

# APPLICATION OF GEOPHYSICAL METHODS TO DELINEATE CONTAMINATION IN FRACTURED ROCK AT THE UNIVERSITY OF CONNECTICUT LANDFILL, STORRS, CONNECTICUT

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## Abstract

An integrated suite of geophysical methods was used to characterize the hydrogeology of a fractured-rock aquifer to identify contamination or pathways for contaminant migration near a former landfill at the University of Connecticut, Storrs, Connecticut. Surface-geophysical methods were used to identify the dominant direction of fracture orientation and to locate potential leachate plumes. Two shallow, electrically conductive anomalies near surface-water discharge areas north and south of the landfill were interpreted as leachate plumes. Two other sheet-like electromagnetic (EM) anomalies were identified and targeted for drilling and borehole-geophysical investigation. These methods were used to determine the location, orientation, and lateral continuity of fractures and to quantify the hydraulic properties of the transmissive fractures.

One borehole was located to intersect an anomaly observed at a depth of about 18 meters. The EM-conductivity log measured a high electrical conductivity anomaly at a depth of 21 meters, which coincides with a layer observed to contain sulfide mineralization. The lack of high conductivity fluids in the borehole supports the interpretation that this anomaly is caused by a lithologic change rather than by fractures that contain conductive leachate.

The second borehole was positioned to intersect a conductive feature at a depth of about 18 meters. A fracture with similar strike and dip was observed at a depth of about 22 meters in optical- and acoustic-televiwer images, in borehole-radar surveys, and was determined to be hydraulically conductive during heat-pulse flowmeter tests. This feature was also characterized by a high-conductivity spike in the EM log. Although the specific conductance of the fluid in this depth zone was high, it could not account for the spike in the EM log. The anomaly is interpreted to be caused by a combination of conductive fluids in the fracture and of conductive minerals in the rock. Water-quality samples from a discretely isolated zone near a depth of 22 meters indicated the presence of landfill leachate. This investigation illustrates the effectiveness of the use of combined geophysical methods for identification and evaluation of electrically conductive contaminant plumes.

## Introduction

The University of Connecticut operated a landfill and chemical waste-disposal pits from about 1966 to 1989. In the early 1970s, it was estimated that the landfill received 18,000 cubic yards of waste annually including the sand and gravel for waste-cell construction and cover. Chemical waste-disposal pits, which are located to the west of the landfill, operated from 1966 to 1978. Pesticides, chlorinated hydrocarbons, solvents, ammonium hydroxide, acids, ethers, peroxides, heavy metals, cyanide, arsenic, toluene, acetone, benzene, and herbicides were thought to be disposed of in the chemical waste-disposal

pits (Bienko and others, 1980; Haley and Aldrich, Inc., 1999a). In 1987, the soil in and around the chemical waste-disposal pits was removed (Connecticut Department of Environmental Protection, 1993). Preliminary investigations identified contaminants indicative of the disposed chemicals and landfill leachate in water samples from the bedrock and overburden near the former chemical waste-disposal pits and the landfill (Haley and Aldrich, Inc., 1999a).

In 1999, the U.S. Geological Survey (USGS), in cooperation with the University of Connecticut (UConn), used a suite of surface- and borehole-geophysical methods to characterize the fractured-bedrock aquifer near the UConn landfill. Because of the heterogeneous nature of fractured-rock, multiple methods of investigation are required to characterize hydrogeologic properties of the bedrock and its interaction with overburden materials (Shapiro and others, 1999). Surface-geophysical methods were used to determine the extent of the landfill, anisotropy caused by fracture or bedrock fabric, and potential zones of electrically conductive contamination. Borehole-geophysical methods were used to characterize rock properties; identify the location, orientation, and lateral continuity of fractures; quantify hydraulic properties of transmissive fractures in 11 boreholes near the landfill; and further evaluate anomalies observed by surface methods. Collectively, the surface and borehole methods were used to identify contamination or potential pathways for contaminant migration from the landfill and former chemical waste-disposal pits and to refine the site conceptual model. This paper focuses on selected results of the investigation that illustrate the effectiveness of combined surface- and borehole-geophysical methods.

## **Description of the Study Area**

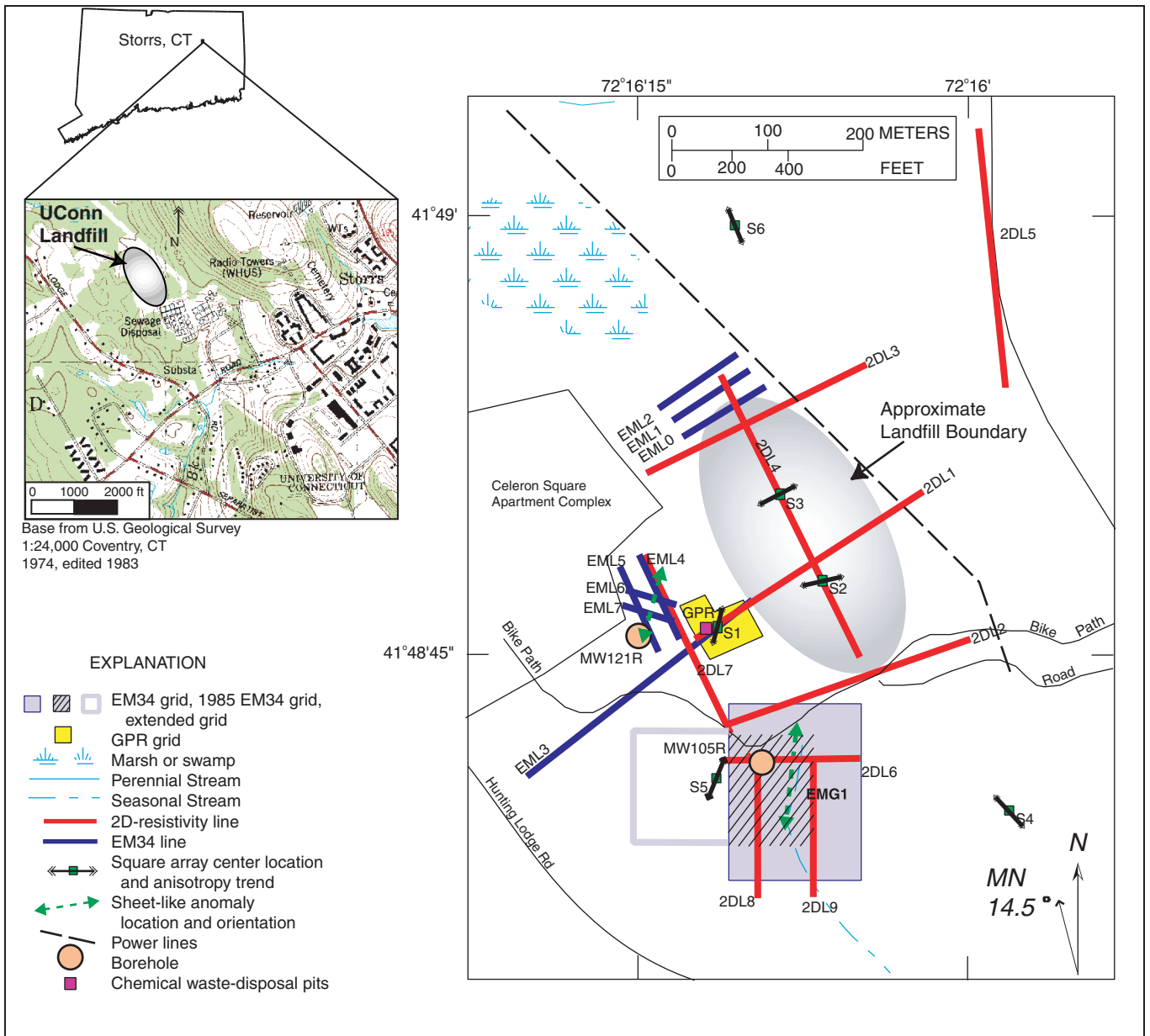
The UConn campus is located in Storrs, Connecticut, in the northeastern part of the State (fig. 1). The study area occupies a north trending valley with highlands to the northeast and southwest. The 5-acre landfill is situated over a minor ground-water divide that drains to the north and south along the axis of the valley (Haley and Aldrich, Inc., 1999b). Surface runoff flows north through a wetland towards Cedar Swamp Brook and south towards Eagleville Brook through a seasonal drainage. The study area is bounded on the east by a steep hill and on the west by minor hills.

The bedrock that underlies the UConn landfill study area is folded, faulted, and fractured sillimanite-biotite-garnet schist and gneiss with sulfide layers (Fahey and Pease, 1977). The fabric of the rock has been mapped in the area around the landfill, and although it shows variation, the foliation generally strikes northeast and dips to the west. The bedrock aquifer is overlain by glacial till and unconsolidated deposits, which range in thickness from 0 to about 6 meters (m).

## **Geophysical Methods**

### ***Surface-Geophysical Methods***

Azimuthal (Lane and others, 1995) and two-dimensional (2D) direct-current (dc)-resistivity, inductive terrain-conductivity (McNeil, 1980), and ground-penetrating radar (GPR) methods were used on and around the landfill. The surface-geophysical methods were used to (1) identify landfill structure, including the extent and location of solid waste-disposal trenches, which received solid waste and were surrounded by sand and gravel; subsurface structures in the area of the former chemical waste-disposal pits; and excavation of the former chemical waste-disposal pits; (2) identify anisotropy caused by fractures and fabric in the rock; and (3) identify electrically conductive features, such as transmissive fractures, conductive sulfide-rich layers in bedrock, and landfill leachate. The information gained from



**Figure 1.** Location of the surface-geophysical surveys and boreholes MW121R and MW105R, UConn landfill study area, Storrs, Connecticut.

the surface-geophysical investigations was used to guide the initial phase of exploratory drilling. Data were collected and processed using the methods described by Powers and others (1999).

### ***Borehole-Geophysical Methods***

Borehole-geophysical methods provide information about the physical and chemical properties of rock, sediments, and fluids in the subsurface and provide important information on subsurface structures, including the lithology, the rock fabric, and the location, orientation, extent, and hydraulic properties of fractures. Multiple logs that measure a range of earth properties at different scales of resolution were collected in each of 11 bedrock boreholes. The geophysical data from each borehole were analyzed together to provide an integrated interpretation, thereby reducing the ambiguity that can occur by

interpreting each geophysical log individually. Both conventional and advanced borehole-geophysical methods were used in this study. The conventional methods are caliper, gamma, fluid temperature, fluid conductivity, and electromagnetic (EM) induction (Keys, 1990). The advanced methods are deviation, optical-televiwer (OTV) and acoustic-televiwer (ATV) imaging (Williams and Johnson, 2000), flowmeter (under ambient and pumping conditions) (Hess and Paillet, 1990; Paillet, 1999), and single-hole directional radar reflection (Olsson and others, 1992; Lane and others, 1994).

Used in conjunction with the high-resolution acoustic- and optical-imaging methods, directional radar can provide information on the location, orientation, and areal extent of fractures, fractures zones, or conductive lithologic layers. The length of individual radar reflectors was estimated using measurements of the maximum radial extent over which a given reflector could be observed in the radar record and applying a correction factor that accounts for the dip of the reflector. Because this estimate is controlled by the maximum radial radar penetration distance, the actual length of a reflector may be greater than that estimated from the radar images.

The hydrogeologic interpretation included determination of the magnitude and direction of vertical flow within boreholes and the specific capacity and transmissivity of the open holes. Fractures that were determined to be transmissive from the heat-pulse flowmeter data were isolated with a straddle-packer apparatus and sampled for water-quality analysis.

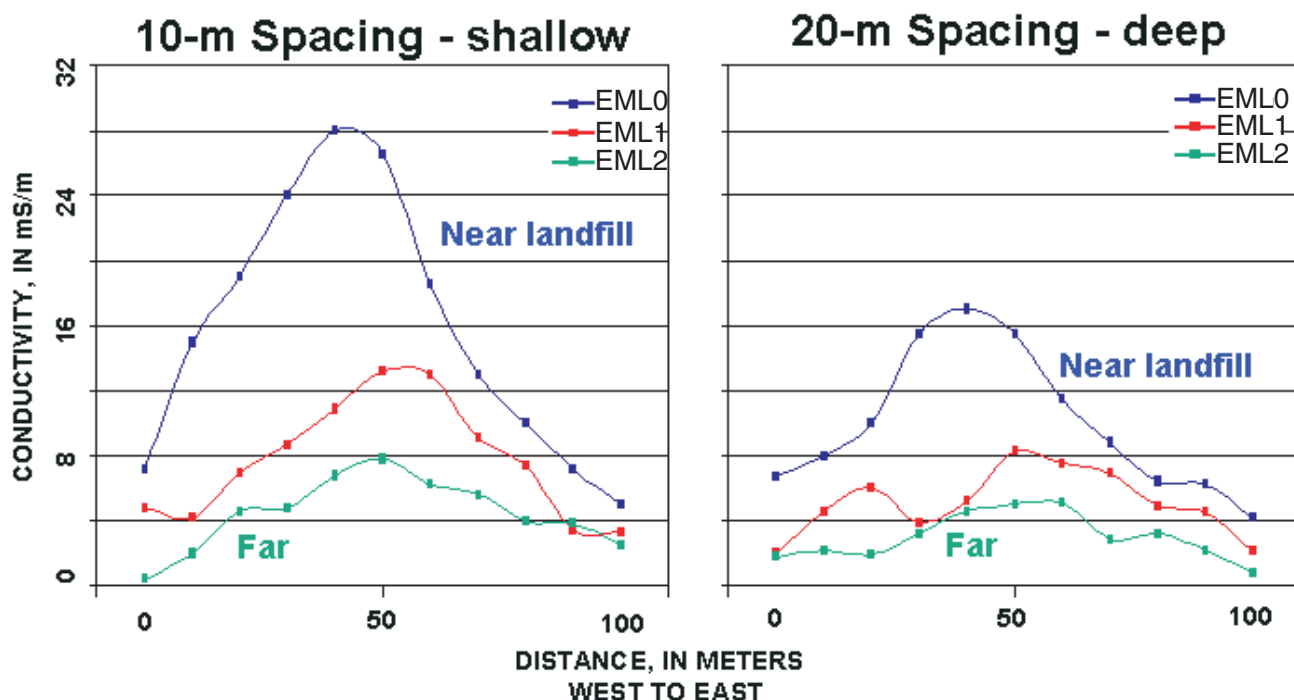
Five boreholes that had measurable ambient flow were equipped with temporary borehole liners to prevent vertical flow and the potential for cross-contamination. Semi-permanent borehole packers were installed to monitor hydraulic heads and obtain water-quality samples from isolated zones in the boreholes.

## **Results of Geophysical Investigations**

### ***Results of Surface-Geophysical Investigations***

Six azimuthal square-array dc-resistivity surveys conducted on and adjacent to the landfill indicated the dominant strike direction for the bedrock fractures and rock fabric was N285 to 30°E of north (Powers and others, 1999). Inductive terrain-conductivity and 2D dc-resistivity profiling detected two electrically conductive anomalies that were interpreted as possible leachate plumes near two surface-water discharge areas north and south of the landfill. One conductive anomaly, to the north of the landfill, is interpreted as shallow conductive leachate. Three parallel inductive terrain-conductivity horizontal-dipole surveys with both 10- and 20-m coil separations (EML0, EML1, EML2, fig.1) are shown in figure 2. The magnitude of the apparent conductivity anomaly decreases to almost background levels with depth and laterally at about 46 m north of the landfill. The other anomaly, to the south of the landfill (EMG1, fig.1), is interpreted as a shallow leachate plume that extends vertically through the overburden into the shallow bedrock and laterally along the intermittent drainage to Eagleville Brook.

The inductive terrain-conductivity and 2D dc-resistivity profiling also detected two sheet-like conductive anomalies. One anomaly is west of the former chemical waste-disposal pits (EML4, EML5, EML6, EML7, 2DL7, fig.1) and the other is south of the landfill (EMG1, 2DL6, fig. 1). South of the landfill, a grid (EMG1) of several east-west oriented inductive-terrain conductivity profiles (fig. 3A) shows a steeply dipping conductive anomaly that strikes approximately north-south. The dip and conductivity of the anomaly was estimated by comparing the observed data with forward models of conductors with known dip and conductivity (fig. 3B). Results from a 2D dc-resistivity line are shown in figure 4. Figures 4A and B are inversions of the field data, which show that the conductive anomaly intersects the ground surface at the topographic minimum of the line. A resistivity model (Loke, 1997)



**Figure 2.** Inductive terrain-conductivity horizontal dipole data for three lines (EML0, EML1, and EML2) at the northern end of the UConn landfill study area with 10-meter spacing (left) and 20-meter spacing (right).

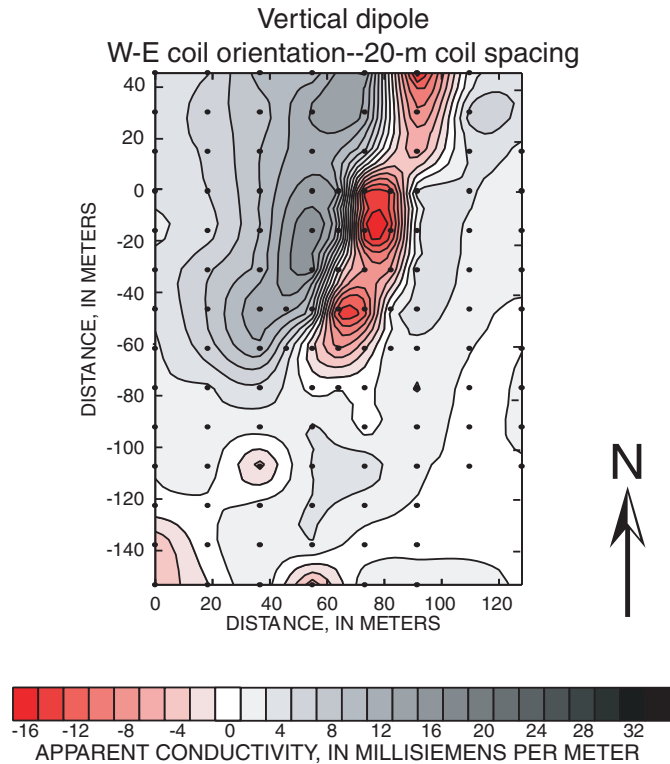
was used to constrain the 2D dc-resistivity interpretations. A forward model with resistive bedrock underlying a conductive layer of till or weathered bedrock, and cut by a thin dipping conductive unit is shown in figure 4C. Inversions of the synthetic model data are shown in figures 4D and E. The similarity of these inversions to the inverted field data (fig. 4A and B) suggests that the anomaly observed in the field data could be induced by a conductive unit dipping about  $30^\circ$  west, which is consistent with the results of the inductive terrain conductivity field data.

The anomalies to the west and south of the landfill strike approximately north-south and dip  $30^\circ$  to the west. Based only on the surface-geophysical methods, the anomalies were interpreted as either fracture zones filled with conductive fluids or conductive lithologic zones within more resistive bedrock.

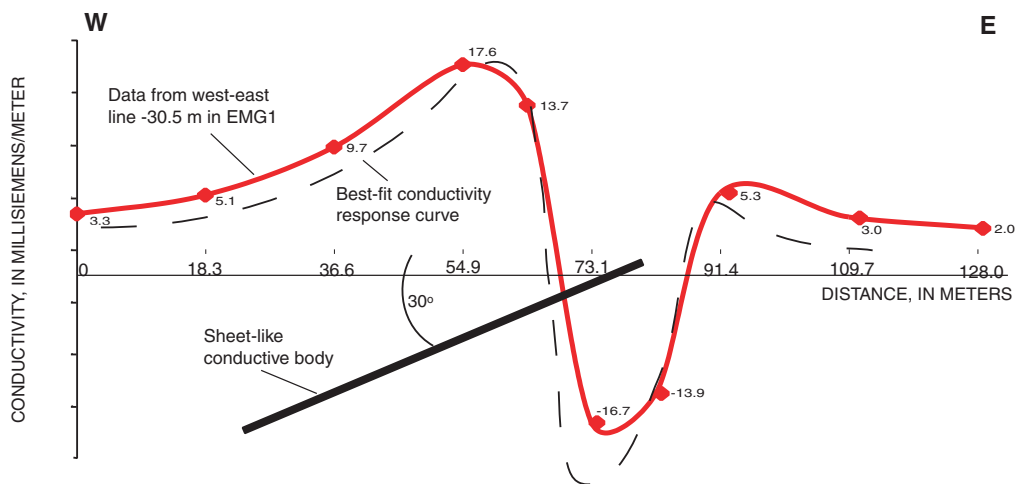
### ***Results of Borehole-Geophysical Investigations***

Borehole MW121R was located to intersect the westward dipping anomaly shown, which was observed in the 2D dc-resistivity (2DL7, fig. 1) and inductive terrain conductivity surveys (EML4, EML5, EML6, EML7, fig. 1) collected west of the landfill, at about 18 m below ground level. Integrated interpretation of OTV and ATV logs for MW121R indicate that the fractures intersected by the borehole represent two sets of fractures. One set is parallel to the foliation at  $N180$  to  $230^\circ E$ , dipping  $10$  to  $30^\circ NW$ , and the other (apparently sealed) set strikes  $N180$  to  $231^\circ E$  and dips  $40$  to  $60^\circ$  to the west. The rock types and orientation of foliation are consistent with those mapped in the region (Fahey and Pease, 1977). The transmissive fractures were identified by heat-pulse flowmeter logging under pumped conditions to be near depths of 16 and 20 m (table 1).

A.

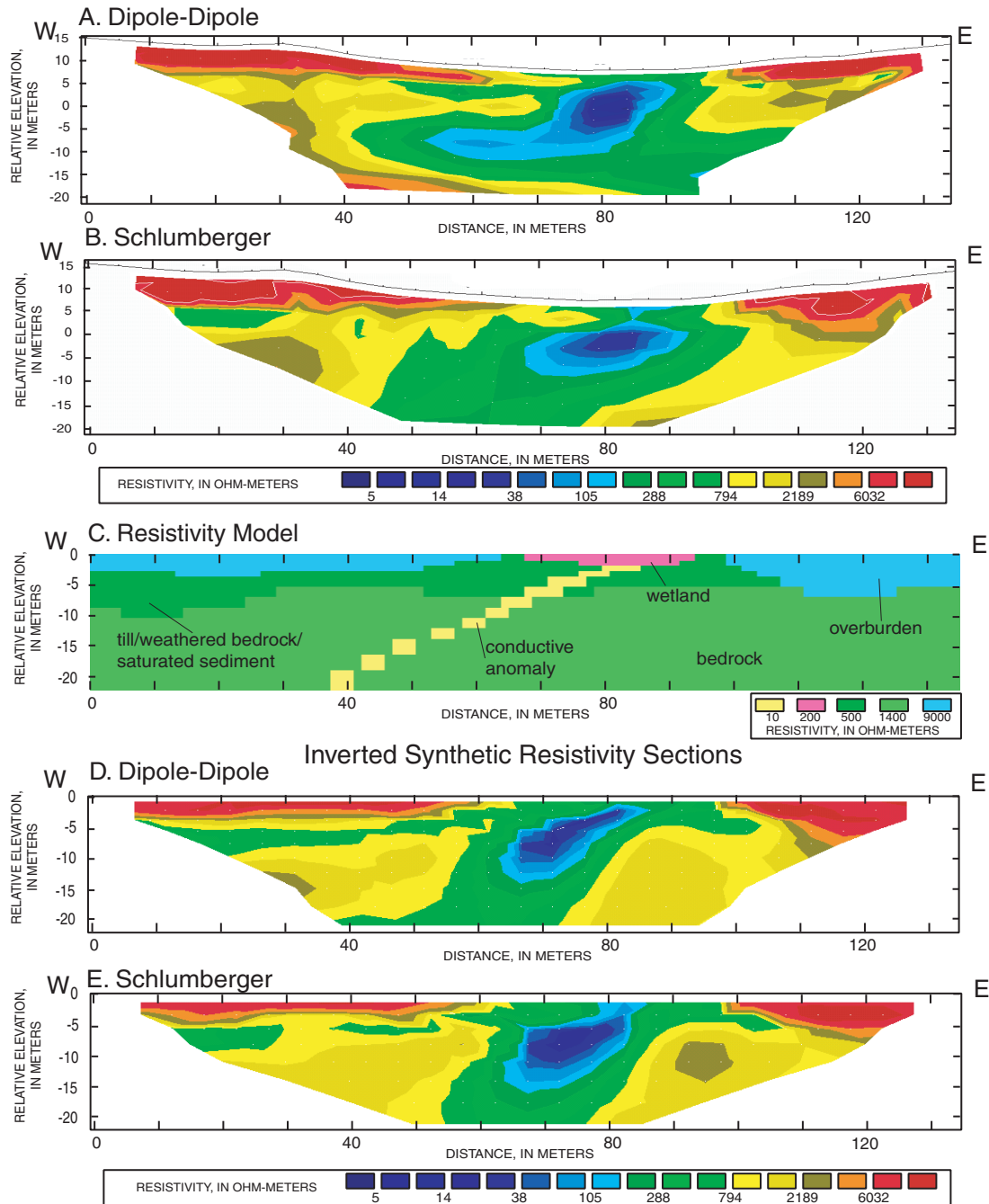


B.



**Figure 3.** **A.** Contoured inductive-terrain conductivity vertical dipole data for grid EMG1 collected with 20-meter coil spacing and west-to-east transmitter-receiver orientation, UConn landfill study area, Storrs, Connecticut. **B.** Conductivity response curve generated by a forward-modeling program and data collected from grid EMG1, UConn landfill study area, Storrs, Connecticut.

## 2DL6 - Inductive Terrain-Conductivity Grid Inverted Resistivity Sections



**Figure 4.** Inverted resistivity sections of two-dimensional direct-current-resistivity data for profile 2DL6, UConn landfill study area, Storrs, Connecticut. **A.** Dipole-dipole array. **B.** Schlumberger array. **C.** Resistivity model. **D.** Dipole-dipole array, inverted synthetic resistivity sections. **E.** Schlumberger array, inverted synthetic resistivity sections. [Data were collected with 5-meter spacing between electrodes. The data (A and B) were used to create a resistivity model. Inverted synthetic data (D and E) generated from the model are used to check the validity of the resistivity model.]

**Table 1.** Location and orientation of transmissive fractures and interpreted reflectors and length of interpreted reflectors from borehole MW121R at the UConn landfill study area, Storrs, Connecticut

[Negative depths indicate a projected plane intersects above the well. The strike is reported in RHR, "right-hand rule", where the direction of dip is to the right of the strike. Reflector continuity is on a scale of 1 (good) to 5 (poor). A - means no data is available.]

Transmissive fractures			Reflectors in directional borehole radar				
Depth, in meters	Strike, in degrees	Dip, in degrees	Depth, in meters	Strike, in degrees	Dip, in degrees	Estimated reflector length, in meters	Reflector continuity
-	-	-	-84.0	165	82	24	3
15.8	202	39	15.3	205	64	37	3
19.7	199	24	16.6	205	46	18	3
-	-	-	38.1	315	67	44	4

Four reflectors were interpreted from the directional borehole radar reflection data in MW121R (table 1). The data also showed four zones of high radar attenuation centered at depths of 3.4, 16.8, 21.0, and 32.0 m (fig. 5). These zones correlate with EM-conductivity anomalies identified on the EM-induction log from MW121R (fig. 5). The spike at 16.8 m in the EM-induction log coincides with a radar reflector that strikes N205°E, 46°W (table 1), which parallels the foliation.

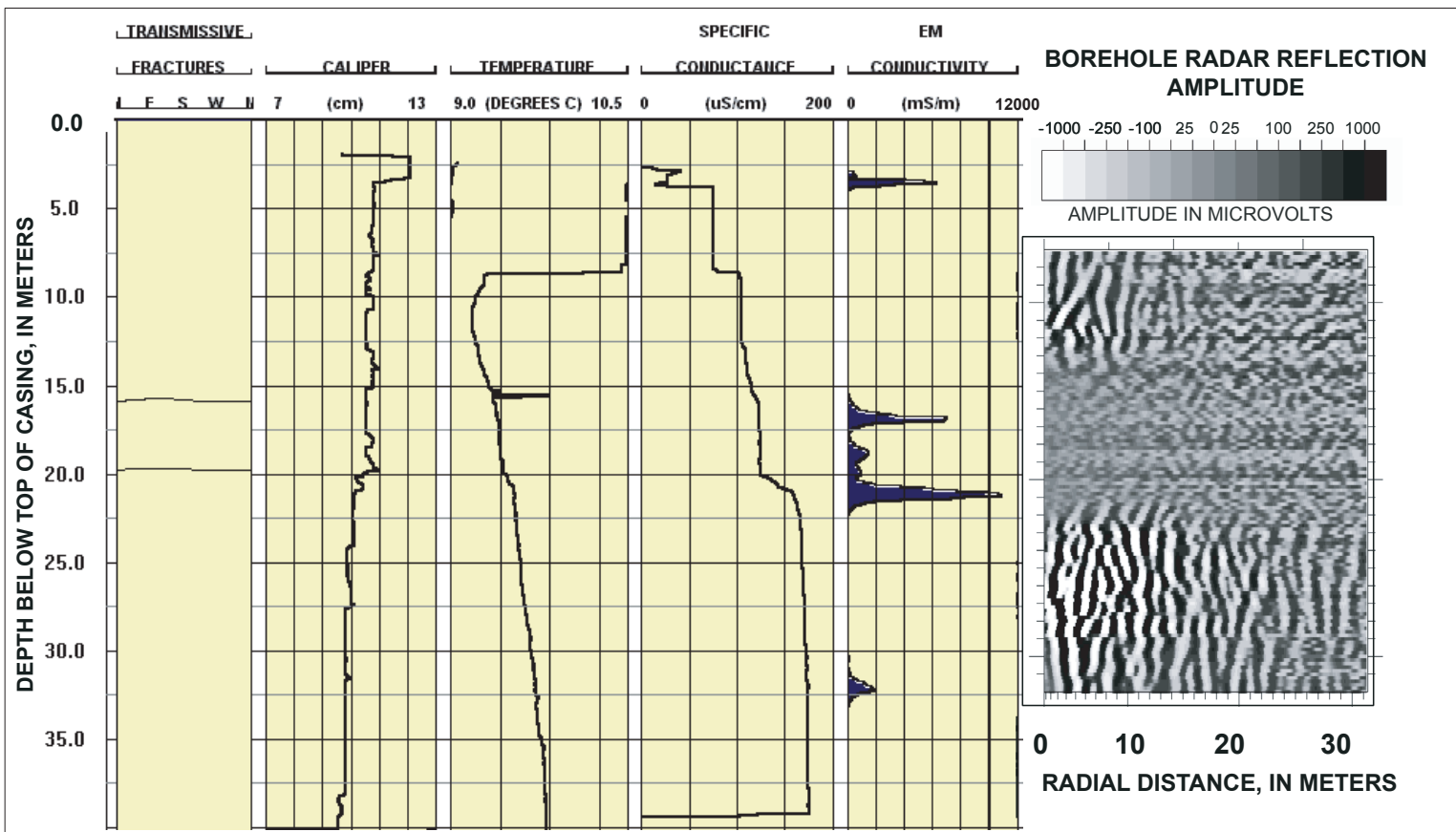
The EM-conductivity log in MW121R contains a high electrical-conductivity anomaly at a depth of 21 m (fig. 5). The magnitude of this anomaly is nearly 11,000 millisiemens per meter (mS/m). This anomaly coincides with a layer that contains sulfide mineralization observed in the OTV and drilling logs. Fluids in the borehole next to the EM spikes have relatively low electrical conductivity (fig. 5). The low specific conductance of the fluids in the borehole further supports the interpretation that the electrically conductive unit detected by surface-geophysical methods and the feature imaged in the borehole-radar log is related to a lithologic change rather than fractures.

Borehole MW105R was positioned to intersect the projection of the north-south trending, westward dipping conductive feature (fig. 3 and fig. 4) in the middle of the borehole at about 18-m depth. The foliation over most of the borehole is nearly horizontal with dips that range 2 to 29° to the northwest. From about 29 to 32 m, the foliation observed in OTV logs strikes N320 to 350°E and dips 11 to 61° to the northeast. Most of the fractures in MW105R are nearly parallel to the foliation. There are a few fractures that cross-cut the foliation and layering of the schist and gneiss at high angles. The orientations of the transmissive fractures are listed in table 2.

Eight reflectors were interpreted from the directional borehole radar data (table 2). Seven of the reflectors correlate with fractures observed in the OTV and ATV logs from MW105R. A south-striking, westward-dipping (N185°E, 21°W) feature was identified in the radar log of MW105R at 17.4 m, which is coincident with a fracture in the ATV log. Another feature at about 22 m strikes south and dips gently west (N181°E, 12°). The fracture at about 22 m was observed in the OTV, ATV, and borehole-radar surveys and is characterized by a distinct increase in electrical conductivity (200 mS/m) in the EM log (fig. 6). The location and orientation of this conductive feature generally matches the anomaly interpreted from the surface-geophysical data.



**Figure 5.** Data from borehole logs and borehole radar reflection in MW121R, UConn landfill study area, Storrs, Connecticut.



**Table 2.** Location and orientation of transmissive fractures and interpreted reflectors and length of interpreted reflectors from borehole MW105R at the UConn landfill study area, Storrs, Connecticut

[The strike is reported in RHR, "right-hand rule", where the direction of dip is to the right of the strike. Reflector continuity is on a scale of 1 (good) to 5 (poor). A - means no data is available.]

Transmissive fractures			Reflectors in directional borehole radar				
Depth, in meters	Strike, in degrees	Dip, in degrees	Depth, in meters	Strike, in degrees	Dip, in degrees	Estimated reflector length, in meters	Reflector continuity
-	-	-	13.5	175	19	4	5
-	-	-	16.9	205	4	2	4
22.4	181	12	17.4	185	21	8	4
27.5	29	38	20.3	295	6	2	4
33.5	149	32	22.4	185	12	5	4
33.6	314	8	33.5	145	32	11	4
34.0	334	57	33.6	315	8	2	4
34.5	183	6	44.1	205	8	3	4

No ambient flow was detected in MW105R with the heat-pulse flowmeter. However, fluid conductivity logs suggested the possibility of different water quality in the transmissive zones. Under ambient conditions, the specific conductance was about 100 microsiemens per centimeter ( $\mu\text{S}/\text{cm}$ ) at depths from 5 to 15 m and increases to almost 1,250  $\mu\text{S}/\text{cm}$  at about 22 m (fig. 6). From 22 to 34 m, the specific conductance declined to about 500  $\mu\text{S}/\text{cm}$ . The specific-conductance log suggests that the water from the fracture at about 22 m has different chemistry than the water from the fracture zone at a depth of about 34 m.

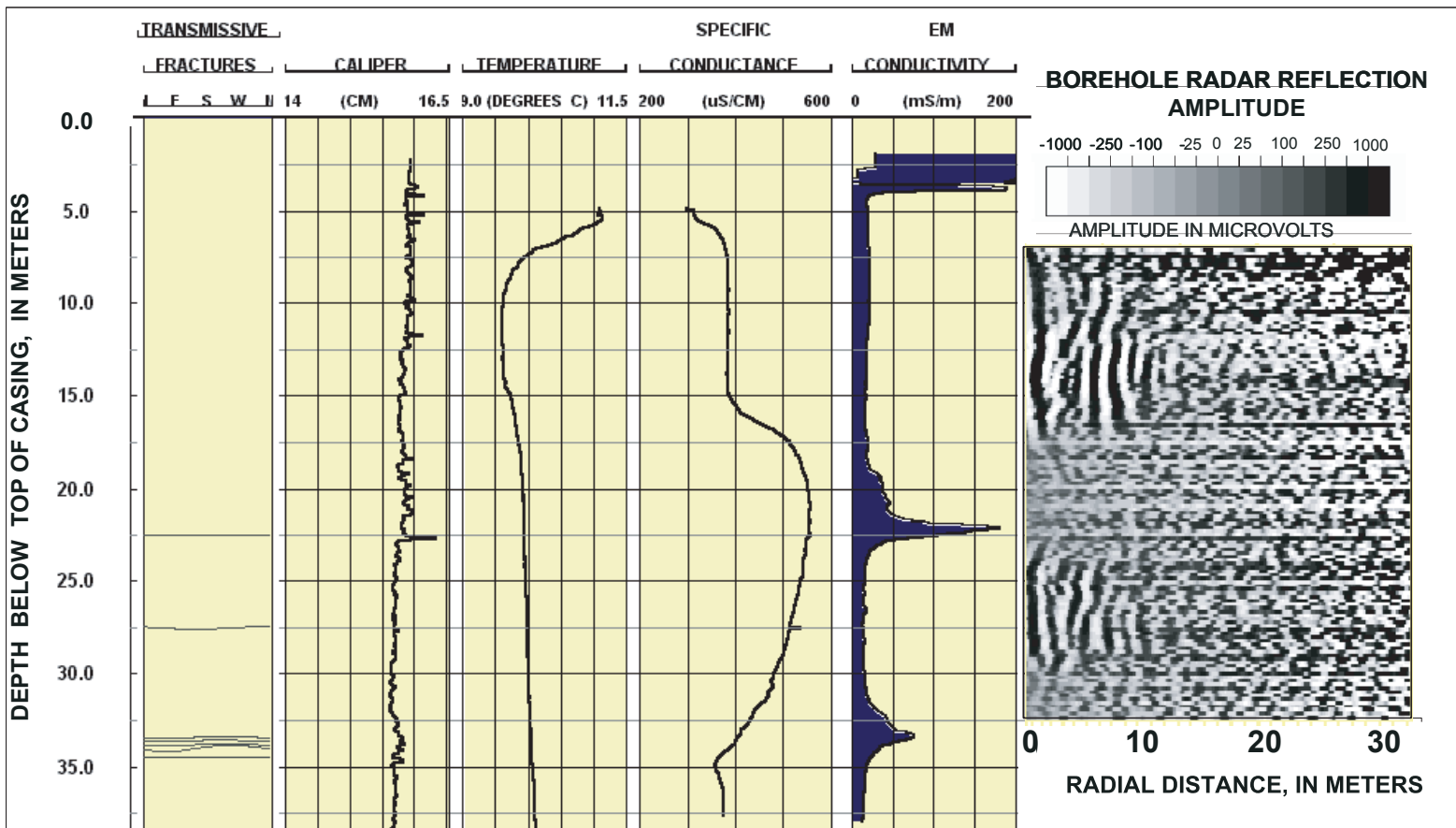
Consecutive specific conductance logs were collected in MW105R, a 15.2-cm diameter borehole, while it was being pumped at 3.7 liters per minute (fig. 7). The logs indicate that water with a specific conductance of 370  $\mu\text{S}/\text{cm}$  entered the well at a depth of about 34 m and displaced the more conductive water above it. After 1 hour of pumping, the most conductive water in the borehole (650  $\mu\text{S}/\text{cm}$ ), which was adjacent to the fracture near 22 m, reached the pump that was at about 10 m. These logs indicate the lower fracture zone at about 34 m is more transmissive than the fracture zone at about 22 m. The logs also indicate that the water coming from the lower fracture zone is less electrically conductive than the water in the 22-m depth zone.

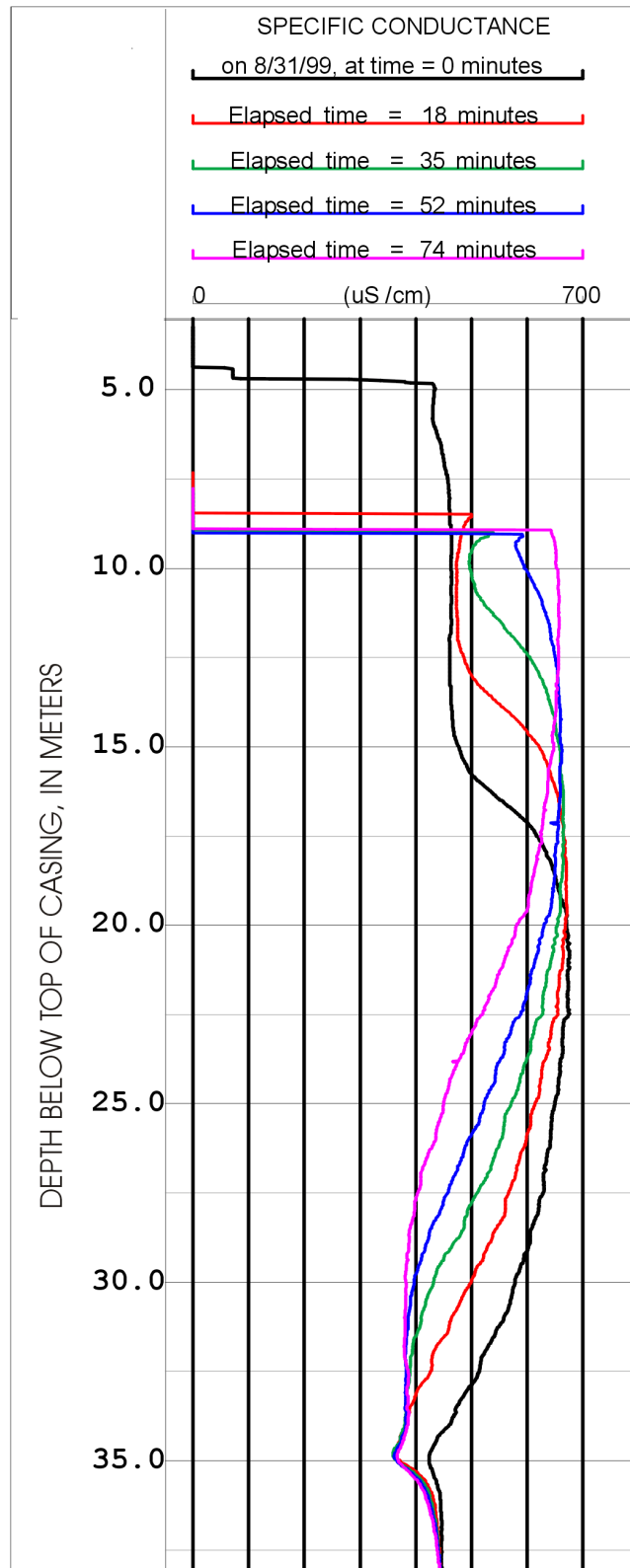
The response of the borehole EM tool is a combination of the conductivity of the fluids surrounding the borehole, the conductivity of the rock matrix, and metallic minerals. The electromagnetic response surrounding MW105R near 22 m is too high to be attributed solely to the specific conductance of the fluids. The highest measured specific conductance was 1,250  $\mu\text{S}/\text{cm}$  (125 mS/m). Use of a simple two phase mixing law,

$$\sigma_{\text{total}} = [(1-\phi) * \sigma_{\text{rock}}] + [\phi * \sigma_{\text{fluid}}],$$

where  $\phi$  is porosity and  $\sigma$  is conductivity, illustrates that the specific conductance of the fluid has little influence on the EM response when the porosity is small, as in crystalline rocks. For known values of

**Figure 6.** Data from borehole logs and borehole radar reflection in MW/105R, UConn landfill study area, Storrs, Connecticut.





**Figure 7.** Specific conductivity in MW105R, UConn landfill study area, Storrs, Connecticut, in response to pumping at 3.7 liters per minute (individual logs shown for elapsed time in minutes from start of pumping).

fluid conductivity (125 mS/m) and reasonable estimates of bedrock conductivity (1 to 2 mS/m), the relation also shows that the conductive anomaly at about 22 m cannot be accounted for by fluid conductivity changes within the average rock. Conductive mineralization such as sulfide minerals could account for the remainder of the EM response.

Water-quality samples collected in MW105R in October 1999 from an isolated zone from a depth of 21.8 to 23.3 m indicated elevated specific conductance (810  $\mu\text{S}/\text{cm}$ ), high iron and cadmium, a negative oxidation-reduction potential, and chlorobenzene (Haley and Aldrich, Inc. 1999a). Collectively, these chemical parameters indicate the high specific conductance in borehole fluids in MW105R was caused in part by landfill leachate. Therefore, the anomaly identified by borehole- and surface-geophysical surveys is interpreted as a conductive lithologic feature and a permeable fracture zone containing landfill leachate.

## Summary

This paper focuses on the results of selected surface- and borehole- geophysical surveys that were collected near UConn landfill and former chemical waste-disposal pits. A suite of surface- and borehole-geophysical methods was used to demonstrate an integrated approach to characterize the hydrogeology in fractured-rock investigations.

Surface-geophysical methods were used as a screening tool to identify potential contamination pathways and to locate potential leachate plumes. Inductive terrain-conductivity and 2D dc-resistivity profiling detected two shallow, electrically conductive anomalies near surface-water discharge areas north and south of the landfill. These were interpreted as shallow leachate plumes. Data from the surface-geophysical investigation also showed two sheet-like conductive anomalies. The locations of the two sheet-like anomalies were used to locate two of the boreholes that were drilled for the UConn landfill investigation.

A total of 11 boreholes were logged with geophysical methods to characterize the hydrogeology of the bedrock underlying the landfill and vicinity and to further evaluate the anomalies identified in the surface geophysical surveys. An integrated interpretation of data from surface and borehole methods was done to determine the location, orientation, and extent of fractures; rock type; bedrock foliation; and refine the site conceptual model.

High-resolution continuous images from the OTV show rock units similar to those mapped in the region. The gneiss and schist are characterized by quartz-feldspar-biotite-garnet and locally by sulfide-rich layers. High electrical-conductivity zones measured by the borehole EM-induction logs confirm the presence of sulfide-rich layers. In general, the foliation in the borehole data strikes to the northeast-southwest and dips to the west.

The borehole-geophysical results constrain the interpretations of the surface-geophysical investigations. Borehole MW121R was located in order to intersect a dipping anomaly that was observed in the 2D dc-resistivity survey collected west of the landfill. The EM-conductivity log in MW121R contains a high electrical-conductivity anomaly at 21 m. The magnitude of this anomaly is nearly 11,000 mS/m and coincides with a layer containing sulfide minerals, rather than open fractures. The nearest fractures in the borehole and the fluids in the borehole adjacent to the EM spikes have relatively low electrical conductivity. The lack of high conductivity fluids in the borehole further supports the interpretation that the electrically conductive unit in the surface-geophysics and the feature imaged in the borehole radar log is induced by a lithologic change.

A second surface-geophysical anomaly was identified southwest of the landfill and is a north-south trending, westward dipping feature. Borehole MW105R was positioned to intersect the

conductive feature in the middle of the borehole. A south-striking, westward dipping (N185°E, 21°W) feature was identified in the borehole-radar log of MW105R at 17.4 m, which is coincident with a fracture observed in the ATV log. Another feature at about 22 m strikes south and dips gently west (N181°E, 12°). It was observed in the OTV, ATV, and borehole-radar surveys. The feature at about 22 m is also characterized by a high (200 mS/m) conductivity spike in the EM log, which shows a combined response of the water in the fractures and rock matrix and conductivity of the rock surrounding the borehole. Although the specific conductivity of the fluid from this zone was relatively high, it was still less conductive than the spike in the EM log, which indicates that the conductive anomaly is caused by a combination of conductive fluids in the fracture at about 22 m and metallic or conductive minerals in the rock. Water-quality samples from a discretely isolated zone near a depth of 22 m had elevated specific conductance (810  $\mu$ S/cm), high iron and cadmium, a negative oxidation-reduction potential, and chlorobenzene, which is interpreted as the presence of landfill leachate. This investigation illustrates the effectiveness of the use of combined surface- and borehole-geophysical methods for identification and evaluation of electrically conductive contaminant plumes.

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