# Case Study Abstract

**Trail Road Landfill**
**Nepean, Ontario, Canada**

<table>
<tr><td>Site Name and Location:<br>Trail Road Landfill<br>Nepean, Ontario, Canada</td><td rowspan="2">Geophysical Technologies:<br>Natural gamma<br>Magnetometry<br>Electrical conductivity<br>Density<br>Temperature</td><td>CERCLIS #<br>Not applicable</td></tr>
<tr><td>Period of Site Operation:<br>Early 1980's to the present<br><br>Operable Unit:<br>Not applicable</td><td>Current Site Activities:<br>The Nepean Landfill is capped and closed. Stages 1and 2 of the Trail Road Landfill are capped and closed. Stage 3 is currently being filled and stage 4 is ready to be opened. Stages 3 and four have leachate collection systems. In general, groundwater is monitored 3 - 4 times a year for chemical contamination.</td></tr>
<tr><td>Point of Contact:<br>Keith Watson, 613-838-2799<br>Darin Abbey, 604-291-5429<br>C. Jonathan Mwenifumbo, 613-996-2312</td><td>Geological Setting:<br>A complex mixture of sand, gravels, and silt overlying a lacustrine clay plain. Limestone bedrock underlies a glacial till deposit of sand and gravel which lies under a silty clay layer. There is a shallow aquifer which discharges into a deep aquifer.</td><td>Technology Demonstrator:<br>Darin Abbey, Carleton University, Ottawa, Canada,</td></tr>
<tr><td colspan="3">Purpose of Investigation:<br>The overall goal of this investigation was to show that leachate plume delineation could be accomplished through interpreting data from a full suite of geophysical logs.</td></tr>
<tr><td colspan="3">Number of Images/Profiles Generated During Investigation:<br>Eight composite profiles illustrating the results of the logs from each of the above mentioned technologies.</td></tr>
<tr><td colspan="3">Results:<br>The use of geophysical measurements from boreholes can provide a continuous vertical profile of the geology and hydrogeology. This information can be used to understand the factors controlling the groundwater composition, and ultimately leachate movement in the subsurface. The geophysical techniques overcome the traditional monitoring limitation of fixed vertical sampling positions for chemical analytes.</td></tr>
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## EXECUTIVE SUMMARY

The Trail Road and Nepean Landfill sites are located within the Region of Ottawa-Carleton, Canada, with a population of 750,000. The site, approximately 500 acres, is surrounded by light industry, and farmland. The Nepean Landfill began operation in the early 1960s and accepted waste until the early 1980s when it was deemed nearly full and the Trail Road Landfill was opened. The Trail Road Landfill is currently serving as a municipal sanitary landfill accepting non-hazardous waste including residential garbage, construction, commercial, institutional, and light industrial waste.

Leachate, believed to originate from the unlined Nepean Landfill and the stages 1 and 2 of the Trail Road Landfill, has been detected in the groundwater below the site. The leachate consists of a complex mixture of organic and inorganic constituents as well as elevated levels of calcium, magnesium, chloride, sulphate, potassium, ammonia, other nitrogen compounds, other dissolved organic carbons, phenols, and iron.

The landfill site is positioned on a glacial outwash plain which has a complex mixture of sands, gravels, cobbles, clays, and silt. The surface soil consists of a discontinuous dense layer of silt and clay (approximately two meters) beneath which is a layer of sand and gravel which overlies a limestone bedrock forming a deep aquifer, present at a depth of 10 to 30 meters. A clay layer is present beneath part of the Trail Road Landfill site. The clay layer separates the sand and gravel ridge into an upper and lower aquifer.

A geophysical investigation was conducted at the landfill to demonstrate an innovative method for monitoring a landfill leachate plume. The information contained in this report was extracted from the interpretive report of the investigation. Six different geophysical methods were combined in borehole applications to collect the geophysical data for this investigation. The six methods were: natural gamma, gamma-gamma, total magnetic and magnetic susceptibility, electrical conductivity and temperature. Geophysical logs were developed in eight existing monitoring wells.

The geophysical logs correlated well with existing lithologic logs, and identified the presence of a surficial clay layer and a perched aquifer on that layer where leachate may collect. Logs of the deeper aquifer generally showed little evidence of contamination, with the exception of one well, in which a significant anomaly was detected. The conductivity and temperature logs were interpreted to show the presence of leachate contamination in this one well.

Lessons learned at the Trail Road Landfill site were that the major advantage of geophysical logs over traditional sampling techniques is that they provide a continuous representation of the subsurface conditions. The logs can provide a measurement of total dissolved solids as a proxy for ions in water. A major failing of the traditional sampling approach is the fixed vertical screen position. Although actual chemical identification cannot be done by geophysical methods, groundwater with anomalously high conductivities would indicate the need for chemical analyses. These examples show the need for conductivity data to be interpreted in conjunction with other geophysical measurements to illustrate the anomaly in conductivity at a certain depth within a well.

# SITE INFORMATION

## Identifying Information

Trail Road Landfill
Environment and Transportation Department
Solid Waste Division
Region of Ottawa-Carleton
4475 Trail Road, R.R. #2
Richmond, Ontario, KOA 220
CANADA

## Background

**Physical Description:** The Trail Road Sanitary Landfill site, which includes the Nepean and Trail Road landfills, is located within the Region of Ottawa-Carleton, Canada, with a population of 750,000. The site, approximately 500 acres, is surrounded by light industry and farmland. The terrain consists of grasslands and light forests. Running tangent to the eastern side of Trail Road Landfill is Highway 416. Likewise the southern side is bordered by a lesser road, Trail Road, which also borders the northeastern side of the Nepean Landfill (which is located southwest of the Trail Road Landfill). Moodie Drive runs along the western boundary of the Nepean Landfill. The south end of the entire site is bordered by Barnsdale Road and Cambrian Road runs northeast through the northern boundary of the site, but is not immediately adjacent to the landfills (see Figure 1)[1, 2, 3]. South of the Trail Road Landfill, there is a sand and gravel ridge which serves as a divide for surface water runoff. Surface water flows from this ridge to either the north or the south. For the Trail Road Landfill, the general site surface water flow is in a north to northeasterly direction but is interrupted by site excavations.

The Nepean Landfill began operation in the early 1960s and accepted all landfill waste until the early 1980s when it was deemed nearly full and the Trail Road Landfill was opened. Thereafter, until is was capped in 1993, only construction waste was disposed of in the Nepean Landfill. This landfill is not lined but it is capped with a polyethylene liner and soil [1].

**Site Use:** The Trail Road Landfill is currently serving as a municipal sanitary landfill accepting solid non-hazardous waste including residential garbage, construction, commercial, institutional, and light industrial waste. The Trail Road Landfill was opened in 1980 and has been continuously operated in stages (see Figure 1). The first two stages are closed and capped with polyethylene and soil but are not lined and do not have leachate collection systems. Stage 3 was constructed with a 60 centimeter (cm)- thick competent clay and a high density polyethylene liner. The third stage, which opened in 1991, is nearly full, and will be capped with a polyethylene liner and soil. Stages 3 and 4 have leachate collection systems. Stage 4 is not yet operational [1, 2].

## SITE INFORMATION

**Release/Investigation History:** Leachate, believed to originate from the unlined Nepean Landfill and the stages 1 and 2 of the Trail Road Landfill, has been detected in the groundwater below the site. The leachate consists of a complex mixture of organic and inorganic constituents as well as elevated levels of calcium, magnesium, chloride, sulphate, potassium, ammonia, other nitrogen compounds, other dissolved organic carbons, phenols, and iron [3].

The groundwater is monitored on a variable basis. All wells are monitored up to 3 times a year for indicators including chloride, boron, bromide, BOD, DOC, and iron [1, 2].

**Regulatory Context:** Not Applicable

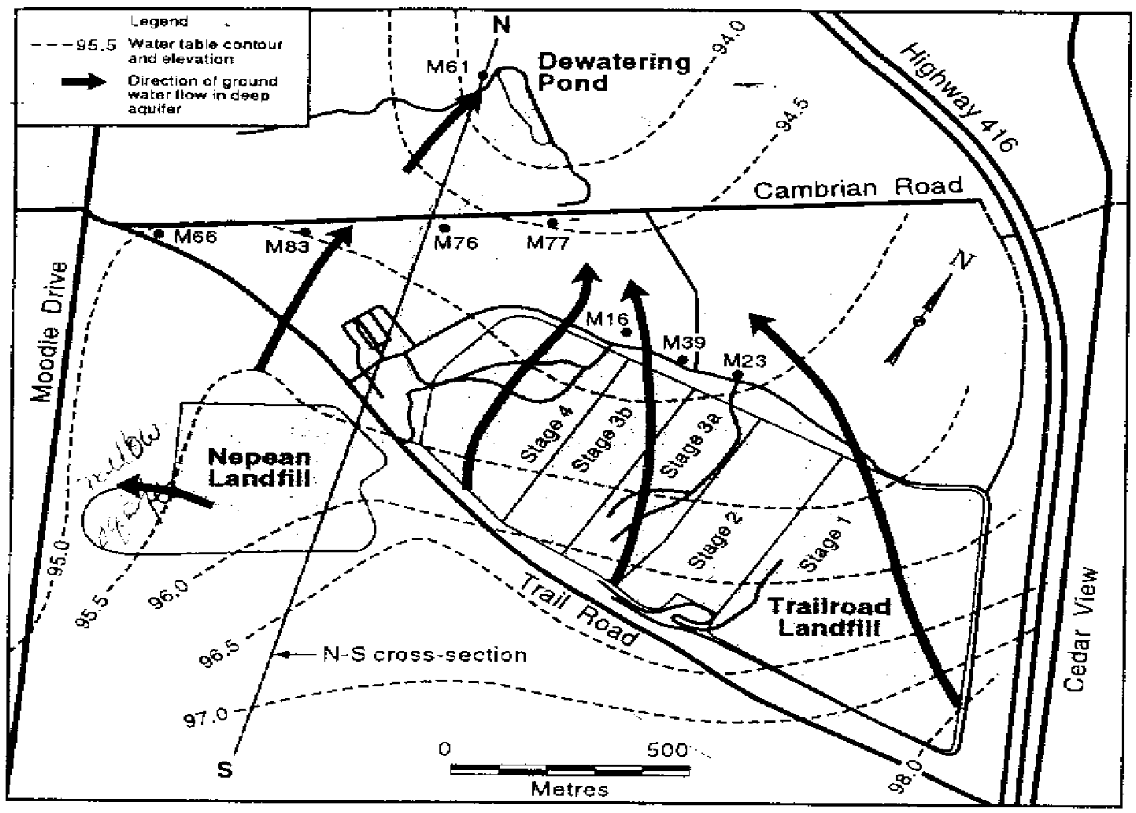


**Figure 1: Site Map [3] [Poor Quality Original]**

# SITE INFORMATION

## Site Logistics/Contacts

**Site Contact:**
Keith Watson
Regional Municipality of Ottawa-Carleton
4475 Trail Road, R.R. #2
Richmond, Ontario, KOA 220
(613) 838-2799

**Geophysical Investigator:**
Geological Survey of Canada
Mineral Resources Division
601 Booth Street
Ottawa, Ontario, K1A 0E8
CANADA

# MEDIA AND CONTAMINANTS

## Matrix Identification [3, 5]

**Type of Matrix Sampled and Analyzed:** Subsurface clays, cobbles, sands, and gravels

## Site Geology/Stratigraphy [3, 5]

The landfill site is positioned on a glacial outwash plain which has a complex mixture of sands, gravels, cobbles, clays, and silt (Figure 2). A discontinuous dense layer of silt and clay (approximately two meters in thickness) separates two aquifers. The silt and clay layer is complete under the Nepean Landfill but not under all of the Trail Road Landfill and acts as an aquitard to a perched aquifer.

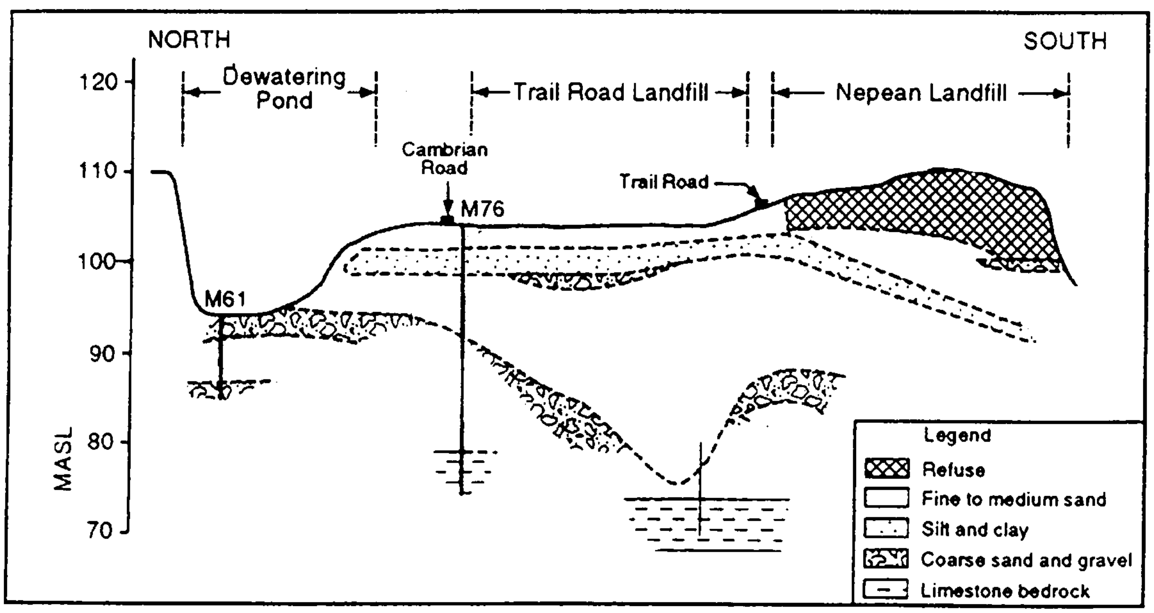


**Figure 2: North to South Cross Section of Site [3]**

# MEDIA AND CONTAMINANTS

Approximately 500 meters from the northern boundary of Trail Road Landfill on the north side of Cambrian Road is a large de-watering pond used to catch the local groundwater discharge. The pond water eventually discharges into the Jock River which is located approximately 1 km to the north. Southwest of Trail Road is the Nepean Landfill. Surface water runoff flows in a south to southwesterly directly from Trail Road [2, 3].

There are two aquifers, separated by clay, underlying the entire site. A shallow sand aquifer flows in a north to northeasterly direction under the Trail Road Landfill. Surface water penetration creates a shallow groundwater flow in a south to southwesterly direction under the Nepean Landfill. The deep aquifer, located in a layer of bedrock at a depth ranging from 10-30 meters flows in a south to north direction[2].

## Contaminant Characterization

**Primary Contaminant Groups:** The contaminants consists of chemicals within groundwater from landfill leachate. The leachate consists of a complex mixture of organic and inorganic constituents, and is produced by the percolation of water through the waste, which dissolves and suspends some of the chemicals by chemical reaction. The leachate has elevated concentrations of calcium, magnesium, chloride, sulphate, potassium, ammonia, other nitrogen compounds, other dissolved organic carbons, phenols, and iron [3]. The leachate has characteristically high conductivity, hardness, alkalinity, and total dissolved solids (TDS). Exothermic reactions within the landfill can cause elevated groundwater temperatures.

## Matrix Characteristics Affecting Characterization Cost or Performance [3, 5]

The density readings taken for sediments above the water table contained a low bias because the density calibration logs assumed a water-filled well. No other characteristics of this site affected the performance of the geophysical technologies.

# GEOPHYSICAL INVESTIGATION PROCESS

## Investigation Goals [3, 5]

The purpose of this study was to show that by measuring the physical properties of the subsurface, borehole geophysics can refine the hydrogeological interpretation of the landfill site. The interpretation of gamma ray, density, magnetic susceptibility, total magnetic field, electrical conductivity and temperature logs can serve to refine the understanding of the underlying geology and the existence of a leachate plume. Borehole geophysics can also be used to delineate areas of leachate contamination with greater efficiency than sampling and chemical analysis of analytes.

# GEOPHYSICAL INVESTIGATION PROCESS

## Geophysical Methods [3, 5]

Six different geophysical methods were combined in eight borehole applications to collect the geophysical data for this investigation. The six methods were: natural gamma, gamma-gamma, total magnetic and magnetic susceptibility, electrical conductivity, and temperature.

### Gamma Ray and Density

The natural gamma probe detects variation in natural radioactivity of the material surrounding the well. In sediments, $^{40}K$ is the principal source of natural gamma radiation which is present in clay minerals such as illite and montimorilloninte. The presence of clay layers can be detected by an increase in gamma emissions. Clays, with their low permeability can have the effect of precluding the vertical flow of groundwater and leachate. The technique can be used to determine accurate boundaries between sediment layers, sequences in grain size fining or coarsening which are generally much more accurate than lithologic logs developed by hand.
A gamma-gamma method was used to estimate the density of the geologic units. The density is determined by reading the “scatter back” of a gamma ray emitted from a source crystal containing Cobalt 60 on the probe. The application of density measurements to hydrogeology relies upon the assumption that the lower the density of the formation the greater the porosity and therefore potential for groundwater flow. It can be predicted that the areas within the sands, gravels and cobbles with lower densities will likely have the most water flow, while the limestone bedrock and clays having the least water flow. The gamma data were collected using the IFG Corporation Logging System, utilizing a dual-purpose 512 channel spectral natural gamma and gamma-gamma density probe

### Magnetometry (Total and Susceptibility)

Magnetic susceptibility provides a direct measure of the presence of magnetic sediments. Most unconsolidated sediments have little or no magnetic signature. Thus a higher magnetic susceptibility indicates the presence of iron rich mafic sand, gravel or cobbles. The use of both total field magnetic and magnetic susceptibility logs allow for the detection of ferromagnetic minerals such as pyrite ($FeS_2$). The measurement of the three orthogonal magnetic field components, which represent the local value of the normal ambient field of the Earth as modified by the remnant magnetization of adjacent sediments. The identification of such magnetic zones indicates layers that may have higher permeabilities, and, therefore, may be potential flow paths for groundwater. Total magnetic field, magnetic susceptibility and temperature were measured using the BMP–04 multi-parameter probe containing a 3 orthogonal fluxgate magnetometer.

### Electrical Conductivity

Perhaps the most useful geophysical measurement for detecting groundwater contamination is electrical conductivity. This geophysical method measures the conductivity of subsurface media by generating a current between two electrodes and measuring the potential difference. Electrical

## GEOPHYSICAL INVESTIGATION PROCESS

conductivity is measured in units of milliSeimens per meter (mS/m). Because soil is a poor conductor, most electric current flow occurs in the soil water when ions such calcium, magnesium, potassium, sodium, dissolved iron, chloride and sulphates are present. Leachate from a landfill typically contains large amounts of these type of ions. Since natural waters can contain many different ions, both ionic and uncharged, electrical conductivity cannot be used to make accurate estimates of specific ion concentrations. A linear relationship between total dissolved solids (TDS) and the electrical conductivity of groundwater exists.

Conductivity measurements were taken using the Geonics EM-39 system consisting of one transmitter coil and one receiver coil operating at 39.2 kHz.

**Temperature**

Temperature readings can indicate at what depths there is flowing groundwater as well as aid in determining location of exothermic chemical reactions from contamination. This information can be used to characterize the extent of leachate plumes and potential areas of groundwater contamination. The temperature is measured by a thermistor is cable of detecting temperature variations of +/- 0.001 °C. Characteristic water temperature profiles can be amplified using calculated temperature gradient logs to compare with measured temperatures. The temperature-depth profile can be modified by water flow, or exothermic chemical reactions in the leachate.

## GEOPHYSICAL FINDINGS

### Technology Calibration [3]

Geophysical methods often include calibration of the measurement instrument to a quantitative/ semi-quantitative standard. Natural gamma probes are calibrated to models of known $^{40}K$ radioactivity. Density is calibrated to models with a known density. Conductivity was calibrated to the ambient conductivity of monitoring wells in which chemical sampling had found no contamination. A background conductivity level of approximately 11 mS/m was established. Temperature was calibrated to the ambient temperature of an upgradient background well. Total magnetic field and magnetic susceptibility readings were zeroed by holding the probe at least 1.5 m above the ground and away from any metal objects.

### Investigation Results [3, 5]

Each of eight existing monitoring wells were used in the geophysical investigation. Four of the wells, M66, M83, M76, and M77, are located downgradient from the landfills. The wells are arranged along a line perpendicular to the groundwater flow between the landfills and the quarry (see Figure 1). Three others are located at the downgradient edges of Trail Road Landfill. The two sets of monitoring wells are well placed to monitor contaminant migration from the landfill toward the quarry.

## GEOPHYSICAL FINDINGS

The geophysical logs taken in the four wells located midway between the landfills and the quarry are shown in Figures 3 to 7. These four wells were selected for use in this analysis because of their location across the groundwater migration pathway. If leachate contamination were migrating to the quarry, it would be detected in one or more of these four wells.

The use of multiple geophysical methods allows the results of one method to be used to validate the findings of another. For example, in each of the four lithologic logs shown, a clay layer is present at shallow depths, i.e. less than 5 meters. In each case, the results of the gamma and the spectral gamma-gamma logs confirm this finding, as indicated by the sharp peak in counts per second at similar depths. The results of the density logs taken at depths above the water table are not valid, as the instrument calibration assumed a water-filled well. The magnetic logs, both total and susceptibility, are used to detect a coarsening in the subsurface materials, resulting from the presence of gravels and cobbles. Such coarse layers may be potential migration pathways for groundwater. In Figures 3 to 7, the magnetic logs do not indicate such layers at the depth at

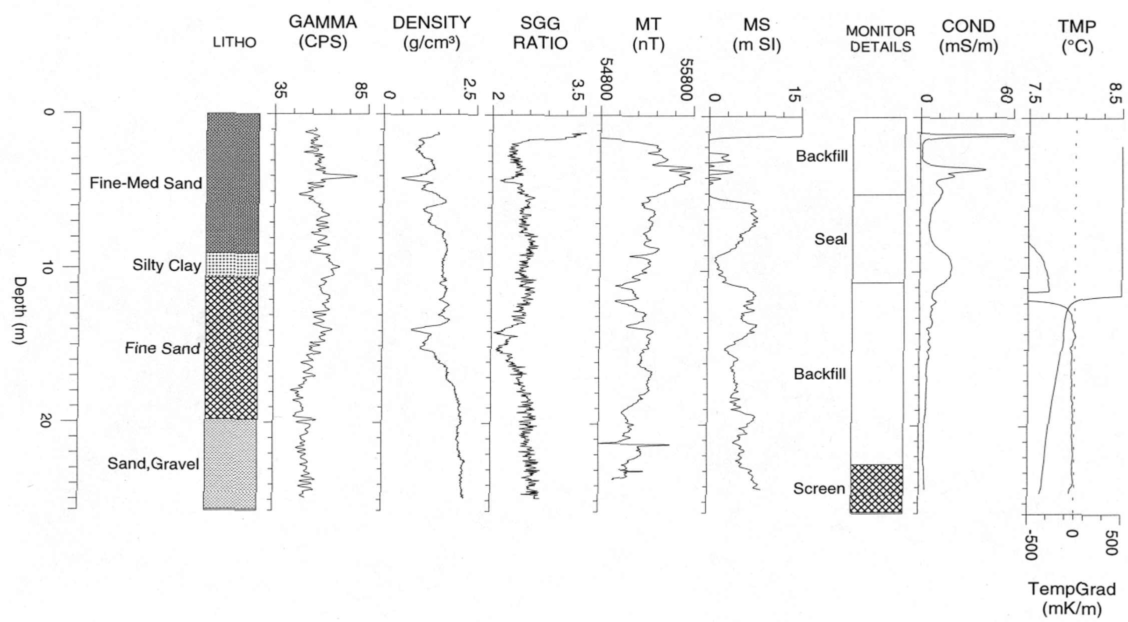


**Figure 3: Geophysical Log for Well M66**

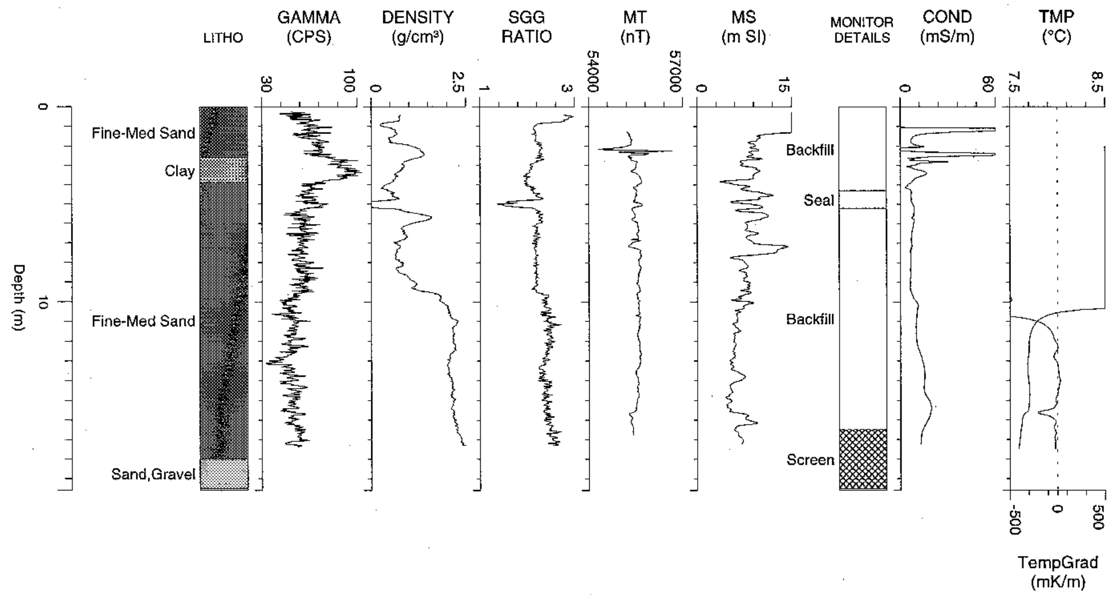


**Figure 4: Geophysical Log for Well M83 [5]**

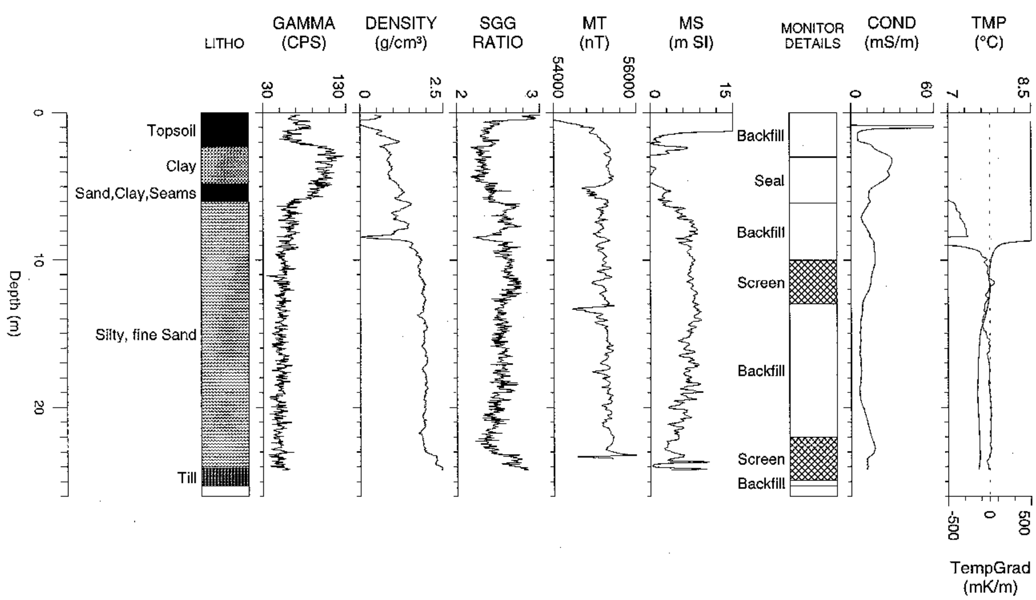


**Figure 5: Geophysical Log for Well M76 [5]**

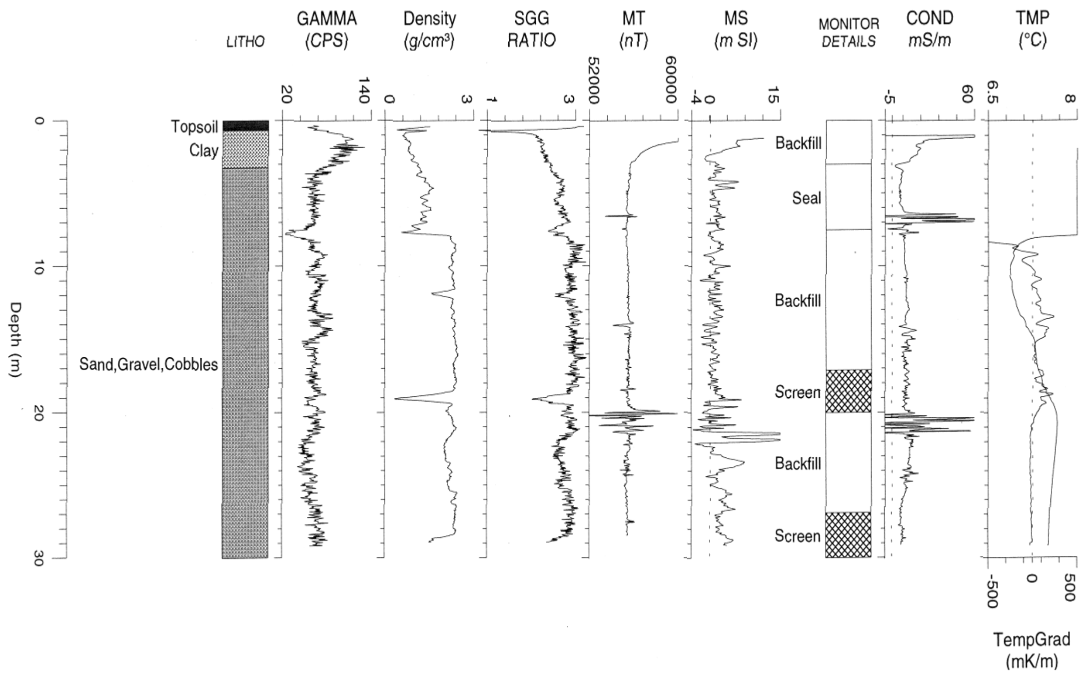


**Figure 6: Geophysical Log for Well M77**

which the clay layer is encountered. By inference, this result can be taken as a validation of the lithologic findings. Electrical conductivity logs also confirm the presence of the clay layer at the depths shown in the lithologic logs. The peak in conductivity measurements shows a distinct peak at depths at which clay is present in the lithologic log and lower values where sandy soils predominate. Conductivity and temperature logs were taken to identify the presence of leachate contamination. An examination of these logs in the four wells does suggest that in only one well, M77, may such contamination be present. The conductivity log for M77 clearly shows two anomalous spikes at depths of approximately eight and 20 meters. The first peak occurs at the water table. While some conductivity increase can be expected as the probe comes into contact with water, the reading in this well may also indicate the presence of contaminated groundwater. The second peak in conductivity occurs at approximately 20 meters. At this depth, there is no indication in the gamma or lithologic logs of clay lenses that might cause such a peak in conductivity measurements. Density and magnetic logs, indicators of porosity, both show the presence of a porous layer which may be controlling groundwater flow at this depth. The temperature log at this depth shows a marked increase in temperature, rising to a maximum of 7.7 °C, that may be due to the presence of exothermic reactions occurring in the groundwater. These findings, taken together, suggest the presence of leachate contamination at this depth.

## GEOPHYSICAL FINDINGS

### Results Validation [3, 5]

Chemical sampling at the landfill, as part of the on-going monitoring effort, confirmed the findings of the geophysical investigation.

## LESSONS LEARNED

Lessons learned at the Trail Road Landfill site were the following:

- Geophysical logs provided a continuous representation of the subsurface conditions which was a major advantage over the fixed depth readings obtained with traditional monitoring methods. The information obtained using fixed-depth sampling was relevant only at the depth the readings were taken. Geophysical logs provided continuous readings for the full depth of the borehole.

- The geophysical logs successfully delineated the leachate plume migrating from the landfill as regions of groundwater with anomalously high electrical conductivity. Chemical analyses conducted as part of the on-going monitoring program at the landfill confirmed the presence of leachate contamination moving from the landfill.

- The use of several, complementary, geophysical methods provided a cross-validation between the results of various methods. This cross-validation increases the confidence with which the geophysical data are interpreted.

# REFERENCES


1. Personal Communication with Dave Ryan, Trail Road Landfill Engineer, Region of Ottawa-Carleton, Ontario, Canada. December 1, 1998.

2. Personal Communication with Keith Watson, Site Manager, Region of Ottawa-Carleton, Ontario, Canada. November 25, 1998.

3. Abbey, Daron G., et al. *The Application of Borehole Geophysics to the Delineation of Leachate Contamination at the Trail Road Landfill site: Nepean, Ontario.* Proceedings of the Symposium on the Application of Geophysics to Engineering and Environmental Problems (SAGEEP) 1998.

4. Personal Communication with Barbara Elliot, Borehole Geophysical Scientist, Geological Survey of Canada, Mineral Resources Division, Borehole Geophysics Section, Ottawa, Ontario, Canada. December 14, 1998.

5. Abbey, Daron G. *The Application of Borehole Geophysics to the Delineation of Leachate Contamination at the Trail Road Landfill site: Nepean, Ontario.* Carleton University, Ottawa, Ontario. December 1995.

6. Personal Communication with John Stowell of Mt. Sopris Instruments. Golden, CO. December 1, 1998.

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# Case Study Abstract

**Wurtsmith Air Force Base**
**Oscoda, Michigan**

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|---|---|---|
| **Site Name and Location:**<br>Wurtsmith Air Force Base<br>Oscoda, MI 48750 | **Geophysical Technologies:**<br>Ground penetrating radar<br>Electromagnetic induction<br>Magnetometry | **CERCLIS #**<br>MI5570024278 |
| **Period of Site Operation:**<br>1923 - 1993<br>**Operable Unit:**<br>OT-16b | | **Current Site Activities:**<br>None |
| **Point of Contact:**<br>Paul Rekowski<br>BRAC Environmental Coordinator<br>AFB Conversion Agency/DD<br>Wurtsmith<br>3950 East Arrow Street<br>Oscoda, MI 48750<br>(517) 739-5161<br>prekowski@afbda1.hq.af.mil | **Geological Setting:**<br>Coastal sand plain consisting of 60 feet of sand and gravel overlying glacial-lacustrine silty clays | **Technology Demonstrator:**<br>William A. Sauck, PhD<br>Department of Geosciences<br>Western Michigan University<br>Kalamazoo, MI 49008<br>(616) 387-4991<br>sauck@wmich.edu |

**Purpose of Investigation:**
To better explain/define a GPR shadow zone discovered during an earlier geophysical investigation of a well-established dissolved hydrocarbon plume to the west. This GPR shadow zone was suspected to be a light non-aqueous phase liquid (LNAPL) plume.

**Number of Images/Profiles Generated During Investigation:**
2700 feet of GPR lines/profiles

**Results:**
The investigation was a complete success and verified the accidental discovery of the newly named OT-16b LNAPL plume found during a previous GPR investigation of the neighboring FT-02 plume site that was conducted during December 1994. Overall, results indicate that biodegradation of a residual light hydrocarbon product plume and subsequent chemical processes led to changes of the conductivity of soils and groundwater in the capillary fringe. In general, the GPR shadow zone is coincident with the dissolved residual product plume.

## EXECUTIVE SUMMARY

Wurtsmith Air Force Base is located in northeastern Iosco County and covers a 5,223-acre area located on the northeastern part of Michigan's lower peninsula, approximately 2 miles west of Lake Huron. The land surface is a five-mile wide plain bounded on the west by 80-foot high bluffs. Several small streams flow from the bluffs and discharge into a swampy area west of the base. The shallow subsurface stratigraphy is known to consist of uniform and well sorted fine to medium sands that coarsen with depth. A sand and gravel aquifer of glacial origin underlies the base. The water table is about 10 to 12 feet below land surface at the OT-16b site.

Three non-intrusive geophysical techniques were used in the characterization of a newly discovered plume. These included electromagnetic (EM) induction, ground penetrating radar (GPR), and magnetometry. An EM survey was chosen to search for any buried metal objects. Magnetometry was used to determine the presence and location of buried magnetic materials that may have been missed by the EM survey. Due to the uniform geologic conditions present at the site, GPR was used to further investigate the newly discovered plume.

The EM survey identified an unmarked utility line and areas where caution should be exercised when drilling wells at the site. The magnetometer survey revealed that no unknown buried steel objects existed at the site. The GPR data identified that the conductive plume is located in the upper portion of the aquifer. Overall, results indicate that biodegradation of a residual light hydrocarbon product plume and subsequent chemical processes led to the generation of a secondary conductive plume in the aquifer. Generally the anomalous GPR zone is coincident with the dissolved product plume.

One of the goals of this investigation was to challenge the conventional model of the geophysical properties of hydrocarbon plumes. The conventional model, based on controlled spill and lab experiments, is that groundwater and soils contaminated with hydrocarbons exhibit lower electrical conductivity and lower relative permittivity than the surrounding uncontaminated media. The alternative model tested in this study is that hydrocarbon spills in the natural environment will change the impacted zone from electrically resistive to electrically conductive over time due to biodegradation of the hydrocarbons.

Geophysical methods at the newly-discovered OT-16b site provided coverage of a large area in a short period of time. The geophysical methods were non-intrusive and were less expensive than drilling wells randomly or on a grid for plume delineation downgradient from the possible source. The results obtained from the three different techniques were complimentary in making conclusions. The exceptional geologic uniformity of this site provided a uniform background resistivity environment for a geophysical investigation where even a subtle shadow effect could be observed. The conductive nature of this plume, totally derived from insulating hydrocarbon fuels, fits the chemical and electrical model for mature plumes undergoing natural attenuation.

## SITE INFORMATION

### Identifying Information

Wurtsmith Air Force Base
Oscoda, MI 48750
Operable Unit: OT-16b
CERCLIS No.: MI5570024278

### Background [2, 5, 6]

**Physical Description:** Wurtsmith Air Force Base (AFB) is located in northeastern Iosco County and covers a 5,223-acre area located on the northeastern part of Michigan's lower peninsula, approximately 2 miles west of Lake Huron. The site is bordered to the north and northeast by Van Etten Lake; to the southeast and east by the Village of Oscoda; to the northwest by State Forest woodlands, and to the southwest by Allen Lake and wooded marshlands. Approximately 1,943 acres of the base are owned by the Air Force, 2,466 acres are leased, and 814 acres are registered as easement tracts.

The land surface is a five-mile wide plain bounded on the west by 80-foot high bluffs. Several small streams flow from the bluffs and discharge into a swampy area west of the base. The Au Sable River, which flows eastward and discharges into Lake Huron, is located less than one mile south of the base. The land between the base and the river is swampy. The altitude of the land surface drops from 750 to 580 feet as it slopes toward the river.

The newly discovered OT-16b plume study area where this geophysical investigation took place is located 450 feet to the east of a former fire training area site known as FT-02, shown in Figure 1.

**Site Use:** The FT-02 site was used by the Air Force for 24 years as a bi-weekly fire training facility. Typical exercises involved the combustion of several thousand gallons of JP-4 jet fuel and other hydrocarbon fuels. Most but not all of the fuel would burn, which would leave the rest to percolate into the ground along with fire retardant chemicals used to extinguish the fires. In 1982, a concrete fire-containment basin with an oil-water separator was constructed to help reduce the amounts of fuel entering into the subsurface. Until this point, an unknown quantity of fuel had already infiltrated into the subsurface. It was reported that overflows persisted after the separator was installed in 1982.

**Release/Investigation History:** Fuels used in the fire training exercises at FT-02 were stored nearby in a vaulted underground storage tank (UST) at the OT-16b site. This underground collection and supply tank was removed in 1993, but a concrete pad and steel perimeter posts still mark its location. The protective vault was free of any signs of hydrocarbon spillage. Therefore, the tank was removed and the vault was backfilled. An underground pipeline had been used to transport the waste fuels and solvents from the collection tank to the burning pad at the center of the fire training area (Figure 1). This pipeline passed leak tests at the time it was decommissioned

[6]. Contamination may have occurred in the past from spillage during refilling activities of the UST.

In December of 1994 an integrated geophysical investigation was undertaken at the FT-02 study site 450 feet to the west of OT-16b. This investigation consisted of ground penetrating radar (GPR), electrical resistivity using dipole-dipole profiling and Schlumberger vertical electrical sounding, and self potential methods [6]. The results of several reconnaissance GPR survey lines conducted to examine the background response of FT-02 revealed several strong reflectors. One zone of attenuated GPR reflections was spatially correlated with the area of known hydrocarbon contamination, as determined from soil borings and hydrochemical studies [6]. When the positions of the GPR 'shadow' zones were plotted on a map, the resulting pattern was spatially coincident with the mapped position of the plume from hydrochemical studies [6]. Some of the 'shadow' zones were not coincident with the area of the known FT-02 plume (Figure 1) and caused speculation as to what they represented. The investigator came back in the Spring of 1996 to initiate this geophysical investigation in the area of the OT-16b site to determine what these other 'shadow' zones represented.

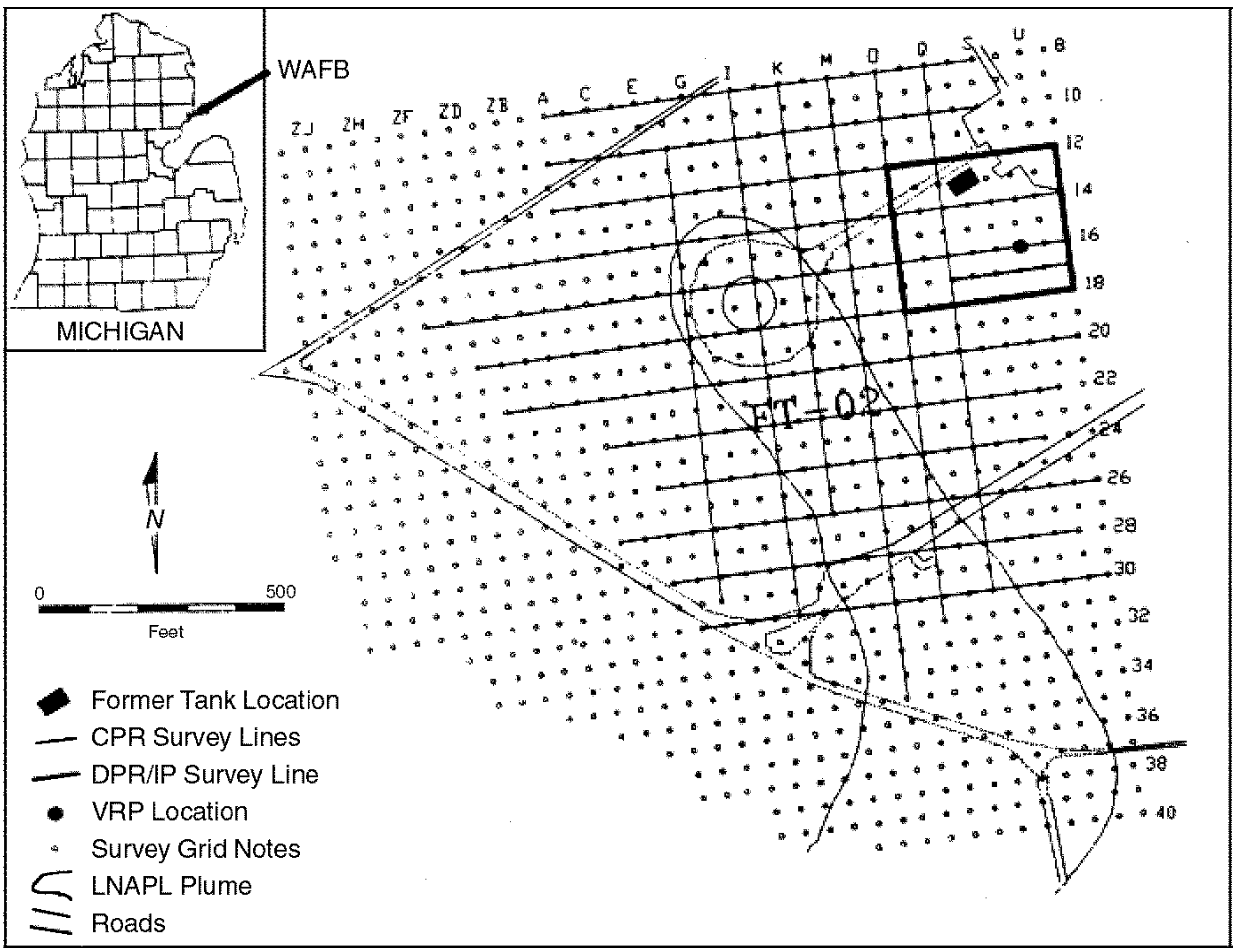


**Figure 1: Study area location with GPR profile lines shown. The boxed area to the east of the FT-02 plume site is the OT-16b site. Source: [4, 5].**

## SITE INFORMATION

**Regulatory Context:** The site is being addressed through Federal actions. Wurtsmith AFB was proposed to the National Priorities List (NPL) on January 18, 1994, but its addition to the NPL has not yet been finalized. In July 1991, the Base Realignment and Closure (BRAC) Commission recommended the closure of Wurtsmith AFB. On June 30, 1993, the installation closed as scheduled. The BRAC Cleanup Team (BCT) was formed in fiscal year 1994. The BCT consists of representatives of the Air Force, U.S. Environmental Protection Agency (EPA) Region 5, and the Michigan Department of Environmental Quality (MDEQ). The BCT works with a number of other agencies and organizations to complete environmental actions necessary before property at the base can be transferred to the private sector.

### Site Logistics/Contacts

**Federal Lead Agency:**
United States Air Force

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# MEDIA AND CONTAMINANTS

## Matrix Identification

**Type of Matrix Sampled and Analyzed:** Groundwater and subsurface soil

## Site Geology/Stratigraphy [4]

Based on previous borings completed by the United States Geological Survey (USGS) at the neighboring FT-02 site, the shallow subsurface stratigraphy is known to consist of uniform and well-sorted fine to medium sands that coarsen with depth. A sand and gravel aquifer of glacial origin underlies the base and is comprised of a brown to gray-brown medium coarse sand containing some gravel. The water table is about 10 to 12 feet below land surface at the OT-16b site. The aquifer overlies a thick clay layer found at an average depth of 65 feet. The clay layer is mostly brown to gray, relatively impermeable, and cohesive. Its thickness at the base is not accurately known because no lithologic logs exist that extend to the maximum depth of the clay layer. However, the clay is known to be at least 13 feet thick in one location. At Oscoda and at places east and north of Van Etten Lake, the clay unit is at least 125 feet thick and may be as thick as 250 feet. It slopes downward to the east at 10 to 30 feet per mile. In general, the surface of the unit dips inward to low points in the northeast part of the base and in an area just northeast of Van Etten Lake. Mississippian sandstone, shale, and limestone formations dipping southwest into the Michigan Basin constitute the bedrock beneath the base.

A groundwater divide cuts diagonally across the base from northwest to southeast. South of the divide, groundwater flows to the Au Sable River; north of the divide, it flows to Van Etten Creek and Van Etten Lake. Groundwater flow ranges from about 0.8 feet per day in the eastern part of the base to about 0.3 feet per day in the western part.

## Contaminant Characterization [4]

**Primary Contaminant Groups:** The primary contaminants of concern at the OT-16b site include fuel related contaminants such as benzene, toluene, ethylbenzene, and xylene (BTEX).

## Matrix Characteristics Affecting Characterization Cost or Performance [2, 5]

For the electromagnetic (EM-31) method in the vertical dipole mode, 18 feet is the maximum depth of detection of a highly conductive. Since the contaminant plume found at the site is only moderately conductive, approximately 3.3 times the conductivity of the background aquifer, it is not likely that the EM-31 can effectively discriminate between the weak signature of the contaminant plume below the water table and the conductivity of the uncontaminated groundwater. The depth of the contaminant plume is below the water table (15 feet), which is close to the limit of penetration for the EM-31 instrument. However, results from the EM-31 survey are still useful for other aspects of site characterization, since they clearly indicate where subsurface objects or utilities may exist and caution should be used in drilling future wells at the site.
There were no reported characteristics of the site that affected the magnetometer survey results.

## MEDIA AND CONTAMINANTS

However, there are some limitations when using a magnetometer generally. In a relatively "clean" area, a single drum may be theoretically detected to a depth of 20 feet from the surface. In practice, however, numerous smaller, near-surface iron objects will obscure the weaker deep target. A more realistic maximum depth of detection is 5 to 10 feet. Large masses of drums may be detected easily to depths of 10 to 40 feet.

The clarity of Ground Penetrating Radar (GPR) results can be affected by heterogeneous conditions in the subsurface. However, the study site has been noted to have exceptional geologic uniformity. The results of the GPR survey were enhanced by these uniform conditions.

## GEOPHYSICAL INVESTIGATION PROCESS

### Investigation Goals

Overall, the goal of this geophysical investigation was to use three different geophysical techniques (GPR, magnetometry, and EM) to explore and better define a suspected light non-aqueous phase liquid (LNAPL) plume that was encountered during a GPR investigation approximately 450 feet to the west of the FT-02 plume site [8]. A specific goal of the magnetometer survey was to search for any buried steel objects that might have been missed by the EM induction survey [2, 5]. GPR was then used to delineate the boundaries of the newly discovered plume.

One of the goals of this investigation was to challenge the conventional model of geophysical properties of hydrocarbon plumes. The conventional model, based on controlled spill and lab experiments, is that groundwater and soils contaminated with hydrocarbons exhibit lower electrical conductivity and lower relative permittivity than the surrounding uncontaminated media. The alternative model tested in this study is that hydrocarbon spills in the natural environment will change the impacted volume from electrically resistive to electrically conductive over time due to biodegradation of the hydrocarbons. Conductivity is enhanced by the leaching of inorganics from the soil and aquifer materials by organic acids and carbonic acid produced by microbial activity during degradation of the hydrocarbons. This model suggests that the conventional model can not be applied uniformly to all hydrocarbon plume sites and the geoelectrical signature of a plume will vary with time and position [7].

### Geophysical Methods [2, 5]

The investigation took place over several days in May 1996. The EM induction method is often used to explore for metal objects based on the principle of EM induction. This induction technique uses two coils: a transmitter and a receiver. EM surveys detect variations in the conductivity of subsurface materials. Buried objects, conductive fluids, and geologic discontinuities can be detected by artificially applying known electric fields to the ground surface by means of the transmitter, and the receiver records the presence of disruptions to the known field. These disruptions, termed EM anomalies, can result from geological changes or the presence of metallic objects, such as pipes, drums, cables, tanks, etc., in the subsurface.

For the EM survey, a Geonics EM-31 was carried at waist level using the vertical dipole mode. A grid of 25 feet by 50 feet was established and results from the survey were plotted using Geosoft™ software.

The second method used in this investigation was the magnetometry survey. Magnetometers measure variations in the magnetic field of the earth, and local disruptions to the earth's field, the presence of naturally occurring ore bodies, and man-made iron or steel objects such as buried drums, tanks, or ordinance. Whether on the surface or below, iron objects or minerals cause local distortions or anomalies in this field. Originally designed for mineral exploration, magnetometers are now used in the environmental field for locating buried steel drums, tanks, pipes, and iron debris in trenches and landfills. A magnetometer's response is proportional to the mass of iron in the target. The magnetometer can only sense ferrous materials such as iron and steel; other metals like copper, tin, aluminum, and brass are not ferromagnetic and cannot be located with a magnetometer. The effectiveness of magnetometry results can be reduced or inhibited by interference (noise) from time-variable changes in the earth's field and spatial variations caused by magnetic minerals in the soil or iron debris, pipes, fences, buildings, and vehicles. Many of these problems can be minimized by careful selection of the type of instrument and field procedures used for the survey.

Magnetometry was used in this investigation to determine the presence and location of buried magnetic materials using a 50 feet by 50 foot grid, which had already been established for the EM survey, magnetic data were collected using a Geometrics G-858 cesium vapor magnetometer. Using this data, a magnetic field intensity map of the area was produced for interpretation.

The third geophysical method used in the OT-16b site geophysical investigation was ground penetrating radar (GPR). GPR uses high-frequency radio waves to determine the presence of subsurface objects and structures. A GPR system radiates short pulses of high-frequency EM energy into the ground from a transmitting antenna. This EM wave penetrates into the ground at a velocity that is related to the electrical properties of subsurface materials. When this wave encounters the interface of two materials having different electromagnetic properties (i.e., soil and water), a portion of the energy is reflected back to the surface, where it is detected by a receiver antenna and transmitted to a control unit for processing and display. The major principles involved for GPR are similar to reflection seismology, except that EM energy is used instead of acoustic energy, and the time scale for GPR is a million times shorter than that of seismic phenomena.

For this investigation a Geophysical Survey Systems, Inc. (GSSI) Subsurface Interface Radar (SIR) System-10 GPR system along with 100 MHZ antennae recording for a scan time of 400 nanoseconds (ns) was used. The 100 MHZ Transmitter-Receiver pair were operated with a separation of 1.45 meters between mid-points. The site was traversed in the west to east and south to north directions along lines spaced 50 feet apart, using a van to tow the antennae. No post-processing was done other than horizontal scales normalization. This GPR system used fixed gain vs. depth function. No gain equalization or automatic gain control processing were used.

# GEOPHYSICAL FINDINGS

## Technology Calibration [8]

For the EM-31 the only calibration necessary is setting the zero on the instrument. A region of very resistive ground was identified and its conductivity was accurately measured using conventional techniques. GPR readings were taken in the same location and the instrument gains were set at this point. No further calibration was reported to be necessary for the GPR or magnetometer used in this investigation.

## Investigation Results [2, 5]

The EM survey revealed a linear alignment of anomalies extending from a manhole located at coordinate S18 to coordinate P12 (Figure 1), and at least three other anomalies parallel to this alignment. These anomalies were attributed to communication or electric cables buried in the ground. No anomalous regions associated with the suspected conductive groundwater plume were visible on any of the interpretive maps produced from the EM survey. The lack of EM-31 response from the conductive plume just below the water table at 15 feet was attributed to the plume being nearly at the limit of depth penetration for the instrument. One unmarked utility line was discovered. The results indicated where caution should be taken when drilling wells at the site. A strong anomaly beneath the old taxiway in the northeast corner of the map was detected but the source is unknown.

The magnetic survey revealed that there was a strong low in the magnetic field in the vicinity of the old UST vault. The UST vault (still in place, but now filled) had been surrounded at the surface by 20 steel posts filled with concrete. The posts were attached to a flat slab of concrete. The strong low was attributed to the potential for the steel having a strong reversed remnant magnetization. The magnetic survey revealed no other buried steel objects at the site. This was an indicator that the buried cables found by the EM-31 survey are nonmagnetic but electrically conductive. A strong magnetic low found beneath the asphalt taxiway in the northeast corner of the map remains unexplained.

The GPR data revealed that there is a particularly strong reflector representing the water table at approximately 10 to 12 feet (five meters) shown on Figure 2 as an inverted triangle. This was caused by the sharp change in the relative permittivity in the transition from unsaturated to saturated sand. The central areas of the pair of two-dimensional profiles show pronounced signal attenuation, creating an amplitude shadow zone (between “R” and “T” on line 14 in Figure 3, and between “S” and “U” on line 16 in Figure 4). The conductive zone causing the attenuation is at the tops of these shadows. The shadow begins at or just below the water table, so the conductive plume is located in the upper part of the aquifer. This same phenomenon was seen along all other lines crossing the plume area. This conductive plume in the groundwater below the highly resistive hydrocarbon liquids fits the alternative geoelectrical model proposed for mature plumes [7].

## GEOPHYSICAL FINDINGS

The investigator's recognition and understanding of the significance of the GPR shadow zone below the FT-02 plume led to the discovery of the new contaminant plume. From the shadow zones on the GPR profiles, it was possible to create a map that showed the extent of the conductive plume at the OT-16b site (Figure 2). The broad proximal end of the plume is possibly due to the spillage of fuel on the asphalt taxiway, as well as possible surface spillage during refilling operations at the former underground collection tank location. Another result of the GPR

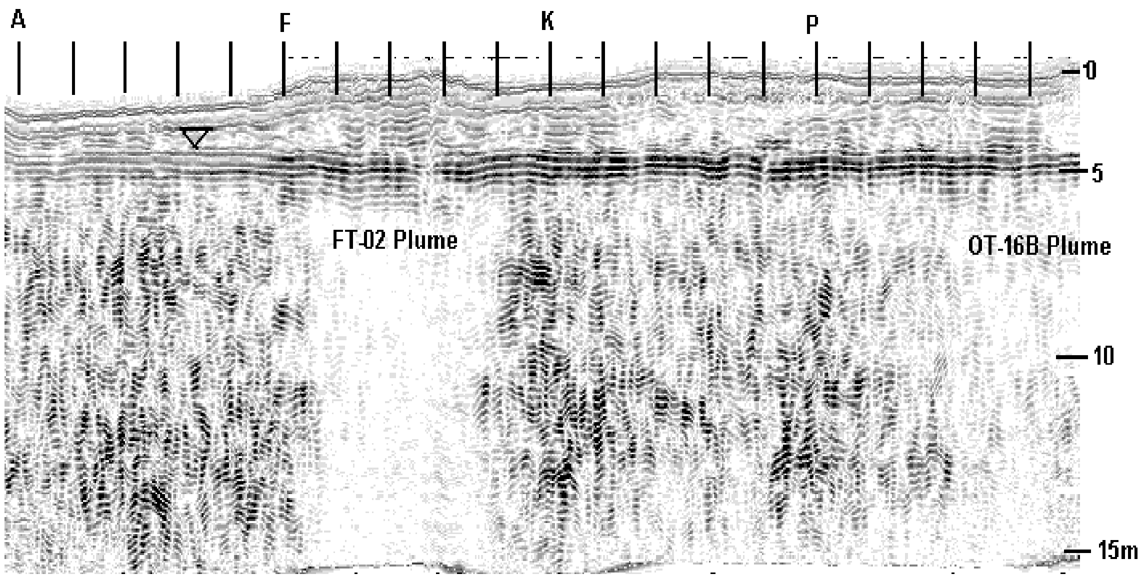


**Figure 2: Ground penetrating radar profile of Line 14 showing the strong amplitude shadow caused by the proximal end of the neighboring FT-02 plume, and the somewhat weaker shadow at the right end caused by the OT-16b plume. Source: [8]**

investigation was the observation of some paleo-dune morphologies that underlie the area at a depth of approximately 40 feet (Figure 4 at location "Q").

Overall, results indicate that biodegradation of a residual light hydrocarbon product plume and subsequent chemical processes led to the generation of a secondary conductive plume in the aquifer that is coincident with the dissolved product plume. This coincides with the newly developed hypothesis that hydrocarbon spills in the natural environment cause changes from electrically resistive to electrically conductive over time due to biodegradation of the hydrocarbon impacted zone. Conductivity is enhanced by the leaching of inorganics from the soil and aquifer materials by organic acids produced by microbial activity during degradation of the hydrocarbons [7]. Generally the GPR shadow zone is coincident with the dissolved product plume (Figure 2).

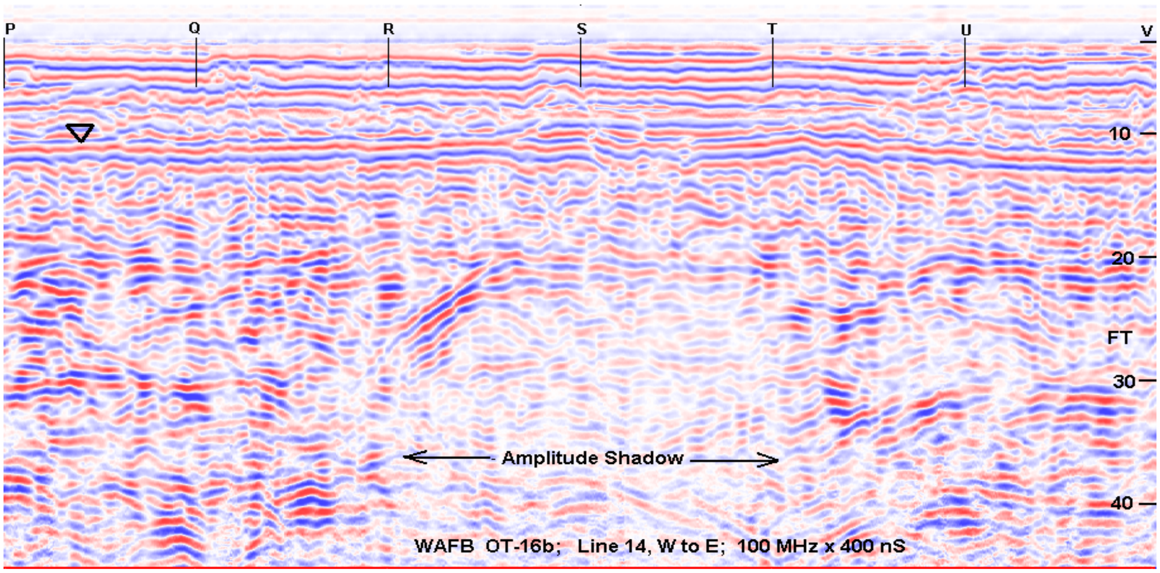


**Figure 3: 100 MHZ GPR profile for line 14 (at 150 feet N coordinate on Figure 1) oriented with west to the left. Scan length is 400 ns, showing amplitude shadows starting below the water table (about 70 ns or 12 feet); horizontal scale is 50 feet between marks. Source: [2, 5]**

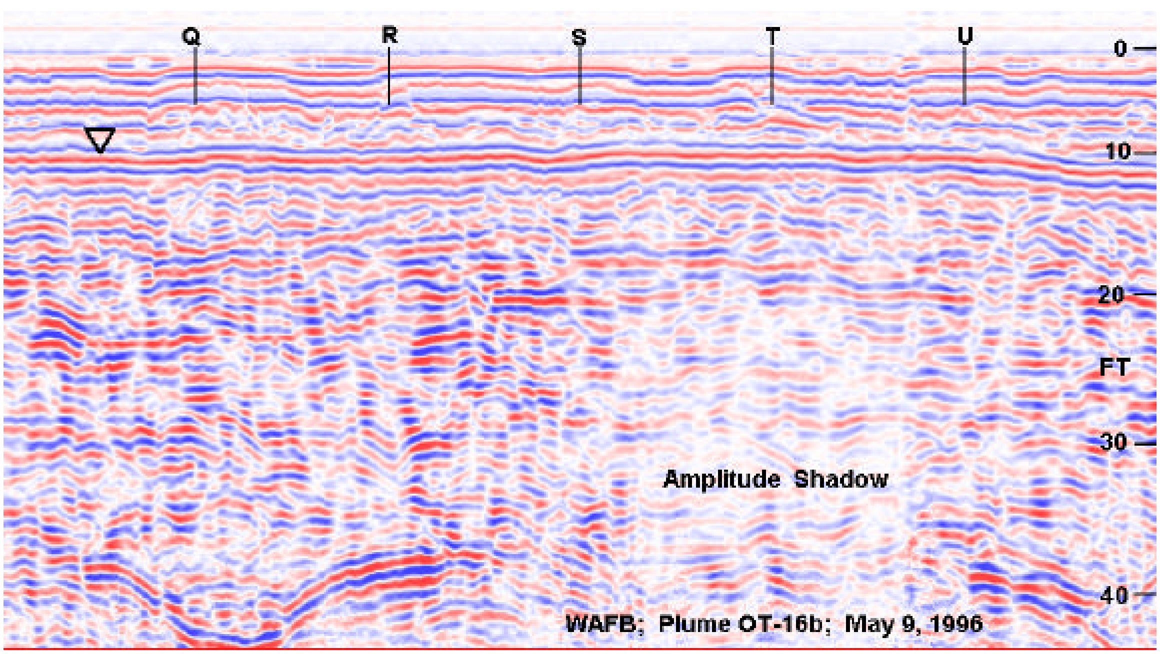


**Figure 4: 100 MHZ GPR profile for line 16 oriented with west to the left. Scan length is 400 ns, showing amplitude shadows starting below the water table (about 70 ns or 12 feet); horizontal scale is 50 feet between marks. Source: [2, 5]**

## Results Validation [2, 5]

Several months after the initial geophysical investigation took place in May of 1996, borings were taken at three locations on the newly discovered OT-16b plume. Soil and groundwater samples were taken at various depths. One soil sample revealed approximately 16 inches of a dark, viscous residual hydrocarbon product near the water table. The conductivities of the aquifer water were at a maximum at the top of the saturated zone and then diminished to background levels at depths of 10 feet below the water table. This indicated that the anomalous conductive zone was less than 10 feet thick and the water samples had a conductivity contrast of 2.5 to 3.3 above background levels.

In addition, after the geophysical investigation was completed, a review of Wurtsmith AFB air photo archives led to the discovery that a maintenance building occupied the site area until the 1970's. The UST was installed later, after the building was removed. When the UST was removed there was no evidence of soil contamination. This indicates that the source of the newly discovered contaminant plume was probably as a result of the drainage of solvents and fuels from the floor of the maintenance building.

## LESSONS LEARNED

Lessons learned at the Wurtsmith site include the following:

- Geophysical methods at the newly discovered OT-16b site provided coverage of a large area in a short period of time. The geophysical methods were non-intrusive and were less expensive than drilling wells randomly or on a grid for plume delineation downgradient from the possible source. The investigation was considered a complete success and, using purely surface geophysical methods, verified the 1994 initial “blind” discovery of a new groundwater contaminant plume [2, 5].

- The use of more than one geophysical method provided synergy, as each technique was responsive to a different property. Therefore, the results obtained using the different techniques were complimentary. The GPR outlined the conductive groundwater plume and also revealed the details of the sand stratigraphy. The shallow EM discovered a complex of buried electrical utility lines where only one line had been previously known. Finally the magnetic survey revealed no buried steel objects, which was helpful in characterizing the site as “tank-free [2, 5].”

- The conductive nature of this plume, totally derived from insulating hydrocarbon fuels, fits the chemical and electrical model for mature plumes undergoing natural attenuation [7]. The anomalous geophysical response is due to the electrically conductive ionic nature of the plume, not due to any direct response to residual or dissolved hydrocarbons. The investigators would not extrapolate these results to investigations of dense non-aqueous phase liquid spills [2, 5].

- It is clear that at this site biodegradation of a residual light hydrocarbon product plume and subsequent chemical processes led to changes of the conductivity of soils and groundwater in the capillary fringe and underlying aquifer. The broad proximal end of the plume is potentially due to fuel spillage on the asphalt taxiway, as well as possible surface spillage during refilling operations at the former underground collection tank location and the floor of the maintenance building [2].

- The exceptional geologic uniformity of this site provided a uniform background environment for a geophysical investigation where the shadow effect could be observed [8]. The amplitude shadow is not visible if the GPR scan length or range can only reach the water table. The shadow will also be destroyed if automatic gain control or other gain equalization is applied during either acquisition or post-processing of data. Therefore the appropriate setting of field acquisition parameters and careful post-processing are necessary to record and preserve the GPR amplitude shadows [2, 5].

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