U.S. DEPARTMENT OF THE INTERIOR
U.S. GEOLOGICAL SURVEY

In cooperation with the U.S. Environmental Protection Agency

# Geology, Hydrology, and Ground-Water Quality of the Upper Part of the Galena-Platteville Aquifer at the Parson's Casket Hardware Superfund Site in Belvidere, Illinois

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## CONVERSIDN FACTORS, VERTICAL DATUM, AND ABBREVIATED WATER-QUALITY UNITS

| Multiply | By | To obtain |
|---|---|---|
| | **Length** | |
| inch (in.) | 2.54 | centimeter |
| foot (ft) | 0.3048 | meter |
| mile (mi) | 1.609 | kilometer |
| | **Volume** | |
| gallon (gal) | 3.785 | liter |
| | **Flow rate** | |
| cubic foot per day ($ft^3/d$) | 0.02832 | cubic meter per day |
| gallon per minute (gal/min) | 3.875 | liter per minute |
| | **Velocity** | |
| foot per day (ft/d) | 0.3048 | meter per day |
| foot per microsecond (ft/μs) | 0.3048 | meter per microsecond |
| | **Hydraulic conductivity** | |
| foot per day (ft/d) | 0.3048 | meter per day |
| | **Hydraulic gradient** | |
| foot per foot (ft/ft) | 0.3048 | meter per meter |
| | **Transmissivity*** | |
| foot squared per day ($ft^2/d$) | 0.09290 | meter squared per day |
| | **Sound Intensity** | |
| decibels per foot (db/ft) | 0.3048 | decibels per meter |

**Sea level**: 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.

**Altitude**, as used in this report, refers to distance above or below sea level.

Abbreviated water-quality units used in this report: Chemical concentration is given in metric units. Chemical concentration is given in micrograms per liter (μg/L). Micrograms per liter is a unit expressing the concentration of chemical constituents in solution as weight (micrograms) of solute per unit volume (liter) of water. One thousand micrograms per liter is equivalent to one milligram per liter (mg/L).

***Transmissivity:** The standard unit for transmissivity is cubic foot per day per square foot times foot of aquifer thickness [$(ft^3/d)/ft^2$]ft. In this report, the mathematically reduced form, foot squared per day ($ft^2/d$), is used for convenience.

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## Abstract

The geology, hydrology, hydraulic properties, and distribution of contaminants in the upper part of the Galena-Platteville aquifer at the Parson's Casket Hardware Superfund site in Belvidere, Illinois, were characterized on the basis of data collected from boreholes by use of packer assemblies, flowmeter logging, and borehole ground-penetrating radar. Four permeable intervals were identified in the upper part of the Galena-Platteville aquifer: (1) a shallow, subhorizontal fracture from 37 to 40 feet below land surface; (2) an inclined fracture from 75 to 85 feet; (3) a shallow, vuggy interval from 90 to 100 feet; and (4) a deep, vuggy interval from about 140 to 180 feet. The calculated horizontal hydraulic conductivity of the two fractured intervals exceeds 50 feet per day and is more than an order of magnitude greater than that of the vuggy intervals. Water levels in the Galena-Platteville aquifer respond to pumping cycles in the Belvidere municipal-supply wells below a depth of at least 180 feet.

Results of flowmeter logging and constant-discharge aquifer testing indicate that the shallow, subhorizontal fracture is hydraulically connected to the overlying unconsolidated aquifer. Discrete inclined fractures are the primary conduits for vertical ground-water flow between the permeable units within the upper part of the Galena-Platteville aquifer, and perhaps for flow to the deeper parts of the aquifer. The inclined fractures may become less permeable with depth.

A maximum effective porosity in the deep, vuggy interval of 8.8 percent was calculated from hydrologic and borehole radar-tomography data collected during tracer testing. The average maximum horizontal ground-water velocity through this interval was calculated at 21.4 feet per day using cross-hole radar tomography under a hydraulic gradient of 1.25 feet per foot.

Trichloroethene, trichloroethane, and tetrachloroethene are the primary volatile organic compounds detected in the aquifer. There is no distinct pattern of the concentration of volatile organic compounds with depth; however, the highest concentrations tend to be present in the shallow part of the aquifer at the site. Movement of organic compounds through vertical fractures may account for their presence in the deeper parts of the aquifer.

## INTRODUCTION

Accurate hydrologic and hydraulic characterization of fractured-rock aquifers requires the identification of the location and orientation of the fractures, vugs, and solution openings in the aquifers and determination of the location and hydraulic properties of the flow pathways. Historically, these data have been difficult and expensive to acquire. The increased use of packer assemblies in the mid-1980's to isolate specific parts of a borehole has allowed more accurate and complete characterization of hydraulic properties and water quality in fractured-rock aquifers. Testing of an entire borehole with a packer assembly, however, can be time consuming and requires use of specialized equipment. Development of flowmeter logging tools in the early 1980's has permitted quick and accurate identification of the flow pathways at boreholes open to fractured-rock aquifers. Identification of the flow pathways has resulted in more efficient characterization of fractured-rock aquifers by enabling testing of only the hydraulically active features in the borehole (Hess, 1986; Paillet and others, 1987). More recent application of flowmeter-logging techniques has enabled quantification of the hydraulic properties of the specific flow pathways at a borehole, which has the potential to produce additional improvements in the characterization of fractured-rock aquifers. Development of borehole ground-penetrating radar logging systems in the late 1980's also has improved the ease and completeness with which fractured-rock aquifers are characterized by identifying fractures and flow pathways that do not intercept a borehole, allowing characterization of a larger volume of an aquifer (Niva and others, 1988; Lane and others, 1994).

The U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (USEPA), used packer assemblies, flowmeter logging, and borehole ground-penetrating radar to efficiently characterize the geohydrology, hydraulic properties, and distribution of contaminants in the upper part of the fractured-rock aquifer beneath the Parson's Casket Hardware Superfund site in northern Illinois. This site was chosen as the test site because the bedrock had been partially characterized during previous investigations (Mills, 1993a, 1993b, 1993c; Mills and others, 1998). Additional characterization of the site also would support assessment of ground-water remediation alternatives.

The Parson's Casket Hardware Superfund site is in the northern part of the city of Belvidere, in Boone County, Illinois (fig. 1). The bedrock aquifer beneath the site is composed of dolomite of the Galena and Platteville Groups and referred to as the Galena-Platteville aquifer. The area of concern for this investigation (hereafter referred to as the study area) is confined to the southern part of the Parson's Casket Hardware Superfund site in the vicinity of boreholes T1 through T8 from the bedrock surface to a depth of 215 ft (fig. 1)(table 1). The reference point for all measurements, unless otherwise noted, is the top of the casing in the borehole or well being tested (table 1). The top of the casing at boreholes T1–T8 typically is about 1 ft above the land surface. The altitude of the top of the casings at boreholes T1–T8 varies by as much as 1.02 ft in the study area (table 1). The top of the casing at wells G115BD, G127GP, and G127SP typically is less than 2 ft above the land surface and varies by less than 1.7 ft from the altitude of the top of the casings at boreholes T1–T8 (table 1).

The study comprised six principal efforts: (1) geophysical logging using conventional logging techniques, (2) collection of static water-level measurements, (3) aquifer testing, (4) geophysical logging using borehole ground-penetrating radar tomography and single-hole directional radar reflection surveys, (5) borehole radar tomography in conjunction with tracer testing, and (6) water-quality sampling. Conventional geophysical logging was done to determine stratigraphy, fracture orientation, and depths and directions of ground-water flow at the boreholes. In addition, this information was used to confirm the validity of the geologic interpretations made using borehole ground-penetrating radar. Static water-level measurements were collected during packer testing to identify the vertical direction of ground-water flow in the boreholes. Slug tests and multiple-well constant-discharge aquifer tests quantified the hydraulic properties of the bedrock aquifer and the vertical trends in the hydraulic properties. Water-level and aquifer-test data were used to plan the tracer test and also helped confirm the validity of the interpretations made from the borehole tomography done in conjunction with the tracer testing. Borehole ground-penetrating radar tomography and single-hole directional radar reflection surveys were used to characterize the bedrock geology by identifying the location and orientation of fractures and other secondary-permeability features in the dolomite in the vicinity of the boreholes. Borehole tomography in conjunction with tracer testing was used to identify the rate and pathways of ground-water movement through the upper part of the Galena-Platteville aquifer. Water-quality sampling was used to determine ground-water quality and the spatial distribution of contaminants in the upper part of the Galena-Platteville aquifer underlying the study area.

## Purpose and Scope

This report describes the results of a study that used packer assemblies, flowmeter logging, and borehole ground-penetrating radar to characterize the geology, hydrology, and distribution of contaminants in the upper part of the Galena-Platteville aquifer underlying the study area in the southern part of the Parson's Casket Hardware Superfund site in Belvidere, Ill. The results of geophysical logging, using conventional logs, heat-pulse flowmeter, and borehole ground-penetrating radar, are presented in addition to the results of a series of aquifer tests and water-quality sampling in the study area. The report identifies the pathways of ground-water flow and contaminant movement through the upper part of the Galena-Platteville aquifer underlying the study area. The effectiveness of borehole ground-penetrating radar, acoustic televiewer,

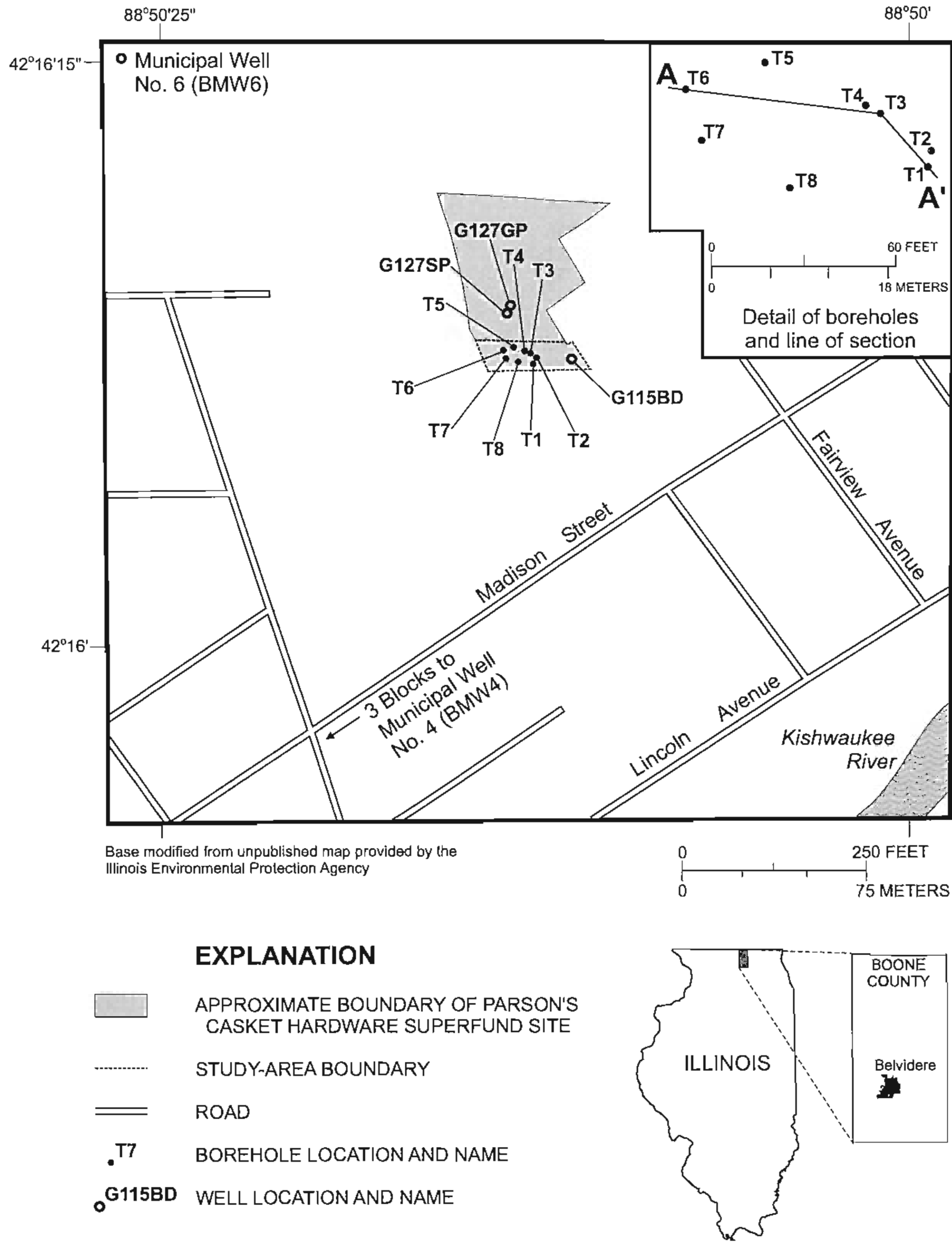


**Figure 1.** Location of study area, boreholes, wells, and line of section A-A', Parson's Casket Hardware Superfund site, Belvidere, Illinois.

**Table 1.** Borehole and well information, altitude of top of bedrock, and selected water-level data, Parson's Casket Hardware Superfund site, Belvidere, Illinois
[nt, measurement not taken; unk, unkown]

| Borehole or well name (figure 1) | Open interval (feet below land surface) | Top of borehole or well casing altitude (feet above sea level) | Bedrock-surface altitude (feet above sea level) | Water-level altitude, September 13, 1996 (feet above sea level) | Water-level altitude, September 18, 1996 (feet above sea level) | Water-level altitude, October 30, 1996 (feet above sea level) |
|---|---|---|---|---|---|---|
| T1 | 49–215 | 784.23 | 740 | 763.55 | 763.69 | 763.09 |
| T2 | 48–215 | 784.02 | 741 | 763.64 | nt | 763.16 |
| T3 | 50–215 | 784.34 | 744 | 762.28 | 763.03 | 762.84 |
| T4 | 45–50 | 784.06 | 744 | 764.07 | 763.96 | nt |
| T5 | 30–146 | 784.01 | 751 | 764.06 | 763.96 | 763.26 |
| T6 | 37-215 | 783.59 | 751 | 763.04 | 762.96 | 762.25 |
| T7 | 35-215 | 784.39 | 754 | 764.05 | nt | 763.22 |
| T8 | 40–215 | 784.61 | 749 | 764.06 | 763.94 | 763.24 |
| G115BD | 141–151 | 784.48 | 745 | nt | nt | 753.57 |
| G127GP | 289–294 | 785.20 | 750 | nt | nt | nt |
| G127SP | 371–376 | 785.28 | 750 | nt | nt | nt |
| BMW4 | 152–1,800 | 777 | unk | nt | nt | nt |
| BMW6 | 110–868 | 782 | unk | nt | nt | nt |

and heat-pulse flowmeter logs for identifying the location, orientation, and hydraulic properties of ground-water-flow pathways in fractured-rock aquifers also is discussed.

## Acknowledgments

The authors extend their thanks to Allen Shapiro of the U.S. Geological Survey for his suggestions regarding data analysis. Mark Vendl of the U.S. Environmental Protection Agency is thanked for his assistance with the planning and execution of this investigation. Filtersystems Incorporated and Eric Runkel of the Illinois Environmental Protection Agency (IEPA) also are thanked for their assistance with the study.

# GEOLOGY

The bedrock geologic units of concern at the Parson's Casket Hardware Superfund site (hereafter referred to as the site) are sandstone and dolomite of Ordovician age. From oldest to youngest, these units are the St. Peter Sandstone and Glenwood Formation of the Ancell Group, and the Platteville and Galena Groups. Quaternary glacial and glaciofluvial deposits unconformably overlie the bedrock deposits. The stratigraphic nomenclature used in this report is that of the Illinois State Geological Survey (Willman and others, 1975, p. 61–81).

The geohydrology in the vicinity of the study area has been extensively studied by previous investigators (Mills, 1993a, 1993b, 1993c; Mills and others, 1998; Science Applications International Corporation, 1993). The study area also is part of an investigation of the hydrogeology and ground-water quality in the greater Belvidere area being done by the USGS in cooperation with the USEPA and IEPA. These prior studies have provided a good foundation of the hydrogeology at the site and the surrounding region upon which to base the current investigation.

The St. Peter Sandstone is a coarse-to-medium grained quartz arenite, characterized by a high percentage of well-rounded quartz grains. The top of the St. Peter Sandstone is about 361 ft below the land surface at the site (Mills, 1993c).

The Glenwood Formation overlies the St. Peter Sandstone and is composed of interbedded sandstone and argillaceous dolomite beneath the site. Sandstone layers predominate at the base of the formation, and dolomite layers predominate at the top of the formation. The top of the Glenwood Formation is about 332 ft below the land surface at the site (Mills, 1993b).

The Platteville and Galena Groups are the uppermost bedrock deposits beneath the site and consist of fractured, vesicular to vuggy, partly cherty, partly argillaceous dolomite with numerous shale partings. The groups are lithologically similar and are subdivided into formations primarily on the basis of subtle variations in clay and silt content (Willman and Kolata, 1978). Stratigraphy determined from a composite of partial cores recovered from five borings at the site indicates the deposits of the Platteville Group are about 120 ft thick in the study area and separate the underlying Glenwood Formation from the overlying Galena Group (Mills and others, 1998). Core samples from wells G115BD, G127GP and G127SP (fig. 1) indicate that the deposits of the Galena Group extend to a depth of about 214 ft at the site (figs. 2, 3). All boreholes, except T4 and T5, penetrate the entire thickness of the Galena Group and terminate at the top of the Platteville Group.

The altitude of the top of the bedrock surface in the western part of the study area at boreholes T6 and T7 is about 753 ft above sea level. In the eastern part of the study area at boreholes T1 and T2, erosion has decreased the altitude of the top of the bedrock surface to about 740 ft above sea level (figs. 2, 3; table 1). The uppermost part of the bedrock typically is highly weathered and fractured. This highly weathered area is restricted to primarily the upper 10 ft of the dolomite.

Quaternary deposits overlie the bedrock throughout the study area and the surrounding area. Glaciofluvial sand-and-gravel deposits directly overlie the bedrock throughout the site (fig. 2)(Science Applications International Corporation, 1993, figs. 3-12 to 3-17). The sand-and-gravel deposits are overlain by a silty clay deposit throughout the site (Science Applications International Corporation, 1993, figs. 3-12 to 3-17).

Natural-gamma, acoustic televiewer, normal resistivity, and neutron porosity logging was done by Frederick Paillet of the USGS (written commun., 1995, 1996, 1997) and Jim Ursic of the USEPA. Mr. Paillet's analysis of these logs forms the basis for much of the following discussion. Single-hole directional radar reflection surveys and cross-borehole ground-penetrating radar surveys were done with the assistance of Mark Vendl of the USEPA.

Natural-gamma logs were run in boreholes T1, T2, T3, T5, T6, T7, and T8 (figs. 4–10). Except for the shale bed identified at about 122 ft, the natural-gamma logs indicate the bedrock consists of alternating pure-to-argillaceous dolomite. Previous investigators have determined that the shale bed is present throughout the site (Mills, 1993c).

Acoustic televiewer logs were run in boreholes T1, T2, T3, T5, T6, T7, and T8 to obtain a more complete characterization of the fractures and vugs in the upper part of the dolomite (figs. 4–10). Vuggy intervals were measured through most or all of the dolomite in each of the boreholes. Vugs were less extensive in boreholes T2 and T8 than in the other boreholes.

Acoustic televiewer logs indicate numerous subhorizontal fractures through the entire thickness of each of the boreholes, including a prominent fracture associated with the shale bed at about 122 ft. Less prominent horizontal fractures were detected at approximately 133, 142, and 187 ft throughout the study area. The shallow, subhorizontal fracture from about 37 to 40 ft at boreholes T5–T8 probably terminates against the Quaternary deposits as the altitude of the bedrock surface declines near borehole T3 (table 1; figs. 2, 3).

A nearly vertical fracture was measured from about 74 to 86 ft below the top of the casing in borehole T1 (fig. 4). This fracture strikes approximately 43 degrees east of north and intersects borehole T2 from about 75 to 85 ft (fig. 5). The trend of this fracture indicates it extends beneath the lagoon, formerly used for disposal of industrial wastes generated at the site. These wastes are the source of much of the ground-water contamination at the site. A second nearly vertical fracture intersects borehole T6 from about 162 to 178 ft (fig. 8). The strike of this second fracture is about 50 degrees east of north. The strike of the inclined fractures identified from the televiewer logs differs from the dominant fracture strike in the dolomite of about 60 degrees west of north, which was identified by earlier investigators (Foote, 1982).

The inclined fractures observed at boreholes T1, T2, and T6 have a similar orientation and may be part of a set of fractures striking about 45 degrees east of north. The inclined fractures have an average dip of about 85 degrees, giving an angle of intersection of 5 degrees with the boreholes. If the top of the fracture is projected to a depth of 50 ft below the land surface, the distance from the fracture to the borehole ($D$) is given by

$$D = V \tan(a), \qquad (1)$$

where

$V$ is the vertical distance from the intersection of the top of the fracture in the borehole to a depth of 50 ft (24 ft at borehole T1 and 112 ft at borehole T6), and

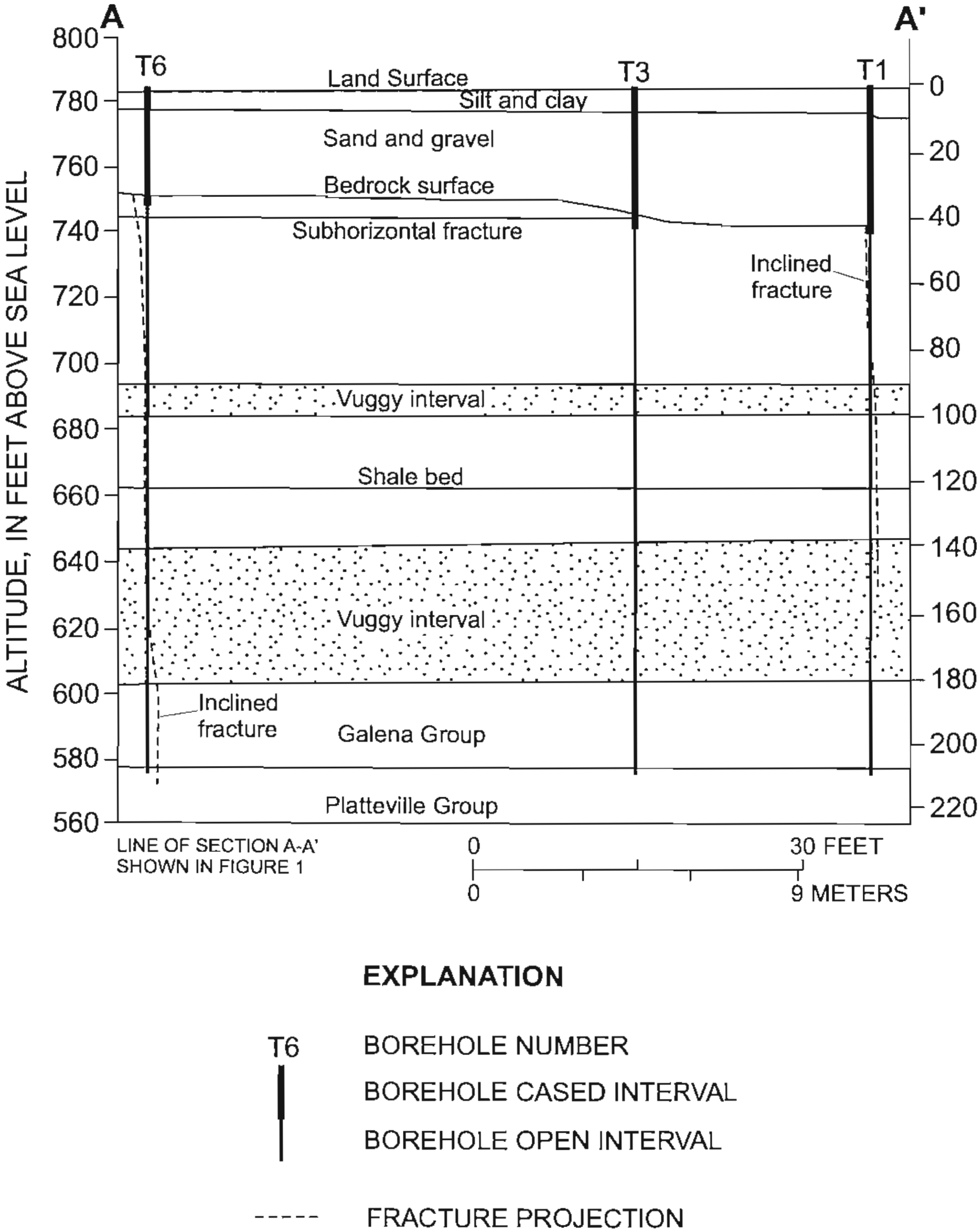


**Figure 2.** Geologic section A-A' at Parson's Casket Hardware Superfund site, Belvidere, Illinois.

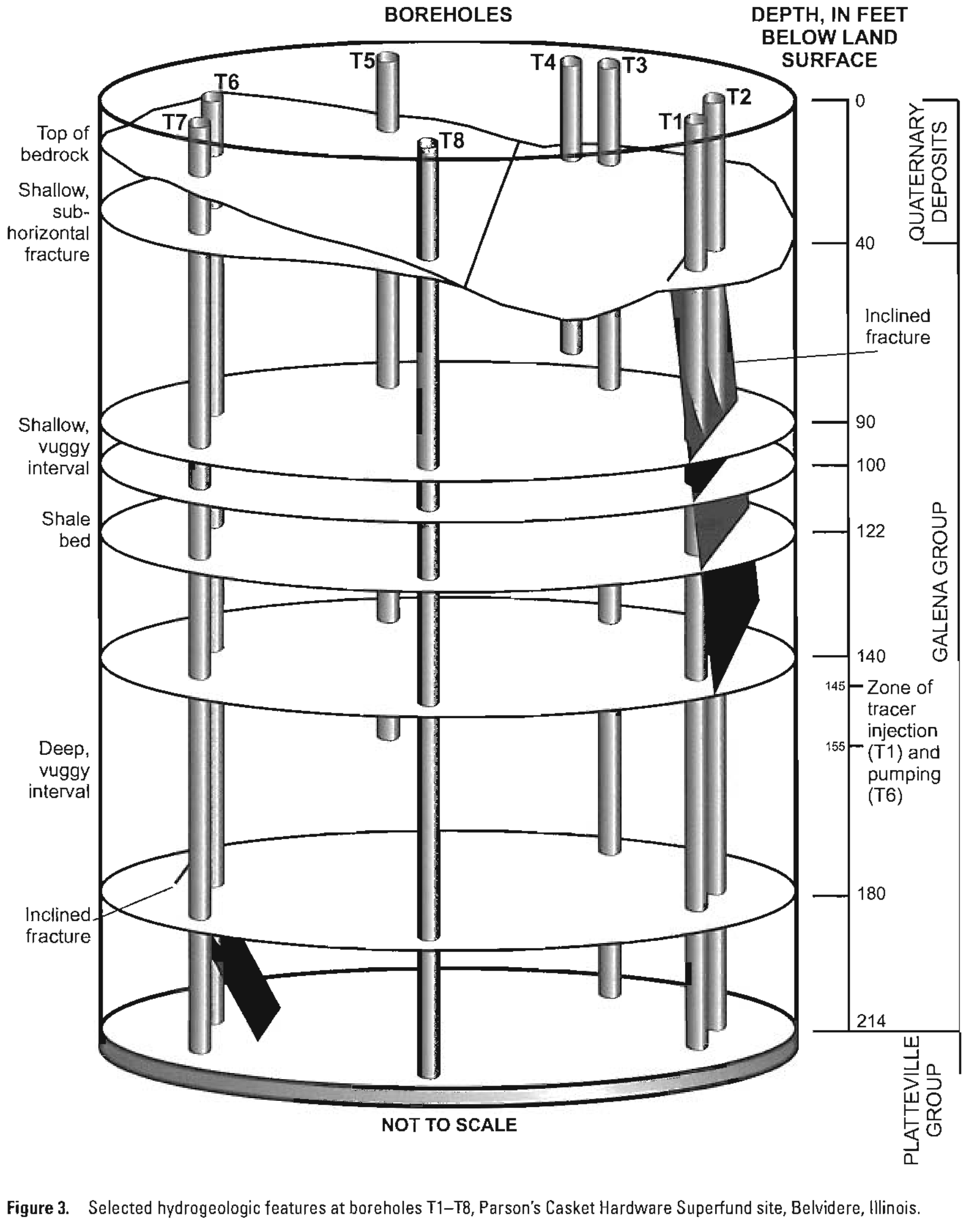


**Figure 3.** Selected hydrogeologic features at boreholes T1–T8, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

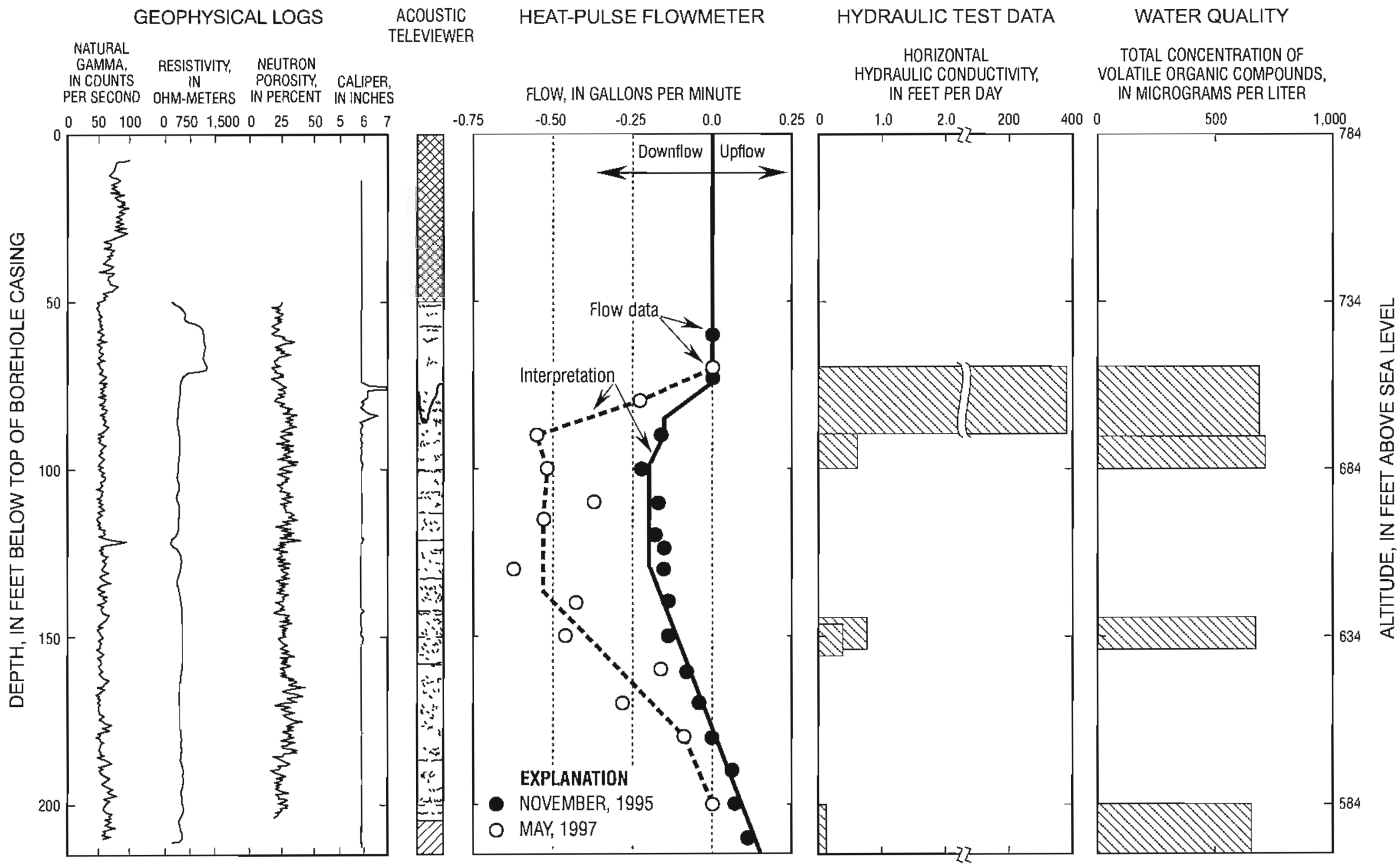


**Figure 4.** Natural-gamma, normal resistivity, neutron porosity, caliper, acoustic televiewer, flowmeter logs, horizontal hydraulic conductivities, and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole T1, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

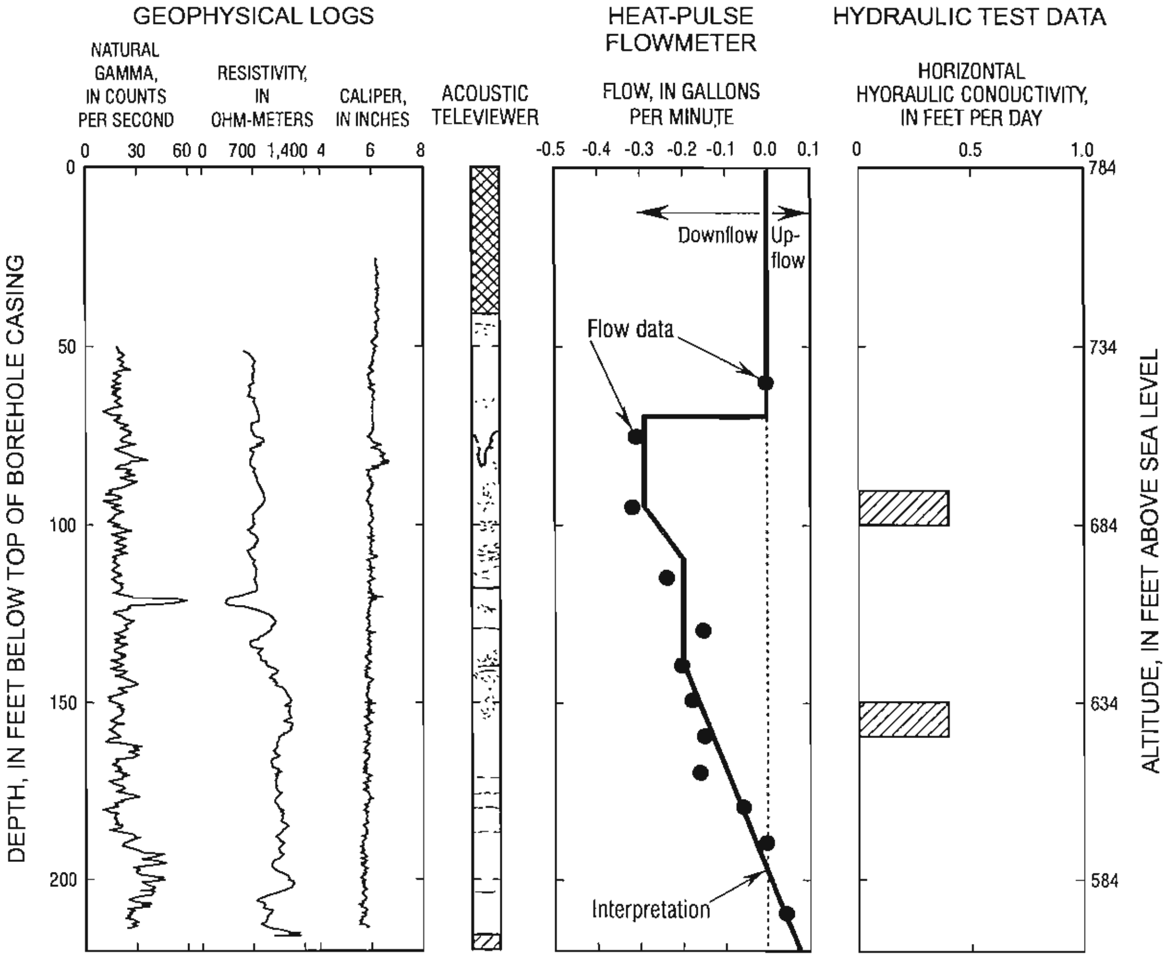


**Figure 5.** Natural-gamma, normal resistivity, caliper, acoustic televiewer, flowmeter logs, and horizontal hydraulic conductivities for borehole T2, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

tan($a$) is the tangent of the angle of intersection between the fracture and the borehole (5 degrees).

Solving equation (1) for $D$ indicates that the fracture is about 2 ft west of borehole T1 and 10 ft west of borehole T6, 50 ft below the top of the borehole casing. Borehole T1 is 60 ft from borehole T6 along a line 60 degrees west of north, which is nearly perpendicular to the orientation of the fractures. Assuming that these fractures actually are present to a depth of 50 ft and that the fracture orientations are nearly parallel, the inclined fractures identified at boreholes T1 and T6 are about 68 ft apart. This distance can be considered the maximum spacing of this fracture set.

A more accurate estimate of the fracture spacing, given that the data set consists of only two fractures, can be obtained if it is assumed that these boreholes are open to the dolomite for an average length ($L$) of about 175 ft (data on depths of open intervals are presented in table 1). The thickness of the dolomite penetrated normal to the orientation of the fracture ($DN$) is given by

$$DN = L \sin(a), \qquad (2)$$

where

sin($a$) is the sine of the angle of intersection between the fracture and the borehole (Terzaghi, 1965).

Solving equation (2) for $DN$ indicates each borehole intersects about 15 ft of dolomite normal to the fractures. Together, boreholes T1, T3, T6, and T8 intercept a total length of about 60 ft of dolomite normal to the fracture orientation. Because borehole T1 and T2 are oriented near the direction of fracture strike, the boreholes sample essentially the same length of rock and are not considered separately. The presence

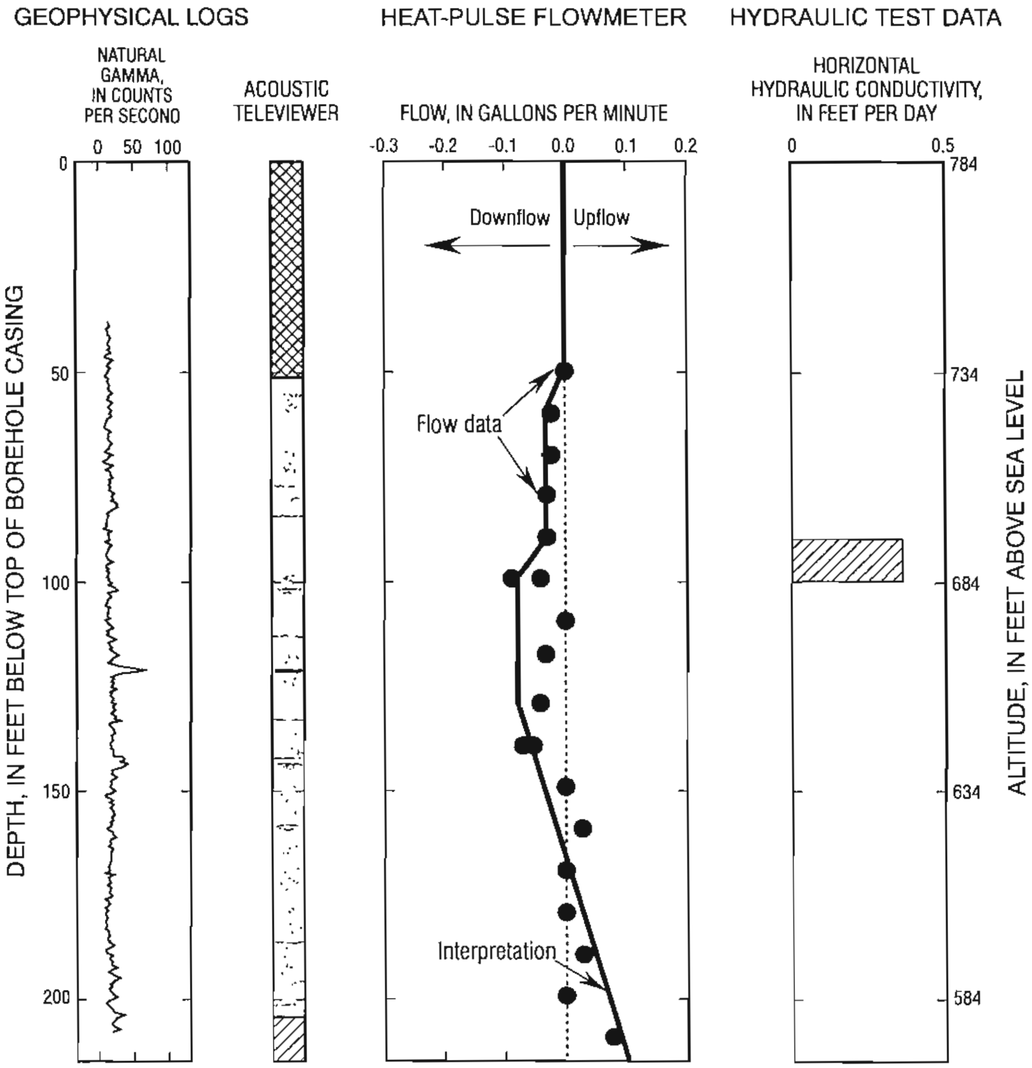


**Figure 6.** Natural-gamma, acoustic televiewer, flowmeter logs, and horizontal hydraulic conductivities for borehole T3, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

of two fractures in a sample of rock with a length of 60 ft indicates a fracture spacing of 30 ft in and around the study area. If the actual fracture spacing is 30 ft and fractures are observed to be present approximately 68 ft apart at boreholes T1 and T6, a third inclined fracture may be present approximately midway between boreholes T1 and T6.

Normal resistivity logs were run in boreholes T1, T2, T5, T6, T7 and T8 (figs. 4, 5, 7–10). Resistivity values were consistent for most of the length of the boreholes. Resistivity values lower than the typical values (about 500 ohm-meters for most logs) were measured at the depth of the shale bed at 122 ft and a fracture near 133 ft in all logs. Low normal-resistivity values are typical of porous and poorly consolidated deposits. Normal-resistivity values above 1,000 ohm-meters were measured above 72 ft in logs from boreholes T1, T6, and T7 (collected in March 1996) but were not detected in the logs from boreholes T1 and T7 (collected in November 1996) or in the logs from boreholes T2, T5, and T8 (collected in May 1997). It is assumed that the elevated resistivity values detected in March 1996 are inaccurate and not representative of actual conditions.

Single-hole directional radar reflection surveys were done in boreholes T1, T3, T6, and T8 using a 60 megahertz magnetic dipole directional antenna. During the surveys, the distance of penetration of the radar signal varied from about 15 to 30 ft. Single-hole directional radar reflection surveys have been used to

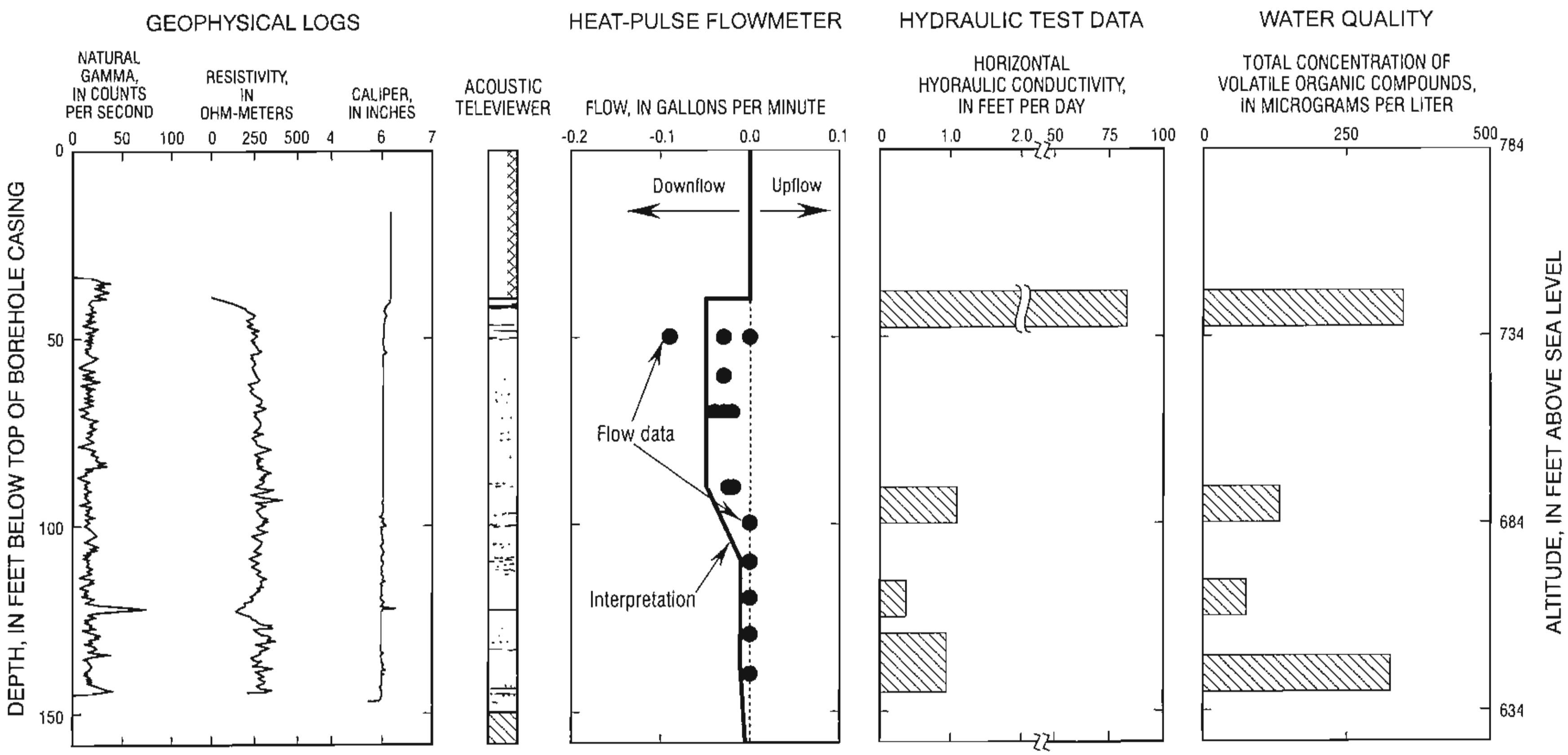


**Figure 7.** Natural-gamma, normal resistivity, caliper, acoustic televiewer, flowmeter logs, horizontal hydraulic conductivities, and total concentration of volatile organic compounds in the test intervals isolated with a packer assembly for borehole T5, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

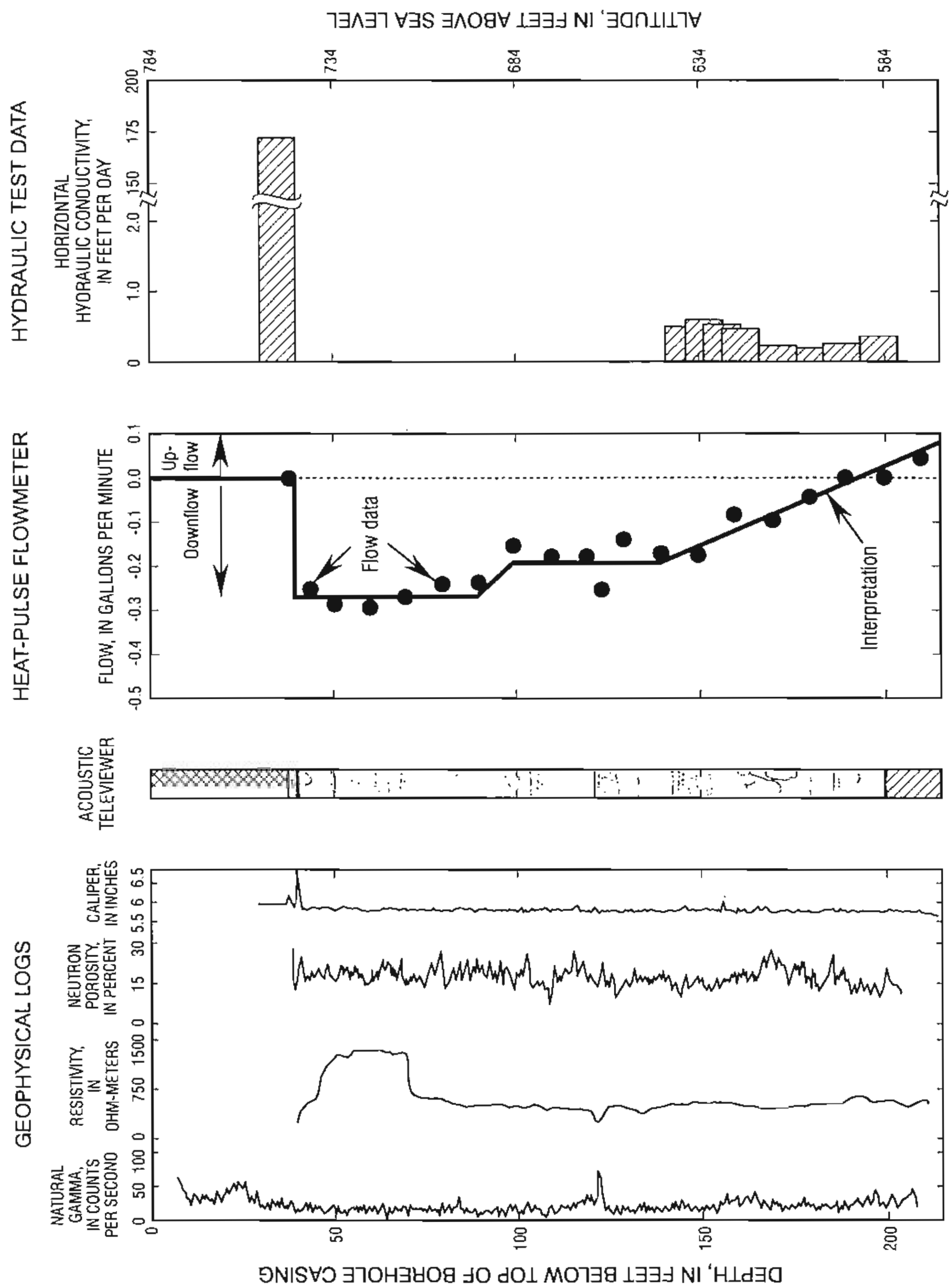


**Figure 8.** Natural-gamma, normal resistivity, neutron porosity, caliper, acoustic televiewer, flowmeter logs, and horizontal hydraulic conductivities for borehole T6, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

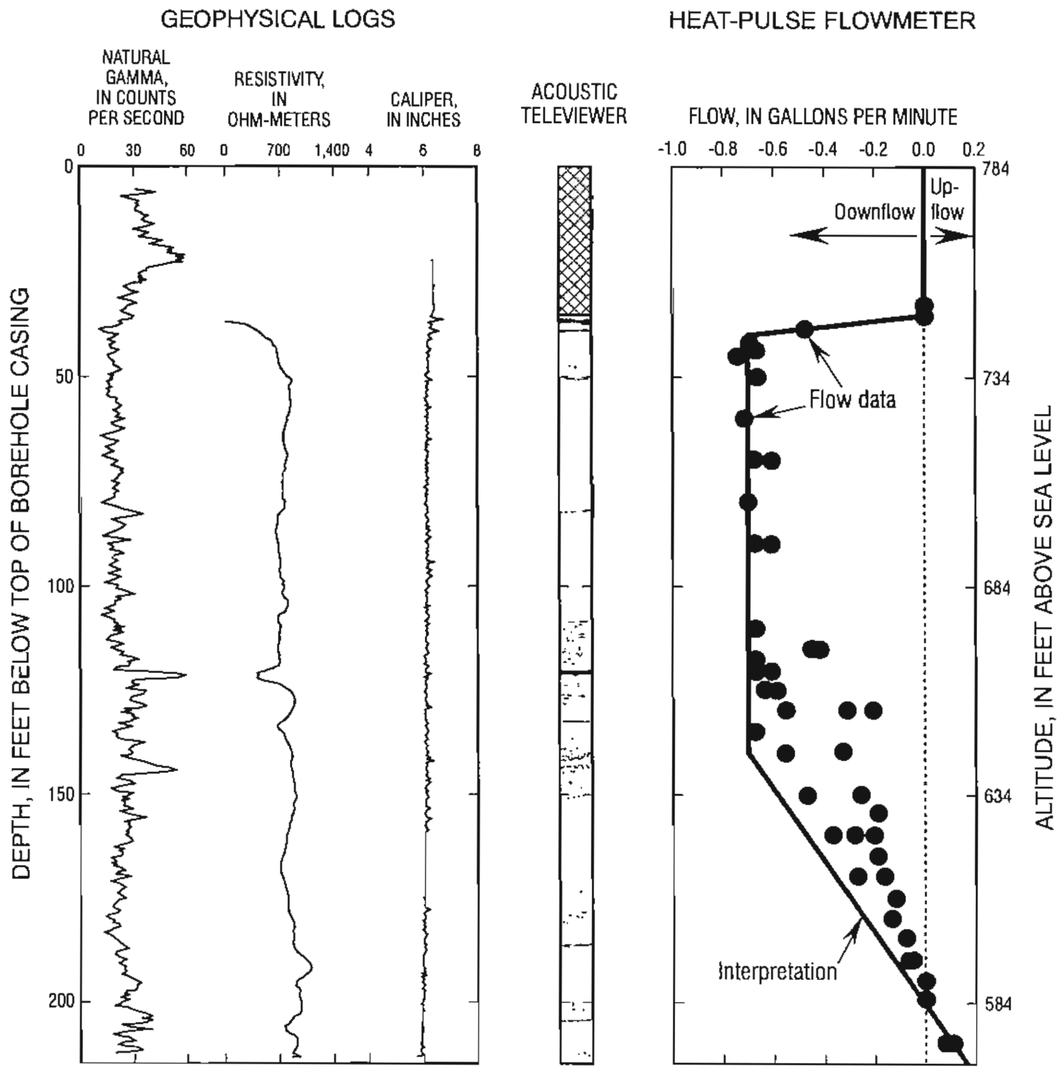


**Figure 9.** Natural-gamma, normal resistivity, caliper, acoustic televiewer, and flowmeter logs for borehole T7, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

identify the location and orientation of radar reflectors that may be associated with fractures in the dolomite (Falk, 1992; Lane and others, 1994).

Between 8 and 13 reflectors were identified in the vicinity of these boreholes (table 2). Two distinct populations of reflector orientation are interpreted from the radar reflection data. The most frequently measured direction of reflector strike is northeast-southwest from 30 to 50 degrees and its counterpart from 210 to 230 degrees. This orientation is consistent with the inclined fracture orientations identified at boreholes T1, T2, and T6 from the televiewer logging. A second population of reflectors strikes roughly north-south from 150 to 190 degrees. Most of the reflectors dip between 40 and 60 degrees from horizontal. Except for a subhorizontal reflector associated with the shale bed at about 122 ft, the reflectors do not project between boreholes. Comparison of the acoustic televiewer logs with the projected depth of intersection of the reflectors with the boreholes indicates the reflectors typically do not intersect the boreholes. The reflectors appear to be areally restricted and poorly connected, except through the matrix porosity.

A reflector that appears to be the steeply dipping fracture identified on the acoustic televiewer logs in boreholes T1 and T2 was interpreted from the radar reflection data for borehole T3 (data not shown). The reflector terminates somewhere between 147 and 164 ft, but it is probable that the inclined fracture

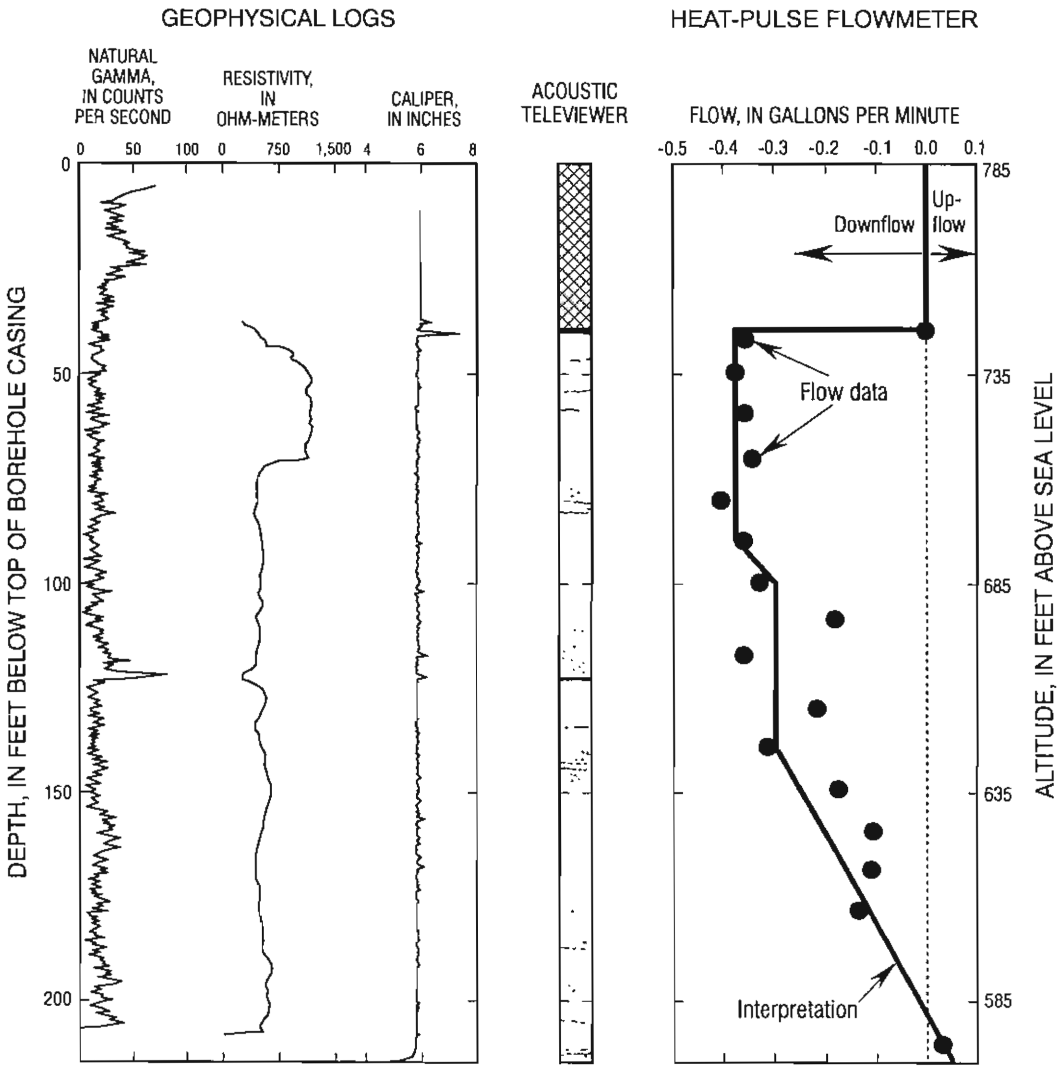


**Figure 10.** Natural-gamma, normal resistivity, caliper, acoustic televiewer, and flowmeter logs for borehole T8, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

actually extends below this depth. However, the disappearance of the reflector indicates the size of the inclined fracture decreases in the deeper part of the dolomite.

The inclined fractures observed in the acoustic televiewer logs at boreholes T1 and T6 were not measured by the borehole radar surveys done in these boreholes. There may be two possible explanations for this absence: (1) The fractures are discontinuous over their length or do not provide a high enough contrast in electromagnetic properties to generate a good reflection, or (2) The steep dip of the fractures combined with low-frequency ringing in the data might obscure the reflections. For a reflection to be identified in the radar record, the reflection must arrive at the receiver after the wave that propagates directly from the transmitter to the receiver (the direct arrival). The geometry created by the steep fracture dip and the limited well depth might prevent the fracture plane from being far enough from the borehole to be imaged by the 60 megahertz antennas. If the fracture is present in the images, the fracture is obscured by low-frequency ringing. The absence of an identified reflection, therefore, does not necessarily demonstrate the absence of fractures.

**Table 2.** Summary of reflector data identified during single-hole directional radar reflection surveys in boreholes T1, T3, T6, and T8, Parsons's Casket Hardware Superfund site, Belvidere, Illinois
[nd, no data]

| Borehole name (figure 1) | Strike of reflector (degrees from magnetic north) | Dip of reflector (degrees from horizontal) | Projected depth of intersection with borehole (feet below top of casing) |
|---|---|---|---|
| T1 | 50 | 81.9 | [1]-31.49 |
| T1 | 250 | 43.4 | 28.87 |
| T1 | nd | 68.4 | 52.49 |
| T1 | 50 | 49.9 | 117.78 |
| T1 | 30 | .0 | 123.69 |
| T1 | nd | 16.6 | 124.34 |
| T1 | nd | 38.9 | 141.08 |
| T1 | nd | 52.5 | 149.94 |
| T1 | nd | 36.4 | 150.92 |
| T1 | nd | 57.9 | 205.06 |
| T1 | 90 | 51.6 | 208.01 |
| T1 | 120 | 65.4 | 266.74 |
| T1 | 130 | 72.4 | 278.88 |
| T3 | nd | 84.9 | [1]-101.71 |
| T3 | 230 | 59.3 | 15.42 |
| T3 | nd | 48.6 | 39.37 |
| T3 | nd | 43.8 | 94.49 |
| T3 | nd | 48.9 | 110.56 |
| T3 | nd | .0 | 124.67 |
| T3 | 170 | 58.5 | 124.67 |
| T3 | 180 | 65.3 | 140.42 |
| T3 | 170 | 44.3 | 155.84 |
| T3 | nd | 37.6 | 171.92 |
| T3 | 230 | 38.9 | 167.65 |
| T3 | 210 | 46.8 | 141.73 |
| T3 | 230 | 64.2 | 84.64 |
| T6 | nd | 89.1 | [1]-2,138.88 |
| T6 | nd | 74.3 | [1]-28.54 |
| T6 | 150 | 55.3 | 14.76 |
| T6 | 40 | 40.1 | 94.16 |
| T6 | 220 | 41.3 | 105.32 |
| T6 | 40 | .0 | 125.00 |
| T6 | nd | 56.7 | 131.89 |
| T6 | nd | nd | 154.20 |
| T6 | nd | 40.9 | 155.84 |
| T6 | 190 | 64.6 | 215.88 |
| T6 | 150 | 74.9 | 270.35 |
| T8 | 30 | 38.3 | 37.07 |
| T8 | 60 | 34.5 | 93.83 |
| T8 | nd | 27.8 | 106.96 |
| T8 | 50 | .0 | 125.66 |
| T8 | 190 | 50.0 | 169.29 |
| T8 | 50 | 53.8 | 203.75 |
| T8 | 40 | 52.6 | 230.65 |
| T8 | 10 | 70.3 | 255.26 |

[1]Negative value indicates the projected intersection with the borehole is above the top of the casing.

Cross-borehole ground-penetrating radar surveys were done using the T2–T7, T2–T8, T2–T3, T3–T8, T3–T7, and T7–T8 borehole pairs. Cross-borehole surveys measure the velocity and attenuation of the radar pulse between the two investigated boreholes. The velocity of the pulse through the dolomite is affected primarily by the presence of water-bearing fractures and porous matrix. Velocity data were used to calculate the porosity of the dolomite deposits between the borehole pairs. The attenuation of the pulse through the dolomite is affected primarily by the mineralogy and competence of the rock. Areas of variation in the velocity and attenuation of the signal identified from the cross-borehole radar-tomography surveys can be interpreted as lithologic boundaries or intervals of variation in primary or secondary porosity. Intervals of low signal velocity and high attenuation typically are associated with elevated porosity or high amounts of clay minerals. A summary of the anomalies identified from the ground-penetrating radar tomographic surveys is presented in table 3.

Comparison of the velocity and attenuation tomograms from the different borehole pairs indicates a fairly uniform lithologic sequence across the site with some variation between different borehole pairs. The lithology identified in the tomograms can be divided into three major units. The depth of these units, particularly the lowermost unit, varies within the study area. The lowermost unit is present below 180 ft and is characterized by low attenuation and high velocity (table 3; figs. 11, 12). This unit consists of competent, unfractured dolomite with porosity from 12 to 13 percent, based on the tomogram response. The middle unit is present between 82 and 180 ft and is characterized by low velocity with alternating beds of high and low attenuation. This unit consists of generally competent bedrock with alternating beds of low and high porosity. The porosity of most of this interval was calculated to be about 13 percent on the basis of the response of the tomogram. Tomograms indicated porosity values from 13.5 to 14 percent from about 89 to 101 ft and at about 115 ft. Porosity values from 13.5 to 15 percent are indicated from about 167 to 177 ft. Porosity values from 12 to 13 percent were calculated at about 106 ft. The uppermost unit is present from about 82 ft to about 5 ft below the bottom of the borehole casing, where the signal is lost. This unit is characterized by low attenuation and high velocity, indicating that the dolomite is competent.

**Table 3.** Summary of borehole-ground-penetrating radar tomographic anomalies, Parson's Casket Hardware Superfund site, Belvidere, Illinois

[d, discontinuous anomaly; <, less than, >, greater than]

| Borehole pair (figure 1) | Time period | Depth of low-velocity intervals (feet below top of borehole casing) | Depth of high-velocity intervals (feet below top of borehole casing) | Depth of low-attenuation intervals (feet below top of borehole casing) | Depth of high-attenuation intervals (feet below top of borehole casing) |
|---|---|---|---|---|---|
| T2–T7 | Background | 92, 118, 134d 107.5, 170.5 | <82, 105, >180 | <79, 170.5, >180 | 121, 141 82–105 by borehole T2 |
| T2–T8 | Background | 92, 118, 134d, 107.5, 170.5 | <82, >180 | <79, >164 | 105, 121, 138 |
| T3–T2 | Background | 98–131, 170.5 | <82, >180 | <79 | 115–131 |
| T3–T8 | Background | 92, 115, 131d, 107.5, 170.5 | <72, >190 | <82, 170.5, >174 | 124.7, 144 |
| T7–T3 | Background | 92, 115, 138d, 170.5 | <78, >180 | <78, >164 | Alternating high and low; 118–154 |
| T7–T8 | Background | 92, 115, 134d, 167 | <82, >180 | <82, >167 | 121–124.7 |
| T2–T8 | 12–18 hours after tracer injection | Not applicable | Not applicable | Not applicable | 147–154 |
| T2–T8 | 34–38 hours after tracer injection | Not applicable | Not applicable | Not applicable | 144–164 |
| T2–T8 | Difference, hackground and 12–18 hours after tracer injection | Not applicable | Not applicable | Not applicablc | 144–157 |
| T2–T8 | Difference, background and 34–38 hours after tracer injection | Not applicahle | Not applicable | Not applicable | 138–164, 115 by borehole T8 |

The porosity of this interval was calculated to be from 11 to 12.5 percent.

Although the absolute porosity values measured from the neutron porosity logs were greater than from the tomograms, trends in porosity values obtained from the tomograms generally are consistent with the trends of the neutron porosity logs done in boreholes T1 and T6 (figs. 4, 8). Neutron porosity logs in boreholes T1 and T6 indicate variable porosity throughout that part of the dolomite open to the borehole. Although the depths vary between the boreholes, intervals of lower porosity were detected above 75–80 ft and below 190 ft (figs. 4, 8). Intervals of higher porosity were detected from about 75–100, 110–120, and 165–185 ft.

Porosity values measured at core samples collected from the boring for wells G115BD and PCHG125B ranged from 5.3 to 14.2 percent from 30 to 82 ft (Mills and others, 1998), with a mean value of 9.4 percent. Porosity values measured at core samples collected from the boring for well G115BD ranged from 8.7 to 24.8 percent between 83 and 180 ft, with a mean value of 13.8 percent. Porosity values measured at core samples collected from the boring for well G115BD ranged from 6.1 to 12.1 percent between 181 and 215 ft, with a mean value of 7.9 percent. These values generally are consistent with the porosity values determined from the velocity and attenuation tomograms but are substantially lower than the values obtained from the neutron porosity logging.

## HYDROLOGY

The hydrologic units of concern in the study area can be divided into the semiconfining unit, the unconsolidated aquifer, the Galena-Platteville aquifer, and the St. Peter Sandstone aquifer. The semiconfining unit is composed of unconsolidated silt and clay deposits that overlie the unconsolidated aquifer (Science Applications International Corporation, 1993). The unconsolidated aquifer is composed of saturated sand-and-gravel deposits. The saturated sand and gravel deposits that compose the unconsolidated aquifer are likely to be in good hydraulic connection with the underlying Galena-Platteville aquifer, particularly near the top of the Galena-Platteville aquifer where it is

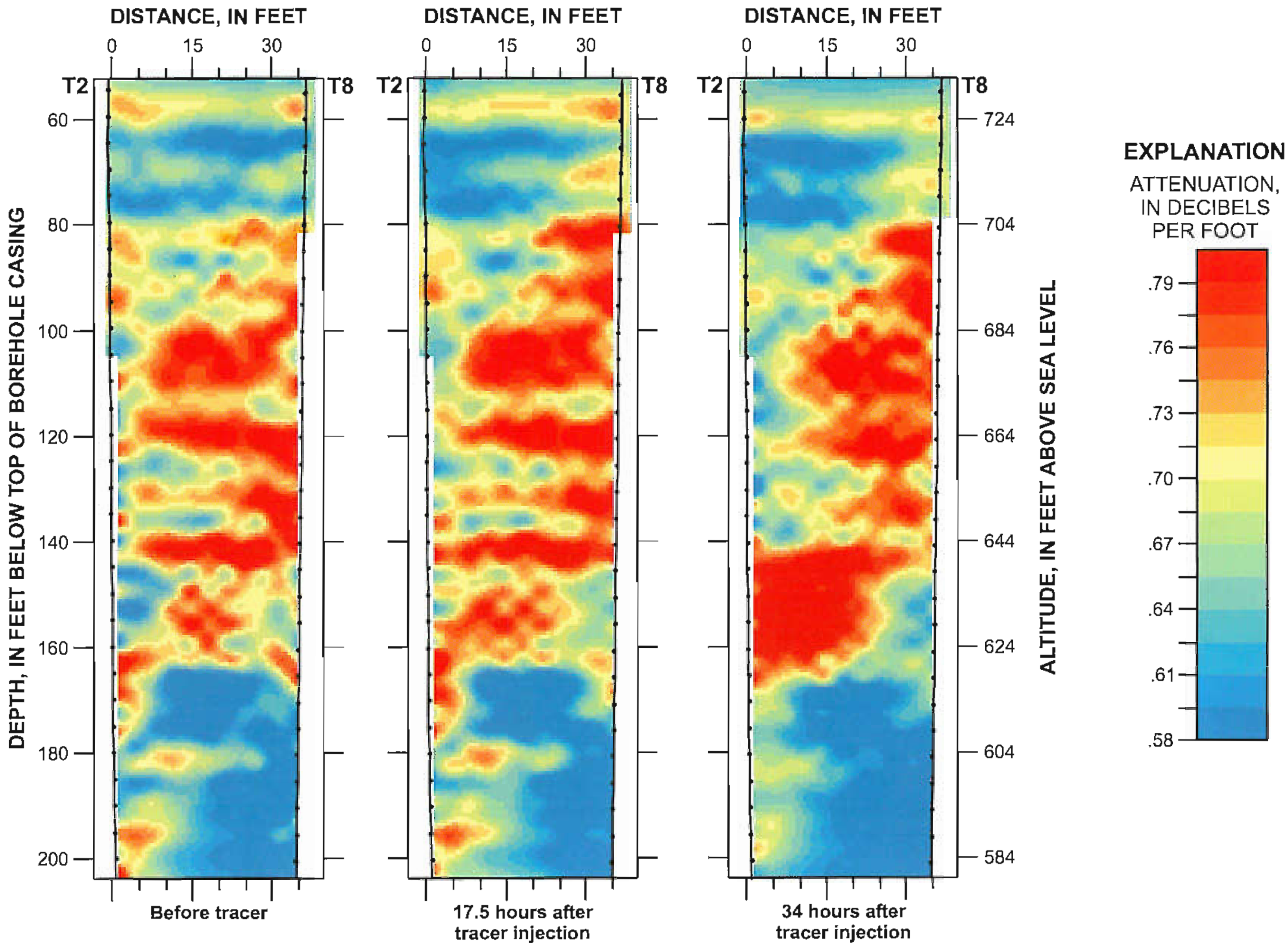


**Figure 11.** Borehole radar attenuation tomogram between boreholes T2 and T8 before the tracer test and at 17.5 and 34 hours after tracer injection, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

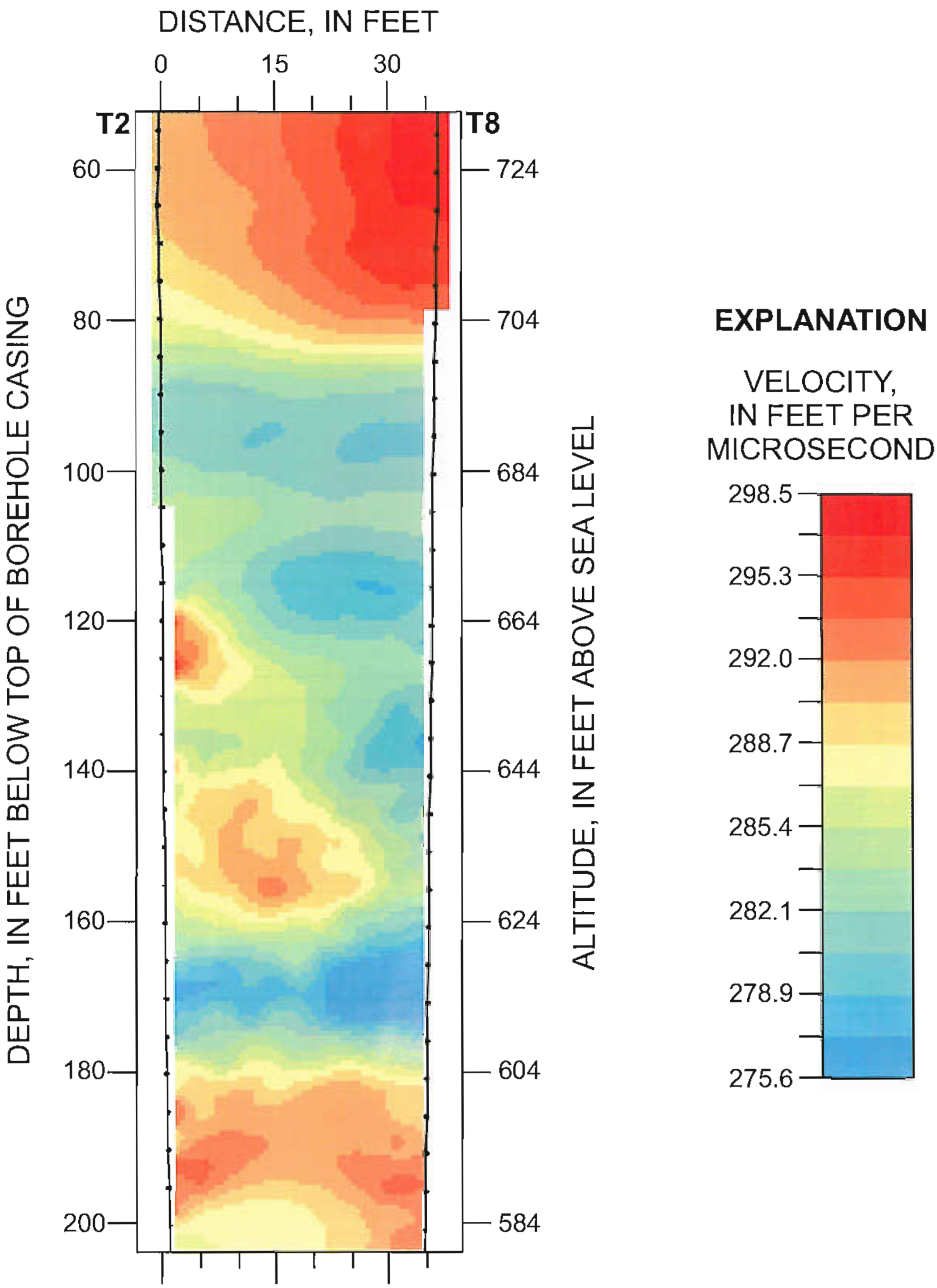


**Figure 12.** Borehole radar velocity tomogram between boreholes T2 and T8, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

highly weathered. The St. Peter Sandstone aquifer underlies the Galena-Platteville aquifer and is composed of the sandstones of the Glenwood and St. Peter Formations. Hydraulic interconnection between the St. Peter Sandstone aquifer and the upper part of the Galena-Platteville aquifer in this area is minimal. This study focused on the part of the Galena-Platteville aquifer above a depth of 215 ft. The hydrology of the unconsolidated and St. Peter Sandstone aquifers and the lower part of the Galena-Platteville aquifer are not discussed in this report, except as they pertain to the hydraulic response of the upper part of the Galena-Platteville aquifer in the study area.

### Water Levels

Vertical variations in water levels within the upper part of the Galena-Platteville aquifer were measured in discrete test intervals isolated with a packer assembly in April, September, and October 1996 (table 4). The packer assembly consists of two 4-ft long inflatable nitrile packers separated by 10 ft (20 ft for the 70 to 90 ft interval in borehole T1) of stainless-steel screen (fig. 13). The packer assembly was constructed so that ground-water levels could be measured above, within, and below the test intervals after the packers were inflated and the water levels had equilibrated. Water levels above, within, and below the test intervals were not equal, which indicates the packers were effectively isolating the test intervals from the rest of the borehole.

Test intervals isolated with the packer assembly consisted of most of the open interval of borehole T1 and parts of boreholes T2, T3, T5, T6, T7, and T8 (table 4). Water levels obtained from the test intervals indicate the potential for downward flow within the Galena-Platteville aquifer above about 186 ft throughout the study area. Water-level data from borehole T6, and perhaps boreholes T1 and T7, indicate the potential for upward ground-water flow below a depth of about 186 ft during at least some of the periods of measurement.

Water levels obtained using the packer assembly can be used to indicate the relative permeability of the aquifer at the test intervals. The water level in an open borehole is affected by the vertical distribution of water levels and aquifer permeability in the borehole (Sokol, 1963). If there are no substantial differences in the permeability of the aquifer at the borehole, the water level in the borehole is an average of the water level at each point in the aquifer along the open interval. However, if one part of the aquifer at the borehole is substantially more permeable than the aquifer in the remainder of the open interval, the water level in the borehole will approximate the water level of the most permeable interval. Comparison of the water levels above, within, and below the test intervals with the water level in the open borehole, therefore, can be used to identify intervals of elevated permeability within the borehole.

Water levels measured before the packers were inflated in boreholes T5–T8 differed by less than 0.10 ft from the water level in the test interval when the test interval was open to the subhorizontal fracture from 37–40 ft (table 4, figs. 7–10). As the parts of the aquifer below 40 ft were isolated with the packer assembly, the difference between the water level in the test interval and the open borehole increased, whereas the water level above the test interval (which was open to the subhorizontal fracture) always approximated the water level measured in the open borehole before packer inflation. The similarity between the water level in the open borehole and the water level in the interval open to the shallow, subhorizontal fracture indicates the shallow, subhorizontal fracture is the most permeable feature in these boreholes and has a substantial effect on the water level in the open borehole.

As parts of the aquifer below 90 ft in boreholes T1 and T2 were isolated with the packer assembly, the difference between the water levels in the test interval and the water level in the open boreholes increased. The water level above the test interval, which was open to the inclined fracture above 90 ft, typically differed by less than 0.20 ft from the water level in the open borehole. The similarity between the water levels in the open borehole and the water levels in the interval open to the inclined fracture indicates the inclined fracture is permeable.

Water levels taken before packer inflation in borehole T3 differed from the water levels in the test intervals after packer inflation by more than 0.25 ft (table 4). There is no indication from the water-level data that any one interval in borehole T3 is substantially more permeable that any other interval.

Water levels were monitored in wells G127SP and G127GP, and in test intervals between 40–176 (T8APZ), 180–190 (T8PZ), and 194–215 ft (T8BPZ) in borehole T8, from October 5–November 18, 1998, to establish the effects of pumping from offsite wells on vertical flow in the aquifer (figs. 14, 15). The test

**Table 4.** Depth to water measured during testing with a packer assembly under approximately hydrostatic conditions, Parson's Casket Hardware Superfund site, Belvidere, Illinois, 1996

[na, not applicable; nt, measurement not taken]

| Borehole name (figure 1) | Date of measurement | Depth of test interval (feet below top of borehole casing) | Depth to water (feet below top of borehole casing) | | | |
|---|---|---|---|---|---|---|
| | | | Open borehole before packer inflation | Above test interval | In test interval | Below test interval |
| T1 | 4/16/96 | 200–215 | 22.50 | 24.12 | 26.58 | na |
| T1 | 4/16/96 | 144–154 | nt | 24.08 | 25.55 | 25.60 |
| T1 | 4/17/96 | 90–100 | nt | 23.99 | 24.37 | 24.94 |
| T1 | 4/17/96 | 70–90 | nt | 25.40 | 25.71 | 26.14 |
| T1 | 9/10/96 | 90–100 | 20.25 | 20.19 | 20.26 | 20.72 |
| T1 | 9/11/96 | 90–100 | nt | 20.35 | 20.39 | 20.95 |
| T1 | 9/13/96 | 90–100 | nt | 20.21 | 20.86 | 22.32 |
| T1 | 9/17/96 | 145–155 | nt | 20.53 | 21.29 | 21.26 |
| T1 | 9/18/96 | 145–155 | nt | 20.54 | 21.31 | 21.44 |
| T1 | 9/27/96 | 145–155 | 20.87 | 20.57 | 21.28 | 21.35 |
| T1 | 10/24/96 | 146–156 | 21.02 | 21.00 | 22.06 | 22.53 |
| T1 | 10/24/96 | 146–156 | nt | 21.02 | 22.76 | 23.55 |
| T1 | 10/28/96 | 156–166 | 21.11 | 21.05 | 24.20 | 24.88 |
| T1 | 10/30/96 | 49–86 | 21.14 | na | 21.03 | 23.73 |
| T1 | 10/31/96 | 49–86 | 21.29 | na | 20.94 | 22.52 |
| T2 | 9/13/96 | 90–100 | nt | 19.99 | 20.79 | na |
| T2 | 10/24/96 | 151–161 | 20.88 | 20.80 | 21.49 | 22.36 |
| T2 | 10/24/96 | 151–161 | 20.88 | 20.75 | 21.99 | 22.91 |
| T2 | 10/24/96 | 151–161 | 20.88 | 20.76 | 22.62 | 23.62 |
| T2 | 10/24/96 | 146–156 | nt | 20.73 | 23.19 | 24.39 |
| T2 | 10/25/96 | 146–156 | nt | 20.98 | 25.51 | 26.81 |
| T2 | 10/28/96 | 157–167 | 20.83 | 20.77 | 23.84 | 24.89 |
| T2 | 10/30/96 | 90–100 | 20.86 | 20.75 | 22.34 | 23.62 |
| T2 | 10/31/96 | 90–100 | 20.82 | 20.65 | 21.16 | 21.70 |
| T3 | 10/24/96 | 146–156 | 21.97 | 21.37 | 25.65 | 26.69 |
| T3 | 10/28/96 | 156–166 | 22.00 | 21.54 | 24.07 | 24.70 |
| T3 | 10/30/96 | 90–100 | 21.52 | 21.25 | 22.58 | 24.05 |
| T3 | 10/30/96 | 90–100 | 21.50 | 21.00 | 21.06 | 21.82 |
| T5 | 9/11/96 | 90–100 | nt | 19.86 | 20.10 | 24.36 |
| T5 | 9/13/96 | 90–100 | nt | 19.94 | 20.53 | 21.47 |
| T5 | 10/24/96 | 116–126 | 20.69 | 20.68 | 20.86 | 22.13 |
| T5 | 10/25/96 | 116–126 | nt | 20.67 | 20.92 | 23.77 |
| T5 | 10/28/96 | 116–126 | nt | 20.70 | 20.93 | 21.63 |
| T5 | 10/30/96 | 30–46 | 20.75 | na | 20.70 | 22.75 |
| T6 | 9/12/96 | 90–100 | 20.49 | 20.48 | 20.75 | 22.30 |
| T6 | 9/13/96 | 90–100 | 20.53 | 20.52 | 21.50 | 22.83 |
| T6 | 9/13/96 | 145–155 | nt | 20.52 | 22.66 | 23.87 |
| T6 | 9/18/96 | 145–155 | nt | 20.63 | 20.66 | 21.35 |
| T6 | 10/21/96 | 37–40 | 21.26 | na | 21.24 | 21.70 |
| T6 | 10/22/96 | 37–40 | 21.27 | na | 21.25 | 21.70 |
| T6 | 10/22/96 | 176–186 | 21.22 | 21.22 | 23.55 | 24.55 |
| T6 | 10/22/96 | 183–193 | 21.26 | 21.22 | 24.08 | 23.99 |
| T6 | 10/22/96 | 183–193 | nt | 21.22 | 24.50 | 24.44 |
| T6 | 10/22/96 | 193–203 | 21.23 | 21.23 | 24.75 | 24.60 |
| T6 | 10/23/96 | 141–151 | 21.25 | 21.25 | 22.05 | 23.05 |
| T6 | 10/23/96 | 151–161 | 21.29 | 21.27 | 22.37 | 23.66 |
| T6 | 10/23/96 | 156–166 | 21.27 | 21.28 | 22.58 | 24.02 |
| T6 | 10/23/96 | 166–176 | 21.32 | 21.26 | 22.85 | 24.34 |
| T6 | 10/25/96 | 145–155 | 21.19 | 21.25 | 25.56 | 26.75 |

**Table 4.** Depth to water measured during testing with a packer assembly under approximately hydrostatic conditions, Parson's Casket Hardware Superfund site, Belvidere, Illinois, 1996—Continued

| Borehole name (figure 1) | Date of measurement | Depth of test interval (feet below top of borehole casing) | Depth to water (feet below top of borehole casing) | | | |
|---|---|---|---|---|---|---|
| | | | Open borehole before packer inflation | Above test interval | In test interval | Below test interval |
| T6 | 10/28/96 | 156–166 | 22.12 | 21.30 | 24.34 | 25.67 |
| T6 | 10/30/96 | 37–45 | 21.34 | na | 21.30 | 23.54 |
| T6 | 10/31/96 | 37–45 | 21.30 | na | 21.22 | 22.71 |
| T7 | 9/12/96 | 90–100 | 20.32 | 20.29 | 19.96 | na |
| T7 | 9/13/96 | 90–100 | nt | 20.38 | 21.19 | na |
| T7 | 9/13/96 | 90–100 | nt | 20.35 | 20.55 | na |
| T7 | 10/25/96 | 145–155 | 20.99 | 21.06 | 25.46 | 27.52 |
| T7 | 10/28/96 | 156–166 | 21.12 | 21.10 | 24.17 | 25.40 |
| T7 | 10/30/96 | 35–46 | 21.17 | na | 21.11 | 23.55 |
| T7 | 10/31/96 | 35–46 | 21.05 | na | 21.01 | 22.75 |
| T8 | 10/24/96 | 145–155 | 21.30 | 21.30 | 23.25 | 23.89 |
| T8 | 10/24/96 | 145–155 | nt | 21.30 | 23.89 | 24.53 |
| T8 | 10/25/96 | 145–155 | nt | 21.29 | 26.35 | 27.51 |
| T8 | 10/28/96 | 156–166 | 21.32 | 21.32 | 24.52 | 25.69 |
| T8 | 10/30/96 | 39–46 | 21.37 | na | 21.32 | 24.13 |
| T8 | 10/31/96 | 39–46 | 21.26 | na | 21.25 | 22.13 |

intervals in borehole T8 were isolated with a packer assembly. Water-level changes in wells G127SP and G127GP, and the test intervals in borehole T8 were measured every 15 minutes with a calibrated pressure transducer and recorded by a datalogger. Periodic comparisons of water levels obtained from the transducer data with water levels obtained from electric tapes showed agreement within 0.10 ft. Belvidere municipal well no. 4 (BMW4), located within 0.5 mi of the study area, was the only well pumped during most of the monitoring period because Belvidere municipal well no. 6 was being serviced (fig. 1). Belvidere municipal well no. 6 (BMW6), located within 0.25 mi of the study area, was test pumped at about 2,610; 4,230; 5,385; 9,780; 20,160; and 21,510 minutes into the monitoring period and returned to normal service about 55,000 minutes into the monitoring period. The municipal wells are open from the upper part of the Galena Dolomite to a depth of 868 ft for well BMW6 and 1,800 ft for well BMW4 (table 1). Well BWM6 obtains water primarily from the St. Peter Sandstone and Ironton-Galesville aquifers and is pumped for extended periods of time. Well BMW4 obtains water primarily from the St. Peter Sandstone, Ironton-Galesville, and Mt. Simon aquifers and is pumped frequently for short periods of time. A horizontal bedding-plane fracture is present in the Platteville Group at about a depth of 260 ft at well G127GP (Mills, 1993b). It is assumed this fracture also is present beneath the study area. This fracture also was identified at a monitoring well within 40 ft from well BMW6 (Mills, 1993b; Mills and others, 1998). It is unclear if this fracture is present at well BMW4.

Water levels in wells G127GP and G127SP, as well as the T8PZ and T8BPZ intervals in borehole T8, showed good correlation with each other and large (greater than 1.0 ft), abrupt changes in water level that are interpreted to be in response to pumping cycles in wells BMW4 and BMW6 (figs. 14, 15). The trend in water levels is consistent with the results of previous investigations, which demonstrated that water levels in wells G127GP and G127SP are affected by pumping cycles in wells BMW4 and BMW6 (Mills, 1993b; Mills and others, 1998).

During the entire period of monitoring, water levels in the St. Peter Sandstone aquifer at monitoring well G127SP varied from about 62 to 71 ft below the well casing (713.88 to 722.95 ft above sea level) (fig. 14). Depth to water in well G127SP typically was between 63 and 67 ft but decreased by as much as 5 ft when well BMW6 was pumped. Water levels in well G127SP showed a smaller, more subdued response to pumping cycles in well BMW4.

Water levels near the bottom of the Galena-Platteville aquifer at well G127GP varied from about 48 to 76 ft below the well casing (708.83 to 737.67 ft

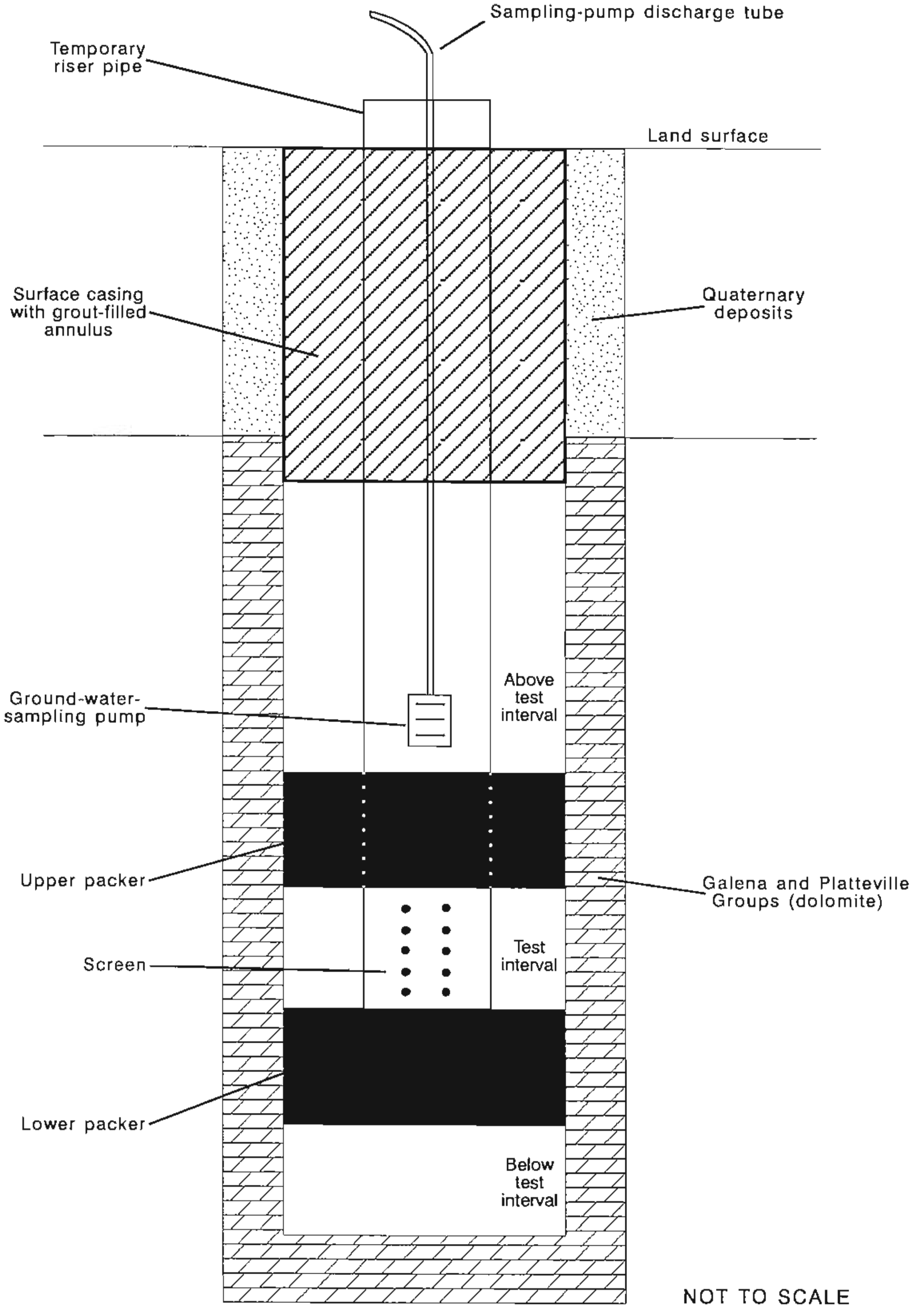


**Figure 13.** Packer assembly and ground-water-sampling pump in a borehole.

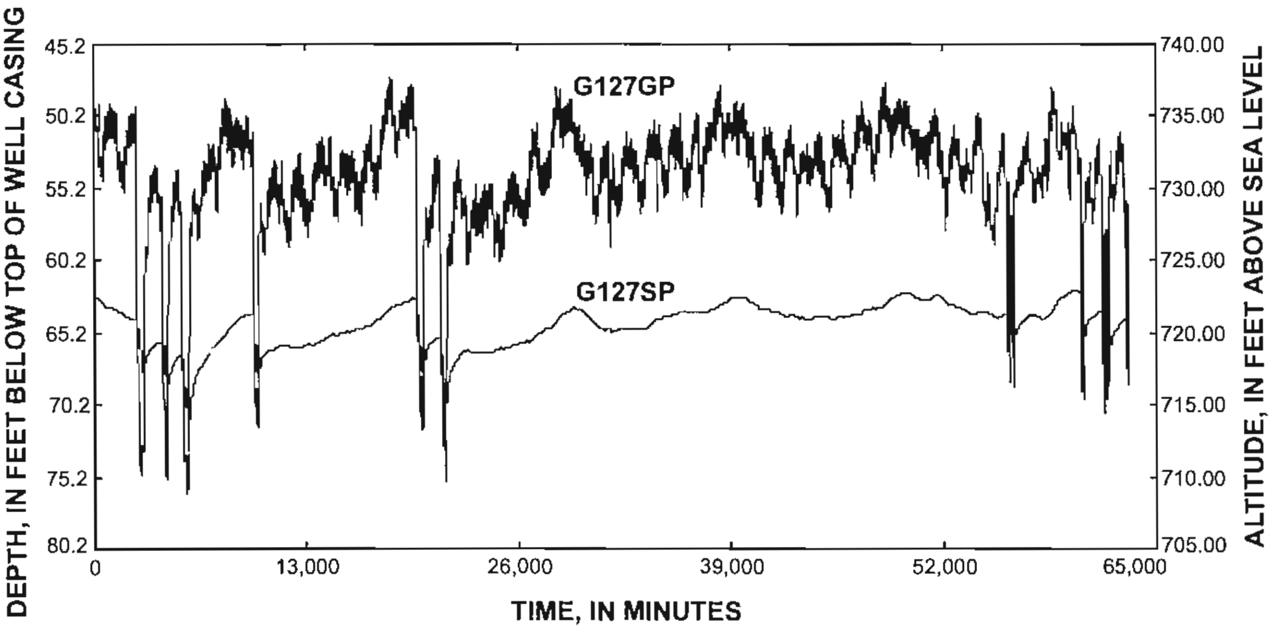


**Figure 14.** Water levels in wells G127SP and G127GP, October 5–November 18, 1998, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

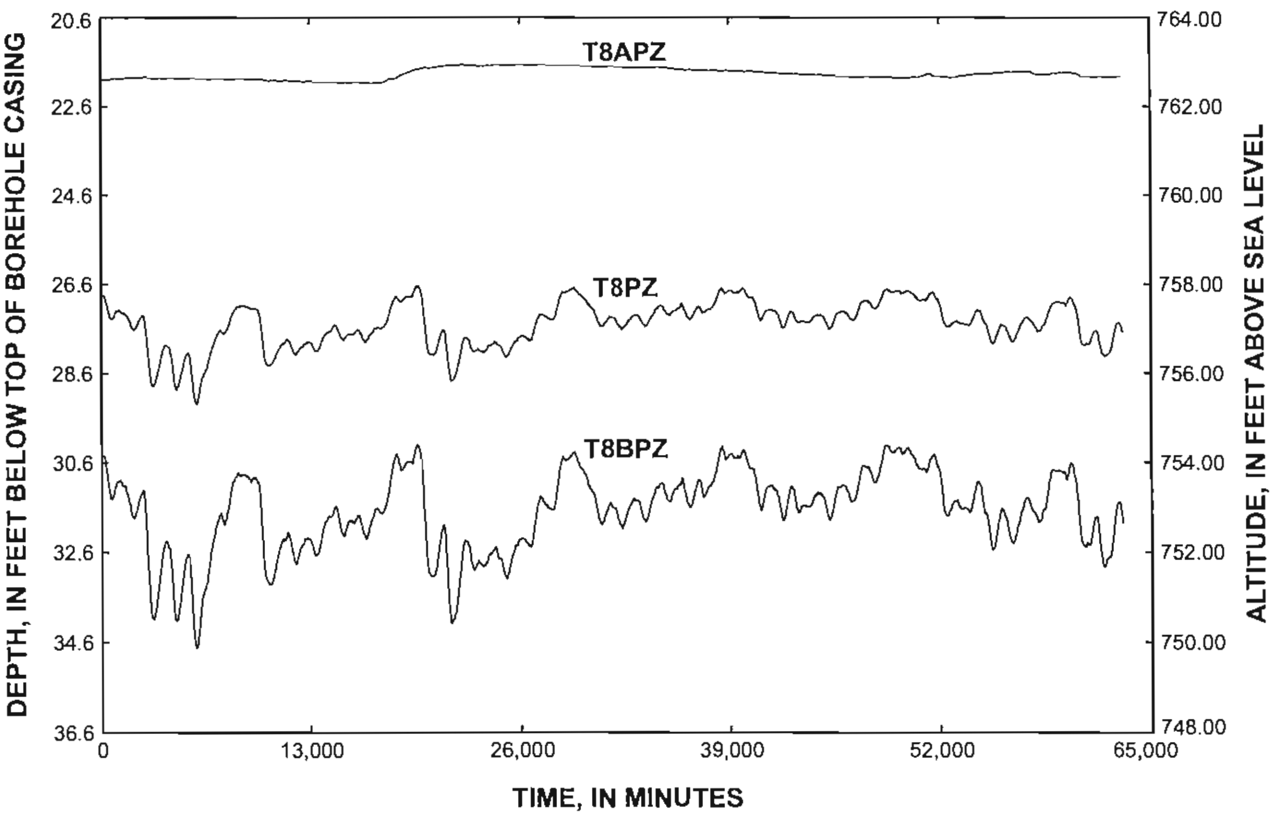


**Figure 15.** Water levels in the T8APZ, T8PZ, and T8BPZ intervals of borehole T8, October 5–November 18, 1998, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

previous investigations in boreholes surrounding the study area (Mills, 1993b, 1993c). Inflow was identified from shallow fractures near the top of the dolomite, as well as from the matrix porosity from 90 to 100 ft. However, substantial inflow was identified (by previous investigators) from the shaley interval at 122 ft in boreholes surrounding the study area but was not observed in the study area during the current investigation. In addition, the flow measured from 140 to 190 ft in the study area was not observed during previous investigations, nor reversals in flow direction below 180 ft.

Comparison of the data from the flowmeter logging and the borehole ground-penetrating radar tomography indicates minimal ground-water flow through the competent, low-porosity dolomite above 82 ft, unless fractures are present to transmit the flow. The flowmeter and ground-penetrating radar data also indicate that only a small amount of flow is through the competent, low-porosity dolomite below about 180 ft. Flowmeter data indicate the presence of elevated amounts of ground-water flow through matrix porosity at intervals from about 90 to 100 ft and 140 to 180 ft. There is no apparent correlation between depths of elevated porosity identified from the ground-penetrating radar tomography at 115 ft and increased ground-water flow. Although part of the interval of increased flow from 140 to 180 ft, flowmeter logs indicate the interval of elevated porosity identified by the borehole ground-penetrating radar at 167–177 ft does not have substantially more flow than the rest of the 140–180 ft interval. The interval of elevated porosity identified by the ground-penetrating radar tomography at 92 ft is associated with an interval of increased flow.

Interpretation of all available geophysical and water-level data indicates that pumping in wells BMW4 and BMW6 induces drawdown in the fractures and vugs in the deeper part of the Galena-Platteville aquifer, including the horizontal fracture at about 260 ft. Drawdown is transmitted vertically upward, potentially through the features such as the deep inclined fracture observed at borehole T6, through the aquifer to a depth of at least 180 ft. If pumping continues for a sufficiently long period of time, or perhaps using a proper combination of wells, preferential hydraulic communication between a horizontal feature near 180 ft and the underlying vertical flow pathways could result in enough drawdown to overcome the downward ambient flow, reversing the vertical direction of flow at this depth. The preferential flow pathway has not been defined, and its presence was not indicated during monitoring in the T8PZ and T8BPZ intervals in borehole T8. A preferential flow pathway is required, however, to induce the flow reversals observed on the flowmeter logs. The preferential flow pathway may be associated with the horizontal fracture at about 186 ft in the study area (figs. 4–6, 8–10).

Water-level data collected during the packer testing was combined with the ambient flowmeter data and the flowmeter data collected in conjunction with pumping to estimate the hydraulic properties of each permeable interval in the study area (Paillet, 1997; Paillet and others, 1998). The transmissivity and storage coefficient of the shallow, subhorizontal fracture from 37 to 40 ft were determined to be 216 $ft^2/d$ and greater than 0.001, respectively. The transmissivity of the inclined fracture from about 75 to 85 ft was determined to be 130 $ft^2/d$. The storage coefficient of this interval could not be determined because the water level in the inclined fracture appears to be affected by the water level in the underlying permeable intervals. The transmissivity, storage coefficient, and horizontal hydraulic conductivity of the vuggy permeable interval from 90 to 100 ft were calculated to be 8.6 $ft^2/d$, $2.0 \times 10^{-5}$, and 0.86 ft/d, respectively. The transmissivity, storage coefficient, and horizontal hydraulic conductivity of the vuggy permeable interval from 140 to 180 ft were calculated to be 43.2 $ft^2/d$, $2.0 \times 10^{-5}$, and 1.1 ft/d, respectively.

## Aquifer Tests

A series of slug tests, a constant-discharge aquifer test, and a tracer test were done to quantify the hydraulic properties of the upper part of the Galena-Platteville aquifer and to help identify the pathways of ground-water flow in the study area.

### Slug Tests

Transmissivity and (or) horizontal hydraulic conductivity were calculated from data collected during slug testing in 22 discrete intervals isolated by the packer assembly at boreholes T1, T2, T3, T5, T6, and T8 (figs. 4–8, table 5). Packer assemblies were used to isolate each of the permeable features from the rest of the aquifer so that the hydraulic properties of each discrete unit could be determined.

Slug tests involved insertion of a solid cylinder below the water level and measurement of water-

**Table 5.** Results of slug testing in test intervals isolated with a packer assembly, Parson's Casket Hardware Superfund site, Belvidere, Illinois

[nc, not calculated]

| Borehole name (figure 1) | Test interval | Depth of test interval (feet below top of borehole casing) | Horizontal hydraulic conductivity (feet per day) | Transmissivity (feet squared per day) |
|---|---|---|---|---|
| T1 | A | 70–90 | 385 | 7,700 |
| T1 | A | 70–90 | 95 | 1,900 |
| T1 | B | 90–100 | .61 | nc |
| T1 | B | 90–100 | .58 | nc |
| T1 | C | 144–154 | .56 | nc |
| T1 | C | 144–154 | .78 | nc |
| T1 | D | 146–156 | .39 | nc |
| T1 | E | 200–215 | .072 | nc |
| T1 | E | 200–215 | .082 | nc |
| T2 | A | 90–100 | .33 | nc |
| T2 | A | 90–100 | .37 | nc |
| T2 | B | 151–161 | .38 | nc |
| T2 | B | 151–161 | .41 | nc |
| T3 | A | 90–100 | .38 | nc |
| T3 | A | 90–100 | .38 | nc |
| T5 | A | 38–48 | 83 | nc |
| T5 | A | 38–48 | 56 | nc |
| T5 | A | 38–48 | 30 | nc |
| T5 | A | 38–48 | 17 | nc |
| T5 | B | 90–100 | .67 | nc |
| T5 | B | 90–100 | 1.16 | nc |
| T5 | C | 116–126 | .26 | nc |
| T5 | C | 116–126 | .39 | nc |
| T5 | D | 130–146 | .48 | nc |
| T5 | D | 130–146 | .93 | nc |
| T5 | D | 130–146 | .90 | nc |
| T5 | D | 130–146 | .81 | nc |
| T6 | A | 37–40 | 172 | 516 |
| T6 | B | 141–151 | .50 | nc |
| T6 | B | 141–151 | .50 | nc |
| T6 | C | 146–156 | .56 | nc |
| T6 | C | 146–156 | .60 | nc |
| T6 | D | 151–161 | .52 | nc |
| T6 | D | 151–161 | .41 | nc |
| T6 | E | 156–166 | .48 | nc |
| T6 | E | 156–166 | .36 | nc |
| T6 | F | 166–176 | .22 | nc |
| T6 | F | 166–176 | .21 | nc |
| T6 | G | 176–186 | .20 | nc |
| T6 | H | 183–193 | .27 | nc |
| T6 | H | 183–193 | .18 | nc |
| T6 | I | 193–203 | .37 | nc |
| T8 | A | 180–190 | .26 | nc |

level decline with time using a pressure transducer connected to a datalogger (falling-head test), then removal of the cylinder and measurement of water-level rise with time (rising-head test). Results of the rising-head test and the falling-head tests typically were similar.

Slug-test data for test intervals A of boreholes T1 (open to the inclined fracture) and T6 (open to the shallow, subhorizontal fracture) were analyzed utilizing the oscillatory-response technique of van der Kamp (1976). This technique was developed for analysis of slug-test data from highly permeable aquifers where the effects of inertia of water in the well dominate the aquifer response. With this technique, a fully penetrating well in a confined aquifer where head loss resulting from friction is minimal is assumed. Aquifer storage coefficient (*S*) was assumed to be 0.0008 when using the van der Kamp technique, on the basis of the *S* values provided by Paillet's (1997) analysis of the flowmeter data.

Slug-test data from the remaining test intervals were analyzed using the technique of Bouwer and Rice (1976). This technique was developed for use in unconfined aquifers with wells that fully or partially penetrate the aquifer. The following conditions are assumed in the application of the van der Kamp, and Bouwer and Rice techniques: (1) Drawdown of the water table in the vicinity of the well is negligible; (2) Flow above the water table can be ignored; (3) As the water enters the well, head losses are negligible; and (4) The hydraulic unit is homogeneous and isotropic. These conditions are likely to be met or approximated at the test intervals over the scale of aquifer affected by the slug tests.

When analyzing the slug-test data using the Bouwer and Rice technique, it was assumed that the value of the length of the well through which water enters the aquifer is equal to the length of the test interval (typically 10 ft) and the borehole radius is equal to the nominal outside diameter of the borehole. When horizontal hydraulic conductivity was calculated from the transmissivity determined from the van der Kamp technique, the thickness of the aquifer was assumed to equal the length of the test interval. Because the aquifer response to the slug test is primarily through the fractures, which are considerahly thinner than the test interval, the calculated horizontal hydraulic conductivities are less than the actual values.

Although most of the slug tests analyzed using the Bouwer and Rice technique had clearly defined trends in water level with time that were easily analyzed, slug-test data from some of these test intervals did not show a linear decline in water level with time, complicating the data analysis. Differences in water-level trends with time can most likely be attributed to skin effects changing the horizontal hydraulic conductivity of the aquifer away from the borehole (Bouwer, 1989). Where possible, these anomalous data were analyzed in accordance with the recommendations of Bouwer (1989) to obtain the value most representative of the horizontal hydraulic conductivity of the test interval.

Calculated values for horizontal hydraulic conductivity of the test intervals open to the subhorizontal fracture from 37 to 40 ft ranged from 17 to 83 ft/d at borehole T5 and was 172 ft/d at borehole T6 (figs. 7, 8; table 5). The calculated horizontal hydraulic conductivity of the test intervals open to the inclined fracture from 75 to 85 ft at borehole T1 ranged from 95 to 385 ft/d (fig. 4, table 5). As indicated by the water-level measurement and the flowmeter logging, these fractures are the most permeable features in the study area.

Horizontal hydraulic conductivities calculated for the test intervals open to the Galena-Platteville aquifer from 90 to 100 ft ranged from 0.33 to 1.16 ft/d (table 5), with a mean value of 0.56 ft/d. A horizontal hydraulic conductivity of 0.33 ft/d was calculated for the interval including the shale bed at 122 ft in borehole T5. Horizontal hydraulic conductivities for those test intervals open to the Galena-Platteville aquifer from about 130 to 166 ft ranged from 0.36 to 0.93 ft/d, with a mean value of 0.56 ft/d. The highest horizontal-hydraulic-conductivity values were calculated for the 146 to 156 ft interval at borehole T6; the borehole with the largest amount of data. Horizontal hydraulic conductivities calculated for the test intervals open to the Galena-Platteville aquifer below 166 ft ranged from 0.072 to 0.37 ft/d and had a mean value of 0.21 ft/d. This interval includes most of the inclined fracture identified near the bottom of borehole T6 and the horizontal fracture at about 186 ft.

If the inclined fractures observed at boreholes T1, T2, and T6 are part of the same fracture set and have similar properties, the lower horizontal hydraulic conductivities (less than 0.25 ft/d) associated with the intervals open to the deep inclined fracture at borehole T6 indicate these fractures become less permeable with depth. Borehole-radar and acoustic-televiewer data indicate this decrease in permeability may be caused by a decrease in the aperture of the fracture with depth.

The areas of elevated permeability identified by the slug tests are in good agreement with the areas of elevated permeability identified by the flowmeter logging. Horizontal hydraulic conductivities determined from slug tests done on the 90–100 and 145–165 ft intervals were in good agreement with the conductivity values determined from the analysis of the flowmeter data for these intervals (Paillet, 1997) (table 6). Transmissivity values determined from analysis of the slug-test data are in good agreement with the transmissivity values determined from analysis of the

**Table 6.** Aquifer parameters estimated from borehole flow tests, Parson's Casket Hardware Superfund site, Belvidere, Illinois (from Paillet, 1997)
[na, not applicable; >, greater than]

| Hydraulically active feature | Borehole intercepting feature | Depth of feature (feet) | Estimated transmissivity (feet squared per day) | Estimated horizontal hydraulic conductivity (feet per day) | Estimated storage coefficient |
|---|---|---|---|---|---|
| Shallow, subhorizontal fracture | T5, T6, T7, T8 | 38–42 | 216 | na | >0.001 |
| Inclined fracture | T1, T2 | 75–85 | 130 | na | na |
| Shallow, vuggy interval | T1, T2, T3, T5, T6, T7, T8 | 90–100 | 8.6 | 0.9 | .00002 |
| Deep, vuggy interval | T1, T2, T3, T6, T7, T8 | 140–180 | 42.3 | 1.1 | .00002 |

flowmeter data for the shallow, subhorizontal fracture but are in poor agreement with the transmissivity values determined from analysis of the flowmeter data for the inclined fracture.

Comparison of horizontal hydraulic conductivities obtained from slug testing and porous intervals identified from the borehole radar tomograms and the neutron porosity logs does not indicate a straightforward relation between porosity and horizontal hydraulic conductivity in the upper part of the Galena-Platteville aquifer in the study area. The area of elevated porosity identified by the borehole radar tomograms from about 89 to 101 ft had a geometric mean horizontal hydraulic conductivity of 0.51 ft/d. The highest horizontal hydraulic conductivities associated with unfractured dolomite, geometric mean value 0.56 ft/d, were measured in the test interval from about 145 to 155 ft. This interval does not have elevated porosity as defined by the borehole radar tomography and neutron porosity logging. Intervals of elevated porosity from about 160 to 190 ft, identified by the borehole radar tomograms and the neutron porosity logs, had a mean horizontal hydraulic conductivity of 0.26 ft/d. The test intervals associated with the low-porosity intervals below 190 ft had a geometric mean horizontal hydraulic conductivity of 0.13 ft/d. The lack of correlation between porosity and horizontal hydraulic conductivity indicates the areas of interconnected matrix porosity in the aquifer typically are different than the areas with high total porosity.

### Constant-Discharge Tests

Constant-discharge aquifer tests were done to test the hydraulic properties of the permeable intervals from 156 to 166 ft, 146 to 156 ft, and 75 to 85 ft in borehole T1 and the permeable interval at 40 ft in borehole T6. The interval from 90 to 100 ft could not sustain pumping for more than a few minutes, and a test of this interval could not be done. The test intervals were isolated using a packer assembly in the pumped borehole and the observation boreholes (table 7). Use of the packer assemblies allowed a three-dimensional depiction of the drawdown distribution to be obtained, enabling determination of the hydraulic properties of each permeable unit and characterization of the hydraulic interconnection between the units.

Drawdown data from the depth intervals in the observation boreholes that approximated the depth of the pumped intervals were analyzed using the straight-line method of Cooper and Jacob (1946) to determine the transmissivity and storage coefficient of the aquifer at the test intervals (table 8). The effects of the partial penetration of the pumped intervals on the magnitude of drawdown in the aquifer prevented calculation of representative values of storage coefficient from the tests from 156 to 166 ft and from 146 to 156 ft in borehole T1 but should have no effect on the transmissivity calculations (Edwin Weeks, U.S. Geological Survey, oral commun., 1997). Horizontal hydraulic conductivities for the test intervals below 146 ft in borehole T1 were determined by dividing transmissivity by the thickness of the packed interval. Because the thickness of the fractures affecting flow from 75 to 85 ft in borehole T1 and at about 40 ft in borehole T6 could not be accurately determined, horizontal hydraulic conductivities from these test intervals were not calculated. Drawdown data from the test intervals also were considered qualitatively.

All constant-discharge aquifer tests were 100 minutes in length. Pumping was interrupted 70 minutes into the test of the interval from 75 to 85 ft in borehole T1. This interruption lasted about 3 minutes before pumping was resumed. The discharge rate was determined by measuring the time required to fill a 2-gal bucket. Water-level measurements were collected above, within, and below the test intervals in the observation boreholes using pressure transducers

**Table 7.** Configuration of packers and distribution of drawdown during constant-discharge aquifer testing, Parson's Casket Hardware Superfund site, Belvidere, Illinois

[na, not applicable; >, greater than]

| Pumped borehole name (figure 1) | Depth of pumped interval (feet below top of borehole casing) | Observation borehole name (figure 1) | Depth of interval above packed interval (feet below top of borehole casing) | Depth of packed interval (feet below top of borehole casing) | Depth of interval below packed interval (feet below top of borehole casing) | Drawdown above packed interval (feet) | Drawdown in packed interval (feet) | Drawdown below packed interval (feet) |
|---|---|---|---|---|---|---|---|---|
| T1 | 156–166 | | 50–152 | 156–166 | 170–215 | 0.57 | 63.51 | 11.62 |
| | | T2 | 48–152 | 156–166 | 170–216 | .57 | 36.64 | 12.67 |
| | | T3 | 50–153 | 157–167 | 171–215 | 1.63 | 18.88 | 11.93 |
| | | T5 | 38–112 | 116–126 | 130–144 | .06 | .45 | 2.85 |
| | | T6 | 37–152 | 156–166 | 170–215 | .05 | 11.87 | 8.85 |
| | | T7 | 39–152 | 156–166 | 170–216 | .06 | 12.69 | 10.09 |
| | | T8 | 36–152 | 156–166 | 170–217 | .04 | 16.68 | 12.24 |
| T1 | 146–156 | | 50–142 | 146–156 | 160–215 | .32 | >55.5 | 11.66 |
| | | T2 | 48–142 | 146–156 | 160–216 | .32 | 39.45 | 12.78 |
| | | T3 | 50–142 | 146–156 | 160–217 | 1.12 | 18.39 | 12.24 |
| | | T5 | 38–112 | 116–126 | 130–144 | .02 | .48 | 9.93 |
| | | T6 | 37–141 | 145–155 | 159–215 | .04 | 13.67 | 9.98 |
| | | T7 | 39–141 | 145–155 | 160–215 | .04 | 13.88 | 10.82 |
| | | T8 | 36–46 | 146–156 | 160–216 | .07 | 17.41 | 12.59 |
| T1 | 50–86 | | na | 50–86 | 90–215 | 9.25 | na | 1.54 |
| | | T2 | 48–86 | 90–100 | 104–215 | 9.15 | 2.84 | 1.43 |
| | | T3 | 50–86 | 90–100 | 104–215 | .84 | 2.27 | 1.12 |
| | | T5 | na | 38–46 | 51–146 | na | .08 | .62 |
| | | T6 | na | 37–46 | 50–215 | na | na | 1.06 |
| | | T7 | na | 39–46 | 50–215 | na | .07 | 1.03 |
| | | T8 | na | 36–46 | 50–215 | na | .07 | 1.19 |
| T6 | 37–46 | | na | 37–46 | 50–215 | na | .22 | .04 |
| | | T1 | na | 50–86 | 90–215 | na | .09 | .01 |
| | | T2 | 48–86 | 90–100 | 104–215 | .09 | .19 | .00 |
| | | T3 | 50–86 | 90–100 | 104–215 | .09 | .04 | .00 |
| | | T5 | na | 38–46 | 50–146 | na | .10 | .02 |
| | | T7 | na | 39–46 | 50–215 | na | .16 | .03 |
| | | T8 | na | 36–46 | 50–215 | na | .14 | .00 |

**Table 8.** Estimated transmissivity, storage coefficient, and horizontal hydraulic conductivity calculated from constant-discharge aquifer tests in test intervals isolated with a packer assembly, Parson's Casket Hardware Superfund site, Belvidere, Illinois

[nc, could not be calculated because of limitations of the analytical method or aquifer geometry]

| Pumped borehole name (figure 1) | Depth of pumped interval (feet below top of borehole casing) | Observation borehole or well name (figure 1) | Depth of interval analyzed (feet below top of borehole casing) | Transmissivity (feet squared per day) | Storage coefficient (dimensionless) | Horizontal hydraulic conductivity (feet per day) |
|---|---|---|---|---|---|---|
| T1 | 156–166 | | | | | |
| | | T2 | 156–166 | 8.35 | nc | 0.84 |
| | | T3 | 157–167 | 14.25 | nc | 1.43 |
| | | T5 | 130–144 | nc | nc | nc |
| | | T6 | 156–166 | 22.02 | nc | 2.20 |
| | | T7 | 156–166 | 20.36 | nc | 2.04 |
| | | T8 | 156–166 | 16.15 | nc | 1.62 |
| | | G115BD | 141–151 | nc | nc | nc |
| T1 | 146–156 | | | | | |
| | | T2 | 146–156 | 9.69 | nc | .97 |
| | | T3 | 146–156 | 15.14 | nc | 1.51 |
| | | T5 | 130–144 | nc | nc | nc |
| | | T6 | 145–155 | 17.95 | nc | 1.80 |
| | | T7 | 145–155 | 17.95 | nc | 1.80 |
| | | T8 | 146–156 | 17.06 | nc | 1.71 |
| | | G115BD | 141–151 | nc | nc | nc |
| T1 | 50–86 | | | | | |
| | | T2 | 48–86 | 22.56 | 0.00076 | nc |
| T6 | 37–46 | | | | | |
| | | T5 | 38–46 | 7,414 | .020 | nc |
| | | T7 | 39–46 | 7,414 | .020 | nc |
| | | T8 | 36–46 | 7,414 | .020 | nc |

during the pumping phase of all tests and during the recovery phase of the tests in borehole T6 and the 50–86 ft interval in borehole T1. Water-level measurements were recorded on a logarithmic time scale using a datalogger. Water-level measurements were collected before the start and termination of pumping in the observation boreholes with an electric water-level indicator to verify the accuracy of the transducer values. Water-level change measured with the pressure transducers and the electric water-level indicators were in good agreement. Water-level measurements were collected periodically before and during the tests in well G115BD with an electric water-level indicator to provide additional characterization of the aquifer. Pumped water was discharged to a sanitary sewer offsite.

The interval from 156 to 166 ft at borehole T1 was pumped at a constant rate of 3.4 gal/min (656 $ft^3/d$). This depth corresponds to the lower part of the permeable interval in the Galena-Platteville aquifer from 140 to 160 ft in the study area. Over 60 ft of drawdown was measured in the packed interval at borehole T1 (table 7). Over 10 ft of drawdown was measured at the 156–166 ft interval in boreholes T2, T3, T6, T7, and T8. More than 2.5 ft of drawdown was measured in the interval from 130 to the bottom of borehole T5 at 144 ft. More than 1.3 ft of drawdown was measured at well G115BD, open to the aquifer from 141 to 151 ft. Although less than measured in the test intervals, drawdown below the test intervals also was typically greater than 10 ft. The drawdown distribution indicates flow in the 156–166 ft interval is predominately horizontal, but there is good vertical hydraulic connection between this interval and the aquifer below the bottom of the lower packers at 170 ft. Slightly more than 1 ft of drawdown was measured above the test interval at borehole T3, indicating hydraulic connection between the 156–166 ft interval and the overlying 146–156 ft and 90–100 ft intervals. Less than 1 ft of drawdown was measured above the test interval in boreholes T1 and T2. The small amount of drawdown in these intervals indicates some hydraulic connection between the test interval and the overlying permeable intervals, but the inclined fracture is so permeable that little drawdown results in response to the pumping. Less than 0.5 ft of drawdown was measured at the 116–126 ft interval in borehole T5. Less than 0.10 ft of water-level change was measured above the test intervals in boreholes T5, T6, T7, and T8. The data from boreholes T5–T8 indicate the shallow fracture is so transmissive that little or no drawdown was induced.

Transmissivity values from the 156–166 ft interval calculated using the time-drawdown method ranged from 8.35 to 22.02 $ft^2/d$ (table 8) with a geometric mean of 15.38 $ft^2/d$. All time-drawdown plots deviated below the straight-line solution near the end of the test, indicating a source of recharge (probably inflow from overlying permeable intervals) to the test interval. Horizontal hydraulic conductivities calculated from analysis of the constant-discharge-aquifer test data are about a factor of 5 higher than the values calculated from analysis of the slug-test data.

The interval from 146 to 156 ft at borehole T1 was pumped at a constant rate of 3.4 gal/min (656 $ft^3/d$). This depth corresponds to the middle part of the permeable interval in the Galena-Platteville aquifer from 140 to 160 ft in the study area. Over 50 ft of drawdown was measured in the packed interval at borehole T1. More than 10 ft of drawdown was measured at the 146–156 ft interval in boreholes T2, T3, T6, T7, and T8. Nearly 10 ft of drawdown was measured in the interval from 130 ft to the bottom of borehole T5. More than 1.5 ft of drawdown was measured in well G115BD. Although less than that measured in the test intervals, drawdown below the test intervals typically was greater than 10 ft. The drawdown distribution indicates that flow within the 146–156 ft interval is predominately horizontal, but there is good vertical hydraulic connection between the upper and lower parts of the permeable interval in the Galena-Platteville aquifer from 140 to 160 ft in the study area. Slightly more than 1 ft of drawdown was measured above the test interval at borehole T3, indicating hydraulic connection between the 146–156 ft interval and the permeable interval at 90–100 ft. Less than 0.5 ft of drawdown was measured above the test interval in boreholes T1 and T2, indicating some hydraulic connection between the test interval and the overlying permeable intervals, but the inclined fracture is so permeable that little drawdown resulted in response to the pumping stress. Less than 0.5 ft of drawdown was measured at the 116–126 ft interval in borehole T5. Less than 0.10 ft of water-level change was measured above the test intervals in boreholes T5, T6, T7, and T8. The data from boreholes T5 –T8 indicate that the shallow fracture is so permeable that little or no drawdown was induced above the test interval. The drawdown distribution in the 145–155 ft and 155–165 ft intervals do not indicate substantial anisotropy in the deep, vuggy interval.

Transmissivity values from the 146–156 ft interval calculated using the time-drawdown method ranged from 9.69 to 17.95 $ft^2/d$ (table 8) with a geometric mean of 15.18 $ft^2/d$. Data from well G115BD did not result in a consistent straight line and could not be analyzed. These transmissivity values are essentially identical to the values from the 156–166 ft interval, indicating the 146–166 ft interval is homogenous. All time-drawdown plots deviated below the straight-line solution near the end of the test, indicating a source of recharge to the test interval. Horizontal hydraulic conductivities calculated from analysis of the constant-discharge aquifer test data are about a factor of 3 higher than the values calculated from analysis of the slug-test data. Transmissivity and horizontal-hydraulic-conductivity values determined from the flowmeter logging for the 140–180 ft interval (table 6) are in good agreement with the values determined from the constant-discharge aquifer tests in the 146–156 and 156–166 ft intervals.

The interval between the bottom of the borehole casing at 50 ft and the top of the upper packer at 86 ft at borehole T1 was pumped at a constant rate of 4.4 gal/min (849 $ft^3/d$) to determine the hydraulic properties of the inclined fracture in the Galena-Platteville aquifer from 75 to 85 ft at boreholes T1 and T2. The interval from 90 to 100 ft was isolated with the packer assembly in these boreholes to differentiate the hydraulic response of the permeable intervals at 90–100 ft and 140–160 ft to pumping in the fracture. Nearly 10 ft of drawdown was measured in the test interval above 86 ft at boreholes T1 and T2. More than 2 ft of drawdown was measured in the packed intervals from 90 to 100 ft at boreholes T2 and T3, and more than 1 ft of drawdown was measured below the packers at about 104 ft at these boreholes. From 0.5 to 1.3 ft of drawdown was measured below about 50 ft in boreholes T5 through T8 and at well G115BD. The distribution of drawdown indicates that the inclined fracture in boreholes T1 and T2 is hydraulically connected with the deeper, permeable intervals in the study area. Less than 0.1 ft of drawdown was measured in the packed intervals from about 35 to 45 ft at boreholes T5–T8, indicating some hydraulic connection between the inclined fracture at boreholes T1 and T2 and the shallow, subhorizontal fracture at 35 to 40 ft at boreholes T5 through T8. This hydraulic connection probably is through the upper, weathered part of the bedrock and the unconsolidated aquifer overlying the Galena-Platteville aquifer.

The transmissivity of the inclined fracture, 22.56 $ft^2/d$, was calculated by analyzing the data from above the packed interval in borehole T2 using the time-drawdown method (table 8). The calculated value for storage coefficient was $7.6 \times 10^{-4}$. The transmissivity value calculated from the constant-discharge data is in poor agreement with the value calculated from the slug-test data (values of greater than 1,500 $ft^2/d$) and in moderate agreement with the transmissivity value of 130 $ft^2/d$ calculated from the flowmeter data (table 6). This discrepancy may be related to the amount of aquifer tested by the different methods. If the fracture becomes less permeable away from its intersection with boreholes T1 and T2, a lower transmissivity value would be calculated by methods that test a larger part of the aquifer, such as the constant-discharge tests, than by methods that test smaller parts of the aquifer, such as the slug test and the flowmeter logging. The lower permeability may be because of a decrease in the fracture aperture with depth. The time-drawdown plot deviated below the straight-line solution near the end of the test, indicating a source of recharge to the test interval. The source of recharge is probably water from the unconsolidated aquifer.

The interval from 37 to 46 ft at borehole T6 was pumped at a constant rate of 4.6 gal/min (888 $ft^3/d$). This interval tested the shallow, subhorizontal fracture in the Galena-Platteville aquifer from 37 to 40 ft at boreholes T5, T6, T7, and T8. Less than 0.25 ft of drawdown was measured in the test intervals. No clearly identified drawdown was measured below the test interval in these boreholes. Less than 0.10 ft of drawdown was measured above 90 ft at boreholes T1, T2, and T3. Water-level changes that could clearly be attributed to pumping were not measured below 100 ft in boreholes T1–T3. The data from boreholes T5–T8 indicate good hydraulic connection within the permeable interval from 37 to 40 ft and little or no hydraulic connection between this interval and the deeper permeable intervals in the western part of the study area. The data from boreholes T1–T3 indicate some hydraulic connection between the shallow, subhorizontal fracture and the inclined fracture in boreholes T1 and T2, probably through the unconsolidated aquifer. Drawdown in the inclined fracture at boreholes T1 and T2 appears to have been transmitted down to the permeable interval from 90 to 100 ft in this area but not to the permeable interval from 145 to 165 ft.

The transmissivity of the shallow, subhorizontal fracture from 37 to 40 ft was calculated to be 7,414 $ft^2/d$ by analyzing the drawdown data from the packed intervals in boreholes T5, T6, T7, and T8 at 10 minutes into the test based on the distance-drawdown method (table 8). An oscillatory response was noted in the water-level data during the pumping and recovery phases of this test, preventing analysis using the time and drawdown data. The transmissivity calculated from the constant-discharge data is an order of magnitude greater than the value determined from the slug-test data (table 5) and the flowmeter data (table 6). This discrepancy may be attributed to recharge to the fracture from the unconsolidated aquifer, lowering the amount of drawdown in the fracture and resulting in an overestimation of its transmissivity.

### Tracer Test

Electrolyte tracers (such as sodium chloride) have been used in conjunction with borehole radar and electromagnetic tomography surveys to interpret flow paths and estimate aquifer hydraulic characteristics (Ramirez and Lytle, 1986; Niva and others, 1988; Olsson and others, 1992; Kong and others, 1994; Lane and others, 1996; Wright and others, 1996). Electrolyte tracers increase the electric conductivity of the ground water. The presence of an electrically conductive tracer along the path of the radar pulse results in an increased attenuation of the pulse with respect to a tracer-free path, allowing the overall location and pathways of ground-water flow and tracer migration to be identified. Comparison of the background wave amplitudes and attenuation in tomograms run before tracer injection with amplitude and attenuation data collected during tracer injection allows subtle changes in the signals to be identified so the location and extent of the tracer in the aquifer can be more completely determined.

A sodium chloride tracer with a concentration of about 20,000 mg/L of chloride was injected into the test interval from 145 to 155 ft in borehole T1, while the test interval from 145 to 155 ft in borehole T6 was pumped at a constant rate of 3.0 gal/min (579 $ft^3/d$) for 2,805 minutes. The test intervals in boreholes T1 and T6 were isolated with the packer assembly. This interval was selected for testing because it had the highest horizontal hydraulic conductivity and lowest porosity of any permeable interval that was present throughout the entire study area and had sufficient borehole above and below the interval for tomography to be done. This combination of high horizontal hydraulic conductivity and low porosity ensures the fastest rate of tracer movement. Borehole T6 was pumped for 355 minutes before the start of tracer injection. About 70 ft of drawdown was measured in the test interval at borehole T6 before the start of tracer injection, and about 3 ft of drawdown was measured in the test interval at borehole T1. Drawdown measurements in the test intervals and the surrounding boreholes indicated that the flow field had stabilized by the time tracer injection began. Attempts were made to control the rate of tracer injection so that no more than 5 ft of water-level rise was induced in the test interval at borehole T1 during injection. Water-level measurements at borehole T1 demonstrate that the water levels in the injection (packed) interval exceeded water levels in the intervals above and below the injection interval during much of the period of tracer injection. The tracer was injected for 2,170 minutes. About 445 gal of tracer solution was injected during the test. After termination of pumping in the test interval in borehole T6, about 22,200 gal of water was pumped from the tracer-injection interval in borehole T1 to remove the tracer. Water extracted from boreholes T1 and T6 was discharged to an offsite sanitary sewer.

Background borehole radar surveys were done between borehole pairs T2–T8, T2–T7, and T3–T8 before the start of tracer injection. Between 1 and 4 surveys were run, depending on the borehole pair, from 11 to 39 hours after the start of injection. Boreholes T2 and T7 were lined with polyvinyl chloride casing to prevent the saline tracer from having direct contact with the borehole radar probes. Packers were not present in boreholes T2, T3, T5, T7, and T8 during the test.

The borehole radar attenuation tomogram collected between boreholes T2 and T8, approximately 34 hours after the start of tracer injection, showed an interval of elevated attenuation near borehole T2 from about 143 to 161 ft extending toward borehole T8 (figs. 11, 16, 17). The attenuation pattern indicates primarily horizontal tracer movement and ground-water flow from the injection interval in borehole T1 toward the pumping interval in borehole T6.

Attenuation of the radar signal across the T2–T8 plane increased continuously relative to background values from about 143–161 ft at 11.3, 17.5, 31, and 34 hours after tracer injection (fig. 16). The pattern of increasing attenuation indicates the tracer had begun to migrate into the plane of the radar survey between boreholes T2 and T8, a distance of 9.5 ft from borehole T1, within 11.3 hours of the injection. If the first indication of the presence of the tracer was detected 9.5 ft from the borehole within 11.3 hours after the tracer was injected, the maximum ground-water velocity through this interval is calculated to be 20.2 ft/d. The continual increase in attenuation suggests the tracer concentrations had not reached steady-state conditions 34 hours after injection.

Along the T2–T8 plane of survey, the tomogram of the difference in the attenuation signal before tbe start of the test and at about 17.5 and 34 hours after the tracer injection shows a large difference from about 145 to 160 ft near borehole T2 (fig. 17). This pattern is consistent with the results of the attenuation data (fig. 11). The pattern of change in the attenuation signal also indicates moderate differences in attenuation below 144 ft near borehole T8 at 17.5 and 34 hours after tracer injection, which is not apparent in figure 11. The zone of moderate attenuation indicates a leading edge of tracer migration down through the hydraulically interconnected permeable interval from 145 to 180 ft between borehole T2 and T8. A horizontal interval of moderate differences in attenuation at about 133 ft near borehole T8 indicates that between 18 and 34 hours into the test there may have been some tracer movement througb a horizontal fracture identified on the televiewer logs (figs. 5, 10). This fracture was identified as a discontinuous low-velocity interval during the background tomographic surveys along the T2–T8 borehole pair (table 3). A number of smaller, discrete intervals of increased attenuation were measured at about 72, 92, and 115 ft between the boreholes 34 hours after tracer injection. The 72 and 92 ft depths correspond to permeable intervals in the aquifer. No flow pathways have been identified at the 115 ft interval. The depth of these intervals increases and becomes more extensive from borehole T2 to borehole T8, indicating downward migration of the tracer (perhaps through the inclined fracture near boreholes T1 and T2) from borehole T2 toward borehole T8 between 18 and 34 hours after tracer injection.

A small increase in radar attenuation relative to the background signal was observed between boreholes T2 and T7 at the 151–156 ft interval 32 hours after the start of the tracer injection. This increase indicates the tracer had begun to migrate

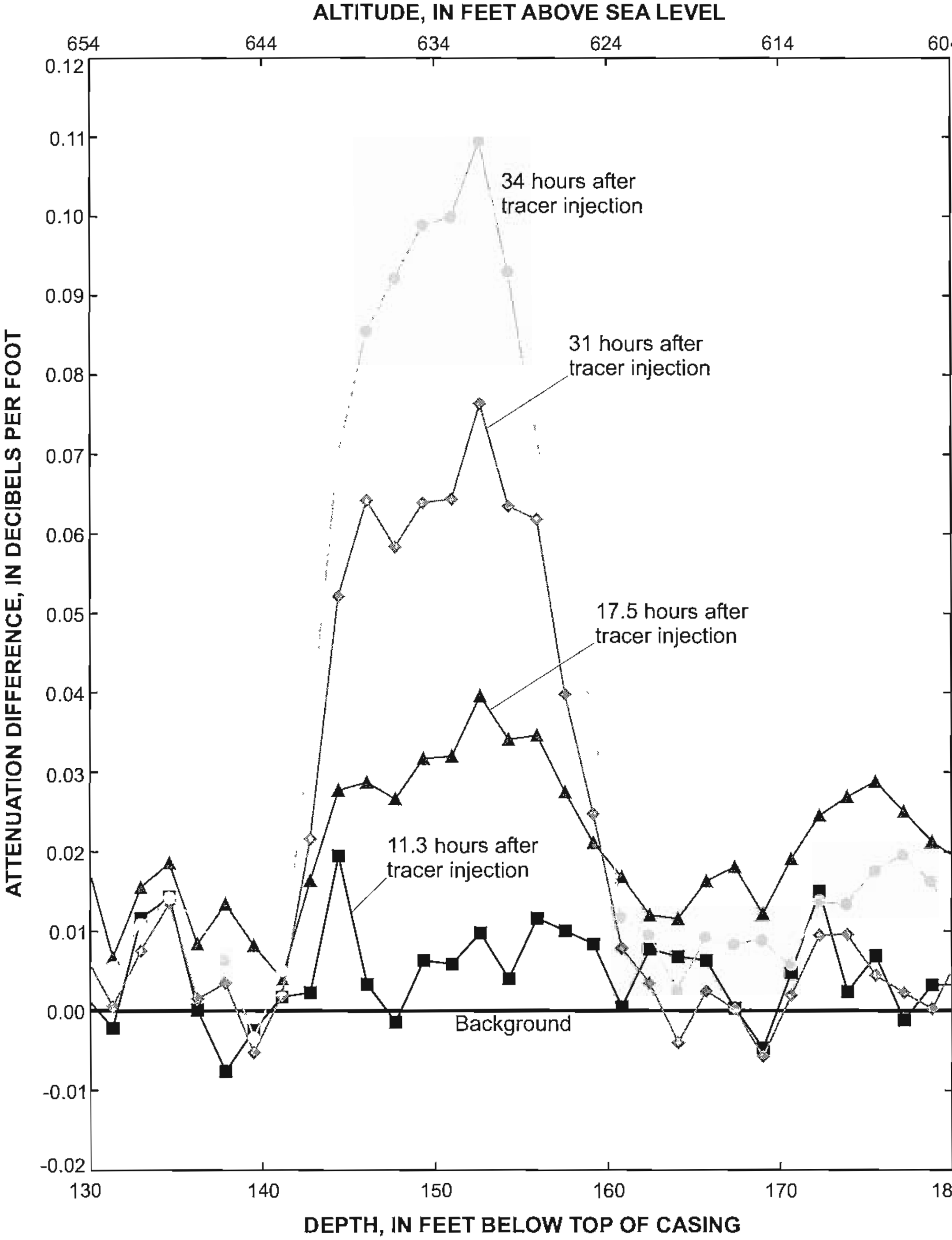


**Figure 16.** Attenuation difference from background values between boreholes T2 and T8, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

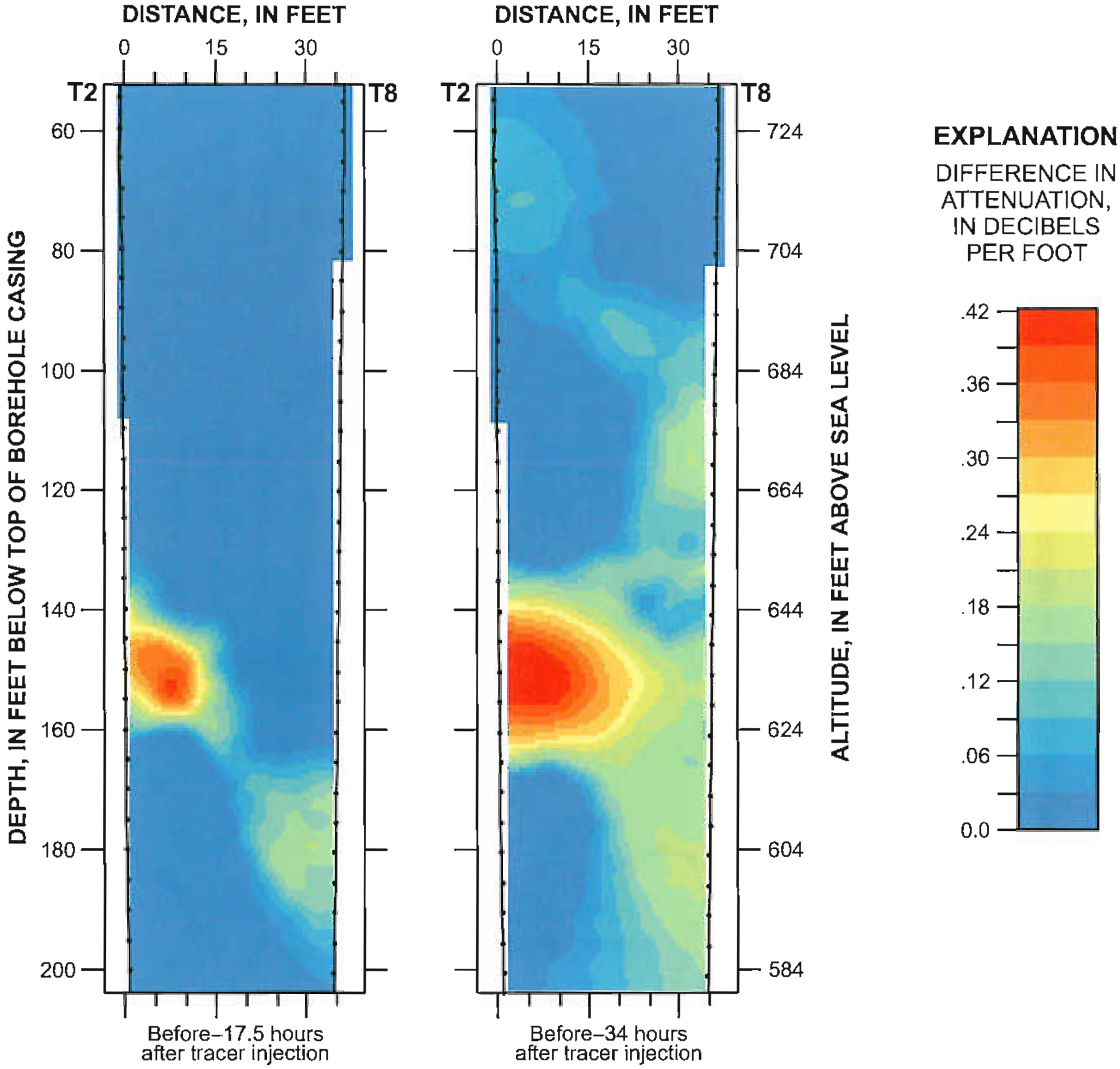


**Figure 17.** Borehole radar difference tomogram showing changes in attenuation between boreholes T2 and T8, 17.5 and 34 hours after tracer injection in borehole T1, Parson's Casket Hardware Superfund site, Belvidere, Illinois.

into the plane of the survey, a horizontal distance of about 23 ft from borehole T1 and a total distance of about 30 ft from the center of the injection interval in borehole T1 about 32 hours after the injection. A maximum rate of tracer migration of 22.5 ft/d was calculated on the basis of these data. This maximum rate is comparable to the maximum velocity of 20.2 ft/d calculated from the travel time in the T2–T8 plane.

No increase in radar attenuation was observed in the data collected between boreholes T3 and T8 after 19, 30, and 39 hours of injection relative to the background signal. The T3–T8 plane defines the limit of tracer migration during the test and indicates the maximum horizontal extent of substantial tracer migration in 39 hours was less than 24 ft from the injection borehole. The T3–T8 plane is about 24 ft from borehole T1 and intercepts the line between boreholes T1 and T6 at approximately the same location as the T2–T7 plane. Detection of tracer along the T2–T7 plane at 32 hours and the lack of tracer detection along the T3–T8 plane at 39 hours indicates the tracer is not moving along a straight line between boreholes T1 and T6. It appears there is a component of flow toward borehole T2.

Downward migration of water below the 145–155 ft injection interval is probably caused by the increased density of the tracer water, perturbations in the flow field because of the increase in water level associated with the tracer injection, and perhaps the effects of pumping in the municipal wells. The mechanism for the upward migration of the tracer near borehole T2 is unclear, but the hydraulic field induced by pumping and injection at the 145–155 ft interval in boreholes T1 and T6 (including the potential for upward flow above the injection interval in borehole T1) was modified by vertical flow through boreholes T2, T3, T5, T7, and T8. Diffuse downward flow of the tracer is taking place in the study area, but upward flow takes place through discrete intervals. The patterns of tracer migration tend to confirm the conclusions made from the analysis of the geophysical, water-level, and aquifer-test data. The deep, vuggy interval from 145 to 165 ft in the Galena-Platteville aquifer has good vertical hydraulic interconnection. The deep, vuggy interval also is hydraulically interconnected to overlying permeable intervals through discrete vertical fractures (figs. 2, 17).

The maximum velocity ($v$) of tracer movement through the deep, permeable interval in the upper part of the Galena-Platteville aquifer under the hydraulic gradient imposed by the pumping and injection was calculated to be 20.2 ft/d between borehole T1 and the plane of the tomographic survey between boreholes T2 and T8. The maximum velocity of tracer movement through this interval under the hydraulic gradient imposed by the pumping and injection was calculated to be 22.5 ft/d between borehole T1 and the line of the tomographic survey between boreholes T2 and T7.

The average linear ground-water velocity ($v$) is given by

$$v = K/n(dh/dl), \qquad (3)$$

where

$n$ is the effective porosity of the aquifer,

$K$ is the horizontal hydraulic conductivity of the aquifer,

$dh$ is the difference in water level in the direction of flow, and

$dl$ is the distance over which $dh$ is measured and is equal to the distance between boreholes T1 and T6.

The value of $v$, 21.4 ft/d, was assumed to be the average value calculated from the tomography data between boreholes T2–T8 and T2–T7. The measured difference in water level ($dh$) was about 75 ft during the test. If it is assumed that flow is directly from borehole T1 to T6, $dl$ is 60 ft and the horizontal hydraulic gradient ($dh/dl$) is 1.25 ft/ft. If the horizontal hydraulic conductivity of the interval from 145 to 155 ft is 1.5 ft/d, as determined from the constant-discharge aquifer tests, the maximum effective porosity for the 145–155 ft interval is calculated to be 8.8 percent. This value is substantially less than the mean porosity of 15.7 percent, calculated from core samples collected from the 145–155 ft interval at borehole G115BD (Mills and others, 1998). The difference in the calculated porosity values indicates the matrix porosity is not completely hydraulically interconnected. The presence of incomplete hydraulically interconnected matrix porosity in the dolomite matrix is consistent with the analysis of the data from the borehole tomography, neutron porosity logging, and slug testing.

## GROUND-WATER QUALITY

Ground-water samples were collected from open boreholes T1, T2, T4, and T6 during well development (table 9), several test intervals isolated with the packer assembly in boreholes T1 and T5 (table 10), and the test intervals in borehole T6 during the tracer test (table 11) and borehole T1 during tracer removal (table 12). All samples were analyzed for concentrations of volatile organic compounds (VOC's). The samples collected from open boreholes T1, T2, and T6 also were analyzed for concentrations of metals and cyanide. Samples collected from open boreholes T1, T2, and T6 and the test intervals isolated with the packer assembly in borehole T1 were collected in April 1996. The remaining samples were collected in September 1996. Samples from open boreholes T1, T2, and T6 and the test interval in borehole T6 during the tracer test were collected from a port connected to the discharge hose of a high-capacity submersible centrifugal pump. The remaining samples were collected with a low-capacity sampling pump. All samples were collected after at least three packed-interval volumes were purged from the sample interval and preserved, stored, shipped, and analyzed in accordance

**Table 9.** Results of water-quality sampling in open boreholes during borehole development, Parson's Casket Hardware Superfund site, Belvidere, Illinois, April 1996

[<, less than]

Volatile organic compound detected: 1,1-DCE, 1,1-dichloroethene;
1,1-DCA, 1,1-dichloroethane;
1,2-DCE, 1,2-dichloroethene;
1,1,1-TCA, 1,1,1-trichloroethane;
TCE, trichloroethene;
PCE, tetrachloroethene;
TDL, toluene

Volatile organic compound concentration: J, estimated concentration below detection limit;
D, sample diluted

| Borehole name (figure 1) | Volatile organic compound detected/concentration (micrograms per liter) | Total concentration of volatile organic compounds (micrograms per liter) |
|---|---|---|
| T1 | 1,1-DCE/3; 1,1-DCA/3; 1,2-DCE/6; 1,1,1-TCA/120D; TCE/260D; PCE/79D | 471 |
| T2 | 1,1-DCE/4; 1,1-DCA/3; 1,2-DCE/6; 1,1,1-TCA/170D; TCE/280D; PCE/69D | 460 |
| T4 | 1,1-DCE/2J; 1,2-DCE/5J; 1,1,1-TCA/260D; TCE/480D; PCE/67; TOL/1J | 815 |
| T6 | 1,1-DCE/2; 1,1-DCA/1; 1,2-DCE/5; 1,1,1-TCA/92D; TCE/210D; PCE/120D | 430 |

| Compound | Sample from borehole T1 (micrograms per liter) | Sample from borehole T2 (micrograms per liter) | Sample from borehole T6 (micrograms per liter) | U.S. Environmental Protection Agency Maximum Contaminant Level for compound (micrograms per liter) |
|---|---|---|---|---|
| Aluminum | 4,660 | 3,250 | <80 | None |
| Antimony | <2 | <2 | <2 | 6 |
| Arsenic | 21 | 11 | <2 | 50 |
| Barium | 163 | 132 | 77.7 | 2,000 |
| Beryllium | 1.2 | <1 | <1 | 4 |
| Cadmium | <.2 | <.2 | <.2 | 5 |
| Calcium | 187,000 | 142,000 | 121,000 | None |
| Chromium | 18 | <8 | <8 | 100 |
| Cobalt | 14.5 | 10.6 | <6 | None |
| Copper | 45.9 | 32.7 | 47.7 | 1,300 |
| Cyanide | <8 | <8 | <8 | 200 |
| Iron | 29,500 | 19,700 | 405 | None |
| Lead | 19 | 13 | <2 | 15 |
| Magnesium | 70,600 | 50,700 | 39,600 | None |
| Manganese | 571 | 156 | 9.9 | None |
| Mercury | <.1 | <.1 | <.1 | 2 |
| Nickel | 124 | 94 | 139 | 140 |
| Selenium | 6 | 7 | 2 | 50 |
| Silver | 6 | <6 | 6.7 | None |
| Sodium | 26,100 | 25,500 | 21,700 | None |
| Thallium | 3 | <2 | <2 | 2 |
| Vanadium | 8.8 | 6.9 | <5 | None |
| Zinc | 205 | 160 | 65.9 | None |

**Table 10.** Results of water-quality sampling in test intervals isolated with a packer assembly, Parson's Casket Hardware Superfund site, Belvidere, Illinois, September 1996

Volatile organic compound detected: 1,1-DCE; 1,1-dichloroethene; 1,1-DCA, 1,1-dichloroethane; 1,2-DCE, 1, 2-dichloroethene; 1,1,1-TCA, 1,1,1-trichloroethane; TCE, trichloroethene; PCE, tetrachloroethene; TOL, toluene
Volatile organic compound concentration: J, estimated concentration below detection limit; D, sample diluted

| Borehole name (figure 1) | Depth of test interval (feet below measuring point) | Volatile organic compound detected/concentration (micrograms per liter) | Total concentration of volatile organic compounds (micrograms per liter) |
|---|---|---|---|
| T1 | 70–90 | 1,1-DCE/5; 1,1-DCA/2J; 1,2-DCE/5; 1,1,1-TCA/290D; TCE/330D; PCE/55 | 687 |
| T1 | 90–100 | 1,1-DCE/6J; 1,1-DCA/3; 1,2-DCE/6; 1,1,1-TCA/280D; TCE/330D; PCE/76; TOL/4 | 705 |
| T1 | 144–154 | 1,1-DCE/5; 1,1-DCA/3; 1,2-DCE/5; 1,1,1-TCA/260D; TCE/340D; PCE/52; TOL/1J | 666 |
| T1 | 200–216 | 1,1-DCE/3; 1,1-DCA/2; 1,2-DCE/5; 1,1,1-TCA/280D; TCE/320D; PCE/50; TOL/1J | 661 |
| T5 | 38–48 | 1,2-DCE/5; 1,1,1-TCA/120; TCE/200; PCE/18 | 340 |
| T5 | 89–99 | 1,1-DCE/2J; 1,1-DCA/4J; 1,2-DCE/2J; 1,1,1-TCA/30; TCE/72; PCE/4J | 114 |
| T5 | 116–126 | 1,2-DCE/1J; 1,1,1-TCA/27; TCE/51; PCE/4J | 83 |
| T5 | 136–146 | 1,1-DCE/3J; 1,2-DCE/3J; 1,1,1-TCA/97; TCE/180; PCE/28 | 312 |

**Table 11.** Concentration of volatile organic compounds in water pumped from borehole T6 during tracer testing, Parson's Casket Hardware Superfund site, Belvidere, Illinois, September 1996

Volatile organic compound detected: 1,1-DCE, 1,1-dichloroethene; 1,2-DCE, 1,2-dichloroethene; 1,1,1-TCA, 1,1,1-trichloroethane; TCE, trichloroethene; PCE, tetrachloroethene; TOL, toluene
Volatile organic compound concentration: J, estimated concentration below detection limit; D, sample diluted

| Sample number | Time of sample collection since start of tracer test (minutes) | Volatile organic compound detected/concentration (micrograms per liter) | Total concentration of volatile organic compounds detected (micrograms per liter) |
|---|---|---|---|
| T6-1 | 2,150 | 1,1-DCE/2J; 1,2-DCE/4J; 1,1,1-TCA/140D; TCE/270D; PCE/61D; TOL/4DJ | 481 |
| T6-2 | 2,775 | 1,1-DCE/2J; 1,2-DCE/5DJ; 1,1,1-TCA/160D; TCE/300D; PCE/60D; TOL/5DJ | 532 |
| T6-3 | 4,165 | 1,2-DCE/3J; 1,1,1-TCA/88; TCE/220; PCE/42; TOL/3J | 356 |

**Table 12.** Concentration of volatile organic compounds in water pumped from borehole T1 during tracer removal, Parson's Casket Hardware Superfund site, Belvidere, Illinois, September 1996

Volatile organic compound detected: 1,1-DCE, 1,1-dichloroethene;
1,2-DCE, 1,2-dichloroethene;
1,1,1-TCA, 1,1,1-trichloroethane;
TCE, trichloroethene;
PCE, tetrachloroethene;
TOL, toluene
Volatile organic compound concentration: J, estimated concentration below detection limit

| Sample number | Time of sample collection since start of tracer removal (minutes) | Volatile organic compound detected/concentration (micrograms per liter) | Total concentration of volatile organic compounds detected (micrograms per liter) |
|---|---|---|---|
| T1-1 | 290 | 1,2-DCE/4J; 1,1,1-TCA/120; TCE/250; PCE/52; TOL/3J | 429 |
| T1-2 | 1,335 | 1,1,1-TCA/190; TCE/350; PCE/86 | 626 |
| T1-3 | 2,595 | 1,1,1-TCA/160; TCE/280; PCE/79 | 519 |
| T1-4 | 4,600 | 1,1-DCE/3J; 1,2-DCE/4J; 1,1,1-TCA/140; TCE/290; PCE/61; TOL/3J | 501 |
| T1-5 | 6,435 | 1,2-DCE/4J; 1,1,1-TCA/130; TCE/280; PCE/58; TOL/3J | 475 |
| T1-6 | 7,125 | 1,2-DCE/4J; 1,1,1-TCA/100; TCE/260; PCE/51; TOL/2J | 417 |

with USEPA standard procedures for VOC samples. Compounds considered to be present because of field or laboratory contamination are not presented in this report. Where a duplicate sample was collected, the highest reported concentration is presented. Results of analysis of duplicate samples typically were similar to the results of the original-sample analysis.

Trichloroethene (TCE), trichloroethane (TCA), and tetrachloroethene (PCE) are the primary VOC's present in the upper part of the Galena-Platteville aquifer in the study area (tables 9–12). Concentrations of TCE and PCE exceeded the USEPA's Maximum Contaminant Level (MCL) for ground water in at least one sample from every borehole sampled for this study (U.S. Environmental Protection Agency, 1996). The concentration of TCA exceeded the USEPA MCL for ground water in at least one sample from boreholes T1 and T4.

The total concentration of volatile organic compounds (TVOC's) in the open boreholes T1, T2, and T6 varied by less than 45 µg/L and were higher at boreholes T1 and T2 than at borehole T6 (table 9). Concentrations of TCA are more than 25 µg/L higher in the eastern part of the study area at boreholes T1, T2, and T4 than in the western part of the study area at borehole T6. Concentrations of TCE were at least 50 µg/L higher at boreholes T1, T2, and T4 than at borehole T6. Concentrations of PCE at borehole T6 were more than 40 µg/L higher than PCE concentrations in boreholes T1, T2, and T4.

Concentrations of metals and cyanide in water from open boreholes T1, T2, and T6 are less than the USEPA's MCL for drinking water, except for thallium and lead in the sample from borehole T1 (U.S. Environmental Protection Agency, 1996) (table 9). The concentration of nickel in the sample from borehole T6 is only 1 µg/L below the MCL. Concentrations of most metal compounds were higher in boreholes T1 and T2 than in borehole T6.

TVOC concentrations in borehole T4, which is open to only the upper few feet of the Galena-Platteville aquifer, were more than 100 µg/L higher than TVOC concentrations measured in any other sample collected during this study. Water-quality data obtained from the test intervals isolated with a packer assembly show no clear variation in the concentration of TVOC's with depth in borehole T1, although TVOC concentrations in the upper two intervals are slightly higher than TVOC concentrations in the lower two intervals (table 10). The similarity of water quality with depth at borehole T1 may result from the good vertical hydraulic interconnection within the aquifer caused by the inclined fracture at the borehole. TVOC concentrations in the top and bottom test intervals at borehole T5 are more than 190 μg/L higher than in the middle intervals.

The data from borehole T4 and the test intervals isolated with the packer assembly in boreholes T1 and T5 indicate that the highest concentrations of VOC's are present in the upper part of the Galena-Platteville aquifer. Discrete inclined fractures appear to be the pathway for vertical movement of VOC's deeper into the aquifer. Those intervals in good hydraulic connection with the inclined fractures appear to have the highest concentrations of VOC's.

Water pumped from the 145–155 ft interval at borehole T6 was sampled for VOC's at 2,150; 2,775; and 4,165 minutes after the start of pumping in the borehole during the tracer test (table 11). Concentrations of TVOC's in these samples decreased overall through time, indicating that water with lower TVOC concentrations than the water near the 145–155 ft interval in borehole T6 was being drawn into the pumped interval.

Water pumped from the 145–155 ft interval at borehole T1 was sampled for VOC's at 290; 1,335; 2,595; 4,600; 6,435; and 7,125 minutes after the start of pumping to remove the tracer injected into this borehole. Concentrations of TVOC's in these samples increased by almost 200 μg/L from 290 and 1,335 minutes (table 12). This increase is probably caused by the removal, prior to 1,335 minutes, of the bulk of the water with low concentrations of TVOC's put into the aquifer when the tracer was injected. TVOC concentrations decreased consistently after 1,335 minutes, indicating water with a lower concentration of TVOC's than the water near the 145–155 ft interval in borehole T1 was being drawn to the pumped interval.

## SUMMARY AND CONCLUSIONS

Hydrologic and geophysical data indicate four intervals of elevated permeability in the Galena-Platteville aquifer underlying the Parson's Casket Hardware Superfund site: (1) a shallow, subhorizontal fracture from 37 to 40 feet (ft) below land surface at boreholes T5 through T8; (2) an inclined fracture from 75–85 ft at boreholes T1 and T2; (3) a shallow, vuggy interval from 90 to 100 ft throughout the study area; and (4) a deep, vuggy interval from about 140 to 180 ft throughout the study area. Transmissivity, storage coefficient, and horizontal hydraulic conductivity of these intervals were estimated on the basis of analysis of static-water level and flowmeter data. Values of transmissivity and horizontal hydraulic conductivity determined from the flowmeter and water-level data are in good agreement with the values determined from slug test and constant-discharge aquifer test data for the vuggy intervals. The agreement between values of hydraulic properties determined from slug tests and constant-discharge aquifer tests and the values determined from the flowmeter and water-level data for the fractured intervals varies from good to poor.

Water levels in the deep, vuggy interval (and perhaps shallower intervals in the study area) respond to pumping changes in the Belvidere municipal-supply wells, probably through inclined fractures that connect the deep, vuggy interval with permeable units in the deeper part of the aquifer. An unidentified feature at a depth of 180–190 ft, perhaps a horizontal fracture at about 186 ft, may be exhibiting preferential hydraulic connection with the deeper vertical flow pathways.

Constant-discharge aquifer tests indicate the deep, vuggy interval is homogeneous. There is good vertical hydraulic interconnection within this interval. Results from constant-discharge aquifer tests also indicate the inclined fracture is hydraulically connected to the deeper, permeable intervals in the Galena-Platteville aquifer and the overlying unconsolidated aquifer. The inclined fracture appears to become less permeable with depth. Inclined fractures are the most likely pathways for vertical flow of ground water and contaminants in ground water.

During the tracer test, cross-borehole radar tomograms collected along the borehole T2–T8 plane demonstrated predominately horizontal flow, with some tracer movement downward through the aquifer with increasing time and distance from the injection interval. Some upflow into a horizontal fracture was measured near borehole T2. Downward migration of tracer water below the pumping and injection interval probably is caused by density effects of the tracer and perturbations in the flow field caused by offsite pumping effects and the water-level increase associated with tracer injection. Upward migration of the tracer near borehole T2 may result from interaction of the hydraulic field induced by pumping and injection, and vertical flow through open boreholes. Analysis of the data collected from the tomograms and aquifer tests resulted in a maximum-effective porosity calculation of 8.8 percent for the interval from 145 to 155 ft. Borehole radar data indicate the average maximum ground-water velocity was 21.4 feet per day under the hydraulic gradient induced by the tracer test.

Results of sampling for volatile organic compounds (VOC's) in open boreholes and test intervals isolated with a packer assembly indicate that trichloroethene, trichloroethane, and tetrachloroethene are the primary VOC's measured in the Galena-Platteville aquifer. Concentrations of metals and cyanide in water from the open boreholes are less than the U.S. Environmental Protection Agency's Maximum Contaminant Levels for drinking water, except for thallium and lead at borehole T1. The highest concentrations of total volatile organic compounds (TVOC's) are present in the shallow part of the Galena-Platteville aquifer. Discrete inclined fractures appear to be the pathway for vertical movement of VOC's deeper into the aquifer. Those intervals in good hydraulic connection with the inclined fractures appear to have the highest concentrations of TVOC's.

Use of packer assemblies, borehole flowmeter logging, and borehole ground-penetrating radar tomography have proven to be effective technologies for efficient characterization of bedrock geology, ground-water-flow pathways, and hydraulic properties of the Galena-Platteville aquifer at this site. Packer assemblies were used to provide detailed characterization of the hydrologic properties and water quality associated with specific features (fractures, vuggy intervals) in the aquifer. Flowmeter logging has enabled rapid identification of the permeable intervals in the aquifer and, in combination with water-level data collected using the packer assemblies, estimation of the hydraulic properties of these intervals. Single-hole and cross-borehole radar tomographic surveys have enabled characterization of the location and extent of fractures in the study area away from the boreholes and semiquantitative estimation of the maximum effective porosity of the bedrock. Cross-borehole tomography, done in conjunction with tracer testing, has identified flow pathways in the aquifer under the hydraulic conditions induced by pumping and allowed estimation of ground-water-flow velocities under pumping conditions even though tracer breakthrough did not occur.

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