INTEGRATION OF GEOPHYSICS, GEOLOGIC MAPPING AND WATER-LEVEL MONITORING TO CHARACTERIZE THE HYDROGEOLOGY OF A FRACTURED BEDROCK SITE IN BERLIN, NEW HAMPSHIRE

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Abstract

Elemental mercury is found in fractured depressions and potholes on the bedrock surface, in the overburden, and is dissolved in ground water at the site of a former chlor-alkali plant (cell house) along the bank of the Androscoggin River, in Berlin, N.H. The cell house has been demolished, ground-water flow impeded by installation of an up-gradient-slurry wall, and capped with an impermeable geomembrane. Mercury has been removed from fractures at the surface on the riverbank five times; however, more continues to be found. Potential pathways for movement of mercury and ground water were indicated with the results of a geohydrologic study. The study demonstrates the integration of geophysical surveys, geologic mapping, and water-level monitoring in three areas: (1) the riverbank, (2) the site perimeter, and (3) the capped area.

Results from ground-penetrating radar and two-dimensional-resistivity surveys along the riverbank indicate electrically conductive zones that are interpreted as bedrock fractures, which are potential ground-water-flow paths. Geologic mapping along the riverbank shows that bedrock fracturing is more prevalent in gneiss than pegmatite and is associated with schist in shear zones that correspond to geophysical anomalies. Nearly horizontal anomalies in ground-penetrating-radar survey results beneath areas mapped as pegmatite may represent locations where vertical fractures in gneiss terminate on a horizontal fractured contact between gneiss and pegmatite. Significant hydraulic connections were identified by analysis of stage changes in the Androscoggin River and bedrock water levels. Assessment of hydraulic heads in bedrock and overburden show vertical ground-water gradients in both directions. Resistivity-survey results along the site perimeter indicate fractures and overburden-filled bedrock troughs where ground water may bypass a slurry wall. Overburden water levels and discharge from a drainage pipe suggest that ground water is passing through or beneath the slurry wall. Response of overburden water levels do not show connections with the river.

Introduction

Elemental mercury contamination resulting from a historical chemical production process represents a risk to human health and the environment. During the early to mid-1900s, a chlor-alkali plant, termed the cell-house site, was used to produce chlorine gas for the paper industry in Berlin, N.H. (Figure 1). Elemental mercury used as cathodes in electrolytic cells produced chlorine by hydrolyzing a brine solution. Elemental mercury was released and seeped into the overburden and underlying fractured bedrock as a result of this process. Remediation, in 1999, included demolishing the last cell house, covering the site with an impermeable cap to prevent precipitation infiltration, and installing a slurry wall to the bedrock surface to impede ground-water flow through the overburden into the capped area. Currently (2003), ground water continues to seep into the overburden under the capped area and flow into the

Androscoggin River (Margaret A. Bastien, New Hampshire Department of Environmental Services, written commun., 2002). Despite five removal efforts, elemental mercury continues to appear in bedrock fractures along the riverbank at the cell-house site (Figure 2). The extent of mercury contamination in bedrock and mechanisms of transport to the riverbank are unknown. The capped area appears to be the source of the mercury contamination (Margaret A. Bastien, New Hampshire Department of Environmental Services, written commun., 2002).

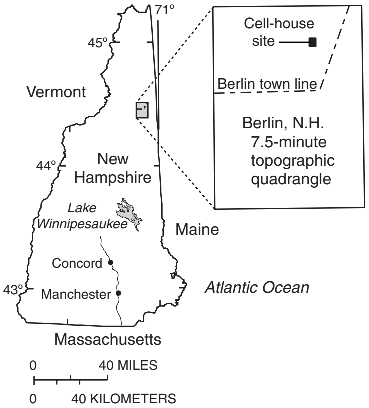
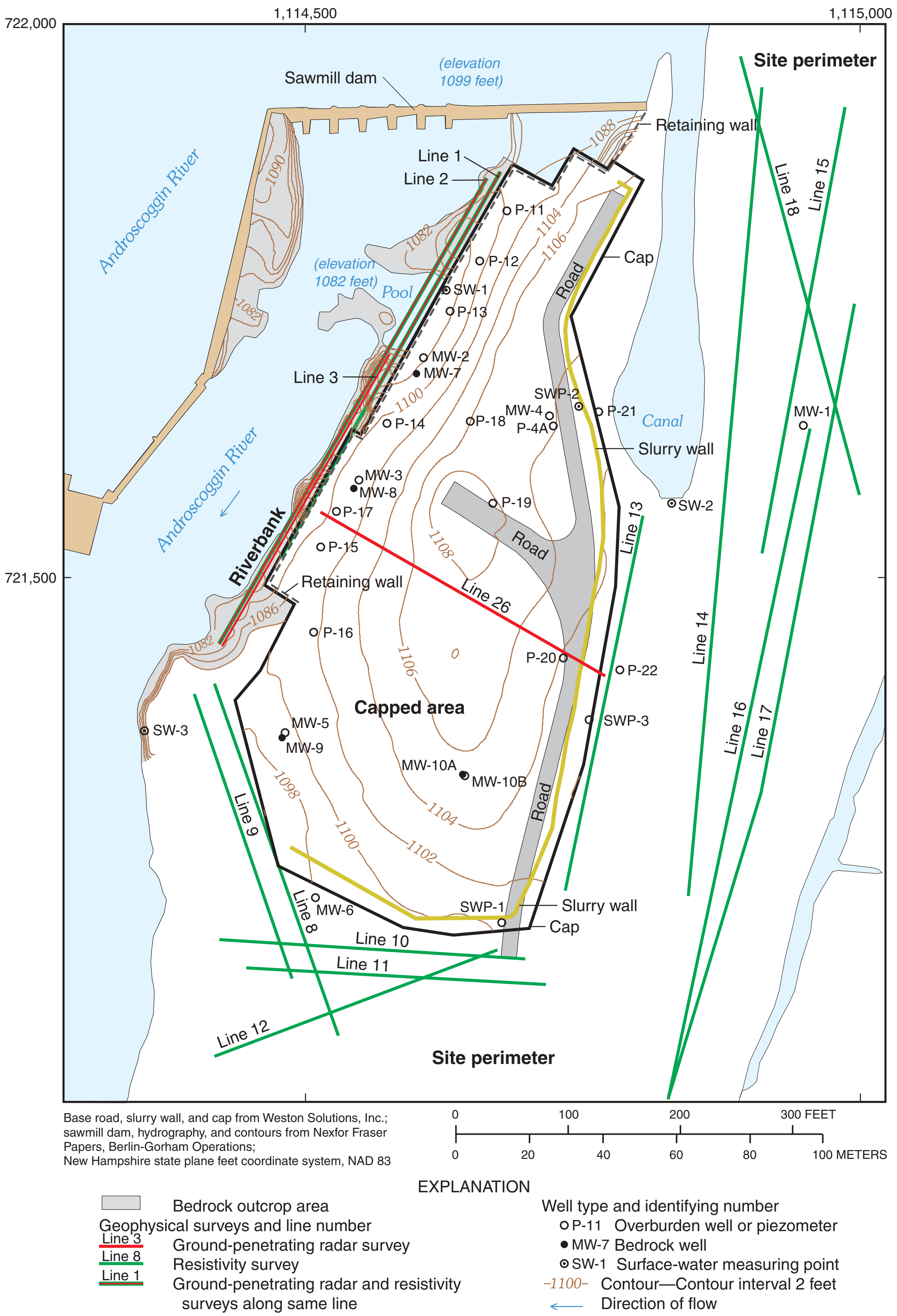


Figure 1.: Location of study area in northern New Hampshire.

The U.S. Geological Survey (USGS), in cooperation with the New Hampshire Department of Environmental Services (NHDES), have designed this study to demonstrate the integration of techniques to characterize the hydrogeology. Results of the study indicate potential ground-water-flow paths (fracture zones) in the bedrock and provide a preliminary assessment of hydraulic interactions between bedrock, overburden, and surface water. An understanding of potential transport mechanisms and routes is needed by water-resource managers to determine if migration of mercury away from the cell-house site is possible. Data collection targeted three main areas at the cell-house site: (1) the riverbank, (2) the site perimeter, and (3) the capped area. Mercury is found at the riverbank where ground water discharges under a retaining wall and through a pipe in the wall. Ground water enters and exits the site through or around the slurry wall along the site perimeter and is kept at a nearly constant head on the north east side by the canal (Figure 2) water level. The capped area is the site of the cell house bounded by the slurry wall and the retaining wall.

Bedrock exposed in the river, along the riverbank, and beneath the retaining wall (Figure 2), consists of weakly foliated fine- to medium-grained gray gneiss cut by pegmatite. These rocks have been described as a biotite-quartz monzonite of the Oliverian Plutonic Suite (Billings and Billings, 1975). This characterization is shown in recent regional compilations (Monech and others, 1995) and the Bedrock Geologic Map of New Hampshire (Lyons and others, 1997). Overburden at the site is generally less than 20 feet thick and consists of thin deposits of glacial till (an unsorted mixture of clay, silt, sand, cobbles, and boulders) and demolition debris.



Base road, slurry wall, and cap from Weston Solutions, Inc.; sawmill dam, hydrography, and contours from Nexfor Fraser Papers, Berlin-Gorham Operations; New Hampshire state plane feet coordinate system, NAD 83

EXPLANATION

▨	Bedrock outcrop area
Geophysical surveys and line number	
Line 3 🟥	Ground-penetrating radar survey
Line 8 🟩	Resistivity survey
Line 1 🟩🟥	Ground-penetrating radar and resistivity surveys along same line

Well type and identifying number

○ P-11	Overburden well or piezometer
● MW-7	Bedrock well
⊙ SW-1	Surface-water measuring point
–1100–	Contour—Contour interval 2 feet
←	Direction of flow

Figure 2.: Location of the cell-house site, geophysical survey lines, surface-water measuring points, and wells, Berlin, N.H.

Methods

Site characterization consisted of detailed co-interpretation of geophysical surveys, geology, and water-level data, facilitated by a surveyed grid with reference bolts along the riverbank. Surface-geophysical survey methods are useful in locating and determining the orientation of bedrock-fracture zones (Powers and others, 1999; Degnan and others, 2001). Two geophysical survey methods were used to characterize the subsurface at the study site—ground-penetrating radar and two-dimensional direct-current electrical resistivity. Ground-water head and river-stage data near the site were used to assess the connectivity of the ground-water-flow systems with the river.

Ground-Penetrating Radar

Ground-penetrating radar (GPR) surveys were used to image the fractures along the riverbank, and to identify depressions in the bedrock surface where mercury in the capped area could pool. A 300-MHz frequency antenna was used to generate and detect electromagnetic (EM) waves. The radar-wave propagation from GPR is affected by differences in electromagnetic properties of the material it is passing through, which include dielectric permittivity, electrical conductivity, and magnetic susceptibility (Beres and Haeni, 1991). These properties are useful in defining differences in water content, overburden type, and lithology. Hansen and others (1999) used GPR to identify fluid-filled bedrock-fracture zones and overburden interfaces through the dielectric permittivity contrast. The utility of GPR, however, is limited at sites with electrically conductive clay-rich overburden (such as till at this site) because the EM wave can be attenuated before it reaches bedrock (Ayotte and others, 1999). GPR surveys used a point-survey mode where the antenna is placed at 5-foot intervals along a line. Repeated measurements at each point are stacked to amplify weak reflectors and filter out data scatter. Survey profiles were adjusted for topographic relief.

Two-Dimensional Resistivity

Two-dimensional direct-current electrical resistivity (2D-resistivity) surveys were used throughout much of the cell-house site to image the bedrock surface and fractures. 2D-resistivity could not be applied on the capped area because the geomembrane electrically insulates the materials below the membrane from the surface. Dipole-dipole and Schlumberger array (Zohdy and others, 1974) survey configurations were used, with minimum electrode spacings of 5 feet along the riverbank, and 10 or 15 feet along the site perimeter. Interpretations relied largely on the dipole-dipole array because of its fine lateral resolution. However, the Schlumberger array has a better signal to noise ratio, so in areas where the dipole-dipole array surveys were missing large amounts of data, interpretations were made from the Schlumberger-array surveys. The elevation of the land surface at each electrode was then surveyed and factored into the processing of the data. Electrodes located on the bedrock outcrop were wrapped in an absorbent fabric soaked in a saline solution to provide an electrical connection.

Apparent-resistivity data represent an average value for a location and depth. 2D-resistivity data were processed using RES2DINV version 3.52 (Loke, 1999) to produce inverted resistivity cross sections from the apparent-resistivity data. Inversion gives a more realistic resistivity value projected to a relative elevation. Bathymetry data for the pool in the river was extracted from the GPR record, using a 2-way velocity of 0.06 feet per nanosecond and used to create a fixed resistivity model layer (Loke and Lane, 2002). The conductivity of the water in the pool is 40.7 microsiemens per centimeter (resistivity 806 ohm ft), which was used to constrain the resistivity inversion.

Geologic Mapping

Bedrock fractures within a 1-mile radius of the cell-house site were measured to gain an understanding of regional fracture patterns that may control regional ground-water flow. Along the riverbank, lithology was mapped and fractures were measured to identify potential local ground-water-flow paths. Fracture data were collected using mapping techniques described by Walsh and Clark (2000). Principal trends of fractures were defined for each outcrop by plotting normalized azimuth-frequency (rose) diagrams using software (DAISY 3.41b) by Salvini (2002). Along the riverbank at the site, detailed geologic mapping was used to delineate lithology, determine fracture and fracture-zone orientation and spacing, characterize the fracture aperture and mineralization, analyze fracture terminations, and identify faults and relative motion of faults. Contacts between gneiss, pegmatites, and schist (locally in shear zones) were mapped.

Water-level Analysis

Ground-water level and river-stage data at the site were collected and evaluated to determine ground-water-flow directions, gradients, and hydraulic interactions between the bedrock, overburden, and surface water. Monitoring included the collection of ground- and surface-water specific-conductance data to assist the geophysical survey and geohydrologic interpretations. Site water levels were recorded using a continuous monitoring network that included overburden and bedrock well pairs and surface-water-level monitoring. In addition, discrete head measurements were collected at 19 overburden, 5 bedrock, and 3 surface-water sites (Figure 2). Continuous water-level-monitoring data were collected from eight wells inside (4 pairs) and three points outside the capped area, including continuous stage data at two locations on the Androscoggin River. Synoptic surveys of all of the wells and piezometers at the site were used to create potentiometric head maps of ground water in the overburden and bedrock. Integrated analysis of such surveys, particularly unique or isolated hydrologic events (short-term recharge or stage changes), was useful in assessing the effectiveness of the slurry-wall ground-water-containment systems (Brayton and Harte, 2001).

Geohydrologic Characterization

The cell-house site is near a regional boundary between fracture domains (regions with different principal fracture trends) and is underlain by fractures with an average trend of 035 (from analysis of fractures mapped on the riverbank). Steeply dipping fractures define a domain with principal azimuthal trends of 252-295° and 312-328° south and east of the Androscoggin River in Berlin. North and west of the river, principal trends of the steeply dipping fractures are 348-008° and 021-038°. Detailed geohydrologic characterizations of the riverbank, site perimeter, and the capped area are provided in the following sections.

Riverbank

Several electrically conductive anomalies indicating fractures were found with geophysical surveys along lines 1-3 on the riverbank that correlate with fractures found during geologic mapping. Geologic mapping at the riverbank revealed that fracture frequency varies with rock type. Pegmatites are relatively unfractured compared to gneisses. Asymmetrically folded irregular ductile shear and planar brittle shear zones cut the gneiss. The folded ductile shear plunges to the northeast. Brittle fracture forms parallel and en echelon fracture sets and zones. Steeply dipping fractures in gneisses often truncate at ductile shear boundaries. Fractures measured in bedrock outcrops support interpretations of geophysical results.

GPR results at a distance of 50 to 100 ft along lines 1 and 2, show several horizontal and shallow-dipping reflectors that are consistent between the two lines (Figure 3) beneath areas mapped as pegmatite. Nearby geologic mapping indicate that these anomalies may represent locations where vertical fractures in gneiss terminate on sub-horizontally fractured contacts between gneiss and pegmatite. Core logs from adjacent boreholes in the capped area show alternating layers of pegmatite and gneiss. 2D-resistivity results from lines 1 and 2 (Figure 4) indicate electrically conductive anomalies in the bedrock that are in the same locations as the reflections seen in the GPR results.

Several conductive anomalies along line 1 (dipole-dipole array) have resistivity values less than 150-ohm feet. Electrically conductive ground water (greater than 4,000 microseimens per centimeter) was found in the bedrock at well MW-7 near the largest 2D-resistivity anomaly under the high relief bedrock at a distance of 235 feet along the line and with a 60° apparent dip. This feature lines up with an anomaly along line 2 centered at 225 feet with a 50° apparent dip. This is the location of an asymmetrically folded ductile shear zone, a major structural feature on the riverbank at the cell-house site, with open vuggy fractures and chlorite alteration, plunging 47° in a 055° direction. Water-level monitoring near the shear zone, at bedrock well MW-7 and in the river at SW-1, confirms a hydraulic connection between the ground water in the fractured bedrock and the river in this area (Figure 5).

At the southern end of the riverbank, GPR-survey results were not as consistent between survey lines 2 and 3 (Figure 3). In addition to shallow and horizontal reflections, a steeply dipping reflection is centered at 330 feet on line 2. The lack of electrical anomalies from 310 feet to the southern end of line 2 in the dipole-dipole array survey results is due to missing data points. Conductive anomalies are indicated in the Schlumberger array survey results (Figure 4).

Site Perimeter

Seven potential fracture zones that could transmit ground water into or out of the capped area were located with 2D-resistivity surveys along the site perimeter to the east, south, and southwest of the capped area (lines 8-18, Figure 2). On the southern perimeter of the site, 2D-resistivity survey results from lines 10, 11, and 12 indicate a fracture zone with a 160 trend crossing all three survey lines. The projected trend of this zone intersects the slurry wall where a historic map shows a main waterline, which may be the cause of the anomaly. Electrically conductive features near the surface could be buried metal from the demolition of buildings, or main waterlines. Electrically conductive features below the interpreted surface of the bedrock along these lines are likely bedrock-fracture zones.

2D-resistivity survey results along lines 8 and 9, at the southwestern perimeter of the site and parallel to the Androscoggin River, indicate potential overburden and bedrock ground-water-flow paths out of the site past the western end of the slurry wall (Figure 6). The center of an interpreted fracture zone and trough in the bedrock surface striking 80° extends between lines 8 and 9 at an approximate distance of 140 feet along the lines (Figure 6). Results from line 9 indicate a more conductive anomaly in the bedrock than on line 8. Buried metal debris along line 8 may obscure conductive features.

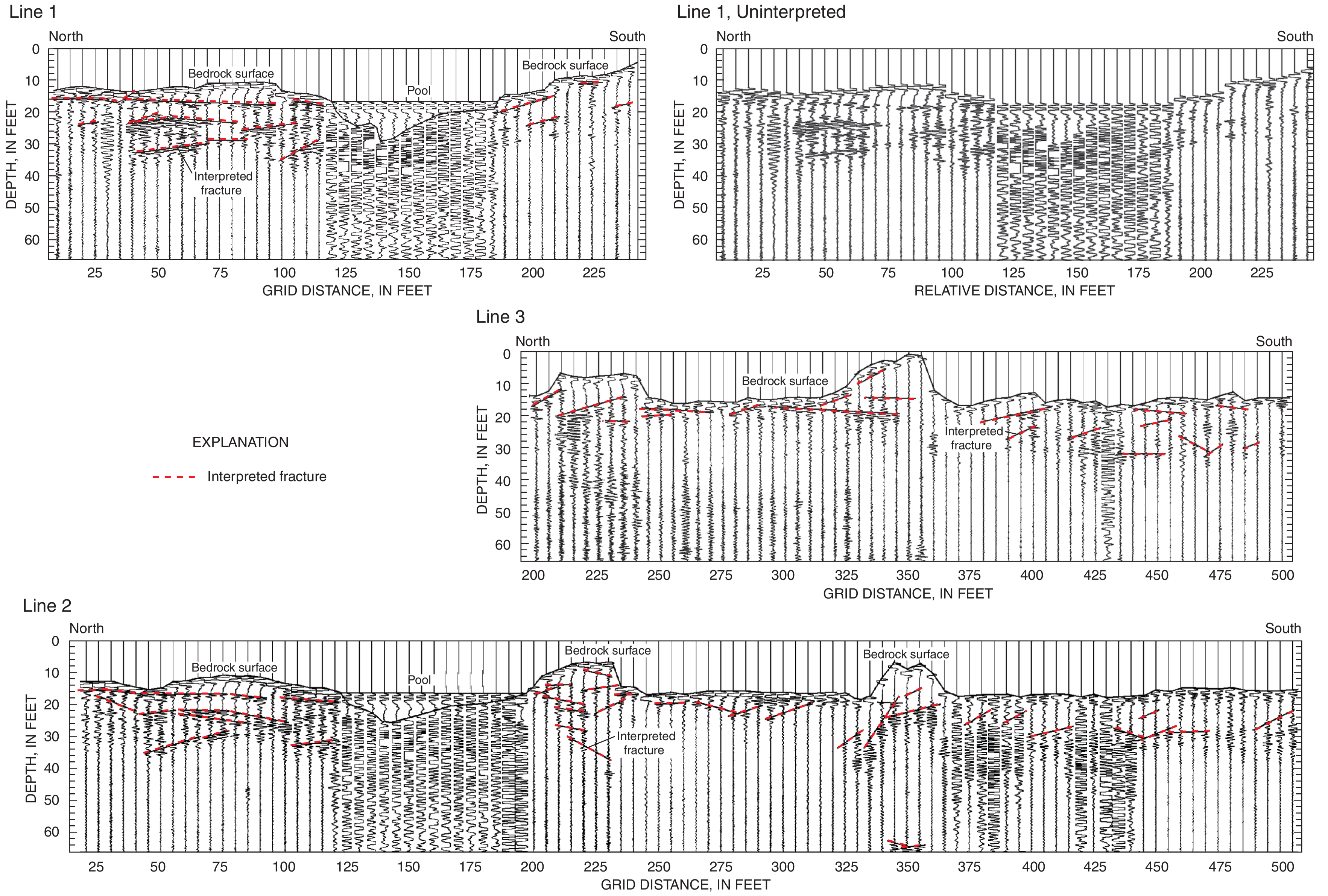


Figure 3.: Processed ground-penetrating-radar profiles and interpretations from parallel lines 1, 3, and 2 on the bank of the Androscoggin River, cell-house site, Berlin, N.H.

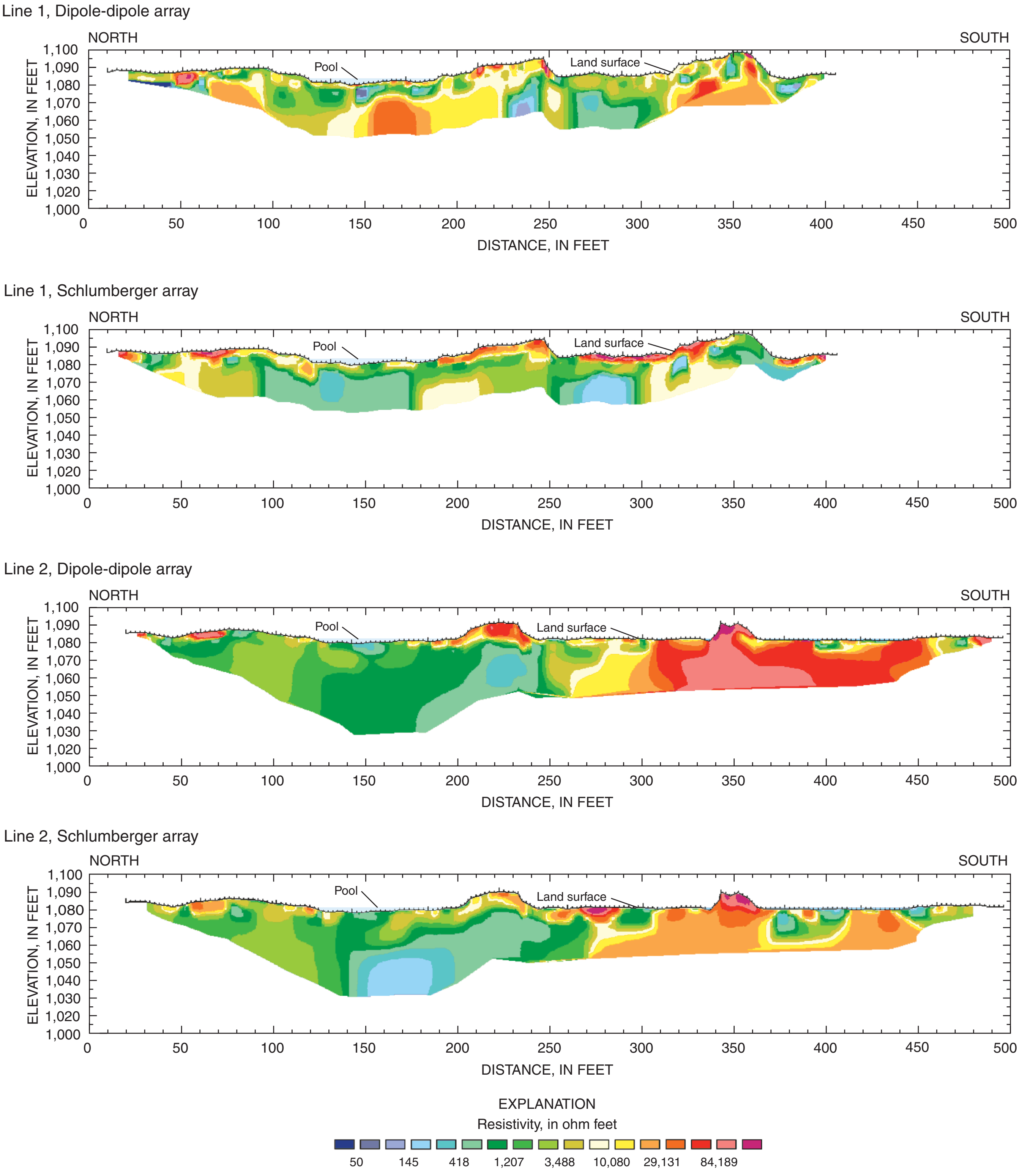


Figure 4.: Cross sections of inverted two-dimensional, direct-current resistivity data from lines 1 and 2 on the bank of the Androscoggin River, Berlin, N.H.

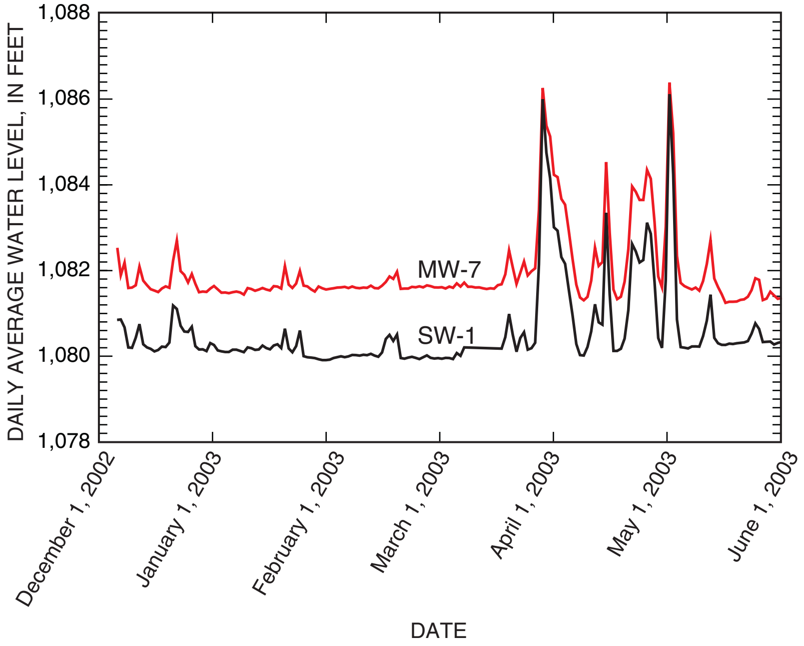


Figure 5.: Hydrograph of bedrock well MW-7 and the Androscoggin River stage (SW-1), cell-house site, Berlin, N.H.

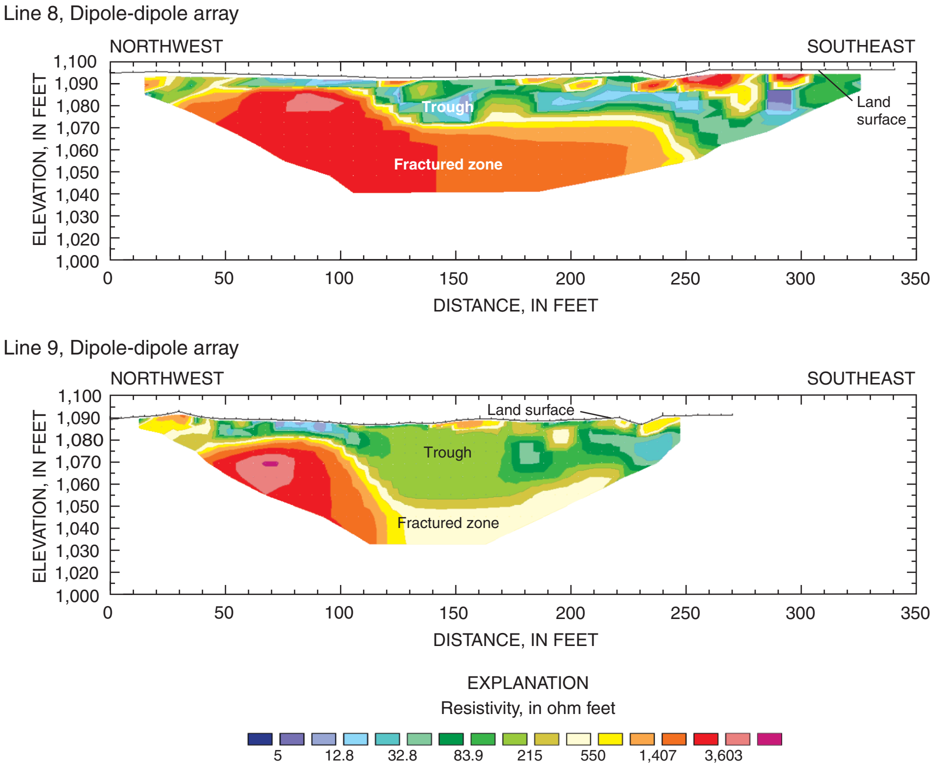


Figure 6.: Cross sections of inverted two-dimensional, direct-current resistivity data and interpretations from lines 8 and 9 on the southwest perimeter of the cell-house site, Berlin, N.H.

Capped Area

GPR surveys on top of the capped area imaged the bedrock surface, depressions in the bedrock surface that could pool mercury, and potential fracture zones. GPR wave reflections along line 26 (Figure 2) provided data for interpretations of four layers: (1) woodchips and geomembrane cap, 3-4 feet thick; (2) overburden, 3-10 feet thick; (3) saturated overburden, 0-5 feet thick and (4) bedrock (Figure 7). Shallow depths to bedrock are confirmed through soil-boring data and observations of outcrops adjacent to the capped area. There is a 2-foot deep trough in the surface of the bedrock between 130 and 150 feet that could be the result of fracturing and could allow pooling of mercury. Water-level data from overburden and bedrock wells in the containment area indicate a complex combination of upward and downward gradients (Table 1). Monitoring data from the MW-5 and MW-9 well cluster show reversals in vertical-head gradients over time between the overburden and bedrock. Upward gradients from the fractured bedrock to the overburden could provide ground-water recharge to the overburden. Hydraulic connectivity between the overburden in the capped area and the river is limited to areas where the overburden is adjacent to the river, such as along the canal on the site perimeter (Figure 2). The hydraulic connectivity between the bedrock and the river shows preferential anisotropic pathways.

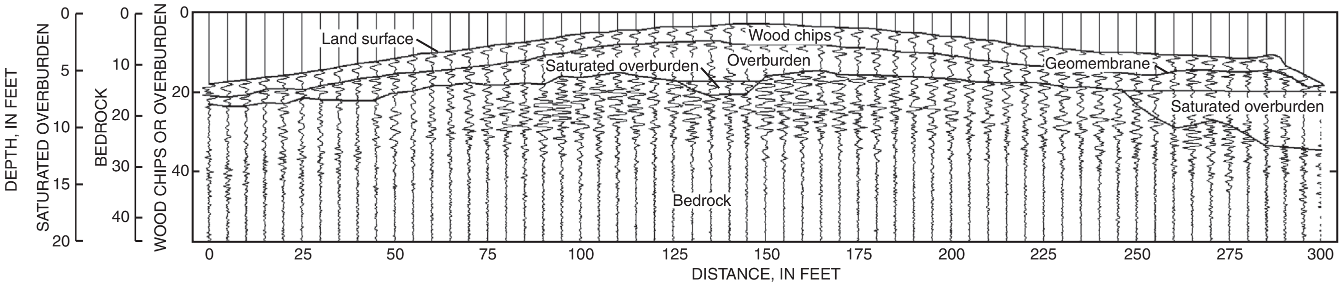


Figure 7.: Processed ground-penetrating-radar profile and interpretations from line 26 across the capped area, cell-house site, Berlin, N.H.

Table 1.: Table Showing Altitudes and Differences of Water Levels in Overburden and Bedrock Well Pairs

Well Pair (overburden/rock)	**Overburden Head, in feet 4/2/2003**	**Bedrock Head, in feet 4/2/2003**	**Head Difference, in feet**	**Comment**
MW-4/P-4A	1,096.18	1,095.74	0.44	Downward gradient
MW-2/MW-7	1,090.63	1,083.66	6.97	Downward gradient
MW-3/MW-8	Dry	1,085.50	-----	Dry overburden
MW-5/MW-9	1,091.72	1,090.42	1.30	Downward gradient
MW-10B/MW-10A	1,093.89	1,094.31	-0.42	Upward gradient

Conclusions

Along the riverbank, electrically conductive and electromagnetic wave-reflecting features are observed that are interpreted as bedrock fractures. On the basis of locations and apparent dips of the anomalies, some interpreted features such as fractures can be projected between survey lines. GPR surveys primarily identified horizontal and shallow dipping anomalies, whereas 2D-resistivity survey anomalies were identified with a variety of apparent dips. Strong, electrically conductive, 2D-resistivity anomalies or GPR reflections can result from fluid-filled fractures. Electrically conductive contaminants in ground water may increase the strength of anomalies observed in the fractured bedrock. Bedrock geologic mapping helped describe the nature and trends of fractures in the subsurface detected with geophysical surveys. Water-level monitoring confirmed that there are substantial hydraulic connections between the river and ground water in the fractured bedrock.

2D-resistivity results from the perimeter of the site indicate an electrically resistive lower zone that is interpreted as the bedrock surface. Near the surface, electrically conductive anomalies likely represent metal debris and resistive anomalies could be caused by concrete or stone foundation material. Bedrock-fracture zones are indicated by conductive features below the bedrock surface. Some of these fracture zones appear to have strikes trending towards the site and may allow for the transport of ground water into or out of the site underneath the slurry wall. Ground-water-level monitoring indicates hydraulic connections across the slurry wall that may follow a weak zone in the wall and (or) a path through bedrock fractures extending beneath the wall.

GPR surveys indicate a complex ground-water-flow system in the bedrock and overburden having downward, upward, and reversing head gradients beneath the site cap. Water-level measurements confirm this complex ground-water-flow system. Response of bedrock water levels to river stage indicates good hydraulic connections exist and that the connection shows preferred and anisotropic pathways.

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