

Surficial Geology and Groundwater Hydrology of the Lincoln and Mount Ellen 7.5-Minute Quadrangles, Vermont¹

Stephen F. Wright
Department of Geology, University of Vermont
2022

Vermont Geological Survey Open File Reports: VG2022-2, 3



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¹ Research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number GS21AS00006. The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U.S. Government.

Executive Summary/Significant Findings

The surficial geology of the Lincoln and Mount Ellen 7.5-Minute Quadrangles west of the Green Mountains was mapped during the summer of 2021. Mapping in the uppermost Huntington River valley (northwestern Mount Ellen Quadrangle) was assisted by seven geology students at the University of Vermont. Areas within the quadrangles east of the Green Mountains was previously mapped by Dunn and others (2007b). Considerable detail has been added to prior mapping done at a scale of 1:62,500 and later incorporated into the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970). Surficial geologic maps, four geologic cross-sections, overburden thickness maps, water table contour and flow line maps, well yield maps, and recharge potential to surficial materials maps of each quadrangle are included with this report (Plates 1-5).

The Lincoln and Mount Ellen Quadrangles contain a variety of glacial landforms and sediments that formed as the Laurentide ice sheet first flowed across north-central Vermont and then thinned and retreated from the area. Two sets of glacial striations are well preserved along the crest of the Green Mountains. The older set is oriented NW-SE, parallel to regional ice flow across New England. Younger striations indicate NE-SW ice flow towards the Champlain valley, possibly due to an ice streaming event that funneled ice through the Champlain and Hudson River valleys. Ice flow shifted to N-S when the ice sheet thinned and its flow became topographically controlled by the Champlain valley to the west and the Mad River valley to the east.

Till mantles all of the upland areas. Most is dense lodgment till, but some may be till remobilized as debris flows sourced from the steep mountain hillsides. Most of the till cover is thin, but limited areas exist where the till is thick enough to completely mask the underlying bedrock topography. Most rocks occurring in the till are sourced locally from metamorphic rock underlying the mountains. However, glacial erratics, sedimentary rocks sourced from the Champlain valley to the northwest, are common. Very large (> 4 m) glacially-transported rocks have been mapped.

During ice retreat rapid summer melting of ice and snow generated large volumes of water that flowed sub glacially and along the ice sheet's borders. Abandoned N-S channels along the western slopes of the mountains mark avenues of water flow along the margins of the ice sheet. Sand and gravel was deposited in subglacial tunnels, in subaqueous fans, and along the margin of the ice sheet as kames and ice-contact deltas. Numerous eskers were mapped along the western flank of the mountains. All are oriented N-S indicating they formed when the ice sheet had thinned enough that its flow was topographically controlled by the Champlain valley and hydraulic gradients within the ice sheet mimicked the slope of the southward-flowing ice. These ice-contact sediments occur both at the surface and beneath younger glaciolacustrine sediments. They can host significant aquifers, both confined and unconfined.

Glacial lakes formed on both sides of the mountains as the ice sheet thinned and retreated to the north. East of the mountains one small, short-lived, high-elevation lake has been documented in the Clay Brook valley. A much larger lake, Glacial Lake Granville, grew in the Mad River valley once the ice sheet retreated north of Granville Gulf. The elevation of this lake was high enough to flood many of the Mad River's tributary valleys. Lake level fell following a reconfiguration of drainage that occurred when the ice sheet retreated north of the Winooski River valley and a regionally extensive lake, Glacial Lake Winooski grew east of the mountains. With the exception of one tributary valley, this lake was below the elevation of areas within these two quadrangles.

West of the mountains numerous, generally smaller, lakes occupied the region's river valleys, particularly where those valleys drained to the north. These lakes were all dammed by the retreating ice sheet and evolved from south to north, following the retreating ice sheet. The oldest documented lake, one which flooded a portion of the Middlebury River valley, bordered the SW corner of the Lincoln Quadrangle. The next lake to form, Glacial Lake Lincoln, occupied progressively larger portions of the upper New Haven River valley. At least 3 distinctive stages to this lake are marked by outlets through the Natural Turnpike, near Cobb Hill, and Alder Brook. This last outlet was utilized for the longest period of time as the lake grew to its fullest extent. A third glacial lake, Glacial Lake Jerusalem, formed in the upper Baldwin Creek valley centered on the village of Jerusalem. A short distance farther north, the last lake to develop, Glacial Lake Huntington, was constrained to the Huntington River valley. While only the uppermost portions of this lake existed in the NW corner of the Mount Ellen Quadrangle, this lake eventually became quite large and merged with lakes occupying the Winooski River valley.

While the Glacial Lake Hitchcock and Glacial Lake Winooski varve sequences have constrained the timing of ice retreat east of the Green Mountains, the timing of ice retreat west of the mountains is less well known. However, while the rate of retreat is unknown, Glacial Lake Winooski's existence east of the mountains, dammed by ice west

of the mountains makes it clear that the much thicker tongue of ice that occupied the Champlain valley retreated northwards at a later date than ice east of the mountains.

Most lacustrine sediments mapped in the valleys occupied by these lakes varies greatly in grain size over short distances both laterally and vertically. This variability is well-displayed in a landslide section observed in this study and similar sections measured by earlier workers. Deltas formed where tributary streams entered the lake and where streams draining the ice sheet entered the lake. The distribution of deltas, abandoned channels, and stream terraces all suggest that many of the valleys occupied by lakes were largely filled with sediments during the lifetime of these lakes.

In post-glacial times debris flows were deposited within stream valleys and alluvial fans where the gradient of streams flowing off the steep mountainsides abruptly changed where they encountered valley bottoms. Many of the alluvial fans mapped in the area are quite large. Streams flowing across the area have eroded both till and bedrock from the high mountain slopes throughout the Holocene. They have also very effectively eroded large channels through the sediments that accumulated in the many glacial lakes.

Well data was utilized to contour the overburden thickness. Similar to most valleys in Vermont, thick sections of surficial materials accumulated in the valleys in both glacial and glaciolacustrine environments whereas the high and steep mountain slopes are overlain by a discontinuous cover of till. That said, relatively few areas are overlain by surficial materials that exceed 100 ft.

The water table across the map largely mimics the ground surface topography. The Green Mountains form a major N-S surface and groundwater divide in these two quadrangles. Large-scale surface and groundwater flow east of the mountains is east towards the Mad River. Surface and groundwater flow west of the mountains enters one of several tributary streams that eventually discharge directly into Lake Champlain or into the Winooski River which itself enters Lake Champlain.

Well yields vary widely across the quadrangle, but the vast majority of drilled wells provide yields adequate for homes and businesses. These yields, particularly in the till-covered uplands, indicate that groundwater recharge through the till is sufficient to replenish the bedrock aquifers. Coarse grained surficial materials in many of the valleys constitute both good areas for groundwater recharge and good surficial aquifers, both unconfined and confined.

Introduction

This report summarizes the results of mapping the surficial geology of the Lincoln and Mount Ellen 7.5-minute Quadrangle in north-central Vermont during the 2021 field season (Fig. 1). A companion report details the surficial geology of the Brookfield Quadrangle that was also mapped during the same 2021 field season (Fig. 1; Wright, 2022a). A principal objective of this work was to contribute to the effort to complete modern, detailed mapping of the entire Montpelier 1-degree sheet outlined in Figure 1.

Two detailed surficial geologic maps accompany this report (Plate 1; Wright, 2022b; Wright, 2022c). These maps and four geologic cross-sections present the bulk of the findings from this study. Additional maps completed for this project (1) show broad patterns of groundwater flow via contours of the water table and inferred flow lines (Plate 2), (2) contour the thickness of surficial materials (Plate 3), (3) show the variation in well yields from private water wells (Plate 4), and infer the relative infiltration potential of the different mapped surficial materials (Plate 5).

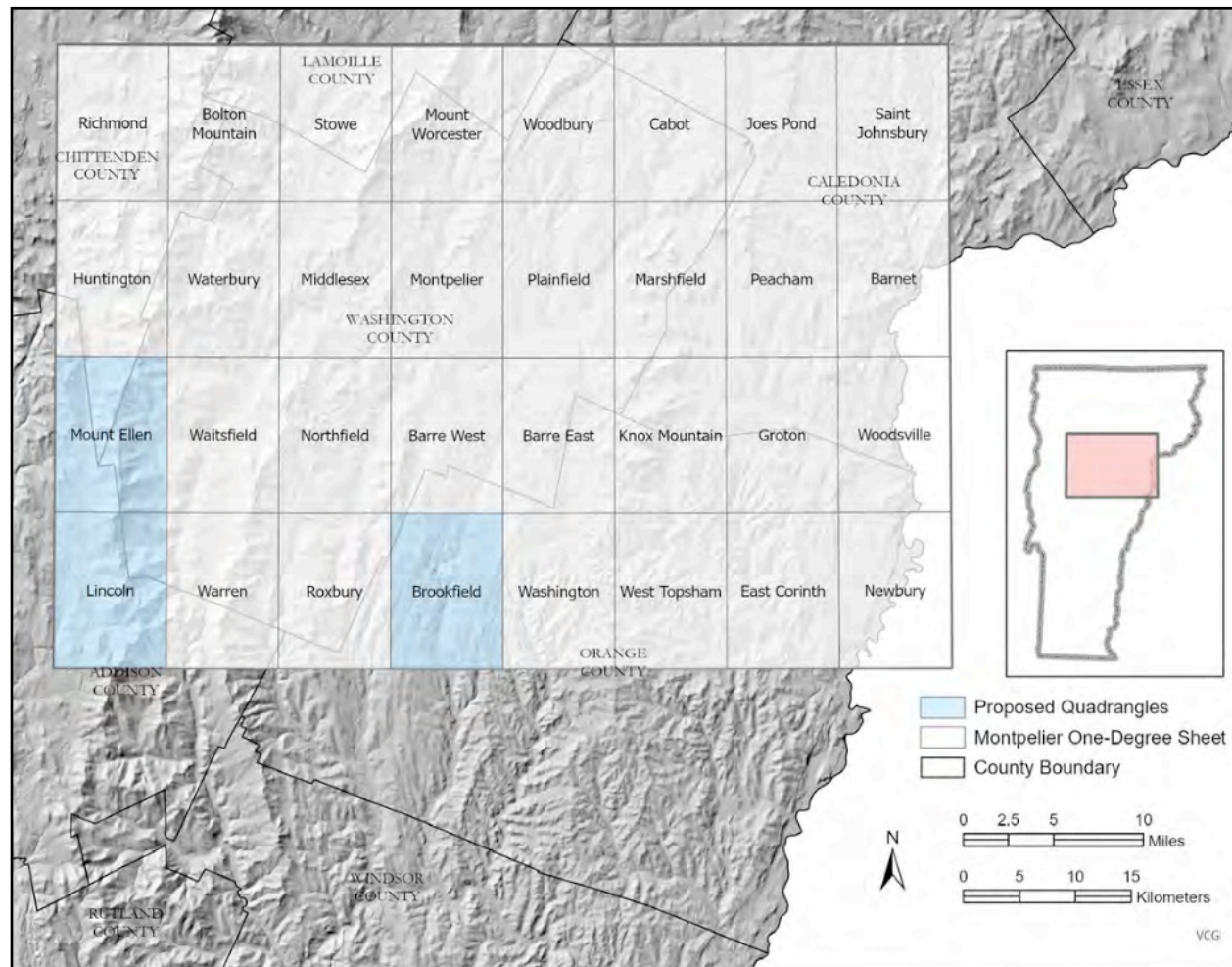


Figure 1: Shaded relief map of north-central Vermont showing the locations of the Brookfield, Lincoln, and Mount Ellen Quadrangles. Map sourced from the RFP for this project prepared by the Vermont Geologic Survey.

Location and Geologic Setting

The Lincoln and Mount Ellen Quadrangles straddle the Green Mountains in north-central Vermont (Figs. 1, 2). Consequently, this is an area of high-relief. Most peaks along the crest of the mountains exceed 1,000 m (Mt Ellen is the highest at 1,245 m, 4,083 ft). The landscape is rugged and largely forested, although limited areas of open farmland occur in an adjacent to the valleys, particularly west of the mountains. Two major downhill ski areas, Mad River Glen and Sugarbush, have been developed on the eastern slopes. Most streams draining the eastern slopes are tributaries of the north-flowing Mad River which eventually flows into the Winooski River and Lake Champlain (Fig. 2). All streams flowing down the western side of the mountains also flow into Lake Champlain and eventually enter the Atlantic via the Gulf of St. Lawrence (Fig. 2). The very southeastern corner of the Lincoln Quadrangle hosts streams that are tributaries to the White River which flows SE and eventually drains into Long Island Sound (Fig. 2).

The bedrock geology of the area is summarized on the Vermont Bedrock Geologic Map (Fig. 2; Ratcliffe et al., 2011). Rocks underlying this area largely consist of metasedimentary rocks (schist and phyllite) that were originally deposited as sediments in the Iapetus Ocean along the margin of Laurentia from late Precambrian through early/middle Ordovician time. Locally igneous rocks intruded these sediments or erupted across the ocean floor. These rocks were subsequently deformed and metamorphosed during the Taconic Orogeny and

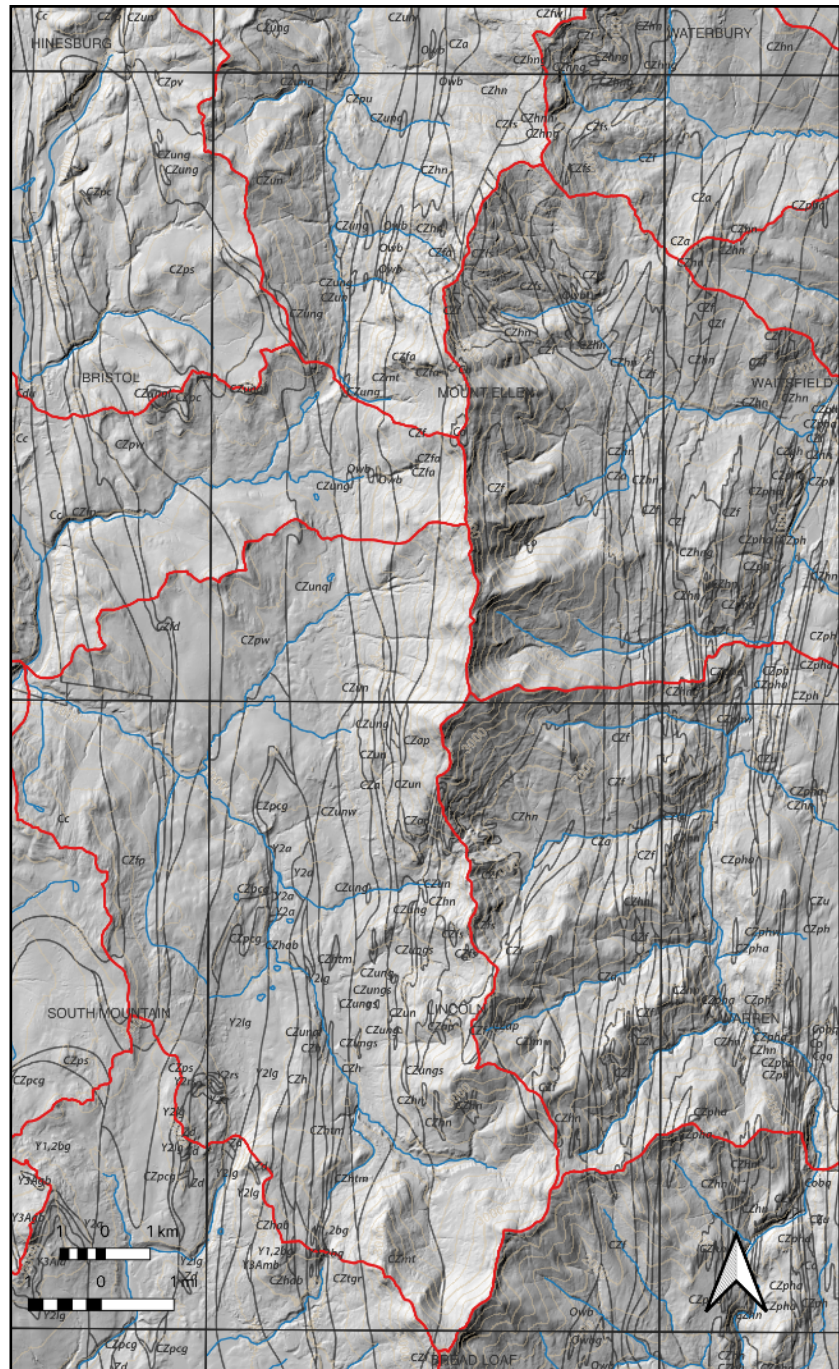


Figure 2: Shaded-relief physiographic map shows the outline of the Lincoln and Mount Ellen Quadrangles straddling the Green Mountains (see Fig. 1 for location). Geologic contacts (black lines) outline a variety of late Proterozoic, Cambrian, and Ordovician meta-sedimentary and meta-igneous rocks (dominantly schists) that underlie this part of the Green Mountains (Ratcliffe et al., 2011). Geologic contacts, major structures (faults), and foliations largely strike N-S. See Vermont State Geologic Map for explanation of unit acronyms (Ratcliffe et al., 2011). Red lines demarcate drainage basins. While the crest of the mountains define a major N-S drainage divide, all surface water, except that in the SE corner, eventually drains into Lake Champlain.

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 (Fig. 2). Additionally, the northernmost occurrence of Grenville age Precambrian rocks in the Green Mountains occurs in the southern portion of the Lincoln Quadrangle (Ratcliffe et al., 2011).

Prior Work

The Lincoln and Mount Ellen 7.5-minute quadrangles make up the western half of the Lincoln 15-minute quadrangle which was mapped in reconnaissance fashion by Calkin and MacClintock (1965). This map used the 1:62,500-scale topographic map as a base map and this open-file map was incorporated into the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970). Subsequent to the publication of this map, more detailed mapping coupled with a better understanding of glacial processes led to an updated interpretation of glacial processes occurring during ice retreat across northern Vermont (Larsen, 1972a, 1987b).

Areas within the Lincoln and Mount Ellen quadrangle that are part of the Mad River watershed (east of the Green Mountains) were mapped by Dunn and others (2007a). This mapping was undertaken using modern methods, but LiDAR coverage was not available for this area when this work was done. West of the Green Mountains, two senior theses by University of Vermont students presented detailed observations of landforms and well-exposed sections within the region's valleys to interpret the sequential history of glacial lakes that flooded these valleys (Bryan, 1995; Heiser, 1990). More recently, the Huntington Quadrangle, immediately north of the Mount Ellen Quadrangle (Fig. 1) was recently mapped by Springston (2019).

Methods

Traditional field techniques and digital mapping were employed to generate a surficial geologic map of the area. Specifically, over 2,500 separate field observations and locations of different surficial materials, landforms, bedrock outcrops, glacial striations, kettles, landslides, and other geologic phenomena pertinent to this study were recorded using the Fulcrum App, a mobile mapping application. A stand-alone GPS unit allowed most field observations to be located with an accuracy of 3–5 m. Field mapping utilized LiDAR hillshade imagery with 4 m contours as a base map supplemented by traditional topographic maps and satellite imagery. The locations and observations gathered in the field were imported into GIS software (QGIS) and utilized to draw geologic contacts between different surficial mapping units. Mapping units are consistent with those used on recently completed surficial geology maps within the Montpelier 1-degree sheet (e.g. Springston, 2019; Wright, 2020; Fig. 1) and conform to the unified set of mapping units developed by the Vermont Geological Survey.

No additional field work was conducted on the east flank of the Green Mountains originally mapped by Dunn and others (2007a). However, geologic units and contacts were substantially revised utilizing the LiDAR hillshade imagery and detailed topography gleaned from the LiDAR derived digital elevation models (DEM's).

Four geologic cross-sections were constructed, two each in the Lincoln and Mount Ellen Quadrangles (Plate 1). Surface observations were augmented by private water well logs to interpret the subsurface surficial geology in these areas. These water well logs were also used to contour the thickness of surficial materials (Plate 3) and the reported yields were used to generate a map showing the distribution of wells with different yields across the two quadrangles (Plate 4).

Seven UVM undergraduate students assisted with the field mapping effort during the last week of June, 2021 as part of their Advanced Field Geology or Independent Geological Research class. The author gratefully acknowledges the work of Evan Choquette, Jason Drebber, Caitlin Farkas, Remy Farrell, Cate Hogan, Ryan Mister, and Will Vanderlan and their help mapping the uppermost Huntington River valley in the northwestern part of the Mount Ellen Quadrangle.

Surficial Geologic Maps: Lincoln and Mount Ellen Quadrangles

The surficial geologic maps that accompanies this report shows the aerial distribution of different types of surficial materials, landforms constructed of these materials, glacial striations, large erratics, landslides, and other geological phenomena. During the spring of 2018 the Vermont Geological Survey developed a uniform set of mapping units (Springston et al., 2018) which are utilized on the Lincoln and Mount Ellen Surficial Geologic Maps. 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 non-planar 2-D surfaces that extend out-of-sight below Earth's surface and their extension above Earth's surface has eroded away. 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 their placement.

Stratigraphic Framework/Surficial Geologic Mapping Units

The different surficial materials and landforms mapped within the quadrangle are described below, in stratigraphic order, from oldest to youngest. These materials and landforms fall into three groups: (1) Glacial Deposits are the



Figure 4: Near-vertical, stream-eroded, unweathered, dense, grey glacial till exposed where Conway Road crosses a tributary of Lewis Creek along the western border of the Mount Ellen Quadrangle. Both angular and sub-rounded rocks of various sizes are embedded in a finer matrix. A weak, sub-horizontal fabric is visible in the till that results from an alignment of "flat" minerals in response to the weight of the overlying ice sheet. Length of auger = 1.2 m, 4 ft.

surficial materials that were initially deposited by or immediately adjacent to the Laurentide ice sheet as it flowed across and then gradually thinned and retreated across the area. (2) Lacustrine Deposits were deposited in ice-dammed glacial lakes that occupied the valleys during ice sheet retreat. (3) A third group of surficial materials largely consists of older glacial or lacustrine surficial materials that have been eroded and redeposited by processes occurring during the Holocene, the time span extending from ice sheet retreat to the present.

Bedrock Outcrops/Glacial Striations



Figure 3: Stream-eroded outcrop of the Underhill Formation (schist) in the Huntington River channel near its headwaters. View looks south. Vermont Route 17 parallels this reach of the river and lies ~100 m to the west.

While surficial materials and landforms are the focus of this project, bedrock outcrops were also mapped when they were encountered during field traverses (Fig. 3). Outcrops are abundant where glacial till and other surficial materials are thin. Additionally, most outcrops occurring along town roads and state highways were also mapped. No attempt was made to map all outcrops, especially in the upland areas where outcrops are numerous and closely spaced.

Relatively few glacially striated outcrops were encountered during field work in the quadrangles. However, earlier field work by Wright (2015) and Ackerly and Larsen (1987) recorded abundant striations along the Long Trail and the high-elevation portions of access trails to the Long Trail. These striations are included on the geologic maps (Plate 1).

Glacial Deposits

Glacial Till (Pt)

Glacial till directly overlies the bedrock in most areas. Within the quadrangle, till is the ubiquitous surficial material on the ground surface in areas above the valley bottoms. The freshest exposures are produced by stream erosion and also appear in landslides where the till is medium to dark gray and very dense (Fig. 4). 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. In most areas the materials occurring in till consist of materials eroded, deformed, and deposited beneath the ice sheet. Frost heaving, plant roots, and animal borrows have loosened the till near the surface. Large glacially-transported boulders, some of which are far-traveled erratics, are common and were mapped where encountered. The thickness of till in the upland areas of the quadrangle varies considerably. In most areas, the till cover is thin (less than 2 to 3 meters) and abundant outcrops are present. However, in limited areas the till is sufficiently thick to completely bury the underlying bedrock.

Ice-Contact (Glaciofluvial) Deposits: Eskers (Pie), Kames (Pik), Deltas (Pid), Undifferentiated Deposits (Pi)

Meltwater streams flowing beneath or along the margins of the thinning and retreating ice sheet deposited sand and gravel both under the ice sheet as eskers (Pie, Fig. 5) and along the margins of the ice sheet in landforms mapped as kames (Pik). The streams depositing both eskers and kames sometimes also deposit ice-contact deltas (Pid) where they flow into lakes dammed by the receding ice sheet. Other areas underlain by sand and gravel but not forming distinctive landforms were mapped as undifferentiated ice-contact deposits (Pi). These deposits may be the eroded remnants of eskers, kames, or deltas or may be irregular accumulations of sand and gravel deposited in subaqueous fans close to the margin of the ice sheet.

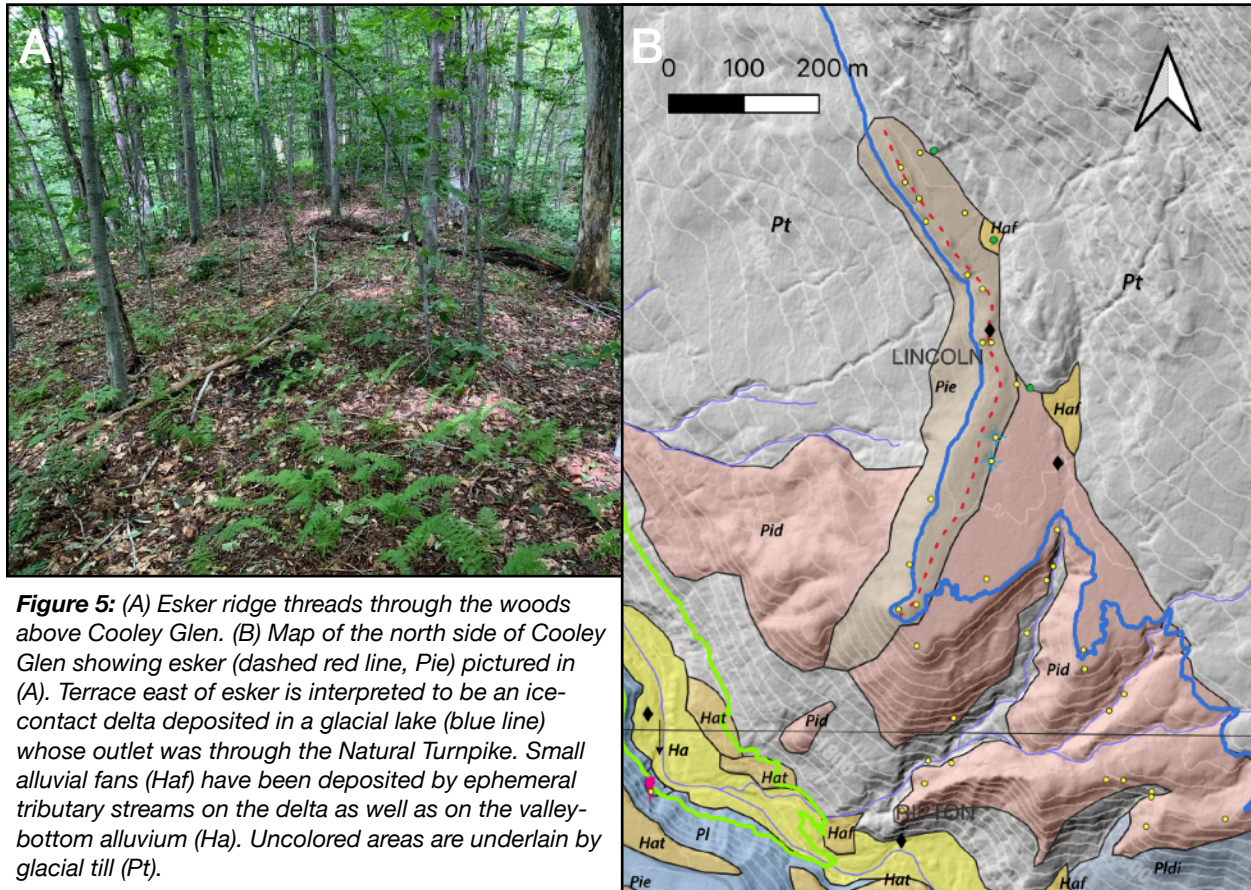


Figure 5: (A) Esker ridge threads through the woods above Cooley Glen. (B) Map of the north side of Cooley Glen showing esker (dashed red line, Pie) pictured in (A). Terrace east of esker is interpreted to be an ice-contact delta deposited in a glacial lake (blue line) whose outlet was through the Natural Turnpike. Small alluvial fans (Haf) have been deposited by ephemeral tributary streams on the delta as well as on the valley-bottom alluvium (Ha). Uncolored areas are underlain by glacial till (Pt).

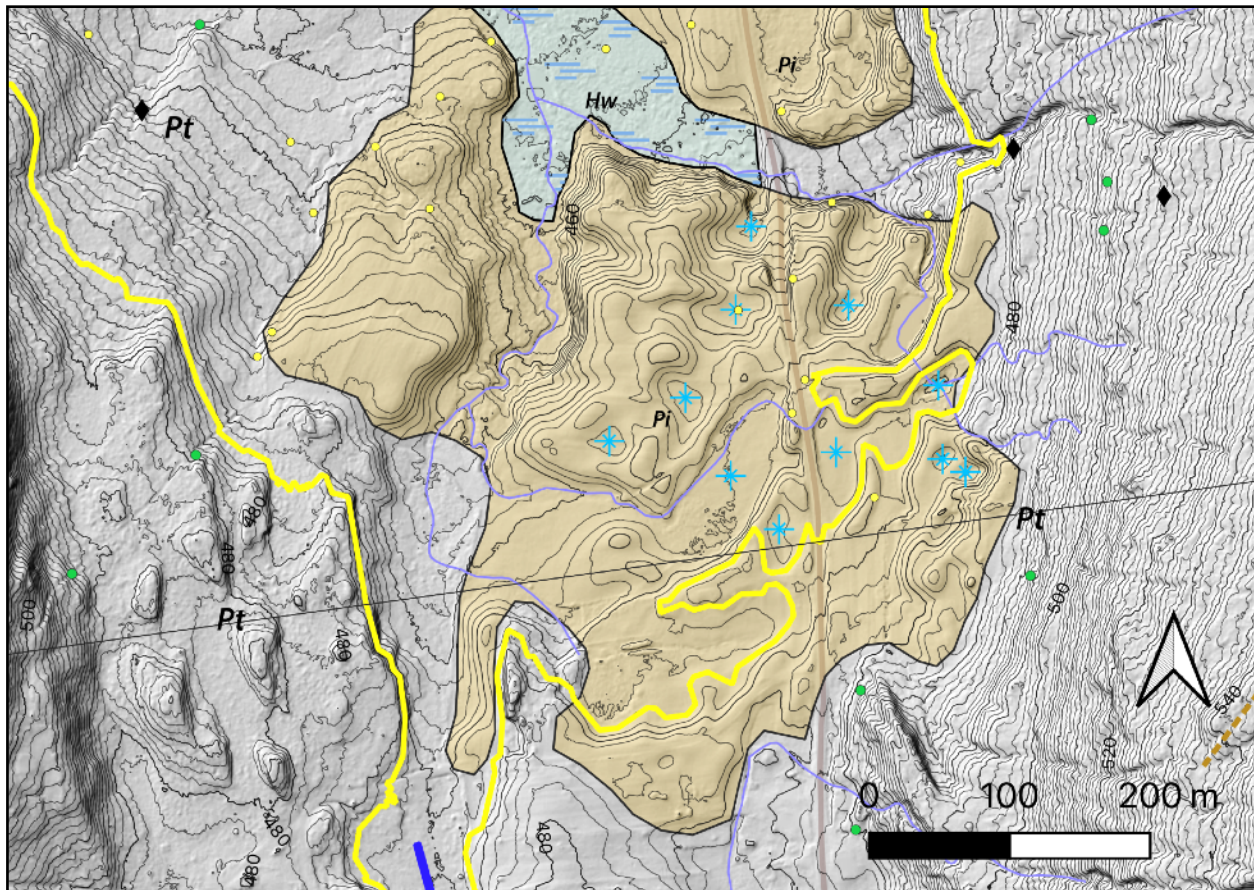


Figure 6: Extensive area of kettles (depressions with inward aqua-colored arrows) occurring in ice-contact sand and gravel (Pi) south of Jerusalem. This area lies at a drainage divide between tributaries to Baldwin Creek (flowing north) and Beaver Meadow Brook (flowing south) where the ice sheet thinned sufficiently during its northward retreat across the divide to become incapable of flow. Large blocks of “dead” brittle ice broke away from the rest of the ice sheet, became partially or fully covered with sand and gravel and later melted to form the closed depressions. The drainage divide immediately south of the map was an outlet to a glacial lake the shoreline of which is shown with the yellow line. Uncolored areas of the map are underlain by till (Pt). Diamonds

In areas where the ice sheet has thinned so much that it can no longer flow, blocks of “dead,” non-flowing ice frequently break off from the ice sheet and can later become partially or wholly buried by sand and gravel deposited by streams flowing adjacent to the ice sheet. This is a particularly common occurrence where the ice sheet retreats across a drainage divide. When these blocks of buried ice eventually melt they leave distinctive depressions referred to as ‘kettles,’ a landform distinctive of ice contact terrains (Fig. 6).

Lacustrine Deposits

Lacustrine deposits are those that accumulated in



Figure 8: Lenses of coarse gravel occurring within fine/very fine sand indicate highly variable energy levels indicative of deposition in an ice proximal lacustrine environment. Small pit near intersection of Stave Brook and the Huntington River.

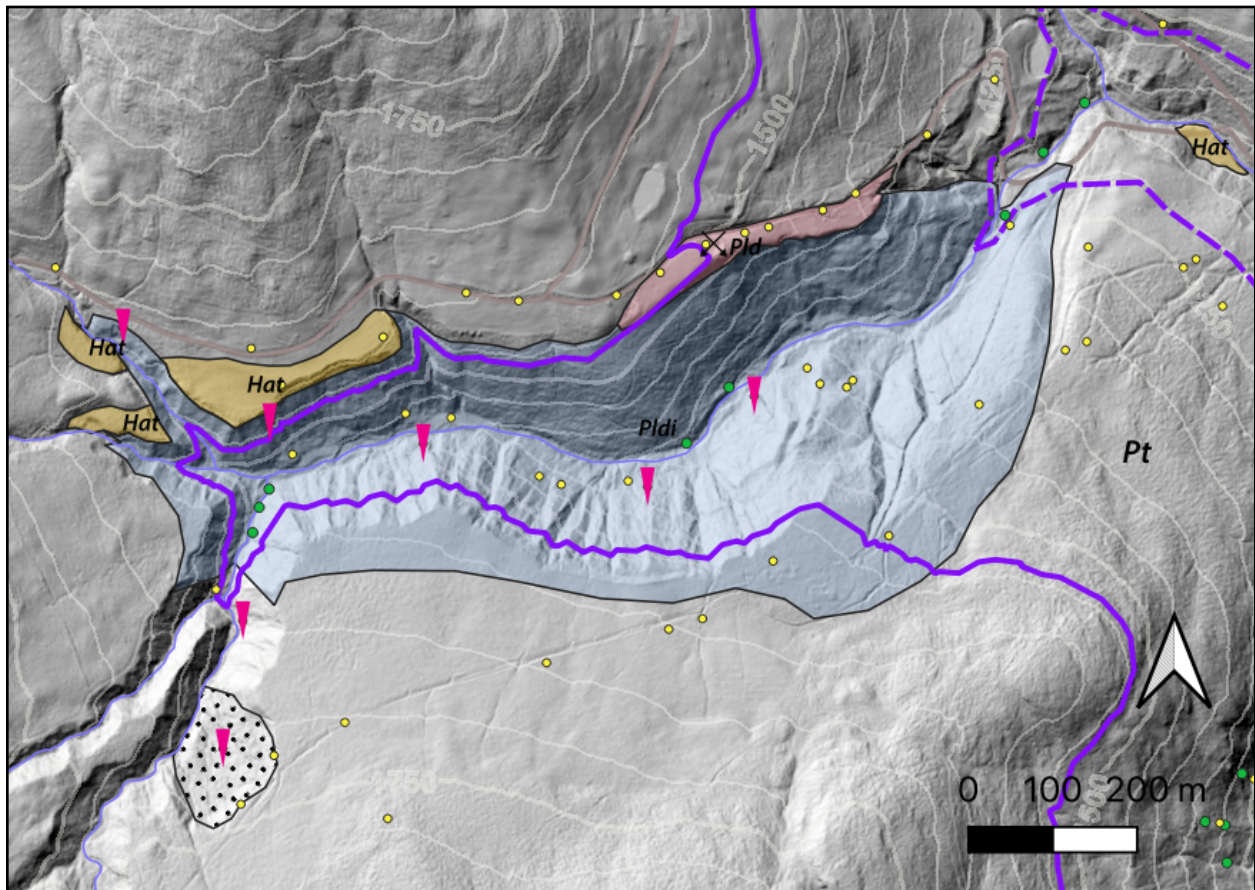


Figure 7: Unnamed tributary joins the Huntington River at Hanksville. Remnants of a delta (Pld) occur along the north side of the valley which coincides with the projected shoreline of the high-stand of Glacial Lake Huntington (blue line) whose outlet was at the drainage divide occurring in the valley parallel to Route 17 ~6 km south of Hanksville. Deep incision by the stream, landslides (inverted red arrows and dot pattern), and abandoned fluvial terraces (Hat) indicate that this valley was largely filled with stratified diamict, till mobilized as debris flows from the surrounding hillsides (Pt), during the short history of the lake.

one of several different glacial lakes that formed along the margin of the ice sheet. Generally, these lakes formed when the ice sheet retreated north of different drainage divides damming water between the glacier and the drainage divide. The projected shorelines of these lakes on both sides of the mountains are shown on the geologic maps (Plates 1).

The valleys that hosted these lakes contain a variety of sediments uniquely deposited in lakes. Stratified diamict (Pldi) consists of interlayered diamict (remobilized till that entered the lake as debris flows—mud slides—from the steep surrounding hillsides) and layers of sand/silt/clay. In most areas this material looks like till, but good exposures (landslides) reveal the layering. In areas lacking good exposures, it's likely that this material underlies many areas mapped as "till." Thick sections of this stratified diamict were deposited in many of the lakes occupying the steep-sided valleys common in the mountains (Fig. 7).

Sand/gravel deposits occurring at the mouths of tributary streams with terrace surfaces at or near the projected elevations of these lakes are mapped as deltas (Pld, Figs. 7, 9). In limited areas fine-grained lacustrine sediments (very fine sand/silt/clay, Plf) were observed. However, most areas of lacustrine sediments mapped in the quadrangle

vary greatly in grain size over short distances laterally and vertically and are mapped as PI—Lacustrine Deposits, Undifferentiated (Fig. 8). The variable grain size of these sediments results from (1) being deposited near the ice margin where the energy of water currents varies widely, (2) the proximity of most parts of these lakes to shore meaning that throughout their history most parts of the lake bottom could receive sediment from tributary streams. In general areas mapped as undifferentiated lacustrine sediment (PI) have a finer grain size than sediments mapped as undifferentiated ice-contact sediments (Pi), but the depositional environment envisaged for both overlaps in time and space and there is often little distinction between these mapping units.

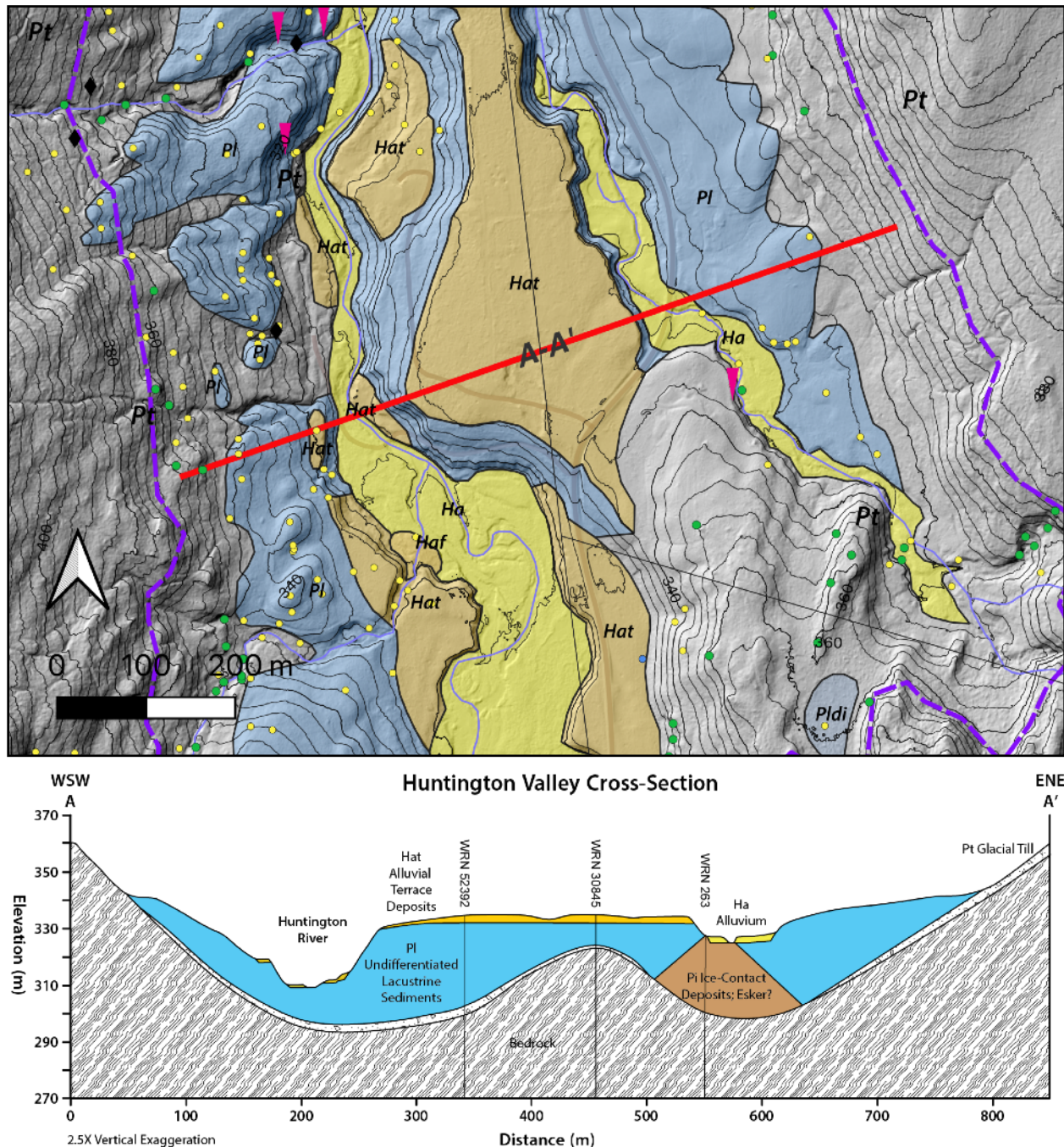


Figure 10: Geologic map and cross-section of part of the upper Huntington River valley (Mount Ellen Quadrangle) showing the distribution of modern alluvium (Ha) and abandoned alluvial terraces (Hat) to the underlying ice contact (esker?) and lacustrine sediments (PI) within the valley. Depth to bedrock controlled by private wells and bedrock exposures (green dots). Contours in meters. Town boundaries separate Starksboro (west), Huntington (northeast), and Buels Gore (southeast).

Holocene Deposits

Alluvial Fan (Haf) and Debris Flow Fan (Hdf) Deposits

Alluvial fans on a wide-range of scales are very abundant in both quadrangles. These form where sediments eroded from the valley sides, generally glacial till, have been carried downhill by tributary streams and deposited where the stream gradient abruptly lessens where it flows out of the mountains forming fan-shaped landforms (Fig. 9A). The apex of these fans frequently consists of coarse, unsorted debris flow deposits. Several large debris flow deposits largely filling tributary valleys have been distinguished from alluvial fans and given their own map symbol (Fig. 9B, Plate 1). Farther down the fan slope fan sediments consist of lenses of sand/gravel that may fine to silt at the far



Figure 11: Wetland immediately north of the Natural Turnpike (top photo, Lincoln Quadrangle) is typical of low-gradient streams dammed by beaver. Broad wetland with bordering tamarack in Jersalem (bottom photo) has formed on top of lake-bottom sediments. Beaver dams near the wetlands' outlet have greatly expanded the flooded area.

edge of the fan. In most areas these fans have been deposited on older surficial deposits, frequently delta or alluvial terraces. Work on alluvial fans in northern Vermont suggests that fans have been episodically active throughout the Holocene and many 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 et al. (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 future climate shifts produce a greater frequency of high-intensity storms, further sedimentation on the area's alluvial fans seems likely.

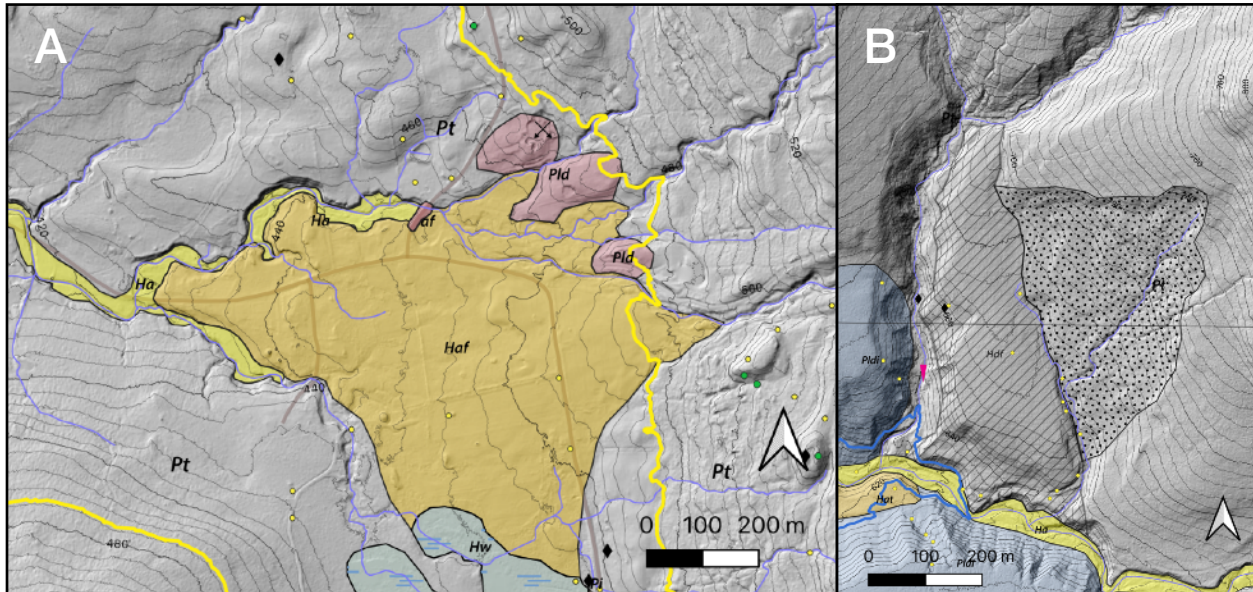


Figure 9: (A) Large alluvial fan (Haf) underlying Jerusalem, Vermont has formed where Baldwin Creek flows out of the mountains. Several smaller streams have also deposited fans that merge with the larger fan. These same small streams deposited deltas (Pld) in a glacial lake that once occupied the valley (shoreline marked by yellow line). Baldwin Creek likely also fed a delta, but the creek eroded that delta once the lake drained from the valley and redeposited its sediment in the fan. (B) Debris flow (Hdf) was deposited along and is currently incised by a tributary stream to the upper New Haven River in Cooley Glen. Large landslide in till (Pt) borders the debris flow.

Alluvium (Ha) and Alluvial Terrace (Hat) Deposits

Alluvium (Ha) refers to sediments deposited by modern rivers and streams. These sediments include sand and gravel deposited in river channels and point bars as well as sand and silt deposited on floodplains. Organic materials are a frequent component of modern alluvium. These sediments were first deposited when streams began flowing across recently deglaciated valley sides and later when valleys occupied by glacial lakes drained. The thickness of alluvium corresponds to the depth of the modern stream channel. Most streams flowing away from the mountains are relatively small with low discharges. Consequently, the extent and thickness of alluvium mapped in the quadrangle is correspondingly small (Fig. 10).

Alluvial terrace deposits (Hat) are stream sediments (alluvium) occurring on terraces above modern streams (Fig. 10). As streams eroded channels more and more deeply through earlier-deposited sediments, older channels and adjacent flood plains were abandoned. Alluvial terraces are underlain by a veneer of sand and gravel corresponding in thickness to the depth of the stream channel that deposited the sediment.

Hw Wetlands Deposits

Wetlands are common in closed basins, low-gradient streams, and areas dammed by beaver (Fig. 11). They display varying amounts of open water depending on the season and the water table elevation. The dominant surficial material in wetland areas consists of both living and partially decayed organic materials but also includes inorganic

fine-grained clastic sediment, “mud,” washed into these areas by streams and overland flow (Fig. 11). Most wetland areas in the uplands are underlain by till.

af Artificial Fill

Artificial fill was mapped where significant volumes of material were utilized for the construction of state highways e.g. VT Route 17 and town roads) as well as dams. In most cases fill consists of sand and gravel (Fig 9).

Interpretation of the Glacial and Post-Glacial history of the Lincoln and Mount Ellen Quadrangles

The surficial geologic materials and landforms mapped in the Lincoln and Mount Ellen Quadrangles provide the basis for the following interpretation of the glacial and post-glacial history of this area. This local history is fit within our broader understanding of northern Vermont’s glacial history based on earlier work.

Ice Flow History

The surficial geologic materials occurring in the region were predominantly deposited during the most recent (Wisconsinan) glaciation in glacial or periglacial environments existing during or shortly after the Laurentide ice sheet retreated across north-central Vermont ~14,200–13,800 years ago (Corbett et al., 2019; Ridge et al., 2012). Glacial till, erratics, and striations on the summits of the region’s highest mountains indicate that the ice sheet in northern New England was sufficiently thick to completely cover the mountains. Figure 12 models the ice sheet profile across New England at a time when the ice sheet was at or near its farthest extent. The ice sheet profile is computed using the ground surface topography and a spreadsheet algorithm developed by Benn and Hulton (2010) that maintains a constant basal shear stress of 100 kPa, a good general value for flowing across mountains. The ice sheet surface was well over 2 km above the Green Mountain ridgeline and almost 3 km above the ground surface in the Champlain valley (right side of Fig. 12).

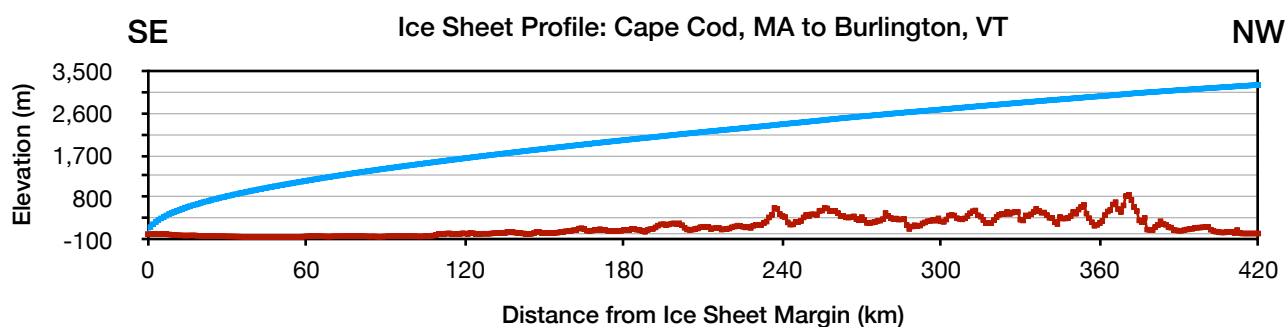


Figure 12: Profile of modeled ice sheet surface and New England topography between Cape Cod, Massachusetts and Burlington, Vermont. Ice sheet model maintains a constant basal shear stress of 100 kPa. Between 2 and 3 km of deforming glacial ice lay above the Green Mountains and adjacent valleys. Vertical Exaggeration = 18X.

Striations on both the high-standing peaks and ridgeline of the Green Mountain indicate that regional ice flow was from northwest to southeast across northern Vermont (Plate 1; Wright, 2015), the orientation of the Figure 12 profile. From Appalachian Gap (northern Mount Ellen Quadrangle) south to Killington, a younger set of striations is oriented from northeast to southwest indicating a shift in ice flow across the mountains into the Champlain valley (Ackerly and Larsen, 1987; Wright, 2015; Plate 1). Wright (2015, 2017) attributed this change in ice flow to the initiation of an ice stream in the southern Champlain and northern Hudson River valleys. Abundant north-south striations, crag and tail structures, and drumlins within the Champlain valley all indicate that once the ice sheet thinned sufficiently, its flow direction, from north to south, was dictated by the orientation of this large-scale topographic trough (Wright, 2015).

Moraines

Till ridges, approximately parallel to topographic contours, occur on both sides of the Green Mountains (Plate 1, Fig. 13). These ridges generally do not have positive relief, but instead form asymmetric “steps” where the slope sequentially steepens and flattens (Fig. 13). Similar landforms are well developed elsewhere in the northern Green Mountains and have been interpreted as recessional moraines (Wright, 2019). The process envisaged to form these landforms is one where till, recently exposed as the ice sheet thins during the summer months, (1) flows down-slope and accumulates at the ice sheet margin and/or (2) is pushed into a ridge as the ice sheet expands upslope during the winter months. Where well preserved, flights of these ridges (moraines) may record yearly thinning of the ice sheet. Farther north in the Green Mountains Wright (2019) has calculated ice sheet thinning rates along the flanks of Mount Mansfield and Belvidere Mountain of between 9 and 13 m/year. This rate is entirely consistent with the rapid ice sheet thinning indicated by exposure age dates on Mount Mansfield (Corbett et al., 2019) and is also a common elevation difference between adjacent ridges mapped in the Lincoln and Mount Ellen Quadrangles (Plate 1, Fig. 13).

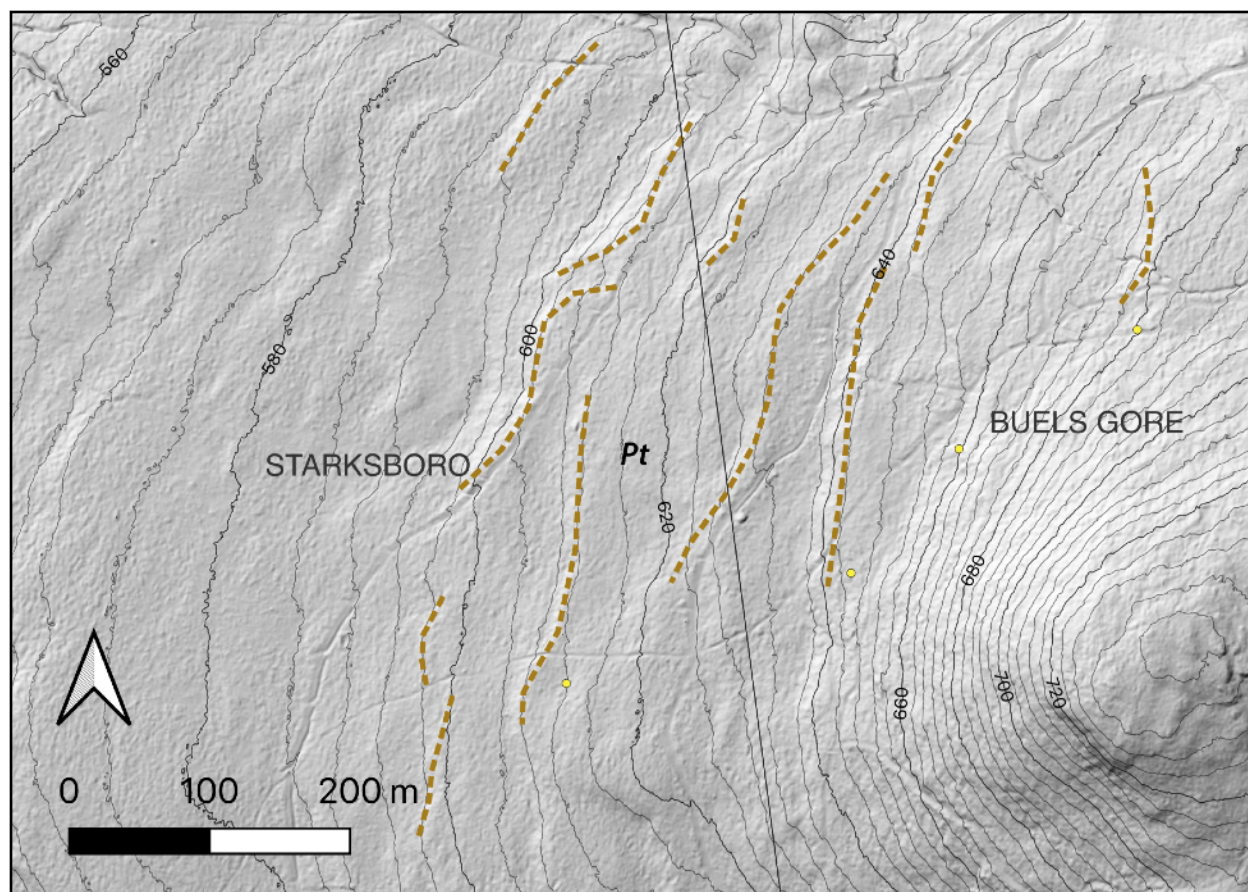


Figure 13: Asymmetric ridges occurring in till (Pt) are highlighted with brown dotted lines along the western flank of the Green Mountains, northeast of Jerusalem, (Mount Ellen Quadrangle, Plate 1). Ridges are interpreted as moraines that formed along the ice sheet margin. Flights of subparallel moraines may record yearly positions of the ice sheet as it rapidly thinned. Lower reach of the Jerusalem Trail crosses map. Contours are in meters.

Ice Sheet Hydrology

The ice sheet was at its maximum extent, the Last Glacial Maximum (LGM) ~25,000 years ago when it built terminal moraines southeast of New England marked by Block Island, Martha's Vineyard, and Nantucket (Ridge, 2016). From this terminal moraine, the ice margin retreated to southeastern Vermont (the junction of Vermont, New Hampshire, and Massachusetts) by ~15,600 years ago and was at the Québec border by ~13,300 years ago (Ridge, 2016), a span of a little over 2,000 years. Rapid thinning and retreat of the ice sheet across northern New England occurred

because the ice sheet was melting (losing mass) much more rapidly during the summer months than it was gaining mass by snowfall during the winter months. A consequence of this was that tremendous volumes of meltwater (melted snow and ice) were routed beneath and along the margins of the ice sheet during those summer months.

Across the Lincoln and Mount Ellen Quadrangles meltwater both eroded channels and deposited sand and gravel in a variety of landforms. South-sloping channels, parallel to the inferred margin of the ice sheet, are common along the western flank of the mountains (Plate 1, Fig. 14). These channels frequently occur in sub-parallel sets and were likely sequentially eroded into recently exposed till by streams flowing parallel to the edge of the ice sheet as the ice sheet thinned from year to year (Fig. 14).

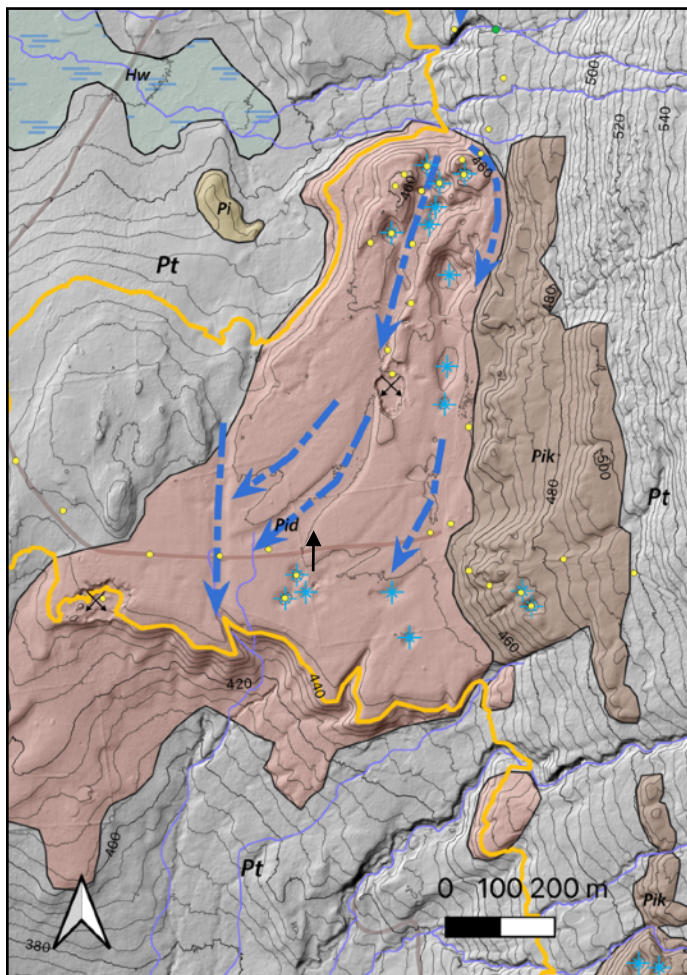


Figure 15: Numerous kettles (closed depressions with inward pointing blue arrows) and channels (dashed blue lines) occur in this ice-contact delta (Pid) deposited in a glacial lake outlined with the orange line. Delta is bordered by sand and gravel comprising a kame (Pik) deposited along the margin of the ice sheet shortly before the delta was deposited. Area lies along Elder Hill Road (Lincoln) immediately south of the channels shown in Figure 14 and includes the Batell trailhead. Black arrow shows view point of photo in Fig. 16. Contours in meters.

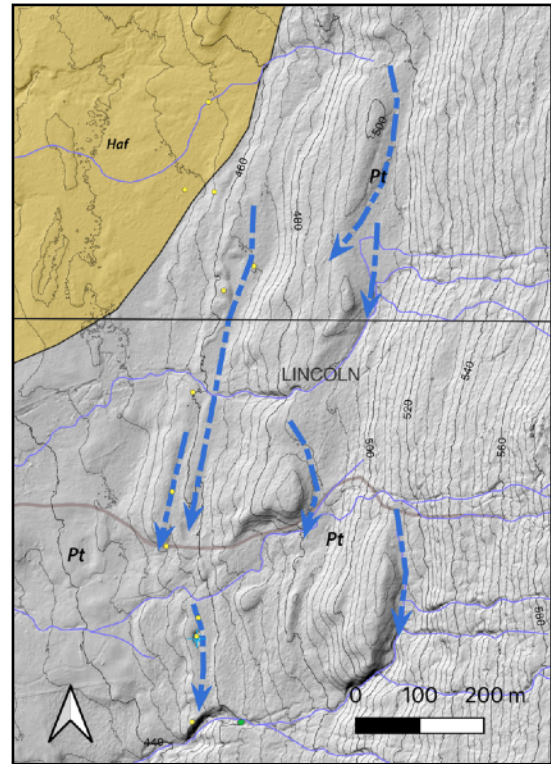


Figure 14: Elongate troughs parallel to hillside are interpreted as ice-marginal drainage channels (blue arrows) eroded into till (Pt). Depicted area lies southeast of Downingsville and north of Beaver Meadow Brook astride the boundary between the Lincoln (south) and Mount Ellen (north) Quadrangles. Haf is part of a large alluvial fan. Contours in meters.

Meltwater emanating from the rapidly thinning and retreating ice sheet transported large volumes of sediment. Most of this sediment was eroded from till beneath or along the edge of the ice sheet, but sediment eroded earlier by the ice sheet, entrained with the ice, and released as the ice melted was also transported by meltwater streams. Those streams flowing between the edge of the ice sheet and adjacent mountain slopes deposited sediment in kames (Fig. 15). Frequently, blocks of thin ice breaking off the edge of the ice sheet were buried by stream sediments and later melted to form kettles (Fig. 15).

During times when the ice sheet bordered and/or

dammed a glacial lake, sediments carried by meltwater streams formed ice-contact deltas where they entered that lake (Figs. 5B, 15). Several of these deltas were mapped along the western side of the Green Mountains. The most striking of these preserves a well-developed set of distributary channels across the top of the delta (Figs. 15, 16).



Figure 16: Portion of wide shallow distributary channel eroded in surface of ice-contact delta shown in Figure 15. View looks north obliquely across channel and towards the source of glacial meltwater depositing the delta (see arrow on map, Fig. 15).

Eskers are sinuous ridges of sand and gravel deposited by meltwater streams flowing in tunnels beneath the ice sheet. Those mapped in the Lincoln and Mount Ellen Quadrangles are generally oriented north-south (e.g. Figs 5, 17). This orientation is consistent with a southward sloping hydraulic gradient within the ice sheet, a consequence of southward ice flow once the ice sheet thinned sufficiently that it was topographically guided by the orientation of the Champlain valley. Eskers in the mapped area are frequently closely associated with areas of ice contact sediments and ice-contact deltas (Figs. 5, 17, 18). Elsewhere, eskers may be buried beneath younger lacustrine sediments (Fig. 10). Eskers are

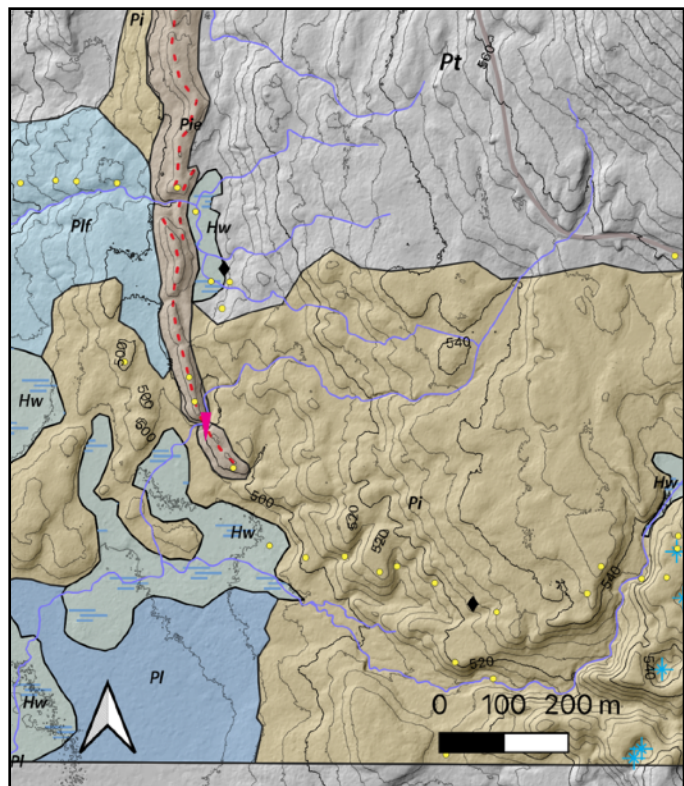


Figure 17: Esker ridge (Pie, red dashed line) merges with an extensive area of hummocky, kettled ice-contact sediments (Pi) in the southwest corner of the Lincoln Quadrangle. Younger glacial lake sediments (Pl, Plf) border this area and likely underlie wetland areas (Hw). Black diamonds mark large erratics. Contours in meters.

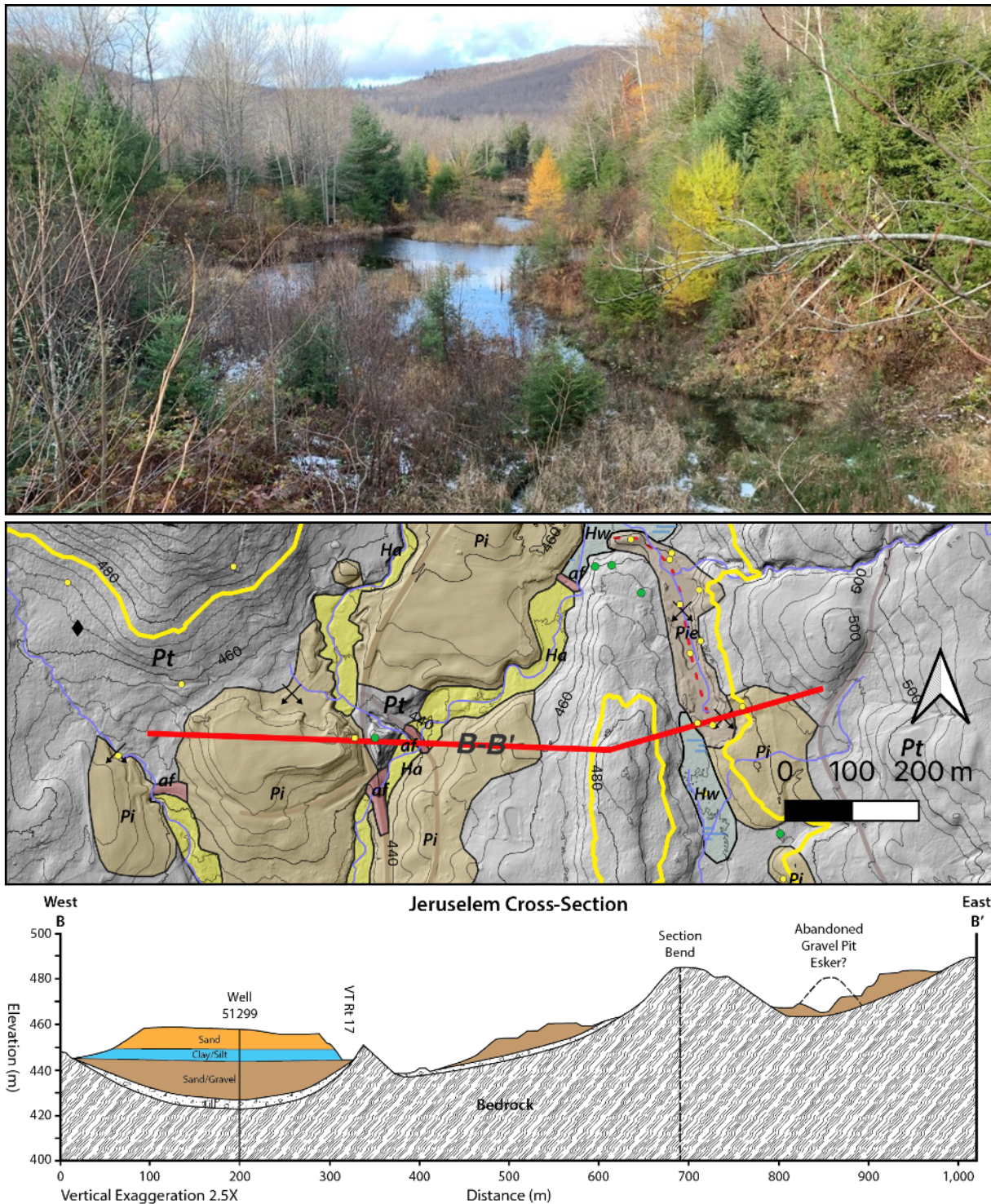


Figure 18: Photo depicts an abandoned gravel pit where an esker has been largely quarried away. View looks north. Map and cross section show the position of this esker and associated ice-contact and younger lacustrine sediments across the valley immediately north of Jerusalem. Logs from two water wells, mapped surficial materials, and bedrock outcrops help to control the vertical distribution of sediments shown in the section.

excellent sources of sand and gravel and have quarried extensively (Fig. 18). Additionally, the very porous and permeable nature of esker sediments mean that rainfall and snowmelt easily infiltrate the ground surface recharging both these surficial sediments and the underlying bedrock.

Glacial Lake History

A series of glacial lakes were impounded by the retreating ice sheet on both sides of the Green Mountains. Larsen (1972b, 1987a), expanding and clarifying earlier work by Merwin (1908), recognized that the three north-flowing tributaries to the Winooski River east of the Green Mountains were each occupied by ice-dammed lakes (Fig. 19). The Mad River valley, immediately east of the Lincoln and Mount Ellen Quadrangles, hosted Glacial Lake Granville which drained across the drainage divide at Granville Notch, the southernmost end of the Mad River valley (Fig. 19). Larsen (1972b, 1987a) also recognized that the elevation of Lake Granville dramatically fell when the ice sheet retreated north of the Winooski River valley and the smaller lakes restricted to the tributary valleys merged to form one larger lake, Glacial Lake Winooski, that drained out the lowest outlet in the basin adjacent to Williamstown Gulf (Fig. 20). Paleo-lake-level elevations, determined by the elevations of deltas in these valleys, confirm this sequence of lake formation east of the Green Mountains (Dunn et al., 2007a; Larsen, 1972b, 1987a).

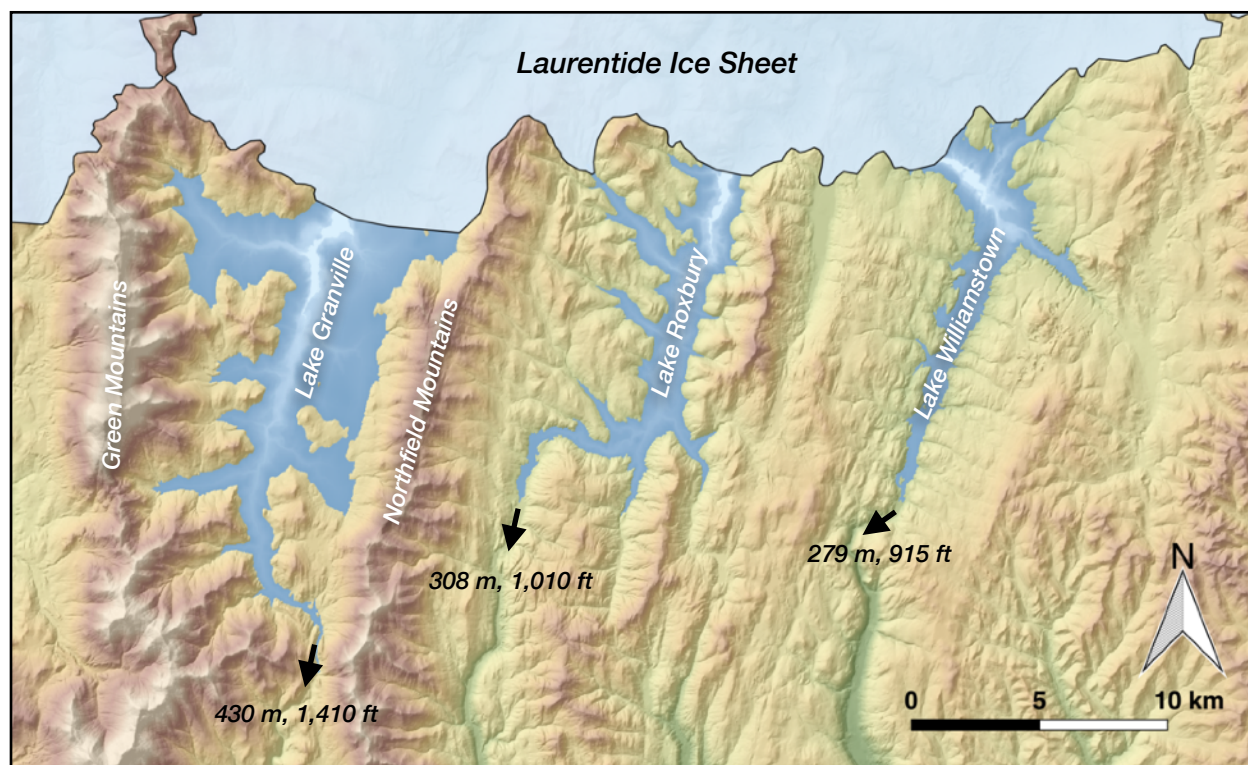


Figure 19: Configuration of glacial lakes in north-flowing tributaries to the Winooski River (Larsen, 1972, 1987; Wright, 2018). Elevations of Lake Granville in the Mad River valley, Lake Roxbury in the Dog River Valley, and Lake Williamstown in the Stevens Branch valley were dictated by the elevations of the drainage divides at the south end of these valleys.

Along the eastern edge of the Lincoln and Mount Ellen Quadrangles several of the valleys hosting tributaries to the Mad River were occupied by Glacial Lake Granville. However, only a small portion of the Mill Brook valley (Route 17) is below the elevation of Glacial Lake Winooski (Plate 1). While mapping the Mad River drainage basin, Dunn and others (2007a) recognized a short-lived high-elevation lake (Glacial Lake Clay Brook) that formed in the Clay Brook valley at the base of the Sugarbush ski resort (Plate 1).

Numerous, generally small and probably short-lived ice-dammed lakes occupied valleys along the western slopes of the Green Mountains. These lakes developed sequentially from south to north in the Alder Brook (Sparks Brook on newer maps), New Haven River, Baldwin Creek, and Huntington River valleys as the ice sheet thinned and retreated northward. None of these lakes appear on the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970) nor are they mentioned in Stewart and MacClintock's (1969) summary of Vermont's glacial history or in Wagner's

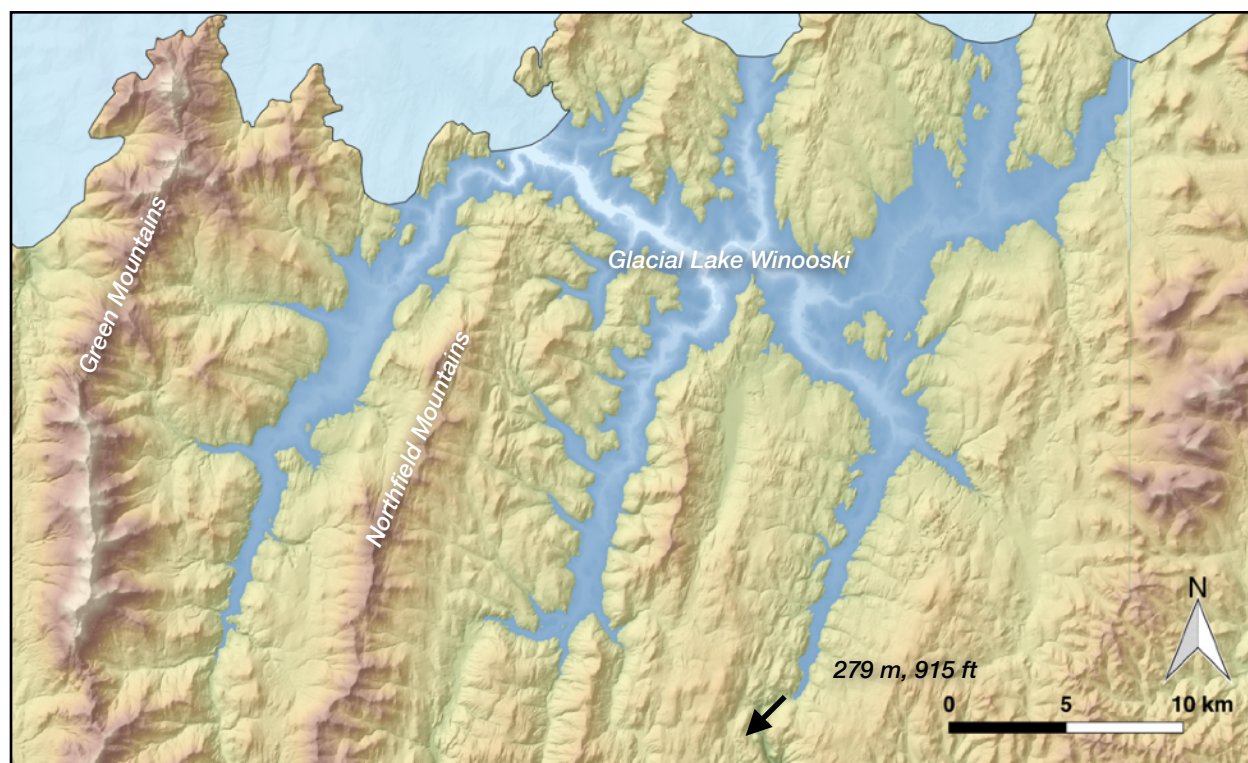


Figure 20: Ice sheet retreat north and west from its position shown in Figure 19 allowed the smaller lakes confined in tributary valleys to merge forming an early stage of Glacial Lake Winooski.

(1972) compilation of lake shoreline features in northwestern Vermont. However, several of these lakes were recognized and described in several University of Vermont theses (Bryan, 1995; Heiser, 1990; Whalen, 1998).

The oldest of these lakes occupied the Sparks Brook valley which extends north and east into the southwestern corner of the Lincoln Quadrangle (Plate 1). A terrace with numerous shallow channels surface extending along and south of the southern border of the Lincoln Quadrangle is interpreted to be an ice-contact delta built into this lake at an elevation of ~590 m (1,936 ft), (Plate 1, Fig. 21). Relatively restricted areas of lake sediments occurring in this corner of the quadrangle likely extend to the south and west, although mapping within adjacent parts of both the Alder Brook and Sparks Brook valleys by Donahue and others (2004), doesn't include lacustrine sediments. Given the limited extent of lacustrine sediments deposited in this lake within the field area, details concerning its origin are not investigated further here.

Several high-elevation lakes were impounded in the uppermost New Haven River valley during ice retreat (Plate 1, Fig. 21), a history first recognized by Heiser (1990). The oldest and highest of these was a lake that occupied both the Blue Bank Brook and New Haven River valleys once the ice sheet retreated north of the drainage divide at the Natural Turnpike (620 m, 2,035 ft, Fig. 21). This is Heiser's (1990) "Turnpike Stage" of "Glacial Lake Lincoln." An esker running the length this drainage divide and extending south along Sparks Brook indicates that subglacial drainage was also routed through this divide (Plate 1). Outflow from this lake, sourced from both the melting ice sheet and meteoric water, eroded a deep, sinuous channel through ice-contact sediments (Fig. 21). Sparks Brook, the modern stream occupying this channel, is grossly under-fit in this valley.

Northward retreat of the ice sheet uncovered two outlets at about the same elevation (542 m, 1,778 ft), allowing lake level in the valley to drop almost 80 m (Fig. 21). Heiser (1990) identified the westernmost of these outlets and referred to this lake as the "Cobb Hill Stage" of Glacial Lake Lincoln. There is little evidence of extensive water flow through these outlets which suggests that water was leaking out of the 620 m lake along the ice margin as the ice sheet retreated allowing its elevation to fall slowly instead of via a catastrophic flood.. In contrast, a well-developed abandoned channel extends from a third outlet, the northernmost, which lies at a slightly lower elevation (528 m, 1,732 ft, Fig. 21). The erosion necessary to produce this channel suggests that retreat of the ice sheet past this

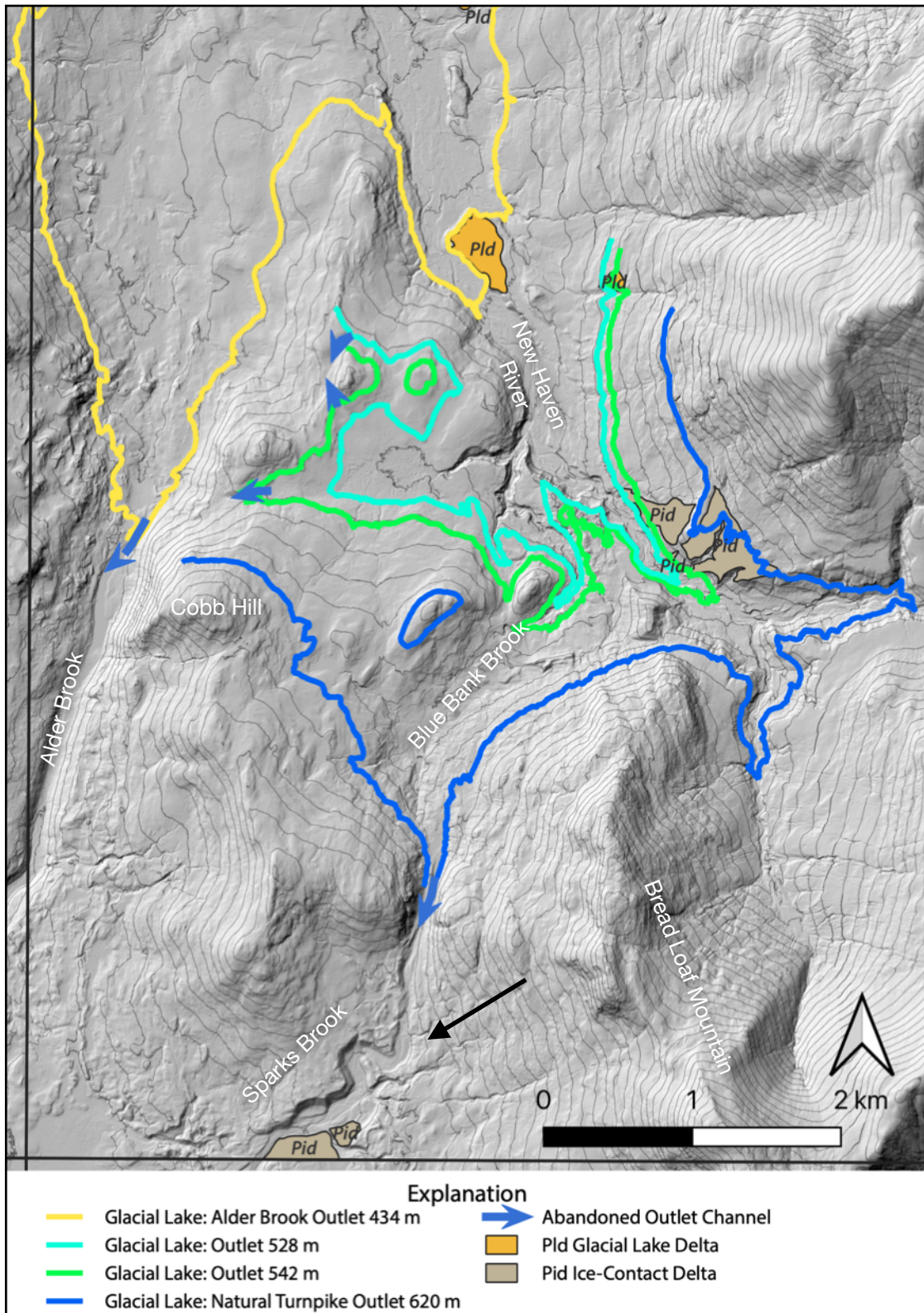


Figure 21: Southwest corner of the Lincoln Quadrangle showing the projected shorelines and outlets (blue arrows) of several glacial lakes that occupied the uppermost New Haven River valley. Blue line traces the highest lake with an outlet through the Natural Turnpike (620 m, 2,035 ft). Northward retreat of the ice sheet uncovered several closely spaced outlets to small lakes outlined in green (542–528 m, 1,778–1,732 ft). Further retreat uncovered an outlet through the Alder Brook valley (434 m, 1,424 ft). Black arrow points to upper Sparks Brook valley, a channel deeply eroded by outflow from the Natural Turnpike lake. Contour interval = 20 m.

outlet may have resulted in a quick 14 m (46 ft) drop in lake level which led to substantial, albeit short-lived water flow and the resulting channel erosion. Lakes utilizing these outlets were small and likely short-lived (Fig. 21).

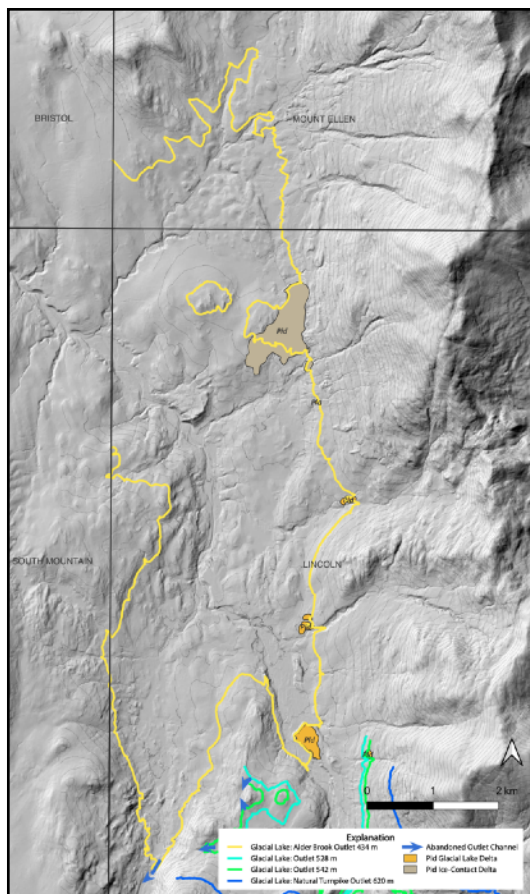


Figure 22: Orange line outlines Glacial Lake Lincoln centered within the New Haven River valley. The outlet to this lake was through the Alder Brook valley.

The Alder Brook valley that hosted extensive outflow from this lake is broad, has a very low-gradient, and is extensively dammed by beaver (Fig. 23). In the adjacent South Mountain Quadrangle outflow from this lake has eroded an extensive channel, much larger than the modern stream is capable of (Fig. 24).

Glacial Lake Lincoln is appropriate for the geographic setting, size, and likely duration of this lake. The author has no objection to following Heiser's (1990) suggestion of referring to the small lakes occurring in the headwaters of the New Haven River as early high-level stages of Glacial Lake Lincoln, although their limited extent might warrant names more indicative of their geographic locations.

A much more significant lake formed when the retreating ice sheet uncovered the drainage divide marking the headwaters of Alder Brook (434 m, 1,424 ft, orange line Figs. 21, 22). Heiser (1990) identified two closely spaced elevations for lakes using this drainage (436 m and 430 m) and referred to these as the "Early and Late Alder Brook Stages" of Glacial Lake Lincoln. This lake grew northward into a valley occupied by an unnamed tributary to the New Haven River and then also spread into the main stem valley (Fig. 22, Plate 1), eventually covering a large area along the western edge of the Lincoln Quadrangle. The inundated area includes the villages of Lincoln and South Lincoln as well as much of the Beaver Meadow Brook valley (Fig. 22, Plate 1).



Figure 23: Alder Brook outlet to Glacial Lake Lincoln along the western border of the Lincoln Quadrangle. (A) Much of the valley is filled with wetland deposits that have accumulated in numerous beaver ponds. (B) Remnant outlet channel at the drainage divide. View looks north in both photos.

As the ice sheet retreated farther north along the western flank of the Green Mountains another lake developed in the Baldwin Creek valley centered on the village of Jerusalem (Fig. 25). The outlet to the lake, at an elevation of 474 m (1,555 ft), is marked by an abandoned channel that cuts through the extensively kettled terrane shown in Figure 6. Several small deltas occur along the eastern margin of the lake. Immediately south of these deltas a much larger stream (the headwaters of Baldwin Creek) meets the projected lake shore but any delta that developed here was apparently eroded and its sediments redistributed in a very large alluvial fan (Plate 1). The terrace of a smaller landform interpreted as a delta lies below the projected elevation of this lake and may have formed when the ice sheet uncovered a lower outlet in the Bristol Quadrangle to the west (Fig. 25).

The youngest lakes to develop in the mapped area occupied the Huntington River valley (Figs. 25, 26). The high stage of this lake drained across the drainage divide separating the Huntington River drainage basin from the

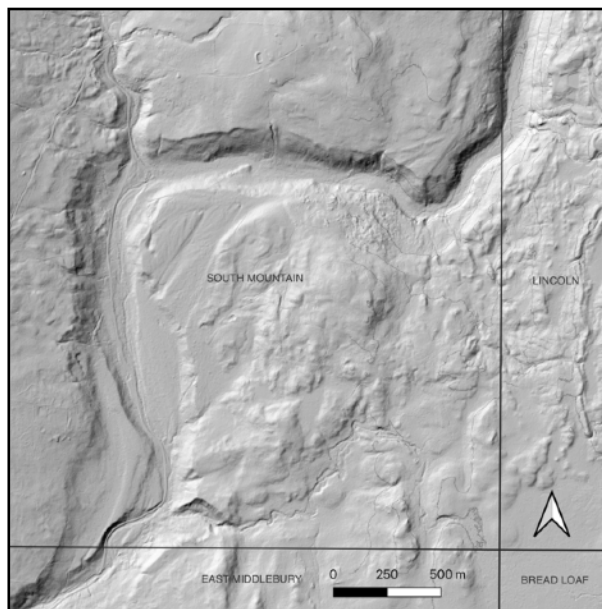
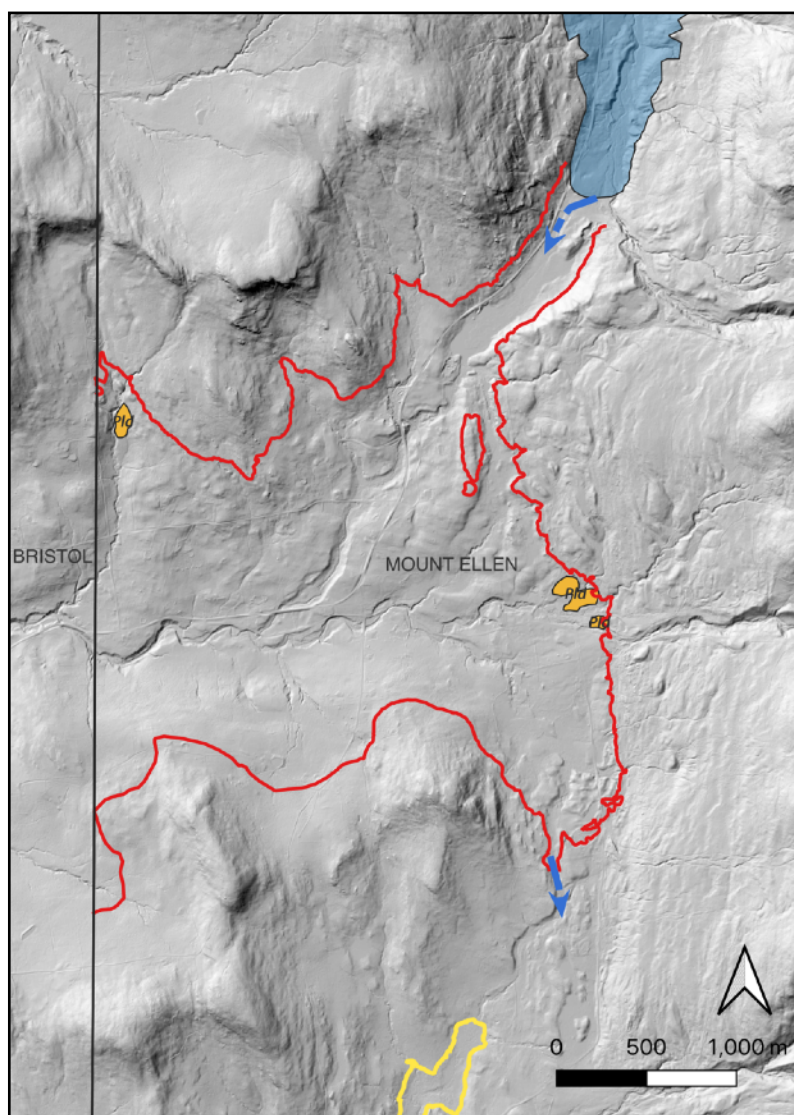


Figure 24: The outflow stream from Glacial Lake Lincoln eroded a deep, wide channel in the Alder Brook valley. The modern stream is quite small and incapable of accomplishing this much erosion, i.e. it is under-fit. Southeast corner of the South Mountain Quadrangle.



Baldwin Creek drainage basin, the headwaters of Hallock Brook (Figs. 25, 26). Largely based on work farther north, lakes in this valley have been described in two UVM theses (Bryan, 1995; Whalen, 1998; Whalen in Wright et al., 1997) and mapping in the adjacent Huntington Quadrangle by Springston (2019).

Two stages of this lake affect the valley within the Mount Ellen Quadrangle (Fig. 26). Additional, lower elevation stages

Figure 25: Red line outlines the extent of Glacial Lake Jerusalem centered on the west-draining Baldwin Creek valley along the western edge of the Mount Ellen Quadrangle. The outlet to this lake (blue arrow) was via a well-preserved abandoned channel cutting through the kame and kettle terrane at the drainage divide (Fig. 6). Several deltas (Pld) formed where tributary streams entered this lake. Yellow line outlines the northern arm of Glacial Lake Lincoln and blue area to north shows the southern end of Glacial Lake Huntington.

have been documented farther north (Springston, 2019). One delta occurs along the projected shoreline of the lake near where a tributary stream enters from the west near the northern border of the quadrangle (Fig. 26). Elsewhere lacustrine sediments are widely distributed within the projected boundaries of the lake (Plate 1).

Whalen (1998; 1997) referred to the high stand of this lake as Glacial Lake Jerusalem because the outlet was near Jerusalem, Vermont. Lower elevation lakes occupying this valley have been referred to as different stages of Glacial Lake Huntington (Bryan, 1995; Springston, 2019; Whalen, 1998). Given that this study has identified another glacial lake centered on the village of Jerusalem, I propose the name *Glacial Lake Jerusalem* be reserved for that lake (Fig. 25) and all lakes occupying the Huntington River valley, regardless of their elevation, be referred to a *Glacial Lake Huntington*, albeit with different stages marking the different elevation outlets.

A wide variety of sediments accumulated in these and other lakes in the region. Stratified diamict, a deposit consisting of interbedded debris flows and lacustrine silt/sand, is particularly common bordering many of the high-elevation lakes where they form gently sloping surfaces between the steep bedrock slopes and the lake margin (Plate 1). These deposits grade from pure debris flow material (remobilized till) above the lake surface to deposits with increasing amounts of fine sand/silt interbedded with the debris flows farther into the lake basin. In many of the narrow valleys bordered by steep mountains, stratified diamict may have completely filled the lakes.

In general, most of these glacial lakes contain a fining-upwards sequence of sediments. The oldest sediments accumulated close to the ice sheet and are dominated by coarse sand and gravel deposited in subaqueous fans near the mouths of subglacial tunnels or in eskers deposited in those tunnels. As the ice sheet retreated farther

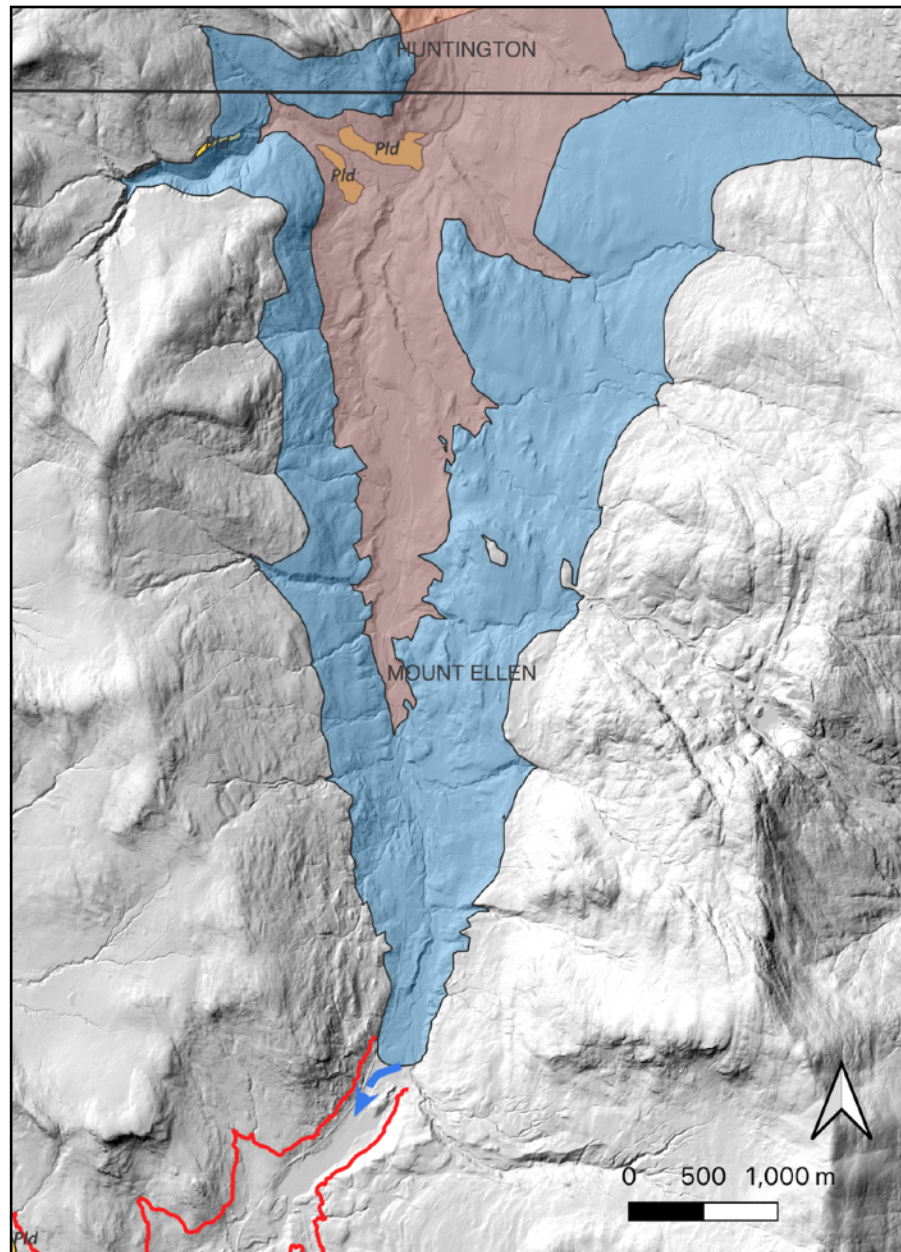


Figure 26: High stage of Glacial Lake Huntington is shown with blue shading. Outlet (blue arrow) is at the drainage divide between the Huntington River and Baldwin Creek drainage basins. Mauve shading outlines a lower stage of the lake. Main ridgeline of the Green Mountains borders the lake to the east whereas an unnamed range borders the lake to the west. Lake projections modified from those provided by Springston (pers. comm., 2022).

away the grain size dropped to fine sand then silt and clay as the energy of this depositional system correspondingly dropped.

Heiser (1990) measured several sections of glacial lake sediments where they were well exposed in working gravel pits or landslides. Figure 27 reproduces a section she measured near the confluence of Blue Bank Brook and the New Haven River (Fig. 21) that carefully documents this fining-upwards sequence. Abundant measurements of current directions in the lower, ice-proximal part of the section all indicate SE flow, consistent with water sourced from a subglacial tunnel in the ice sheet (Heiser, 1990). The section measured by Heiser (1990) includes a diamict layer she interpreted as a readvance till. An alternative hypothesis is that this diamict originated as an underwater landslide, a debris flow, possibly triggered by the drop in water level when the Natural Turnpike outlet was abandoned and the much smaller, lower-elevation lake began draining through the outlets north of Cobb Hill (Fig. 21). Similar to a glacial readvance, a debris flow would exert a strong shear stress on the underlying sediments and deform them producing the contortions and faulting noted below the diamict and the entrained sediment within the diamict (Fig. 27). Heiser (1990) measured a second section a short distance up the Blue Brook valley that similarly includes a distinct diamict layer. Assessment of the shear direction in the underlying sediments might clarify the process that emplaced the diamict.

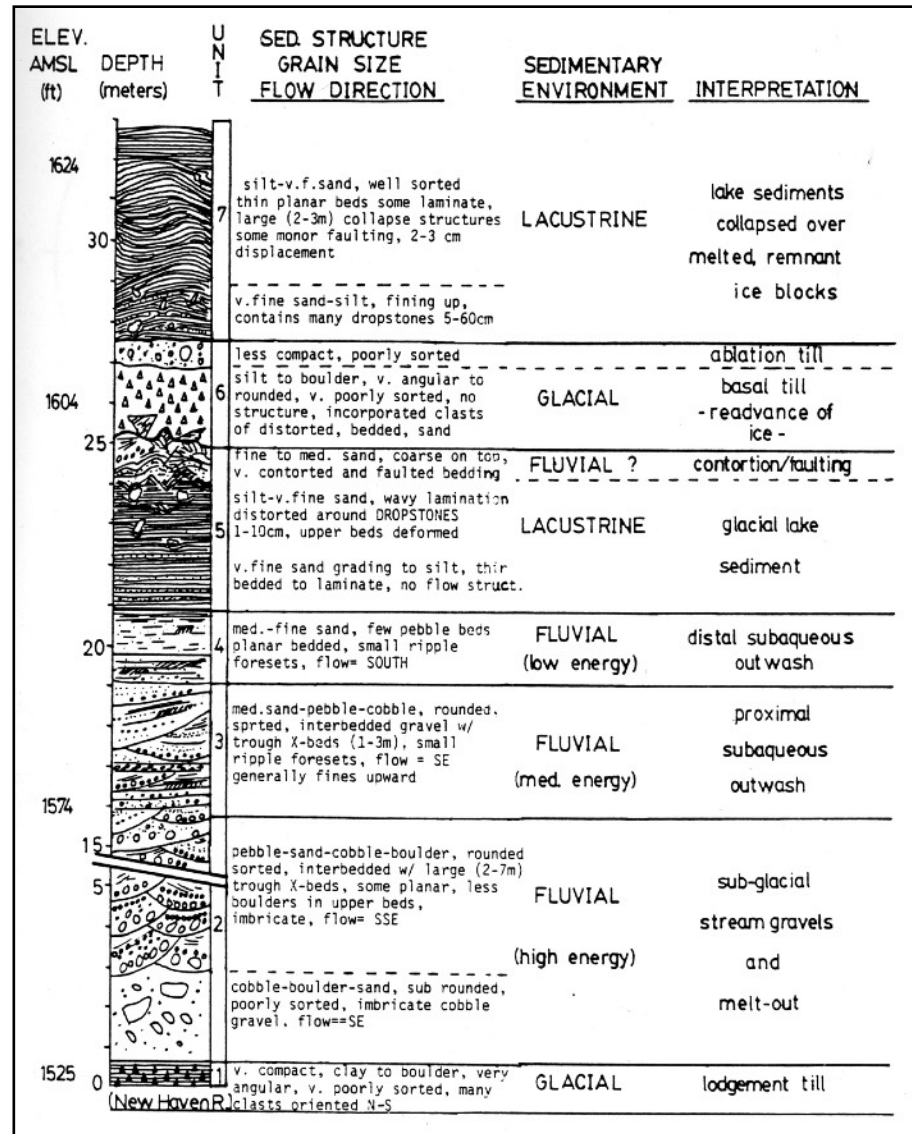


Figure 27: Stratigraphic section measured by Heiser (1990) near the confluence of Blue Bank Brook and the New Haven River (Fig. 21) shows a fining-up sequence of sediments interrupted by a layer of diamict interpreted as a readvance till. Section lies below the elevation of lakes draining through the Natural Turnpike outlet as well as lower-elevation outlets below Cobb Hill (Fig. 21).

Observations made during this study from a section exposed along the New Have River ~0.6 km above the Cooley Glen Trailhead are similar to those in Figure 27 although a less complete section was exposed. Inter-layered medium to coarse sand/pebbles near the base of the section indicate an ice-proximal subaqueous environment with large changes in energy level and extensive sediment disruption by slumping (Fig. 28A). A 2 m thick diamict, similar to one observed by Heiser (1990; Fig. 27) was also observed. This is overlain by thinly bedded very fine sand and silt that is

faulted and slumped, also similar to the section Heiser (1990) observed ~ 2 km farther down the valley (Figs. 27, 28B). Within these lake basins, field observations, mostly via soil probes and augers, revealed large variations in the grain size of glacial lake sediments within short distances implying wide ranging energy levels similar to that observed in the well-exposed sections. These areas have been mapped as “Undifferentiated Lacustrine Sediments, Pl.”

Deltas were deposited by streams originating from (1) the melting ice sheet (ice-contact deltas) and (2) meteoric water flowing off the surrounding mountains (Figs. 15, 16, 21, Plate 1). Deltas have been extensively quarried as sources of sand and gravel and this same sand and gravel allows surface water to recharge groundwater easily. Because the top surfaces of deltas lie very close to the elevation of the lakes they form in, deltas can be used to confirm and refine the projected shorelines of glacial lakes.

Heiser (1990) measured a section exposed in both a landslide along the west side of the New Haven River and a working gravel pit ~0.5 km SSE of South Lincoln (Fig. 29). She interpreted the upper part of the section to be deltaic sediments deposited by the New Haven River in Glacial Lake Lincoln when its outlet was through Alder Brook (orange line of Figure 22). Another terrace identified in this study ~1 km farther south (up-valley) is underlain by sand and gravel, is incised by several abandoned channels, and is similarly interpreted to be a delta built into the same lake (Figs. 30, 31). The implication of these two mapped delta fragments is that the upper reaches of the New Haven River valley were largely filled with a delta as far downstream as South Lincoln during the time when Glacial Lake Lincoln existed and drained through the Alder Creek outlet.

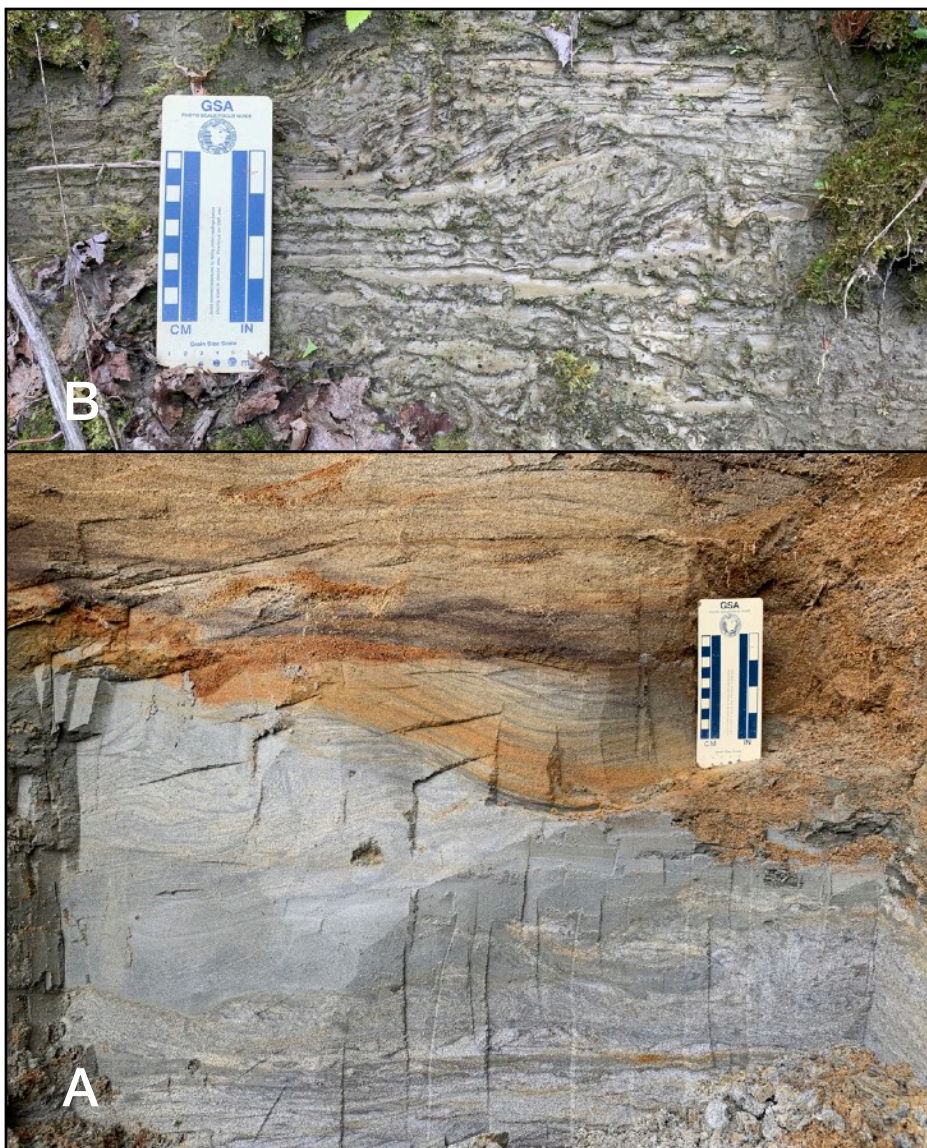


Figure 28: Sediments exposed in a landslide along the southwest side of the New Haven River ~0.6 km upstream from the Cooley Glen trailhead. (A) Medium to fine sand and silt at the bottom of the photo are distorted by slumping. This is overlain by a channel filled with medium to very coarse sand with rip up clasts of silt. Similar to Heiser's Unit 3 (Fig. 22). (B) Thinly bedded very fine sand and silt near the top of the exposed section have slumped producing the chevron fold.

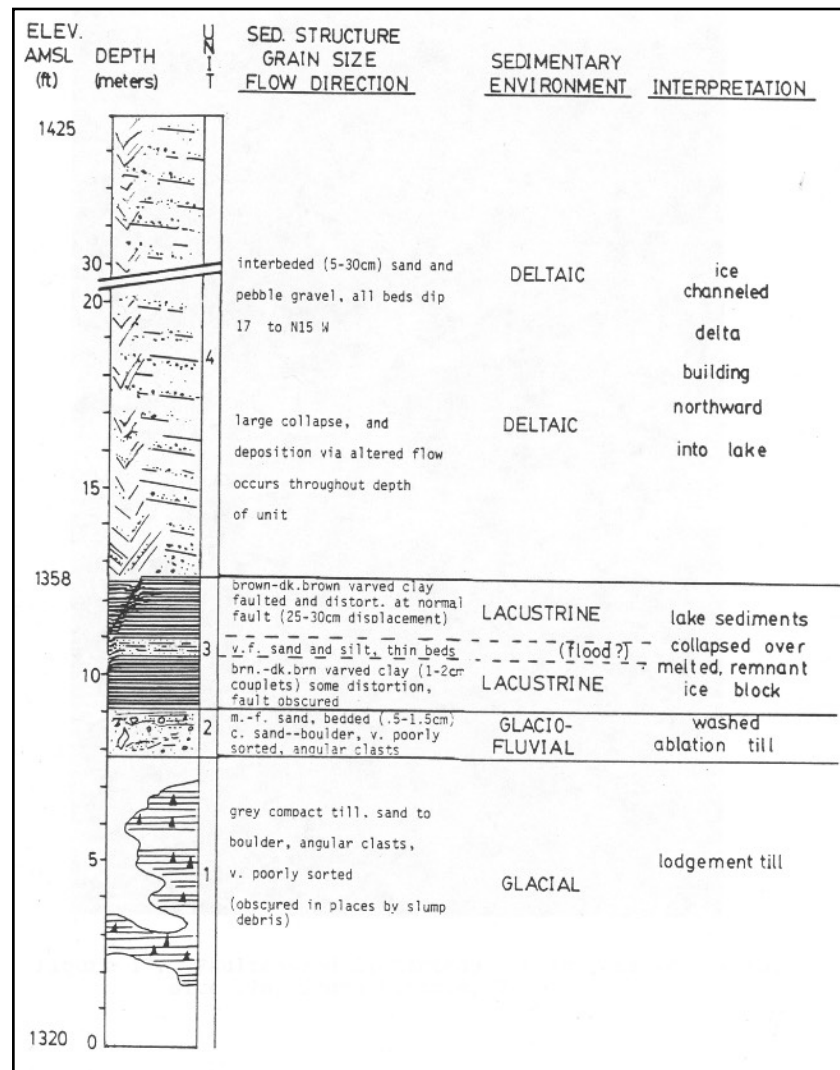


Figure 29: Measured section by Heiser (1990; see Fig. 26 for location) shows a nearly complete transition from (1) till deposited when ice still filled the New Haven River valley to (2) sediments likely deposited in an subglacial tunnel or subaqueous fan to (3) fine-grained glacial lake sediments to (4) sediments deposited in a delta that grew northward into the lake fed by the New Haven River.

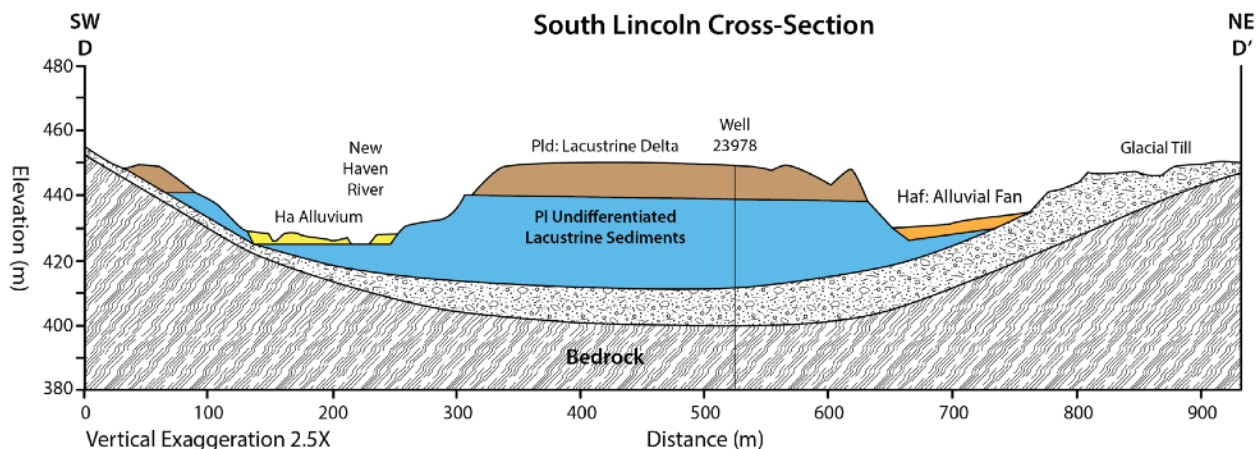


Figure 30: Cross-section D-D' is drawn across a terrace in the New Haven River valley ~1.5 km south of South Lincoln (see Fig. 26 for location). Terrace is underlain by a thick section of sand, gravel, and till.

Post-glacial History

The Holocene Epoch is the geologic period of time that generally encompasses Earth's history since the retreat of the ice sheets. That time epoch formally extends from 11,700 years ago to the present, but locally it's convenient to group those processes that have occurred since the ice receded from a particular area as being "post-glacial" a time interval that includes both the latest Pleistocene and the Holocene Epochs. In the Lincoln and Mount Ellen Quadrangles, the transition from full ice cover to fully ice-free likely extended across at least several hundred years. In general, the timing of ice retreat northward along the Champlain valley is not as well constrained as ice retreat in the Connecticut River valley, but existing dating suggests that deglaciation in the Lincoln/Mount Ellen area occurred roughly between ~14,600 to ~14,100 years ago (Ridge, 2016; Ridge et al., 2012). Over these last ~14,000 years the landscape has changed considerably in response to an array of geologic processes augmented by changes in our climate and the populations of plants growing here. The post-glacial history of the Lincoln and Mount Ellen Quadrangles presented here is interpreted from the materials and landforms mapped within the quadrangles.

The glacial lakes described previously were all dammed by the receding ice sheet. Those lakes all drained, either completely or in stages as the ice sheet both thinned and retreated to the north. Streams began eroding the sediments deposited in those lakes as soon as they drained. Abandoned stream channels and terraces are evidence of this erosion as are the uneroded patches of lake sediments scattered along the hillsides. Broad areas of alluvium in all the major stream valleys are sourced from both older lake sediments as well as till eroded from the uplands. The alluvium filling the upper New Haven River valley is particularly extensive and forms a broad, gently sloping surface historically well-suited to farming (Fig. 31).

Debris flow fans and alluvial fans, on a variety of different scales, are a common landform deposited during the Holocene (see earlier description of these landforms). Virtually every tributary stream flowing down the steep hillsides has deposited an alluvial fan where that stream encounters a sharp change in gradient where it flows onto a relatively flat valley bottom (Lincoln/Mount Ellen Plate 1). Generally, the size of the alluvial fans is proportional to the size of the tributary stream and many of the alluvial fans mapped in these two quadrangle are quite large (Fig. 5, 31). As noted earlier, these fans have been active throughout the post-glacial period, albeit episodically (Bierman et al., 1997; Jennings et al., 2003; Noren et al., 2002). Erosion and subsequent sedimentation was likely rapid immediately following deglaciation when unvegetated till covered the hillslopes. Large storms, landslides, forest fires, and logging have also triggered debris flows and sedimentation on alluvial fans.

Abundant wetland deposits occur in low-lying areas, e.g. closed depressions, across the quadrangles. Most of these are small. The largest and most extensive wetland areas occur in areas extensively dammed by beaver, e.g. the Alder Creek valley (Figs. 11, 23A).

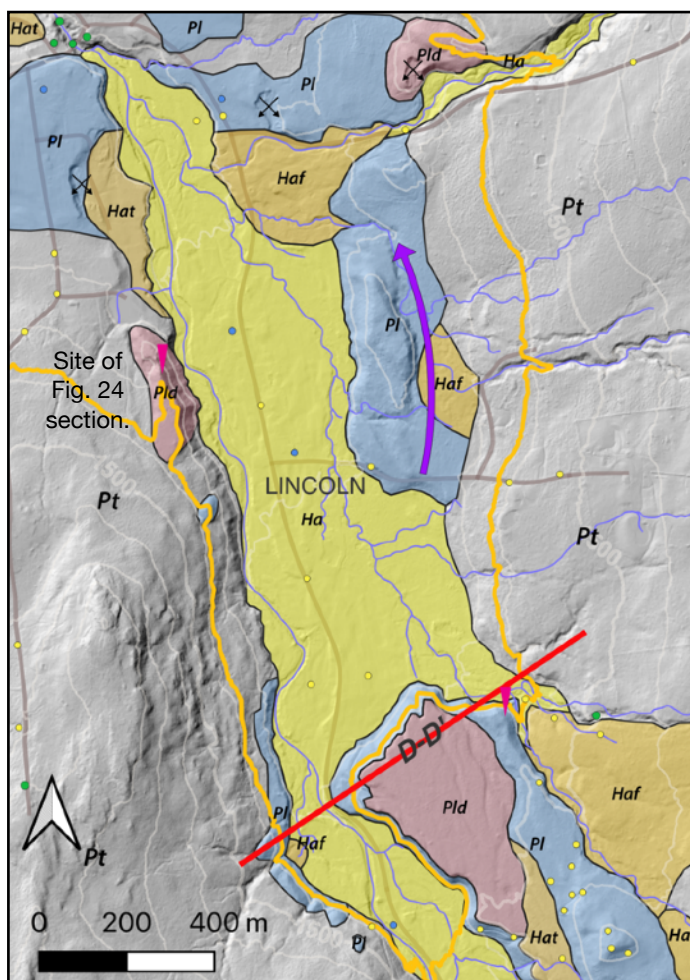


Figure 31: Portion of the Lincoln Surficial Geologic Map south of South Lincoln shows the New Haven River valley covered by a broad swath of alluvium (Ha) partially derived by erosion of glacial lake sediments (Pl, Pld). Deltas (Pld), abandoned channel (purple arrow), and terraces (Hat) suggest that the valley was largely filled with lake sediments when Glacial Lake Lincoln occupied the valley (orange line). Alluvial fans (Haf) have been deposited by streams depositing sediment where their gradients lessen abruptly.

Lincoln and Mount Ellen Overburden Thickness Maps: Plate 3

The “Isopach Map of Surficial Materials” for both the Lincoln and Mount Ellen Quadrangles contours the thickness of surficial materials (overburden) within the quadrangle. The data used to generate these maps are (1) mapped bedrock outcrops (green dots, Plate 3) which indicate areas where surficial materials don’t occur, (2) bedrock outcrops visible on the LiDAR shaded-relief imagery, (3) records of overburden thickness from domestic water wells (blue dots; numbers indicate depth to bedrock, Plate 3), and (4) areas where streams have deeply incised through surficial materials without encountering bedrock. Generally, the well locations were not checked and location errors, some significant, affect the accuracy of these contours. These data are contoured using 20, 50, and 100-foot contours. Contouring algorithms applied to the overburden thickness data produced geologically unrealistic contours, so these data were contoured by hand. In general, isolated wells reporting thick surficial materials were ignored, i.e. bullseyes were not drawn around these isolated wells.

As in most mountainous parts of Vermont, the steep hillsides within the quadrangles, i.e. most of the mapped area, are mantled with a generally thin and discontinuous cover of glacial till. Thick accumulations of surficial materials are restricted to the lower slopes and valleys where surficial materials have accumulated by a variety of processes. The thickest accumulations, areas exceeding 100 ft, occur in areas where till, ice-contact deposits, and glacial lake deposits remain uneroded by post-glacial processes (e.g. Figs 22, 24–26). Most of the larger valley bottoms retain some portion of these earlier-deposited sediments.

Groundwater Hydrology of the Lincoln and Mount Ellen Quadrangles

Within the two mapped quadrangles, most homes utilize private wells for their drinking water supply. Shallow dug wells or deeper drilled wells ending in surficial materials tap aquifers in those materials. While these aquifers are widely available, especially in the valley bottoms, and wells to access them are relatively inexpensive, most residents rely on drilled wells extending variable depths into bedrock for their groundwater supply.

Many different types of bedrock underlie these two quadrangles (Fig. 2). While they differ in their mineralogy and texture, they are all metamorphic rocks and have no primary porosity, meaning there is no open space between the mineral grains to store water. Consequently, groundwater in metamorphic rocks is located in fractures and all drilled wells in bedrock get their water from fractures intersected by that well. 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, i.e. a high percentage of open space between individual sediment grains, typically 15–45% 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 to reach a well, i.e. how permeable these sediments are. Generally, groundwater moves very slowly through fine-grained materials and much more quickly through coarse-grained materials.

The largest groundwater aquifers occurring in the quadrangles are found in coarse-grained surficial materials (sand and gravel) where those materials extend below the water table. These sand and gravel aquifers are generally found in ice-contact sediments (eskers or subaqueous fans), the coarser-grained (ice-proximal) lacustrine deposits, and deltas. Oftentimes the ice-contact and ice-proximal lacustrine sediments lie in the valley bottoms and are buried by younger finer-grained lacustrine deposits which can effectively confine them. Consequently these aquifers are isolated from contamination from human and agricultural sources. Additionally, recharge to these aquifers is upwards from the underlying bedrock, further ensuring the quality of this groundwater. Most rivers in New England are groundwater discharge areas, meaning that groundwater discharges into these streams rather than the streams recharging the underlying groundwater.

Water Table Contour Maps of the Lincoln and Mount Ellen Quadrangles with Flow Lines (Plate 2)

Maps contouring the elevation of the water table in both the Lincoln and Mount Ellen Quadrangles are included with this report (Plate 2). Data used to contour the water table comes from topographic maps 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 and the water table elevation can therefore be easily gleaned. In areas where groundwater does not discharge to the surface, 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. For the groundwater wells, the water table elevation was calculated by taking the surface elevation of the well (garnered from the LiDAR DEM) and subtracting the depth to the static water table. Note: not all wells record the depth to the water table. The calculated water table elevation (in feet above sea level) is labeled adjacent to each well (Plate 2).

Drainage basin boundaries were downloaded from the VCGI database and denote both surface water and groundwater divides (Plate 2). As noted earlier, the major water basin divide in the area cuts north-south along the crest of the Green Mountains and separates water flowing west into streams that drain into Lake Champlain or the Winooski River from water flowing east into the Mad River which then flows north to join the Winooski River and eventually also flows into Lake Champlain. Various sub-basin boundaries are also shown on these maps.

In this mountainous terrain the water table was contoured using a 500-foot contour interval (Plate 2). 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 and 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 general 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 potentially informing users of the sources for naturally occurring dissolved solids, e.g. Ca^{2+} , Mg^{2+} , Fe^{2+} , Mn^{2+} occurring in groundwater coming from different areas. For groundwater contaminated with road salt, 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.

Well Yield Maps of the Lincoln and Mount Ellen Quadrangles (Plate 4)

The reported yields for private wells (gallons per minute) are generally measured during well construction and determine when drilling can cease. The Well Yield Maps (Plate 4) scale the size of the well symbol to the well yield as well as displaying the measured well yield. Most private wells are constructed with casing that extends into the underlying bedrock ensuring that water flowing into the well is coming from the bedrock and not the overlying surficial materials. Of the 1,070 private wells shown on the map that are categorized as either bedrock or surficial wells, 1,043 (97.5%) are bedrock wells and only 27 (2.5%) tap surficial aquifers (gravel wells). The map does not distinguish between these two well types.

Figure 32 categorizes well yields from private wells within the quadrangle. Relatively few (10%) have yields of less than 1 gallon per minute (gpm). Most have significantly higher yields

Private Well Yields: Lincoln and Mount Ellen Quadrangles

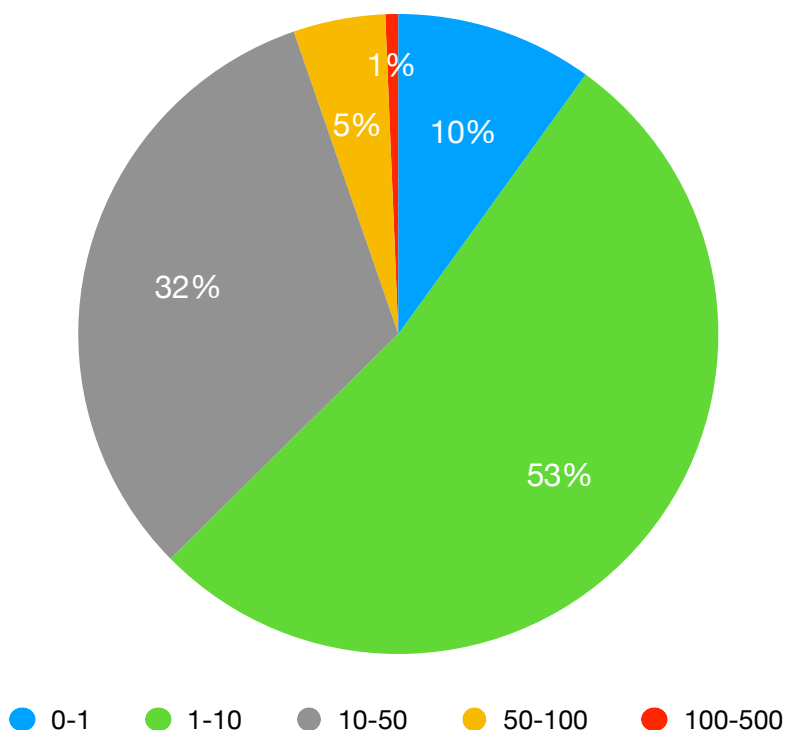


Figure 32: Pie chart categorizes the yields (gallons per minute, gpm) of private wells within the Lincoln and Mount Ellen Quadrangles ($n = 1,135$ wells). Most drilled wells in the area have yields between 1 and 50 gpm (85%), and 90% have yields greater than 1 gpm.

indicating that groundwater in the underlying rocks is both available and flows with some ease to drilled wells. As noted earlier, the metamorphic rocks underlying this area have no primary porosity and water occurring in these rocks occupies fractures that have formed when the rocks were brittle, well after they were deformed during the Taconic and Acadian Orogenies. The very high-yield wells (>50 gpm) likely intersect rock that is highly fractured and that increased fracture density most commonly results from faults or closely spaced joint sets.

Recharge Potential to Surficial Materials Maps (Plate 5)

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 covered with impermeable materials, e.g. asphalt, 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 and infiltrate. Fine-grained surficial materials usually have a low permeability. Even if vegetation allows water to infiltrate, the rate at which it can percolate (seep) through the material may be far slower than the rate at which new water from rainfall or snow melt is available. However, fine-grained materials with low permeability, e.g. many tills and lacustrine sediments, a significant amount of water can move through 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.

High Recharge Potential to Surficial and Bedrock Aquifers

Alluvium, alluvial Fan sediments, fluvial Terrace sediments, ice-contact sediments, deltaic sediments, 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, e.g. till, 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. Wetlands uniquely serve as good recharge sites because they occur in closed depressions where surface water collects. Even if the surficial materials underlying wetland have a low permeability, they will have a near constant flow of well-filtered surface water through them into the underlying groundwater system.

Low to Moderate Recharge Potential to Surficial and Bedrock Aquifers

Lacustrine very fine/fine sand, silt, most till, and artificial fill (commonly covered with pavement) all 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, silt, and clay occurs in the valley bottoms where slopes are gentle which enhances its ability to absorb water. Slow movement of water through these materials can recharge coarse-grained surficial aquifer materials or bedrock, albeit slowly.

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