

Electromagnetic Induction and GPR Measurements for Creosote Contaminant Investigation

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Abstract

Multifrequency EM induction and GPR parallel dipole (co-pole) and orthogonal dipole (cross-pole) surveys were conducted to assist in the characterization of a former industrial site prior to it being remediated by the Ohio EPA and the US EPA. The site has been a major concern to both agencies for the past decade due to high concentrations of creosote present in clay-rich surficial soils, resulting from many years of wood treating at the site. Information provided on the approximate extent of contamination at the site and the locations of several contaminant-filled structures determined through the use of quadrature phase EM data and cross-pole GPR data served as the basis for an efficient, comprehensive and cost-effective site remediation plan. Geophysical data interpretations were confirmed through exploratory trenching and soil sampling subsequent to the completion of this study.

This study demonstrates the potential for mapping the extent and variation with depth of resistive compounds under circumstances where high levels of contamination are present with relatively conductive background materials. The approximate extent and depth of creosote compounds within the near-surface materials at the site was mapped using 4 kHz and 9 kHz out of phase (quadrature) EM data, as contaminated areas exhibited anomalously low conductivity values relative to non-contaminated areas. Anomalies in the EM data that were attributed to high levels of contamination correlated with analytical soil sample test results that were obtained prior to geophysical surveys, and were also consistent with the actual extent of contamination determined through exploratory sampling subsequent to data interpretations.

Multi-component GPR measurements at the site complemented the EM data. Cross-pole GPR data were more useful than co-pole data at the site for imaging several structures containing creosote that would have remained undiscovered and acted as future sources of contamination. A general overview of the GPR surveys at the site is presented in this paper.

Introduction

Electromagnetic (EM) induction and ground penetrating radar (GPR) are geophysical techniques that are routinely used to investigate the shallow subsurface for engineering and environmental purposes (Annan and Daniels, 1998; Greenhouse and Slaine, 1983; and Olhoeft, 1986). Both of these methods have been widely applied over the last few decades to address the growing need for a non-invasive and cost-effective way to assist in the characterization of contaminated sites. Both techniques have been useful for locating subsurface features containing contaminants and for mapping geologic features that can influence or trap subsurface contaminant flow. Terrain conductivity measurements obtained using EM induction devices have been successful in some cases for delineating and monitoring areas that have anomalous subsurface conductivity associated with contamination (Buselli et al., 1990; and Monier-Williams et al., 1990). Most previous studies involving contaminant mapping using EM induction methods have involved conductive inorganic plumes, although in theory it is possible to map high concentrations of organic contaminants that have replaced aqueous fluid and act as electrical insulators against a homogeneous and conductive background (McNeill, 1990).

A multifrequency EM induction survey and co-pole and cross-pole GPR surveys were conducted at a former wood treating facility in Marion, Ohio, that was to be remediated by the Ohio EPA and the US EPA due to extremely high levels of creosote contamination within near-surface soils. The objective of these geophysical studies was to provide the basis for a comprehensive site remediation plan by: 1) approximately mapping the extent of contamination within surficial soils so that an accurate delineation of contaminated materials could be accomplished through exploratory sampling in a cost-effective way, and 2) by locating possible buried waste pits or other contaminant-filled structures that could potentially remain undetected and thus act as future contamination sources.

An approximate mapping of creosote-contamination within near-surface materials at the site was accomplished through the use of multifrequency quadrature EM data. The interpreted extent and variation with depth of creosote within surficial soils correlated with high concentrations of creosote determined through analytical testing of soil samples acquired at the site prior to EM surveys, and also with the actual extent of contamination determined to be present during exploratory sampling subsequent to EM data interpretations. Detection of several subsurface structures that contained creosote at the site was accomplished through the use of cross-pole GPR data, which were more useful than co-pole data because they contained less clutter. A detailed explanation of the GPR data and interpretations used to locate these features and a discussion of the importance of considering polarization and using cross-pole GPR for field surveys was the focus of a previous paper (Guy et al., 1999). Further discussion on the potential significance of cross-pole GPR for improving the signal to noise ratio in high noise environments and an

explanation of antenna ringing is presented in Radzevicius et al. (2000). Aspects of the GPR surveys that were not presented in prior work are presented in this paper, as is a general discussion of the GPR surveys and results to provide a complete overview of the study. Also discussed in this paper are the effects that standing surface water present during geophysical surveys had on the EM and GPR responses. As a result of the successful characterization of this site using EM measurements and cross-pole GPR a cost-effective and thorough site remediation plan was able to be designed.

Site Description and History

The site of these geophysical investigations is located one mile east of the Little Scioto River, at the north-west corner of the intersection of Holland Road and State Route 309 in Marion, Ohio (north-central Ohio). The Baker Wood Creosoting Company operated a wood treating facility on the 100 acre site from the 1890's through the 1960's. Over the past decade this site has been studied by the Ohio EPA and the US EPA, Region V (Ohio EPA, 1991; and US EPA, 1998). Site studies of both organizations concentrated on the detection of polynuclear aromatic hydrocarbon compounds (PAH's) in sediment and surface water samples acquired at and in close proximity to the west of the site. The presence of these compounds has been attributed to the many years of creosote wood treating that took place at the site.

Near-surface materials at the site are in most areas flat laying, mineralogic clay-rich glacial till and lacustrine deposits. The deposits are classified by the US Department of Agriculture (USDA, 1989) as Blount soils, consisting of a 0.6 - 1.0 meter surface layer of clay-silt loam, underlain by 0.8 - 1.1 meters of firm clay loam, followed by a calcareous clay layer. Glacial till containing occasional thin interbedded sand layers extends from beneath the surface soils to Devonian limestone bedrock, which ranges in depth from 4 - 8 meters in close proximity to the site (ODNR, 1962). Ground water flow in materials underlying the low permeability clay layers is controlled by a westward gradient towards the Little Scioto River (US EPA, 1998). Contamination of areas to the west of the site was determined to be the result of direct product discharge into a sewer drainage system just south of the site, and was not the result of gradient controlled ground water migration.

Hydraulic permeability is moderate to extremely low across the site due to the clay-rich surficial deposits and thus the soils are poorly drained. As a result of this low permeability, patches of standing surface water existed in certain areas during geophysical surveys conducted at the site. The suspected confinement of contamination in the near surface soils above the firm clay loam prior to geophysical investigation (based on the presence of non-permeable clay loam and soil sample analyses) was confirmed across most of the site during exploratory sampling and remediation planning at the site. Additional areas of contamination were found at greater depths beneath the storage tank foundations and in the vicinity of the pump house foundation as a result of subsurface leaking creosote-filled features.

Soil Sampling and Analytical Results

The site is currently vacant but concrete foundations that formerly supported creosote storage tanks and a pump house are still present. Soil samples were acquired by the Ohio EPA and the US EPA in the vicinity and also away from these features, and were analyzed for the following parameters: volatile organic compounds (VOC's), semi-volatile organic compounds (SVOC's), pesticides, PCB's and target analyte list (TAL) metals. Analytical results of these samples indicated extremely high concentrations of creosote-related SVOC's in close proximity to the tank and pump house foundations, and these concentrations were some of the highest that have been reported in published literature (US EPA, 1998). Based on these analytical results, EM and GPR surveys were conducted over a 30 by 91 meter rectangular grid positioned just north of Holland Road that encompassed the area of known contamination. A map depicting the geophysical survey area relative to site features and soil sample locations is shown in Fig. 1. Data regarding concentrations of more than 50 different SVOC's present at the site varied greatly (US EPA, 1998), ranging from zero to 33,000,000 parts per billion (ppb) present at different sample locations. Because the analytical SVOC concentration data are so extensive, a simplified explanation of the amount of creosote constituents for each sample location shown in Fig. 1 is provided in Table 1. Creosote compounds were present in such high concentrations at the site that a strong odor existed and product was visually distinguishable with a blue-silver color against non-contaminated light-brown to brown site soils as illustrated in Fig. 2, which is a photograph taken during remediation of the site.

EM Survey Parameters and Instrumentation

A multifrequency EM induction survey was conducted on the 30 by 91 meter grid established just north-west of the intersection of State Route 309 and Holland road to map the approximate extent of creosote compounds within surficial soils prior to exploratory sampling and remediation of the site. Theory regarding EM induction equipment for making terrain conductivity measurements is described by McNeill (1990). Although correlations have been made between areas of known organic contamination and low conductivity measurements made using EM induction (Vickery and Hobbs, 1998), detection of organic materials that act as electrical insulators using this method is presently regarded as a difficult task, and most successful surveys thus far have focussed on mapping conductive inorganic contaminants. It was felt prior to the EM survey in this study that based upon the extremely high levels of creosote at the site an approximate mapping of the organic compounds would be possible. It has been shown through experimentation that when organic contamination interacts with and displaces soil moisture in the vadose zone an appreciable and detectable decrease in conductivity can result (Monier-Williams, 1995). Laboratory conductivity measurements for many of the creosote-related SVOC's that were present in high concentrations at the site have been studied by Lucius, et al. (1990). These studies indicate that a decrease in

conductivity should result when these compounds displace soil moisture. An additional element that was thought to increase the potential for successful mapping of contamination at the site was the abundance of the clay-rich soils, which in theory should enhance the contrast of the resistive creosote compounds against these high conductivity background materials. Along with soil matrix porosity, degree of saturation, and the conductivity of pore-filling fluids, the presence of clay minerals can have a significant impact on terrain conductivity (Keller and Frischknecht, 1966).

In-phase and quadrature response measurements were made across the survey grid using a GEM-300 frequency domain electromagnetic induction system at frequencies of 2010 Hz (2kHz), 4410 (4kHz) and 9810 (9kHz). Data for all three frequencies were recorded simultaneously using the GEM-300 system with the long axis of the instrument oriented parallel to the north-south survey lines and the dipole axis oriented vertical to the plane of the ground (referred to as vertical dipole mode). Measurements were made every 0.6 meters along transects with a spacing between north-south lines of 0.9 meters. The measured in-phase and quadrature phase components of the secondary field are expressed in parts per million (ppm) of the primary induced field strength. The in-phase response is commonly interpreted as being related to metal conducting targets and is referred to as the metal detector mode, while the quadrature phase response is interpreted as being related to non-metallic conductors and is referred to as the terrain conductivity mode. The effective measuring point for the GEM-300 does not correspond to the center position of the operator. Since data at the site were recorded by walking back and forth along transects with the instrument held alongside the operator, a correction was applied to reduce these effects in the data prior to contouring and plotting. Quadrature component data were contoured in ppm values relative to the primary induced field strength rather than in calculated conductivity mS/m values, as actual values of conductivity were not essential for the identification of possible anomalous lows corresponding to areas of soil contamination.

EM Data Interpretations and Results

In-phase data at all frequencies measured indicated anomalous regions of relatively high conductivity in the vicinity of the former tanks and pump house, resulting from the reinforcing bar and other metal associated with these foundations. These regions of relatively high conductivity (black to dark gray) were also evident in the quadrature response near the foundations as shown in the 4 kHz (Fig. 3a) and 9kHz data (Fig. 3b). Scattered patches of standing surface water (water patches averaged 20 cm deep) were present during the EM survey and also had an effect on the quadrature EM data by producing anomalous conductivity highs as shown in Fig. 3a and Fig 3b. A north-east trending anomalous conductivity high is present in the western part of the survey area and conductivity highs at a few other locations are present in the eastern part of the survey area as a result of these surface water patches. The location of

these anomalies corresponded to the locations of water that were mapped at the time of data acquisition. The recorded high conductivity from both the foundations and the water made it difficult to make interpretations regarding the presence of any possible contamination in the immediate vicinity of these features as they dominated the EM response. However, EM measurements were unaffected by these features in areas adjacent to and away from them, where no indication of associated high conductivity anomalies are evident. The EM response in areas adjacent to and away from these features was apparently dependent only upon the conductive clay soils, surface water and any possible relatively resistive creosote contamination present.

Areas of relatively low conductivity (white to light gray) in areas surrounding the foundations in the quadrature data (from 15 -74 meters on x-axis in Fig. 3a and Fig. 3b) were interpreted to represent the approximate extent of contamination at the site, and provided insight concerning the variation of contamination with depth. Quadrature data recorded at 2 kHz indicated no anomalous areas of low conductivity that could be correlated with known locations of the creosote compounds, and therefore led to the interpretation that contamination where present was predominately in the near surface. Areas of low conductivity are shown to be less prominent in the 4 kHz data than in the 9 kHz data (Fig. 3a and Fig. 3b), which served as further evidence to help substantiate the interpretation that the contamination where present was probably mostly in the very near surface. Data interpretations regarding the approximate extent of contamination both laterally and with depth were consistent with the locations of high concentrations of creosote determined through soil sample analysis prior to this study (see Fig. 1 and Table 1), and were also consistent with the actual extent of contamination determined to be present through exploratory sampling subsequent to data interpretations (exploratory sampling and the actual extent of creosote determined to be present is discussed in the following section and presented in Fig. 6). Contamination was found through exploratory sampling subsequent to EM data interpretations to be confined to the top 1.0 - 1.3 meters across most of the site which correlated well with resistive anomalies in the 9 kHz data (Fig. 3b). Additionally, contamination found to be present at depth in areas around the tank and pump house foundation resulting from leaking subsurface creosote-filled features correlated with relatively resistive anomalies in the 4 kHz data (Fig. 3a) in these locations. Resistive anomalies are also present in the north-eastern-most area of the survey grid where contamination was also confirmed to exist.

GPR Surveys, Data Interpretations and Results

GPR surveys were conducted on two separate occasions (January and February 1999) over the survey grid, with a spacing of 0.9 meters between the north-south traverse lines. Co-pole and cross-pole GPR data were acquired using a 500 MHz multi-component antenna system in distance-based mode. A cross-pole configuration, which is not frequently used for GPR field surveys, consists of transmit and re-

ceive antennas aligned orthogonal to each other. Cross-pole GPR data had a better signal to noise ratio at this site because this arrangement was less sensitive to ringing and energy with the same polarization as the incident energy scattered from near-surface layering and water, and was more sensitive to depolarized energy scattered from rough targets of interest (Guy et al., 1999; and Radzevicius et al., 2000). Two GPR surveys were conducted at the site to improve the potential for accurate interpretation, as the GPR response can vary significantly depending on soil moisture content. No discernable differences between these data sets were evident, and therefore only data from the January 1999 survey are discussed and presented in this paper.

The standing surface water present at the site which affected the EM measurements also had an effect on the GPR response, as illustrated using a cross-pole GPR 2D profile across the western part of the survey area in Fig. 4a. Areas where water was present resulted in late arrival times of direct and scattered depolarized energy from the rough water bottom and soil interface (interface is at 6 ns) due to the water having a relatively lower velocity than the surrounding areas where standing water was not present. The direct arrival over the surface water as shown is of low amplitude in the cross-pole data, whereas the amplitude of the direct arrival in the co-pole data over water was much higher. Events beneath the water and soil interface are a result of multiple pulses emitted from the antenna because of the impedance mismatch of the antenna with the water, and are also a result of multiple reflections from the water bottom and water-air interface. Higher amplitude earlier arrivals over areas where water is not present in Fig. 4a are caused by depolarized scattered energy from surface roughness along this transect. Limited GPR penetration is also evident along this transect as a result of the clay-rich soils.

Because soils across much of the site contained mineralogic clays that had a high moisture content, GPR penetration was limited in most places from 1.0 to 1.3 meters depth. GPR was useful despite the highly attenuating soils across most of the site. Penetration was adequate enough to image back-filled trenches and less attenuation occurred through concrete foundations, beneath which several structures containing contaminant were imaged. A back-filled trench and a creosote-filled vault beneath a tank foundation that were located using the cross-pole data are shown in a 2D cross-section in Fig. 4b (note the rebar imaged at 10 ns within southern-most tank foundation). A 3D display of a back-filled trench and a creosote-filled vault beneath the northern-most tank pad at the site is presented as Fig. 5 (an anomaly from the vault beneath the southern tank foundation is not evident from this 3D view angle).

Detection of liquid contaminants using GPR is an area of research that has received a great deal of attention in recent past. A number of contaminated site studies have identified anomalous GPR responses related to areas of known contamination (Daniels et al., 1995; and Grumman and Daniels, 1995). Experimental and theoretical research has additionally provided information in regards to the applicability of GPR for the detection of different liquid contaminants under certain conditions (DeRyck et al., 1993;

and Greenhouse et al., 1993). Although GPR has been proven to have the potential to determine the extent of contamination in some situations, no discernable correlations between the recorded GPR data and the extent of contamination at this creosote site were identified.

Geophysical Data Validation

Areas for sampling using a flame ionization detector and exploratory trenching were positioned from the interpreted approximate extent of soil contamination and the location of subsurface targets prior to site remediation. The actual extent of creosote contamination was confined within the top meter of soils as suspected, except for the immediate areas surrounding the tank foundations where additional contamination had occurred at depth from leaking creosote-filled vaults. The locations of several anomalous features interpreted from the cross-pole GPR data were confirmed during this invasive investigation, and were found to represent creosote-filled vaults beneath the tank foundations and a waste pit south-east of the pump house foundation. Areas interpreted as back-filled trenches were confirmed and were found to contain creosote-filled ceramic drainage piping at depths of 1.0 - 1.5 m. The locations of all targets of interest and the actual extent of creosote contamination in soils within the survey area determined subsequent to geophysical interpretations during the exploratory sampling at the site are shown in Fig. 6. A correlation between the areas of low conductivity in the quadrature data with the actual extent of contamination within the geophysical survey area is clear when comparing the 9 kHz data in Fig. 3a with the actual extent of contamination in the geophysical survey area shown in Fig. 6. The area of actual extent of contamination as shown in Fig. 6 is more extensive than the anomalous areas of low conductivity in the quadrature EM data. This was expected, as lower concentrations of creosote farther away from the tank pads, which were the source of contamination, would be less likely to be detected than in areas of very high contamination.

Conclusions

The potential effectiveness of EM terrain conductivity for mapping the approximate extent of high levels of organic contamination has been demonstrated through this study, as low conductivity anomalies in the 9 kHz quadrature data (where the EM response wasn't dominated by highly conductive foundations and surface water) correlated with areas of contamination that were subsequently excavated at the site. The potential effectiveness of considering GPR polarization and acquiring cross-pole GPR data for site characterization studies was also demonstrated through this study, as cross-pole data were more effective for imaging targets of interest at this site. Despite the clay-rich soils present that attenuated the GPR signal and the resulting limited penetration across much of the site, GPR was useful for imaging several shallow features within the soils and beneath foundations.

By paying close attention to site-specific circumstances that can influence geophysical responses, the probability for successful site characterization using EM and GPR can be significantly increased. The geophysical techniques chosen for this study were successful in mapping the approximate extent of contamination at the site and were also able to locate features that contained contaminant and would have otherwise remained undetected. Information on the extent of contamination at this site and the locations of these features based on geophysical interpretations prior to exploratory sampling allowed for the design of an efficient, comprehensive and cost-effective site remediation plan.

Acknowledgements

We wish to thank the US EPA Region V, Chicago, Illinois, for their support of this and related geophysical research. Also appreciated is the assistance provided by Mark Durno and the US EPA Region V, Cleveland, Ohio throughout the course of this study. Gratitude is additionally extended to David Grumman of Grumman Exploration, Inc., Columbus, Ohio, for allowing us to use the GEM-300 system for this study.

References

- Annan, A.P., and Daniels, J.J. 1998. Ground Penetrating Radar (short course notes): Symposium on the Application of Geophysics to Engineering and Environmental Problems, Chicago, IL.
- Buselli, G., Barber, C., Davis, G.B., and Salama, R.B., 1990, Detection of Groundwater Contamination Near Waste Disposal Sites with Transient Electromagnetic and Electrical Methods, in: Ward, S.H. (ed.), *Geotechnical and Environmental Geophysics*. Vol. 2: Environmental and Groundwater. Tulsa: Society of Exploration Geophysicists, 27-39.
- Daniels, J.J., Roberts, R., and Vendl, M., 1995, Ground Penetrating Radar for the Detection of Liquid Contaminants, *Journal of Applied Geophysics*, **33**, 195-207.
- DeRyck, S.M., Redman, J.D., and Annan, A.P., 1993, Geophysical Monitoring of a Controlled Kerosene Spill, in: *Symposium on the Application of Geophysics to Engineering and Environmental Problems*, San Diego, California, 5-19.
- Greenhouse, J.P. and Slaine, D.D., 1983, The Use of Reconnaissance Electromagnetic Methods to Map Contaminant Migration, *Ground Water Monitoring Review*, **3**, no. 2, 47-59.
- Greenhouse, J.P., Brewster, M., Schneider, G., Redman, D., Annan, P.I., Olhoeft, G.R., Lucius, J., Sander, K., and Mazzella, A., 1993, Geophysics and Solvents: The Borden Experiment, *The Leading Edge*, **12**, no. 4, pp. 261-267.
- Grumman, D.L., and Daniels, J.J., 1995, Experiments on the Detection of Organic Contaminants in the Vadose Zone, *Journal of Environmental and Engineering Geophysics*, **0**, no. 1, 31-38.

- Guy, E.D., Daniels, J.J., Radzevicius, S.J., and Vendl, M.A., 1999, Demonstration of Using Crossed Dipole GPR Antennae for Site Characterization, *Geophysical Research Letters*, **26**, no. 22, 3421-3424.
- Keller, G.V., and Frischknecht, 1966, *Electrical Methods in Geophysical Prospecting*, Pergamon Press, New York, 519 p.
- Lucius, J.E., Olhoeft, G.R., Hill, P.L., and Duke, S.K., 1990, Properties and Hazards of 108 Selected Substances, U.S. Geological Survey, Open File Report 90-408, 559 p.
- Mneill, J.D., 1990 Use of Electromagnetic Methods for Groundwater Studies, in: Ward, S.H. (ed.), *Geotechnical and Environmental Geophysics. Vol. 2: Environmental and Groundwater*. Tulsa: Society of Exploration Geophysicists, 191-218.
- Monier-Williams, M.E., Greenhouse, J.P., Mendes, J.M. and Ellert, N., 1990, Terrain Conductivity Mapping with Topographic Corrections at Three Waste Disposal Sites in Brazil, in: Ward, S.H. (ed.), *Geotechnical and Environmental Geophysics, Vol. 2: Environmental and Groundwater*, Tulsa: Society of Exploration Geophysicists, 41-55.
- Monier-Williams, M.E., 1995, Properties of Light-Non Aqueous Phase Liquids and Detection Using Commonly Applied Shallow Sensing Geophysical techniques: in *Proceedings of the Symposium on the Applications of Geophysics to Engineering and Environmental Problems*, Orlando, Florida, 1-14.
- Ohio Department of Natural Resources (ODNR), Division of Geological Survey, 1962, *Well and Boring Logs for Marion County*, Columbus, Ohio.
- Ohio Environmental Protection Agency (Ohio EPA), Division of Ground Water, 1991, *Berwind Railway Services and Baker Woods Creosoting, Marion County: Preliminary Site Evaluation*, I.D.# 351-0094, Ohio EPA, Bowling Green, OH.
- Olhoeft, G.R., 1986, Direct Detection of Hydrocarbon and Organic Chemicals with Ground Penetrating Radar and Complex Resistivity, in *Proceedings of the NWWA/API Conference on Petroleum Hydrocarbons and Organic Chemicals in Ground Water - Prevention, Detection and Restoration*, Dublin, OH, NWWA, pp. 284-305.
- Radzevicius, S.J., Daniels, J.J., Guy, E.D., and Vendl, M.A., 2000, Significance of Crossed-Dipole Antennas for High Noise Environments, in: *Symposium on the Application of Geophysics to Engineering and Environmental Problems*, Arlington, Virginia, pp. 407-413.
- United States Department of Agriculture (USDA), 1989, *Soil Survey of Marion County, Ohio*. United States Department of Agriculture, Soil Conservation Service.
- United States Environmental Protection Agency (US EPA), 1998, *Baker Wood Creosoting, Marion, Ohio; Integrated Assessment Report*, I.D.# OH-001-326-610, U.S. EPA Region V, Chicago, IL.
- Vickery, A.C., and Hobbs, B.A., 1998, Contributions of Surface Geophysics to Environmental Site Investigation of Former Oil Distribution Terminals, *Journal of Environmental and Engineering Geophysics*, vol. 3, issue 3, pp. 101-109.

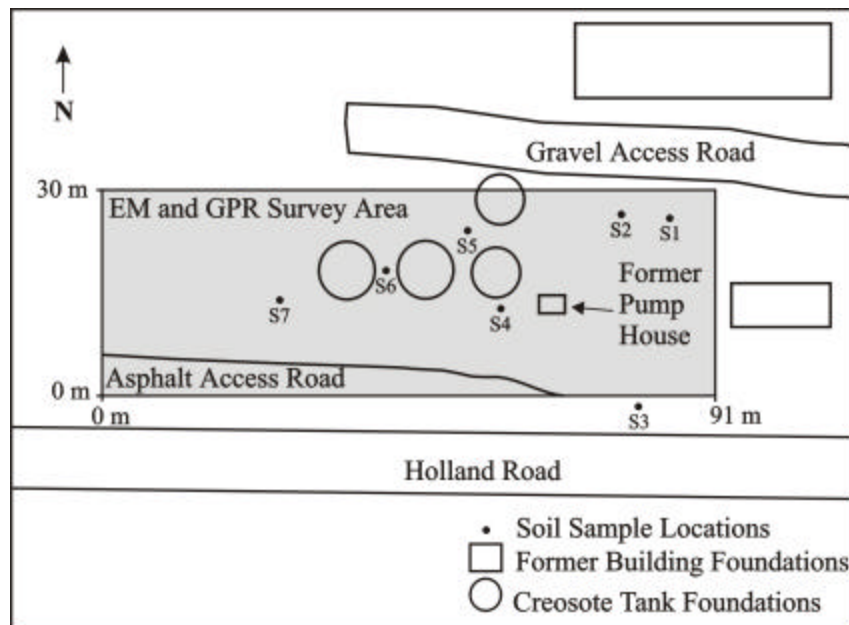


Figure 1. Map showing multifrequency EM and GPR survey area relative to site features and soil sample locations at the former Baker Wood Creosoting site.

Soil Sample	Sample Depth (cm)	Relative amount of SVOC's
S1	10 – 15	High ^{***}
S2	25 – 30	High ^{***}
S3	305 – 365	Low [*]
S4	25 – 30	High ^{***}
S5	229 – 259	Medium ^{**}
S6	198 – 259	Medium ^{**}
S7	0 – 20	Medium ^{**}

^{*}Majority of SVOC's < 1,000 ppb

^{**}Majority of SVOC's 1,000 - 100,000 ppb

^{***}Majority of SVOC's > 100,000 ppb

Table 1. Simplified semi-volatile organic compound (SVOC) analytical results of soil samples acquired at the former Baker Wood Creosoting site, soil samples correspond to the locations indicated on Figure 1 (Modified from US EPA, 1998).



Figure 2. Highly concentrated residual and liquid phase creosote contamination (blue-silver color) visually distinguishable against site soils (light brown to brown) near a tank foundation. Photograph was taken during remediation of the site.

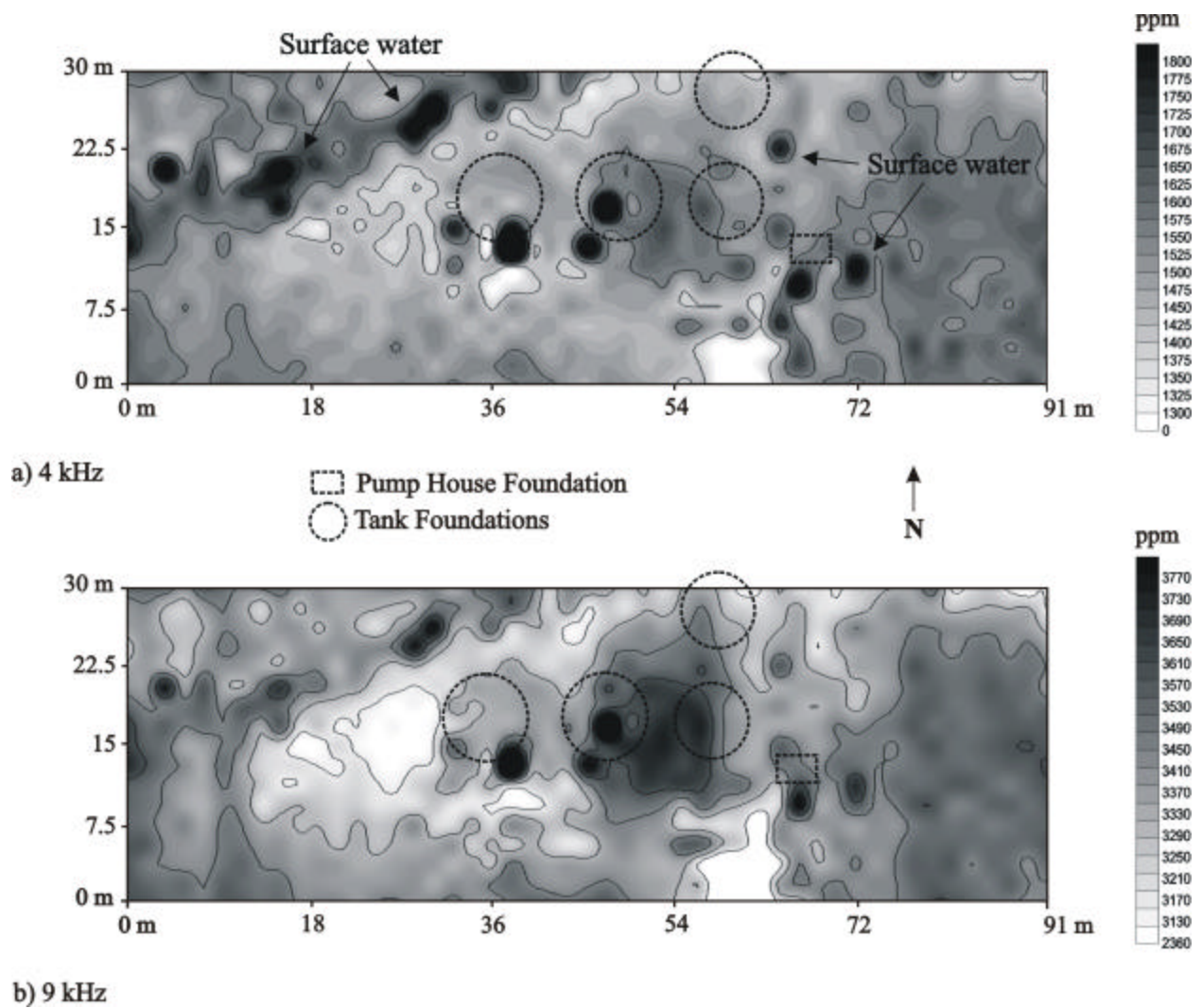
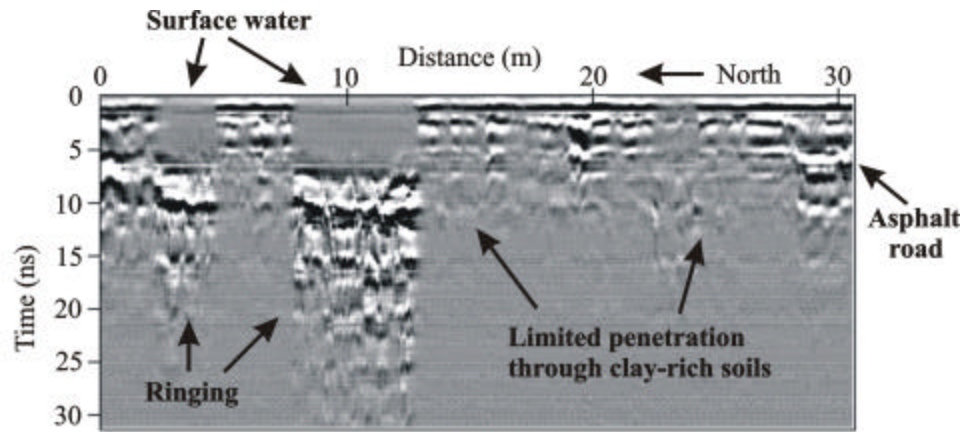
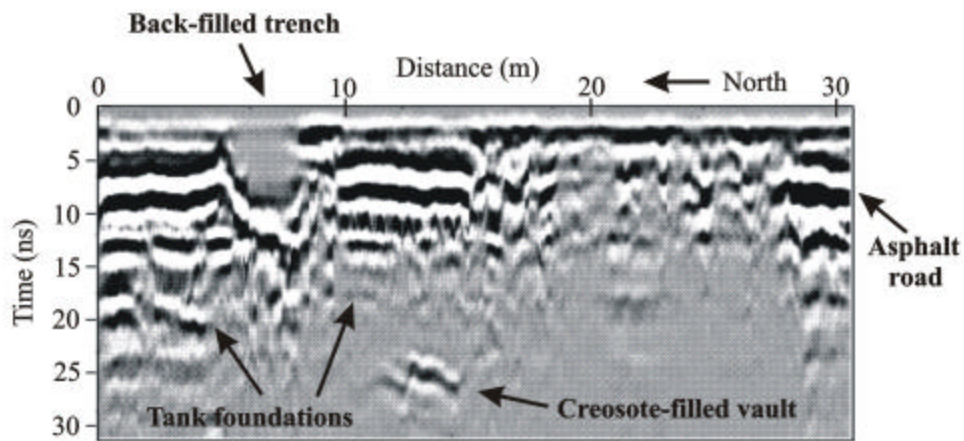


Figure 3. EM quadrature response over geophysical survey area relative to site features: a) 4kHz, and b) 9kHz. Areas of low conductivity (white to light gray) surrounding the highly conductive (black to dark gray) tank foundations and pump house, and in the north-east corner of the survey area, correlate with high concentrations of creosote in soil samples and the actual extent of creosote determined through exploratory sampling. Areas of high conductivity resulting from patches of standing surface water are also indicated.



a) 2D section showing effects of surface water and clay-rich soils



b) 2D section showing a back-filled trench and a creosote-filled vault

Figure 4. Cross-pole GPR 2D cross-sections showing: a) the effects of surface water on the radar response and limited GPR penetration through clay-rich soils, and b) a back-filled trench that contained creosote-filled ceramic piping and a creosote-filled vault imaged beneath a tank foundation.

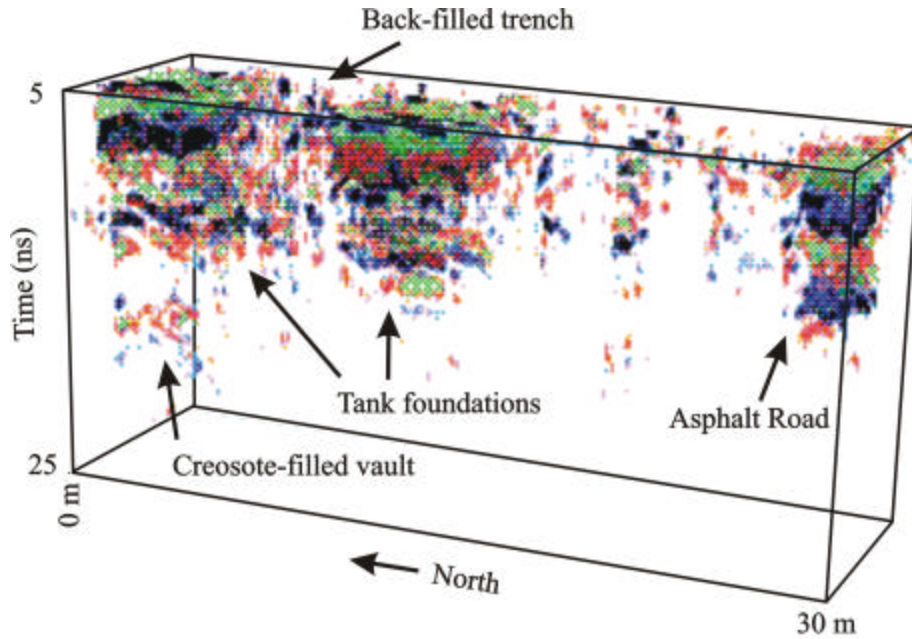


Figure 5. 3D cross-pole GPR display across the western half of the two eastern-most tank foundations at the site showing a back-filled trench and a creosote-filled vault (modified from Guy et al., 1999).

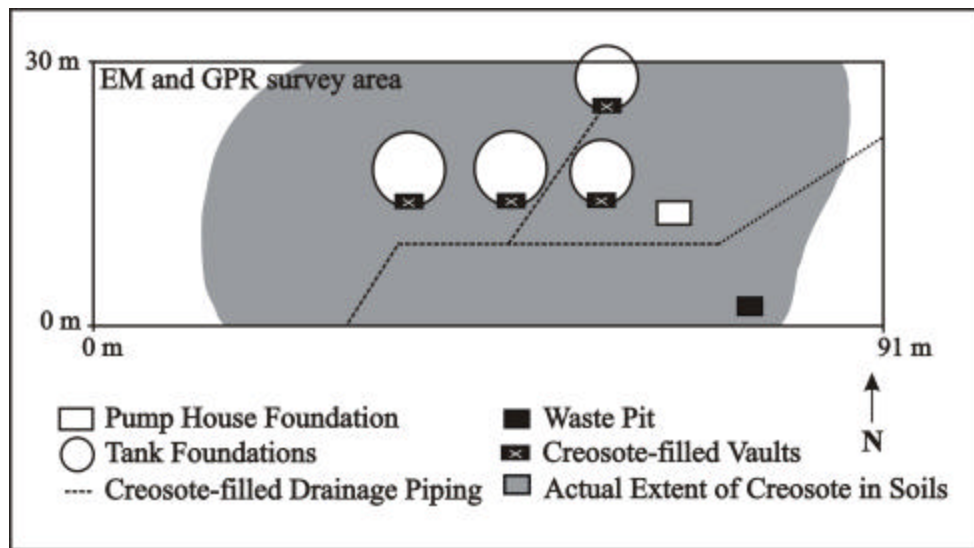


Figure 6. Locations of targets of interest and the actual extent of creosote contamination within the geophysical survey area determined through exploratory sampling.