Project Number: 70052

Title: Material Property Estimation for Direct Detection of DNAPL using Integrated Ground-Penetrating Radar Velocity, Imaging and Attribute Analysis

Date: 6-15-2003

Lead PI: John Bradford, (208) 426-3898, johnb@cgiss.boisestate.edu
CGISS, Boise State University
1910 University Drive, Boise, Idaho 83725

Co-PIs: Scott B. Smithson, (307) 766-5280, sbs@uwyo.edu
W. Stephen Holbrook, (307) 766-2427, steveh@uwyo.edu
University of Wyoming, Department of Geology and Geophysics
Laramie, Wyoming 80271-3006

Graduate Students: Jake Deeds

Research Objective

The focus of our work is direct detection of DNAPLs, specifically chlorinated solvents, via material property estimation from surface ground-penetrating radar (GPR) data. We combine sophisticated GPR processing methodology with quantitative attribute analysis and material property estimation to determine the location and extent of residual and/or pooled DNAPL in both the vadose and saturated zones. An important byproduct of our research is state-of-the-art imaging which allows us to pinpoint attribute anomalies, characterize stratigraphy, identify fracture zones, and locate buried objects. Implementation and verification of these methodologies will be a significant advance in GPR research and in meeting DOE's need for reliable in-situ characterization of DNAPL contamination.

Chlorinated solvents have much lower electric permittivity and conductivity than water. An electrical property contrast is induced when solvents displace water in the sediment column resulting in an anomalous GPR signature. To directly identify zones of DNAPL contamination, we focus on three aspects of reflected wave behavior - propagation velocity, frequency dependent attenuation, and amplitude variation with offset (AVO). Velocity analysis provides a direct estimate of electric permittivity, attenuation analysis provides a measure of conductivity, and AVO behavior is used to estimate the permittivity ratio at a reflecting boundary. Areas of anomalously low electric permittivity and conductivity are identified as potential DNAPL rich zones. Preliminary work illustrated significant potential for quantitative direct detection methodologies in identifying shallow DNAPL source zones. It is now necessary to verify these methodologies in a field setting. To this end, the project is field oriented and has three primary objectives:

1) Develop a suite of methodologies for direct detection of DNAPLs from surface GPR data
2) Controlled field verification at well characterized, contaminated sites
3) Exploratory contaminant detection in a field setting to be verified through direct sampling

Field experiments are being conducted at the Savannah River and Hanford sites, at five DOD sites (Dover AFB, DE; McClellan AFB, CA; Port Hueneme, CA; Wurtsmith AFB, MI; Hill AFB, UT), at a former refinery site near Cincinnati, Ohio, and at a creosote wood preserving site in Fayetville, NC.

Research Progress and Implications

This section summarizes work after 42 months (3yr project + 12 month extension). Although one entire field season was lost due to the lead P.I. suffering a leg fracture, we will meet or exceed all objectives outlined in our original workplan, including an extensive field effort involving over 11 sites located throughout the continental U.S. Additionally we have conducted or are conducting a number of ancillary experiments at little or no additional cost to the project. We have completed our field data acquisition effort with acquisition of full scale 2D and 3D multi-offset, multi polarization datasets at 9 research sites in 7 field areas. These include:

- DOE Savannah River Site (A-14 Outfall)
- DOE Hanford Site (Z-9 Trench, 618-10 Burial Ground/316-4 Crib, 100N Interception Trench)
- Hill Air Force Base (Operable Unit 1)
- Dover Air Force Base - Dover National Test Site
- Former Wurtsmith Air Force Base (FT-02)
- EPA Cape Fear Wood Preserving Site, Fayetville, NC.
- Former Chevron Refinery, Cincinnati, OH.

The data are comprised of 37,250 linear ft. of 25-fold multi-offset GPR data which includes 91,800 sq. ft. of 3D surveying. Additionally, we have completed implementation of a non-linear inversion algorithm for computing the permittivity ratio at a reflecting boundary from GPR AVO data (Bradford et al., in review). We are continuing development of GPR specific AVO and attenuation analysis software suitable for application to production scale data volumes. Training of six undergraduate research assistants and one graduate student have been supported by this project, exceeding the goals outlined in the original proposal. We have made significant strides towards achieving the primary research objective: field demonstration of NAPL detection using GPR velocity and attribute analysis. Processing of all data is nearing completion and current results of site specific studies are in Appendix A.

It should be noted that our original work plan called for acquiring datasets at two National Environmental Technology Test Sites (NETTS) in California (Port Hueneme and McClellan AFB). Feasibility tests during September, 2001, demonstrated that soil conditions at these sites were not suitable for GPR investigation, and we began to search for additional contaminated test sites. This led to the identification of the former Chevron refinery outside Cincinnati, OH (LNAPL), and the Cape Fear Wood Preserving Site (DNAPL) as substitute test sites.

APPENDIX A: SITE SPECIFIC RESULTS

Savannah River Site

Between 1952 and 1979, approximately 1,395,000 lbs of chlorinated solvents were released at the A-014 outfall of A/M area (U) at the Savannah River site (Jackson et al., 1999). About 72% was tetrachloroethylene (PCE). Until recently, it was thought that significant concentrations of DNAPL were confined to the deeper section of the vadose zone. In 1999, significant accumulations of solvent were discovered at depths less than 30 ft in the vicinity of the A-014 outfall. Sediments at the site consist of relatively coarse grained sands at the surface, a primarily kaolinitic clay layer at a depth ranging from 5 - 10 ft, and a thick, coarse grained sand unit at with top-of-sand at a depth of about 22 ft.

In January, 2000, we conducted a 2366 sq. ft., 3-D, multi-offset, GPR survey at the A-014 outfall. The survey was designed to encompass the shallow DNAPL zone, with little or no contamination near the edges and a strongly contaminated zone near the center. Kaolinite typically has relatively low conductivity, so we felt there was a good chance we could penetrate the clay. To date, we have completed a preliminary 3-D velocity model and initial interpretations of the data correlate reasonably well with available lithologic, electric resistivity, and water content data (Figures 1 & 2). Further refinement of the velocity model is necessary, and once this is complete we will begin more detailed attribute analysis.

Using pre-stack depth migration velocity analysis and imaging, we have identified a high velocity anomaly associated with a channel-like feature that had not been previously identified. The channel appears to cut about 3- 4 ft into the top of the clay, is adjacent to previously identified areas of DNAPL concentration and lies below the current position of the A-14 outfall. Since the channel is directly below the outfall, which maintains a stream of running water, we would expect higher water saturation, and therefore lower velocities within the channel. However, the velocity within the channel (350 ft/ns) is near the highest velocity in the survey (390 ft/ns) which is measured from the direct wave traveling at the surface near the east side of the survey. Our initial interpretation was that the high velocity within the trough could be related to high levels of DNAPL concentration or lithologic variation. The channel likely formed a DNAPL migration route, and that once trapped at the base of the channel, DNAPL migrated laterally into the adjacent clay formation where it is currently observed.

In August, 2001 four cores were acquired to test for the presence of DNAPL. Two cores were acquired within the high velocity zone, and two were acquired just east of the high velocity zone. No NAPL was found directly within the high velocity zone, but relatively high concentrations were found adjacent to, and below the trough feature. We are left to conclude that the high velocities we measured are related to a change in lithology. However, the presence of high levels of contaminate directly adjacent to, and below the trough, supports the interpretation of this feature as a primary DNAPL migration route.

Analyses of these data are ongoing, and we are particularly interested in extracting additional information from the low signal-to-noise areas which form the fine grained portion of the sediment column. Reflections from this region are evident in the data so there is potential to extract additional attributes consistent with the presence of DNAPL. We are testing 3D velocity filtering techniques to remove surface scatter from this region and improve the signal to noise ratio.

Even at the current stage, we feel the experiment is successful for a three reasons, 1) we identified an electric property anomaly that was independently verified using a different geophysical methods, 2) it appears that we identified a major contaminant migration route which improves understanding of the hydrogeologic system, and 3) we extracted an accurate estimate of near surface water content which may also be valuable in understanding the vadose zone hydrology. The dataset does illustrate the non-uniqueness of the geophysical response and the need for verification using direct sampling methods. However, it is also clear that these data may be useful in guiding a future drilling and a remediation program.

Hanford Site

In April, 2002, we acquired two 3D surveys near the Z-9 trench, in the 200W Area. The Z-9 trench received the majority of the CCl_4 at the Hanford site, and is thought to be the primary source area for the extensive CCl_4 groundwater plume that now exists below 200W. Our target was a caliche layer at a depth of approximately 30m, where it is believed that some CCl_4 is trapped and is a likely location for DNAPL pooling. Unfortunately, we were unable to penetrate to the target depth, with the maximum penetration ranging from 10 - 15 m. The data were heavily contaminated with coherent noise scattered from surface objects associated with the nearby soil vapor extraction plant. Through velocity filtering (fk or tau-p) we were able to remove the air velocity scatter, but this created relatively large artifacts in the deeper part of the data. We felt that there was still some potential to use radar at the site if we could acquire data a good distance from the surface structures. On a positive note, the detailed surveys are proving valuable in demonstrating the utility of the multi-offset approach in characterizing water content variation and other properties in the shallow sediments (See the ancillary experiment section below).

In September, 2002, we returned to the Hanford Site. During this second field investigation we had two primary objectives; 1) to conduct additional tests in the 200W area to determine if the problems encountered during the first survey were prevalent throughout the site, and 2) to conduct reconnaissance surveys at the 100-N-65 Interceptor Trench, and the 618-10 Burial Ground/316-N Crib, both of which are LNAPL contaminated sites. Presently, we have completed image processing for qualitative interpretation of all data collected at Hanford and are in the quantitative analysis and material property estimation stage. In the 200W area, we found that our penetration depth was limited to 10 - 15 m at 3 additional locations which were considered likely to have DNAPL contamination. At that time, we concluded that GPR was not a suitable tool for DNAPL characterization in the 200W Area. However, at the 618-10/316-4 and 100-N-65 sites we were able to reach the target depths and have some exciting preliminary results.

The 100-N-65 Interceptor Trench was excavated along the Columbia River just northeast of the 166N Tank Farm. The purpose of the trench was to intercept diesel fuel that had reached the water table through several unplanned releases totaling more than 80,000 gallons. Fuel that accumulated in the trench was ignited and burned. In 1994, the trench was backfilled, but gross contamination was found in characterization wells (Jacques, 1985). It is likely that a significant component of the fuel was not burned and remains in the subsurface. To evaluate the potential for using GPR to characterize the site, and to look for anomalies related to remaining NAPL contamination, we acquired a set of 600 ft long, multi-offset surveys, along the axis of the in-filled trench, in both TE and TM modes. We supplemented these data with a short (90ft) cross-axis multi-offset profile.

The target depth was at the water table about 6 m below the surface. We found a strong radar signature associated with the trench and identified additional radar anomalies that are likely associated with remaining LNAPL contamination (Figure 3). Outside the boundaries of the trench, we imaged a reflecting boundary at a depth of about 9 m. Within the trench area, we reach water table depths, but get very little data below this, and do not see the 9 m reflection. This may be a zone of high attenuation associated with LNAPL contamination as was observed at the Wurtsmith AFB site. There is additional evidence of a NAPL signature at the 100-N-65 site. There is a strong water table reflection outside the trench boundaries, but the reflection appears to be depressed at the trench boundary then disappears below the trench. There is a weak reflection at the water table depth within the trench, but this reflection is more variable and along one section has polarity opposite that of the water table reflection. This indicates that there is a positive velocity contrast as opposed to the expected negative contrast expected for the water table boundary. Since the fill material is native, it is difficult to explain these observations with only lithologic variations. A more likely explanation is alteration of the electrical properties at the water table boundary via a significant accumulation of NAPL. This may be weathered fuel present in a smear zone, or less volatile (and likely more viscous) hydrocarbon components that remained after burning. While we feel confident that we are seeing a NAPL effect, the analysis is not yet complete. We are currently conducting quantitative analysis of the velocity, AVO and attenuation responses. Additionally, we are trying to better constrain our interpretation through a search of historical documentation that may provide details on the construction of the trench and backfill.

The 618-10 Burial Ground is located approximately 4 miles northeast of Hanford's 300 Area. This site contains several pits that received solid mixed waste from the mid 1950's until 1960. The pits were later backfilled. During a surface stabilization project in 1983, a black oily substance was observed bubbling to the surface above one of the pits. No samples were taken, but this is thought to be a potential contributor to groundwater contamination. The 316-4 Crib is located about 100 ft southeast of 618-10 and consists of two buried, open bottomed tanks. Approximately 200,000 l of liquid organic and uranium wastes were pumped into the disposal tanks during the 1950s and 1960s. Radiological and volatile organic contamination has been found in a well near the site (Bechtel Hanford Inc., 1995). Groundwater lies approximately 60 ft below the surface. What is thought to be a low permeability cemented gravelly layer, at a depth of about 35 ft, is suspected of having a significant role in contaminant migration (Department of Energy, 1997), and was our primary target at this site. Sediments at the site are comprised of surficial eolian deposits overlying the sands and gravels of the Hanford Formation (Bergstrom et al., 1995).

We acquired 2000 linear ft of multi-offset, 2D profiles at the site consisting of three roughly East/West profiles, and two North/South profiles. Along two of the East/West profiles we acquired data in both TE and TM modes. We obtained excellent results at the site with 30-40 ft of penetration with 100 MHz antennas, and 45-60 ft of penetration with 50 MHz antennas (Figure 4). Due to surface vegetation, it was not feasible to acquire all of the data with the bulky 50 MHz antennas which were deployed only along one of the East/West profiles. While we have not seen any obvious NAPL indicators in the GPR data, quantitative analysis is ongoing, which may illuminate anomalies that are not obvious from qualitative interpretation alone. However, qualitative interpretation brings out several interesting features that may have a significant impact on contaminant transport at the site. There is a strong, reflection at a depth of around 30 ft that is continuous throughout the site and dips gently toward the southeast. Below this horizon is evidence for a paleochannel network (Figures 4, 5, and 6). This is approximately the depth at which the cemented gravels were encountered, therefore this channel system may have a significant impact on contaminant transport. The burial pits in the 618-10 Burial Ground are clearly imaged and the base of these pits lies just above the 30 ft reflector, with the irregular topography of the channel system evident below (Figure 6). Furthermore, the tanks in the 316-4 Crib are clearly imaged, and a large paleochannel lies below the tanks (Figures 4 and 5). Spreading laterally beneath the tanks is a zone of high attenuation (Figure 4). The high attenuation may be due to increased metal concentrations along the contaminant migration route, or potentially due to degradation of the organics as we have observed at other sites.

Our early results suggest that radar imaging can provide a significant contribution to the characterization and potentially future remediation of Hanford's 618-10, 316-4, and 100-N-65 sites.

Hill Air Force Base

At Operable Unit 1 (OU-1), Hill AFB, UT, a variety of both LNAPL and DNAPL contaminants were dumped in two chemical disposal pits (CDPs 1 & 2) and burned from 1952-1973. A significant quantity of non-combusted liquids leaked from the CDPs to the underlying aquifer and now comprise a free product plume that covers approximately 7 acres with measured thickness as much as 1 ft. The plume is a highly heterogenous mixture composed primarily of jet fuel and light lubricating oil with a significant dissolved solvent phase. In addition to the floating pool, the contaminant accumulates in a smear zone that is controlled by water table fluctuation, with the relative amounts of pooled and smeared NAPL dependent on water table elevation. Previous work by Enfield et al. (1998) indicated that contaminated soil at the site has relatively low electric conductivity. We also expect low electric permittivity to be associated with zones of soil contamination. This, coupled with favorable results of previous GPR imaging work (Young and Sun, 1996, 1998) led us to select Hill Air Force Base as a research site. At the site, 6 - 10 m of gravel to silty sand comprising the Provo Alluvium overly the clays of the Alpine Formation. The Alpine clay acts as an aquitard as the water table fluctuates about the sand/clay boundary on an annual cycle. This site was particularly challenging for three primary reasons:

- Significant heterogeneity in the surface material related to variations in fill material associated with capping and landfill activities.
- Significant heterogeneity at the target depth. The NAPL is present near the sand/clay boundary. Variable topograpy along this surface had a significant impact on contaminant migration. This was further complicated by seasonal water table fluctuations about the sand/clay interface.
- A highly heterogeneous NAPL resulting in variable electric properties and heterogeneous contaminant migration and distribution.

In October of 2000, we acquired a 32,000 sq. ft., 3-D multi-offset GPR survey designed to bound CDP 1 on the east, west and north sides and to extend beyond the known boundary of the free LNAPL plume. Survey objectives included imaging the sand/clay interface and direct detection of the LNAPL plume. Using pre-stack depth migration velocity analysis and imaging we were able to extract a detailed map of the sand/clay boundary (Figure 7). Depth to clay interpreted from the processed radar image is accurate to within about 1 ft based on extensive borehole information located within the 3-D patch. The radar image indicates that the clay surface topography is significantly more complicated than previously mapped using borehole information alone.

We identified an anomalous reflection arching roughly 5 ft over a topographic low in the clay surface. We found a high velocity anomaly in the interval between the anomalous reflector and clay reflector (Figure 8). Additionally, we found that the AVO response of the anomalous reflection departs significantly from that of the clay reflection (Figure 9). Fitting the Fresnel equation to the amplitude data, we estimate a velocity ratio (v_2 / v_1) at the reflecting interface of 1.39 ± 0.16. This is in good agreement with migration velocity model, which predicts a velocity ratio of 1.33. Error is estimated by calculating the standard deviation of velocity ratio estimates over all 20 CMPs used in the AVO analysis.

Suspecting that the high velocity anomaly was associated with a NAPL rich zone, we initiated a verification coring program. In September, 2001, four continuous cores (UW-1 – UW-4) were pulled from within the anomalous zone. Additionally, a fifth core was pulled just outside of anomalous zone for background control (UW-5) where only a thin trace of hydrocarbon was detected. The cores indicate a relatively homogeneous stratigraphy from the surface to the clay layer, and no lithologic boundary is evident that explains the anomalous reflection. Elevated hydrocarbon levels (varying from 1% - 4% total volume) were discovered in sediments pulled from within the high velocity zone. The hydrocarbon rich zone forms the only significant boundary in the cores and is the most likely explanation for the origin of the reflection. The large velocity increase below the reflection indicates low electric permittivity. This is in contrast with the background effect where increasing water saturation with depth, particularly near the water table, leads to decreased velocity. Given all the available information, we interpret the high velocity zone as correlating with a zone of elevated NAPL saturation. The correlation of low permittivity with NAPL contaminated soil at this site is consistent with the results of a previous resistivity study (Lien and Enfield, 1998) located several hundred feet south of our survey area.

While we are confident that the measured GPR response is caused by the NAPL rich zone, it is difficult to explain how the large observed velocity increase can originate from the relatively low NAPL concentration recorded in the verification boreholes. Using simple mixing laws or an empirical formulation such as the Topp equation (Topp et al., 1980), the velocity we measured would require nearly total displacement of the pore water with NAPL or air. This is not likely the case. We believe that either 1) the contaminant has replaced water as the wetting agent in which case relatively low concentrations of NAPL may lead to large increases in velocity, or 2) the viscous NAPL has clogged the pore throats leading to a low permeability zone that is largely free of water. Previous work has indicated that the OU1 plume is a mixed wet system (Meinardus, 2000) so this is a reasonable interpretation. Endres and Redman (1996) present the results of a modeling study of a NAPL/water pore fluid that illustrate the significance of fluid distribution within the pore system. Their results are not directly applicable to this study since we are dealing with a three-phase pore fluid – NAPL/water/air. Further analysis is needed to develop a petrophysical model that describes the measured radar response.

In May and July 2002, we conducted a large scale exploration survey at OU-1. We first acquired a 1,000,000 sq. ft. common-offset survey to identify anomalies or stratigraphic features potentially containing elevated NAPL concentrations. Through these data we identified an anomaly similar to that investigated in the 2000 study, and located within 200 ft of that anomaly. This feature was also a stratigraphic low with an unusual arching reflector approximately 5 ft, above the clay surface. Subsequent multi-offset profiling verified that this reflection was associated with a high-velocity zone. Laser induced fluorescence profiling conducted by Intera, Inc. in September, 2002, indicated that a low level of NAPL was present within the anomalous zone. In addition to identification of this anomaly, we identified a previously unmapped paleo-channel that has been identified as a major contaminant transport route and contains a significant, previously unidentified NAPL accumulation.

Our results at OU-1 are significant for several reasons. First, we believe this to be the first reported case of GPR AVO and migration velocity analysis being used for direct detection of NAPL in an uncontrolled field setting over an existing plume. And second, the NAPL was found in a location previously thought to lie outside the NAPL plume. The key to this success was quantitative analysis of multi-offset radar data to identify electric property anomalies that may otherwise have gone unnoticed in qualitative interpretation of conventional radar profiles.

Wurtsmith AFB

This site is a former fire training facility, designated FT-02, located on the now decommissioned Wurtsmith AFB, in Oscoda, MI. Over a period of about 24 years, large quantities of fuel were burned on open ground during weekly training exercises. A significant volume of hydrocarbons did not burn and seeped into the underlying aquifer. In 1982 a concrete catch basin was constructed to minimize the amount of contaminant reaching the subsurface. By the early 1990s, the free product plume was up to 1 ft thick, and extended more than 600 ft downgradient from FT-02 (Bermejo et al., 1997; Sauck et al., 1998).

The stratigraphy below the site consists of fine to medium grained sand and gravel deposits extending to a depth of approximately 65 ft. Below this is a 20 - 100 ft thick silty clay layer which is thought to be the lower boundary for contaminant migration. The surficial aquifer is unconfined, with the water table present 10 - 15 ft below the surface. The site was formerly a National Environmental Technology Test Site (NETTS), and was the site of a long term natural bioremediation investigation. Although no longer an active NETTS site, the wealth of characterization data available make this an excellent location for a semi-controlled GPR field experiment. Central to the selection of this site for the current study are a series of geophysical investigations carried out by Sauck et al. (1998) and Bermejo et al. (1997). They found that the site provided excellent conditions for GPR with strong reflections well below the water table. Additionally, they found that there was a well defined, high attenuation anomaly coincident with the LNAPL plume. Through resistivity and self potential measurements, and by inference from the GPR data, they concluded that high electric conductivity was associated with both the LNAPL and the dissolved phase plume. This site provided an excellent opportunity to study a conductive type plume.

During July, 2002, we acquired 5500 linear ft. of multi-offset data, including a 10,000 sq. ft 3D survey and data acquired in both TE and TM modes. The 3D survey was oriented such that one edge of the plume would cross diagonally through the 3D patch. Additionally,data were acquired along two 400 ft east/west profiles that bounded the 3D patch to the north and south. These profiles extend well beyond the east and west boundaries of the plume. Our first objective was to reproduce the results of Sauck et al. (1998) and we found a similar attenuation anomaly. This is most evident as an area of low reflection amplitudes, or “shadow zone”, beginning just below the water table and extending to depth (Figure 10). Although the character of the attenuation anomaly is the same, the geometry of the LNAPL plume appears to have changed significantly in the 8 years since Sauck et al.’s initial investigation. Most notably, the width of the plume has decreased significantly, being only about half as wide as that measured by Sauck et al. Additionally, the plume axis appears to have shifted.

Plots of the AVO gradient show a clear, well defined anomaly, in both TE and TM modes, that roughly coincides with the attenuation anomaly (Figure 11). We also find that the water table reflection amplitude decreases by as much as 40% over the attenuation anomaly. This decrease in amplitude correlates with the AVO gradient anomaly. Through quantitative analysis, we have shown that the observed response cannot be due to an attenuation or radiation pattern anomaly, or to topographic effects (Bradford, in press). Furthermore, through thin-bed modeling using an analytical solution to Maxwell’s equations for a multi-layered medium (King and Owens, 1992), we have shown that the trend of the AVO response correlates very well with a model having a 1 ft thick intermediate permittivity anomaly just above the water table in the on-plume area, and a simple boundary in the off-plume area (Figures 12,13). Critical to this analysis were the additional constraints provided by including both the TE and TM data.

There are two scenarios that could result in a zone of intermediate permittivity: 1) The contaminant has low permittivity and a mixed LNAPL/water zone decreases the permittivity in the capillary fringe and upper part of the saturated zone, or 2) the LNAPL zone has anomalously high permittivity giving an increase in the vadose zone permittivity just above the water table. In either case, this is the first successful demonstration of NAPL detection using GPR AVO in a conductive plume environment.

Cape Fear Wood Preserving Site

The Cape Fear Wood Preserving Site is located in Fayetteville, North Carolina. The facility produced creosote-treated wood between 1953 and 1978. In 1977 the site was found to be contaminated with coal tar and coal tar creosote of which the primary constituents are PAHs (DNAPL). In the mid 1980s some remediation activities were initiated including excavation and removal of some contaminated soils. In 2001 and 2002 additional characterization revealed that a significant quantity of DNAPL remained. Current activities include a new round of characterization and remediation design. Shallow sediments at the site consist of fine grained sands and silty sands to a depth of about 30 ft where a thick silty clay unit is present. A shallow (3 ft) water table is present in the unconfined surficial aquifer.

We acquired 50 and 100 MHz multi-offset data along a 300 ft 2D profile in both TE and TM modes. The profile was placed to span an area of low contamination to a zone of high contamination. There are laterally coherent reflections recorded at depths up to 30 ft (Figure 14). For the following analysis, we focus on two depth intervals; 10-23 ft and 23-30 ft. These two intervals are bounded by strong reflections and thus represent significant stratigraphic units. It should be noted that from 0 to approximately 75 ft, the interval from the surface to a depth of 18 ft was previously excavated and backfilled, and therefore is not representative of the natural stratigraphy.

We have conducted both PSDM velocity analysis and attenuation analysis for both the shallow and deep intervals. Attenuation coefficients were estimated from the log of amplitude ratios of reflections bounding the interval. Conductivity was then computed from the attenuation coefficients using the equation for low loss media given by Davis and Annan (Davis and Annan, 1989). This analysis provides a measure of relative conductivity variation within each layer. We are currently investigating the frequency dependent attenuation which should minimize artifacts due to lateral heterogeneity. Throughout the formation, we find relatively high-conductivity to the east that gradually decreases toward the west. This is consistent with increasing DNAPL toward the west. For the 10 - 23 ft interval, their is a minima in conductivity (potentially maximum DNAPL) just to the east of the excavated section. Conductivity in the 23 - 30 ft interval decreases gradually reaching a minimum at the beginning of the profile. This is consistent with velocity analysis which shows increasing velocity toward the west. Using a form of the CRIM equation (Greaves et al., 1996), we estimate both DNAPL and water concentration from the velocity profile in the 23 - 30 ft interval. This yields a maximum DNAPL concentration of around 4.5% near the west end of the line. The general trend of the conductivity and DNAPL concentration estimates, in both intervals, are consistent with the DNAPL distribution mapped using CPT LIF, and ROST logs (Black and Veach Special Projects Corp., 2002). It must be noted that the analysis is non-unique and that significant lithologic changes could potentially give similar results. However, two independent modes of analysis (attenuation and velocity) produce consistent results, and these results are consistent with direct observations. This is the first reported use of GPR attenuation analysis and PSDM velocity analysis for detection of DNAPL.

Cincinnati, Ohio Refinery Site

At this site, an estimated minimum of 4,000,000 gallons of leaded gasoline and diesel fuel were released to the environment from the early 1930s to the early 1980s. This contaminant now forms a thick zone of hydrocarbon contamination that interacts dynamically with the fluctuating water table. Approximately 2,500,000 gallons of contaminant have been removed through extraction wells over the last 10 - 15 years, but a significant source term remains. The water table fluctuates by 10 - 15 ft annually. At low water table conditions, the hydrocarbon forms a pool at the top of the water saturated zone, and at high water table conditions, the contaminant remains trapped in the pore space below the water table forming a thick smear zone. The sediment column consists of course sands and gravels to a depth of 80 ft to 100 ft where a clay aquitard is present. The water table is roughly 30 ft - 60 ft below the ground surface depending on topographic relief and temporal ground water variations.

In January, 2002 we acquired approximately 5600 linear ft. of 2D multi-fold GPR data (50 MHz) consisting of both TE and TM configurations along three transects ranging in length from 500 ft to 900 ft. We chose a large scale 2D acquisition geometry to evaluate "regional" variations in plume geometry due to the sparse distribution of borehole characterization points. We acquired data at high water table conditions with the contaminant forming a 10 ft - 15 ft thick smear zone and essentially no floating product.

Data quality at the site is excellent with good penetration to depths of 40 ft - 80 ft. In initial processing we have identified reflections from the top and bottom of an interval consistent with the contaminated zone identified in boreholes (Figure 15). Whether the radar response in this interval is stratigraphy controlled or controlled purely by the fluid distribution remains to be determined but in this preliminary analysis, potential for successful detection of the NAPL zone appears high. The results of ongoing quantitative analysis will solidify our interpretation at this site.

Controlled DNAPL Injection at the Dover National Test Site

In July 2001, we completed data acquisition for a controlled DNAPL (tetrachloroethylene) injection and GPR monitoring project at the Dover National Test Site, Dover AFB, DE. Data from this site contain significantly higher noise levels than initially expected, but reflections are evident from within the target interval and potential for successful DNAPL detection is reasonable. Processing of these data are ongoing. In conjunction with planning the controlled injection experiment, we have implemented a methodology for integrating multi-phase flow and GPR modeling. This allows us to investigate temporal changes in GPR response to a dynamic contaminant distribution.

In August, 2002, we revisited the Dover National Test Site in an attempt to better understand the GPR response to site conditions. This field effort included conductivity profiling using a Geoprobe mounted instrument. Conductivity data were acquired adjacent to the test cell, and at several other locations around the site. In conjunction with this effort, we acquired a set of 2D and 3D multi-offset surveys. Analyses are ongoing, but we believe these data will lead to a fuller understanding of the GPR response observed during the DNAPL injection.

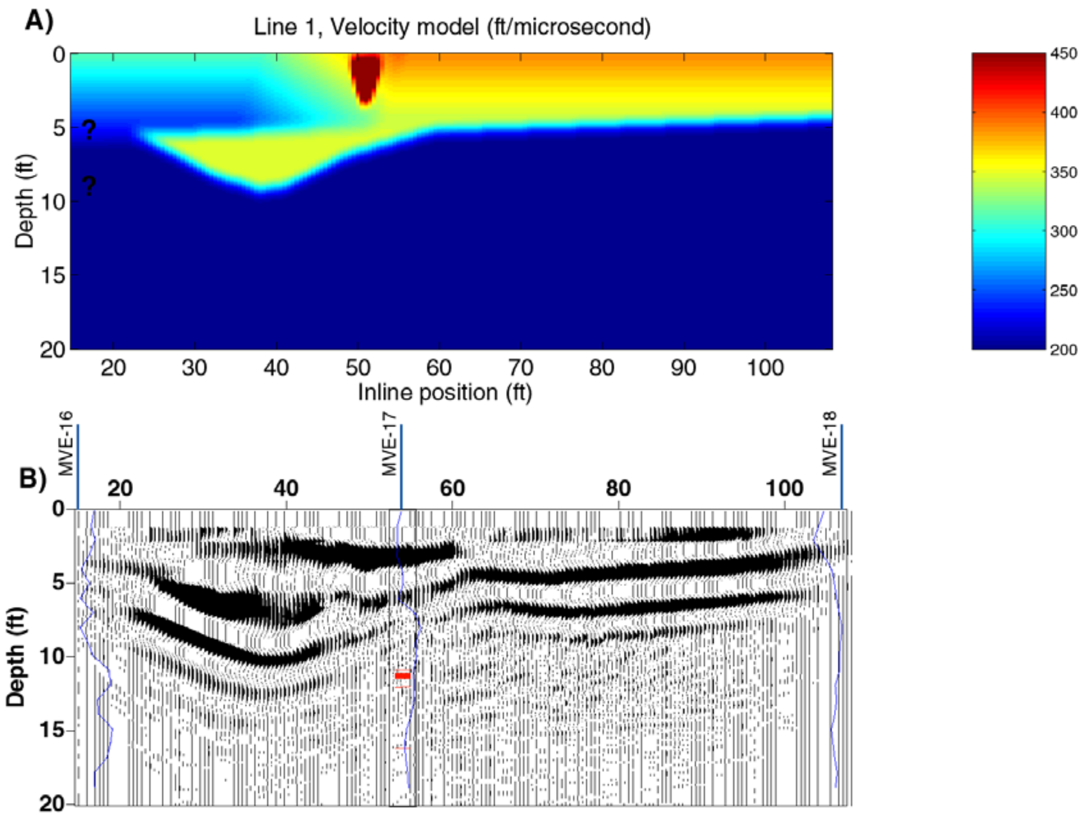
Laboratory Scale Controlled DNAPL Injection

We believe it is important that we obtain data from at least one site with rigid control of contaminant distribution and concentration. We had originally intended the Dover AFB data to serve in this role, however, the unexpectedly poor data quality has lead us to pursue an additional data acquisition effort. We have constructed a small test tank (~1.2 m diameter x 1 m deep) on the Boise State University campus suitable for a second controlled injection experiment. While this lacks the natural stratigraphy of the Dover site, we have constructed alternating sand and gravel strata and the experiment include both a vadose zone and saturated zone component. In April 2003, we injected 20 l of a mixture containing 12 l of perchloroethylene and 8 l of trichloroethane. The tank was monitored with full 3D multi-offset, multi-polarization GPR data acquistion over a period of 48 hrs, at which point no further changes were evident. Addditionally, we acquired 450 MHz data, and 900 MHz transmission data. For control, downhole TDR probes were installed and monitored over the same period, and upon completion of GPR data acquisition, sediment samples were extracted from contaminated and uncontaminated intervals. These samples were sent to a commercial lab for DNAPL concentration and water content analysis. The GPR data clearly show a significant reflectivity response and increase in velocity associated with the DNAPL pool (Figure 16). Our initial analysis indicates a significant AVO response is also associated with DNAPL pool reflection. We will esimate DNAPL concentration based on quantitive analysis of the GPR response for comparison to the control data.

Ancillary Experiments

In addition to the work summarized above, we have completed a number of experiments at little or no additional cost to the project. This includes:

- 3D multi-offset experiments at the Dover National Test Site and Hanford's 200W area designed to investigate multi-offset methodology for characterization of water content variation
- a 3D multi-offset, multi-azimuthal experiment at Hanford's 200W Area designed to investigate electric property anistropy in the shallow (<10 m) sediments
- 3D common and multi-offset experiments designed to image subsurface reactive barriers at the Dover National Test Site. We are using these data to investigate the migration response of a variety of migration algorithms to various acquisition geometries.



Line 1, Cross-Line - 2 ft

Figure 1 A) Migration velocity model for Line 1 from the Savannah River Site study. B) Pre-stack depth migrated image. Neutron logs converted to water saturation from MVE-16, MVE-17, and MVE-18 are overlain. Also a log showing the position of observed DNAPL in MVE-17 is shown with the presence of DNAPL indicated in red. The continuous reflection from in-line positions 25 to 106 ft appears to correlate with an increase in moisture content that is slightly shallower than the top-of-clay surface. This is expected and the reflector likely tracks the top-of-clay topography. A flat event below MVE-17 appears to correlate with the top-of-DNAPL, and is consistent across several lines. However, the quality of data in this zone does not warrant a confident interpretation at this time. Further processing and analysis is necessary. The topographic low between in-line positions 25 and 55 ft is interpreted as a channel and is consistent across the entire survey. This feature had not been previously identified.

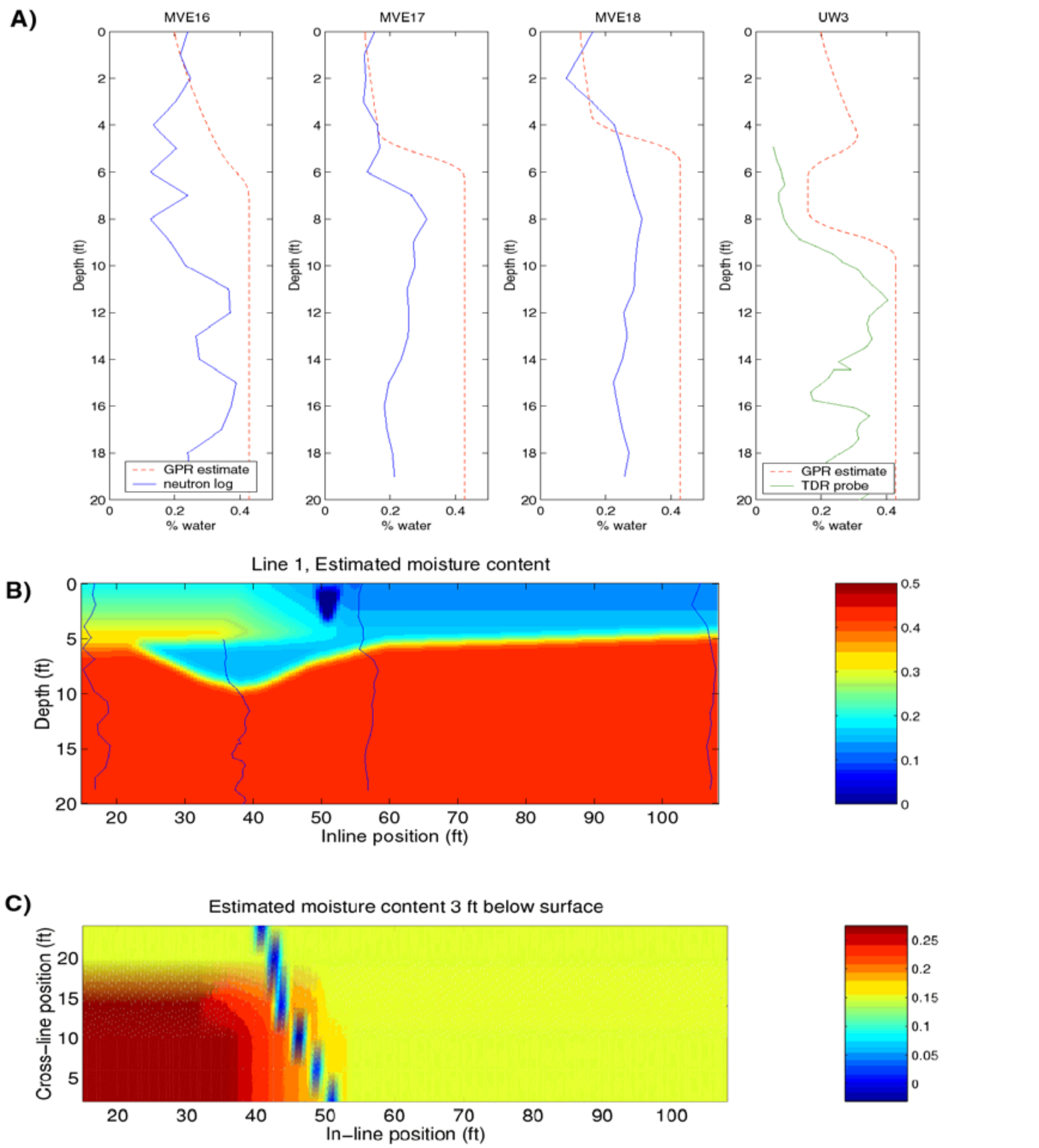


Figure 2 A) Water saturation from neutron logs and a downhole TDR probe compared to estimates computed from GPR velocity data. The GPR estimate at MVE-16 is only valid within about 3 ft of the surface. Water content is estimated from GPR data using a time average equation given by: $Sw = (K^{1/2} - (1-\rho)K_Q^{1/2} - \rho)/(K_W^{1/2} - 1)$ where ρ is porosity, K_Q is the dielectric constant of the soil grains, and K_W is the dielectric constant of water. In this case, we assume ρ=0.4, $K_Q = 4.5$, and $K_W = 80$. This equation works well for sandy sediments with very low conductivity. The GPR estimates correlate very well with the neutron logs near the surface. The correlation is not as good in the clay where the time average equation is not valid. B) Water saturation estimates along Line 1 with neutron logs overlain. C) Depth slice of the Sw estimate at 3ft . There is a significant increase in water content in the vicinity of MVE-16 which does not correlate with the outfall ditch. This suggests that the change is related to lithology, although we don't presently have the data to confirm this interpretation.

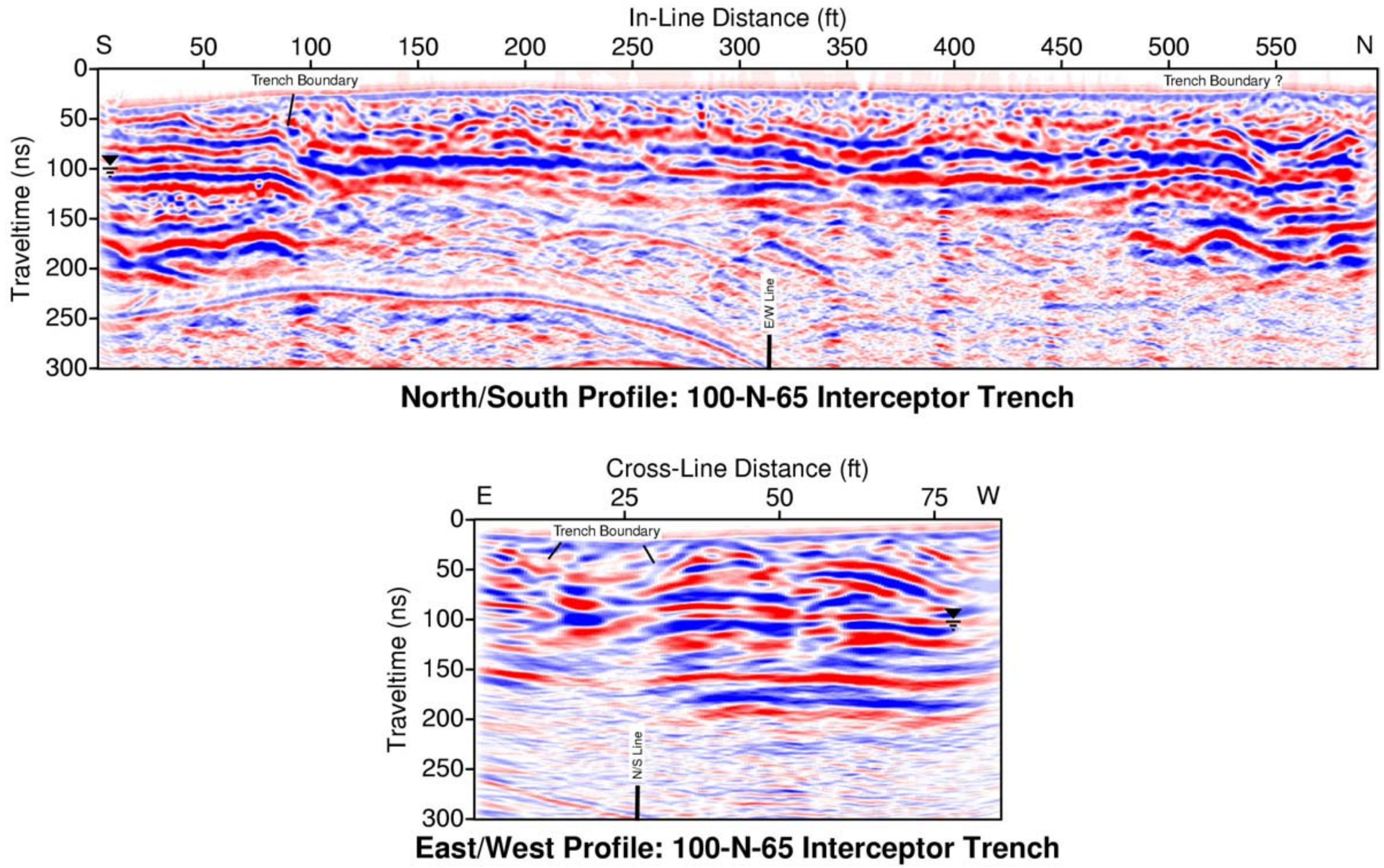


Figure 3 Migrated, 25 fold, 100 MHz TE stacked profiles from the 100-N-65 Interceptor Trench. The water table reflection is at 100 ns, and is evident near the edges of the profile. In the North/South profile, there is an obvious phase reversal in the reflection at 100 ns between 350 ft and 550 ft. This may be due to alteration of the permittivity structure caused by NAPL accumulation. There is a high attenuation zone below the trench between 100 ft and 475 ft that is likely related to the presence of NAPL.

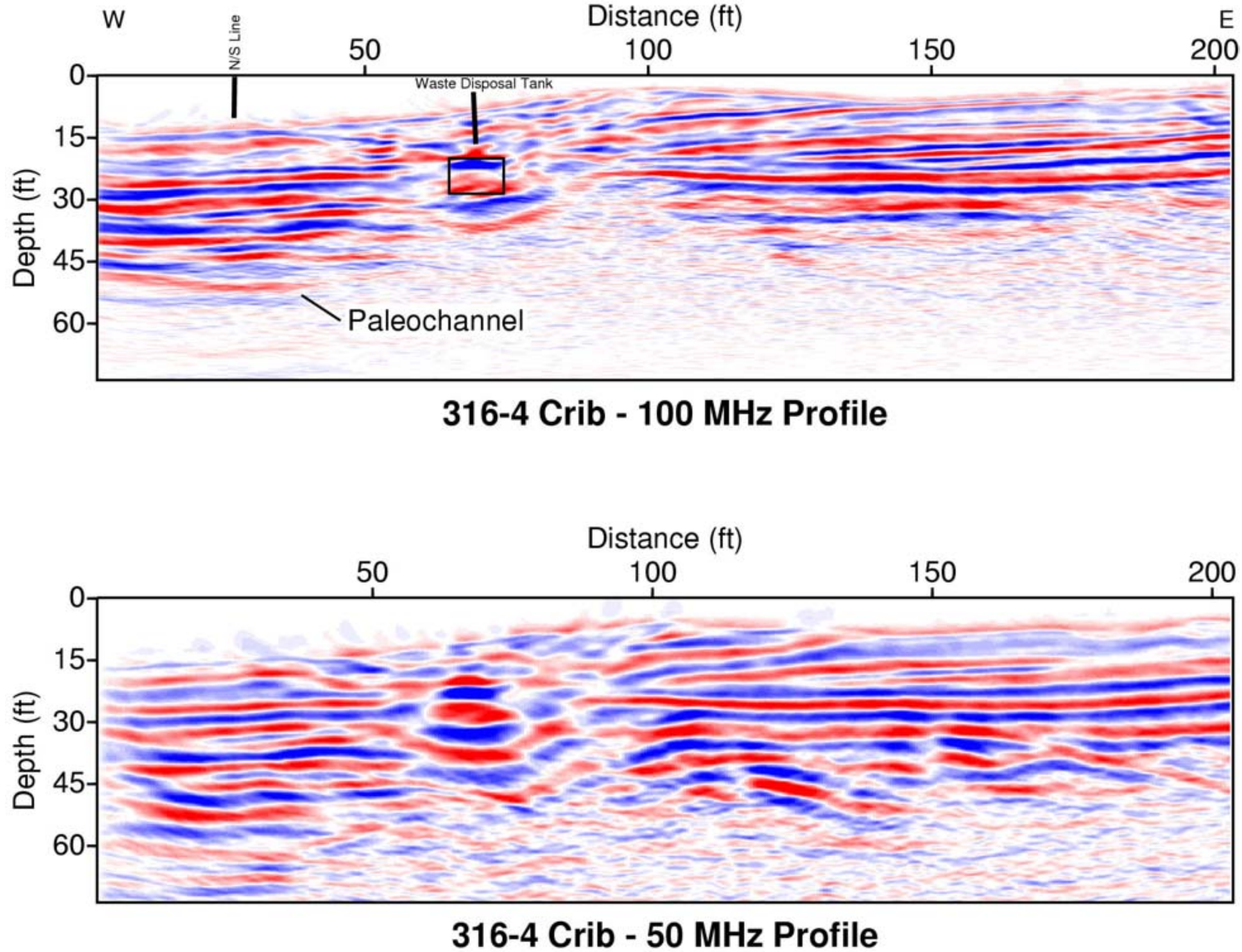


Figure 4 Migrated 100 MHz, and 50 MHz stacks from the 316-N Crib near the 618-10 Burial Ground. Reflections are evident to as deep as 60 ft in the 50 MHz data. A zone of high attenation appears to spread laterally below the disposal tank and a paleochannel appears to lie just below the disposal tank (see also Figure 5).

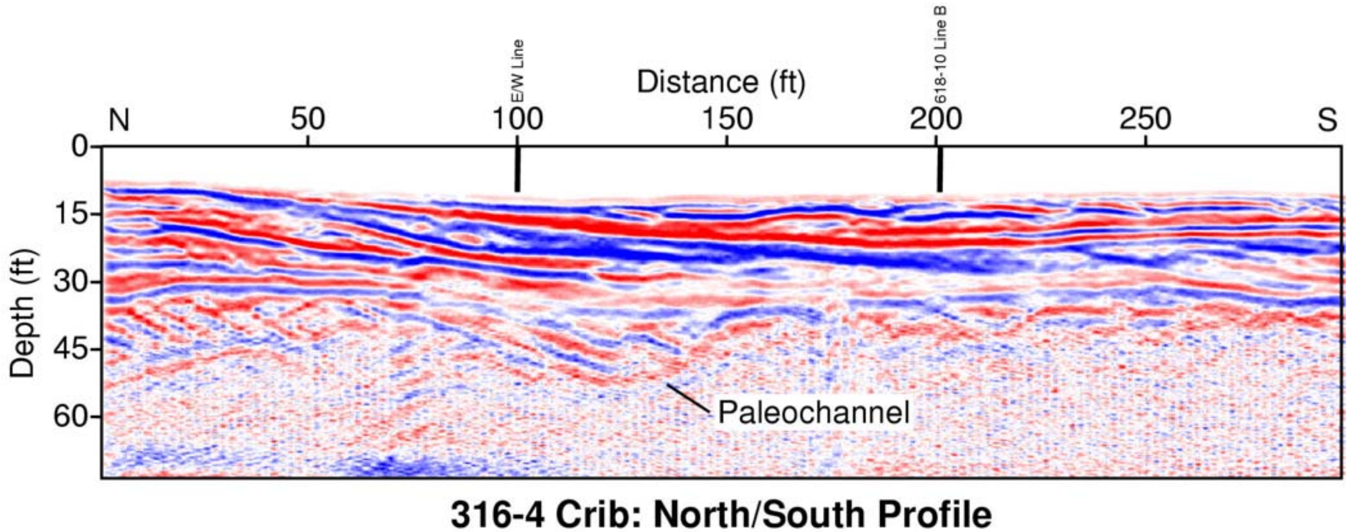


Figure 5 100 MHz stack acquired between the 618-10 Burial Ground and 316-4 Crib. Note the large paleo-channel between 75 ft and 150 ft. This channel appears to cross just under 618-10 and 316-4, and appears to be part of a larger paleo-channel network (see also Figure 4).

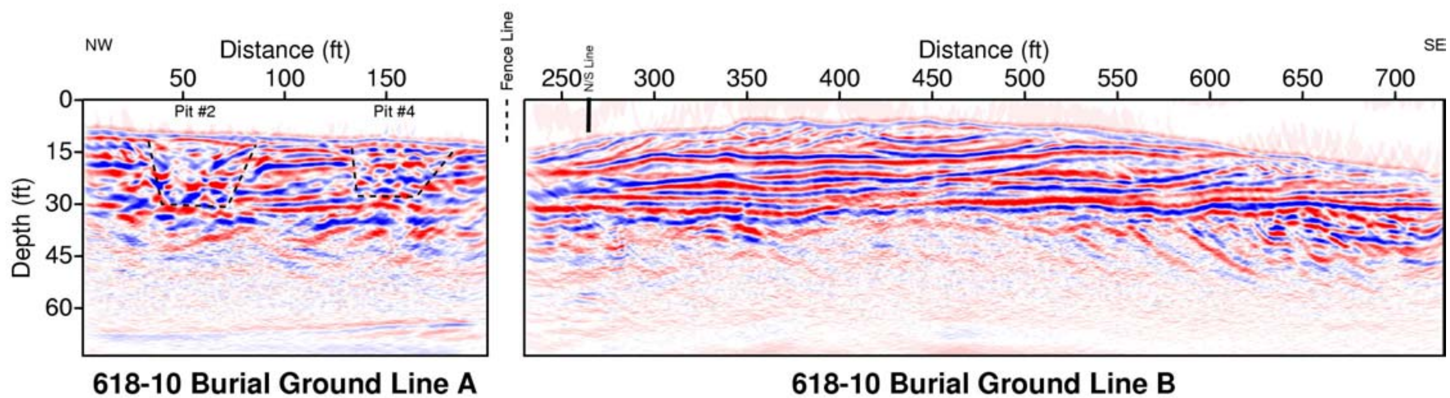


Figure 6 Migrated 100 MHz, TE stack taken from within, and just outside the 618-10 Burial Ground. The burial pits are clearly imaged. Additionally, the paleochannel network is evident below the pits. This network is apparently present throughout the site and may strongly influence contaminant transport.

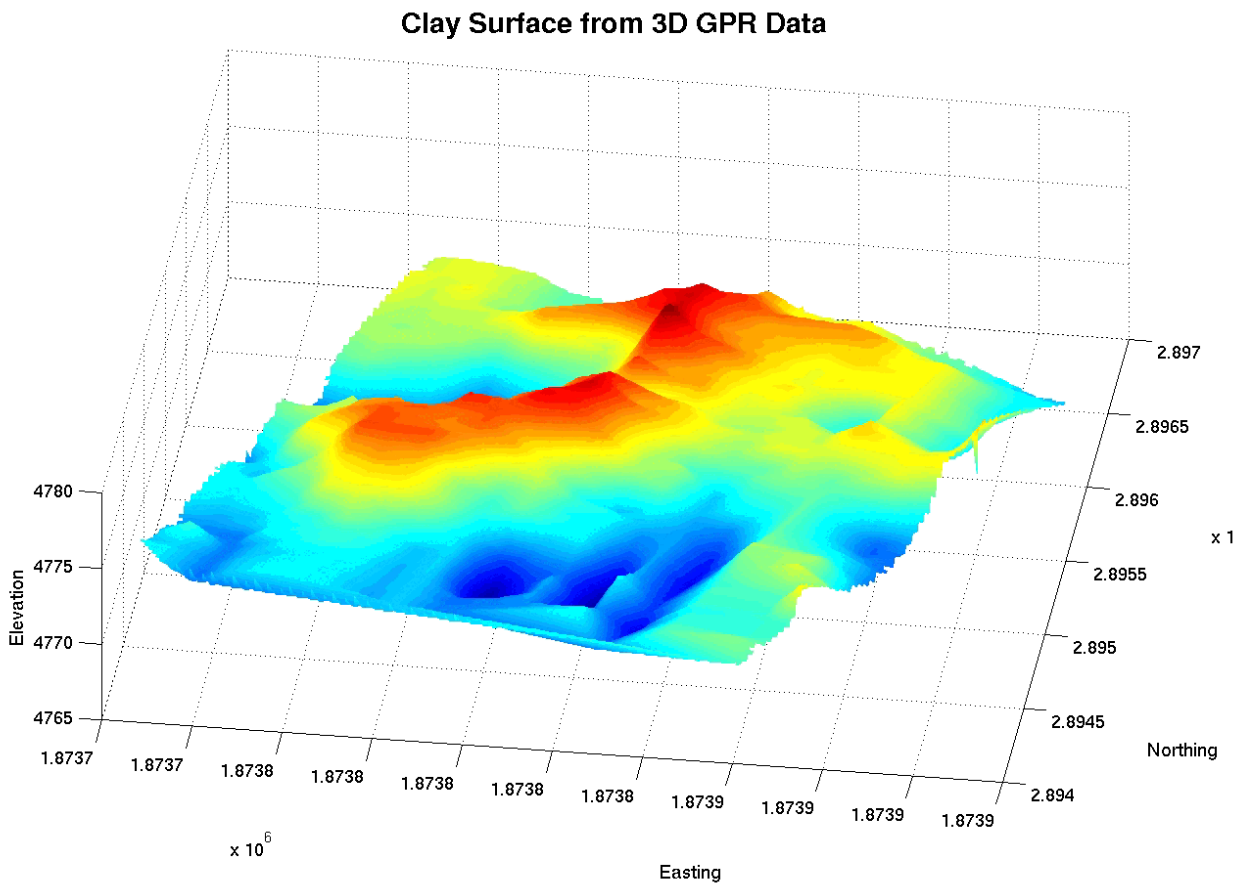


Figure 7 The radar data provide a relatively detailed image of the clay surface at OU-1,Hill AFB. The most striking feature is the ridge and trough located in the northwest portion of the survey with a total relief of about 10 ft. This feature appears to have formed a stratigraphic trap in which NAPL accumulated.

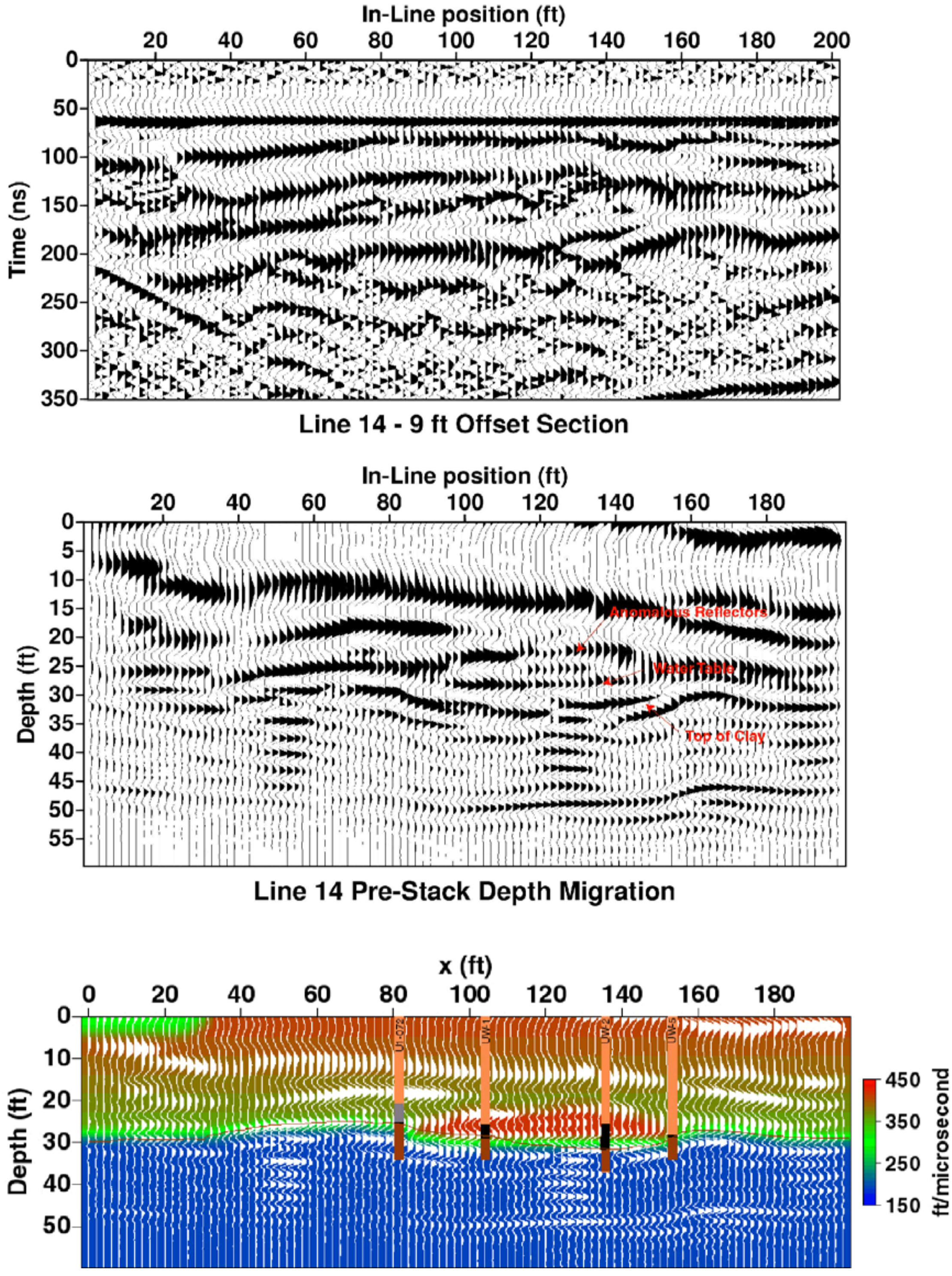


Figure 8 One line in the 3D survey at Hill AFB through several stages of processing. The color image shows the migration velocity model with the migrated image as a wiggle trace overlay. Cores indicate locations where NAPL was found in black, and the clay unit in dark brown. The high velocity zone is a significant velocity anomaly particularly given its position just above the water table where we expect a large decrease in velocity related to an increase in water saturation.

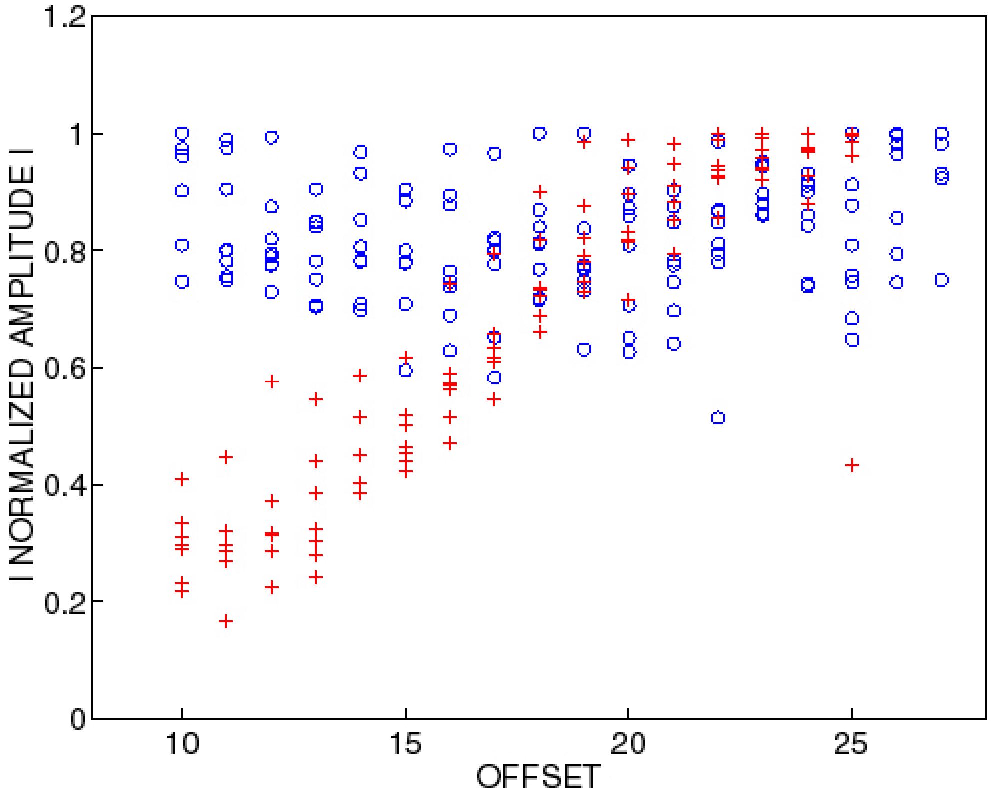


Figure 9 Comparison of AVO behavior for the clay reflection and top-of-NAPL reflection at Hill AFB. Blue circles and red crosses indicate clay reflection and NAPL anomaly reflection amplitudes respectively. Anomalous reflection amplitudes grow considerably with offset as expected for a large positive impedance contrast.

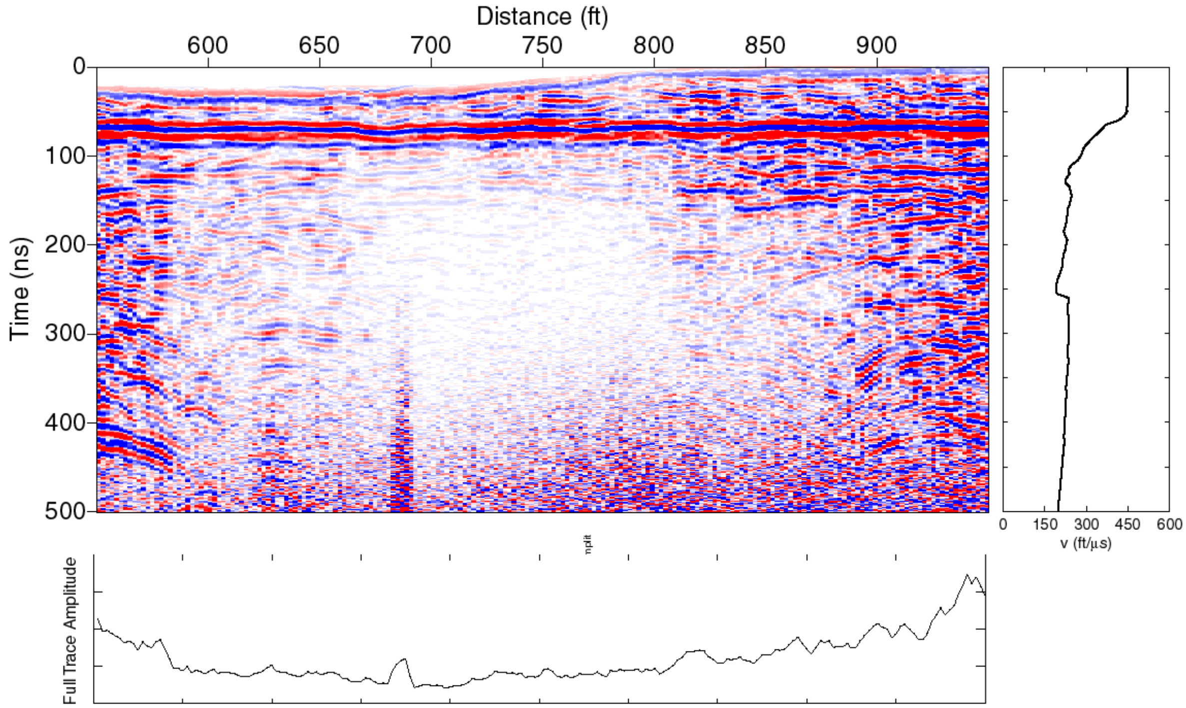


Figure 10 Line 1 stack from Wurtsmith AFB with average interval velocity model and full trace amplitude plot. The attenuation anomaly associated with the LNAPL plume extends from about 590 ft to 890 ft. The full trace amplitude plot suggests a gradational plume boundary with the attenuation gradually increasing toward the center with the highest attenuation at around 700 ft.

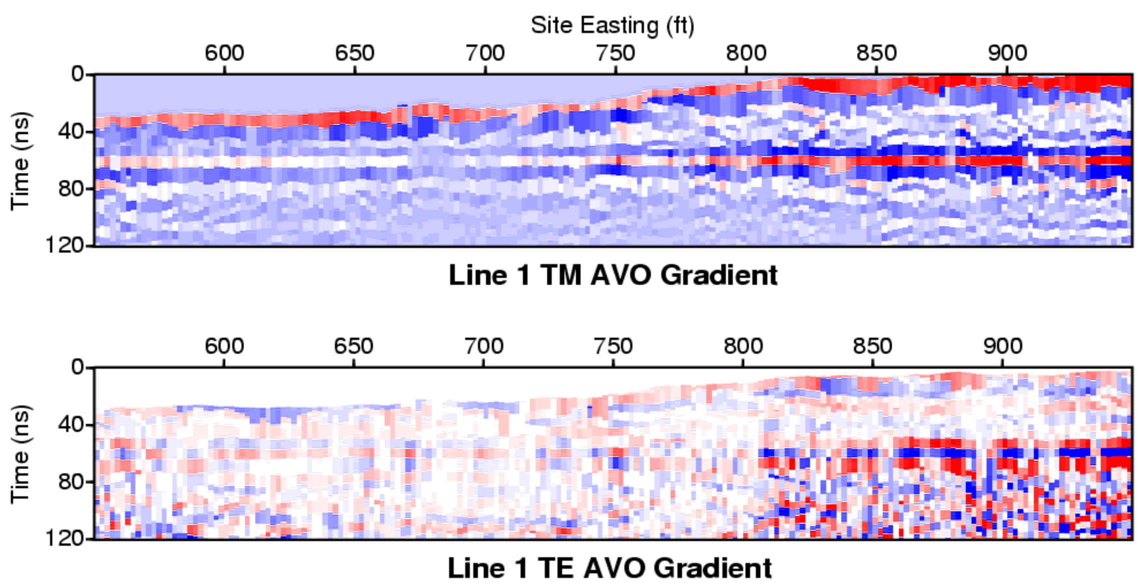


Figure 11 Plots of the TE and TM AVO gradient along Line 1. The water table reflection is at 60 ns. The gradient is estimated from a $\sin^2\theta$ fit to the data. Note that the water table horizon has been flattened.

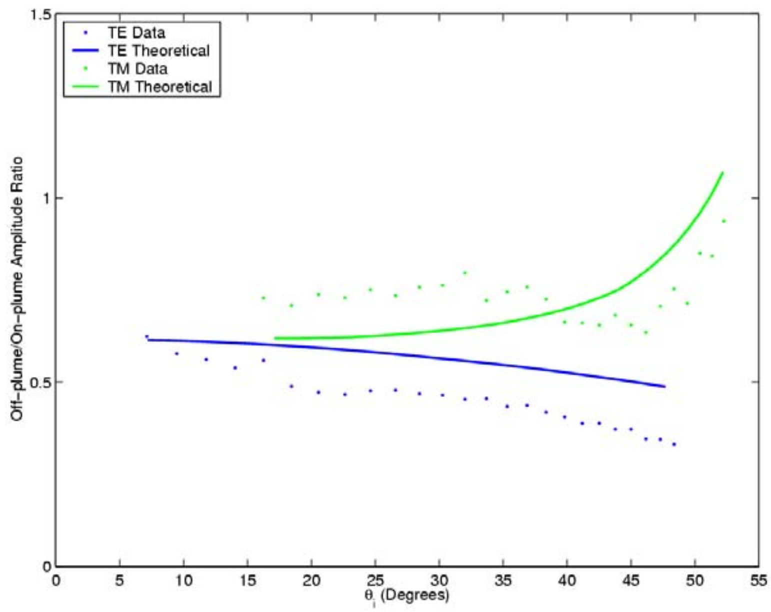


Figure 12 Comparison of on-plume to off-plume amplitude ratios for the field data and the models shown in Figure 13.

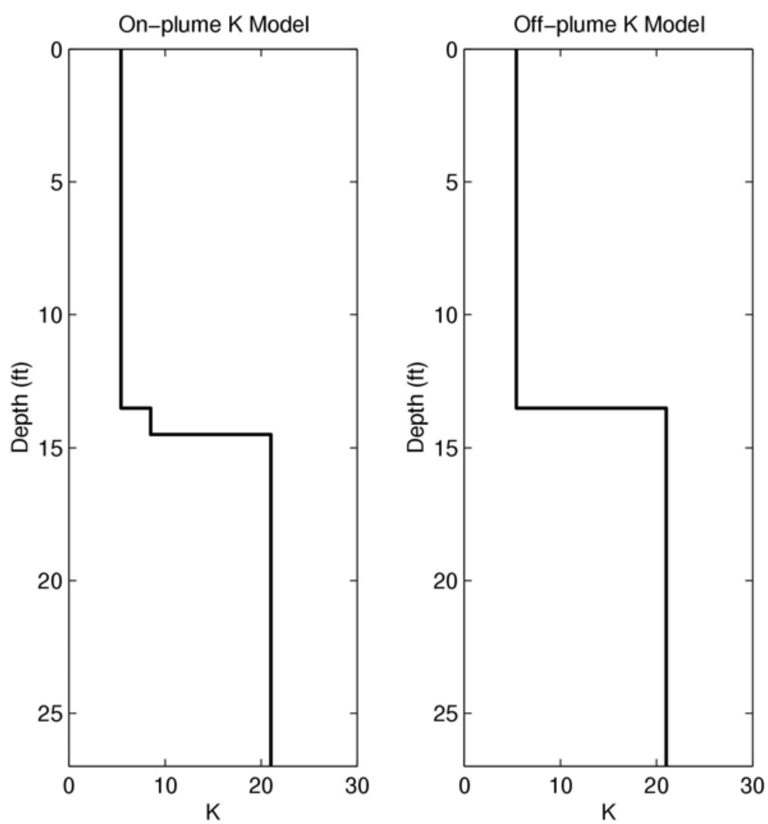


Figure 13 Relative permittivity models for the on-plume and off-plume areas. Inclusion of an intermediate permittivity layer produces the AVO trend observed in the field data.

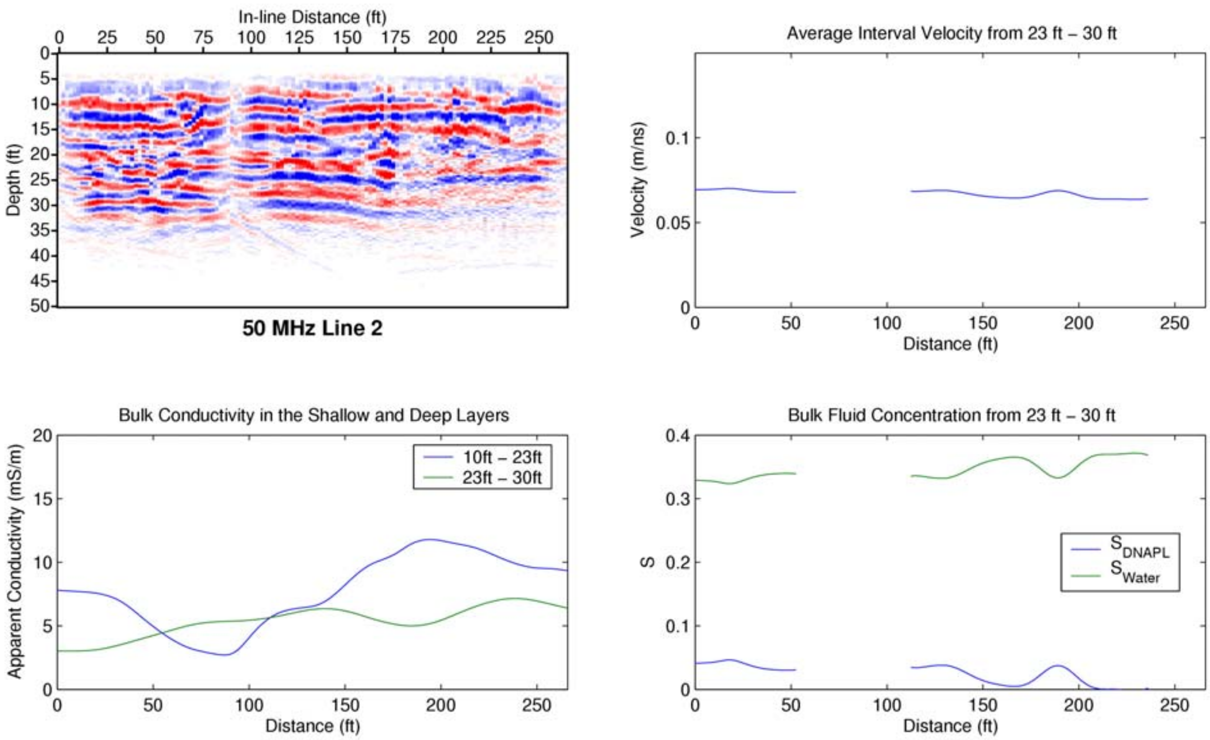
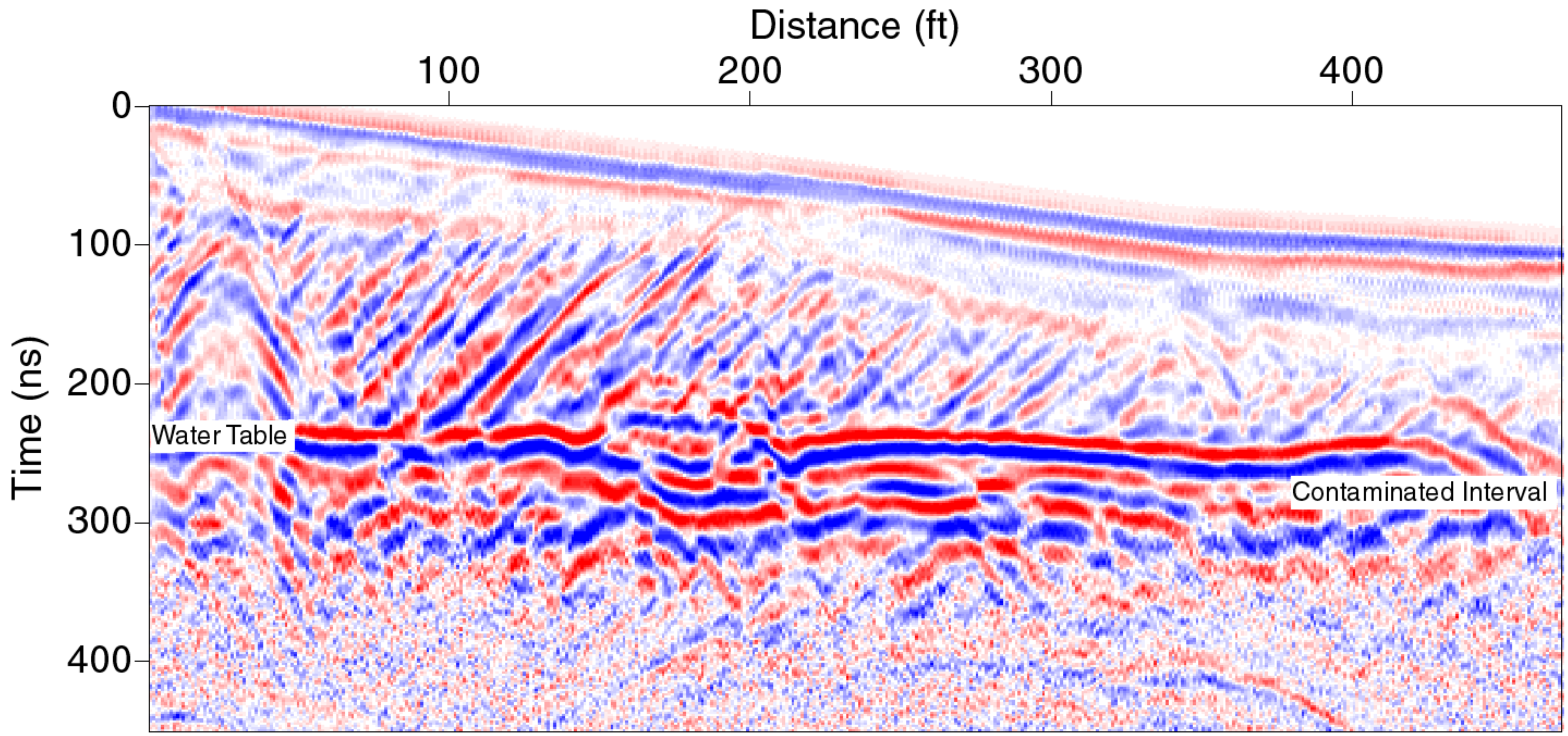


Figure 14 Data from the Cape Fear Wood Preserving Site showing: PSDM, 50 MHz TE stack, velocity estimates from PSDM velocity analysis, and conductivity and DNAPL concentration estimates. See text for computational details. The general trend and relative variability of all computated values indicates increasing DNAPL concentration toward the west. This is consistent with DNAPL accumulations mapped using CPT LIF, and ROST logs. The water table is at a depth of 3 ft. Computed conductivities and velocities are consistent with tabulated values for water saturated silty sands. Note that the low amplitude zone between 75 and 100 ft is a migration artifact related to a no-data zone. We completed amplitude analyses with the unmigrated data so artifacts did not effect the conductivity estimates.



Former Chevron Refinery, Cincinnati, OH

Figure 15 Preliminary stack of multi-offset 50 MHz TE data acquired at the contaminated refinery site near Cincinnati, OH. Data quality is excellent to about 320 ns. These data were acquired under high water table conditions when most of the LNAPL is trapped below the water table in a thick smear zone. Maximum thickness of the contaminated interval is known to be 10 - 15 ft thick which correlates well with the right side of the profile. The radar image indicates that the interval pinches out toward the left in agreement with available well data.

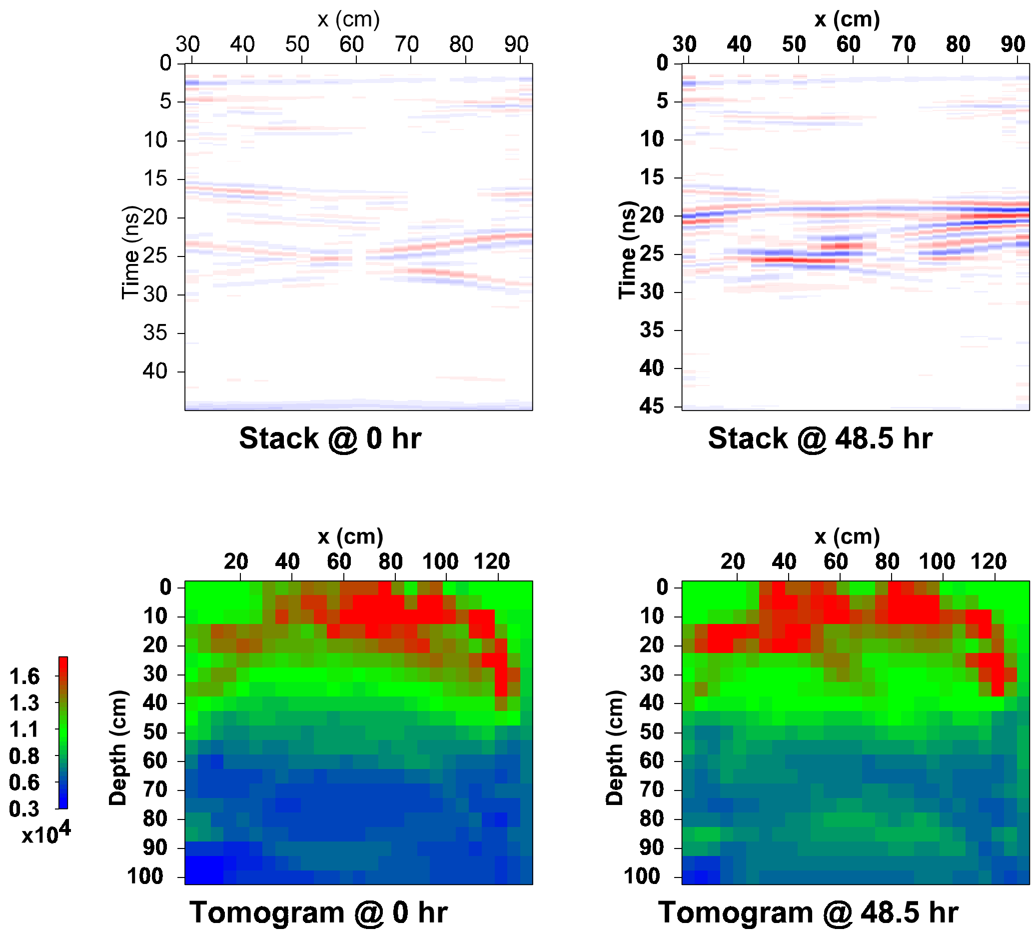


Figure 16 Velocity tomograms from transmission data, and reflectivity stacks for the laboratory scale DNAPL injection experiment. There is a significant increase in velocity and a high amplitude reflection associated with the DNAPL pool that has formed at a depth of 70-80 cm. The water table is located at 43 cm. Note that the reflection data image the center 60 cm of the tank, while the tomograms image the full diameter.

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