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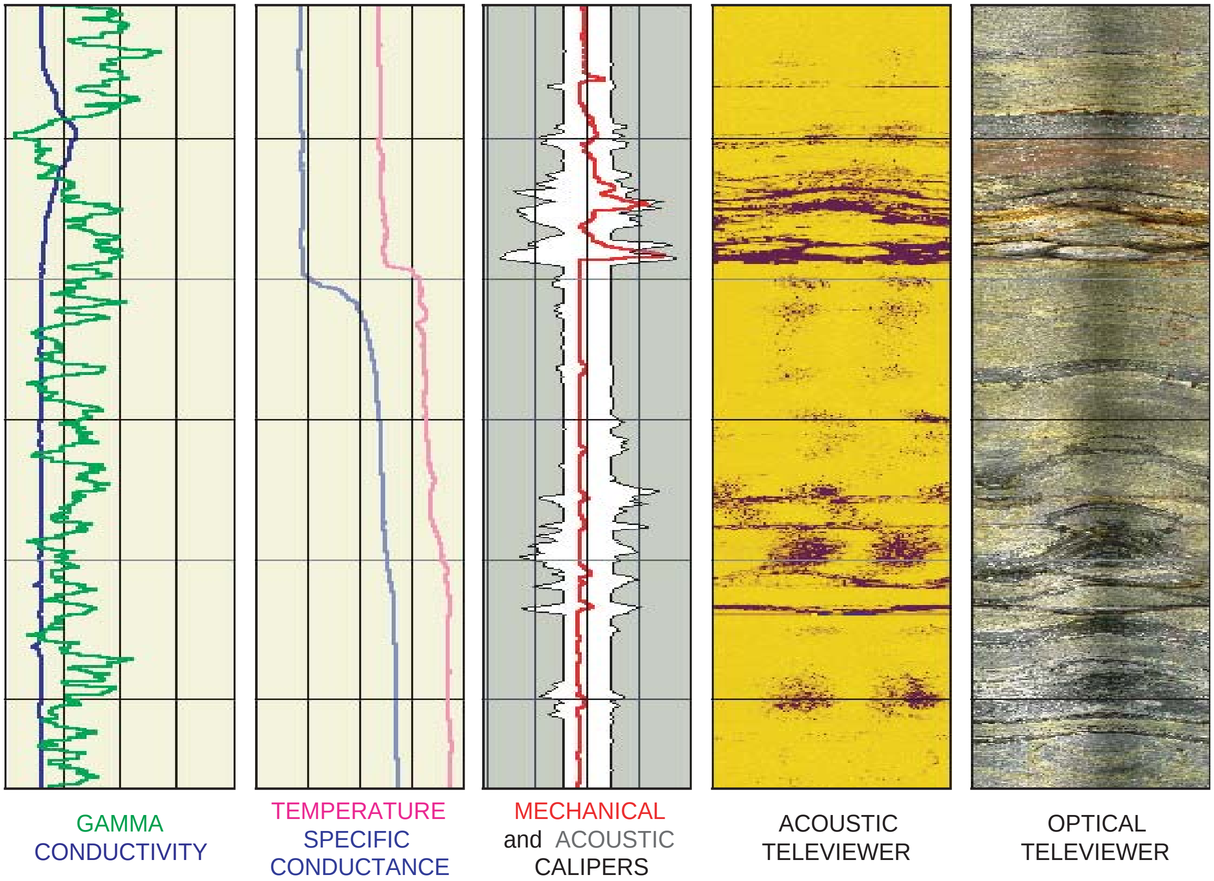
Borehole-Geophysical Investigation of the University of Connecticut Landfill, Storrs, Connecticut

Water-Resources Investigations Report 01-4033



Prepared in cooperation with the University of Connecticut

U.S. Department of the Interior
U.S. Geological Survey

Cover: Borehole-geophysical logs from a section of borehole MW109R, University of Connecticut landfill study area, Storrs, Connecticut.

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Storrs, Connecticut
2002

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CONVERSION FACTORS, VERTICAL DATUM, AND ABBREVIATIONS

Multiply	By	To obtain
inch (in)	25.4	millimeter
foot (ft)	0.3048	meter
foot squared (ft^2)	0.09290	meter squared
gallon (gal)	0.003785	cubic meter

Temperature in degrees Fahrenheit (°F) may be converted to degrees Celsius (°C) as follows:

°C= (°F - 32)/1.8

Vertical datum: In this report, "sea level" refers to the National Geodetic Vertical Datum of 1929 (NGVD of 1929) – a geodetic datum derived from a general adjustment of the first-order level nets of both the United States and Canada, formerly called Sea Level Datum of 1929.

Other abbreviations used in this report:

°, degrees

d, day

ft/µs, foot per microsecond

ft^2/d, foot squared per day

ft^2/s, foot squared per second

gal/d, gallon per day

gal/min, gallon per minute

gal/min/ft, gallon per minute per foot

MHz, megahertz

µs, microsecond

µS, microsiemen

µS/cm, microsiemen per centimeter

min, minute

mS/m, millisiemen per meter

s, second

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ABSTRACT

A borehole-geophysical investigation was conducted to help characterize the hydrogeology of the fractured-rock aquifer and the distribution of unconsolidated glacial deposits near the former landfill and chemical waste-disposal pits at the University of Connecticut in Storrs, Connecticut. Eight bedrock boreholes near the landfill and three abandoned domestic wells located nearby were logged using conventional and advanced borehole-geophysical methods from June to October 1999. The conventional geophysical-logging methods included caliper, gamma, fluid temperature, fluid resistivity, and electromagnetic induction. The advanced methods included deviation, optical and acoustic imaging of the borehole wall, heat-pulse flowmeter, and directional radar reflection. Twenty-one shallow piezometers (less than 50-feet deep) were logged with gamma and electromagnetic induction tools to delineate unconsolidated glacial deposits. Five additional shallow bedrock wells were logged with conventional video camera, caliper, electromagnetic induction, and fluid resistivity and temperature tools.

The rock type, foliation, and fracturing of the site were characterized from high-resolution optical-televiewer (OTV) images of rocks penetrated by the boreholes. The rocks are interpreted as fine- to medium-grained quartz-feldspar-biotite-garnet gneiss and schist with local intrusions of quartz diorite and pegmatite and minor concentrations of sulfide mineralization similar to rocks described as the Bigelow Brook Formation on regional geologic maps. Layers containing high concentrations of sulfide minerals appear as high electrical conductivity zones on electromagnetic-induction and borehole-radar logs. Foliation in the rocks generally strikes to the northeast-southwest and dips to the west, consistent with local outcrop observations. The orientation of foliation and small-scale gneissic layering in the rocks, however, varies locally and with depth in some of the boreholes. In two of the boreholes, the foliation strikes predominantly to the northwest and dips to the northeast. Although small-scale faults and lithologic discontinuities were observed in the OTV data, no large-scale faults were observed that appear on regional geologic maps.

Fractures were located and characterized through the use of conventional geophysical, OTV, acoustic-televiewer (ATV), and borehole-radar logs. The orientation of fractures varies considerably across the site; some fractures are parallel to the foliation, whereas others cross-cut the foliation. Many of the transmissive fractures in the bedrock boreholes strike about N170°E and N320°E with dips of less than 45°. Other transmissive fractures strike about N60°E with dips of more than 60°. Most of the transmissive fractures in the domestic wells strike about N60°E and N22°E with dips of more than 45°. The strike of N60°E is parallel to the trend of a thrust fault that appears on regional geologic maps. Vertical flow in the boreholes was measured with the heat-pulse flowmeter under ambient and (or) pumping conditions. Results of ATV, OTV, and conventional logs were used to locate specific zones for flowmeter testing. Ambient downflow was measured in three

boreholes, ambient upflow was measured in two other boreholes, and both ambient downflow and upflow were measured in a sixth borehole. The other five bedrock boreholes and domestic wells did not have measurable vertical flow. The highest rate of ambient flow was measured in the background borehole in which upflow and downflow converged and exited the borehole at a fracture zone near a depth of 62 feet. Ambient flow of about 340 gallons per day was measured. In the other five wells, ambient flow of about 20 to 35 gallons per day was measured. Under low-rate pumping (0.25 to 1 gallon per minute), one to six inflow zones were identified in each well. Usually the fractures that are active under ambient conditions contribute to the well under pumping conditions. To prevent ambient vertical flow and the potential for cross-contamination, temporary borehole liners were installed in five of the boreholes.

Specific-capacity and open-hole transmissivity values were determined in eight boreholes completed in bedrock. The specific capacity estimated for these boreholes ranges from 0.14 to 1.6 gallons per minute per foot. The values for open-hole transmissivity range over two orders of magnitude and when proportioned to individual fracture transmissivity, range from 23 to 340 feet squared per day.

Two boreholes had been drilled to intersect electrically conductive zones identified by previous surface-geophysical investigations. The borehole-geophysical results indicate that the boreholes penetrate electrically conductive structures consistent with the anomalies interpreted from the surface-geophysical data. Borehole MW121R was located to intersect a dipping electrically conductive anomaly at about 60 feet, interpreted from the two-dimensional direct current-resistivity survey conducted on the western side of the landfill. The electromagnetic-conductivity log in the borehole contains a high electrical conductivity anomaly at a depth of 69 feet. The magnitude of this anomaly is nearly 10,000 millisiemens per meter and is coincident with a layer containing sulfide mineralization, rather than fractures.

The other borehole, MW105R, was located to intersect another anomaly south of the landfill. This anomaly was interpreted as a north-south striking, westward dipping feature. In the borehole, two south-striking, westward dipping fractures were identified in the ATV, OTV, and radar logs. The specific conductance of the fluid measured near these fractures was as high as 1,250 microsiemens per centimeter. Water-quality samples collected in October 1999 from an isolated zone from 71.5 to 76.5 feet indicated high specific conductance (810 microsiemens per centimeter), high concentrations of iron and cadmium, negative oxidation-reduction potential, and chlorobenzene. Collectively, these parameters indicate that the high specific conductance in the borehole logs for MW105R was caused 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 that contains landfill leachate.

INTRODUCTION

The University of Connecticut (UConn) in Storrs, Connecticut, operated a landfill and chemical waste-disposal pits from about 1966 to 1989. In the early 1970s, the landfill was estimated to receive 18,000 cubic yards of waste annually, including the sand and gravel for waste-cell construction and cover. About 85 percent of the landfill contents were paper products (Izraeli, 1985). The chemical waste-disposal pits, which are located to the west of the landfill, were operated from 1966 to 1978. No official documentation of the wastes that were disposed of in the chemical waste-disposal pits is available; however, Bienko and others (1980) thought that pesticides, chlorinated hydrocarbons, solvents, and ammonium hydroxide may have been deposited. A detailed review by Haley and Aldrich, Inc. and others (1999a) indicates acids, ethers, peroxides, heavy metals, cyanide, arsenic, toluene, acetone, benzene, and herbicides also were disposed of in the chemical waste-disposal pits. In 1987, the soil in and around the chemical waste-disposal pits was removed (Connecticut Department of Environmental Protection, 1993).

In 1998, the Connecticut Department of Environmental Protection issued a consent order to UConn requiring an investigation of the potential effect of the UConn landfill on human health and the environment. The initial hydrogeologic investigation included a preliminary assessment of the amount of soil, surface-water, and ground-water contamination near the landfill (Haley and Aldrich, Inc. and others, 1999b). 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). The methods of investigation included surface geophysics, borehole geophysics, exploratory drilling and monitoring-well installation, and surface-water, ground-water, sediment, leachate, soil, and soil-gas sampling. In 1999, the U.S. Geological Survey (USGS), in cooperation with UConn, conducted a borehole-geophysical investigation of the fractured-bedrock aquifer near the UConn landfill. Borehole-geophysical methods were used to characterize the hydrogeology of the fractured-bedrock aquifer and the distribution of unconsolidated glacial deposits near the landfill and former chemical waste-disposal pits to identify contamination or potential pathways for contaminant migration (primarily landfill leachate).

Purpose and Scope

The purpose of this report is to describe the borehole-geophysical logging methods used in the UConn landfill study, to report the interpretation of the geophysical measurements, and to compare the data with surface-geophysical data (Powers and others, 1999) and with the local fracture patterns mapped in nearby outcrops (Fahey and Pease, 1977). An integrated suite of borehole-geophysical methods was used to determine the location, extent, and nature of fractures in the bedrock aquifer near the landfill. Geophysical logs were collected from 11 bedrock wells and 21 shallow piezometers completed in overlying unconsolidated deposits (fig. 1). The borehole methods used in this investigation include conventional and advanced geophysical logs. Conventional geophysical logs were used to characterize and delineate unconsolidated sediments penetrated by the shallow piezometers and to delineate fractures and provide information on fracture hydraulic properties. Advanced geophysical logs were used in the bedrock boreholes to obtain information on the locations, orientations, and lateral continuity of fractures identified in the boreholes and to quantify the hydraulic properties of the transmissive fractures.

Description of the Study Area

The UConn campus is in Storrs, Connecticut, in the northeastern part of the State. The study area occupies a northeast-trending valley with highlands to the northeast and southwest. The UConn landfill is in the northwestern corner of the campus and covers about 5 acres. The 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. and others, 1999b). The 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 local minor topographic hills and Hunting Lodge Road. Regional ground-water flow is inferred to follow the topography; however, the local flow and transport in bedrock follows fractures that may be oriented differently than the regional gradient. In this report, the term “UConn landfill study area” is used to describe the area shown in figure 1 that includes the landfill, the former chemical-waste disposal pits, and the southern end of Hunting Lodge Road.

The rocks that underlie the UConn landfill study area are folded, faulted, and fractured metasedimentary rocks of the Bigelow Brook Formation (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 other unconsolidated deposits, which range in thickness typically from 0 to about 20 ft and locally up to 50 ft.

Previous Investigations

Regional geologic mapping was done by Fahey and Pease (1977). The rocks underlying the landfill and vicinity were mapped as Bigelow Brook Formation, which consists of an upper unit that is characterized by rusty weathered sillimanite schist with gneiss and sulfide layers and a lower unit that is a gray weathered sillimanite gneiss with fewer sulfide layers. The foliation in the immediate vicinity of the landfill strikes S-SW and dips 50° to the west. Foliation in the area surrounding the landfill varies from 15° west of north to 15° east of north and dips 20 to 60° to the west.

Joints and faults are reported to strike south-southwest and dip 30 to 40° to the west. Fahey and Pease (1977) mapped a north-trending tear fault, which transects the study area to the west of the landfill and former chemical waste-disposal pits. This north-trending fault is truncated to the south by a west-trending thrust fault, which was mapped south of the landfill and north of North Eagleville road.

A suite of surface-geophysical methods was used to study the hydrogeology of the area (Powers and others, 1999). Azimuthal and two-dimensional (2D) direct-current (dc)-resistivity, inductive terrain-conductivity, and ground-penetrating radar 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 trash disposal trenches that received trash 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.

Inductive terrain-conductivity and 2D dc-resistivity profiling detected electrically conductive anomalies that were interpreted as possible leachate plumes near two surface-water discharge areas. One conductive anomaly, to the north of the landfill, is interpreted as shallow conductive leachates that dissipate to almost background levels about 150 ft north of the landfill. The other anomaly, south of the landfill, is interpreted to extend vertically through the overburden into the shallow bedrock and laterally along the intermittent drainage to Eagleville Brook (fig. 1). In addition, two sheet-like conductive anomalies were detected in the inductive terrain-conductivity and 2D dc-resistivity profiles west of the former chemical waste-disposal pits and south of the landfill. These anomalies strike approximately north-south and dip 30° to the west and are interpreted as either fracture zones that are filled with conductive fluids or conductive lithologic zones within more resistive bedrock.

Acknowledgments

The authors gratefully acknowledge the homeowners along Hunting Lodge Road who permitted access to their private wells. The authors thank Susan Soloyanis of Mitretek Systems, John H. Williams of the USGS, and the many individuals from Haley and Aldrich, Inc. who provided information and technical assistance. We appreciate and acknowledge the many USGS personnel who provided assistance with geophysical logging and analysis: Alton Anderson, Marcel Belaval, Marc Buursink, C.B. Dawson, John Dunnigan, Peter Joesten, Christopher Kochiss, Remo Mondazzi, James Norris, C.J. Powers, Kamini Singha, and Christine Witkowski.

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, and hydraulic properties of fractures. Both conventional and advanced borehole-geophysical methods were used in this study. The conventional methods are caliper, gamma, fluid temperature, fluid resistivity, and electromagnetic induction. The advanced methods are deviation, optical- and acoustic-televiewer imaging, flowmeter (under ambient and pumping conditions), and single-hole directional radar reflection.

Multiple logs that measure a range of earth properties at different scales of resolution were collected in each of the 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. 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. Borehole liners were used to isolate transmissive zones and prevent vertical flow and the potential for cross-contamination in five boreholes.

Conventional Borehole-Geophysical Methods

Conventional geophysical-logging methods are used to determine rock properties, infer locations where water enters or exits boreholes, and identify variations in dissolved solids in the fluids within a borehole and in the rock adjacent to the borehole.

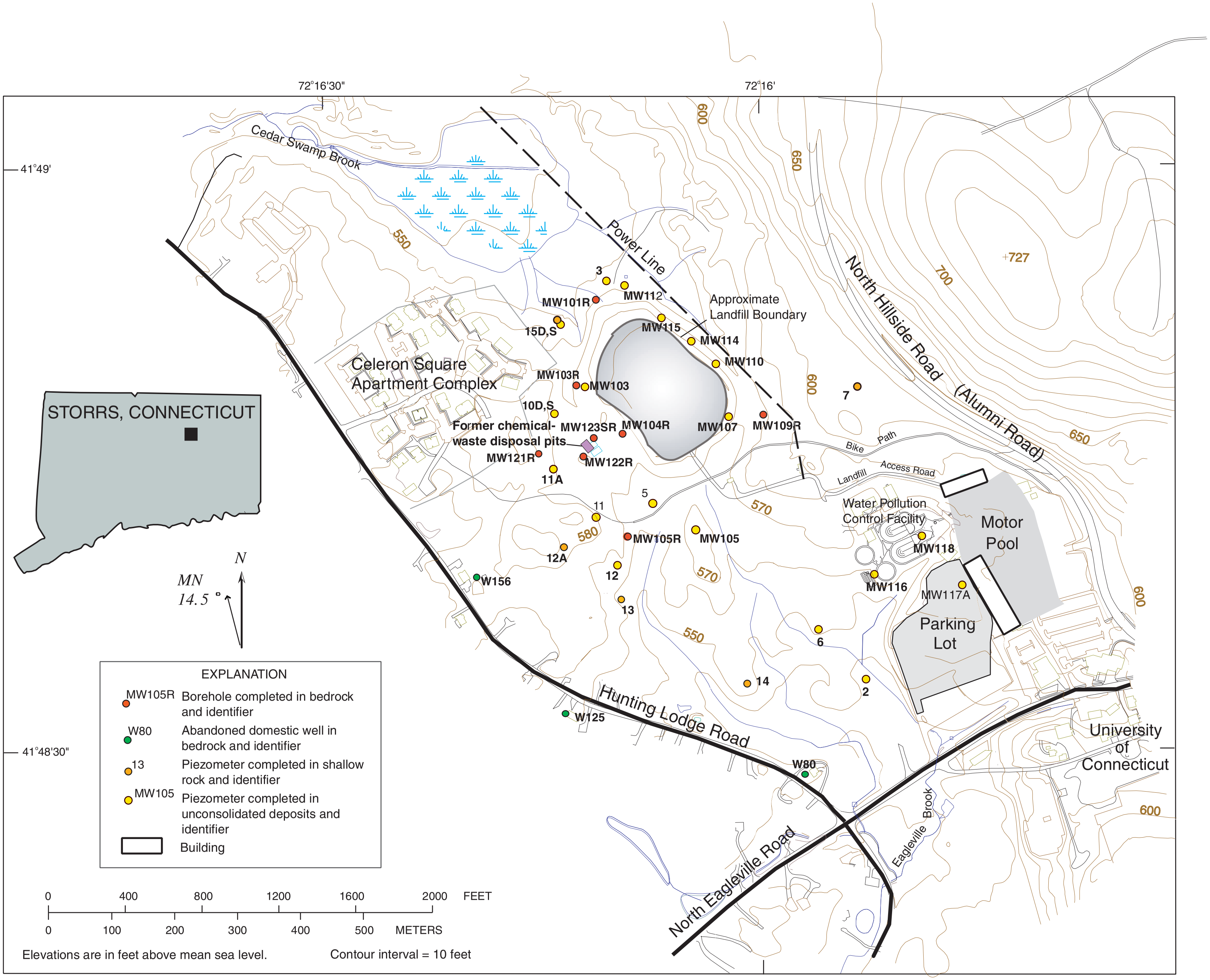

Figure 1. Location of boreholes and piezometers in the UConn landfill study area, Storrs, Connecticut.

Caliper Logging

Caliper logging is used to generate a continuous profile of the borehole diameter with depth. The caliper tool is pulled up the borehole allowing three spring-loaded arms to open as they pass borehole enlargements (Keys, 1990). Enlargements in the borehole diameter generally are related to fractures, but also can be caused by changes in the lithology or borehole construction.

Gamma Logging

Gamma logging measures the natural-gamma radioactivity of the formation surrounding the borehole (Keys, 1990). The most significant naturally occurring sources of gamma radiation are potassium-40 and daughter products of uranium and thorium decay series. Gamma emissions can commonly be correlated with rock type or with fracture infilling. Potassium-40 is abundant in some feldspar and mica, and uranium and thorium can be concentrated by geochemical processes. Gamma logs are recorded in American Petroleum Institute units, APIu.

Deviations in the gamma log indicate changes in lithology or the presence of altered zones or mineralized fractures. The vertical resolution of the gamma probe is 1 to 2 ft, and the probe is able to detect gamma radiation through plastic and steel casing. Because the gamma log does not have a unique lithologic response, interpretation must be correlated with other information such as drilling logs and other geophysical logs.

Fluid-Temperature Logging

Fluid-temperature logging is used to identify where water enters or exits the borehole (Williams and Conger, 1990). In the absence of fluid flow in the borehole, the temperature gradually increases with the geothermal gradient, about 1°F per 100 ft of depth (Keys, 1990). Deviations from the expected geothermal gradient indicate potential transmissive zones in the borehole. Changes in the fluid temperature indicate water-producing and (or) water-receiving zones. Intervals of vertical flow are characterized by little or no temperature gradient. The differential or “del” temperature, which is the first derivative of the temperature plot, is calculated and plotted to identify changes in the slope of the temperature profile.

Fluid-Resistivity Logging

Fluid-resistivity logging measures the electrical resistivity of the fluid in the borehole (Williams and Conger, 1990). Changes in the electrical resistivity indicate differences in the concentration of the total dissolved solids in the fluid in the borehole. These differences typically indicate sources of water that have contrasting chemistry and have come from different transmissive zones. Specific conductance is the reciprocal of the fluid resistivity.

Fluid resistivity and temperature usually are measured simultaneously with a single borehole tool. These logs are typically run first in order to measure an undisturbed water column that represents the ambient conditions. The logs can be collected after pumping has stopped, and a comparison between ambient and pumping conditions can help identify where water has entered the borehole.

Electromagnetic-Induction Logging

Electromagnetic (EM)-induction logging records the electrical conductivity of the rocks and the fluids in the rocks surrounding the borehole (Williams and others, 1993). Changes in electrical conductivity are caused by variations in porosity, borehole diameter, dissolved concentration of the water in the rocks, and mineralogy (metallic minerals). The EM-induction tool is most sensitive to the bedrock and pore water approximately 1 ft away from the probe, and the tool has a vertical resolution of approximately 2 ft. In boreholes with diameters of 6 in. or less, the conductance of the borehole fluids has a negligible effect on the induction log response. The log is used to delineate changes in rock type or in electrical properties of water in the rock formation. EM conductivity is recorded in millisiemens per meter (mS/m).

Advanced Borehole-Geophysical Methods

Advanced borehole-geophysical logs are used to aid in the identification of the lithology of the boreholes and in the determination of the location and orientation of foliation and laminations in the bedrock and of fractures intersected by the boreholes.

Deviation Logging

Deviation logging records the three-dimensional geometry of the borehole (Keys, 1990). The deviation log records the azimuthal direction (0-360°) and the inclination (0-90°) of the borehole over the depth of the borehole. Borehole deviation tools generally indicate direction to within ±2° and inclination to within ±0.5°. The results of this log are used to correct the orientation of fractures determined from the acoustic and optical imaging tools.

Optical-Televiewer Logging

Optical-televiewer (OTV) logging records a continuous, magnetically oriented, and digitized 360° color image of the borehole wall (Williams and Johnson, 2000). The images permit the direct inspection of the borehole, which can be examined for fractures, changes in lithology, water level, bottom of casing, and borehole enlargements. Optical images can be collected above or below the water surface, provided the water is sufficiently clear for viewing the borehole wall. Fracture characteristics such as the presence of iron oxidation or fracture infilling (a sealed fracture) can be visually confirmed. These characteristics sometimes provide information on the hydraulic properties of the borehole. In this investigation, the relative sizes of the fracture apertures were described with terms such as “wide fracture,” “fracture,” or “minor fracture.” The term “possible fracture” was used to describe a planar feature if the interpretation was unclear from the image and from integrated interpretation with other logs. The vertical resolution of the OTV is 0.01 ft. Because the resolution of this tool is higher than the resolution of the acoustic and electromagnetic imaging tools, it is able to see features that the other tools cannot resolve.

The digital image of a borehole can be viewed as an unrolled, flattened image that shows the depth along the vertical axis and the magnetic direction along the horizontal axis. The x-axis represents a 360° scan of the borehole wall from south through west, north, east and south again (fig. 2A). The depth in feet is shown along the y-axis. The sinusoidal curves on the flattened image represent planar surfaces. Thus, planar features such as fractures, foliation, lithologic contacts, and the water level can be identified directly on the images. Because the image is oriented to North, the strike and dip can be determined. An OTV log also can be viewed as a “virtual core” (fig. 2B).

Acoustic-Televiewer Logging

The acoustic televiewer (ATV) produces a high-resolution, magnetically oriented, digital image that is used to map the location and orientation of fractures that intersect the borehole (Williams and Johnson, 2000). The ATV tool emits a narrow acoustic beam that rotates 360° and is focused at the borehole wall. The acoustic wave moves through fluid in the borehole and is reflected off of the borehole wall and recorded by the tool. The log records the amplitude and traveltime of the reflected signal, which can be displayed as a flattened 360° view of the borehole wall (fig. 3). The vertical resolution of the ATV tool is 0.02 ft.

A fracture that intersects the borehole causes scattering of the acoustic wave and appears as a high contrast, low amplitude line (red feature) on the acoustic amplitude log (fig. 3, far right side). On the acoustic traveltime log, a fracture is indicated by an increase in the one-way traveltime of the wave, due to an increase in borehole diameter. The traveltime can be displayed in the form of an acoustic caliper log that shows the oriented cross-sectional dimensions of the borehole. Borehole diameter is shown in two directions, north-south and east-west. The scale of the north-south caliper has been reversed and decreases from 18 to 2 in., whereas the scale of the east-west caliper extends from 2 to 18 in. (fig. 3, left side). Plotted this way, the two adjacent traces give the appearance of a cross section of the borehole diameter. The ATV actually measures the diameter of the borehole in 256 directions by recording acoustic traveltime from the tool to the borehole wall. The acoustic caliper log is used to confirm whether a feature observed in any of the other logs corresponds to an enlarged borehole diameter.

Because the OTV and ATV tools measure different properties, not all features are seen by both imaging tools. Characteristics such as oxidation, precipitation, or fracture infilling, may be seen only by the OTV, helping to identify a fracture. The ATV image may show an increase in borehole diameter where a fracture cannot be confirmed in the OTV image. The best interpretation is with a side-by-side integration. In general, transmissive fractures were detected by both the OTV and ATV tools.

Heat-Pulse Flowmeter Logging

Heat-pulse flowmeter logging measures the direction and rate of vertical flow in a borehole. Used in conjunction with other geophysical logs, individual fractures or fracture zones where water enters or exits the borehole can be identified. Under ambient conditions, differences in hydraulic head between two transmissive fractures produce vertical flow in the borehole. Water enters the borehole at the fracture zone with the

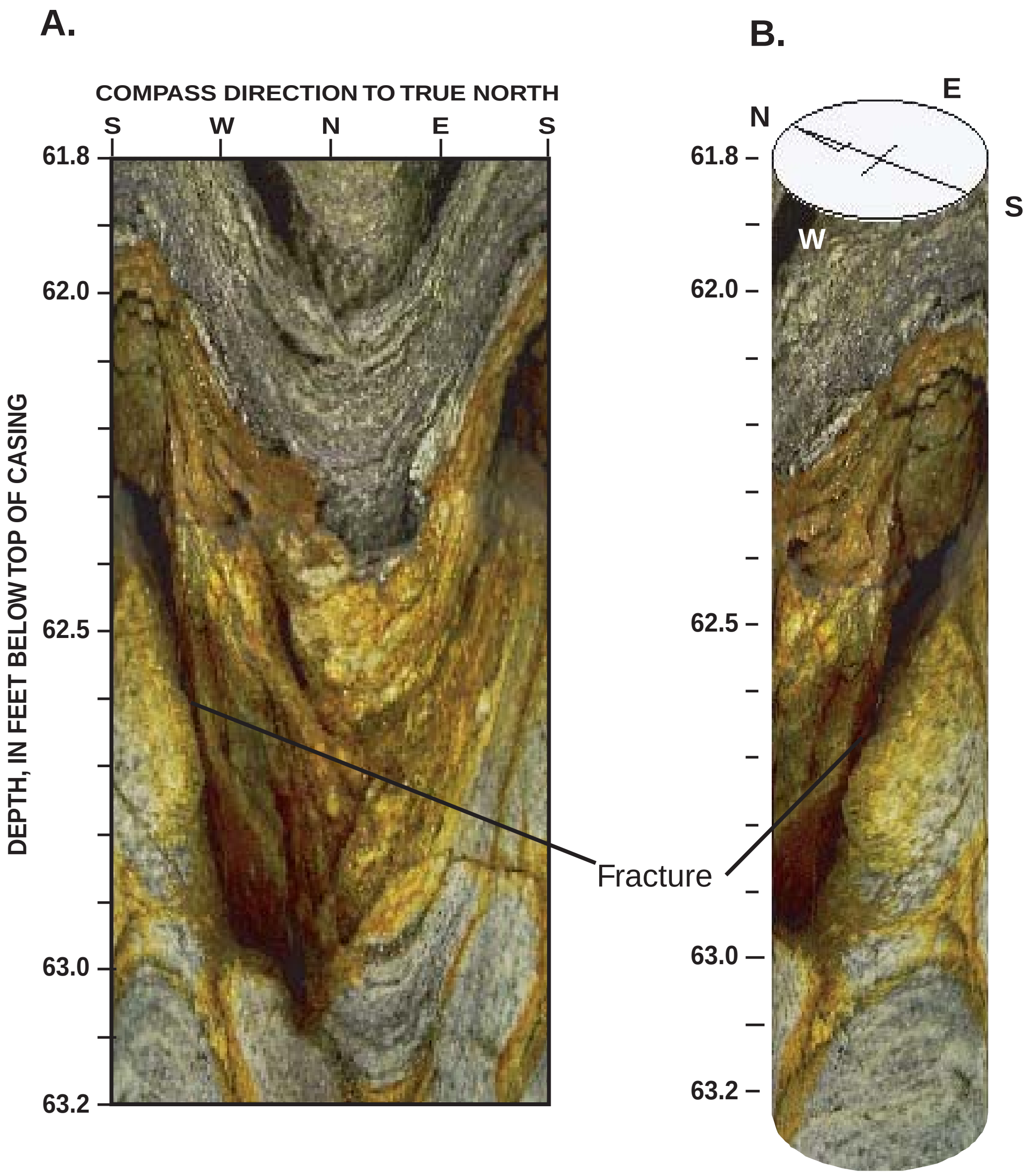

Figure 2. Optical televiewer (OTV) log of borehole MW109R in the UConn landfill study area, Storrs, Connecticut.

A. An "unrolled" 360-degree scan of the borehole wall.
B. OTV image "rolled" into a virtual core.

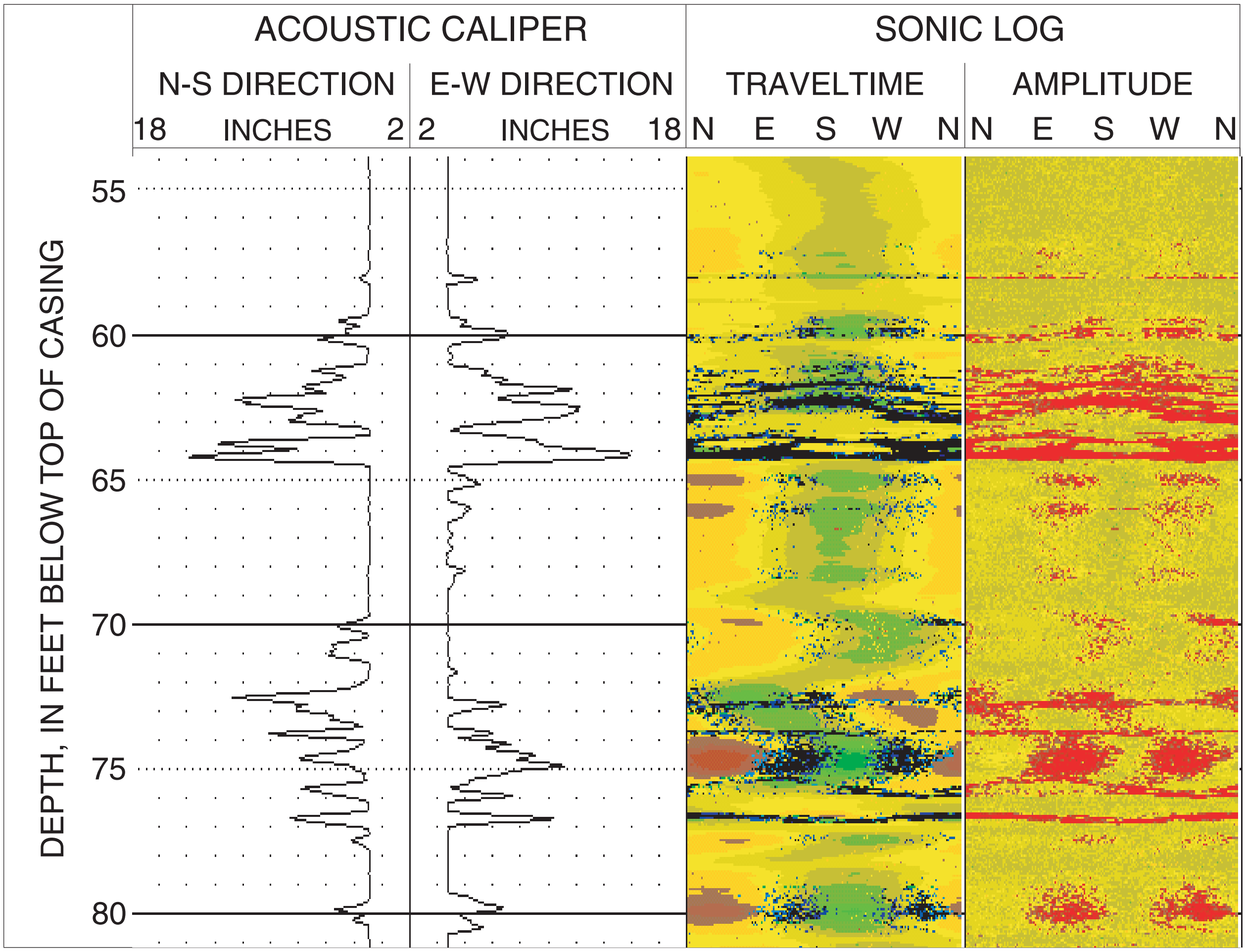

Figure 3. Acoustic-televiewer log of borehole MW109R in the UConn landfill study area, Storrs, Connecticut.

higher head and flows towards and out of the fracture with the lower head. If the heads in transmissive zones are the same, no vertical flow will occur in the borehole. Therefore, flowmeter logging also is conducted under low-rate (0.25 to 1 gal/min) pumping conditions to identify transmissive zones with similar ambient heads that would not be identified without stressing the aquifer. The flow under pumped conditions can be proportioned and attributed to specific fracture zones in the borehole. The ambient flow regimes were incorporated into the calculation using methods described by F.L. Paillet and P.A. Stamile (U.S. Geological Survey, written commun., 1999).

The flowmeter used in this investigation uses a heat-pulse tracer that moves upward or downward in the presence of vertical flow. The measurements were collected at discrete locations, usually above and below fractures. The heat-pulse flowmeter can measure flows as small as 0.01 ± 0.005 gal/min (Hess and Paillet, 1990), which corresponds to a transmissivity of 10^{-5} ft^2/s (Paillet, 1999). The water levels were recorded during pumping and heat-pulse flowmeter measurements were made after the borehole reached a quasi-steady state in which the amount of water coming out of storage was less than the measurement resolution of the tool. In this study, a second pumping rate was used to confirm the results of the first test.

Borehole-Radar Reflection Logging

Borehole-radar reflection logging records the directly transmitted and reflected wave amplitude and transit time of high-frequency EM waves using a pair of downhole transmitting and receiving antennas (fig. 4). The EM waves emitted by the borehole-radar tool penetrate into the formation surrounding the borehole. The waves are reflected by water-filled fractures, faults, bedding, and changes in rock type or water quality. The total radial penetration of EM waves into the formation depends on the electrical resistance of the rock and water surrounding the borehole, and on antenna frequency and separation. In electrically resistive rock, radar reflections can be detected from more than 100 ft into the rock. In electrically conductive rocks, EM waves are rapidly attenuated, severely reducing or eliminating penetration. Used in conjunction with the high-resolution acoustic- and optical-imaging methods, the radar tool can provide information on the location, orientation, and areal extent of fractures or fractures zones.

Based on methods described in Lane and others (1994), single-hole directional-radar reflection surveys were conducted in the 10 bedrock boreholes greater than 100 ft in depth. A directional antenna was used to determine the orientation and location of discrete fractures or fracture zones surrounding the borehole. For this investigation, the radar tool was configured with a broadband electric-dipole transmitting antenna and a magnetic-dipole directional-receiving antenna with center frequencies in air of 60 MHz. The center points of the antennas were separated by a distance of 20.7 ft. Radar measurements were made every 0.65 ft along the open portion of each logged borehole. A total of 64 complete scans were stacked (averaged) at each measurement location to enhance the signal quality.

Interpretation of the dip of planar radar reflectors and estimates of the distance to point reflectors requires an estimate of the radar-wave propagation velocity through the bedrock. The velocity of the radar waves can be determined from analysis of vertical radar profile (VRP) measurements. For this method, either the transmitting antenna or the receiving antenna remains stationary in the borehole while the other antenna is moved away in small increments. Radar measurements are made at each successive location. Radar-wave propagation velocity is interpreted from a linear regression on the change in antenna offset and the change in traveltime of the direct wave from the transmitting antenna to the receiving antenna. For this investigation, a VRP survey was conducted in W156, because it is the deepest borehole studied. The velocity of the radar waves through the rock surrounding W156 as determined by VRP analysis was 372.4 ft/µs. This velocity was used for the processing and interpretation of the other radar reflection surveys.

Data processing of directional-radar reflection surveys included removal of direct-current offsets, application of linear and exponential gains, and band-pass filtering to remove random and coherent noise. Interpretation included the determination of the strike, dip, and projected borehole intersection depth of planar reflectors as well as determination of the distance and azimuthal direction to point-like reflectors. Methods of interpretation are described by Olsson and others (1992).

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 affected by the maximum radial radar penetration distance, the actual length of a reflector may be greater than that estimated from the radar images.

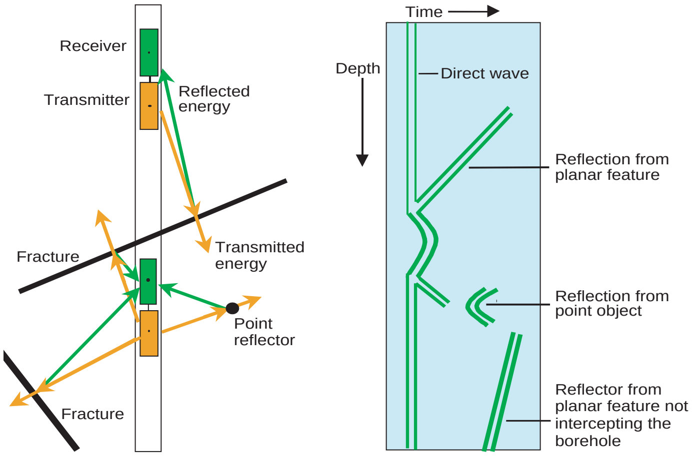

Figure 4. Transmitter and receiver antenna arrangement for borehole-radar reflection logging and the typical reflection patterns from planar and point reflectors.

Hydraulic Methods

Flow in fractured rock is a function of the hydraulic head gradient and the physical properties of the bedrock such as location, orientation, openness, and connectivity of fractures. Water flows from higher hydraulic head to lower hydraulic head through the fractures in the rock. Although a small amount of water enters the primary pores that constitute the matrix of the bedrock, most water is channeled through a set of connected fractures and is driven by the hydraulic gradient. Thus, to characterize the flow and transport of solutes through fractured crystalline rock, the physical and hydraulic properties of the rock have to be defined and understood. It is necessary to identify the fractures in the network, determine which fractures in the network are transmissive, and estimate the connectivity of these fractures.

The hydraulic head in fractures can be measured by isolating the individual fracture zones. Open-borehole hydraulic heads cannot accurately assess the hydraulic head in individual fractures that intersect the borehole, unless the borehole intersects only one fracture or all of the fractures have the same head. Determining the hydraulic head of individual fractures and the hydraulic gradients between connected fractures is beyond the scope of this investigation; however, the flowmeter measurements have provided information on locations of individual transmissive fracture zones. This information can be used to develop sampling strategies and design packer systems to isolate transmissive zones. By isolating these zones and measuring the hydraulic head in these zones, meaningful vertical and horizontal hydraulic gradients can be obtained.

The transmissivity was estimated in open boreholes from specific-capacity data collected concurrently with the heat-pulse flowmeter logging under pumped conditions. The water-level drawdown was recorded in response to low-rate pumping and elapsed time of pumping. The duration of the test was typically 1 hour, but ranged from 0.6 to 1.2 hours. The pumping rates for these tests were 0.25 to 1 gal/min. Specific capacity, which is the yield of the borehole per unit length of drawdown, was calculated and recorded in gallons per minute per foot. In addition, an open-hole transmissivity was calculated using the methods described by Bradbury and Rothschild (1985) with a storage coefficient of 0.0005 (Freeze and Cherry, 1979). Well-loss coefficient is a parameter that quantifies the effects of turbulent flow, which causes drawdown in the borehole relative to the formation. The well-loss coefficient was not determined explicitly for these boreholes; thus, it was set equal to 1.0 (Bradbury and Rothschild, 1985).

The total transmissivity determined for the entire open borehole can be distributed among specific transmissive zones in proportion to the relative contribution of each transmissive zone as measured by the heat-pulse flowmeter under pumping conditions. Proportioning the transmissivity to the individual fracture zones provides estimates of fracture zone transmissivity; however, the transmissivity values determined by this method should be viewed qualitatively. The most reliable quantitative values of transmissivity are obtained from injection tests conducted in discretely isolated zones (Shapiro and Hsieh, 1998). Using the injection-test method at the USGS fractured-rock research site in central New Hampshire, Shapiro and Hsieh measured transmissivities as low as 10^{-9} ft^2/s, which is orders of magnitude lower than transmissivities that can be measured by the methods used in this report.

Temporary Borehole Liners

Open boreholes can connect fractures with different hydraulic heads and permit vertical flow through the borehole. The vertical flow within an open borehole may cause cross-contamination and dilution by providing a conduit between fractures containing different chemical constituents and concentrations. Thus, in order to prevent vertical flow in the boreholes the transmissive fractures must be isolated. For this investigation, vertical flow in selected open bedrock holes was prevented with the use of removable borehole liners designed by Flexible Liner Technology, Inc. A borehole liner, also referred to as a “well sock,” is a long flexible plastic tube that is attached to the top of the borehole casing, inverted, and filled with water until it is lowered to the bottom of the borehole. The temporary liners provide a method for preventing flow until a semi-permanent packer system is designed, built, and installed.

DATA FROM THE BOREHOLE-GEOPHYSICAL INVESTIGATION AT THE UCONN LANDFILL STUDY AREA

For this investigation, borehole-geophysical logging was conducted in 11 bedrock boreholes from July to October 1999. Seven of the bedrock boreholes were drilled as part of a hydrogeologic investigation of the area surrounding the UConn landfill (Haley and Aldrich, Inc. and others, 1999a). The boreholes are 4.5- and 6-in. diameter and completed to depths of about 125 ft below land surface. One shallow bedrock borehole was drilled to a depth of 41 ft below land surface. The other three bedrock boreholes are abandoned domestic-supply wells on private property on Hunting Lodge Road to the south and west of the landfill. The domestic wells vary in depth from 125 to 245 ft below land surface. Information on borehole construction and location is provided in table 1.

Ten shallow piezometers that were installed in 1999 in unconsolidated deposits were logged with EM-induction and gamma tools to characterize the unconsolidated deposits. The geophysical logs were compared to descriptions of split-spoon samples (Haley and Aldrich, Inc. and others, 1999a). These piezometers range in depth from 14 to 23 ft below land surface. In addition, 16 piezometers that were installed to depths of 60 ft below land surface during the 1980s were logged with a submersible video camera, caliper, gamma, fluid-temperature, fluid-resistivity, and EM-induction tools. Five of these piezometers were completed in competent bedrock, and 11 have a screened interval open to the unconsolidated deposits. The geophysical logs were used to help determine the construction and completion intervals of these piezometers. Information on the piezometer construction is shown in table 2.

Conventional Borehole-Geophysical Logs

The complete suite of conventional borehole-geophysical logs was collected and examined for the 11 bedrock boreholes. The logs are shown in appendix 1. The most useful conventional logs were fluid temperature, fluid resistivity, and EM induction. The relative utility of the caliper and gamma logs was quite variable, providing important information for some boreholes, while contributing little to the interpretation of other boreholes. The results of the conventional logs are not discussed in detail; however, results that support or conflict with the results of advanced logs are noted in the discussion below.

Advanced Borehole-Geophysical Logs

The advanced logs provide information on the location, orientation, and hydraulic properties of fractures that intersect a borehole. The logs of all boreholes are presented in the appendixes. Not all fractures are observed by each of the optical, acoustic, and electromagnetic imaging methods. Thus, the individual interpretations have been provided and the results section provides the integrated interpretation.

The orientations of planar features interpreted from the OTV, ATV, and borehole-radar data have been plotted in the form of stereoplots, which provide a graphical method for assessing the pattern of planar features (fig. 5). A stereoplot reduces each fracture plane to a point that represents the intersection of a pole, perpendicular to a fracture plane, with the lower hemisphere projected onto the equatorial plane of the hemisphere. For example, a nearly horizontal fracture would have a pole that projects to the center of the stereoplot. The pole of a steeply dipping fracture would project to the outside of the stereoplot and would be located on the side of the circle (which represents the equatorial plane) opposite from the direction of dip. By convention, the orientations of planar features are reported in right-hand rule, which specifies that the dip is always in a direction 90° to the right of the strike. The stereoplots provide a graphical method for assessing the clustering or variability of the poles to planes. Because it is difficult to determine the direction of strike and dip on shallow features (with dips less than 30°), there is more uncertainty and variability in the poles that plot in the center of the stereograms. In addition, a nearly vertical borehole is more likely to intersect the shallow dipping fractures than the steeply dipping fractures.

Deviation Logs

The borehole deviation is shown in a radial plot, in which the center of the plot represents the borehole location at the top of casing. The borehole location is plotted as a function of depth with respect to True North. Plots of the deviation are provided in appendix 2. The boreholes installed as part of the hydrogeologic investigation are nearly vertical, with less than 8 ft of offset for the entire length of the borehole. Little is known about the construction of the abandoned domestic wells on Hunting Lodge Road. W156 is offset 13.6 ft to the southeast over a total drilled depth of 241 ft. Although the magnitude of the deviation for the

Table 1. Description of boreholes in the UConn landfill study area, Storrs, Connecticut

[~, approximation; --, no data; TOC, top of casing (steel); BOC, bottom of casing. Height of measuring point relative to land surface. Elevation based on sea level. All length measurements are in feet]

Borehole identifier	Date drilled	Diameter	Elevation of land surface	[1]Measuring point elevation	[1]Height of measuring point	[2]New measuring point elevation	[2]New height of measuring point	Total depth from TOC	Depth to BOC from TOC	Location
MW101R	08/24/99	0.5	552.85	553.53	0.7	--	--	127	23.0	North of landfill
MW103R	08/20/99	0.5	570.01	571.0	1.0	--	--	130	26.5	Northwest of landfill
MW104R	08/17/99	0.5	572.72	573.62	0.9	575.42	2.7	128	11.5	West of landfill
MW105R	07/23/99	0.5	563.62	566.02	2.4	--	--	126	12.5	Southwest of landfill
MW109R	07/02/99	0.4	580.11	582.18	2.1	582.31	2.2	127	20.0	East of landfill
MW121R	07/15/99	0.4	587.04	588.82	1.8	--	--	130	11.0	West of landfill
MW122R	07/22/99	0.5	578.74	581.24	2.4	--	--	127	11.3	West of landfill
MW123SR	08/16/99	0.5	576.53	579.32	2.8	--	--	44	11.0	West of landfill
W80	09/17/79	0.5	~544	~545	1.0	--	--	125	40.5	Southwest of landfill
W125	--	0.5	~563	~563	0.1	--	--	132	44.0	West of landfill
W156	10/01/77	0.5	~577	~577.7	0.7	--	--	248	17.0	West of landfill

[1] All measurements in this report are referenced to this measuring point, unless new measuring point elevation was used.

[2] In early August 1999, the measuring points of selected wells were changed.

Table 2. Description of piezometers in the UConn landfill study area, Storrs, Connecticut

[TOC, top of casing (steel); BOC, bottom of casing; --, no data. Height of measuring point relative to land surface (a negative value indicates TOC is below land surface). Elevation based on sea level. All length measurements in feet. All piezometers are 2-inch diameter]

Piezometer identifier	Date drilled	Elevation of land surface	Measuring point elevation	Height of measuring point	Well depth below land surface	Well depth from TOC	Screened or open interval from TOC	Depth to BOC from TOC
Piezometers in unconsolidated deposits								
MW103	07/29/99	574.09	576.13	2.04	23.0	25.0	13.0 - 23.0	--
MW105	07/28/99	561.82	564.39	2.57	14.9	17.5	6.6 - 16.6	--
MW107	07/26/99	569.88	572.18	2.30	15.3	17.6	7.5 - 17.5	--
MW110	07/29/99	568.53	571.12	2.59	14.0	16.6	6.1 - 16.1	--
MW112	07/27/99	555.06	557.39	2.33	14.1	16.4	4.9 - 15.9	--
MW114	07/28/99	572.47	574.57	2.10	20.0	22.1	12.1 - 22.1	--
MW115	07/30/99	568.56	571.38	2.82	20.0	22.8	11.8 - 21.8	--
MW116	08/02/99	553.55	555.84	2.29	15.0	17.3	7.3 - 17.3	--
MW117A	08/02/99	571.86	574.26	2.40	20.2	22.6	12.4 - 22.4	--
MW118	07/30/99	561.37	560.77	-0.60	15.0	14.4	4.4 - 14.4	--
2	05/03/83	536.71	537.55	0.84	23.5	24.3	19.4 - 23.4	--
3D	05/03/83	551.75	553.05	1.30	25.5	26.8	21.3 - 25.3	--
5D	06/02/83	562.24	566.55	4.31	44.2	48.5	41 - 48.5	--
5S	11/14/83	562.24	566.51	4.27	27.8	32.0	14.4 - 18.4	--
6	06/02/83	537.36	539.68	2.32	29.0	31.3	27.3 - 31.3	--
10D	10/24/86	573.21	574.61	1.40	20.2	21.6	16 - 21.6	--
10S	10/24/86	573.34	576.99	3.65	8.5	12.2	5 - 12.2	--
11	11/10/83	571.61	572.37	0.76	35.4	36.1	24 - 36.1	--
11A	11/10/83	576.52	578.39	1.87	22.0	23.8	17 - 23.8	--
12	--	565.25	565.95	0.70	40.4	41.1	29 - 41.1	--
15S	11/14/83	549.32	550.63	1.31	8.5	9.8	3 - 8	--
Piezometers in shallow rock								
7	11/14/83	602.76	605.16	2.40	20.6	23.0	15 - 23	15
12A	02/06/84	583.35	585.09	1.74	62.0	63.7	16.3 - 64.3	16
13	02/03/84	549.87	550.77	0.90	17.0	17.9	9.9 - 17.9	9
14	02/02/84	537.06	538.59	1.53	15.0	16.5	10 - 18	9
15D	11/15/83	549.32	550.93	1.61	20.6	22.2	16.1 - 23.1	15

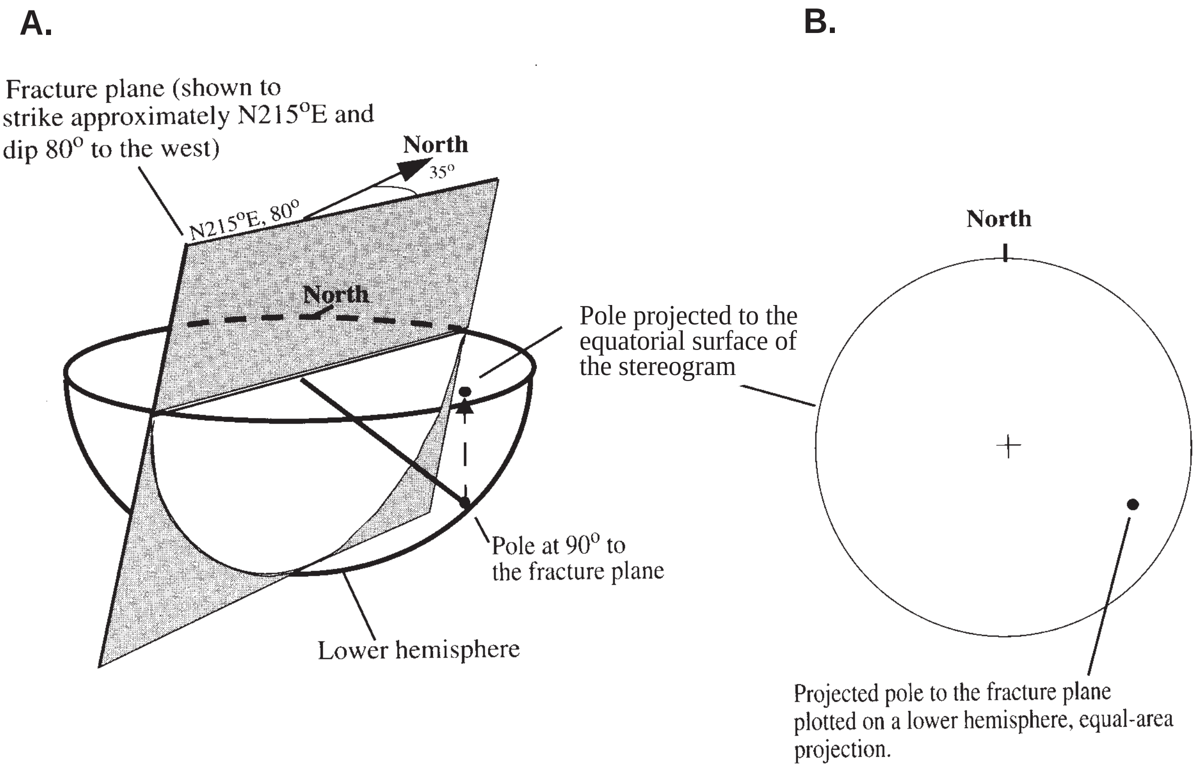

Figure 5. Schematic diagram of stereographic projections. The stereographic projection reduces the orientation of a fracture plane to a point on a stereogram by plotting the pole to the plane on a lower hemisphere and projecting it up to the plotting surface of the stereogram.

A. A three-dimensional representation of the fracture plane as it intersects the hemisphere and the projected pole to the plane.
B. The stereogram that would correspond to the example.

boreholes generally was small, the data were used to correct the orientations of the features observed in the boreholes to account for the borehole inclination. The boreholes typically deviate normal to the fabric of the bedrock. For example,W156 deviates towards the east at N110°E, whereas the foliation dips gently towards the west-northwest.

Optical-Televiewer Logs

In general, the quality of the OTV images is good. The water in the boreholes was fairly clear, and although some of the images are dark, the fractures and features of the rock can be detected. The logs for W80, W125, and W156 have somewhat blurred images near the bottom of the boreholes. The OTV images are provided in appendix 3A. Selected plots of the transmissive fractures in each borehole are provided in appendix 3B.

The OTV tool collects and records depth in meters. Commercial software was used to interpret the OTV data. The commercial software corrects the orientation for the deviation and inclination of the borehole. The midpoint depths of interpreted features were converted to feet and listed in appendix 3C. The interpretation of fractures and foliation are provided in stereoplots for each borehole in appendixes 3D and 3E, respectively.

Acoustic-Televiewer Logs

Plots of the ATV data are provided in appendix 4A. Interpretation of features in the ATV data is presented in tables in appendix 4B and in stereoplots in appendix 4C. The ATV data were used to determine the location and orientation of fractures and to determine the roughness of the borehole wall. Although foliation can sometimes be easily imaged with the ATV data, the foliation was not easy to detect in these boreholes. Thus, the interpretation of oriented features of the bedrock and foliation was done exclusively with the OTV data.

Heat-Pulse Flowmeter Logs

The results of the heat-pulse flowmeter surveys are shown in tables in appendix 5A and B. The rate of flow that was measured in each borehole is reported in gallons per minute. By convention, upflow in a borehole is designated with a positive value and downflow with a negative value. A change in the measured rate of vertical flow in the borehole indicates an addition or removal of water between the two measurement locations. The flowmeter measurements were made in July through September 1999 during a severe regional drought and record the effect of hydrologic conditions. Because vertical flow in a borehole is controlled by the hydraulic heads and transmissivity of the fractures that intersect the borehole, and those heads vary with time, the magnitude and direction of ambient flow may vary temporally.

Borehole-Radar Reflection Logs

The processed borehole-radar data are shown for each borehole in appendix 6A. The radar plots show radar direct-wave and reflection amplitudes plotted as a function of depth. The horizontal axis represents the two-way traveltime, in microseconds, as well as the radial distance from the borehole, in feet. The location, orientation, and estimated length of reflectors are presented in tables in appendix 6B and in stereoplots in appendix 6C.

Hydraulic Test Data

Hydraulic test data, including the specific capacity, pumping rate, and duration of test, are provided in appendix 7. The open-hole transmissivity estimates are provided in feet squared per second, feet squared per day, and gallons per day per foot.

RESULTS OF THE BOREHOLE-GEOPHYSICAL INVESTIGATION AT THE UCONN LANDFILL STUDY AREA

In this report, the term “fracture” refers to planar discontinuities in the rock. No attempt was made to determine the genesis or mode of fracturing. The term “transmissive fracture” refers to a single fracture that was identified with the heat-pulse flowmeter to transmit water to or from the borehole under ambient or low-rate pumping conditions. The heat-pulse flowmeter measures transmissivities as low as 10^{-5} ft^2/s. The term “transmissive zone” refers to a zone of the borehole where two or more closely-spaced fractures were identified with the ATV and (or) OTV and where water flowed in or out of the borehole under ambient or pumping conditions. Because the heat-pulse flowmeter could not be placed between the fractures, measured inflow was attributed to all fractures in the zone.

Hydrogeologic Characterization of Boreholes

For this investigation, seven boreholes were drilled to a depth of about 125 ft. An additional borehole was drilled to about 40 ft, the depth at which water was detected in the borehole. Two of the boreholes, MW109R and MW121R, were drilled using a tri-cone roller-bit method, and the other six boreholes were drilled using an air-hammer rotary method (Haley and Aldrich, Inc. and others, 1999a). All the boreholes were completed with steel casing that was installed through the unconsolidated materials and 2 to 5 ft into rock. The steel casings were grouted to prevent flow between the unconsolidated sediments and the bedrock.

A detailed explanation of data and interpretation is provided for MW109R, the background borehole, followed by the interpretation of data from all other boreholes. The data for all boreholes are presented in the appendixes.

Borehole MW109R

Location and construction. Borehole MW109R was sited upgradient of the landfill to provide background water-quality information. The borehole (4.5-in. diameter) has a yield of 30 gal/min, which is the highest yield of any of the wells near the landfill (Haley and Aldrich, Inc. and others, 1999a). The borehole is cased with steel to a depth of 20 ft and is open below the casing to a depth of 127 ft. The borehole deviates about 8 ft to the southeast (appendix 2). The ambient water level on August 20, 1999, was 19.71 ft below the top of casing. All measurements are referenced to the top of casing, which was at 2.2 ft above land surface.

Lithologic characterization. MW109R intersects more igneous rock units than the other boreholes in this study. Images from the OTV show that MW109R penetrates multiple coarse-grained, felsic igneous dikes, which are interpreted as quartz diorite. The felsic dikes are weakly foliated, with contacts that are parallel to the foliation of the gneiss and schist that they intrude. The foliation strikes to the northwest and dips over a range of 5 to 75° towards the northeast. The igneous dikes comprise more than half of the bedrock exposed in the open borehole.

Fracture characterization. The fractures observed on the OTV and ATV from this borehole strike to the northwest and the southeast (N265 to 325°E and N135 to 156°E), and dip from 8 to 54° towards the southwest and the northeast. The orientations of the fractures that were identified as transmissive in the heat-pulse flowmeter surveys are listed in table 3. Stereoplots of the transmissive fractures are provided in appendixes 3D and 4C. The fractures at 61.9 to 63.6 ft and at 113.1 ft are nearly cross-joint fractures that have the same trend in the strike but dip in opposite directions.

Hydraulic characterization. The fractures at depths of about 25, 32, 44, 61-64, and 73-77 ft are highly stained with iron oxides (fig. 2), which can be an indicator of flow. The diameter of the borehole in these zones is enlarged on the caliper and ATV logs (figs. 3 and 6). The fluid-resistivity and fluid-temperature logs indicate water entering the borehole near 25, 44, 62, and 75 ft (fig. 6).

Table 3. Transmissive fractures in borehole MW109R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
25.7	1	N151°E	47	SW
43.9	2	N319°E	11	NE
61.9	3	N297°E	45	NE
62.7	3	N265°E	54	N
63.6	3	N165°E	36	W
75.6	4	N191°E	57	W
113.1	5	N303°E	36	NE
113.1	5	N108°E	48	S

Under ambient conditions, the direction and rate of vertical flow were measured with the heat-pulse flowmeter. The results (table 4) indicate that the flow regime in MW109R is complex. Upflow and downflow are simultaneously indicated in the borehole under ambient conditions. This means that the hydraulic heads at depths of about 24, 45, 62, 75, and 113 ft are different, causing water to flow from the fractures with the higher heads towards the fracture with the lowest head. Because the measurements were taken between known fractures, any changes in the vertical flow rate can be attributed to inflow or outflow at fractures between the measurement sites. Under ambient conditions, water enters the borehole at about 25 and 44 ft and flows downward at 0.21 gal/min to about 62 ft where it exits (fig. 7). In addition, water enters the borehole at about 113 ft and flows upward at 0.01 gal/min. An additional 0.02 gal/min enters the borehole at fractures between 73 and 77 ft and flows upward in the borehole to about 62 ft where it exits the borehole. Under ambient conditions, about 302 gal/d flow from the upper zone in the borehole down to and out at the fracture zone near 62 ft and 43 gal/d flows from the lower zone upward, exiting the borehole near 62 ft. Under a pumping rate of 1 gal/min, the fracture zone near 62 ft accounted for over 80 percent of the flow. The remaining flow was from the fractures near 25, 75, and 113 ft. Under the pumping conditions, no additional transmissive fractures were identified.

MW109R was pumped at 1.0 gal/min for 1.2 hours, which caused the water level to decline 0.69 ft. The specific capacity for the borehole is 1.45 gal/min/ft, and the open-hole transmissivity is 320 ft^2/d.

Table 4. Heat-pulse flowmeter measurements in borehole MW109R in the UConn landfill study area, Storrs, Connecticut

[--, indicates no measurable flow]

Depth of measurement, in feet below top of casing	Flow direction	Average rate, in gallons per minute	Interpretation
July 20, 1999 - Ambient conditions			
23.0	--	0	
29.0	down	- 0.12	Inflow at 26 feet
38.0	down	- 0.15	
49.0	down	- 0.21	Inflow at 44 feet
57.0	down	- 0.21	Outflow at fracture zone from 62 to 64 feet
69.5	up	0.02	Inflow at fracture near 75 feet
78.5	up	0.01	
95.0	up	0.01	
116.0	--	0	Minor inflow at fracture near 113 feet
July 20, 1999 - Pumped at 1.0 gallons per minute			
24.1	up	--	
29.0	up	0.74	
38.0	up	0.77	
49.0	up	0.74	Minor inflow near 44 feet
57.0	up	0.68	
69.5	up	0.14	Inflow at fracture zone from 62 to 64 feet
78.5	--	--	Inflow from fracture near 75 feet
95.0	--	--	
116.0	--	--	

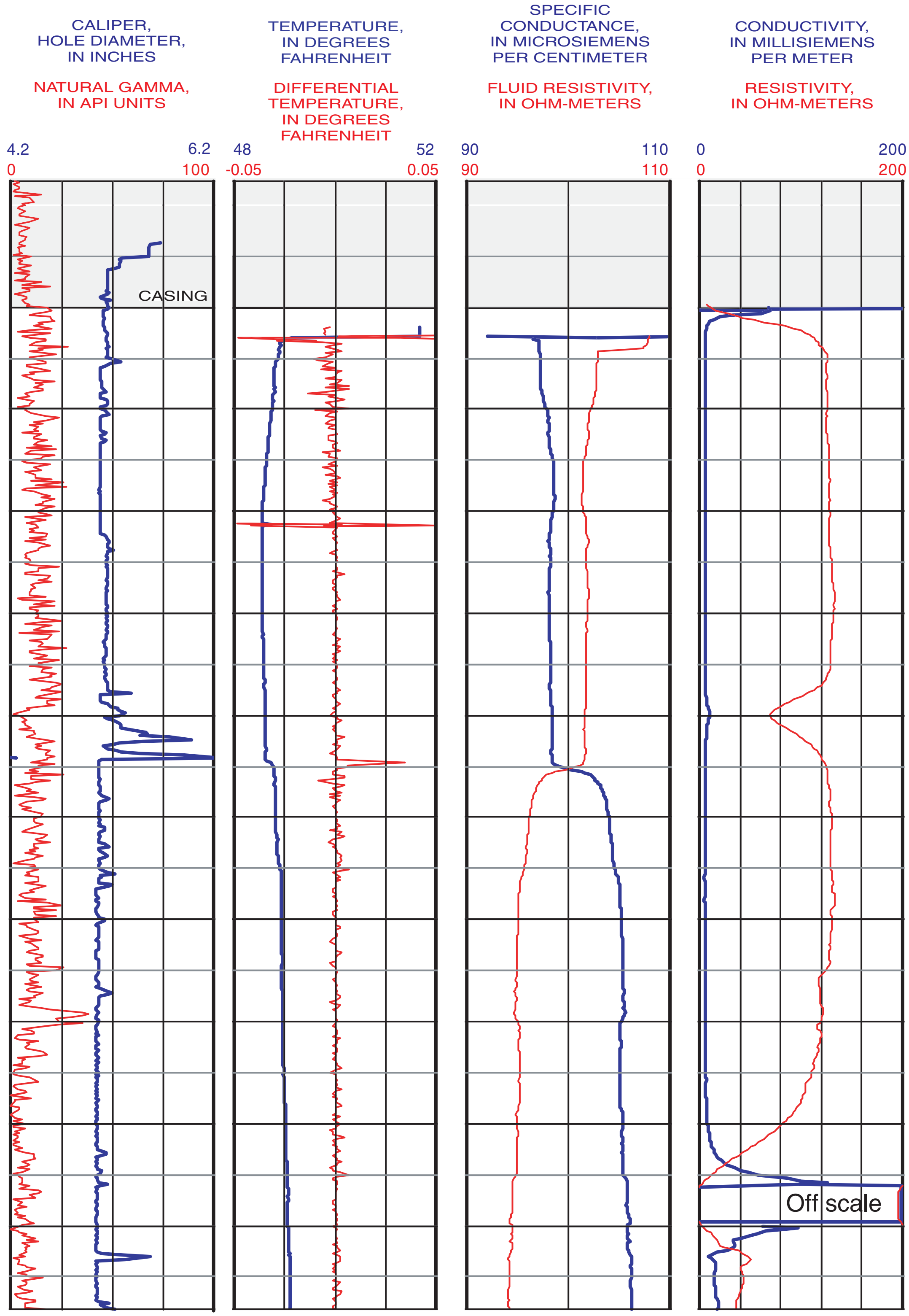

Figure 6. Conventional borehole-geophysical logs for MW109R, UConn landfill study area, Storrs, Connecticut.

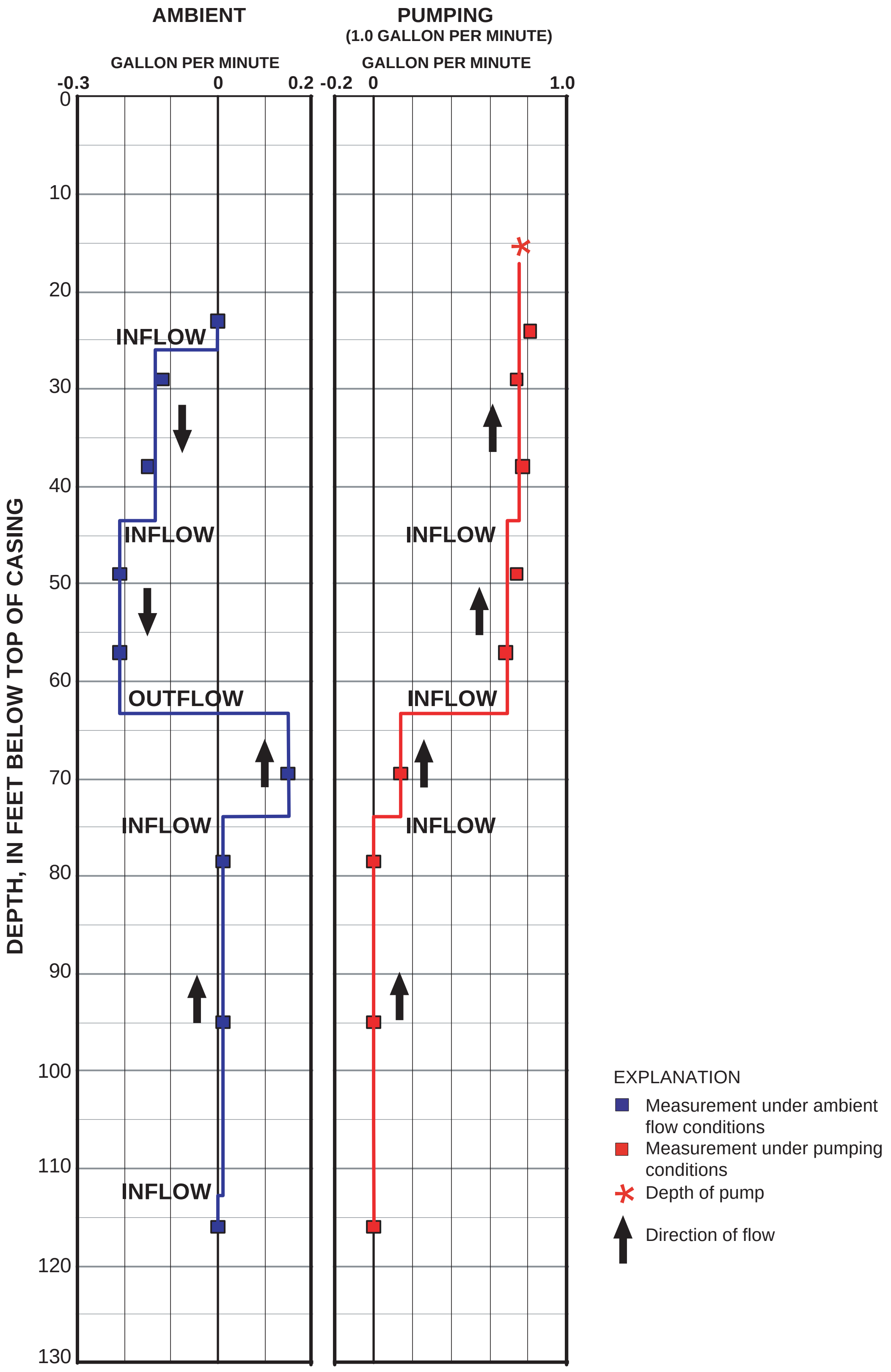

Figure 7. Heat-pulse flowmeter data from borehole MW109R in the UConn landfill study area, Storrs, Connecticut. Flow is shown under ambient (left) and pumping (right) conditions.

Borehole-radar reflectors. Ten reflectors were interpreted from the directional borehole-radar data (table 5). On the borehole-radar data shown in figure 8, reflections from steeply dipping structures are highlighted. The projected borehole intersection depth, strike, dip, estimated reflector length, and reflector continuity score for each interpreted reflector are listed in table 5. Because the radar method can image fractures and fracture zones that might not intersect the borehole, projected borehole intersection depths can exceed the drilled depth, or be negative indicating a projection to the borehole axis above land surface. The reflector continuity score is a qualitative measure of the strength and lateral continuity of a reflection. A score of 1 indicates the reflector is very distinct and continuous, whereas a score of 5 indicates the reflector is discontinuous. All of the reflectors in table 5 correlate with fractures observed in the OTV and ATV logs. The estimated length of the reflectors averages about 30 ft, ranging from 14 to 50 ft. Radar reflectors with cross-joint dips project to the transmissive zones near 62 and 113 ft.

Table 5. Location, orientation, and length of interpreted radar reflectors for borehole MW109R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity. Reflector continuity is on a scale of 1 (good) to 5 (poor)]

Projected borehole intersection depth, in feet below top of casing	Strike	Dip, in degrees	Estimated reflector length, in feet	Reflector continuity
25.6	N155°E	55	50	3
48.9	N175°E	46	29	3
60.0	N325°E	40	17	1
62.0	N295°E	45	20	1
62.7	N265°E	54	27	1
63.7	N125°E	55	28	1
75.5	N185°E	59	33	1
113.2	N305°E	36	37	1
113.2	N105°E	15	14	1
113.2	N105°E	40	43	1

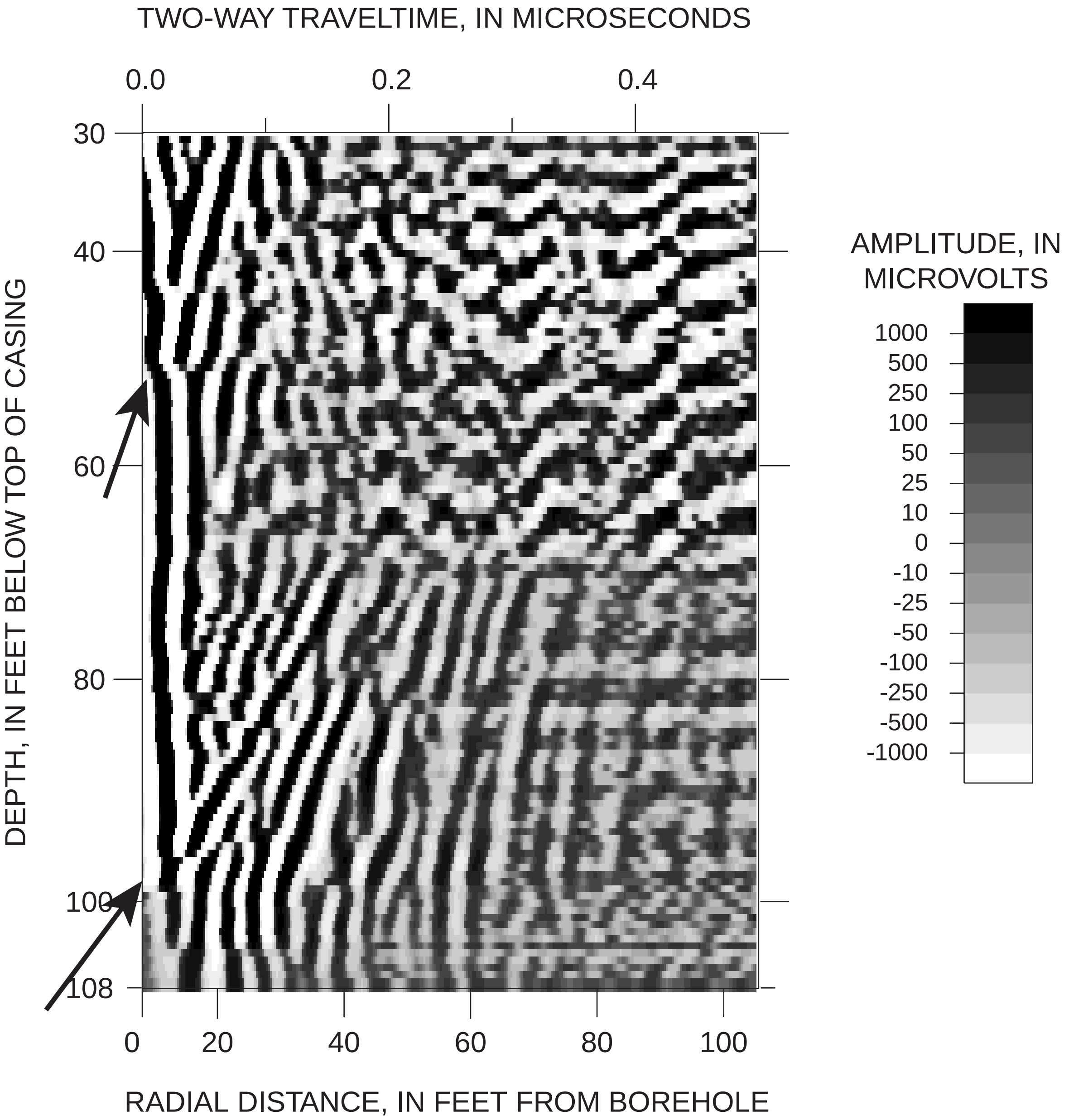

Figure 8. Processed borehole-radar log for borehole MW109R in the UConn landfill study area, Storrs, Connecticut. Reflections from steeply dipping structures are indicated with arrows. Radial distances are based on an average travel velocity of 372.4 feet per microsecond.

Borehole MW101R

Location and construction. MW101R is on the northwestern end of the landfill, between the landfill and the wetland that is part of Cedar Swamp Brook (fig. 1). This borehole was installed to identify potential leachate from the landfill and to define the hydrogeology in the northwest surface drainage from the landfill. MW101R has a total of 23 ft of 6-in. diameter steel casing. Below the casing, the hole is open to the bedrock to a depth of 127 ft below the top of casing. MW101R deviates about 4 ft towards the east. The ambient water level was 0.91 ft below the top of casing on August 1, 1999. All measurements are referenced to the top of casing, which is 0.7 ft above land surface.

Lithologic characterization. The borehole intersects schist and gneiss with layers of felsic porphyroblasts. Several rusty, weathered layers are evident near the top of the borehole and are interpreted to be sulfide-rich layers. In addition, narrow igneous dikes are present that are parallel to the foliation. The foliation is fairly uniform over the entire length of the borehole and strikes N283-317°E, dipping 3-24° to the northeast.

Fracture characterization. The fractures in the borehole are oriented in two fracture sets. One set strikes to the northwest and dips northeast, and the other strikes southwest and dips northwest. All of the transmissive fractures are in the northwest-striking set, oriented parallel to the foliation. Fracture orientations range from N346-7°E, 15-52° (E-NE). The orientations for the transmissive fractures are summarized in table 6, and stereoplots are provided in appendixes 3D and 4C.

Hydraulic characterization. Under ambient conditions, upflow was measured in borehole MW101R. Water enters the borehole at about 65.5 ft and flows upward at about 0.02 gal/min, exiting through two fractures around 35 ft. At this flow rate, approximately 29 gal/d flows through the borehole. Under low-rate pumping conditions of 0.5 gal/min, the majority of the water is produced by the fractures at 35 ft. The remainder of the water was produced from the fractures between 45 and 50 ft and at 65 ft.

The fluid-temperature log indicates possible flow at 25 and 65 ft under ambient conditions. The specific conductance log indicates the possibility for inflow at 65 ft. The specific conductance of the borehole fluids, which is approximately 65 mS/m, is higher than background levels around the landfill, but also is much lower than the conductivity observed at spikes in the EM-induction log at 36 and 42 ft. The EM-induction spike at 36 ft is 2,500 mS/m, whereas the spike at 42 ft is 1,400 mS/m. The EM-induction spike at 36 ft may coincide with the fractures near 35 ft; however, no fractures are present at 42 ft. The EM-induction spike at 42 ft coincides with rusty-red layers in the bedrock observed near 38 ft and from 41-49 ft, with the most oxidized zone at about 45 ft. The EM-induction anomalies are induced by sulfide minerals in these zones. When pumped at 1.0 gal/min for 1.2 hours, the specific capacity is 0.14 gal/min/ft. The open-hole transmissivity is 23 ft^2/d.

Table 6. Transmissive fractures in borehole MW101R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
34.6	1	N308°E	22	NE
35.4	1	N322°E	15	NE
44.5	2	N331°E	34	NE
45.2	2	N7°E	52	E
46.4	2	N339°E	29	E
47.5	2	N304°E	42	NE
65.1	3	N345°E	58	E
65.6	3	N346°E	16	E

Borehole-radar reflectors. Nine reflectors were interpreted from the directional borehole-radar data. Seven of the reflectors correlate with fractures observed in the OTV and ATV logs. The estimated length of the reflectors averages about 38 ft, ranging from 15 to 62 ft. The radar record for MW101R shows a zone of high attenuation and high conductivity near the top of the borehole from 36 to 42 ft. This zone coincides with the two major spikes in the EM-induction log. A reflector with an orientation of N305°E, 23° (NE) was observed in the radar log at 41.7 ft. Seven reflectors were interpreted to intersect the borehole between 40 and 50 ft. The reflector continuity ranges from fairly continuous to discontinuous. No radar reflectors correlate with the transmissive fractures at 35 and at 65.5 ft.

Two additional radar reflections were observed in the images. One feature, oriented at N205°E, 41° (NW) is projected to intersect the borehole at 122 ft. No corresponding fracture features are observed in the OTV and ATV logs. The other feature is projected to intersect the borehole 46.9 ft above land surface. The orientation of that feature is N205°E, 71° (NW). These reflectors do not coincide with foliation or bedding nor are they parallel to the transmissive fractures.

Temporary borehole liner installation. A borehole liner was installed in MW101R to prevent upward vertical flow of 29 gal/d from the fracture at 65 ft to the fracture at approximately 35 ft, thereby minimizing the potential for cross-contamination. The borehole liner was installed on September 21, 1999, removed on October 13, 1999, for water-quality sampling, and reinstalled on October 26, 1999.

Borehole MW103R

Location and construction. MW103R is a 6-in. diameter borehole cased in steel to a depth of 26.5 ft and completed to a depth of 130 ft below the top of casing. This borehole is on the northwest side of the landfill. MW103R deviates about 4 ft to the south. The water level was 11.6 ft below the top of the casing on August 24, 1999. All measurements are referenced to the top of casing, which was 1.0 ft above land surface.

Lithologic characterization. The borehole intersects alternating layers of gneiss and laminated schist whose foliation is fairly uniform over the entire borehole. The foliation is nearly horizontal and dips 7 to 24°. The strike and dip direction shows wide variation; however, it is difficult to accurately pick the strike of a nearly horizontal feature on the OTV, ATV, and radar logs.

Fracture characterization. Several sealed fractures were identified in the borehole from 26 to 79 ft. The strikes of the sealed fractures range from 10-90°E and 205-245°E and dip on average greater than 50° to the SE and NW, respectively. Another group of fractures strike N209-235° with a large range of dips. The transmissive fractures have variable orientations; however, the most steeply dipping fractures strike northeast-southwest, with dips ranging from 60 to 81° to the southeast and northwest (appendixes 3C, 3D, 4B, and 4B). The locations and orientations of the most transmissive fractures are listed in table 7.

Hydraulic characterization. Under ambient conditions, water enters the borehole at 30 and 33 ft, flows at 0.02 gal/min down the borehole, and exits at about 82 ft. At this flow rate, approximately 29 gal/d flows from the upper bedrock to a lower fracture zone through the open borehole. The fractures in the outflow zone were not evident in the ATV images; however, three fractures were observed in the OTV data near 82 ft.

Several fractures produce water under low-rate pumping conditions. At a pumping rate of 0.5 gal/min, about half of the water was produced at two fractures. About 0.20 gal/min of inflow was produced at 30 ft and 0.10 gal/min was produced at 33 ft. Minor amounts of inflow (0.03, 0.02, and 0.02 gal/min, respectively) were produced at 27, 50, and 119 ft. At a pumping rate of 1 gal/min, the majority of flow entered the borehole at the same fractures at 30 and 33 ft as at the lower pumping rate. In addition, minor inflow (of 0.03 gal/min) was produced near 43, 57, 65, 82, and 119 ft. After pumping MW103R at 1.0 gal/min for 1 hour, the water level declined 3 ft. The specific capacity was 0.33 gal/min/ft and the open-hole transmissivity was 62 ft^2/d.

Borehole-radar reflectors. Nine reflectors were interpreted from the directional borehole-radar data. Five of the reflectors correlate with fractures observed in the OTV and ATV logs. The estimated length of the reflectors averages about 26 ft, ranging from about 7 to 67 ft. In general, the reflectors in the borehole-radar images strike southwest and dip towards the northwest. This general orientation of the reflectors is parallel to the transmissive fractures observed at 33 and 50.7 ft. The borehole-radar data show a highly electrically conductive zone from about 38 to 62 ft. Three reflectors are interpreted in this conductive zone.

Table 7. Transmissive fractures in borehole MW103R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
30.7	1	N92°E	41	S
33.3	1	N209°E	60	NW
81.7	2	N109°E	41	S
82.4	2	N61°E	70	SE
82.4	2	N40°E	81	SE
119.2	3	N327°E	27	NE

These reflectors coincide with fractures that intersect the borehole at 43, 51, and 56 ft. The reflectors at 43 and 51 ft are fairly continuous in the radar record. The reflector at 56 ft is discontinuous and difficult to trace across the radar record. The orientation of the reflector at 115.5 ft (N315°E, 42° to the north) is close to the orientation of the transmissive fracture identified at 118-119 ft (N327°E, 27° to the north). No reflector was interpreted at the transmissive zone at 82 ft where the ambient flow exits the borehole. The closest feature to the 82-ft zone is a strong, continuous reflector with a center-point depth of 90.6 ft and an orientation of N165°E, 23° to the west, which is nearly parallel to the feature at 56.6 ft.

Temporary borehole liner installation. Under ambient conditions, about 29 gal/d would flow through MW103R. To prevent potential cross-contamination of fracture zones, a temporary borehole liner was installed upon completion of the geophysical logging. The borehole liner first was installed on September 23, 1999. It was removed for water-quality sampling on October 8, 1999, and reinstalled on October 14, 1999.

Borehole MW104R

Location and construction. This borehole was sited near the base of the landfill and the former chemical waste-disposal pits to provide information on water quality from these potential sources. MW104R is a 6-in. diameter borehole, cased with steel to 11.5 ft, and open to a depth of 128 ft below the top of casing. The borehole deviates about 6 ft to the southeast. The ambient water level was 20.70 ft below top of casing on August 31, 1999. All measurements are referenced to the top of casing, which was 0.9 ft above land surface.

Lithologic characterization. At the top of the borehole, above 60 ft, the foliation that intersects the borehole strikes north-northeast and dips steeply to the west. From 60 to 70 ft, the foliation gradually becomes subhorizontal striking south-southwest. Below 98 ft, the foliation strikes to the north-northeast and dips gently to the south-southeast. The fracture near 81 ft exhibits small scale offset. At about 99 ft, a small-scale offset is present in the fabric of the bedrock that occurs along a fracture that is oriented at N228°E, with a dip of 23° to the northwest.

Fracture characterization. The fractures observed in MW104R strike to the northeast and southwest (over the ranges of N29-76°E and N177-230°E) and dip 50 to 60° towards the southeast and northwest. Several sealed fractures, which were observed in the OTV images, intersect the borehole below about 80 ft. The sealed fractures (appendix 3C) steeply dip towards the southwest and cross-cut the foliation.

The orientations of the transmissive fractures are listed in table 8, and stereoplots are provided in appendixes 3D and 4C. The OTV and ATV data show an open-looking, near-vertical (84°), oxidized fracture that extends from about 80 to 85 ft. The upper portion of the fracture (between 80 and 82 ft) appears to be open on the ATV and OTV images, and the bottom portion of the fracture has a faint trace on the borehole images. Flowmeter logging indicates this fracture is transmissive and provides a pathway for fluid to exit the borehole under ambient conditions. The transmissive fractures near 24 and 45 ft are parallel or nearly parallel to the foliation. The other transmissive fractures are not related to the foliation.

Hydraulic characterization. Under ambient conditions, the water entered the borehole from a fracture near 24 ft below top of casing at a rate of 0.03 gal/min and exited the borehole near 81 ft. Inflow of 0.02 gal/min entered the borehole near 92 ft and exited the borehole at 108 ft. An alternative interpretation is that all flow entered the borehole near 24 ft and exited the well at 108 ft. This alternate interpretation implies that the three measurements between 81 and 92 ft had a poor seal with the borehole wall. At a pumping rate of 0.25 gal/min, half the water was produced from the fracture near 24 ft. Approximately 28 percent was produced from the fracture zone near 108 ft. The remaining flow was produced from the fractures near 81 and 45 ft. Using the alternate interpretation for flow under ambient conditions, half the water entering the well under pumped conditions comes from the fracture at 24 ft and the other half comes from the fractures near 108 ft. A specific capacity of 0.15 gal/min/ft was determined with a pumping rate at 0.25 gal/min for 1 hour, and the open-hole transmissivity was 26 ft^2/d.

Borehole-radar reflectors. Eight reflectors were interpreted from the directional borehole-radar data (appendix 6B). Six reflectors with projected intersection depths of 24, 33.8, 56.1, 57.1, 76.1, and 109.6 ft correlate with fractures observed in the OTV and ATV images. The estimated length of the reflectors averages about 67 ft, ranging from 19 to 114 ft. The reflector that projects to 24 ft has an orientation of N195°E, 62° to the west, which is similar to the fractures and foliation observed in the OTV log at 17.9, 21.7, 23.8 and 27.1 ft. The near-horizontal reflector at 109.6 ft may correspond to the transmissive fracture at 108.1 ft, which dips gently to the east. No radar reflectors correlate with the transmissive fractures at 45.6 and 80.6 ft. Reflections from these fractures could be masked by other reflectors or noise on the radar record, or could indicate that the lateral extent of these fractures is below the resolution of the radar tool.

Table 8. Transmissive fractures in borehole MW104R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
24.2	1	N174°E	54	W
45.6	2	N189°E	63	W
81.0	3	N320°E	84	NE
92.7	4	N220°E	26	W
108.1	5	N352°E	27	E
108.6	5	N25°E	81	SE

A reflector interpreted to intersect the borehole at 57.1 ft corresponds fairly well with a fracture identified in the ATV logging at 56.1 ft and the foliation observed in the OTV images. This reflector strikes to the south and dips westward. The length of this reflector is estimated at 54 ft. Although the strikes match, the dip of the fracture observed in the images of the borehole wall is 17° steeper than the dip of the interpreted trace of the radar reflector. The radar image reflectors extend over long distances, and the dip of these reflectors could vary appreciably over the short distance intersected by the borehole. Two reflectors that do not intersect the borehole are projected to intersect the borehole above the land surface. One reflector that would intersect the borehole 73 ft above land surface dips steeply (67°) towards the southeast. The length of this reflector is estimated at 114 ft. Another reflector is projected to intersect the borehole at 28 ft above land surface. This reflector strikes to the north-northeast and dips at 64° towards the southeast. The orientation of this reflector is parallel to the fractures observed at 108 and 82 ft in the OTV and ATV logs. The estimated length of the reflector is 74 ft.

Temporary borehole liner installation. At an ambient flow rate of 0.03 gal/min, about 36 gal/d would flow through MW104R. In order to prevent potential cross-contamination caused by flow between fracture zones, a temporary borehole liner was installed upon completion of the geophysical logging. The borehole liner was installed on September 14, 1999, removed for hydraulic testing and water-quality sampling on October 15, 1999, and reinstalled on October 21, 1999.

Borehole MW105R

Location and construction. MW105R was installed south of the landfill, adjacent to the intermittent tributary to Eagleville Brook. MW105R is a 6-in. diameter borehole, cased to 12.5 ft and completed at 126 ft below the bottom of the casing. The borehole location was selected to intersect an electrically conductive anomaly interpreted from the results of surface-geophysical surveys (Powers and others, 1999). MW105R deviates 4 ft towards the southeast. The ambient water level was 14.70 ft below the top of casing on August 10, 1999. All measurements are referenced to the top of casing, which was 2.4 ft above land surface.

Lithologic characterization. The rocks that MW105R intersect appear to be lighter in color and more felsic-rich than other boreholes in the study area. Also, many layers of garnets are present along primary layering in the gneiss, and locally, layers of porphyroblasts (large felsic minerals) are present in the gneiss. The layers are approximately 1-ft wide and are parallel to the foliation and primary layering in the gneiss. These features do not appear to have any signature in the conventional logs. The foliation in MW105R is nearly horizontal with dips that range from 2 to 29°. From 15 to 105 ft, the foliation strikes N320-350°E and dips 11 to 61° to the northeast.

Fracture characterization. Most of the fractures in MW105R are nearly parallel to the foliation (appendixes 3D, 3E, and 4C). A few fractures cross-cut the foliation and layering of the gneiss at high angles. The orientations of the transmissive fractures are listed in table 9. In the OTV logs, seven steeply dipping fractures partially intersect the borehole. These fractures were spread out over the borehole and dip in a variety of directions at 64 to 84° (appendixes 3 and 4).

Hydraulic characterization. No ambient flow was measured in MW105R with the heat-pulse flowmeter; however, the fluid conductivity indicated some zones that could be inflow zones. A large increase of 150 µS/cm in the specific conductance was present from 50 to 60 ft under ambient conditions. From 75 to 113 ft, the specific conductance declined to almost 400 µS/cm. The specific conductance log suggests the dissolved solids content of the water from the fracture at 74 ft is different from the fracture zone from 110 to 113 ft.

Specific conductance logs for MW105R showed a gradual dissipation of the high specific conductance in the open borehole after the well was drilled and before it was packed off with a borehole liner. MW105R was drilled on July 27, 1999. On July 29, 1999, under ambient conditions, specific conductance increased with depth, peaking at about 70 ft at 1,250 µS/cm, and gradually decreasing to 420 µS/cm at about 110 ft (fig. 9A). An additional specific conductance log, collected on August 31, 1999, indicates a dilution of the specific conductance. The dilution was caused by either pumping during flowmeter testing on August 15, 1999, or by minor ambient flow in the well.

On August 31, 1999, consecutive specific conductance logs were collected in MW105R while it was being pumped at 1.0 gal/min (fig. 9B). The logs indicate that water with a specific conductance of

370 µS/cm entered the well at about 110 ft and displaced the more conductive water above it. After 1 hour of pumping, the most conductive water in the borehole (650 µS/cm), which was adjacent to the fracture at 74 ft, reached the pump that was at about 34 ft. These logs indicate the lower fracture zone at 110 ft is more transmissive than the fracture zone at 74 ft. These logs also indicate that the water coming from the lower fracture zone is less electrically conductive than the water in the 74-ft zone. A water-quality sample collected from an isolated zone from 71.5 to 76.5 ft had a specific conductance of 810 µS/cm on October 13, 1999, whereas a sample from the zone from 108.5 to 112.5 ft had a specific conductance of 520 µS/cm (Haley and Aldrich, Inc. and others, 1999a).

Under pumping rates of 0.5 and 1.0 gal/min, the heat-pulse flowmeter indicates that the majority of water comes from the fracture zone at 109 to 113 ft. The remainder of the water was produced from fractures near 74 ft. At 1.0 gal/min, water may also be produced by the fracture at 90 ft. The transmissive fractures near 74, 110, and 113 are nearly horizontal and parallel to the foliation. The fractures at 90.3, 109.9, and 111.4 ft are not parallel to foliation, and the fractures at 109.9 and 111.4 appear to be nearly cross-jointed. The fracture at 90 ft is oriented at N295°E, 38° to the southeast. At a pumping rate of 0.5 gal/min, the specific capacity was 0.33 gal/min/ft after 1.2 hours. The open-hole transmissivity was 60 ft^2/d.

Borehole-radar reflectors. Eight reflectors were interpreted from the directional borehole-radar data (appendix 6B). Seven of the reflectors correlate with fractures observed in the OTV and ATV logs. The estimated length of the reflectors averages about 15 ft, ranging from 5 to 36 ft. The radar reflectors correlate with the fractures identified in the ATV logs at depths of 44, 55, 57, 66, 73, 109.9, and 110.2 ft.

Temporary borehole liner installation. Although no ambient flow was measured with the heat-pulse flowmeter in MW105R, water from the borehole has the highest measured specific conductance in the study area. Therefore, a borehole liner was installed over the entire length of the borehole to prevent any vertical flow in the borehole and minimize the potential for cross-contamination. The liner was installed on September 9, 1999, removed on October 7, 1999 for water-quality sampling, and reinstalled on October 26, 1999.

Table 9. Transmissive fractures in borehole MW105R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
73.6	1	N181°E	12	W
90.3	2	N29°E	38	SE
109.9	3	N149°E	32	SW
110.2	3	N314°E	8	NE
111.4	3	N334°E	57	NE
113.2	3	N183°E	6	W

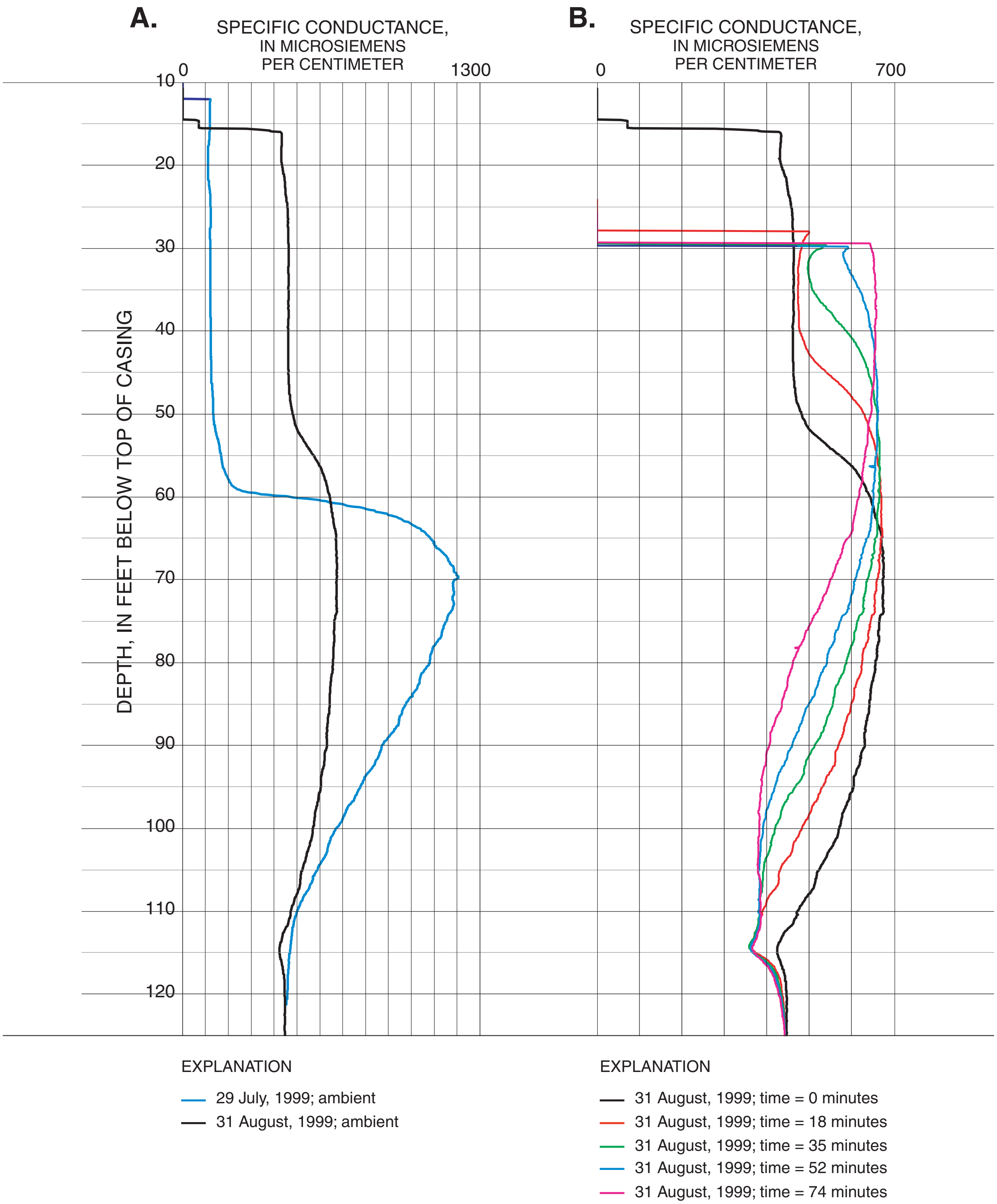

Figure 9. Specific conductance in borehole MW105R at the UConn landfill study area, Storrs, Connecticut.

A. Under ambient conditions on July 29 and August 31, 1999.
B. In response to pumping at 1 gallon per minute (individual logs shown for elapsed time in minutes from start of pumping).

Borehole MW121R

Location and construction. This borehole was sited just west of the landfill and the former chemical waste-disposal pits to intersect a planar conductive anomaly that was identified in surface-geophysical surveys by Powers and others (1999). The conductive feature was estimated to intersect the borehole at 60 ft, at the mid-point depth of the borehole. MW121R is a 4.5-in. diameter borehole, cased with steel to 11 ft, and is open to 130 ft below the top of casing. The borehole deviates a total distance of about 11 ft towards the southeast. The ambient water level was 26.11 ft below the top of casing on July 22, 1999. All measurements are referenced to the top of casing, which was 1.8 ft above land surface.

Lithologic characterization. The borehole intersects interbedded schist and gneiss. Near the top of the borehole, the rock is oxidized. In the bottom half of the borehole, the rock is garnetiferous and contains sulfide-rich layers, as indicated by the EM-induction and OTV logs (appendixes 1 and 3A). The foliation is uniform over the entire borehole and strikes N180-230°E and dips 10-30° to the northwest.

Fracture characterization. The fractures intersected by the borehole represent two sets. One set is parallel to the foliation and the other set appears to be sealed and strikes N180 to 231°E and dips 40-60° to the west. The transmissive fractures were identified under pumping conditions near 52 and 65 ft. Their orientations are listed in table 10, and stereoplots are provided in appendixes 3D and 4C.

Hydraulic characterization. No ambient flow was measured in MW121R with the heat-pulse flowmeter. Under pumping conditions, the borehole produces water at 52 and 65 ft. At a pumping rate of 0.5 gal/min, the specific capacity was 0.15 gal/min/ft. The open-hole transmissivity was 28 ft^2/d.

Borehole-radar reflectors. Four reflectors were interpreted from the directional borehole-radar data for MW121R (appendix 6). Three of the reflectors correlate with fractures observed in the OTV and ATV logs. The estimated length of the reflectors averages about 101 ft, ranging from 60 to 143 ft. Four zones of high radar attenuation are centered at 11, 55, 69, and 105 ft. These zones correlate with EM-conductivity anomalies identified on the EM-induction log. At 11, 55, 69, and 105 ft, the EM-induction log showed high conductivity spikes approaching 10,000 mS/m, which indicates the presence of sulfide minerals in the rock. Some sulfide minerals were noted in the rock cuttings, consistent with iron sulfide layers reported in the bedrock (Fahey and Pease, 1977). Although the spikes do not coincide with the fractures intersecting the boreholes at these depths, radar reflectors still can be identified in some of the high-attenuation zones. For example, the electromagnetic spike at 55 ft coincides with a radar reflection that strikes N205°E, 46° to the west.

Table 10. Transmissive fractures in borehole MW121R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
51.9	1	N202°E	39	W
64.7	2	N199°E	24	W

Borehole MW122R

Location and construction. MW122R was drilled near the former chemical waste-disposal pits. This borehole is west of MW104R and MW123SR. MW122R is a 6-in. diameter borehole, cased with steel to a depth of 11.3 ft. The borehole was drilled to a total depth of 128 ft below top of casing. MW122R deviates to the southeast about 2.5 ft. The ambient water level was 19.76 ft below the top of casing on August 13, 1999. All measurements are referenced to the top of casing, which was 2.4 ft above land surface.

Lithologic characterization. The borehole intersects interbedded garnet-rich gneiss, schist, and layers of porphyroblasts (large felsic minerals). The contacts between the gneiss and schist are gradual, whereas the porphyroblast layers are sharp. The foliation dips are fairly shallow over the entire range of the borehole. The foliation strikes N199-212°E and dips 18-43° towards the west from the bottom of casing to 56 ft. From 56 to 115 ft, the foliation strikes N358-28°E and dips 4-43° to the east. Below 115 ft to the bottom of the borehole, the foliation strikes N182-205°E and dips 17-28° to the west.

Fracture characterization. In general, the fracture orientations strike north-south and dip east and west. The sealed fractures and minor fractures (appendix 3D) that were observed in the OTV log were nearly vertical. They strike about N55°E and N235°E and dip towards the southeast and northwest. Two of the transmissive fractures (table 7, appendixes 3D and 4C) at 62 and 57 ft are considerably steeper than the foliation and are neither foliation nor unloading or sheeting fractures, that generally are parallel to the land surface. The other transmissive fracture at 58 ft is parallel to foliation.

Hydraulic characterization. No ambient flow was measured in the borehole; however, the fluid-resistivity log indicates a minor change in total dissolved solids at depths of 40 and 60 ft, which may indicate flow with a magnitude that is less than the resolution of the heat-pulse flowmeter tool. Under pumping conditions, two productive zones were identified in the borehole near 61.5 and 57 ft. A specific capacity was not calculated for this borehole because the drawdown did not stabilize under pumping conditions.

In the absence of a measurable ambient flow, a second fluid conductivity log was collected after pumping. A comparison of the specific conductance logs collected under ambient conditions and in response to pumping stress can help identify the fractures that contributed water to the borehole. The logs in figure 10 indicate after pumping at 0.5 gal/min for about 75 minutes, more conductive water entered the borehole at about 62 ft and moved upward toward the pump, but was diluted by water that entered the borehole at 57-58 ft. In addition, the conductive water mixed with the water below 62 ft. This mixing probably took place during the time between pumping and logging.

Borehole-radar reflectors. Eight low-amplitude and discontinuous reflectors were interpreted from the directional borehole-radar data in MW122R. Based on orientation, the radar reflectors can be grouped into three sets: (1) southwest-striking and steeply dipping to the northwest, (2) north- to northeast-striking steeply dipping to the east, and (3) nearly horizontal. There is little correlation between radar reflectors and transmissive fractures in this borehole, except for a near-horizontal reflector projected to intersect MW122R at 61 ft, the depth of the most transmissive fracture. The dip of the fracture interpreted from the OTV and ATV high-resolution borehole imagery, however, is much steeper (63°).

Temporary borehole liner installation. Upon completion of the geophysical logging, a temporary borehole liner was installed to prevent potential cross-contamination of fracture zones. The borehole liner was installed on August 31, 1999, removed for hydraulic testing and water-quality sampling on October 7, 1999, and reinstalled on October 31, 1999.

Table 11. Transmissive fractures in borehole MW122R in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
57.2	1	N257°E	70	NE
58.3	1	N350°E	15	E
62.3	2	N200°E	64	W

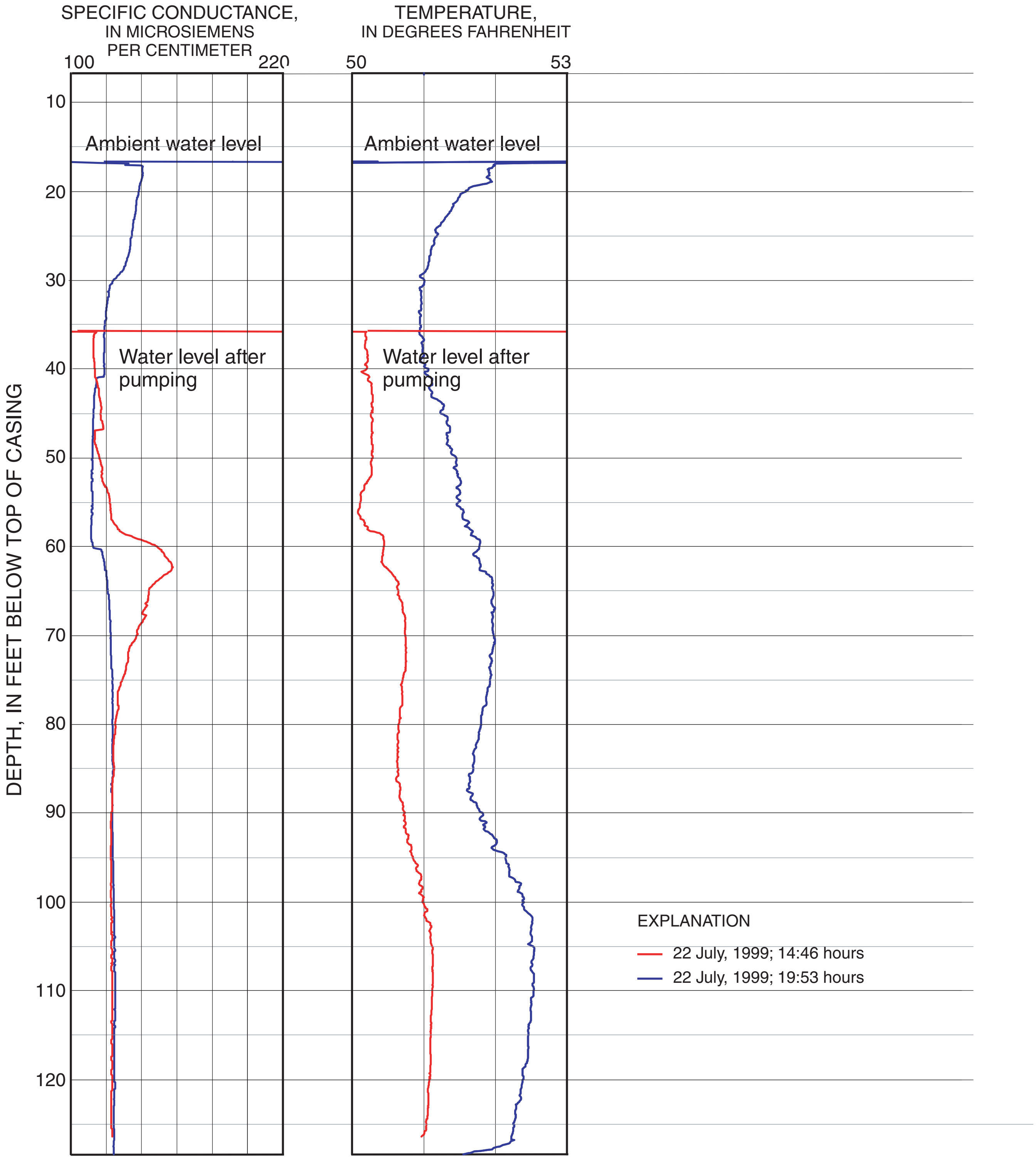

Figure 10. Specific conductance and temperature in borehole MW122R at the UConn landfill study area, Storrs, Connecticut. Ambient conditions after pumping are shown in blue. Response to pumping at 0.5 gallon per minute for 75 minutes is shown in red.

Borehole MW123SR

Location and construction. MW123SR is a shallow bedrock borehole that was installed at the site of the former chemical waste-disposal pits. It is a 6-in. diameter borehole that is cased with steel to 11.4 ft, and completed in bedrock to 44 ft below top of casing. In the middle of the summer of 1999, during a severe regional drought, the water level in this borehole was approximately 40 ft below the top of casing. In August when the ATV logging was performed, the water level was 26 ft below the top of casing. Because the ATV tool requires water in the borehole, the ATV was unable to survey the borehole above the water level. However, the OTV, which does not require water in the borehole, provided images above and below the water surface. All measurements are referenced to the top of casing, which was 2.8 ft above land surface.

Lithologic characterization. The foliation in this borehole strikes approximately N210°E and dips gently (20-30°) to the northwest. The bedrock is fine-grained gneiss with some laminations and felsic bands.

Fracture characterization. The OTV images show a fracture extending from the base of casing to 13.5 ft. The images show water seeping from the fracture into the borehole (appendix 3C). The transmissive fracture at the top of the borehole cross-cuts the foliation, whereas the fracture at 34.5 ft is parallel to the foliation (table 12).

Hydraulic characterization. When the borehole was pumped at a rate of 0.25 gal/min, the water level steadily declined until it dropped below the pump intake, so heat-pulse flowmeter measurements could not be made under pumping conditions. The fluid resistivity and fluid temperature logs show a minor deflection at 34.5 ft. This deflection suggests the possibility of a transmissive fracture at that depth. On October 21, 1999, inflow was observed in the OTV log from the fracture at 12.5 ft, which was above the water level. The orientations of the minor transmissive fractures are listed in the table 12.

Borehole-radar reflectors. This borehole was too shallow to permit logging with the borehole radar.

Temporary borehole liner installation. Because of the shallow depth of the borehole, no borehole liner was installed.

Table 12. Transmissive fractures in borehole MW123SR in the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal
The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
12.5	1	N115°E	74	SW
34.5	2	N212°E	24	NW

Hydrogeologic Characterization of Domestic Wells

Three domestic wells along Hunting Lodge Road were logged to determine the lithology, fractures, and hydraulic properties for comparison with the characterizations of the boreholes near the landfill.

Domestic Well W80, Hunting Lodge Road

Location and construction. W80 is a privately owned well that was drilled in 1979 and used for a domestic supply until the UConn water supply was provided in 1998. W80 is cased with 6-in. steel to 40.5 ft, and open to 125 ft from the top of casing. This well deviates less than 1.5 ft towards the southeast. The ambient water level was 15.38 ft below the top of casing on September 23, 1999. All measurements are referenced to the top of casing, which was 1 ft above land surface.

Lithologic characterization. W80 intersects fine- to coarse-grained schist and gneiss with felsic layers (appendix 3A). Minor pegmatite dikes and garnet-rich zones are present in the borehole. The orientation of foliation is fairly uniform over most of the well, striking southwest and dipping moderately to the west. From 55 to 80 ft, the foliation strikes south-southeast and dips from 7 to 34° to the south-south-west.

Fracture characterization. The transmissive fractures are listed in table 13. The orientations of the transmissive fractures at 75.3, 86.5, and 108.5 ft are very different from the foliation (appendix 3B). The orientation of the transmissive fracture at 75 ft is parallel to the thrust fault between the landfill and W80 (Fahey and Pease, 1977).

Hydraulic characterization. Under ambient conditions, water enters W80 at depths of approximately 75 and 86 ft and flows downward at 0.04 gal/min to 108.5 ft where it exits the well. At this flow rate, about 58 gal/d flow into and out of the well. Under pumping rates of 0.25 and 0.5 gal/min, water is produced from fractures at 108.5, 86, 75, and 52 ft. The majority of the water (about 80 percent) is produced from the fracture at 108.5 ft. At a pumping rate of 0.5 gal/min, the specific capacity is 1.6 gal/min/ft after 1.2 hours. The open-hole transmissivity is 344 ft^2/d.

Borehole-radar reflectors. Five reflectors were interpreted from the directional borehole-radar data (appendix 6). Three of the reflectors correlate with fractures observed in the ATV and OTV logs. The estimated length of the reflectors averages about 23 ft, ranging from 2 to 35 ft. The reflector at 85.6 ft is the only one that correlates with a transmissive zone. This reflector is steeply dipping, with a north-northeast strike (N55°E, 73° to the southeast).

Table 13. Transmissive fractures in domestic well W80 near the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
51.7	1	N223°E	27	NW
75.3	2	N87°E	73	S
86.5	3	N56°E	73	SE
108.5	4	N333°E	27	NE

Domestic Well W125, Hunting Lodge Road

Location and construction. W125 is an abandoned domestic well that was used until approximately 1985. The top of the 6-in. diameter casing, which is inside of a 3-ft diameter cement casing, is 5 ft below land surface. Consequently, the depth of the geophysical logs was referenced to the top of the cement casing. The 6-in. steel casing extends to a depth of approximately 44 ft below the cement casing. The total depth of the well is 132 ft. The borehole deviation is less than 1 ft from vertical. The ambient water level was 20.4 ft below the top of casing on October 4, 1999. All measurements are referenced to the top of cement casing, which was 0.1 ft above land surface.

Lithologic characterization. The general quality of the OTV images is poor, because the borehole walls are coated with iron-oxide precipitate. Thus, the images are dark, particularly at the top of the well. Analysis of the OTV images indicates the foliation in W125 is uniform over the entire length of the well. The foliation strikes southwest and dips moderately to the northwest (N296-338E°, 33-55° to the northwest). The foliation mapped in W125 agrees with the mapped foliation from a nearby outcrop (Fahey and Pease, 1977).

Fracture characterization. Most fractures in the well were parallel to the foliation. As seen in the stereoplots (appendixes 3D and 3E), other fractures are present that dip steeply and cross-cut the foliation. The transmissive fractures and their orientations are listed in table 14. The fractures at 71 and 81.5 ft parallel the foliation, whereas the fractures at 60.5 and 89 ft cross-cut the foliation.

Hydraulic characterization. Under ambient conditions, the heat-pulse flowmeter logs indicate that water enters the well at a depth of 81.5 ft. The water flows upward, exiting the well at the fracture at a depth of 60.5 ft. Under pumping conditions, water enters the well at 60.5, 71, 81.5, and 88 ft. The fractures at 71 and 81.5 ft produce about the same amount of inflow. At a pumping rate 0.75 gal/min for 0.7 hours, the specific capacity is 0.82 gal/min/ft. The open-hole transmissivity is 160 ft^2/d.

Borehole-radar reflectors. Ten reflectors were interpreted from the directional borehole-radar data (appendix 6). Five of the reflectors correlate with fractures observed in the OTV and ATV logs. The estimated length of the reflectors averages about 47 ft, ranging from 22 to 83 ft. The top interval of W125 (30 to 40 ft) is conductive and attenuates the propagation of the radar. None of the radar reflectors correlate with transmissive zones; however, one reflector that projects to intersect at 207.7 ft (below the drilled depth of the well) has an orientation parallel to the transmissive fracture at 60.5 ft.

Table 14. Transmissive fractures in domestic well W125 near the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zone	Strike	Dip, in degrees	Direction of dip
60.5	1	N32°E	52	SE
71.0	2	N228°E	48	NW
81.5	3	N211°E	55	NW
88.8	4	N81°E	66	S

Domestic Well W156, Hunting Lodge Road

Location and construction. W156 is a privately owned well that was drilled in 1977 and used for a domestic supply until the UConn water supply was provided in 1985. The well is cased to about 17 ft with a total depth of 248 ft. W156 has a total deviation of 14 ft towards the southeast. The ambient water level was 22.84 ft below the top of the casing on September 20, 1999. All measurements are referenced to the top of casing, which was 0.7 ft above land surface.

Lithologic characterization. W156 intersects schist and gneiss that appear oxidized and altered (appendix 3A). Foliation is fairly uniform over the length of the well. Most of the foliation strikes N240 to 317°E and dips 0 to 47° to the northwest. Other foliation in the well strikes N66 to 82°E with shallow dips of 7 to 22° towards the south-southeast.

Fracture characterization. Ninety-one fractures were identified in the OTV log for W156. The nine largest fractures have one of the following three orientations: (1) southwest-striking, steeply dipping to the northwest, (2) southeast-striking and nearly vertical, and (3) northwest-striking with a shallow dip. Another set of 13 fractures was described as “sealed.” These fractures plot near the outside of the stereoplot, indicating they are steep. Most of these fractures strike N71 to 107°E and dip 38 to 77° towards the northwest. The sealed fractures are in the lower part of the well below 125 ft. The remaining 69 fractures are described as minor or possible fractures. It is possible that some of these fractures are sealed. The minor fractures have a range of orientations. The orientation of the transmissive fractures is listed in table 15.

Hydraulic characterization. There was no measurable flow under ambient conditions in W156. The profiles for fluid temperature and specific conductance were characterized by minor changes in the fluid temperature and specific conductance at 65 ft, uniform fluid temperature and specific conductance between 65 and 147 ft, and gradually increasing fluid temperature below 147 ft. This pattern suggests minor ambient flow between 65 and 147 ft that is less than the resolution of the heat-pulse flowmeter tool. The zone at 147 ft has a high gamma signature, indicating the possibility of alteration at the fracture zone near 147 ft.

Under a 0.25-gal/min pumping rate, minor inflow was produced from zones at 48, 134, and 146 ft. Under pumping rates of both 0.25 and 0.5 gal/min, water was produced near 147 ft. Also, a major increase in the upflow was detected between the measurements at 132 and 136 ft. This increase would be interpreted as inflow between 132 and 136 ft; however, no fractures were observed in the ATV data at this depth, and an apparently sealed fracture was observed in the OTV log at 133 ft. It is possible that leakage occurred between the flowmeter tool and the borehole wall in the measurement at 136 ft, allowing some flow to bypass the flowmeter measurement chamber. Assuming leakage at 136 ft implies that all the flow came from the large fracture near 147 ft. Under pumping conditions, the wide, oxidized fracture at 65 ft did not contribute inflow to the well. This may indicate a leakage problem at the time of the heat-pulse flowmeter measurement, because the specific conductance log indicates the 65-ft zone is transmissive. The transmissive fracture at 48 ft is nearly horizontal and parallel to the foliation. The transmissive fractures from the zones at 133.7 and 146.5 ft have strikes similar to the upper transmissive zone but are more steeply dipping. The specific capacity and open-hole transmissivity could not be calculated for this well because of problems with the pumping test.

Borehole-radar reflectors. Fourteen reflectors were interpreted from the directional borehole-radar data. Seven of the reflectors correlate with fractures observed in the OTV and ATV logs. The estimated length of the reflectors averages about 71 ft, ranging from 22 to 162 ft. Radar reflectors project near the depths of the transmissive zones near 65 and 147 ft. Three steeply dipping reflectors project above and below the drilled depths of the well. These reflectors trend north-northeast, with cross-joint dips.

Table 15. Transmissive fractures in domestic well W156 at the UConn landfill study area, Storrs, Connecticut

[Strike is reported in right-hand-rule in degrees E of True North. The dip is degrees from horizontal. The compass descriptor (N-E-S-W) of the direction of dip is provided for convenience and clarity]

Depth, in feet below top of casing	Transmissive fracture zones	Strike	Dip, in degrees	Direction of dip
47.8	1	N200°E	29	W
133.7	2	N229°E	73	NW
146.5	3	N228°E	51	NW

Characterization of Unconsolidated Glacial Deposits

Twenty-one shallow piezometers (table 2) were logged with gamma and EM-induction tools to delineate unconsolidated glacial deposits. The correlation of gamma and EM-induction logs with lithologic units that were identified in continuous split-spoon sampling and recorded in the drilling logs is poor (Haley and Aldrich, Inc. and others, 1999a). Glaciofluvial, glaciolacustrine, and till deposits could not be distinguished in the gamma or EM-induction logs. This may be because the units are not sufficiently thick for the tool to measure the change in conductivity, or because the difference in conductivity between the two adjacent units is not large. The logs are shown for three selected piezometers in appendix 8.

INTEGRATION OF BOREHOLE- AND SURFACE-GEOPHYSICAL RESULTS

Powers and others (1999) identified a dipping anomaly in the 2D dc-resistivity surveys collected on the west side of the UConn landfill. MW121R was located to intersect this anomaly at about 60 ft below ground level. The EM-conductivity log in MW121R contains a high electrical-conductivity anomaly at 69 ft. The magnitude of this anomaly is nearly 10,000 mS/m, indicative of a lithologic feature, and coincides with a layer containing sulfide mineralization, rather than fractures. The nearest fractures in the borehole and the fluids in the borehole adjacent to the EM spikes are not electrically conductive. The lack of high specific conductance in the fluids in the borehole further supports the interpretation that the electrically conductive unit detected by Powers and others (1999) and the feature imaged in the borehole-radar log is related to a lithologic change.

A second surface-geophysical anomaly that was identified by Powers and others (1999) southwest of the landfill is a north-south trending, west-dipping feature. Borehole MW105R was positioned to intersect this conductive feature in the middle of the borehole at about 60 ft. A south-striking, west-dipping (N185°E, 21°) feature was identified in the radar log of MW105R at 57.1 ft, which is coincident with a fracture in the ATV log. Another feature at 74 ft strikes south and dips gently west (N181°E, 12°). It 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. The location and orientation of this conductive feature generally matches the surface-geophysical anomaly identified by Powers and others (1999).

The response of the electromagnetic 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 74 ft is too high to be attributed solely to the specific conductance of the fluids. The specific conductance of the fluid measured near these fractures was as high as 1,250 µS/cm. Water-quality samples collected in October 1999 from an isolated zone from 71.5 to 76.5 ft indicated high specific conductance (810 µS/cm), high concentrations of iron and cadmium, negative oxidation-reduction potential, and chlorobenzene (Haley and Aldrich, Inc. and others, 1999a). Collectively, these parameters indicate that the high specific conductance in borehole logs for MW105R was caused by landfill leachate. Therefore, the anomaly at 74 ft identified by borehole- and surface-geophysical surveys is interpreted as a conductive lithologic feature and a permeable fracture zone containing landfill leachate.

SUMMARY AND CONCLUSIONS

In 1999, the USGS, in cooperation with the University of Connecticut, conducted a borehole-geophysical investigation of the fractured-bedrock aquifer near the UConn landfill. Borehole-geophysical methods were used to characterize the hydrogeology of the fractured-bedrock aquifer and the distribution of unconsolidated glacial deposits in the vicinity of the UConn landfill and former chemical waste-disposal pits. The data were collected from June to October 1999. Eleven boreholes ranging in depth from 40 to 242 ft were logged to characterize the hydrogeology of the bedrock underlying the landfill and vicinity. Conventional geophysical-logging methods included caliper, gamma, fluid temperature, fluid resistivity, and electromagnetic induction; and advanced geophysical-logging methods included deviation, optical- and acoustic-borehole imaging, heat-pulse flowmeter under ambient and pumped conditions, and single-hole directional radar.

Twenty-one shallow piezometers were logged with gamma and EM-induction tools to delineate unconsolidated glacial deposits. Because of the short borehole lengths and the distance needed for a full tool response, no correlation was established between the geophysical logs and the description of the geologic materials that were sampled at the time of drilling. Conventional geophysical logs were used to determine well construction.

High-resolution continuous images from the OTV show rock units similar to those described by previous investigations. The gneiss and schist are characterized by quartz-feldspar-biotite-garnet and locally by sulfide-rich layers. High electrical-conductivity zones measured by the 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. However, the orientation of the foliation and the layering in the rock varies with depth in some of the boreholes and locally throughout the study area (fig. 11). In boreholes MW105R and MW109R, the foliation strikes predominantly to the northwest and dips to the northeast. These results are consistent with local outcrop observations (Fahey and Pease, 1977). In well W125, the foliation strikes southwest and dips moderately to the northwest, which agrees with foliation mapped in nearby outcrops. Although small scale faulting and discontinuities were observed in the OTV data, no larger scale faults, such as those mapped by Fahey and Pease, were observed in the borehole data.

The heat-pulse flowmeter was used to measure vertical flow in the boreholes under ambient and (or) pumped conditions. The OTV, ATV, and conventional logs were used to locate and characterize the transmissive zones in the boreholes. Ambient downflow was measured in three boreholes, ambient upflow was measured in two other boreholes, and both ambient downflow and upflow were measured in a sixth borehole. The highest rate of ambient flow was measured in the background well (MW109R), in which upflow (0.03 gal/min) and downflow (-0.21 gal/min) converged and exited the borehole at the fractures near 62 ft. At this ambient flow rate, about 345 gal of water flow through the borehole each day. Ambient downflow occurs in MW103R at the rate of -0.02 gal/min, in MW104R at -0.025 gal/min, and in the well at 80 Hunting Lodge Road at -0.04 gal/min, which correspond to about 29, 36, and 58 gal/d, respectively. Ambient upflow occurred in MW101R (0.020 gal/min or 29 gal/d) and in the well at 125 Hunting Lodge Road (0.016 gal/min or 23 gal/d). No ambient flow was measured using the heat-pulse flowmeter in MW105R, MW121R, and MW122R. To prevent vertical flow and potential cross-contamination, temporary borehole liners were installed in MW101R, MW103R, MW104R, MW105R, and MW122R.

Under low-rate pumped conditions, one to six inflow zones were identified in each borehole. The amount of flow in each zone that was induced by pumping was proportioned by the pumping rate. In the presence of ambient flow, the computed flow rates were compensated for inflow and outflow prior to proportioning the inflow. Typically, the fractures that are active under ambient conditions contribute to the borehole under pumping conditions.

Specific-capacity and open-hole transmissivity values were determined in eight boreholes. When pumped at 0.25 to 1.3 gal/min for 0.7 to 1.3 hours, specific capacity ranged from 1.6 to 0.14 gal/min/ft. Values for open-hole transmissivity range from 23 to 340 ft^2/d, and when proportioned to individual fracture transmissivity, they range over 4 orders of magnitude.

Hundreds of fractures were observed in the boreholes. Some fractures are parallel to the foliation; others are not. The fracture orientations vary in both strike and dip, and collectively appear to be scattered. The orientation of transmissive fractures, however, is fairly uniform across the site (figs. 12A and B). A lower hemisphere equal-area projection (stereogram) of the poles to fracture planes reduces the 3D plane to a point. Fractures from a single fracture set plot together in a cluster on the stereogram. Three sets of poles to planes were indicated in the stereographic projection (fig. 12B). Two clusters are in conjugate sets that strike nearly N-S and dip gently E and W. Many fractures in these sets show very low magnitude dips, which may be caused by the measurement error inherent in the measurement of shallow dipping features. This pattern of fracturing is very common for fractures that are parallel to foliation in a region that has been subjected to folding (T.R. Armstrong, U.S. Geological Survey, oral commun., 2000). The third fracture set strikes nearly east-west and dips steeply to the south. The transmissive fractures shown in figures 12A and B strike N140°E, N170°E, N210°E, and N320°E. The transmissive fractures in the three abandoned domestic wells on Hunting Lodge Road show more variation than the wells at the landfill. In W80, the transmissive fractures strike N60°E, which is parallel to the trend of the thrust fault mapped between the well and the landfill (Fahey and Pease, 1977). This strike is similar to transmissive fractures in MW101R, MW103R, and W125. The interpreted orientations of radar reflectors are similar to the orientations of the transmissive fractures.

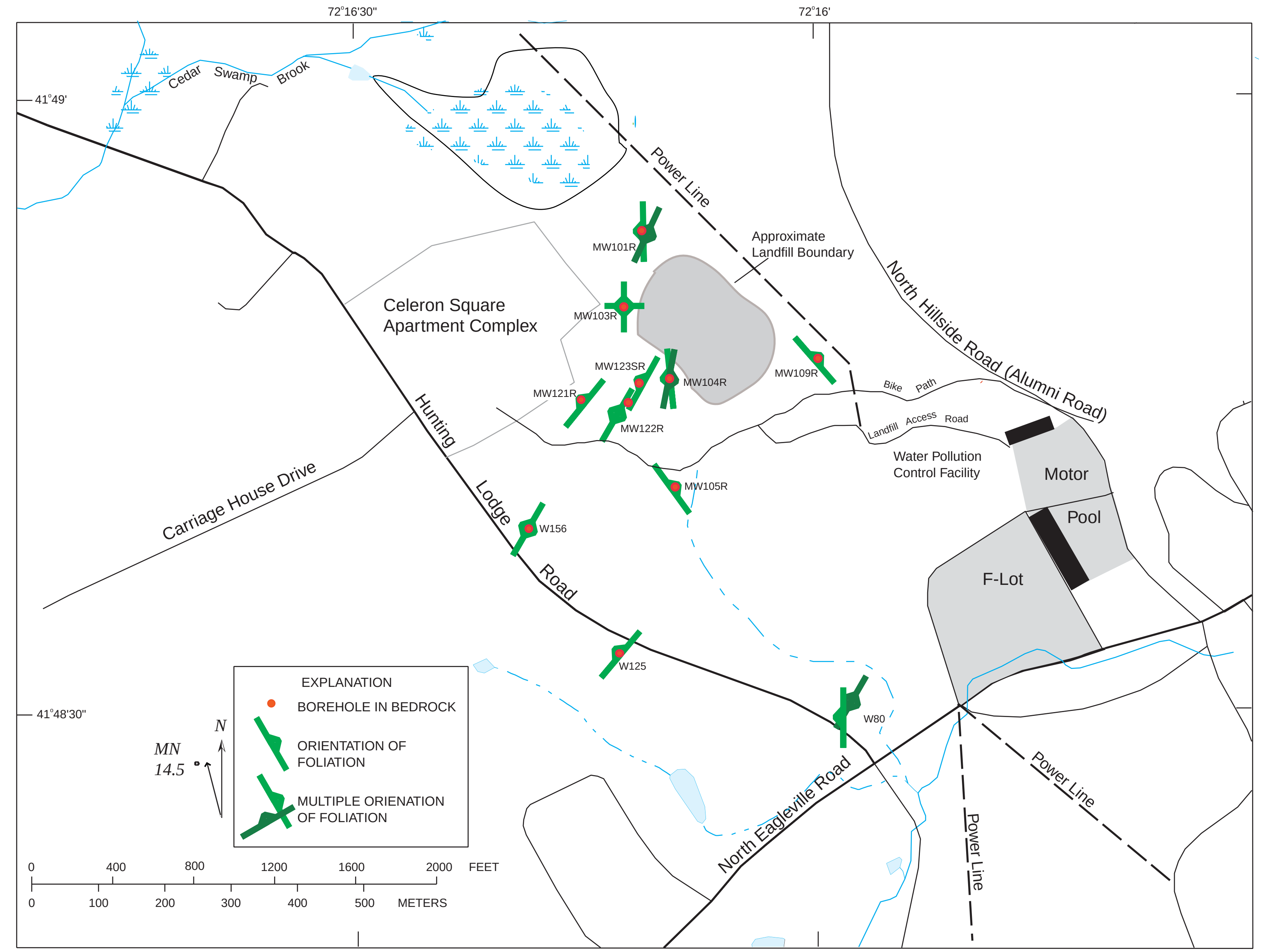

Figure 11. Orientation of foliation in bedrock boreholes at the UConn landfill study area, Storrs, Connecticut.

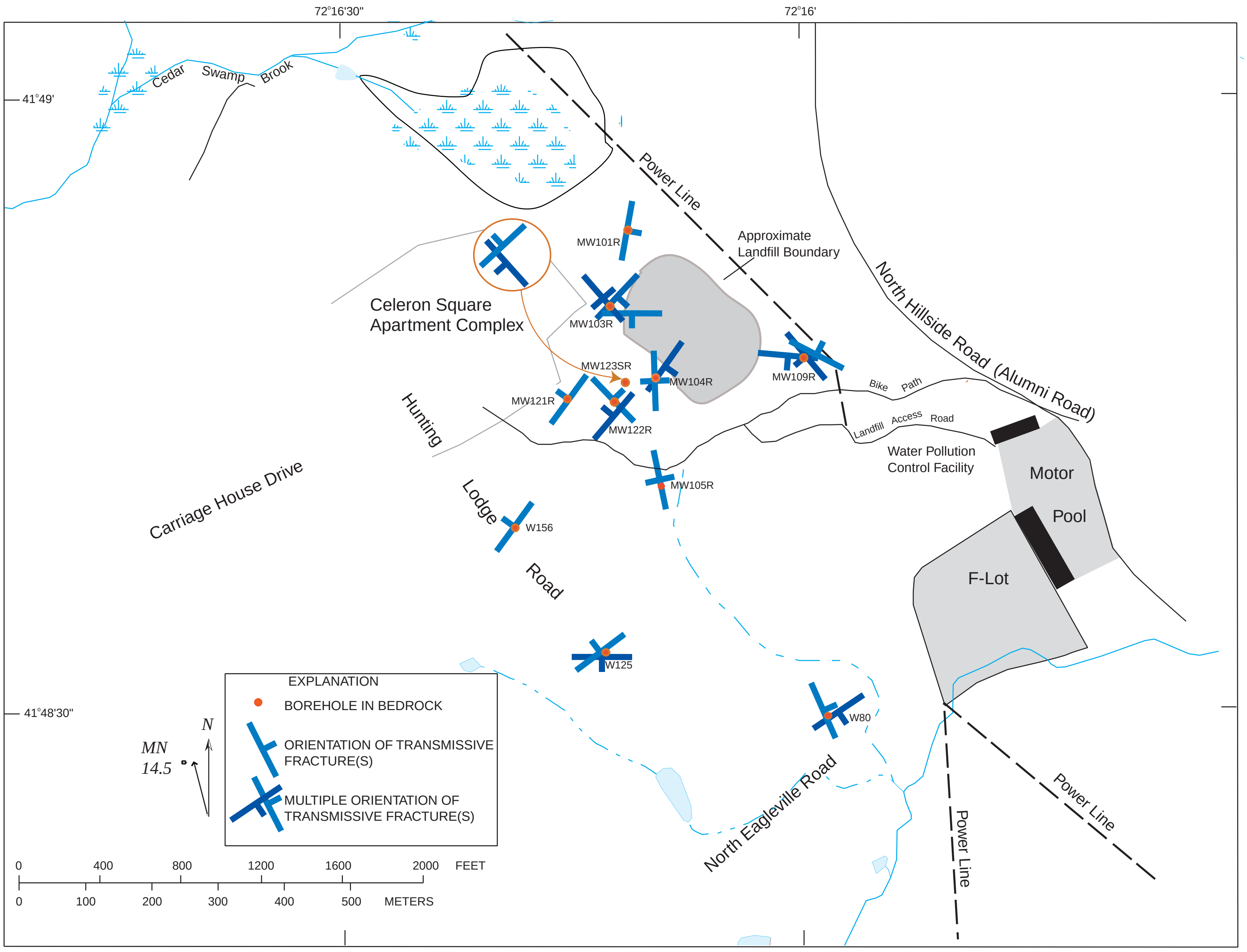

Figure 12A. Orientation of transmissive fractures in bedrock boreholes at the UConn landfill study area, Storrs, Connecticut.

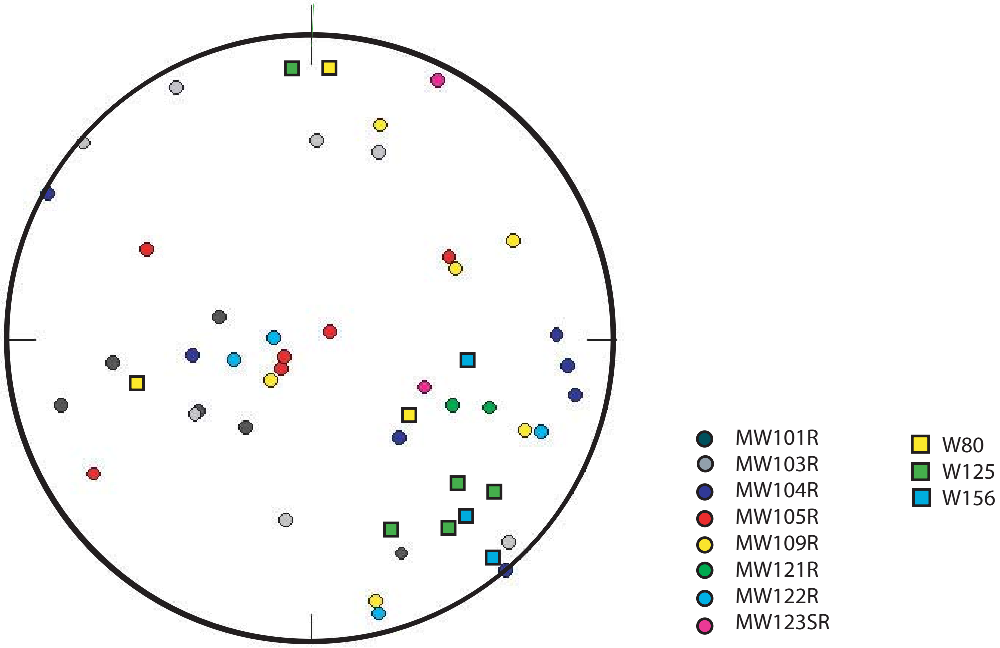

Figure 12B. Lower-hemisphere equal-area projection (stereoplot) showing poles to planes of transmissive fractures in bedrock boreholes in the UConn landfill study area, Storrs, Connecticut.

The borehole-geophysical results verified the interpretations of a previous surface-geophysics investigation that identified a dipping anomaly in the 2D dc-resistivity survey collected on the west side of the landfill. MW121R was located in order to intersect this anomaly at approximately 60 ft. The EM-conductivity log in MW121R contains a high electrical-conductivity anomaly at 69 ft. The magnitude of this anomaly is nearly 10,000 mS/m and coincides with a layer containing sulfide minerals, rather than fractures. The nearest fractures in the borehole and the fluids in the borehole adjacent to the EM spikes are not electrically conductive. The lack of high-conductivity fluids in the borehole further supports the interpretation that the electrically conductive unit identified by Powers and others (1999) and the feature imaged in the borehole-radar log is induced by a lithologic change.

A second surface-geophysical anomaly was identified by Powers and others (1999) southwest of the landfill and is a north-south trending, west-dipping feature. Borehole MW105R was positioned to intersect the conductive feature in the middle of the borehole. A south-striking, west-dipping (N185°E, 21°) feature was identified in the borehole-radar log of MW105R at 57.1 ft, which is coincident with a fracture observed in the ATV log. Another feature at 74 ft strikes south and dips gently west (N181°E, 12°). It was observed in the OTV, ATV, and borehole-radar surveys. The feature at 74 ft also is characterized by a conductivity spike (200 mS/m) 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 in the well adjacent to this was zone was high (56 mS/m), the conductivity spike on the EM log is four times higher, indicating the conductive anomaly is caused by a combination of conductive fluids in the fracture at 74 ft and metallic or conductive minerals in the rock. Water-quality samples from a discretely isolated zone near 74 ft indicated a high specific conductance (810 µS/cm), high concentrations of iron and cadmium, a negative oxidation-reduction potential, and chlorobenzene confirming that the conductivity was in part caused by landfill leachate.

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