VERMONT GEOLOGICAL SURVEY OPEN FILE REPORT VG2018-4

Surficial Geology and Groundwater Hydrology of the Bolton Mountain Quadrangle, Vermont

Stephen F. Wright
Department of Geology, University of Vermont
May 2018

View of Bolton Mountain looking southwest from the ridge separating Lake Mansfield from the upper reaches of Michigan Brook valley.

Table of Contents

Executive Summary/Significant Findings

The surficial geology of the Bolton Mountain, Vermont 7.5-minute Quadrangle, including several areas beyond the quadrangle boundaries, was mapped during the summer of 2017 and the results of this work are presented here. Four University of Vermont undergraduate students and one graduate student assisted with the mapping effort during parts of both June and July. Over 4,000 observations of geologic materials and landforms were recorded on a shaded-relief LiDAR base map. The surficial geologic map was constructed using both field observations and landforms visible on the LiDAR imagery. Geologic cross-sections utilize both the geology mapped at the surface and the subsurface stratigraphy recorded in well logs. The isopach map of surficial materials utilizes the geologic map, well logs, and landforms visible on the LiDAR imagery. Finally, a groundwater contour map was also generated from water levels recorded in well logs and the surface hydrology of the region.

Most of the diversity in materials and landforms lie in the river valleys whereas high-elevation areas are almost universally underlain by glacial till. No pre-Quaternary highly weathered surficial materials were encountered. High-elevation striations, erratics, and asymmetric landforms indicate that ice flow across the region was from northwest to southeast when the ice sheet was thick enough to cover the mountains. Younger, lower elevation striations are oriented parallel to tributary valleys.

The upland areas of the quadrangle are underlain by variable thicknesses of till. Outcrops are abundant along many of the ridges whereas unusually thick areas of till occur in some of the upland valleys, Stevenson and Cotton Brooks. Large (>3 m diameter) erratics are common, but most appear sourced from local rocks and many may have been quarried from the Green Mountain ridge-line and transported in ice short distances to the southeast.

A subglacial drainage tunnel was funneled through Nebraska Notch, southeast down the Miller Brook valley, and then south down the Little River valley. Evidence for this are large (>3 m diameter) potholes and an esker system in the upper reaches of the Miller Brook valley. Farther south, this esker is buried beneath subaqueous outwash and lacustrine sediments. Ice-contact sand and gravel was both subaqueous and subaerial fans. These have been used to mark several positions of the retreating ice-sheet lobe in the Miller Brook valley.

Deposits associated with at least two high-elevation glacial lakes of limited extent have been mapped. More significant lacustrine sediments were deposited in at least three regionally extensive glacial lakes although restricted to elevations below ~1050 ft. The regional lakes formed when the ice sheet, retreating down the Winooski River valley, dammed the west-draining valley and uncovered successfully lower outlets. In addition to fine-grained lake bottom sediments, the partially eroded remains of deltas exist in most valleys mapped. As noted earlier, in some areas fine-grained lake bottom sediments nicely confine older ice-contact gravels making excellent protected aquifers.

Modern alluvium was mapped in all valleys. Abandoned fluvial terraces perched along the valley sides provide evidence that in many areas these valleys were filled to the level of the highest terrace with till and/or lacustrine sediment that has since been eroded following deglaciation and the draining of the ice-dammed lakes. An extensive area of large terraces occurs in the Little River valley downstream from the Waterbury Reservoir. These level areas were first farmed and then occupied by the CCC camp that built the Waterbury Reservoir. It's unclear if this terrace is a lake-bottom terrace or a former fluvial terrace where the gravel was largely removed for dam construction.

Introduction

This report describes the results of mapping surficial geologic materials and landforms at a scale of 1:24,000 in the Bolton Mountain Quadrangle, Vermont and adjacent areas during the summer of 2017. This report also describes several derivative maps generated for this project that focus on the area's groundwater hydrology.

Location and Geologic Setting

The Bolton Mountain 7.5-minute quadrangle lies entirely within the Green Mountains of northern Vermont (Fig. 1). Adjacent parts of the following quadrangles were also mapped: Stowe (east), Waterbury (south), Richmond (west). That part of the mapping area in the Waterbury Quadrangle includes the Winooski River valley which cuts WNW to ESE across the mountains. The bedrock geology of the area is summarized on the Vermont Bedrock Geologic Map (Ratcliffe et al., 2011). Rocks underlying this area consist almost entirely of metasedimentary rocks that were originally deposited in the Iapetus ocean along the margin of Laurentia from late Precambrian through early/middle Ordovician time. These rocks were subsequently deformed and metamorphosed during the Taconic Orogeny and again during the Acadian Orogeny. Rock units in this area are typically bounded by north-south striking thrust faults and lesser normal faults occurring on a wide range of scales that generally mimic the north-south trend of the mountain belt (Ratcliffe, et al., 2011).

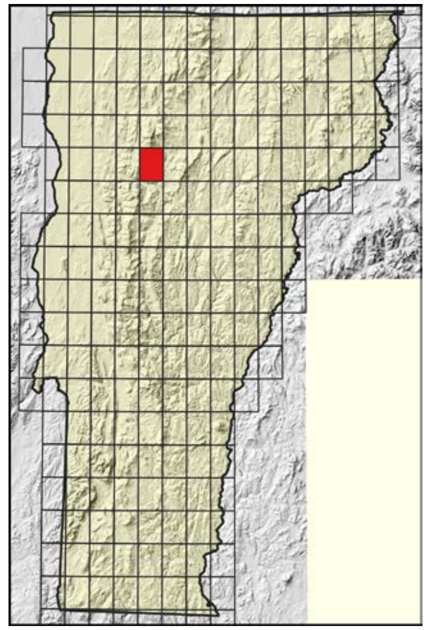

Figure 1: Map showing the location of the Bolton Mountain 7.5-minute Quadrangle, Vermont.

The Surficial Geologic Map of Vermont (Stewart and MacClintock 1970) shows the general distribution of surficial materials in the region. The surficial geologic materials occurring in the region were dominantly deposited during the most recent (Wisconsinan) glaciation in glacial or periglacial environments existing during or shortly after the ice sheet retreated. A variety of surface processes have redistributed those materials during the Holocene. In this mountainous setting the upland areas are largely mantled by till with isolated pockets of organics occurring in wetland areas. Ice-contact sediments, deposited beneath or adjacent to the retreating ice sheet, are found in many of the major river valleys. These ice-contact sediments are largely mantled by glaciolacustrine sediments deposited in a sequence of glacial lakes occurring at successively lower elevations (Larsen, 1972, 1987).

Prior Work

The first systematic mapping of surficial materials in the area was completed in reconnaissance fashion by Stewart (1956–1966) and Connally (1965) using 15-minute (1:62,500-scale) base maps. These open-file maps were incorporated into the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970). The principal investigator on this project has mapped an esker system and lacustrine sediments in the Miller Brook valley (Wright et al., 1997, Wright, 2012, Cronauer and Wright, 2012, Dunn et al., 2011),, made detailed measurements and analyses of varved glacial lake sediments adjacent to the Waterbury Reservoir (Larsen et al., 2003), measured and interpreted a section exposed by a large landslide in the Preston Brook valley (Wright, 2011, Wright et al., 2015), mapped a delta, esker system, and ice retreat stages in Bolton Notch (Wright et al., 2015; Wright and Conroy, 2014), described evidence for ice readvance in West Bolton (Bierman et al., 1999), and mapped a Glacial Lake Vermont delta exposed along the Lee River (Wright et al., 2015). Wright has also interpreted the ice flow history across this part of northern Vermont from a large compilation of glacial striation azimuths (Wright, 2015) and has modeled the readvance of the Laurentide ice sheet in the Winooski River valley (the Middlesex Readvance) during the Older Dryas (Wright, 2015).

Methods

Geologic mapping was conducted during the summer and fall of 2017. Field observations were recorded using a Fulcrum App created by the primary contractor. Figure 2 shows the locations of over 4,000 field sites visited during the course of this study. For geological continuity, field work extended beyond the quadrangle boundaries in some areas (Fig. 2). The attribute table associated with the point locations shown on the below map contains a variety of separate observations made at those sites. During June of 2017 four UVM undergraduate students (Amanda Rossi, Katelyn Czyzk, Peter Sarkis, and Emma Marsters) assisted with the mapping effort and and focused their efforts in the Little River and Stevenson Brook valleys. During July of 2017 one UVM graduate student (Allison Waring) also assisted with the mapping and focused on the Joiner Brook valley and adjacent parts of the Winooski River valley. These students presented their work during the 2018 Geological Society of America Northeastern Section meeting (Czyzk et al., 2018; Waring and Wright, 2018).

Geologic materials and landforms were mapped in considerable detail in the river valleys owing to the large variety of surficial materials and landforms occurring in these valleys. Transects were made across many of the high-elevation areas, but fewer observations were necessary as these areas are, with few exceptions, uniformly underlain by glacial till.

A major objective of this work was to describe the three-dimensional distribution of surficial materials in the mapped area. These surficial materials, in addition to measurements of glacial striations, provide the basis for an interpretation of the different environments that existed during and immediately following ice sheet retreat. Other landforms and associated surficial materials offer insight into processes occurring during the Holocene, after the ice retreated.

Surficial Geologic Map

The surficial geologic map that accompanies this report shows the distribution of different types of surficial materials, landforms constructed of these materials, glacial striations, large erratics, large potholes, kettles, and water wells. During the spring of 2018 the Vermont Geological Survey has been working on a uniform set of mapping units. This map uses these new mapping units. The different surficial materials appearing on the Bolton Mountain Surficial Geologic Map are described below from oldest to youngest. The boundaries between these different materials are geologic contacts and are shown as solid lines on the geologic map. It’s important to realize, however, that these contacts are 2D surfaces that extend out-of-sight below Earth’s surface. In some areas geologic contacts could be closely located in the field and these locations were recorded and used when constructing the map. However, in most areas the location of these contacts is interpreted from field observations, distinctive landforms, and aerial imagery. Every effort was made to make these contacts as accurate as possible, but there is an element of interpretation in the placement of these contacts.

Geologic Mapping Units

<u>Bedrock Outcrops</u>

Bedrock outcrops were mapped whenever they were encountered during field traverses including all outcrops observed along town roads, state highways, and the Interstate.. No attempt was made to map all outcrops, especially in the extensive upland areas. Outcrops digitized from maps by Thompson and Thompson (1995) were imported and cover some parts of the quadrangle. Some of these outcrop polygons have been edited to reflect either field observations or the extent of outcrop visible on the LiDAR imagery.

Most of the surficial materials in the area were deposited by or adjacent to the Laurentide ice sheet as it first flowed across and then gradually thinned and retreated across the area approximately 13,800 years ago (Ridge et al., 2012). The following surficial mapping units are described in stratigraphic order.

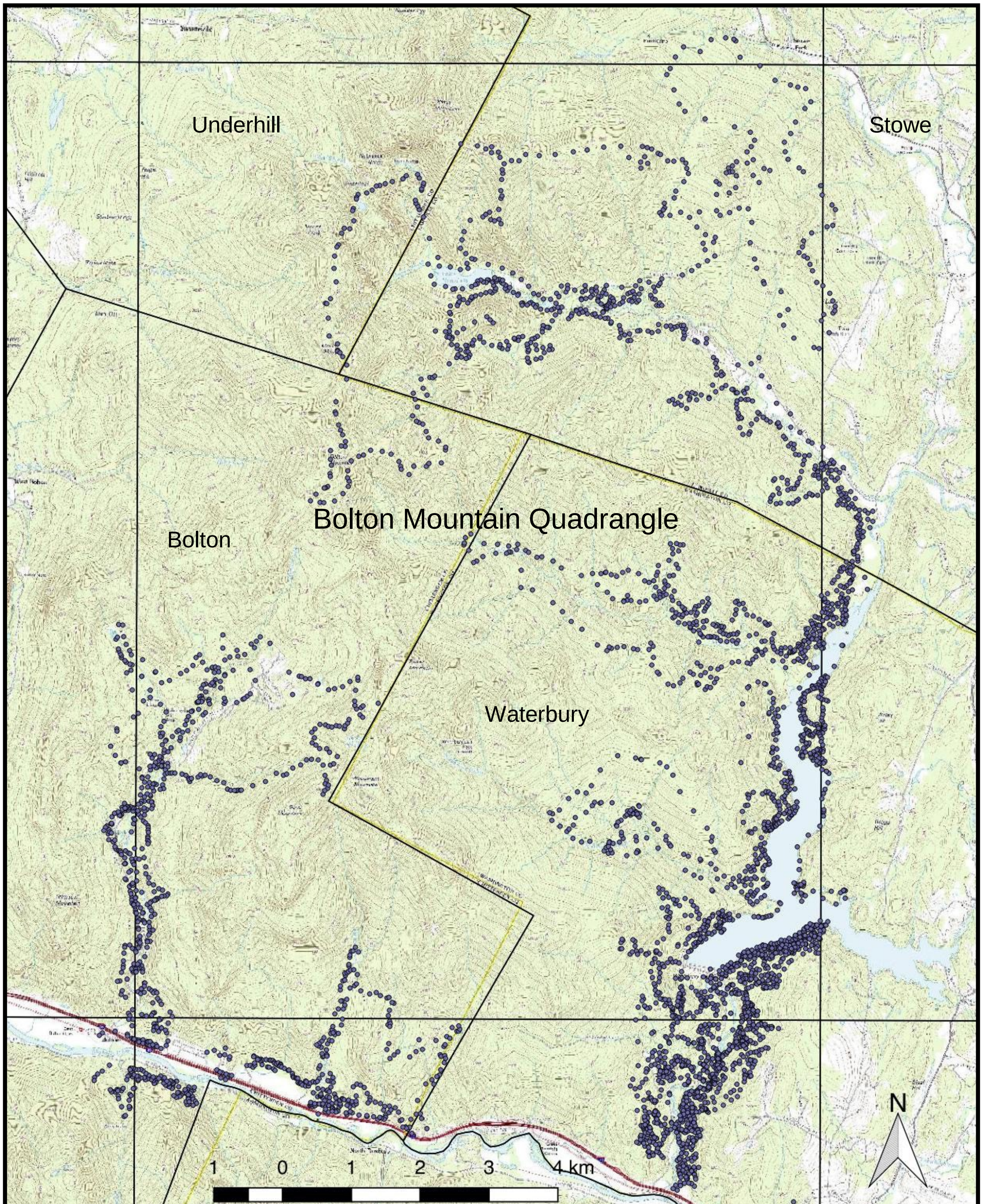

Figure 2: Map shows the location of over 4,000 field observations made during the 2017 field season. Quadrangle and Town boundaries are also shown.

Glacial Till

Glacial till directly overlies the bedrock in almost all areas. Within the quadrangle, till is the ubiquitous surficial material on the ground surface in areas above the valley bottoms. The freshest exposures appear in landslides above streams and in excavations where the till is gray to light brown and very dense (Fig. 3). Till in the area consists of angular to subrounded pebbles, cobbles, and boulders, many with striated surfaces) suspended in a fine clay/silt/ sand matrix (Fig. 3A). Most of the till occurring in this area is lodgement till consisting of materials eroded, deformed, and deposited beneath the ice sheet. Close to the ground surface frost heaving, plant roots, and animal borrows have loosened the till and surface run off has eroded some of the smaller-sized sediment (the “fines”) in the till. No attempt was made to systematically measure the composition of the till by either grain size or composition nor were any till fabric measurements made. Two till exposures, one in the Joiner Brook valley and one in the Cotton Brook valley, include alternating layers of diamict and thin, laminated, water-deposited sediment (Fig. 3B) that may be an under melt till deposited near the grounding line of the ice sheet.

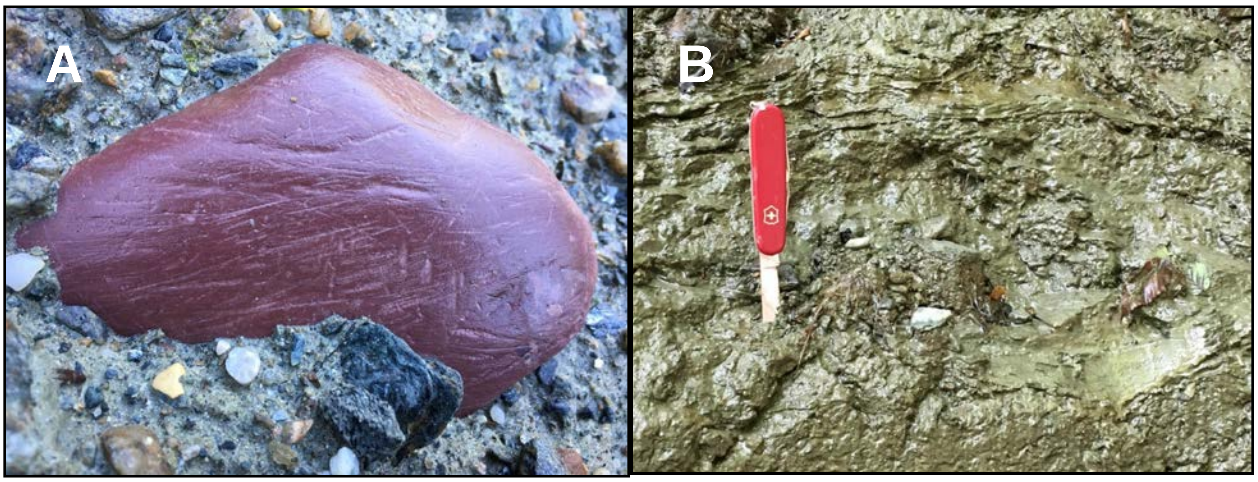

Figure 3: (A) Striated Monkton erratic in till exposed in a landslide along Joiner Brook. (B) Thin discontinuous layers of silt interbedded with diamict from an exposure of till in a landslide along a small tributary brook in the Cotton Brook valley. This till may have been deposited at the grounding line of the ice sheet where it dammed a small glacial lake. Alternatively, the water-deposited silt lamellae may have been deposited in subglacial cavities.

The upland areas of the quadrangle are underlain by variable thicknesses of till. Generally this till is thin (less than 2 to 3 meters) and abundant outcrops are present. However, extensive areas in the upland valleys, notably the Stevenson Brook and Cotton Brook valleys, have a thick till cover. No wells exist in these areas, but tributary streams frequently incise through 10 to 20 m of till (see overburden thickness map). Most of these thick till accumulations occur on the north or northeast facing sides of valleys where the ice sheet apparently deposited the till before flowing up and over the adjacent bedrock ridge. Large (>3 m diameter) erratics, composed of locally derived metamorphic rocks, are common and were mapped where encountered.

Moraines

Well defined moraines are rare in Vermont. One ridge of till lying perpendicular to the Miller Brook esker was interpreted to be a moraine in the Miller Brook valley a short distance down-valley from Lake Mansfield. Where the upland areas are mantled by thick till accumulations, that till frequently forms distinct step-like landforms that contour around valleys. These ridges are clearly visible on the LiDAR imagery and are here interpreted to be recessional moraines and may mark yearly ice marginal positions as the ice sheet thinned across the region. Several well-defined flights of morainal ridges are shown on the map, but not all ridges were mapped.

Ice-Contact Deposits

Ice-contact deposits are fluvial (stream-deposited) sediments deposited under, adjacent to, or in front of a glacier. These streams are generally fast-moving and therefore carry and deposit coarse-grained sediment, dominantly sand and gravel. Sediments deposited in subglacial tunnels form ridges of sand and gravel (eskers) once the glacier melts away. The Miller Brook valley hosts a well exposed esker down-valley from Lake Mansfield (Fig. 4). The subglacial tunnel in which this esker was deposited crossed the Green Mountains through Nebraska Notch. Several very large potholes occur about 1 km east of the notch providing evidence of the large discharge of water that once flowed through this drainage system (Fig. 5). Along much of its length it is mantled by till (ablation till) that was deposited as the debris-covered glacier melted. Wagner (1970) originally interpreted this esker system to be a moraine, but detailed mapping and excavation showed the ridges to be a system of eskers (Wright et al., 1997). In the lower reaches of the Miller Brook valley the esker is buried by younger ice-contact and lacustrine sediments (Fig. 4B; see also Geologic Cross-sections). While well-defined esker ridges in the Little River valley are rare, coarse sand and gravel occurring beneath lacustrine sediments in exposures and well logs are mapped as ice-contact gravel, although it's unclear if this gravel was deposited in a subglacial tunnel or as subaqueous fan deposits. A large pothole mapped in the Little River valley also suggests that a subglacial tunnel existed here (Fig. 5).

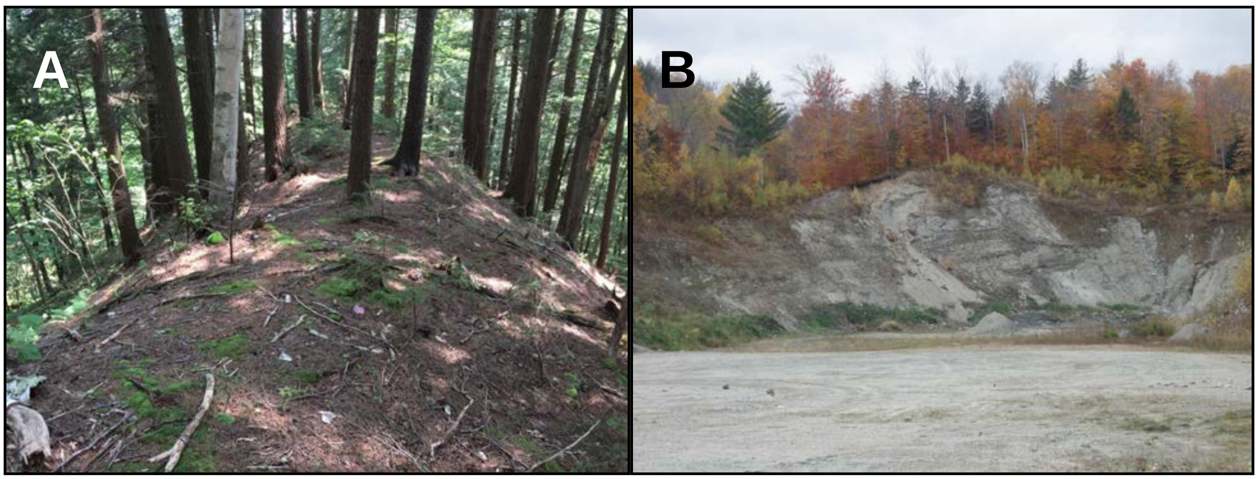

Figure 4: (A) View of the tree-covered Miller Brook esker. (B) The Miller Brook esker exposed in the Town of Stowe gravel pit between Beech Hill Road and Miller Brook Road. The town is excavating gravel from the esker and gravel deposited on the flanks of the esker in a subaqueous fan.

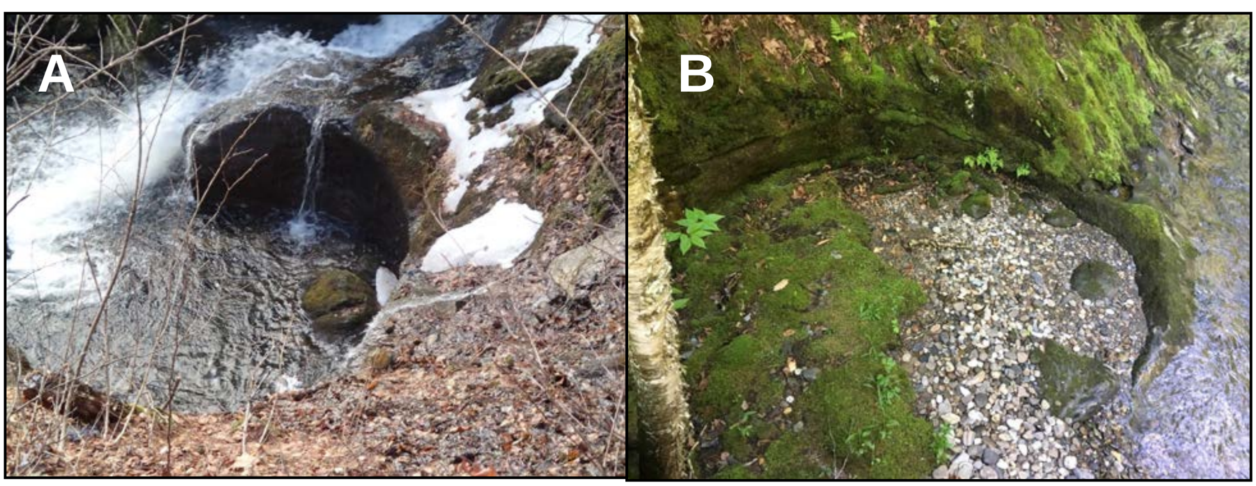

Figure 5: Large potholes produced by high velocity subglacial water flow. (A) Uppermost Miller Brook valley ~1 km east of Nebraska Notch. (B) Gorge in the Little River valley ~100 m below steam gauging station.

<u>Lacustrine (Glacial Lake) Deposits</u>

Glacial lake deposits include both coarser-grained sediments deposited at or near the shorelines of lakes (deltas and beaches) and finer-grained sediments deposited in the deeper quiet-water parts of lakes. Lacustrine sediments are common in most of the valleys in the quadrangle. Larsen (1972, 1987) outlined the sequence of glacial lakes that occupied the Winooski River drainage basin as the retreating ice sheet prevented the river from draining through the Green Mountains. Small, high-elevation lakes also existed as different tributary valleys were dammed. Evidence for two such lakes was found during this study, one in the Michigan Brook valley and the other in the Joiner Brook valley just below the nordic trail system.

The highest regional lake that affected the area is Glacial Lake Winooski (Fig. 6). Most stream valleys contain eroded remnants of deltas deposited in this lake (see geologic map). These deltas all lie at elevations between ~320–340 m (~1,045–1,115 ft). Post glacial isostatic tilt and erosion accounts for differences in these elevations. Sediments deposited in both topset and foreset beds of deltas consist of coarse sand and gravel. Bottomset beds progressively fine farther from the delta. Most mapped deltas include only the gravels constituting the topset and foreset beds. However, some mapped deltas, notably the Glacial Lake Winooski delta in the Miller Brook valley, include bottomset beds as well.

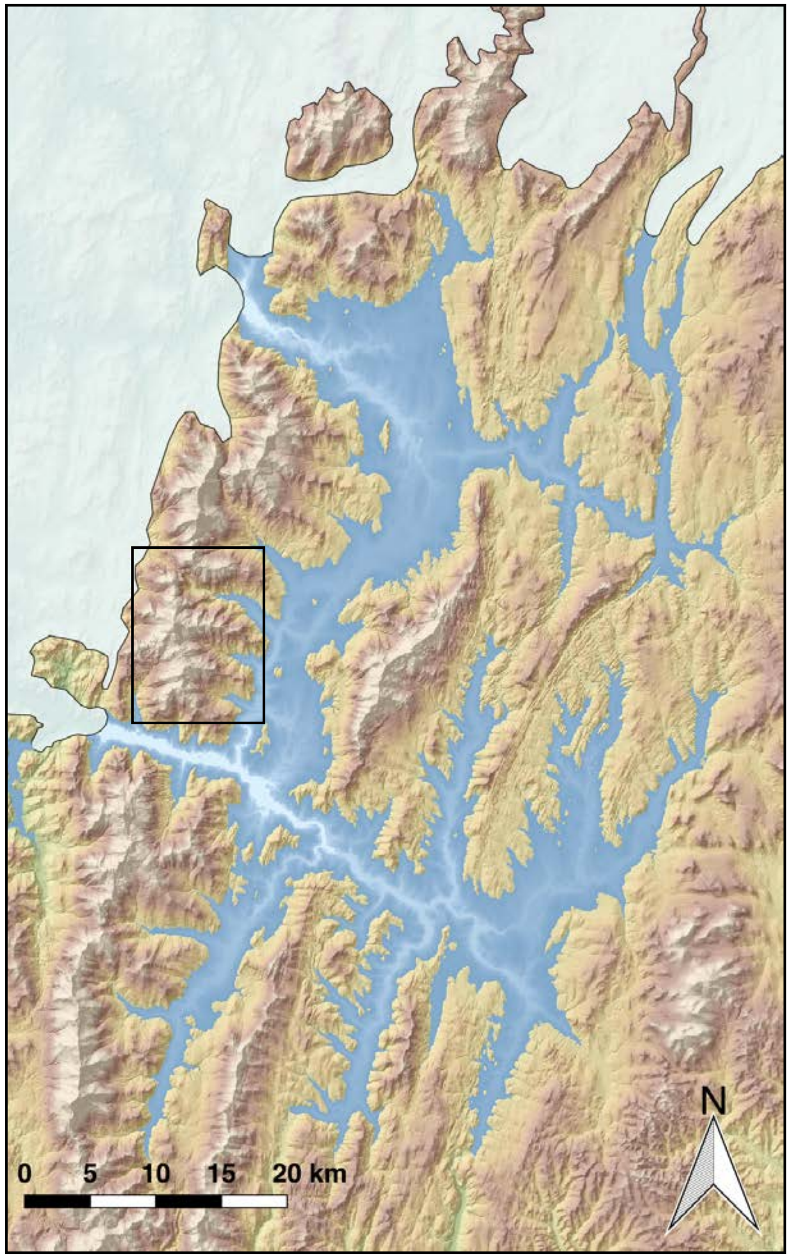

Figure 6: Maximum extent of Glacial Lake Winooski in both the Winooski and Lamoille River valleys (box outlines extent of the Bolton Mountain Quadrangle).Fine-grained sediments (fine sand to clay) were deposited in the deeper parts of this lake whereas sand and gravel were deposited in deltas where streams and rivers entered the lake. Colors in lake correspond to lake depth based on current topography.

Deep-water sediments deposited in this and other glacial lakes consist of fine sand, very fine sand, silt, and clay (Fig. 7). An excellent section of these sediments used to exist in the Little River State Park campground, but this section was destroyed several years ago to “stabilize” the slope. While it was still well-exposed the section was measured by the author (Larsen et al., 2003) and is presented with the Geologic Cross-Sections later in this report.

As the ice sheet retreated down the Winooski River valley it uncovered in quick succession two lower outlets allowing lake water to drain through the Huntington River valley and Hollow Brook into the Champlain Valley (occupied by

Glacial Lake Vermont). The much smaller regional lake in the Winooski River valley is called Glacial Lake Mansfield (Fig. 8). Several Glacial Lake Mansfield deltas were mapped in the field area. In the Little River valley. Deep water Glacial Lake Mansfield sediments in the Little River valley are coarser than corresponding Glacial Lake Winooski sediments as the lower elevation lake was much shallower and all parts of the lake basin in the quadrangle were closer to shore.

Figure 7: Deep water glacial lake sediments consisting of very fine sand, silt, and clay exposed in a small landslide along the shore of the Waterbury Reservoir.

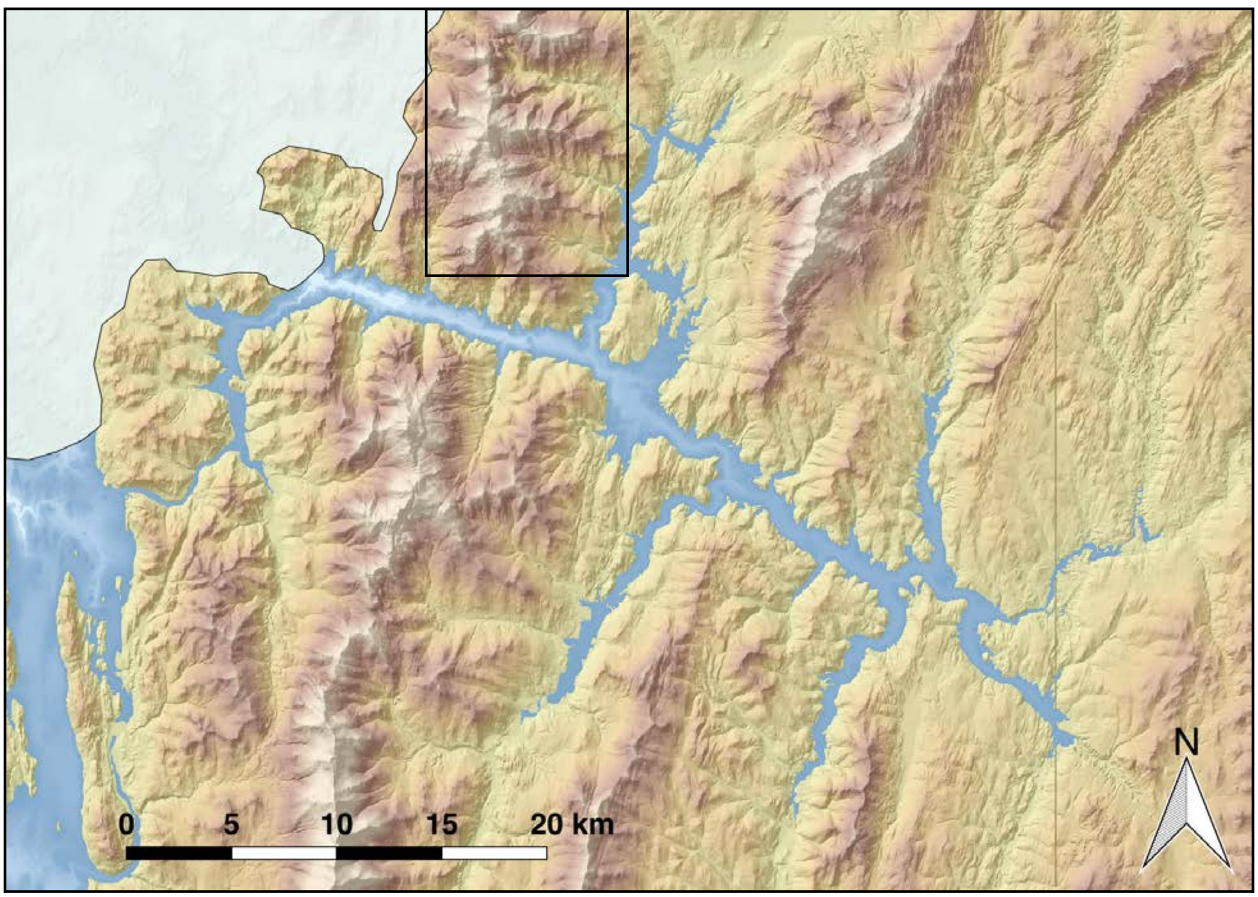

Figure 8: Extent of Glacial Lake Mansfield in the Winooski River valley (box outlines Bolton Mountain Quadrangle). This lake also occupied the Huntington River valley and drained through the Hollow Brook valley into Glacial Lake Vermont in the Champlain Valley. This lake still flooded the Little River valley, but most smaller tributary valleys in the quadrangle are above the elevation of this lake.

Fluvial Terrace Deposits

Fluvial terrace deposits are stream sediments (alluvium) occurring on terraces well above modern streams. Most commonly these sediments were deposited when streams began flowing across and incising into sediment filled valleys after the glacial lakes drained. As streams eroded channels more and more deeply through earlier-deposited sediments, older channels were abandoned. Consequently, in many areas mapped as fluvial terrace deposits there are several terrace levels and old abandoned channels are visible in many of these terraces. In most areas these fluvial terraces are underlain by a veneer of sand and gravel corresponding in thickness to the depth of the stream channel that deposited the sediment. In many areas these gravels have been partially or largely mined away revealing the underlying glacial lake sediments. A former gravel pit adjacent to Stowe's pit in the Miller Brook esker is a good example of this. This pit has recently been developed into a solar farm. The large terraces down-valley from the Waterbury Reservoir dam were occupied by an extensive camp during dam construction. In this area it's unclear if a veneer of gravel was quarried away prior to camp construction. For geological consistency, terraces where the alluvium has been mined were still mapped as fluvial terrace deposits.

Alluvial Fans

Alluvial fans are fan-shaped deposits formed where steeply-sloping streams deposit sediment where they flow out onto a gently-sloping valley floor, e.g. a fluvial terrace or modern floodplain (Fig. 9). Sediments deposited in alluvial fans generally grades from coarse to fine between the apex of the fan to its toe. The absolute size range of sediment in fans depends on the source of sediment. In many upland areas fans are sourced from till remobilized as debris flows and the fans consist largely of unsorted diamict. In areas where streams are eroding channels through fine-grained lacustrine sediment, that will be the size of sediment deposited in the fan. Several alluvial fans of different sizes are shown on the geologic map. Doubtless others were overlooked in the course of field work.

Figure 9: Alluvial fan deposited on the north shore of Lake Mansfield (Lake Mansfield Trout Club property). Toe of fan extends beneath the lake surface.

Studies in northern Vermont indicate that alluvial fans similar to these have been active episodically throughout the Holocene and have often received their most recent pulse of sediment following European land clearing in the late

18th and early 19th centuries (Bierman et al, 1997, Jennings et al., 2003). Related work by Noren and others (2002) recording pulses of clastic sediment deposited in ponds and small lakes, indicates that pre-European settlement erosion has not been uniformly distributed throughout the Holocene and seems instead to be concentrated during periods of increased high-intensity storms. If climate shifts produce a greater frequency of "Irene-like" storms in the future, further sedimentation on the area's alluvial fans seems likely.

Alluvium

Alluvium refers to sediments deposited by modern rivers and streams. Generally alluvium includes sand and gravel deposited in river channels and point bars where it's visible (Fig. 10), but also includes sand and silt deposited on floodplains that are frequently forested or farmed. Organic materials are a frequent component of modern alluvium. In many if not most areas modern alluvium is in contact with fluvial terrace deposits (old alluvium). The contact between these two mapping units is an interpretation of how much area is flooded during high-water events. The thickness of alluvium is proportional to the size of the stream that deposited it, but generally corresponds to the depth of the modern stream channel. In the larger valleys alluvium directly overlies glacial lake deposits. In smaller stream valleys in the uplands, alluvium overlies glacial till.

Figure 10: Point bar and cut bank along the Little River ~2 km upstream from the Waterbury Reservoir expose sand and gravel that typify much of the alluvium in the valley.

Swamp/Wetlands

Wetland areas generally occupy closed basins and are relatively rare in the quadrangle. The dominant sediment in wetland areas consists of both living and partially decayed organic materials as well as inorganic sediment washed into these areas by streams and overland flow. The borders of wetland polygons were mapped using satellite imagery, but the boundaries shown on the geologic map should not be used for regulatory purposes.

Artificial Fill

Artificial fill occurring in dams and for road fill is shown on the geologic map where it could be mapped using the LiDAR imagery, e.g. the Waterbury Reservoir dam. Materials comprising fill are generally sand and gravel, but can also include broken and crushed rock.

Landslides

Many small and large landslides were encountered during field work (Fig. 11). Most are relatively small (5–20 m in length, <10 m in height) and all occur adjacent to streams. Larger landslides were both recognized and mapped using the LiDAR imagery. Some of these landslides were recent and expose good sections of surficial materials whereas others are of unknown age but have a distinctive morphology.

Figure 11: Active landslide along the east side of Joiner Brook ~2 km below the Bolton ski area. Water-saturated glacial till is slowly flowing into the stream.

Geologic Cross-sections

Two approximately east-west geologic cross-sections were constructed, one across the Miller Brook valley and the other in the Little River State Campground (Figs. 10, 11). Cross-sections present an interpretation of what surficial materials lie beneath Earth's surface and their thickness. The best information available about the type of thickness of surficial materials in most areas comes from the logs kept by drillers when completing domestic water wells. Considerable time was spent mapping the locations of as many water wells as possible in these two areas and then trying to match the well-log records maintained by the Agency of Natural Resources with these located wells. The most accurate information recorded by drillers is the "depth to bedrock" or "overburden thickness" as this is approximately equivalent to the length of steel casing needed for a drilled well, a length carefully recorded and charged to the home owner. Otherwise, the quality of records kept by drillers of the type and thickness of the surficial material they drill through varies enormously and frequently requires some interpretation based on field evidence.

Miller Brook Cross-Section

The Miller Brook valley is contains an esker system that was first identified by Wright et al. (1997) and has been mapped in detail as part of this study. A gravel pit (owned by the town of Stowe) exposes a good cross-section of this esker and associated ice-contact deposits (Fig. 12). Gravels comprising the Miller Brook esker are buried by a finingup sequence of sediments deposited in a subaqueous fan. As the the ice sheet retreated up the valley, the mouth of the subglacial tunnel (the primary source of these sediments) also retreated farther up the valley and the average grain-size of sediments progressively decreased until only the suspended silt and clay sediments were deposited. This well exposed section, albeit without any water well data, is used to interpret the cross-section drawn farther down the valley.

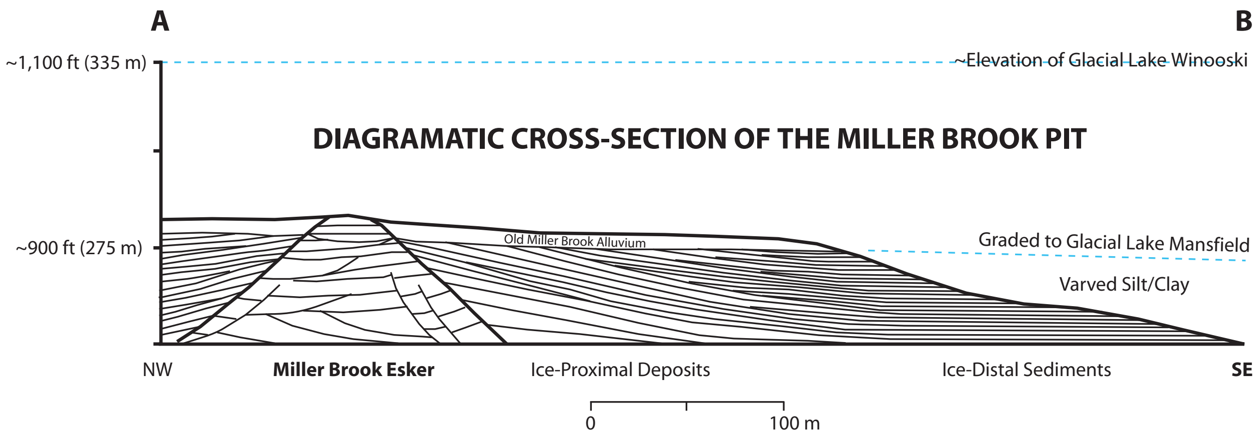

Figure 12: The Miller Brook esker is overlain by a fining-upward sequence sediments ranging from pebble gravel close to the esker to very fine sand, silt, and clay away from the esker. Dropstones are common as are distinct, thin silt layers within the sand horizons. Varved silt and clay layers lie at the top of the section, farthest from the esker. Spectacular folds and faults occur within these varves and were likely produced when these soft yet coherent sediments slid off the northeast side of the esker into deeper water. The sediments overlying the esker are clearly lacustrine in origin and were deposited in Glacial Lake Winooski, the only glacial lake known to have flooded this part of the mountains (Larsen, 1972, 1987). The projected elevation of Glacial Lake Winooski over this part of the Miller Brook valley is ~1,100 ft. Therefore, as the ice sheet retreated the esker and surrounding areas were immediately beneath ~95–195 ft (~30–60 m) of water. Coarse sediments ejected from the esker tunnel were deposited close to the tunnel mouth. As the ice sheet retreated farther up the valley, the average size of sediment originating from the esker tunnel gradually diminished producing the fining-upwards sequence of sediments currently draping across the esker.

The Miller Brook cross-section (Fig. 13) extends across the Miller Brook valley in the northern third of the quadrangle (see geologic map for exact location). Three water wells constrain the subsurface geometry of surficial materials and all indicate that surficial materials in this area are relatively thin (<100 ft). These wells and others in the valley indicate that the Miller Brook valley is largely filled with gravel. Some of this gravel was deposited in the Miller Brook esker which is mapped as a well-defined landform for some distance up-valley from the cross-section. In the lower reaches of the valley the esker is buried by ice contact and lacustrine sediments and has been eroded by Miller Brook. It’s impossible to discern which gravels in the well logs are part of the esker versus part of the ice-contact sediments. Consequently, the position of the esker shown in the cross-section is conjectural. Well-defined fluvial terraces occur throughout the valley and formed as Miller Brook eroded older ice-contact and lacustrine sediments following the draining of glacial lakes in the region..

<u>Little River Campground Cross-Section</u>

The Little River Campground cross-section begins on the hillside west of the entrance to the campground and extends down to the Waterbury Reservoir (Fig. 14; see geologic map for location). One good log from the water-supply well for the campground constrains the middle of the cross-section and a section measured at the eastern end of the campground (since destroyed by the State Park) constrains the eastern end (Fig. 15, Larsen et al., 2003). The section on the eastern end displays a beautiful sequence of varved (silt and clay) lacustrine sediments. These are abruptly overlain by a sequence of interbedded medium to coarse sand with silt. The geologically instantaneous

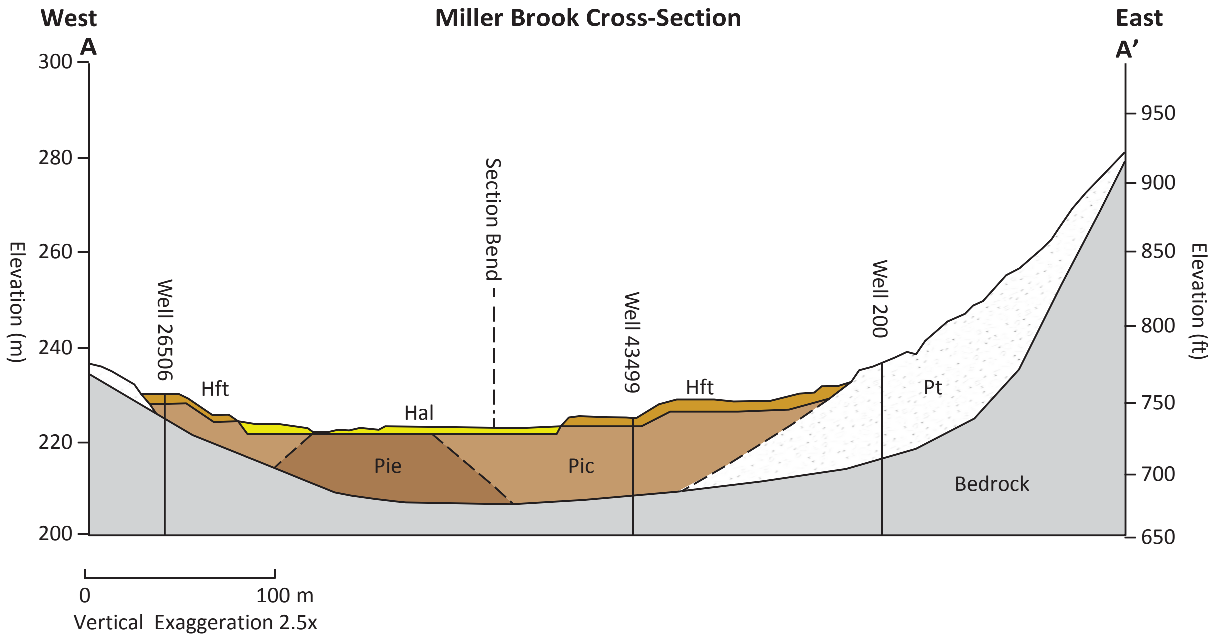

Figure 13: Cross-section depicts an interpretation of the thickness and types of surficial materials occurring across the Miller Brook valley (location of cross-section is shown on the Surficial Geologic Map). Vertical black lines represent water wells and the numbers above them are the Well Report Numbers. Pt: Glacial till; Pie: Esker gravel; Pic: Ice Contact gravels; Hft: Fluvial terrace gravels; Hal: Modern Alluvium. See text for a complete description of the materials occurring on this cross-section.

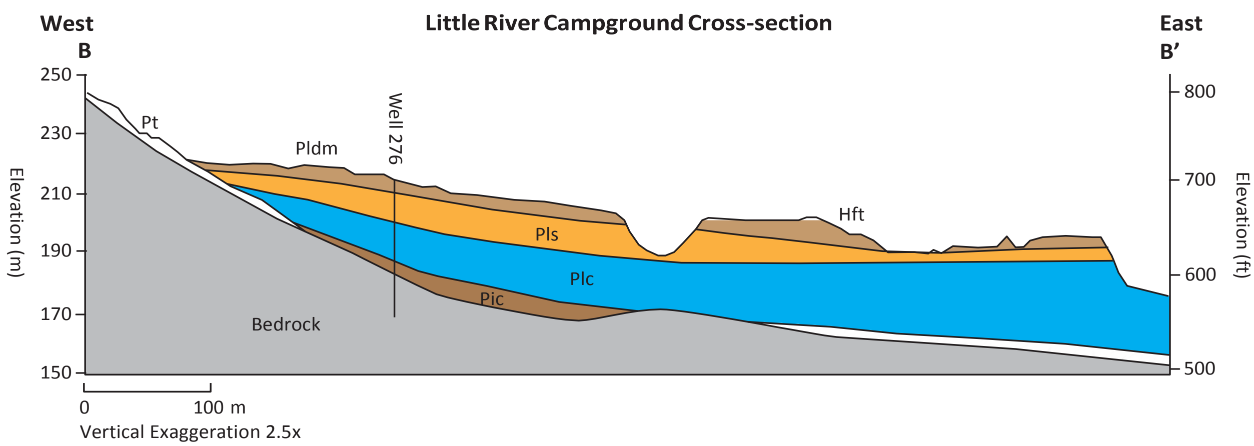

Figure 14: Little River Campground cross-section. Ice-contact gravel (Pic) and glacial till (Pt) cover the bedrock. Varved silt/clay (Plc) was deposited in Glacial Lake Winooski. A sharp contact separates the sitl/clay below from a section of sand (Pls) deposited in Glacial Lake Mansfield fpllowing the sudden drainage of Glacial Lake Winooski. The section is capped by gravel deposited as part of a delta in Glacial Lake Mansfield (Pldm) or as old Little River alluvium (Hft).

transition occurred when Glacial Lake Winooski partially drained. The section is overlain by alluvium. Some of the alluvium was deposited by the Little River after the glacial lakes drained. The gravels occurring at the surface in the west end of the cross-section were likely deposited in a delta as Stevenson Brook flowed into Glacial Lake Mansfield.

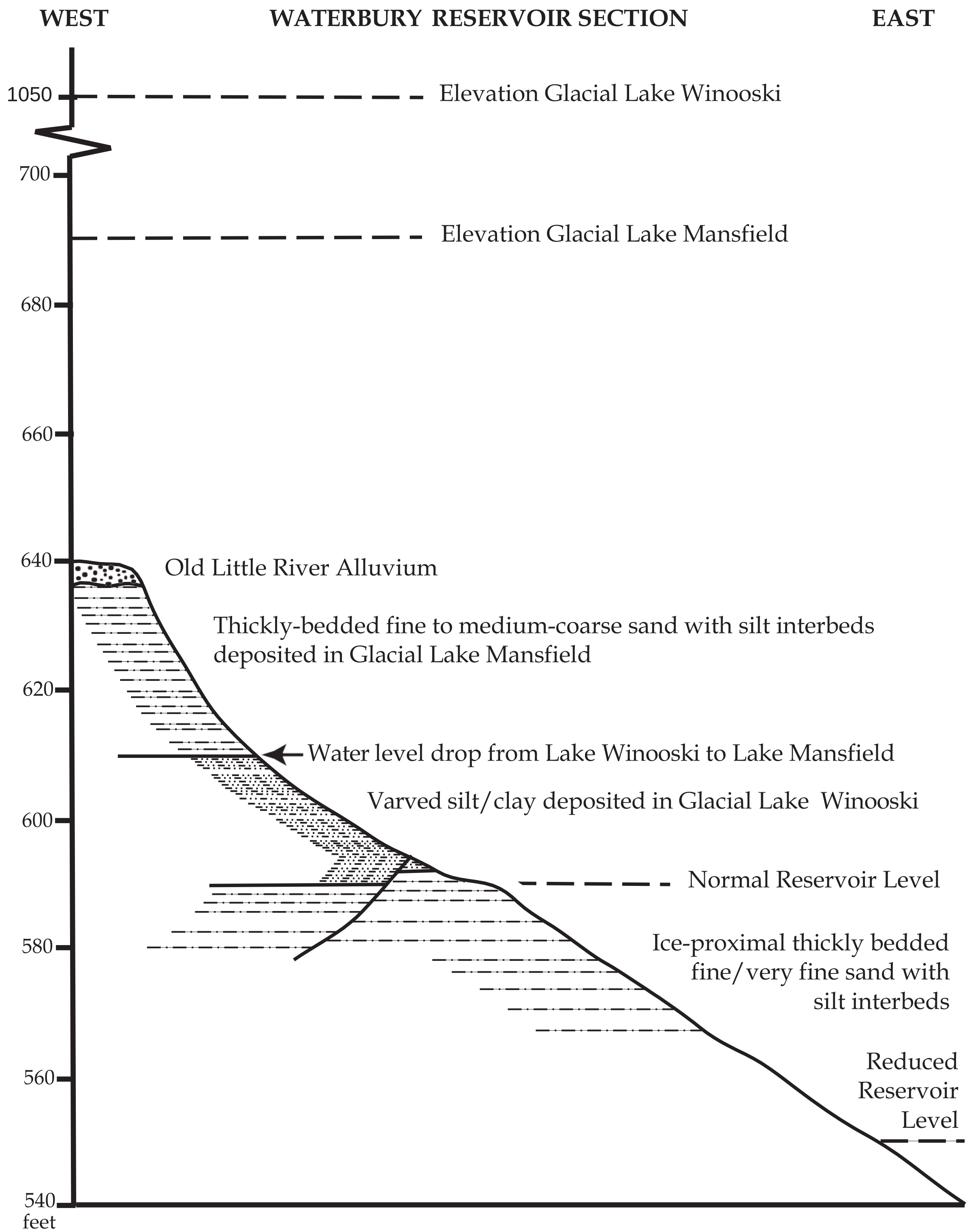

Figure 15: Stratigraphic section exposed at the eastern end of the peninsula occupied by the Little River State Campground (Larsen et al., 2003). Thickly bedded ice-proximal lacustrine sediments are overlain by a sequence of varved ice-distal silt/clay sediments deposited in Glacial Lake Winooski. An knife-edge transition to medium to coarse sand marks the draining of Glacial Lake Winooski. Coarse alluvium at the top of the section was deposited by the Little River following drainage of the glacial lakes.

S.F. Wright

Glacial Striations

Glacial striations (scratch marks on bedrock surfaces) were recorded as part of this study. Most striations in the upland areas are oriented from NW to SE, consistent with observations by Wright (2015) across all of northern Vermont. These striations formed when the ice sheet was thick enough to cover the mountains and indicate regional ice flow to the southeast. Striations in the valleys are oriented parallel to those valleys reflecting the redirection of ice flow when the ice sheet has thinned sufficiently that it's flow was topographically controlled.

Overburden Thickness Map

The "Overburden Thickness Map" contours the thickness of surficial materials (overburden) within the quadrangle. The data used to generate this map are (1) bedrock outcrops (which indicate areas where surficial materials are missing), (2) records of overburden thickness from domestic water wells, and (3) areas where streams have incised through thick sections of surfical material. In this mountainous terrain, the overburden thickness is less than 50 feet in most areas. For this reason only one contour was drawn on the map separating areas having greater than or less than 50 feet of surficial material overlying bedrock. Because much of the land within the quadrangle is mountainous and public land, only restricted areas are settled and contained domestic water wells. These water well data were used to constrain in the Miller Brook valley, the Little River State Campground, and portions of the Joiner Brook valley.

Generally, areas of thick surficial materials occur in the major river valleys. The valleys have accumulated not only the till that's also present in the uplands, but all of the ice-contact (e.g. esker) and glacial lake sediments that accumulated as the ice sheet was retreating across this area. In the upland areas several areas of thick overburden (till) are circled based on deeply incised stream valleys, e.g. the Stevenson Brook and Cotton Brook valleys. These areas of thick till are consistently on the south or southeast sides of these valleys and may result the ice sheet depositing thick accumulations of till before flowing over obstacles (bedrock ridges) on its southeasterly trajectory. Conversely, the north and northwest sides of valleys (the up glacial side) have been eroded down to bedrock and have only a thin till cover. Note that in most areas there is little data to support the exact placement of these contours and what's shown is an interpretation.

Groundwater Hydrology

The Bolton Mountain Quadrangle includes the Towns of Bolton, Waterbury, Stowe, and Underhill. Within the quadrangle area, people in these towns rely entirely on groundwater for their drinking supply. Surficial aquifers are tapped by many residents and the Little River State Park using both shallow dug wells and deeper drilled wells. However, drilled wells extending into bedrock are used by most residents. Most of these extend into bedrock and the portion of the drill hole penetrating surficial materials is cased to keep the well from collapsing and to keep groundwater in the surficial materials from entering the well. Drilled wells can also tap deeper surficial aquifers.

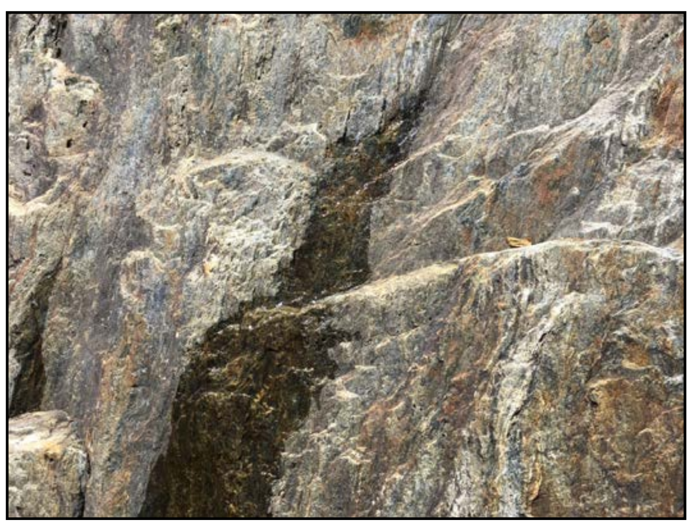

Figure 16: Groundwater seeping out of fracture in bedrock exposed below the Waterbury Reservoir dam.

Many different types of bedrock underlie the town. However, they are all metamorphic rocks and have no primary porosity, meaning there is no open space between the mineral grains in these rocks to store water. Consequently, groundwater in these rocks is located in fractures and any drilled well in bedrock gets its water from fractures that well intersects (Fig. 16). Generally, the volume of groundwater in fractured bedrock aquifers depends on the density of fractures but is typically less than 1% of the rock volume. On the other hand, most surficial materials have a lot of primary porosity, a lot of open space between individual sediment grains, typically 25–45% of the volume of the sediments. The usefulness of water in those pore spaces depends on how easily water can move through these surficial materials. Generally, groundwater moves very slowly through fine-grained materials and much more quickly through coarse-grained materials.

The largest useful groundwater reservoirs occurring in the quadrangle are found in the coarse-grained surficial materials (sand and gravel) where those materials extend below the water table. Of these, the eskers shown on the geologic map and the extensive deltaic and glacial outwash deposits underlying modern alluvium are the best. This type of aquifer is susceptible to contamination from human and agricultural sources.

Water Table Contour Map with Flow Lines

A map contouring the elevation of the water table is included with this report. The data used to construct these contours comes from the topographic map of the area and domestic water wells where the depth to the water table was recorded. Specifically, groundwater discharges to the surface in streams, ponds, lakes, and wetlands so these are areas where the elevation of the ground surface and the elevation of the water table are equal. In areas between these groundwater discharge points the water table is, by definition, at an elevation below the ground surface. Streams are common in the upland areas implying that even in these areas the water table is relatively close to the ground surface.

A major north-south drainage divide follows the crest of the Green Mountains and separates both surface and groundwater flowing west from surface and groundwater flowing east. This divide is shown with a dashed red line on the map. Another drainage divide was drawn that outlines surface and groundwater flow to the south. Many smaller hydrologic divides also occur separating tributary drainage basins. These aren't shown on the map, but can be inferred from the groundwater flow lines (see below).

In this mountainous terrain water table contours were drawn at 500 foot intervals across the quadrangle.
The elevation of the water table varies seasonally. It's generally highest in the early spring when groundwater is recharged by melting snow and rain. It's generally lowest at the end of the summer/early fall when the combination of lower summer rainfall and very high evapotranspiration rates from plants limits recharge. Consequently, water table contour lines on a map shift seasonally, moving up in the spring and down during the summer months. This is why many streams at higher elevations flow in the spring, but go dry during the summer.

Groundwater flows down-gradient (downhill) perpendicular to groundwater contour lines. Interpretive groundwater flow lines (arrows) are drawn on the map showing the approximate directions of groundwater flow across the area. In general, most of these flow lines begin in the upland areas and end at streams where groundwater discharges to the surface. The flow lines can be used to understand the pathways groundwater has taken to reach domestic water wells. The flow lines can also be used to interpret the different types of bedrock and surficial material groundwater has flowed through. These different types of rock and surficial material are the sources of all the naturally-occurring dissolved ions in groundwater. For groundwater contaminated with human/domestic animal waste or other toxic chemicals, the flow lines can be used to search areas up-gradient from the contaminated groundwater for potential sources. Note however that the detailed groundwater flow paths needed to show point sources of groundwater contamination cannot be deciphered from this map.

Bedrock Hydrologic Unit Map

A bedrock hydrologic map was generated for Chittenden County by Gale and others in 2010 using the bedrock map units from the 1961 bedrock map of Vermont and water well data from the well driller database at ANR. Domestic water wells are limited to the Miller Brook valley, the Little River State Park, and the upper part of the Joiner Brook valley in the area around the ski area.

Several high-yield wells (>10 GPM) exist, but some pull their groundwater from coarse-grained surficial materials and others do not seem restricted to any one rock type. An area with a larger number of wells might yield a connection between well yield and rock type, but it's far more likely that well yield is correlated to the density of fractures in the underlying bedrock (specifically the number, width, length, and interconnectedness of those fractures). Extensively fractured bedrock is more susceptible to weathering and erosion than unfractured bedrock and frequently guides the location of large- and small-scale valleys that are quite linear. These linear features can be mapped and used as a guide for drilling high-yield bedrock water wells. A map of this type was not generated as part of this project.

Recharge Potential to Surficial and Bedrock Aquifers Map

Groundwater recharge depends on (1) how easily rainfall and snow melt can infiltrate the ground surface, (2) the rate at which water can move through the surficial material or rock it infiltrates into—its permeability, (3) the amount of time that water is available to enter different groundwater systems. Infiltration is enhanced when the ground surface is permeable and rainfall and snow melt can linger on the ground surface. Coarse-grained surficial materials on level ground provide the best infiltration whereas steep bedrock surfaces provide the worst. Vegetation, burrowing animals, and frost heaving usually enhances infiltration by increasing the permeability of soils and providing a myriad of small depressions where surface water can linger. Fine-grained surficial materials usually have a low permeability. Even if vegetation allows water to infiltrate, the rate it can percolate (seep) into the material may be far slower than the rate at which new water from rainfall or snow melt is available. In fine-grained materials with low permeability, e.g. many tills and lacustrine sediments, a significant amount of water can move though these materials if enough time is available.

The recharge potential map included with this report groups surficial materials into 1) those with high porosity and high to moderately high permeabilities and 2) those with low permeabilities.

<u>High Recharge Potential to Surficial and Bedrock Aquifers</u>

Alluvium, Artificial Fill, Alluvial Fan sediments, Fluvial Terrace sediments, Deltaic sediments, Eskers, and Wetlands are all materials that readily absorb surface water. They all consist of coarse-grained surficial materials and lie in valleys where slopes are gentle. Where these materials overlie moderate- to low-permeability materials, they have the capacity of soak up surface water allowing it to slowly seep into these underlying surficial materials. With the exception of the wetlands areas, these materials make excellent surficial aquifers where they extend below the water table.

<u>Low to Moderate Recharge Potential to Surficial and Bedrock Aquifers</u>

Lacustrine very fine sand, fine sand, silt and most till have moderate to low permeabilities. Till mantles most upland areas and usually directly overlies bedrock, so till itself is the surficial aquifer that's being recharged. As noted earlier, animals, vegetation, and frost heaving enhance near surface infiltration and dug wells utilizing groundwater from till are common. Lacustrine fine sand occurs in the valley bottoms where slopes are gentle which enhances it's ability to absorb water. Shallow dug wells also occur in this material. Slow movement of water through these materials can recharge coarse-grained aquifer materials beneath. Lacustrine silt/clay is the only true very low permeability surficial material in the area and surface exposures are limited.

References

Bierman, P., Lini, A., Davis, P.T., Southon, J., Baldwin, L., Church, A., and Zehfuss, P., 1997, Post-glacial ponds and alluvial fans: recorders of Holocene landscape history: GSA Today, v. 7, p. 1-8.

Bierman, P.R., Wright, S.F., and Nichols, K., 1999, Slope stability and late Pleistocene/Holocene history, northwestern Vermont; in Wright, S.F. ed., New England Intercollegiate Geological Conference Guidebook Number 91, p. 17–50.

Connally, G.G., 1965, Surficial Geologic Map of the Mount Mansfield 15-minute Quadrangle, Open File Map, Vermont Geologic Survey.

Cronauer, S. and Wright, S.F., 2012, Changing glacial environments: Miller Brook valley, Vermont; Geological Society of America Abstracts with Programs, Vol. 44, No. 2, p. 51.

Jennings, K., Bierman, P., and Southon, J., 2003, Timing and style of deposition on humid-temperate fans, Vermont, United States: Geological Society of America Bulletin, v. 115, p. 182-199.

Czyzk, K.A., Rossi, A.M., Sarkis, J.P., and Wright, S.F., 2018, Surficial geologic materials and interpretations in the Little River valley, northern Vermont; Geological Society of America *Abstracts with Programs.* Vol. 50, No. 2 doi: 10.1130/abs/2018NE-311294

Dunn, R.K, Springston, G.E., and Wright, S.F., 2011, Quaternary geology of the central Winooski River watershed with focus on glacial lake history of tributary valleys (Thatcher Brook and Mad River); in West, D. ed., New England Intercollegiate Geologic Field Conference Guidebook, Field Trip C-3, 32 p.

Larsen, F.D., 1972, Glacial history of central Vermont; in Doolan, B.L., ed., NEIGC Guidebook Number 64, pp. 296–316.

Larsen, F.D., 1987, History of glacial lakes in the Dog River valley, central Vermont, in Westerman, D.S., ed. NEIGC Guidebook Number 79, pp. 213–236.

Larsen, F.D., Wright, S.F., Springston, G.E., Dunn, R.K., 2003, Glacial, late-glacial, and post-glacial history of central Vermont; Guidebook for the 66th Annual Meeting of the Northeast Friends of the Pleistocene, 62 p.

Noren, A.J., Bierman, P.R., Steig, E.J., Lini, A., and Southon, J., 2002, Millennial-scale storminess variability in the northeastern United States during the Holocene epoch: Nature, v. 419, p. 821-824.

Ratcliffe, N.M., Stanley, R.S., Gale, M.H., Thompson, P.J., and Walsh, G.J., 2011, Bedrock Geologic Map of Vermont: USGS Scientific Investigations Series Map 3184, 3 sheets, scale 1:100,000.

Ridge, J.C., Balco, G., Bayless, R. L., Beck, C. C., Carter, L. B., Dean, J. L. Voytek, E. B., Wei, J. H., 2012, The new North American Varve Chronology: A precise record of southeastern Laurentide Ice Sheet deglaciation and climate, 18.2-12.5 kyr BP, and correlations with Greenland ice core records; American Journal of Science, v. 312, 685–722.

Stewart, D.P., 1956–1966, Surficial Geologic map of the Camels Hump 15-minute Quadrangle, Open File Map, Vermont Geologic Survey.

Stewart, D.P. and MacClintock, P., 1970, Surficial geologic map of Vermont, Vermont Geological Survey, 1:250,000.

Thompson, PJ and Thompson, TB, 1995, Digital bedrock geologic map of parts of the Huntington, Richmond, Bolton and Waterbury quadrangles, Vermont: VGS Open-File Report VG95-9A, 2 plates, scale 1:24000.

Wagner, W.P., 1970, Pleistocene Mountain Glaciation, Northern Vermont; Geol. Soc. America Bull. 81:2465–2470.

Waring, A.L. and Wright, S.F., 2018, Surficial Geology of the Joiner Brook and Winooski River valleys, Bolton, Vermont; Geological Society of America *Abstracts with Programs.* Vol. 50, No. 2 doi: 10.1130/abs/2018NE-310790

Wright, S.F., Whalen, T.N., Zehfuss, P.H., and Bierman, P.R., 1997, Late Pleistocene–Holocene History: Huntington River and Miller Brook Valleys, Northern Vermont: in, Grover, T.W., Mango, H.N., and Hasenohr, E.J., eds., New England Intercollegiate Geological Conference Guidebook to Field Trips in Vermont and adjacent New Hampshire and New York, pp. C4:1–30.

Wright, S.F., 2011, Ice retreat across the Green Mountain foothills: Bolton and Jericho, Vermont; in West, D. ed., New England Intercollegiate Geologic Field Conference Guidebook, Field Trip A-2, 18 p.

Wright, S.F., 2012, Subglacial drainage, glacial lake history, and subsequent stream incision history, Miller Brook valley, northern Vermont; Geological Society of America Abstracts with Programs, Vol. 44, No. 2, p. 51.

Wright, S.F. and Conroy, M., 2014, Glacial geology of Bolton Notch, Vermont elucidated using ground penetrating radar: Geological Society of America Abstracts with Programs, Vol. 46, No. 2, p. 108.

Wright, S.F., 2015, Extent of the Middlesex Readvance in the Winooski River basin, Northern Vermont: Geological Society of America Abstracts with Programs, Vol. 47, No. 3, p. 83.

Wright, S.F., 2015, Late Wisconsin ice sheet flow across northern and central Vermont, USA; Quaternary Science Reviews, Vol 129: 216–228.

Wright, S.F., Springston, G.E., and Van Hoesen, J.G., 2015, Ice retreat and readvance across the Green Mountain Foothills: Bolton and Jericho, Vermont; New York State Geological Association Guidebook Vol. 87: 327–352.