Sep 29th, 2017

A3: Hydrogeology of the Former Chlor-Alkali Facility Superfund Site and Downstream Bed Sediment Mercury Contamination in the Androscoggin River, Berlin, New Hampshire

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Recommended Citation

Degnan, J., Luce, D., Hoffman, A., and Chalmers, A., 2017, Hydrogeology of the Former Chlor-Alkali Facility Superfund Site and Downstream Bed Sediment Mercury Contamination in the Androscoggin River, Berlin, New Hampshire in Johnson, B. and Eusden, J.D., ed., Guidebook for Field Trips in Western Maine and Northern New Hampshire: New England Intercollegiate Geological Conference, Bates College, p. 61-80. https://doi.org/10.26780/2017.001.0004

HYDROGEOLOGY OF THE FORMER CHLOR-ALKALI FACILITY SUPERFUND SITE AND DOWNSTREAM BED SEDIMENT MERCURY CONTAMINATION IN THE ANDROSCOGGIN RIVER, BERLIN, NEW HAMPSHIRE

By

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INTRODUCTION

Field trip stops will illustrate the hydrologic and geologic setting near Berlin, New Hampshire, and how the setting affects a Superfund site. The trip will include a visit to the former Chlor-Alkali Facility Superfund Site (hereinafter call the “site”), bedrock outcrops, and river reaches. The site’s industrial history, current environmental and regulatory issues, as well as how the geology and groundwater hydrology affect the site cleanup will be discussed. Nearby outcrops of the Ordovician Oliverian Plutonic Suite and Ordovician Ammonoosuc Volcanics, representative of the site and regional geology, will be visited. Stops at several river reaches, with varying settings, will include descriptions of hydraulics, surface water, and sediment chemistry.

Field studies were completed by the U.S. Geological Survey (USGS), in cooperation with the U.S. Environmental Protection Agency (EPA) in August and September 2009 (Chalmers and others, 2013, https://pubs.usgs.gov/of/2013/1076/; Degnan and others, 2011, https://pubs.usgs.gov/sir/2011/5158/), and by the USGS and the New Hampshire Department of Environmental Services (NHDES), Waste Management Division, from October 2002 through February 2004 (Degnan and others, 2005, https://pubs.usgs.gov/sir/2004/5282/). The studies were designed to provide geologic information, provide a conceptual understanding of hydrogeology of the site, and further understand the riverbed sediment and potential contaminant distribution downstream from the site in Berlin, N.H. The site was associated with a pulp and paper mill on the bank of the Androscoggin River (fig. 1). The Chlor-Alkali Facility produced chlorine gas for the papermaking industry. Mercury was released and seeped into the soil, till, and underlying fractured bedrock because of site activities (U.S. Environmental Protection Agency, 2011) and may represent a risk to human health and the environment.

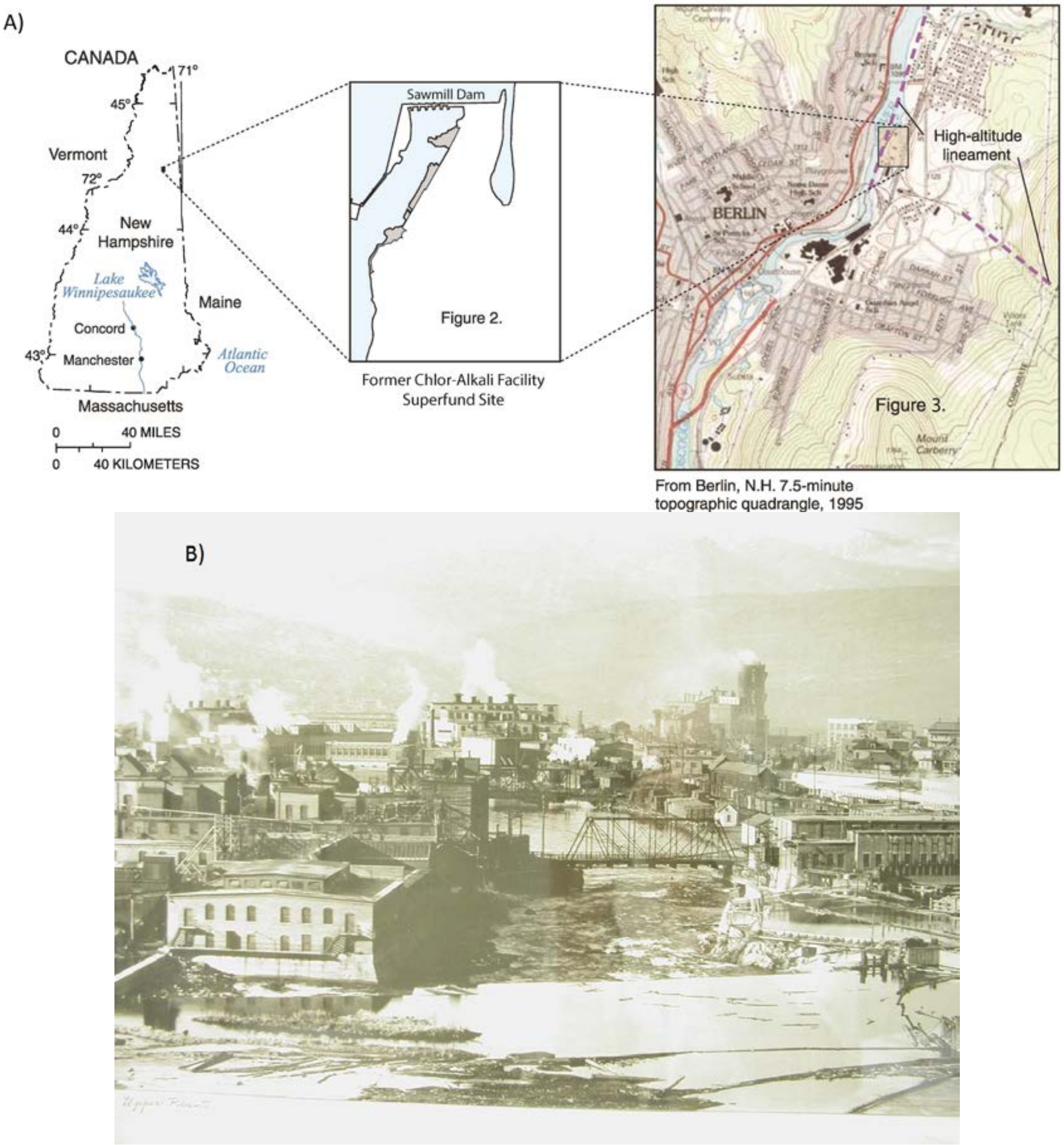
Former Chlor-Alkali Facility industrial history

From 1899 to 1965, a chlor-alkali facility on the east bank of the Androscoggin River was used to produce chlorine gas for the papermaking industry in Berlin, N.H. (fig. 1). The site was associated with a pulp and paper mill, and a sawmill. Chlorine was produced at the site using electrolytic diaphragm and potentially mercury cells. Chlorine was produced primarily to supply the papermaking industry for paper bleaching. Mercuric chloride also may have been produced on site. The sawmill included a wood preserving operation from 1888 to 1930, which used mercuric chloride in a process known as “Kyanization” to preserve the wood (Gove, 1986).

In the 1990s, elemental mercury in the form of a silver-colored liquid was observed, and vapor was detected in and near bedrock fractures along the left riverbank near the site and in river sediment. This prompted the New Hampshire Department of Environmental Services to investigate the site. Since the late 1990s, efforts have been made to contain mercury at the site and eliminate the seepage of contaminated groundwater to the river (Margaret A. Bastien, New Hampshire Department of Environmental Services, written commun., 2003). The site was placed on the EPA National Priorities List in 2005 (U.S. Environmental Protection Agency, 2011; New Hampshire Department of Environmental Services, 2017).

Remedial efforts and environmental concerns

Remedial efforts at the site included (1) removal and demolition (debris left as landfill on site) of buildings associated with the chlor-alkali facility, (2) installation of a subsurface bentonite-soil slurry (barrier) wall on the site perimeter that is connected to the bedrock surface (fig. 2), (3) installation of a synthetic cap over the site to prevent precipitation infiltration, and (4) pressure grouting bedrock fractures along the riverbank. The intent of these remedial actions was to substantially reduce groundwater flow through the site’s overburden and reduce this driving force for contaminant migration. Despite earlier actions to address the source of contamination, mercury continues to be present in the Androscoggin River at bedrock fractures at the edge of the site; the mechanism of transport "flouring" from deeper or adjacent mercury deposits is unknown. Between 1999 and 2006, about 135 pounds of elemental mercury and sediment containing mercury were removed from the river and riverbank (U.S. Environmental Protection Agency, 2011; New Hampshire Department of Environmental Services, 2017).



From Berlin, N.H. 7.5-minute topographic quadrangle, 1995

Figure 1. A) Location of the study area, Berlin, New Hampshire, with lineaments from high-altitude photography. (Lineaments from Ferguson and others, 1999) and B) circa 1920 photograph of the former Chlor-Alkali Facility Superfund Site on the left, looking south from Sawmill Dam.

An understanding of the extent of fine sediment and mercury contamination in the Androscoggin River also was needed to determine the potential effects on the environment. Eggleston (2009) indicated that resuspension of mercury-contaminated sediment can account for a large percentage of the annual downstream mercury load in a point-source, mercury-impaired watershed of the Shenandoah River in Virginia. An understanding of sediment distribution in the Androscoggin River downstream from the site could identify potential zones of contaminant deposition. Elemental mercury, such as that emanating from the site, can be transported with fine-grained, organic carbon-rich, riverbed sediments. Deposition of these sediments pose a concern because they provide an optimal environment for mercury methylation (Marvin-DiPasquale, Lutz, and others, 2009; Marvin-DiPasquale, Agee, and others, 2011). Methylation is the conversion of elemental mercury to the organic form (methyl mercury) through microbial activity. Methylmercury is the toxic form of mercury and more mobile within the food chain. This conversion enables the bioaccumulation of methyl mercury in fish.

Geologic setting

Berlin, N.H., is on the eastern edge of the Bronson Hill anticlinorium and, more specifically, on the southeast flank of the Jefferson Dome (Billings and Billings, 1975). Billings and Billings (1975) describe three stages of rock deformation and associated development of foliation in the area. Bedrock in the Berlin area is primarily composed of the Oliverian Plutonic Suite and the Ammonoosuc Volcanics. The Androscoggin River channel and narrow valley in Berlin is underlain by metamorphosed biotite-quartz monzonite of the Ordovician Oliverian Plutonic Suite (Billings and Billings, 1975; Lyons and others, 1997). Gneisses and amphibolites of the Ordovician Ammonoosuc Volcanics lie immediately east and west of the valley floor (Billings and Billings, 1975; Lyons and others, 1997). Pegmatite of the Devonian New Hampshire Plutonic Suite locally cuts the Oliverian and Ammonoosuc rocks (Billings and Billings, 1975).

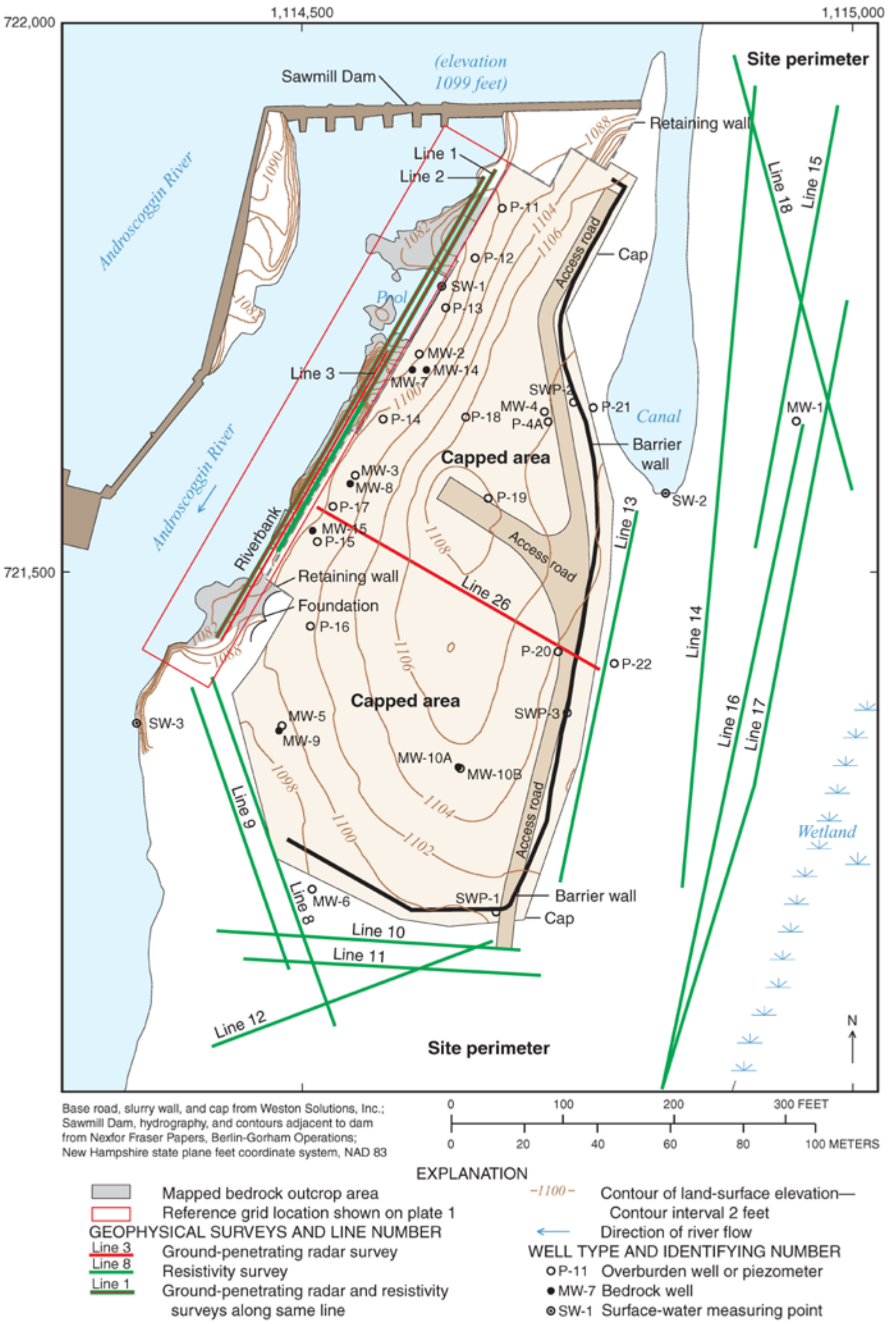
Billings and Billings (1975) describe the Oliverian Plutonic Suite as primarily pink, foliated, medium- to coarse-grained, granoblastic-textured quartz monzonite and pink pegmatite. The Ammonoosuc Volcanics are fine-grained, light-gray, foliated biotite gneiss locally interlayered with hornblende amphibolites. The units are distinguished by the finer grained, locally fragmental and bedded nature of the Ammonoosuc Volcanics and pink character of the Oliverian gneisses. The Oliverian Plutonic Suite intrudes the rocks of the Ammonoosuc Volcanics. Pink pegmatites of the New Hampshire Plutonic Suite locally cut the Oliverian and Ammonoosuc rocks (Billings and Billings, 1975).

Examination of 20 outcrops within a 1-mi radius of the site (fig. 3) support the division of units presented by Billings and Billings (1975). Amphibolites of the Ammonoosuc Volcanics, believed to be xenoliths, are within the area mapped as Oliverian Plutonic Suite rocks. For example, amphibolite (dark green to black, fine-needle, hornblende-plagioclase gneiss) xenoliths are present along Route 16, about 1,000 feet (ft) north of the hospital shown on the 7.5-minute, Berlin, N.H., topographic map. Dark-gray to black hornblende-biotite gneiss with biotite porphyroblasts also are present in rocks mapped as Oliverian in outcrops east of the entrance to the Berlin pulp mill. Unmetamorphosed lamprophyre dikes contain xenoliths of gray gneiss and pink feldspar-bearing gneiss and are present in outcrops east of the entrance to the Berlin pulp mill (about 1,000 ft south of the site).

Analysis of steeply dipping fractures in the Berlin area identifies two distinct fracture domains (fig. 4), which are areas defined by and containing distinct fracture patterns. South and east of the Androscoggin River, principal peaks on normalized azimuth-frequency plots trend west or northwest. West and north of the river (fig. 4), principal peaks trend north or north-northeast. At two localities west of the river, west-northwest and west-southwest principal peaks are present in addition to the north-trending principal peaks. East of the river (fig. 4), however, no north-trending principal peaks are present. The presence of generally west- and north-trending principal peaks at the two localities indicates that domain overlap is happening at these outcrops. The domain boundary and transition zone generally trends northeast along the river. The site is near the boundary between the domains observed in Berlin, N.H. (fig. 4).

Two lineaments (fig. 1) identified from high-altitude areal photographs pass near the site along the riverbank, and towards the southern end of the site (Ferguson and others, 1999). Certain types of lineaments, particularly certain fracture-correlated lineaments, have been associated with more transmissive bedrock in New Hampshire (Moore and others, 2002).

Overburden geologic materials just upstream from the site include stratified sand, gravel, and silt alluvium deposited by glacial outwash. Overburden near the site and downstream to the backwater of the Brown Dam (Cotton, 1975; Gerath, 1978; Olimpio and Mullaney, 1997) was generally less than 20 ft thick and consists of thin deposits of glacial till (an unsorted mixture of clay, silt, sand, cobbles, and boulders). Glacial till covers bedrock on the valley floor and walls where slopes are gentle, but is absent along the Androscoggin River at the site and for 2 mi downstream from the site (U.S. Environmental Protection Agency, 2011).



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

Figure 2. Location of reference grid, geophysical survey lines, mapped bedrock area, and water-level monitoring points at the former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire.

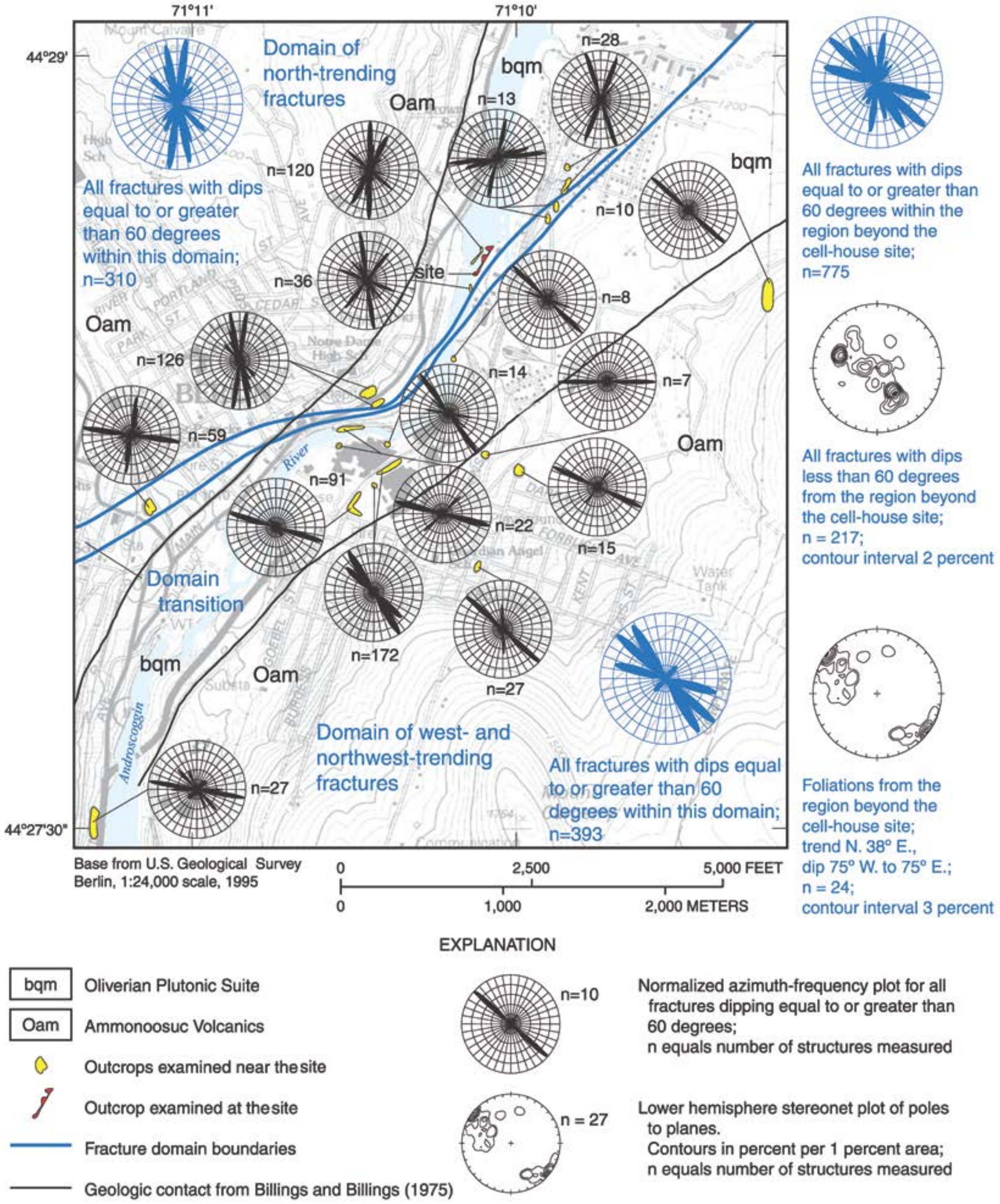


Figure 3. Bedrock geology, azimuth-frequency plots of fractures, fracture domains, and foliation near the former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire.

HYDROGEOLOGY OF THE SITE

The site setting is primarily fractured-rock where little was previously known about the geology and hydrogeology. Data collected during the fall of 2002 through the winter of 2004 were used to produce a geologic description and preliminary understanding of hydrogeology to guide ongoing remedial investigations for mercury contamination and is described in Degnan and others (2005, https://pubs.usgs.gov/sir/2004/5282/).

Site geology

Bedrock in the Androscoggin River, along the west side of the site, consists of gneiss with thin discontinuous lenses of chlorite schist and discontinuous tabular pegmatites as shown in cross section (fig. 4). Two distinct fracture domains overlap near the site (fig. 3). One domain, south and east of the Androscoggin River, is characterized by steeply dipping fractures with principal trends to the northwest. The second domain, north and west of the river, is characterized by steeply dipping fractures with principal trends to the north. The site is near the transition zone between these domains and locally has principal trends common to both fracture domains.

The fractured rock of the site consists of steeply dipping fractures in gneiss that terminate on subhorizontal fractures along contacts with pegmatite, on nonplanar fractures, or at moderately dipping contacts with chlorite schist. The rock types and fractures observed at the riverbank are believed to extend to the east beneath the site. Fractured-rock characteristics of the site include:

- Weakly developed gneissosity with nonplanar (irregular) fractures with a 1-millimeter (mm) (0.04 inch [in.]) aperture that generally conform to the gneissosity. Gneissosity is folded about an axis that plunges N.48°E. at 34°. Fractures that are subparallel to the gneissosity are folded about an axis that plunges N.55°E. at 47°.
- Foliated chlorite-schist lenses, and fractures that parallel these lenses, are folded about an axis that plunges N.37°E. at 26°SE. Vugs in the chlorite schist may contribute to the porosity of fractures in these lenses.
- Fracture intensity is a function of rock type. Rocks at the site, from most to least fractured, include (a) chlorite schist, (b) fine-grained nonfoliated gneiss, (c) coarse-grained weakly foliated gneiss, and (d) pegmatite.
- Fracture aperture varies with fracture type. In general, the aperture of parallel fractures sets are generally less than 1 mm (less than 0.04 in.). Nonplanar (irregular) fractures, locally associated with chlorite schist, often have apertures of about 1 mm (0.04 in.). En échelon fractures have the greatest aperture, generally 1–2 mm (0.04–0.08 in.) and as much as 5 mm (0.2 in.); however, the individual fractures that make up en échelon fracture sets are generally not through going.
- Steeply dipping en échelon fracture zones, parallel fracture zones, and silicified brittle faults show consistent strikes to the NE and on average dip NW.
- Gently dipping to subhorizontal fractures in the gneissic rocks have an average strike and dip of N.43°E., 09°SE.

The geology and hydrology at the site represent a highly complex hydrogeologic environment in terms of groundwater flow and mercury transport. Because mercury is present in the dissolved, elemental, and amalgamated form at the site, the effect of groundwater flow on mercury occurrence and transport will vary according to the form of the mercury. In addition, resuspension and deposition of mercury from turbulent flows in the Androscoggin River may also affect the presence of elemental mercury along bedrock outcrops adjacent to the river.

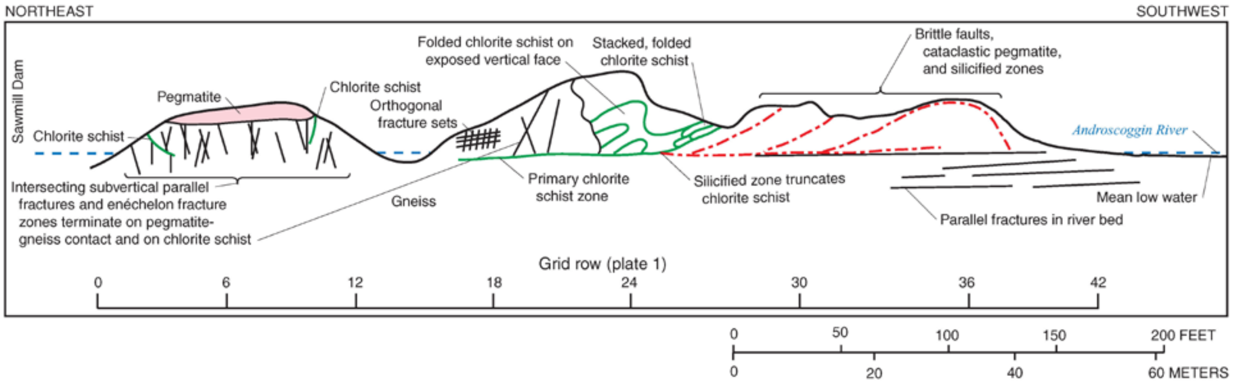


Figure 4. Generalized cross section of the bedrock geology at the former Chlor-Alkali Facility Superfund Site outcrop from grid 0 to 36, (360 ft) looking east, Berlin, New Hampshire.

Groundwater

Monthly measurements at additional sites were used to supplement spatial coverage of continuous measurement sites. Synoptic surveys of all the wells and piezometers at the site were used to create potentiometric-head maps of groundwater in the overburden and bedrock representing high and low water-level conditions. The bedrock aquifer near the river is well connected to the river, and head gradients in the bedrock across the site are large (more than 10 ft). Water movement between the river and the bedrock aquifer is greatest during periods of river stage fluctuations. A bulk horizontal hydraulic conductivity of the bedrock was estimated, from stage and well water-level responses, to be about 0.2 to 20 ft per day (ft/d). Individual fractures or fracture zones likely have hydraulic conductivities much greater than the bulk rock and affect the higher hydraulic conductivity estimates. Groundwater may move readily through near horizontal, or shallow to moderately dipping fractures, along chlorite schist lenses or through near horizontal fractures at the pegmatite contacts near the river. The near-horizontal features may serve as conduits to the bulk of the site for groundwater in steeply dipping fractures in gneiss. The horizontal, or gently dipping, fractures are discontinuous; therefore, the effective hydraulic conductivity across the site is likely to be closer to the low range of the estimated values (0.2 ft/d).

An unsaturated zone in the middle of the capped area caused by a high bedrock surface separates flow in the overburden into a northern and southern area. The flow is to the west toward the river in the northern and southern areas. Because overburden water-level fluctuations are small, head gradients in the overburden remain fairly constant across the cap area, partly because of the result of the relatively stable head in the canal and flow out of the discharge pipe in the concrete wall, in addition to the geomembrane cap on the site. The discharge pipe drains water at the base of the overburden near the river towards an altitude of 1,087.4 ft (the altitude of the base of the pipe). The alternating lenses of pegmatite, chlorite schist, and gneiss in the underlying bedrock may impose a vertical anisotropy so that the saturated overburden is perched above unsaturated bedrock adjacent to the river.

Bedrock water levels measured on March 20, 2003, during low water-level conditions, indicate a large head difference (about 14 ft) across the site, 8 ft greater than the overburden. Head contours indicate a northwesterly bedrock groundwater-flow direction for much of the cap area and a westerly flow direction for the southern part of the cap area. Calculated bedrock head gradients show small variations in maximum azimuthal direction but large variations in the slope of the gradient. The direction of the bedrock head gradient shifts further downstream as river stage rises. This shift also indicates that the river and bedrock are closely connected hydraulically. Water-level data from overburden and bedrock wells in the capped area indicate a combination of upward and downward gradients on April 2, 2003. Upward gradients from the fractured bedrock to the overburden could provide groundwater recharge to the overburden.

Groundwater-level fluctuations measured at continuous sites fluctuated most at bedrock well MW-7 and least at overburden well MW-2 (10 ft south of MW-7) for the period of record. The average vertical head gradient between the overburden and bedrock (at MW-2 and MW-7, fig. 2) is large (more than 8 ft) and indicates a poor vertical connection between the overburden and bedrock near the riverbank (fig. 2). Heads in MW-7 are slightly lower than SW-1, for 180 of 191 days monitored in 2002 and 2003, indicating a connection to the river downstream of the pool at SW-1 (fig. 2). Groundwater specific conductance at MW-7 shows small variations associated with a water-level rise on June 15, 2003 (fig. 5). The specific conductance of groundwater at MW-7 is high, exceeding 4,000 micromohs per centimeter (μmos/cm). A general decrease in the groundwater specific conductance at MW-7, with sustained high river stage, indicates that low specific conductance river water may temporarily flow into the bedrock aquifer with the increased gradient from the river. Average daily river water specific conductance for the period of record (December 2002–July 2003) shows a pattern of dilution with increased streamflow. Gradual rises in specific conductance during low-flow periods may indicate that high-conductivity groundwater is seeping into the pool from the site. Flow reversals are followed by more conductive water in the pool.

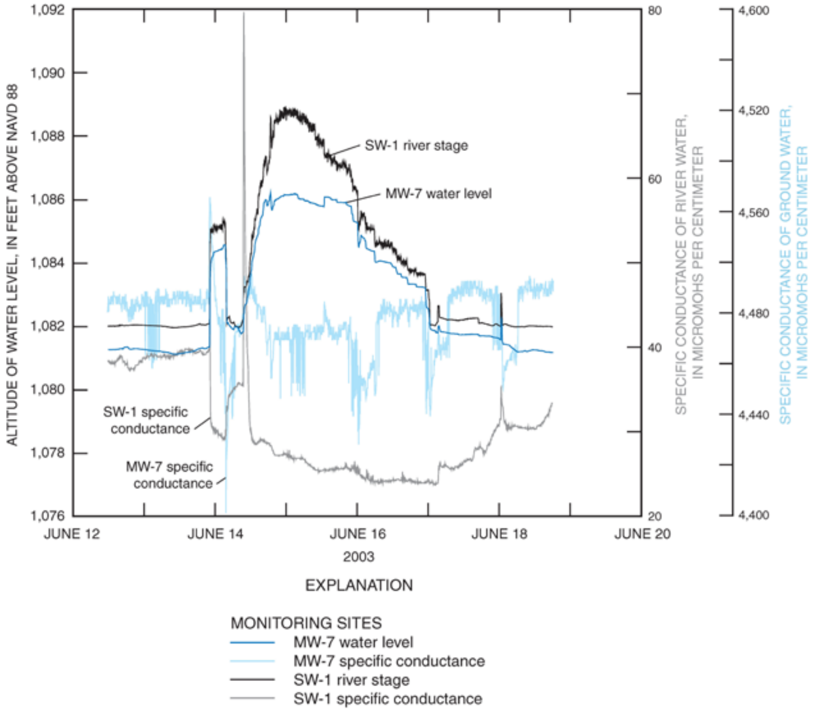


Figure 5. Five-minute interval water level and specific conductance from bedrock well MW-7 and river stage SW-1 at the former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire. (Location of sites shown on figure 2.)

Geophysics

Exposed bedrock at the riverbank provided ideal conditions for ground-penetrating radar (GPR) signal transmission and data collection; GPR surveys were also done on the site cap (fig. 6). The capped area at the site contains demolition debris, including metal, which limited the GPR survey potential. GPR data were collected using a point-survey mode because the rough surfaces at the site prevented data collection in a continuous-survey mode. Survey lines (fig. 2), collected directly on rock on the riverbank, indicate mostly shallow and a few steeply dipping reflections. Several reflections indicating fractures at depth are consistent with the fracture patterns observed at the riverbank; for example, horizontal and shallow-dipping reflectors at the northern end represent contacts with fractures associated with gneiss and pegmatite lenses. Inspection of bedrock cores from boreholes in the capped area (boreholes drilled for wells MW-4 and MW-10) indicate that alternating lenses of gneiss, chlorite schist, and pegmatite, similar to that seen at the riverbank, are present in the capped area.

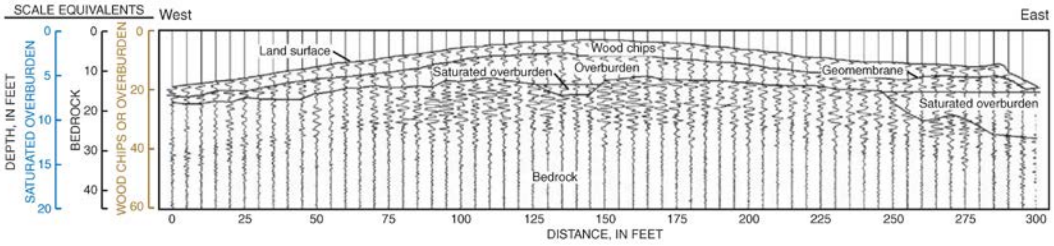


Figure 6. Ground-penetrating radar profiles from line 26 on the capped area of the former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire. (Depth scale is material dependent. Location of line shown on figure 2.)

Resistivity surveys were completed on the riverbank and around the perimeter of the site (fig. 2). Electrical anomalies with resistivity values relatively lower than the surrounding rock apparent in most lines (less than about 1,000 ohm-ft) are fractures. Fracture zones along the site perimeter project towards the site under the barrier wall. The 60° and 85° trending anomalies are of interest because they are parallel to a dominant fracture peak. Various anomalous areas along resistivity line 1 on the riverbank (fig. 7) have resistivities less than 150 ohm-ft and represent fracture zones containing contaminated groundwater. A folded chlorite-schist lense in this area, with vuggy fractures and chlorite alteration, is a major structural feature on the riverbank and is associated with the low-resistivity anomaly. Water levels in bedrock well MW-7 indicate a hydraulic connection between the fractured bedrock and the river in this area (fig. 2). Results indicate electrically conductive anomalies in the bedrock that are in the same areas as the reflections seen in the GPR results.

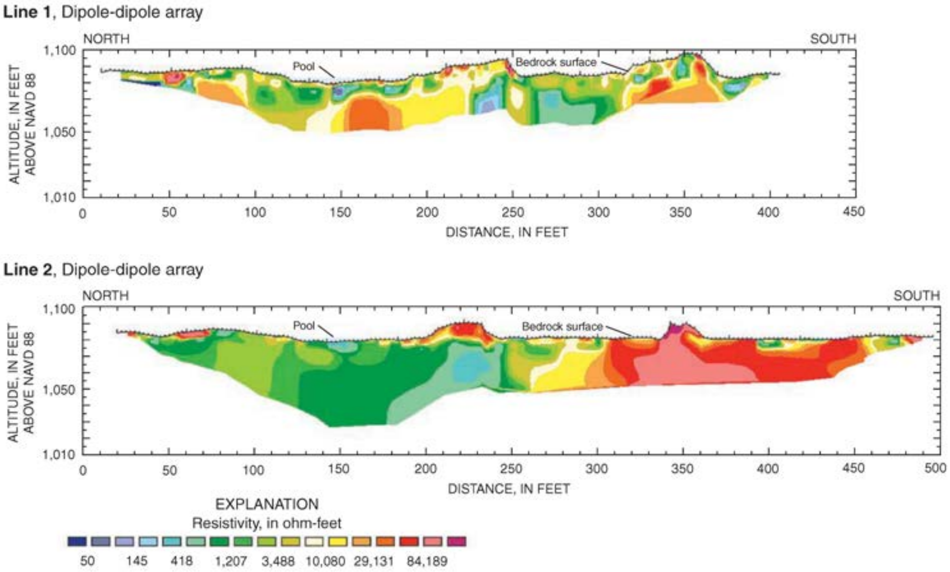


Figure 7. Resistivity profiles from lines 1 and 2 on the bank of the Androscoggin River, former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire. (Location of lines shown on figure 2.)

Borehole-geophysical logs indicate fewer fractures in MW-14 (fig. 8) than in MW-15; however, shallow dipping fractures are present in both wells at about 28 and 30 ft (at an elevation of about 1,074 ft) below the top of the casing and show the strongest indications of groundwater flow. Fluid property logs of wells MW-14 and MW-15 show fluid temperature and conductance inflections at this depth, which indicate hydraulically active fractures. The shallow subhorizontal fracture at about 1,074 ft elevation likely provides the hydraulic connection to the river noted in the water-level analysis of wells MW-7 and MW-8. Electrically conductive groundwater (greater than 4,000 micorsiemens per centimeter [µS/cm]) was detected at wells MW-7 (fig. 5) and MW-14 (fig. 8) near the largest resistivity anomaly at about 235 ft along line 1 and 225 ft along line 2 (fig. 7) with a moderate apparent dip to the northeast.

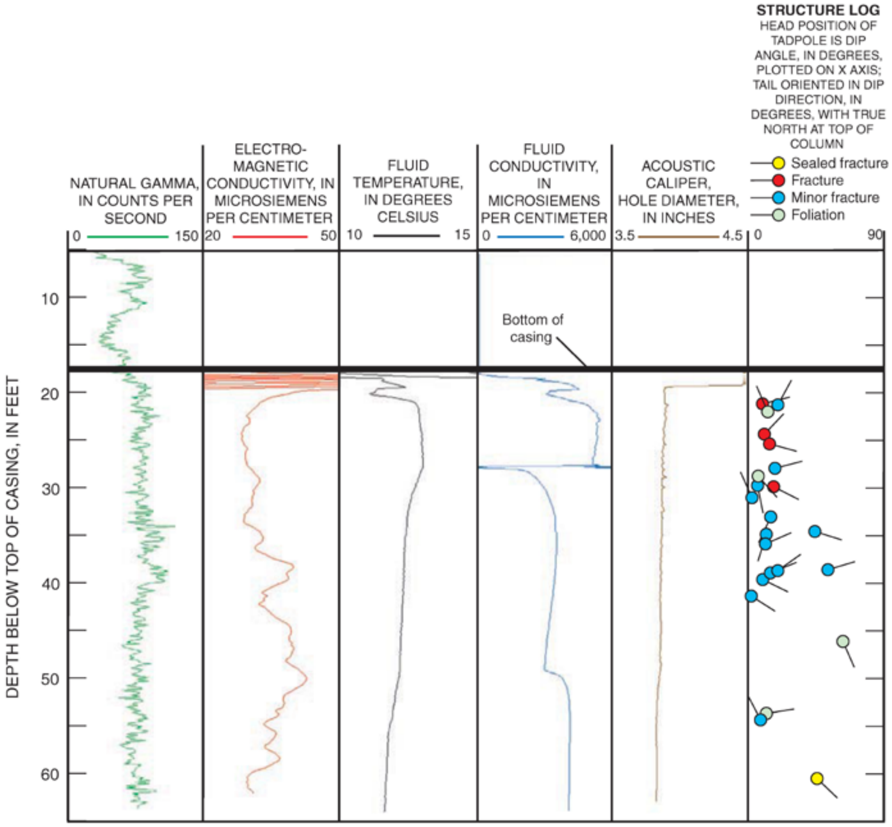


Figure 8. Borehole-geophysical logs of well MW-14, former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire. (Location of well shown on figure 2.)

Conceptual model

A conceptual model and preliminary hydrogeologic characterization of groundwater flow at the site indicates that groundwater flows east to west and follows a stair-step pattern within the bedrock toward the river (fig. 9). The overburden aquifer, which consists of till and fill materials, is perched in places and poorly connected to the bedrock aquifer and, therefore, isolated from short-term changes in river stage downstream of the dam; however, the overburden is likely recharged from groundwater inflow that either moves through or under the barrier wall or from the underlying bedrock aquifer. The site cap limits direct recharge from precipitation. Regional groundwater flow may enter the site at the site perimeter. The bedrock aquifer at the site is connected to the Androscoggin River as indicated by results of geologic mapping and hydraulic analysis. The implications of site hydrogeology on mercury storage and transport require additional studies. Geologic mapping at the riverbank, where elemental mercury has repeatedly been found on the outcrop and along fractures exposed at the bank, shows that fracture frequency varies with rock type (plate 1).

Geologic mapping determined that gneiss, 6–9 ft thick, containing near vertical fractures contains moderately dipping, vug-filled, chlorite-schist lenses bounded by fractures and subhorizontal unfractured pegmatite. Subhorizontal or moderately dipping fractures connect the vertical fractures of the bulk rock. Inspection of borehole cores (appendix 1) and geophysical-survey results indicate this geologic pattern likely extends east from the riverbank across the site. Data on fracture density indicate that groundwater in bedrock at the site is stored in the near vertical fractures in the gneiss that comprise most of the bedrock aquifer. The low hydraulic conductivity of the near-vertical fracturing is probably the limiting hydraulic conductivity in the bedrock aquifer at the site. In fractured rock, the hydraulic conductivity of the aquifer, over a scale similar to the field site, is controlled by the small fractures of the dominant fracture network (Tiedeman and others, 1997); therefore, the bulk hydraulic conductivity for the bedrock aquifer across the site is estimated to be about 0.2 ft/d. The hydraulic conductivity of individual fractures near the river is relatively high as indicated by rapid water-level fluctuations in some observation wells.

The high hydraulic conductivity estimate (2–20 ft/d) from well MW-7 is affected by a direct flow path in a more open subhorizontal fracture similar to those noted in the nearby borehole associated with MW-14 (fig. 8). Conversely, a low hydraulic-conductivity estimate of 0.2 ft/d, based on water-level data at wells MW-8 and MW-9, is representative of the steeply dipping fractures in gneiss that make up the bulk of the rock.

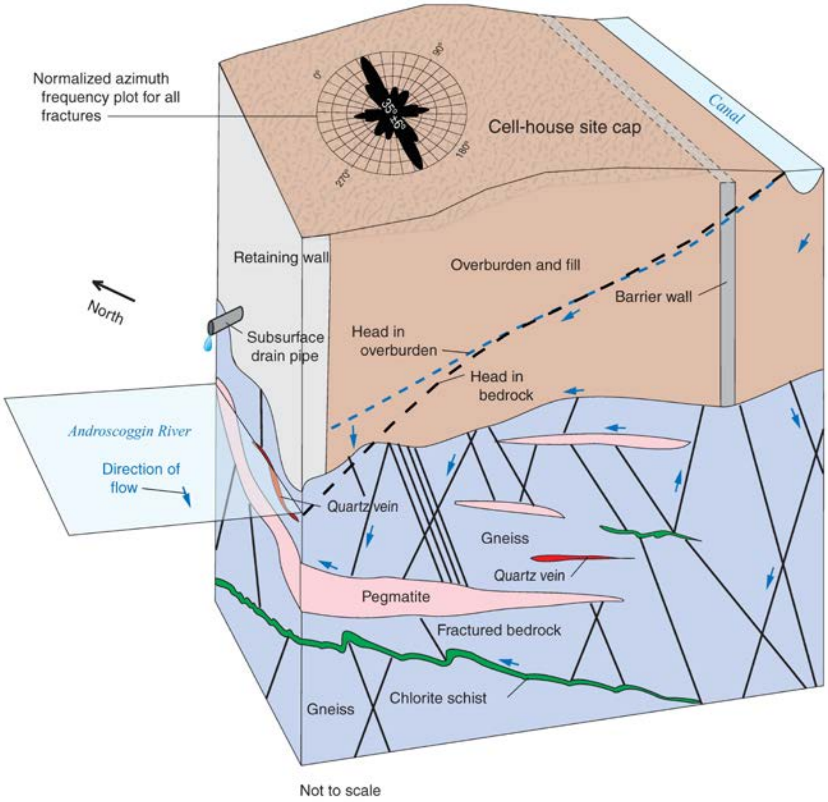


Figure 9. Conceptual model of the hydrogeology at the former Chlor-Alkali Facility Superfund Site, Berlin, New Hampshire.

DOWNSTREAM RIVER REACHES

Flow in the Androscoggin River is regulated by eight hydroelectric dams in the study area; flows are controlled to respond to power demands, floods, and structure maintenance. The mean annual flow measured at USGS gage 01054000 in Gorham, N.H., is 2,110 cubic ft per second (ft^3/s). The month of May has the highest average annual groundwater flow at 4,210 ft^3/s, and August has the lowest at 1,960 ft^3/s. Dams and lakes in the headwaters of the Androscoggin River provide storage for a substantial amount of runoff and reduce flood peaks (Federal Emergency Management Agency, 1994). Though hydroelectric dams in Berlin, Gorham, and Shelburne (fig. 2) control flow and sediment transport during normal flows, because of minimal storage volume they have little effect on controlling flood flows (Federal Emergency Management Agency, 1981). The average channel slope in the study area from the site to the Maine State line is 26.1 ft per mile (ft/mi). The slope is much greater (100 ft/mi, fig. 2) between the site and the Cascade Dam (fig. 2) and greatly increases the river's capacity to produce hydroelectric power, and transport sediment and contaminants in this reach. Most of the dams in the study area make use of the head drop available at the dam site to generate power. The Riverside and Brodie Smith Dams in Berlin (fig. 2) divert water out of the river channel and into a penstock (in this case, a large pipe) to increase heads on the turbines that are farther downstream. Steeper parts of the channel downstream from the Riverside and Brodie Smith Dams receive limited flow during average flows, because of the penstock diversion, but carry large flood flows. Sediment may accumulate in deeper pools in these sections of river; however, these areas are not navigable because of steep channel slopes and were not surveyed in this investigation. The arrangement of dams and penstocks, from the Saw Mill Dam at the site to the Berlin–Gorham town line, creates areas of backwater where sediment can accumulate upstream from the Riverside, Brodie Smith, Cross Power, and Cascade Dams (fig. 2).

Alluvial fan deposits, consisting of sand, gravel, and silt are on the left bank (east) of the river upstream from the Cascade and Brown Dams and on the right bank near the Gorham Dam and Shelburne Reservoir. Stratified sand, gravel, and silt alluvium is the dominant deposit beneath the river channel from the backwater behind the Brown Dam to the New Hampshire–Maine State border. Ice-contact deposits of sand and gravel are downstream from the Shelburne Dam in the river channel in the form of eskers, channel fillings, kames, and kame terraces. Undifferentiated glacial drift, consisting mostly of till, was along the left bank of the river in Gorham and Shelburne (Gerath, 1978; Gerath and others, 1985). The Androscoggin River is incised and boulder filled, and average flows form rapids downstream of the Cascade, Brown, and Gorham Dams in Gorham for about 2, 1.5, and 1.5 mi, respectively. Downstream from the Brown Dam to the Shelburne Reservoir, the channel gradient decreases and grades into a slightly braided sediment-filled channel with anabranching sections. The river runs unobstructed downstream from the Shelburne Dam in Shelburne and has braided and meandering sections for about 6.5 mi to the New Hampshire–Maine State border. A significant process that may alter sediment distribution is ice-scour during the winter. At Riverside Dam, about 1,000 ft south of the site, large amounts of ice have been observed abrading the bottom of the river and being transported over the dam.

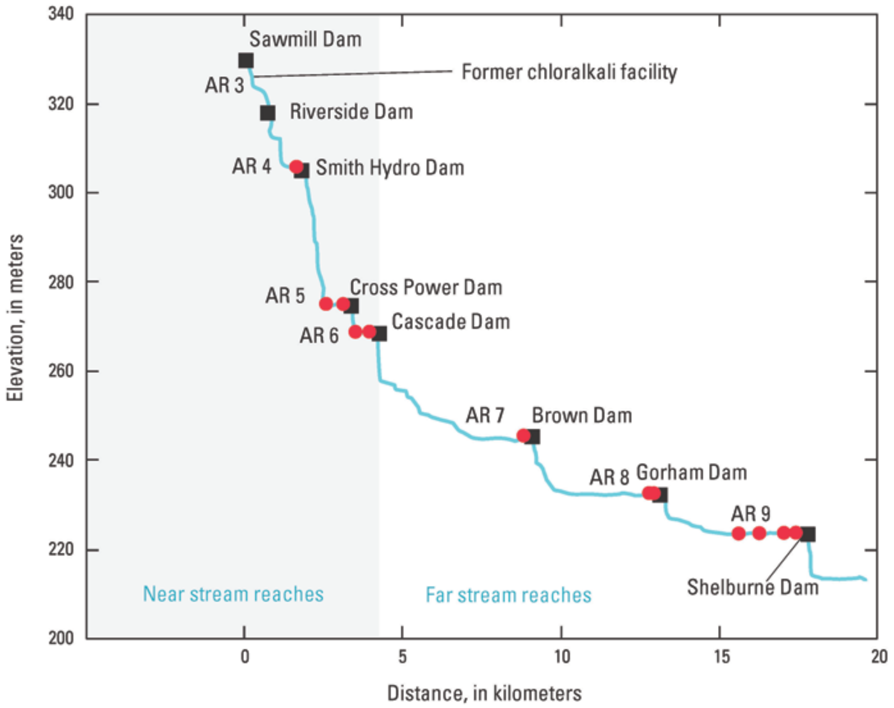


Figure 10. Generalized locations of sediment and pore-water sampling sites on the Androscoggin River downstream from the former Chlor-Alkali Facility Superfund Site in Berlin, New Hampshire. Stream reaches are signified by AR followed by number. The reference reach (AR2) is 16 kilometers upstream from the site and is not shown. Sampling locations are indicated by red circles, and dams are indicated by black squares. Elevation and distance data from Google Earth, February 17, 2012.

Geophysical bed sediment characterization

Surface geophysical surveys, such as GPR and multifrequency electromagnetic (FDEM) surveys, were used to determine the extent and nature of riverbed sediments in the Androscoggin River downstream from the site in Berlin, N.H. A full description of results, processing methods, and presentation in tables, maps, and cross sections is provided in Degnan and others (2011, https://pubs.usgs.gov/sir/2011/5158/). Results are discussed in terms of sediment electrical conductivity, pore-water specific conductance (SC), and potential contaminant distribution in riverbed sediments.

The river reaches surveyed in this study ranged from pooled water conditions to fast moving water-flow conditions that varied with channel geometry, dam operation, and runoff. Results of GPR and FDEM surveys were used to estimate the extent and nature of riverbed sediments (tables 1 and 2). In general, wider, less steep gradient reaches have more fine sediment, and were measured with additional surveys in this study, whereas narrow steep gradient reaches had less sediment. Specific conductance measured during surface-water, pore-water, and sediment sampling (with subsequent grain-size analysis), collected as part of a parallel USGS investigation (Chalmers and others, 2013), were used in processing and interpreting surface geophysical surveys. The electrical resistivity of sediment samples was measured in the laboratory with pore water intact for comparison with FDEM survey results. Geophysical surveys of the reference reach, Wheeler Bay (upstream end of reach AR–2), were completed to assess equipment responses in an environment unaffected by site-related contaminants.

To help understand conductivity variations with depth, the most stable five frequencies for a given survey were used along selected survey paths for inverse modeling of the data for select lines to associate resistivity values with depth (fig. 12). Results of the inversion are given in terms of resistivity (inverse of conductivity). Resistivity values measured from bed sediments (about 200 ohm-meters) and surface-water SC values (converted to about 300 ohm-meters) were used to construct a two-layered starting model. GPR riverbed depth interpretations overlaid on the FDEM inversion indicate a correlation with more resistive river water (green layer on top) and less resistive (blue layer) sediment through about 70 percent of the cross section (fig. 12).

At very low frequencies, electromagnetic induction response is due more to the magnetic properties of the subsurface than electrical properties, and the FDEM survey magnetic susceptibility responses are similar to a magnetometer survey. Magnetic susceptibility was calculated using the raw in-phase component of the lowest frequencies used in the surveys (570; 990; 1,770; 3,090 hertz [Hz]). When a magnetic response occurred, generally all four frequencies gave a similar response, though the lower frequencies indicate magnetic material more often than the higher frequencies. Magnetic susceptibility responses (lower frequency FDEM) were plotted on maps in reaches near the site in Berlin, N.H., to search for metal debris that may affect FDEM responses.

The reach between the former Site and the Riverside Dam (AR-3), had small areas of fine sediment on the upstream left bank and the downstream right bank, with an elevated FDEM conductivity (31.4 milliseimens per meter (mS/m) maximum). The larger FDEM conductivity likely was because of elevated riverbed pore-water SC. Reaches AR–4 and AR–5 were downstream from steep gradient (100 ft/mi) bedrock gorges that convey high flows from the reach adjacent to the site to pooled areas behind dams. Reach AR–4, upstream from the Brodie Smith Dam, had the largest pore-water SC, FDEM, and lab-measured sediment conductivity values measured in the study. Pore-water SC measured in this reach was 279 and 324 mS/m at sediment sample locations AR–4_1 and AR–4_2, respectively (fig. 10), on a sandbar near the left bank. These sediment samples had laboratory-measured sediment conductivity values of 67.4 and 76.8 mS/m, similar to nearby estimated FDEM values of 73.2 and 72.8 mS/m. The largest conductivity measured with FDEM in reach AR–5 was 10.2 mS/m on the downstream left side (fig. 8).

Reach AR–9 between the Gorham and Shelburne Dams contains the largest body of pooled water in the study area, the Shelburne Reservoir. The first one-half of the reach has cobble, boulder, and bedrock bed material; although more than 77 percent of the area of the riverbed surveyed in reach AR–9 is estimated to be covered by gravel or finer material (table 2). The sediment in reach AR–9 had a maximum estimated FDEM conductivity of 12.6 mS/m (table 1), greater than all of the other reaches except for AR–3 and AR–4 (nearby and within 1 mile downstream from the site). In addition to large FDEM values, this reach had the second greatest pore-water SC measured, 45.8 mS/m (table 1).

Through combining results and analysis from GPR and FDEM surveys, with sediment pore water and laboratory measured conductivity, detailed riverbed-sediment characterizations were made. Results from GPR surveys were used to image and measure the depth to the riverbed, depth to buried riverbeds, riverbed thickness and to interpret material-type variations in terms of relative grain size (fig. 11). Fifty-two percent of the riverbed in the study area was covered with gravel and finer sediments. GPR surveys are affected by contrasts in the electrical properties of water and sediment. The electrically resistive river water and sediment in this study area were conducive to the penetration of the GPR and FDEM signals and allowed for effective sediment characterization by geophysical methods.

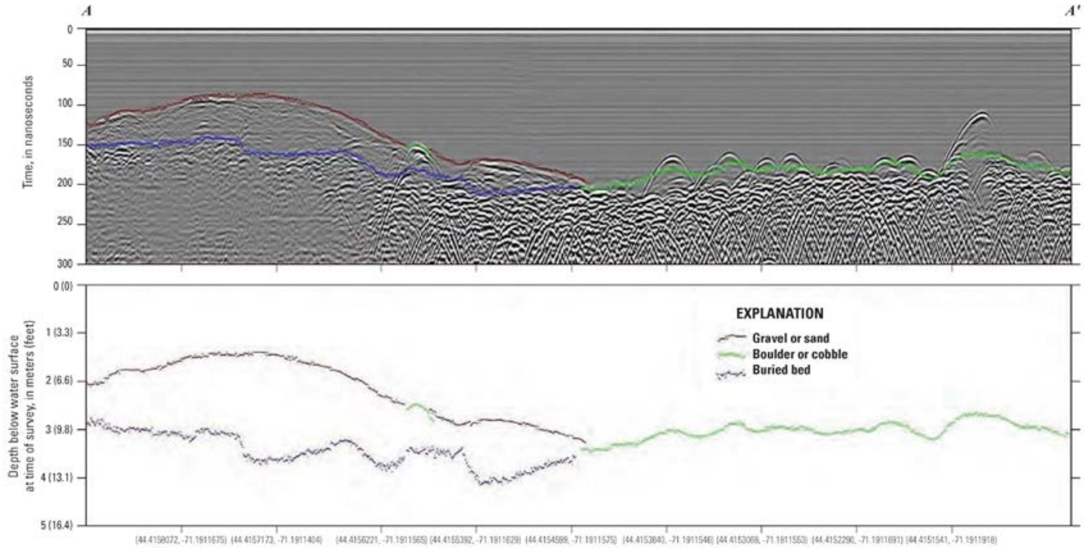


Figure 11. Example of a cross section showing ground-penetrating radar profile and interpretation in reach AR–7 upstream from the Brown Dam, Androscoggin River, Gorham, New Hampshire (location shown in figure 10).

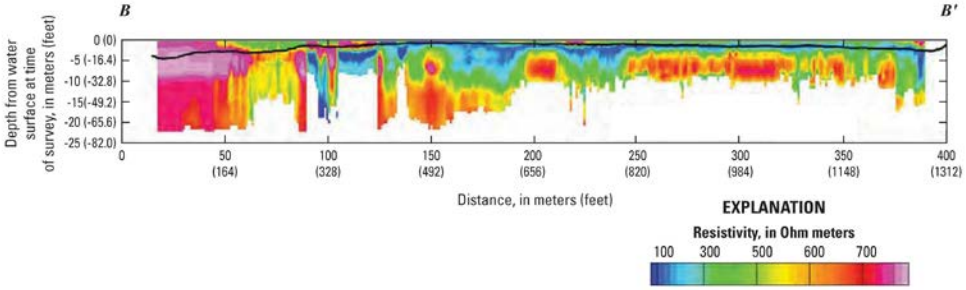


Figure 12. Example of a cross section showing inverted electromagnetic induction profile in reach AR–9 between the Gorham and Shelburne Dams, Androscoggin River, Shelburne, New Hampshire (location shown in figure 10). Solid black line represents riverbed measured with ground-penetrating radar.

Table 1. Estimates of electromagnetic conductivity summarized by reach and correlation with water depth.

Reach name	Reach code	Conductivity, in millisiemens per meter			Water depth and conductivity correlation
		Average	Minimum	Maximum	
Wheeler Bay	AR–2	2.6	0.1	9.4	0.21
Upstream of the Riverside Dam	AR–3	3.1	0.6	31.4	-0.31
Upstream of the Smith Dam	AR–4	10.1	0.9	194.9	-0.49
Upstream of the Power Dam	AR–5	4.2	1.7	10.2	-0.48
Power Dam to Cascade Dam	AR–6	2.7	0.8	7.1	-0.05
Cascade Dam to Brown Dam	AR–7	2.2	0.6	8.9	-0.03
Brown Dam to Gorham Dam	AR–8	0.9	0	7.1	-0.04
Gorham Dam to Shelburne Dam	AR–9	2.5	0	12.6	-0.36
Downstream of the Shelburne Dam	AR–10	1.7	0.9	3.5	0.56

Table 2. Percentage of fine sediment summarized by reach.

Estimates based on gridding of ground-penetrating radar interpretations

Reach name	**Reach code**	**Area of gravel or finer sediment, in square feet**	**Percent of reach area**	
			Gravel or finer sediment	**Cobble, boulder and or bedrock**
Wheeler Bay	AR–2	933,256	97	3
Upstream from the Riverside Dam	AR–3	29,894	11	89
Upstream from the Smith Dam	AR–4	85,109	25	75
Upstream from the Power Dam	AR–5	354,077	61	39
Power Dam to Cascade Dam	AR–6	342,268	51	49
Cascade Dam to Brown Dam	AR–7	1,345,012	42	58
Brown Dam to Gorham Dam	AR–8	432,820	20	80
Gorham Dam to Shelburne Dam	AR–9	5,794,177	77	23
Downstream from the Shelburne Dam	AR–10	6,915,104	86	15
Total		**16,231,717**	**52**	**48**

Mercury contamination

Total mercury (THg) and methylmercury (MeHg) concentrations in Androscoggin River sediment, pore water, and biota were elevated downstream from the site relative to reference sites (figs. 13 and 14); methods and results are described in Chalmers and others (2013, https://pubs.usgs.gov/of/2013/1076/). Sequential extraction of surface sediment showed a distinct difference in mercury speciation upstream compared with downstream from the site. The reference site was dominated by potassium hydroxide-extractable THg consistent with organic mercury or particle-bound divalent mercury (Hg(II)), whereas sites downstream from the point source were dominated by concentrated nitric acid-extractable THg, indicative of Hg0 or mercurous chloride. Mercury metrics from the study indicated Hg(II) at the reference site was more available for Hg(II)-methylation compared with sites downstream from the point source, but the absolute concentrations of whole sediment Hg(II)R and THg in biota were greater downstream from the point source. In addition, whole sediment Hg(II)R and smallmouth bass THg concentrations seemed to increase farther downstream from the point source. The farthest downstream reach (AR9 from Gorham Dam to Shelburne Dam) had larger mass of fine sediment and larger estimated mass inventory of mercury species than any other stream reach by an order of magnitude for both masses.

Toxicity tests and invertebrate community assessment suggest that impairment of invertebrates is not occurring at the 2009 and 2010 levels of mercury contamination downstream from the point source. Concentrations of THg and MeHg in most water and sediment samples from the Androscoggin River were below Federal and consensus-based guidelines, whereas smallmouth bass mercury concentrations were above U.S. Environmental Protection Agency and regional guidelines in all samples. Smallmouth bass THg concentrations from the Androscoggin River downstream from the point source were substantially higher than those reported in a national survey, but only smallmouth bass mercury concentrations from the farthest downstream stream reaches (Cascade Dam to Shelburne Dam) were substantially higher than those in Northeastern region studies.

The apparent greater potential for Hg(II)-methylation and mercury bioaccumulation in the lower gradient stream reaches of the Androscoggin River may reflect changes in the type and size of particles deposited to the benthos and the speciation and availability of mercury for Hg(II)-methylation associated with those particles. These findings suggest that an even greater potential for Hg(II)-methylation and mercury bioaccumulation may exist as the river gradient continues to flatten downstream from Shelburne Dam.

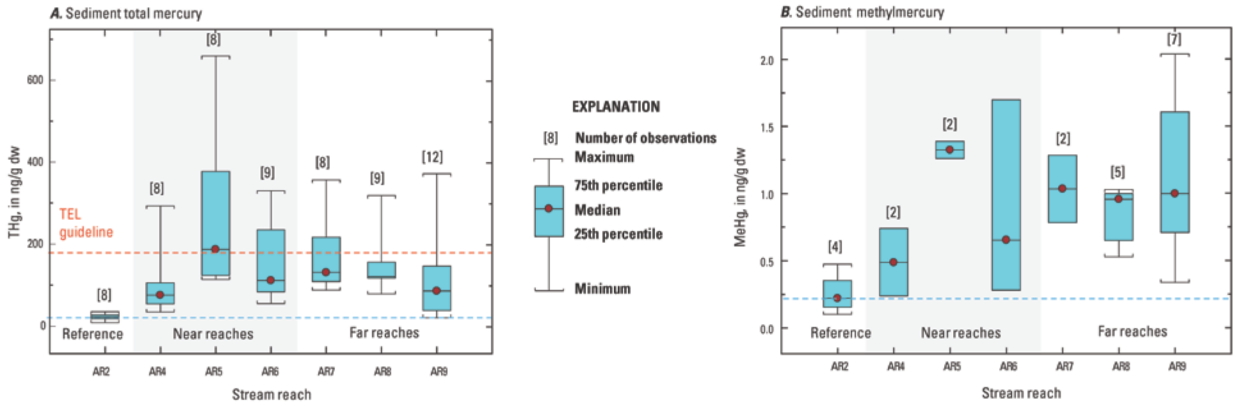


Figure 13. Concentrations of sediment A, total mercury (THg), and B, methylmercury (MeHg), from the Androscoggin River, Coos County, New Hampshire. Samples were collected in 2009 and 2010. Samples from the reference reach (AR2) are from 16 kilometers (km) upstream from a Former Chlor-Alkali Facility Superfund Site in Berlin, N.H. Samples from near-stream reaches (AR4–AR6) are from 2 to 4 km downstream from the Former Chlor-Alkali Facility Superfund Site, and samples from far-stream reaches (AR7–AR9) are from 8 to 16 km downstream from the Former Chlor-Alkali Facility Superfund Site. THg and MeHg nondetect data are excluded from the plot because of high detection levels. The dashed blue line indicates the median reference (AR2) sediment concentration, and the dashed red line indicates the threshold effects level (TEL) concentration of 180 nanograms per gram (ng/g; MacDonald and others, 2000). dw, dry weight.

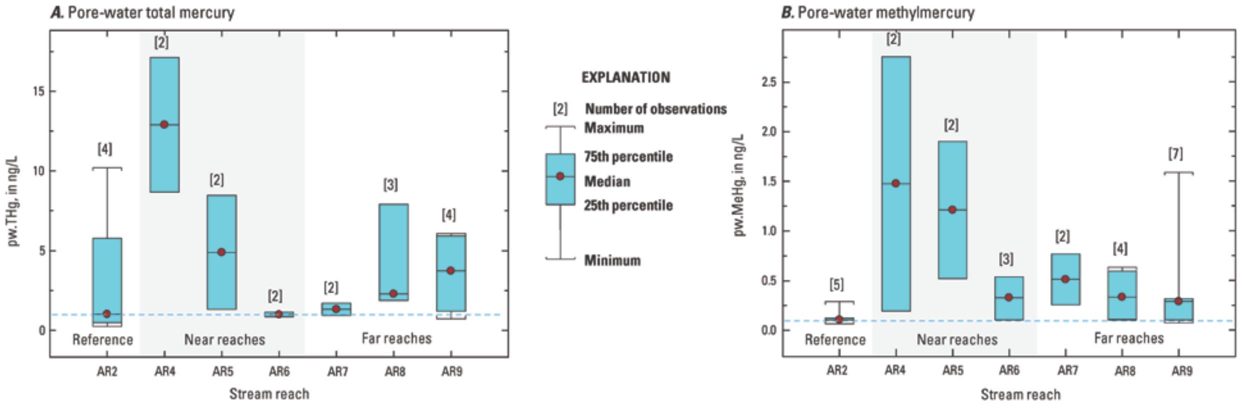


Figure 14. Concentrations of pore-water A, total mercury (pw.THg), and B, methylmercury (pw.MeHg) percentage of THg as MeHg (pw% MeHg) from the Androscoggin River, Coos County, New Hampshire. Samples were collected in 2009 and 2010. Samples from the reference reach (AR2) are from 16 kilometers (km) upstream from a Former Chlor-Alkali Facility Superfund Site in Berlin, N.H. Samples from near-stream reaches (AR4–AR6) are from 2 to 4 km downstream from the Former Chlor-Alkali Facility Superfund Site, and samples from far-stream reaches (AR7–AR9) are 8 to 16 km downstream from the Former Chlor-Alkali Facility Superfund Site. Total mercury nondetect data are excluded from the plot because of high detection level. The dashed blue line indicates the median reference (AR2) pore-water concentration. ng/L, nanogram per liter.

ACKNOWLEDGMENTS

The authors wish to thank the co-authors of the reports that document the data collection and analysis behind the results presented in this field trip: Stewart F. Clark, Jr. (geologic mapping and analysis), Philip T. Harte, Thomas J. Mack, Andrew P. Teeple, Craig M. Johnston, Mark C. Marvin-DiPasquale, James F. Coles, and Jennifer L. Agee. The authors also wish to thank many others who helped support the work in the field, as cooperators, and reviewers including: Fred McGarry, John Cotton, and Margaret Bastien of the NHDES; Vincent DelloRusso, James Soukup, Kathleen Soukup, Joseph Souney, and Joseph Schmidl of Weston Solutions, Inc.; Gregory Walsh, Jeffrey Deacon, Glenn Hodgkins, Robert Flynn, Marc Zimmerman, Jon Denner, Jamie Shanley, Brandon Fleming, Thor Smith, and

Laura Hayes of the USGS; Vivien Taylor of Dartmouth College; Cornell Rosiu of the EPA; and Tammie Lavoie, Dennis Pednault, and David Bolstridge of the Berlin-Gorham Operations of Fraser Paper, Inc.

ROAD LOG

MEETING POINT, Adjacent to the Brodie Smith Dam, Berlin, NH.
(326596.00 m E, 4926285.00 m N)

Friday, September 29th, 10:00 AM, in the parking lot on the south side of Mason St. on an unnamed island adjacent to the Smith Dam and Hydrostation water intake canal in the Androscoggin River. The Smith Dam is about 30 miles (40 minutes) west of Bethel, ME. From Bethel follow Rte. U.S. 2 west to Gorham, N.H., then take Rte. NH 16 north to Berlin. In Berlin, turn right onto Unity St. (truck Rte. 16 N) at the James Cleveland Bridge, then left onto Mason St. The parking lot will be on your left after crossing the first bridge over the Androscoggin River on Mason St. Cumulative mileages given below may differ from those shown on your odometer, but the indicated distances between stops are generally accurate.

Mileage and directions to STOP 1.

0.0 Head southeast on Mason St toward Unity St.
0.1 Turn left onto Unity St.
0.2 Continue onto Coos St.
0.3 Turn left onto Hutchins St.
1.5 Turn left on Bridge St.
1.6 Turn left through gate (access with field trip leaders only)
1.9 To penstock gatehouse at site

STOP 1. Former Chlor-Alkali Facility Superfund Site Site
(327732.00 m E, 4927301.00 m N)

The riverbank outcrop at the site contains a variety of brittle structures that display a consistent pattern of orientation and association. Fracture density and style are related to rock type along the riverbank outcrop. The tabular body of pegmatite at the north end of the riverbank is relatively unfractured compared to gneiss. Fractures present in the gneiss below this pegmatite terminate at the pegmatite-gneiss contact. Coarse-textured weakly foliated gneiss is fractured but contains fewer isolated fractures and fewer fracture sets than fine-grained gneiss, which is highly fractured (fig. 5). Closely spaced individual fractures are shown as zones on the geologic map (plate 1, Degnan and others, 2005). Fracturing in the chlorite-schist lenses is present along the boundaries of the lenses and along parting parallel to foliation within the lenses. En échelon fracture zones, parallel fracture zones, and faults cut the folded foliation of the gneiss at the site. Steeply dipping en échelon fracture zones, parallel fractures, and faults have a similar trend throughout the riverbank outcrop. Two faults form the contacts of a cataclastic pegmatite (plate 1, Degnan and others, 2004).

Surface- and groundwater levels were used to assess hydraulic connections and provide a hydraulic analysis of the bedrock-river aquifer system. The location of the canal; the Androscoggin River; remedial modifications (barrier wall and cap); and relic foundations and plumbing, including the concrete retaining wall and discharge pipe, affect spatial and temporal variability in water-level fluctuations and flow patterns at the site.

Mileage and directions to STOP 2.

1.9 penstock gate house at site to Bridge St.
2.17 Turn right onto Bridge St.
2.2 Turn right onto Hutchins St.
2.5 Turn left onto Success Pond Rd.
3.1 Park at power lines.

STOP 2. Success Pond Rd. Ammonusic Volcanics
(328744.00 m E, 4927196.00 m N)
Analysis of fracture measurements define inclusion in the domain of west- and northwest-trending fractures.

Mileage and directions to STOP 3.

3.1 Turn left onto Success Pond Rd.
3.7 Turn right onto Hutchins St.

4.0 Turn left onto Bridge St.
4.1 turn right, continue onto Hutchins St.
4.5 Turn left onto 12th St.
4.55 Continue onto 12th St. Bridge
4.6 Turn left onto Main St.
5.8 Turn left into court house parking lot, outcrop is in the right back corner

STOP 3. Court House, Oliverian Plutonic Suite
(327165.00 m E, 4926737.00 m N)
Analysis of fracture measurements define inclusion in the domain of north-trending fractures.

Mileage and directions to STOP 4.
5.8 Turn left onto Main St.
6.0 Continue onto Pleasant St.
6.8 Turn right onto Glen Ave.
7.2 Turn right into gas station parking lot, right side

STOP 4. Irving Station, schist, gneiss, Oliverian Plutonic Suite and Description
(325975.00 m E, 4925215.00 m N)
Analysis of fracture measurements define inclusion in the domain of west- and northwest-trending fractures.

Mileage and directions to LUNCH STOP.
7.2 Turn left onto Glen Ave.
7.3 Turn right onto James Cleveland Bridge/Unity St.
7.8 Left at park

LUNCH STOP. Park on Unity St. on the left bank of the Androscoggin River between the Brodie Smith and Cross Power Dams
(326523.00 m E, 4925948.00 m N)

Mileage and directions to STOP 5.
7.8 Head southwest on Unity St.
8.3 Turn left onto Glen Ave. (Rt. 16)
8.6 Left into gravel parking lot by dam

STOP 5. Cross Power Dam
(326002.00 m E, 4924914.00 m N)

Mileage and directions to STOP 6.
8.6 Head south on NH-16 S/Glen Ave. toward Watson St.
11.9 Turn left into gravel parking area

STOP 6. Brown Dam
(325179.00 m E, 4919681.00 m N)

Mileage and directions to STOP 7.
11.9 Tum left onto NH-16 S/Main St.
14.4 Tum left onto Power House Rd.
14.6 Slight right and park

STOP 7. Gorham Dam
(327457.00 m E, 4917291.00 m N)

Mileage and directions to STOP 8.

14.6 Slight left onto Power House Rd.

14.8	Tum left onto US-2 E/Main St.
18.0	Turn left onto North Rd.
18.3	Tum right onto North Rd.

STOP 8. Shelburne Dam
(331575.00 m E, 4918981.00 m N)

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