APPLICATION OF A GEOPHYSICAL "TOOL-BOX" APPROACH TO CHARACTERIZATION OF FRACTURED-ROCK AQUIFERS: A CASE STUDY FROM NORWALK, CONNECTICUT

John W. Lane, Jr., U.S. Geological Survey, Storrs, Conn.
John H. Williams, U.S. Geological Survey, Troy, N.Y.
Carole D. Johnson, U.S. Geological Survey, Storrs, Conn.
Sister Damien-Marie Savino, United Technologies Corp., Washington, D.C.
F. Peter Haeni, U.S. Geological Survey, Storrs, Conn.

Abstract

The U.S. Geological Survey conducted a geophysical investigation at a site in Norwalk, Connecticut where solvents have contaminated a fractured-rock aquifer. Borehole, borehole-to-borehole, and surface geophysical methods were used to characterize the bedrock fractures, lithologic structure, and transmissive zone hydraulic properties in 11 boreholes and their vicinity. The geophysical methods included conventional logs, borehole imagery, borehole radar, flowmeter, and azimuthal square-array dc resistivity soundings.

Integrated interpretation of geophysical logs at borehole and borehole-to-borehole scales indicates that the bedrock foliation strikes northwest, dips northeast, and strikes north-northeast to northeast, dips both southeast and northwest. Although steeply dipping fractures that cross-cut foliation are observed, most fractures are parallel or sub-parallel to foliation. Steeply dipping reflectors observed in the radar reflection data from three boreholes near the main facility building delineate a north-northeast trending feature. Results of radar tomography conducted close to a suspected contaminant source area indicate that a zone of low velocity and high attenuation exists above 50 feet in depth - the region containing the highest density of fractures. Flowmeter logging was used to estimate hydraulic properties in each of the boreholes. Thirty-three transmissive zones were identified in 10 of the boreholes. The vertical separation of the transmissive zones in a borehole typically is 10 to 20 feet.

Open-hole and discrete-zone transmissivity was estimated from flowmeter data acquired under ambient and pumping conditions. The open-hole transmissivity ranges from 2 to 86 feet squared per day (ft^2/d). The estimated transmissivity of individual transmissive zones ranges from 0.5 to 70 ft^2/d. Draw down monitoring in nearby boreholes under pumping conditions identified hydraulic connections along a northeast-southwest trend between boreholes as far as 560 feet apart. The vertical distributions of open fractures can be described by power law functions, which suggest that the fracture network contains transmissive zones consisting of closely spaced fractures surrounded by a less fractured and much less permeable rock mass.

Introduction

The U.S. Geological Survey (USGS) Toxic Substances Hydrology and National Research Programs have been conducting multi-disciplinary investigations at the Mirror Lake fractured-rock field-research site near Thornton, New Hampshire (NH), since 1990. The investigations, conducted over scales ranging from feet to miles, have tested, developed, and integrated geologic, hydrologic, geophysical, geochemical, and biological methods to characterize fluid movement and chemical transport in fractured rocks (Shapiro and others, 1995; Shapiro and Hseih, 1996). One result of this effort has been the development of a hierarchal approach to hydrogeologic characterization of fractured-rock sites that focuses on the characterization of fractured rock over areas of up to several square miles (Shapiro and others, 1999). The multi-disciplinary approach integrates borehole- to regional-scale hydrogeologic information. The specific disciplines and ”tools” used for an investigation are selected from a variety of methods or ”tool box” available. The geophysical component of this approach combines multiple borehole- and surface-geophysical methods to remotely measure rock, fracture, and hydraulic properties over a range of scales. The geophysical methods are selected to be consistent with the project objectives, site conditions, and physical dimensions of the problem, with practical consideration given to time and monetary constraints and the potential level of risk (Shapiro and others, 1999).

This report shows the application of this tool box approach developed at Mirror Lake to a contaminated site in Norwalk, Connecticut.

Purpose and Scope

This paper presents results of an integrated borehole- and surface-geophysical investigation to characterize a contaminated fractured rock site in Norwalk, Connecticut. The USGS conducted the geophysical investigations as part of a Cooperative Research and Development Agreement with United Technologies Corporation implemented to develop and test geophysical methods to monitor active remediation measures. The goal of the geophysical investigation was to identify the occurrence, distribution, and characteristics of lithologic structures, fractures, and transmissive zones in the bedrock to: (1) refine the conceptual model of ground-water flow and solute transport at the site; (2) design a discrete-zone monitoring and sampling network; and (3) guide additional investigations such as high-resolution geologic mapping, hydrologic testing, and modeling required to select an appropriate remedial measure or monitoring strategy.

Conventional borehole logging (Keys, 1979), borehole-wall imaging (Williams and Johnson, 2000), flowmeter (Hess 1986; Paillet, 1998; Paillet, 2000), radar reflection (Ollson and others, 1992), cross-hole radar tomography (Ollson and others, 1992), and surface azimuthal square-array resistivity sounding methods (Lane and others, 1995) were used in this investigation to measure variations in subsurface properties at borehole (10^{-3} to 10^{-1} feet (ft)), near-borehole (10^{-1} to 10^{1} ft), hole-to-hole (10^{1} ft), and surface (10^{1} to 10^{2} ft) scales.

Description Of Study Area

The geophysical investigations discussed in this paper were conducted at a 78.6-acre site located in Norwalk, Connecticut (fig. 1). The site is underlain by fractured granitic gneiss and micaceous schist of Cambrian-Ordovician age locally intruded by pegmatite (Kroll, 1977). Large bedrock outcrops bound the northern and southern property boundaries; less extensive outcrops are exposed at several other locations. The bedrock surface at the site slopes moderately to the southeast. The depth to bedrock near the main building facility is less than 5 ft. Unconsolidated glacial-drift deposits up to 30 feet thick overlie a zone of moderately to highly weathered bedrock about 25 ft thick.

Manufacturing operations conducted from the early 1960's to the early 1980’s utilized solvents, primarily for degreasing. As part of voluntary environmental investigations, a network of monitoring wells in the overburden, weathered bedrock, and shallow portions (up to 60 ft below ground surface) of the more competent fractured bedrock were installed. Concentrations of dissolved solvents exceeding Connecticut State regulatory limits were detected in all three zones. Two plumes of solvent-contaminated ground water were delineated in the overburden and shallow bedrock. One plume emanates from within the main facility building near the location of a former degreaser pit; the other at a loading dock at a former hazardous waste storage building just outside the main facility (fig. 2).

Figure 1. Location of the study area, Norwalk, Connecticut.

Geophysical Methods

Standard tools of a borehole geophysical investigation in fractured rock include conventional, borehole imagery, and flowmeter logs. Additional logging tools and techniques, such as borehole-to-borehole, borehole-to-surface and surface geophysical methods, are selected consistent with the project objectives and site hydrogeologic conditions.

For this investigation, the conventional borehole-geophysical logs used included mechanical caliper, electromagnetic induction, gamma, fluid temperature, fluid resistivity, and deviation. These methods provide preliminary information on borehole construction and conditions, lithology and fractures, hydraulics, and water quality (Keys, 1979). Acoustic and optical televiewers were used to image the boreholes. The acoustic televiewer (ATV) uses a rotating high-frequency transducer to generate an oriented reflective acoustic image of the borehole wall. The location and orientation of fractures, foliation, and lithologic changes that have contrasting acoustic properties can be interpreted from the ATV image. The ATV can be used in turbid water or mud-filled holes but cannot be used in unsaturated portions of a borehole. The optical televiewer (OTV) is a video logging system that provides an oriented, continuous, optical image of the borehole wall. The OTV can be used in low turbidity water and unsaturated portions of boreholes. The location and orientation of fractures, foliation, and lithologic changes can be interpreted from OTV data. However, because the OTV is an optical system, low optical contrast features, such as small fractures in dark rocks, can be difficult to delineate. Furthermore, sediment, oxidation products, and biological activity that mask the borehole wall can degrade the quality of the OTV image.

Flowmeter logging was used to measure the direction and rate of movement of water in a borehole. Flowmeter logging is conducted under ambient and pumped conditions. The logs are used to establish relative hydraulic gradients and identify transmissive fractures and zones. The heat-pulse flowmeter used in this investigation is capable of resolving vertical flows from 0.005 to 1 gallons per minute (gpm). In studies conducted at the USGS Mirror Lake fractured-rock field-research site near Thornton, NH, the transmissivity of fractures measured by packer pumping and injection tests ranges

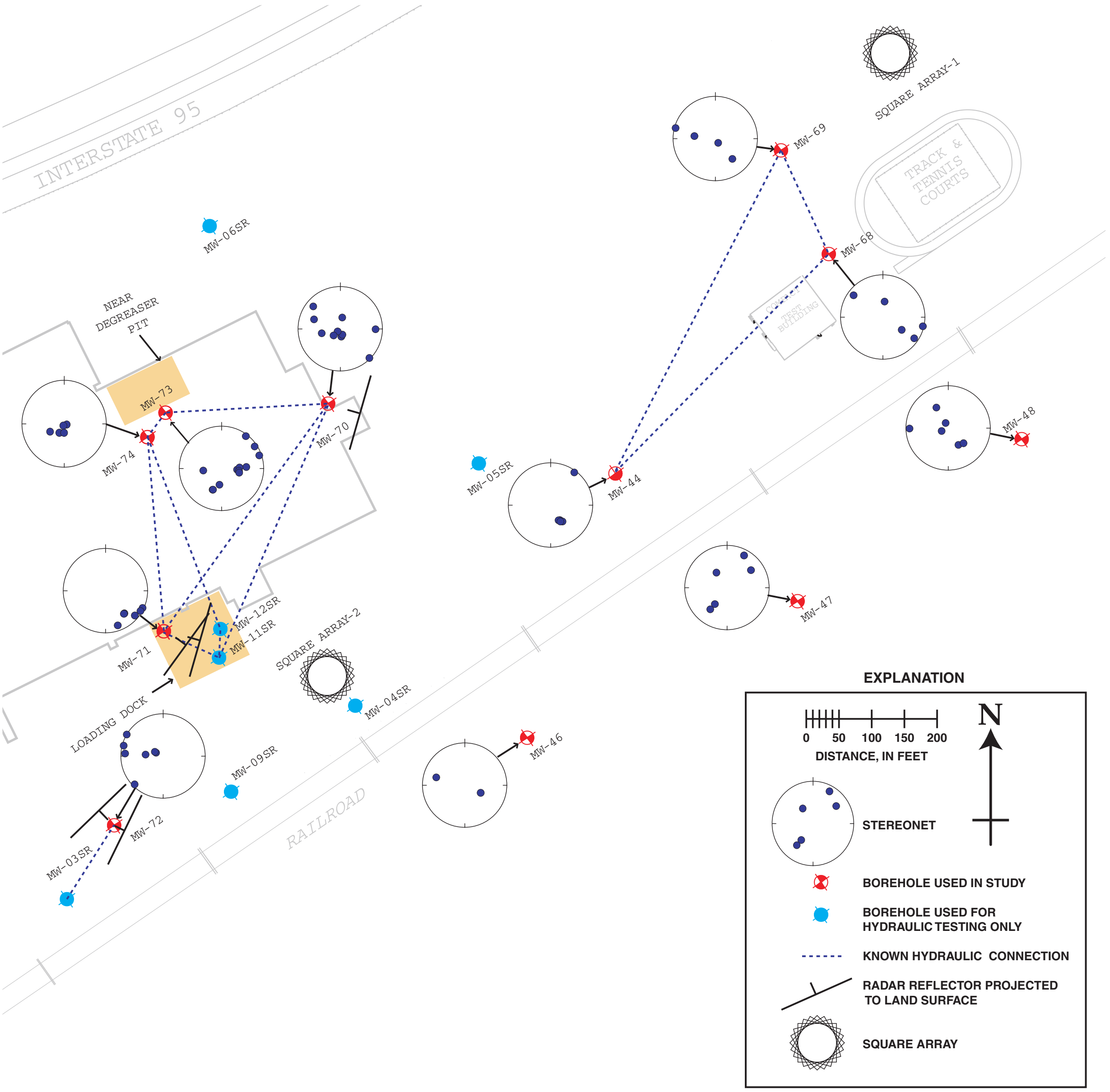

Figure 2. Map of the study site in Norwalk, Connecticut showing well locations, stereonets showing the orientation of transmissive fractures, and lines representing known hydraulic connections between wells.

over 6 orders of magnitude (Shapiro and others, 1999). In studies by Paillet (1998) flowmeter logging conducted at Mirror Lake consistently identified those fractures with transmissivities spanning the upper 1.5-2.0 orders of magnitude. Therefore, the resolution of the heat-pulse flowmeter used in this investigation is sufficient to identify only the most transmissive fractures. The flowmeter data collected under ambient and pumping conditions are interpreted to estimate fracture hydraulic head, transmissivity, and borehole specific capacity.

In fractured-rock investigations, it is important to conduct flowmeter logging under both ambient and stressed conditions because the composite head in an open-hole is weighted by both the head and transmissivity of individual fracture zones, which are preferentially weighted by the head of the most transmissive zone. In cases where the open-hole head approaches the head of the most transmissive zone, there is little or no hydraulic potential to drive flow into or out of the fracture zone. In such cases, flowmeter logging conducted solely under ambient conditions can fail to reveal a very transmissive zone. Pumping and (or) injection to stress the borehole can perturb the head conditions sufficiently to reveal transmissive fractures obscured by the effects of open-hole head blending (Paillet, 1998).

Borehole-radar reflection methods utilize high-frequency electromagnetic (EM) waves in the 10-1000 megahertz (MHz) range to detect fractures and fracture zones. In electrically resistive rocks, such as granite or gneiss, radar radial penetration can exceed 30 ft. Borehole-radar reflection data are interpreted and used to determine the location and orientation of reflections from fracture zones, voids, and lithologic changes, and to estimate the radial extent of planar reflectors.

Cross-hole radar tomography methods are used to estimate the EM properties in the plane between two boreholes. For this investigation, the radar travel-time and amplitude were measured and inverted to create tomograms showing the radar propagation velocity and attenuation properties of the bedrock between two boreholes. Below the water table, decreases in velocity and increases in attenuation can indicate fracture zones and (or) lithologic changes.

Azimuthal square-array direct current (dc)-resistivity soundings measure changes in apparent resistivity with direction and depth about the array center point. Apparent resistivity data measured by an azimuthally rotated square array over a homogeneous earth containing uniformly oriented, saturated, steeply dipping fractures, will have an apparent resistivity minimum oriented parallel to the dominant fracture orientation (Lane and others, 1995; Habberjam and Watkins, 1967). Where electrical resistivity anisotropy is induced by bulk fracture or rock fabric orientation, azimuthal resistivity methods are useful for estimating fracture and(or) foliation orientation trends.

Results Of Geophysical Investigations

Foliation and Fractures

Eleven boreholes were logged for this investigation (fig. 2). The location, distribution, and orientation of fractures, bedrock foliation, and lithologic changes in the boreholes were determined by integrated analysis of the borehole-wall imaging and conventional logs (Keys, 1979; Williams and Johnson, 2000).

The orientation of foliation and fractures observed in the boreholes are shown on lower-hemisphere equal-area stereo nets in figures 3a and b. Although there is considerable variation, some patterns can be detected. Foliation orientations cluster in three sets; one set strikes generally northwest dipping northeast; another set strikes north-northeast to northeast dipping both southeast and northwest (table 1). The orientation of apparently open fractures also clusters about three directions, with most fractures striking north-northeast to northeast dipping southeast and northwest, and one set striking generally northwest dipping northeast. There is a strong correlation between foliation and fracture orientation: most fractures strike sub-parallel to foliation, with dip directions parallel to the foliation. Some of the foliation strike-parallel fractures have high-angle dips that crosscut the foliation (fig. 3a).

The fracture density decreases with depth. Although linear and exponential distributions fit to the data have similar coefficients of determination (R^2 equal about 0.6), it is probably more reasonable to use the exponential distribution for extrapolation because the expected fracture density of the exponential distribution approaches zero with increased depth (Johnson, 1999).

A plot of fracture intensity or ”interfracture spacing”, the distance between all open and oxidized fractures observed in the boreholes, is shown in figure 4. The arithmetic average of the interfracture spacing is 5 ft, which corresponds to an average fracture density of 0.2 fractures per ft. The frequency plot of fracture intensity shown in figure 4 was compared to several theoretical

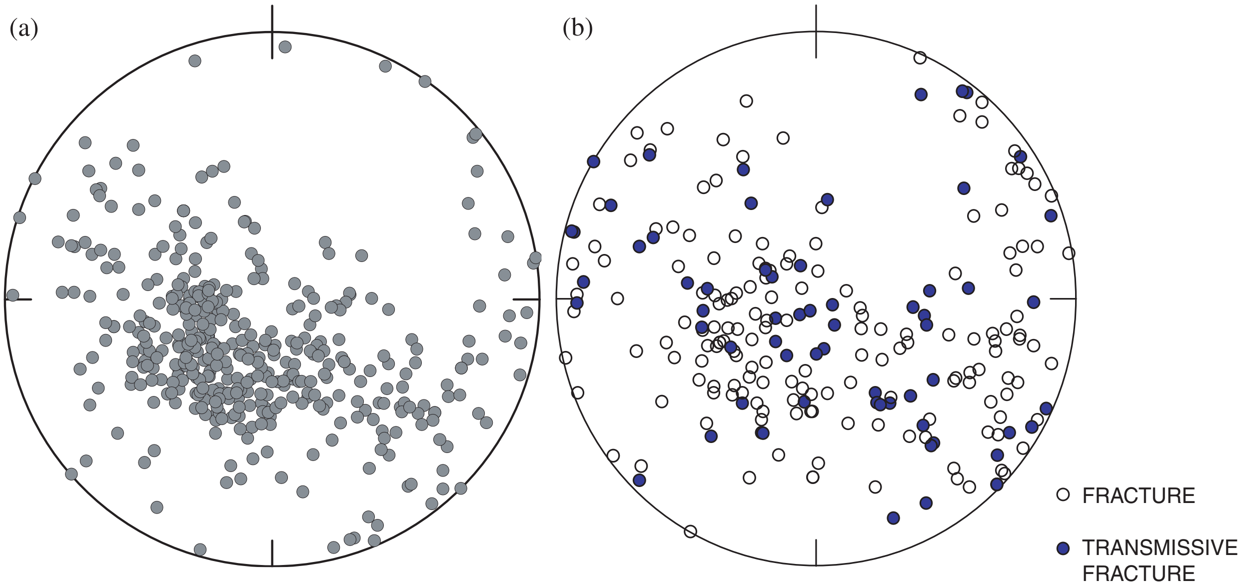

Figure 3. Equal-area stereonets of (a) foliation and (b) fractures, in 11 wells at the study site in Norwalk, Connecticut.

Table 1. Mean strikes and dips interpreted at the site in Norwalk, Connecticut.

	Strike, in degrees	Dip, in degrees	Length, in feet
Foliation	214, *312*	39, *25*	-
Open fractures	209, *315*	45, *30*	-
Transmissive fractures	215, *309*	41, *25*	-
Radar reflectors	209, *305*	43, *35*	65.2
Square array	NE-SW	-	-

distributions including exponential, power, and logarithmic functions. Similar to the findings of Johnson (1999) for fractures in metamorphic rocks at the USGS Mirror Lake fractured-rock field-research site near Thornton, NH, the best fit was obtained for the power law function, $y = 136.8x^{-1.697}$, where x is the distance between fractures and y is the number of fractures. The vertical distribution of fractures observed at the Norwalk site is consistent with a fracture network that contains highly fractured zones surrounded by a rock mass that is significantly less fractured (Johnson, 1999).

Transmissive Fractures

Transmissive fractures were identified by integrated analysis of conventional (caliper, fluid temperature, and specific conductance), borehole imagery (ATV and OTV), and flowmeter logs. Flowmeter logging was conducted with a heat-pulse flowmeter and fluid conductivity tool under ambient and low-rate (0.25-2.0 gpm) pumping conditions. In figure 5, transmissive zones delineated in borehole MW-69 are shown adjacent to caliper, fluid, and flowmeter logs.

The location of the transmissive zones and the orientation of fractures in the transmissive zones are shown in figure 6 for 10 of the boreholes. In most boreholes, 2 or 3 transmissive zones were detected by the heat-pulse flowmeter. A total of 33 transmissive zones were identified in 10 of the

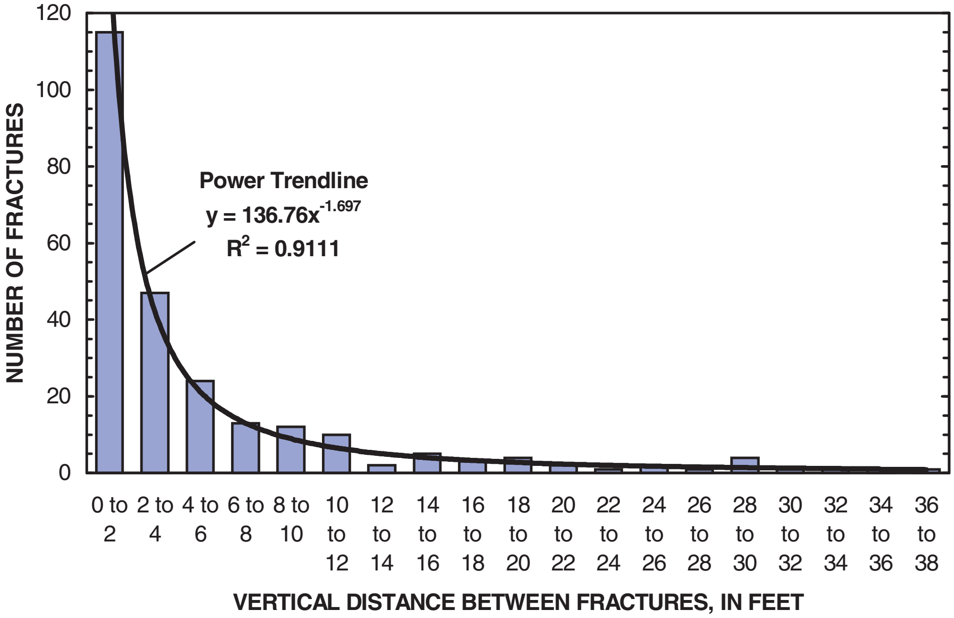

Figure 4. Vertical distance between interpreted fractures, Norwalk, Connecticut.

boreholes. In figure 3b, a lower hemisphere equal-area stereo net shows the orientation of all fractures in the transmissive zones for the site. Individual stereo nets that show the orientation of the transmissive fractures are plotted next to each borehole on the map in figure 2. Most of the transmissive fractures strike generally north-northeast to northeast, dipping both to the southeast and northwest. About 20 percent of the north-northeast to northeast trending fractures are identified as transmissive compared to about 7 percent of the northwest striking fractures.

The fracture intensity for the transmissive fractures in 11 wells is shown in figure 7. The arithmetic average of the vertical interfracture spacings is 16.5 ft, which corresponds to an average transmissive fracture density of 0.06 ft^{-1}. As found for the open and oxidized fractures, a power law function best fit the observed distribution of transmissive fracture spacings, $y=36.9x^{-1.912}$, with a coefficient of determination of 0.91. The vertical distribution of transmissive fractures observed at the Norwalk site is consistent with a network of transmissive fractures that contains zones of transmissive fractures surrounded by a significantly less transmissive rock mass.

Identification of large fractures and fracture zones

Borehole-radar reflection logging was conducted using an electric-dipole transmitter and a magnetic dipole directional receiver with nominal center frequencies (in air) of 60 MHz. Radial penetration of the radar was about 30 ft. A total of 114 reflectors were interpreted from 10 directional-radar reflection logs. The orientations of the interpreted reflectors are generally consistent with the orientation of fractures at the site (table 1).

Radar-reflection methods image the dimension of a planar reflector that is parallel to the borehole. For this paper, the length of the reflector parallel to the borehole was estimated using a straight-ray approximation that accounts for the source-receiver offset and the orientation of the reflector relative to the borehole. Assuming a uniform EM propagation velocity of about 0.4 feet per nanosecond, the mean interpreted reflector length is 65.2 ft with a standard deviation of 52.5 ft. The radar reflection log from MW-71 is shown in figure 8. Two steeply dipping reflectors are highlighted in

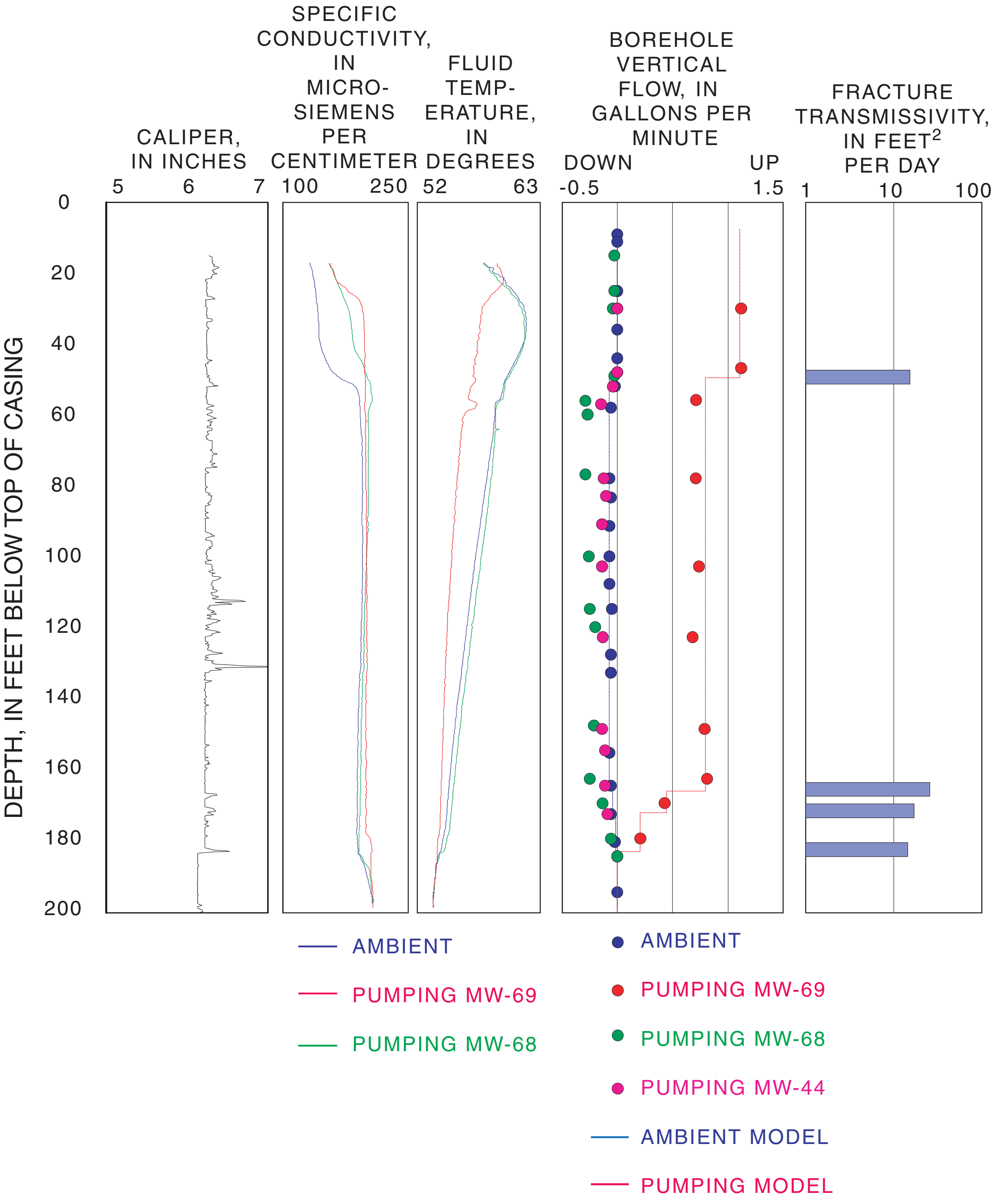

Figure 5. Caliper, fluid temperature and specific conductance, flow logs under ambient and stressed conditions, and transmissive fractures in borehole MW-69, Norwalk, Connecticut.

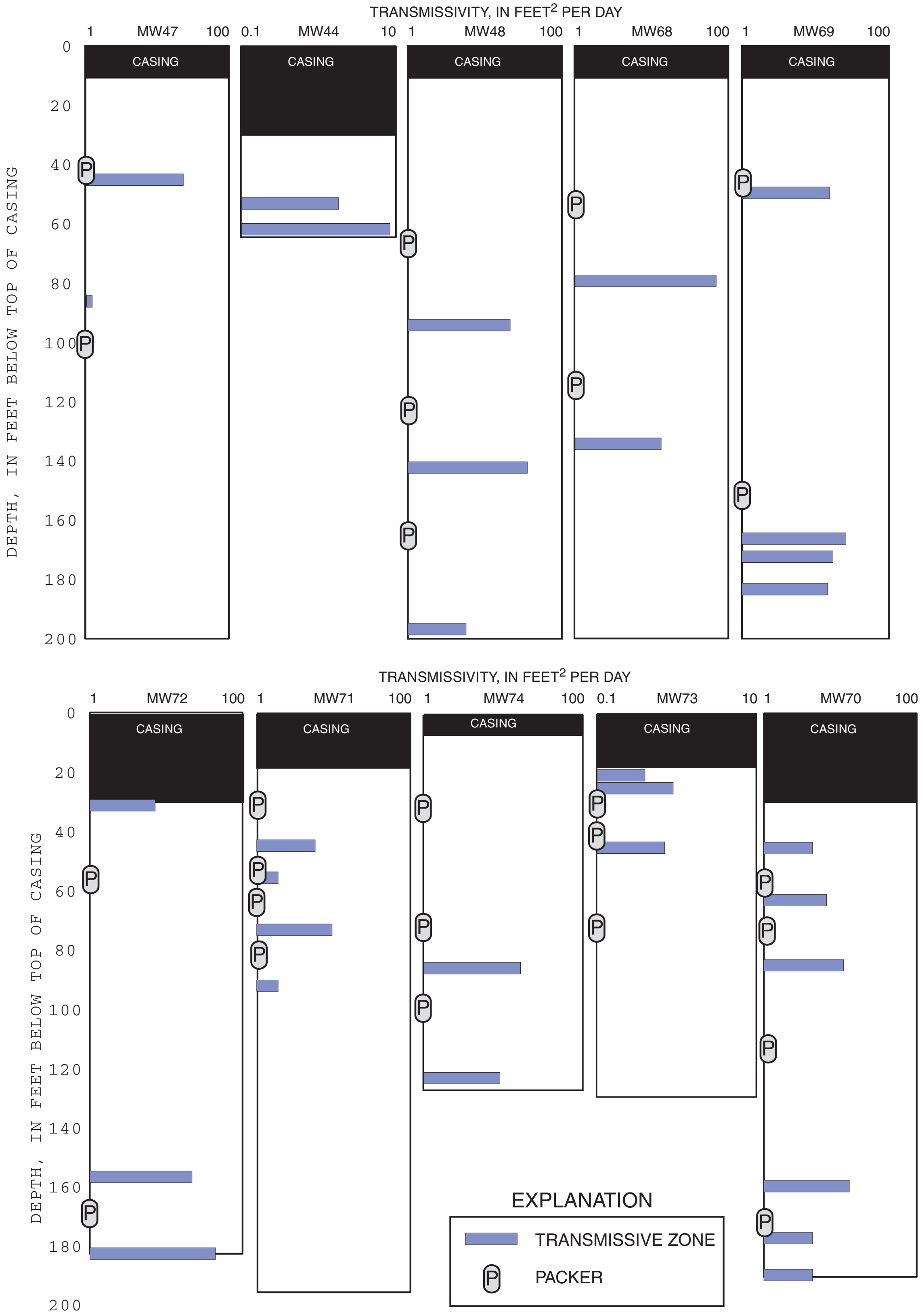

Figure 6. Locations of transmissive zones in several boreholes, with the proposed locations of isolation packers in selected boreholes, Norwalk, Connecticut.

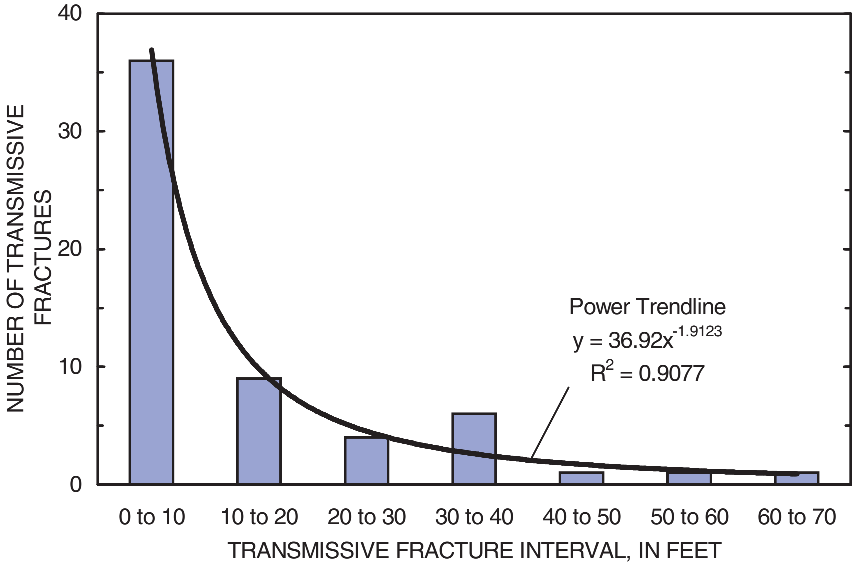

Figure 7. Fracture intensity for transmissive fractures, in 11 wells at the study site in Norwalk, Connecticut.

the figure. In the reflection logs, several steeply dipping reflectors were identified in three boreholes (MW-70, 71, and 72) close to the main building facility (fig. 2). These reflectors are vertically continuous for up to 100 ft, striking generally toward the southwest with dips ranging from about 60 to 80 degrees. Projections of the steeply dipping reflectors to land surface are shown in figure 2. The reflectors are interpreted as a north-northeast trending fracture zone. The boreholes do not penetrate most of the radar reflectors, so the hydraulic characteristics of reflectors are not known. However, one of the steeply southeast-dipping reflectors intersects borehole MW-72 at a major southeast-dipping fracture zone with an estimated transmissivity of 50 feet^2/day, suggesting that the reflector is a significant hydraulic feature.

Results of cross-hole radar tomography conducted between two boreholes near the suspected source areas are shown in figure 9. The tomography was conducted between boreholes MW-73 and MW-74 to delineate EM propagation velocity and attenuation anomalies that might provide insight into hydraulic connections between boreholes and to provide background data for difference tomography should an active remedial measure be attempted near the source zone. The tomographic surveys were conducted using electric-dipole antennas with nominal center frequencies (in air) of 100 MHz. A symmetric 0.82 by 0.82 ft transmitter-receiver geometry was used for the survey. Data were interpreted using a straight-ray conjugant-gradient inversion method. A zone of low EM velocity and high EM attenuation above 50 ft is seen in figure 9. This zone correlates with the locations of fractures recorded by the borehole-wall imagery logs.

Surface Resistivity Anisotropy

Azimuthal square-array dc-resistivity surveys were conducted at two locations (fig. 2). The results of an azimuthal resistivity survey conducted more than 1,000 ft from the general area of the boreholes (Square Array 1) are shown in figure 10. The direction of apparent anisotropy interpreted from both azimuthal square array resistivity surveys is northeast (table 1), consistent with the direction of the predominant foliation and fracture orientation. The results of this surface-geophysical survey

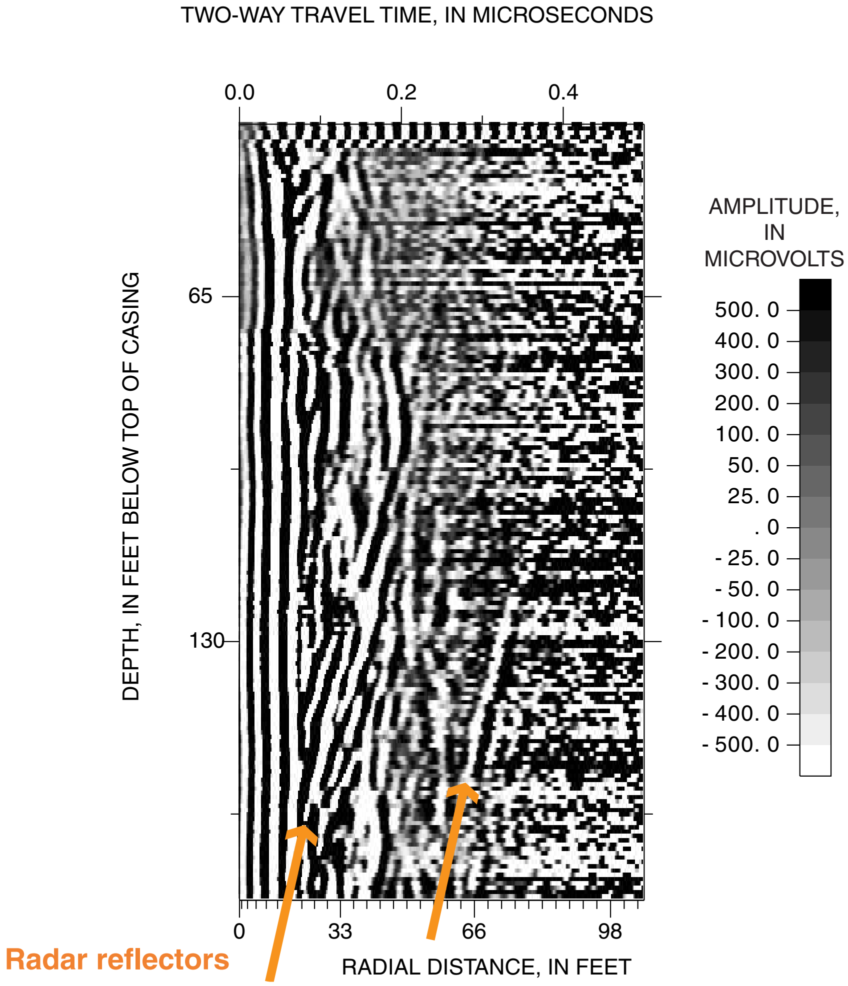

Figure 8. 60-megahertz directional borehole-radar reflection log from borehole MW-71, Norwalk, Connecticut.

suggest that trends in fracture and foliation orientations observed in the boreholes could be extrapolated beyond the location of the boreholes.

Discrete-zone Transmissivity and Hydraulic Head

Specific capacity and open-hole transmissivity can be calculated from head and discharge data measurements made during flowmeter logging. By use of the algorithm of Bradbury and Rothschild (1985), which calculates transmissivity from specific-capacity data (table 2), the transmissivity estimates of the open boreholes at the site ranges from 2 to 86 feet squared per day (ft^2/d).

In boreholes with *no measurable ambient flow*, the open-hole transmissivity was apportioned to individual transmissive fracture zones according to the relative contribution of each zone to the total flow produced under stressed conditions. In boreholes *with measurable ambient flow*, the flow-modeling method described by Paillet (2000) was used to estimate transmissivity and the hydraulic head of each transmissive zone. For example, in figure 5, both measured and simulated ambient and stressed flow profiles and interpreted transmissivity for borehole MW-69 are shown. Transmissivity estimates for individual fracture zones range from less than 0.5 to about 70 ft^2/d. Boreholes MW-48, MW-72, and MW-74 have upward hydraulic gradients with estimated relative head differences of less

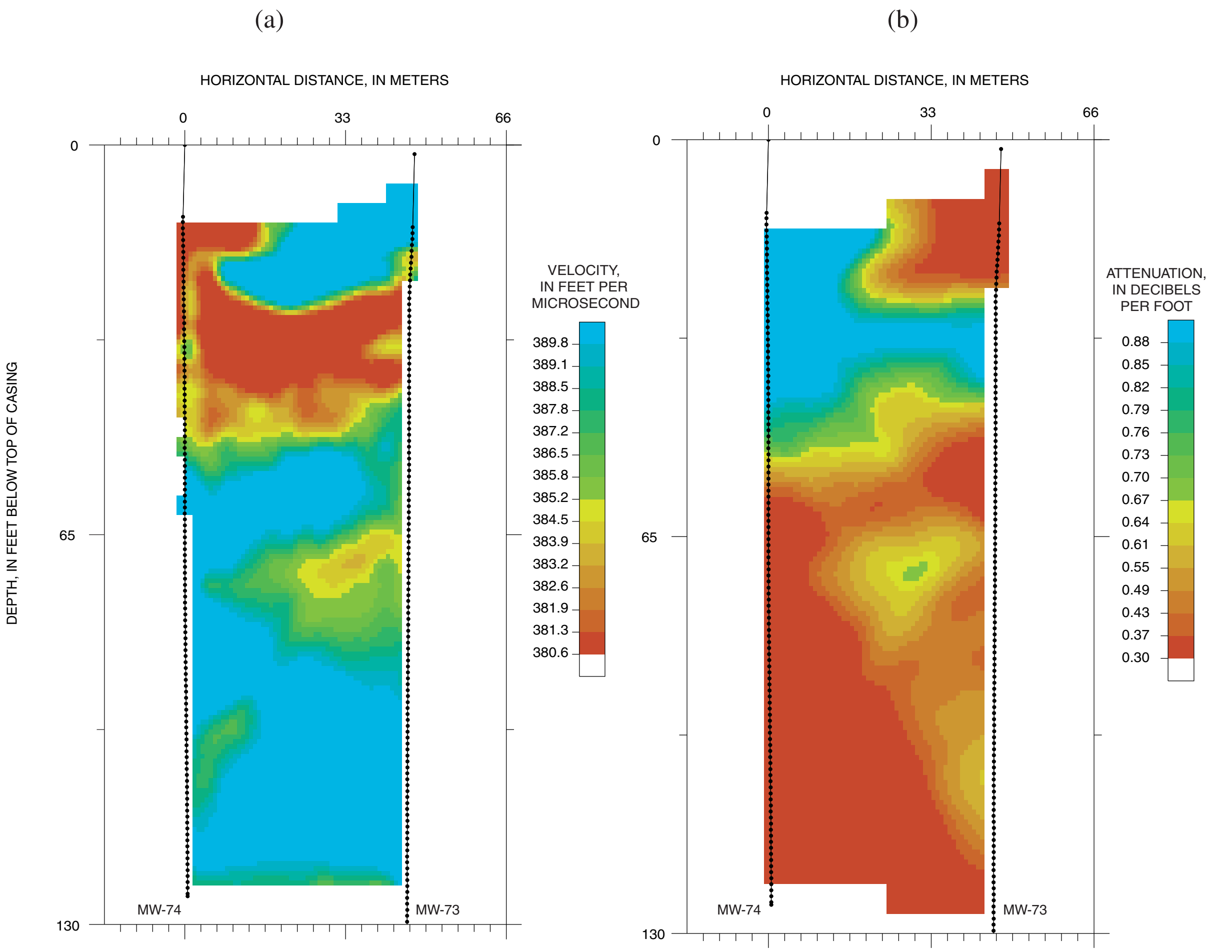

Figure 9. 100-megahertz cross-hole borehole radar tomography between wells MW-74 and MW-73, (a) velocity and (b) attenuation, Norwalk, Connecticut.

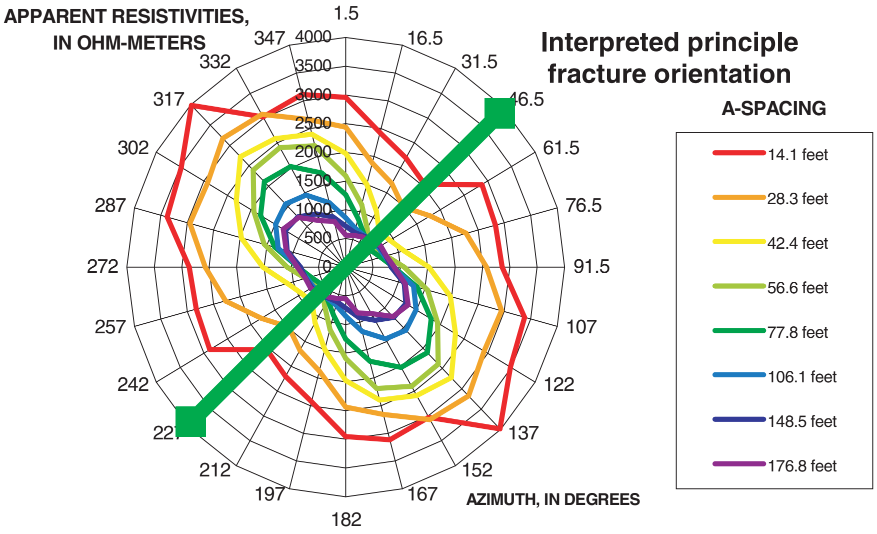

Figure 10. Results of azimuthal resistivity, Square Array 1, Norwalk, Connecticut. The A-spacing is the length of the side of the square.

Table 2. Transmissivity and cross-hole draw down in selected boreholes

Pumped well	Trans-missivity, in ft^2/d	Drawdown and distance from pumped well, in feet									
		MW-44		MW-68		MW-69		MW-70		MW-71	
		Draw-down	Distance	Draw-down	Distance	Draw-down	Distance	Draw-down	Distance	Draw-down	Distance
MW-44	11			0.29	560	0.38	467				
MW-47	24										
MW-48	70										
MW-68	81	1.0	560			3.3	176				
MW-69	86	2.6	467	4.6	176						
MW-70	43									1.24	430
MW-71	19							2.0	430		
MW-72	70										
MW-73	2										
MW-74	25										

than 1 to about 10 ft between the lower and upper transmissive zones. A downward hydraulic gradient exists in MW-69 with an estimated relative head difference of about 1 ft.

Hydraulic Connections

Draw-down measurements made during multiple-borehole, low-pumping rate hydraulic-stress tests indicate the presence of hydraulic connections between boreholes along a northeast-southwest trend. Connections were observed between wells separated by distances of up to 600 ft (table 2 and fig. 2). The trend of the hydraulic connection trend is consistent with the general northeast-southwest strike of the bedrock fabric and the observation that most of the transmissive fractures are striking parallel to the bedrock foliation.

Connections between individual transmissive zones were delineated by fluid and flowmeter logs collected in selected boreholes during the multiple-borehole stress tests. For example, the results of fluid and flowmeter logging conducted in borehole MW-69 when boreholes MW-44 and MW-68 were stressed are shown in figure 5. The increase in downward flow to the lower transmissive zones in borehole MW-69 during these tests suggests this zone is hydraulically connected to boreholes MW-44 and MW-68. Fluid and flowmeter logs in borehole MW-68 indicated that the lower transmissive zone provided a hydraulic connection when boreholes MW-44 and MW-69 were stressed.

Discrete-Zone Monitoring

One of the goals of the geophysical investigation was to provide the information needed to design a discrete-zone monitoring (DZM) network in the fractured rock aquifer. Properly designed DZM systems provide a way to monitor hydraulic head and sample the aquifer from specific zones, while preventing cross-contamination of the aquifer through open boreholes. In order to minimize cross-contamination, open boreholes were temporarily isolated using flexible borehole liners until the completion of testing and the installation of individual DZM systems. EM induction, gamma, and borehole radar logging were conducted with the liners in the boreholes. Borehole-wall imagery, fluid, and flowmeter logging required temporary removal of the liners. The results of borehole and flowmeter logging were used to determine locations packers to isolate the transmissive zones (fig. 6). Preliminary results from the DZM systems show close agreement between observed heads and heads estimated from analysis of the flowmeter logs, and provide zone-specific water chemistry data that gives insight into the nature of fluid flow and solute transport at the site.

Summary

The USGS conducted a geophysical investigation at a site in Norwalk, Connecticut where solvents have contaminated a fractured gneiss and schist aquifer. The geophysical investigation was conducted using a geophysical ”tool box” approach to fractured rock characterization developed at the USGS Mirror Lake fractured-rock field-research site near Thornton, NH. The investigation was conducted to: (1) refine the site conceptual model of ground-water flow and solute transport; (2) provide the information needed to design a discrete-zone monitoring and sampling network; and (3) guide the additional investigations, such as high-resolution geologic mapping, hydrologic testing, and modeling, required to select an appropriate remedial measure or monitoring strategy.

The suite of borehole and surface geophysical methods used for the investigation was selected to remotely measure bedrock fractures, lithologic structure, and transmissive zone hydraulic properties from the borehole to field scale using conventional logs, borehole imagery, directional radar reflection, cross-hole radar tomography, flowmeter, and azimuthal square-array resistivity methods.

Fracture and foliation orientations and distribution were determined by integrated interpretation of borehole geophysical logs from 11 bedrock boreholes. Bedrock foliation at the site strikes northwest dipping moderately northeast and north-northeast to northeast dipping both southeast and northwest. Most fractures are oriented parallel or sub-parallel to foliation, with dips that are parallel to the foliation. Some fractures strike coincident with foliation, but they have high-angle dips that crosscut the foliation.

Over 100 planer reflectors were identified in the directional radar reflection logs. The interpreted orientations of the radar reflectors are consistent with the fracture and foliation orientations. The estimated average length of the reflectors is about 65 ft. Steeply dipping reflectors observed in the radar reflection data from three boreholes located near the main facility building delineate a north-northeast trending feature interpreted as a fracture zone or fault.

Results of radar tomography conducted in two wells close to one of the suspected source zones indicate a zone of low radar velocity and high attenuation exists above 50 ft depth, over the interval in the boreholes containing a high density of fractures.

The axis of apparent electric anisotropy interpreted from azimuthal square-array resistivity surveys conducted at two locations on the site is oriented northeast-southwest, consistent with the orientation of transmissive fractures and one of the foliation directions, suggesting a consistency in fracture and bedrock fabric orientation across the site.

Flowmeter logging identified a total of 33 transmissive zones in 10 of the boreholes. The vertical separation of the transmissive zones is typically 10 to 20 ft. Most of the fractures in the transmissive zones strike north-northeast to northeast, dipping both southeast and northwest; a smaller number of transmissive fractures have northwest strikes, dipping to the northeast. Draw-down monitoring during flowmeter logging under pumping conditions identified hydraulic connections along a northeast-southwest trend between boreholes as far as 560 ft apart.

Open-hole and discrete-zone transmissivity was estimated from flowmeter data acquired under ambient and pumping conditions. The open-hole transmissivity of 10 of the boreholes ranges from 2 to 86 ft^2/d. The estimated transmissivity of the 33 transmissive zones ranges from 0.5 to about 70 ft^2/d. Discrete-zone hydraulic heads interpreted from the flowmeter logs are consistent with available discrete-zone monitoring head measurements. Power law functions describe the vertical inter-fracture spacing of open and transmissive fractures. The power law distribution suggests the fracture network at the site contains transmissive zones consisting of closely spaced fractures surrounded by a less fractured and permeable rock mass.

References

Bradbury, K.R., and Rothschild, E.R., 1985, A computerized technique for estimating the hydraulic conductivity of aquifers from specific-capacity data: Groundwater, v. 23, no. 2, p. 240-246.

Habberjam, G.M., and Watkins, G.E., 1967, The use of a square configuration in resistivity prospecting: Geophysical Prospecting, V. 15, p. 221-235.

Hess, A.E., 1986, Identifying hydraulically conductive fractures with a slow-velocity borehole flowmeter: Canadian Geotechnical Journal, v.23, no. 1, p. 69-78.

Keys, W.S., 1979, Borehole geophysics in igneous and metamorphic rocks: Society of Professional Well Log Analysts Annual Logging Symposium, 20th, Tulsa, Okla., 1979, Transactions, p. 1-26.

Johnson, C.D., 1999, Effects of lithology and fracture characteristics on hydraulic properties in crystalline rock: Mirror Lake research site, Grafton County, New Hampshire, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program-Proceedings of the Technical Meeting, Charleston, South Carolina March 8-12, 1999: U.S. Geological Survey Water Resources Investigations Report 99-4018C, Vol. 3, p. 795-802.

Kroll, Richard, 1977, The bedrock geology of the Norwalk North and Norwalk South quadrangles: State Geological and Natural History Survey of Connecticut, Quadrangle Report No. 34.

Lane J.W. Jr., Haeni, F.P., & Watson, W.M, 1995, Use of square-array direct-current resistivity method to detect fractures in crystalline bedrock in New Hampshire: Ground Water, V. 33, no. 3, p. 476-485.

Olsson, O., Anderson, P., Carlsten, S., Falk, L., Niva, B., and Sandberg, E., 1992, Fracture characterization in crystalline rock by borehole-radar, in Pilon, J., ed., Ground penetrating radar: Geological Survey of Canada Paper 90-4, p. 139-150.

Paillet, F.L., 1998, Flow modeling and permeability estimation using borehole flow logs in heterogeneous fractured formations: Water Resources Research, v. 34, no. 5, p. 997-1010.

Paillet, F.L., 2000, A field technique for estimating aquifer parameters using flow log data: Ground Water, v. 38, no. 4, p. 510-521.

Shapiro, A.M., and Hseih, P.A., 1996, Overview of research on use of hydrologic, geophysical, and chemical methods to characterize flow and chemical transport in fractured rock at the Mirror Lake site, N.H., *in* Morganwalp, D.W., and Aronson, D.A., eds., U.S. Geological Survey Toxic Substances Hydrology Program—Proceedings of the Technical Meeting, Colorado Springs, Colo., September 20-24, 1993: U.S. Geological Survey Water-Resources Investigations Report 94-4015, p. 71-80.

Shapiro, A.M., Hsieh, P.A., and Haeni, F.P., 1999, Integrating multidisciplinary investigations in the characterization of fractured rock, *in* Morganwalp, D.W., and Buxton, H.T., eds., U.S. Geological Survey Toxic Substances Hydrology Program-Proceedings of the Technical Meeting, Charleston, South Carolina March 8-12, 1999: U.S. Geological Survey Water Resources Investigations Report 99-4018C, Vol. 3, p. 669-680.

Shapiro, A.M., Hsieh, P.A., and Winter, T.C., 1995, The Mirror Lake Fractured Rock Research Site--a multidisciplinary research effort in characterizing ground-water flow and chemical transport in fractured rock: U.S. Geological Survey Fact Sheet FS-138-95, 2 p.

Williams, J.H., and Johnson, C.D., 2000, Borehole-wall imaging with acoustic and optical televiewers for fractured-bedrock aquifer investigations, *in* Seventh International Symposium on Logging for Minerals and Geophysical Applications Proceedings, Mineral and Geotechnical Logging Society, Denver, Colorado, October 24-26, 2000.