsurface images.

Two activities performed in Phase II have resulted in improved imaging of thin clay lenses. These are: measurements of both compression (P) and shear (S) wave reflection using vibrators; the use of both P and S wave reflection demonstrates that different reflectors are seen with the different methods. These data can be used in a complimentary fashion to improve interpretations. The use of vibrating sources is shown to improve high frequency signal content which in turn allows for detection of thinner layers.

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Session 3

Contaminant Plume Containment and Remediation Focus Area