Surficial Geology of the Waterbury and Middlesex 7.5-Minute Quadrangles, Northern Vermont[1]

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Report describes Vermont Geological Survey Open File Maps: VG2023-1 & 2

View looks WNW down the Winooski River valley towards Waterbury Village. Main range of the Green Mountains rises in the distance.

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Executive Summary/Significant Findings

The surficial geology of the Waterbury and Middlesex 7.5-Minute Quadrangles was mapped during the summer/fall of 2022. Mapping in the Ridley Brook and Crossette Brook valleys was assisted by six geology students at the University of Vermont. Areas within within the Mad River watershed was previously mapped by Dunn and others (2007b) and their contacts modified utilizing the LiDAR imagery. Similarly, previous mapping in the Southern Worcester Mountains by Springston and Dunn (2006) was also modified to reflect the added detail available in the new imagery. Considerable detail has been added to mapping conducted during the 1960's at a scale of 1:62,500 and later incorporated into the Surficial Geologic Map of Vermont by (Stewart and MacClintock, 1970). Two surficial geologic maps and four geologic cross-sections compliment this report (Wright, 2023a, b).

The Waterbury and Middlesex 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. One set of glacial striations dominate the area. These are oriented NW-SE, parallel to regional ice flow across New England. Within the Winooski River valley striations are aligned WNW-ESE parallel to the river valley indicating late ice flow parallel to the valley when the ice sheet had thinned sufficiently to be topographically controlled.

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. Distinctive glacial erratics, e.g. sedimentary rocks sourced from the Champlain valley to the northwest, are rare. 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. In one limited area abandoned channels along the eastern slopes of the mountains mark avenues of water flow along the margins of the ice sheet. Limited exposures of sand and gravel deposited in subglacial tunnels, subaqueous fans, or along the margin of the ice sheet were mapped. A very short north-south esker was mapped in the Ridley Brook valley, but water well logs and a thick accumulation of sand and gravel in the headwaters of the brook suggest that a north to south subglacial drainage tunnel existed as the ice was thinning across this area. In the Winooski River valley one esker segment mapped immediately west of Middlesex village, sublacustrine gravels noted in well logs, and additional exposures of ice-contact sediments elsewhere in the valley all suggest that the valley served as a significant WNW to ESE subglacial conduit for meltwater.

A series of glacial lakes, originally documented by Larsen (1972b, 1987), formed in the Winooski River valley as the ice sheet retreated across the area. Field work in these quadrangles confirms this lake chronology and knowledge of these lake elevations helped identify the locations of many deltas. Board areas within these two quadrangles are underlain by fine-grained lacustrine sediment most of which accumulated in Glacial Lake Winooski, the large lake which flooded large portions of the Winooski drainage basin.

Erosion of both the till-covered mountain slopes and valleys filled with lacustrine sediments by modern streams has been concurrent with the shrinking ice sheet and the drainage of glacial lakes from the region. Large volumes of sediment have been eroded and transported by the Winooski River and deposited in Lake Champlain. Abandoned alluvial terraces in both the Winooski and tributary valleys provide evidence of the downcutting that's occurred. Two well-documented examples of buried Winooski river channels occur both at Bolton falls and in MIddlesex Village. In both cases waterfalls occur where the modern river is currently flowing across bedrock. At Bolton Falls a deep bedrock valley lies south of the modern channel and is filled with glacial sediments. At Middlesex Village a deep bedrock valley lies north of the modern channel and is similarly filled with glacial sediments.

In post-glacial times alluvial fans are forming where the gradient of streams flowing off the steep mountainsides abruptly changed where they encountered valley bottoms. Relatively small alluvial fans are common in the area.

Landslides are common along many of the steep mountain slopes in the region. Large landslide scarps have been mapped where they were encountered in the field and where they were identified on the LiDAR imagery. Landslides were particularly common along the eastern side of Jones Brook near the eastern boundary of the Middlesex Quadrangle.

Introduction

This report summarizes the results of mapping the surficial geology of the Waterbury and Middlesex 7.5-minute Quadrangles in north-central Vermont during the 2022 field season (Fig. 1). 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 (Wright, 2023a, b). These maps and four geologic cross-sections included on those maps are described and interpreted in this report.

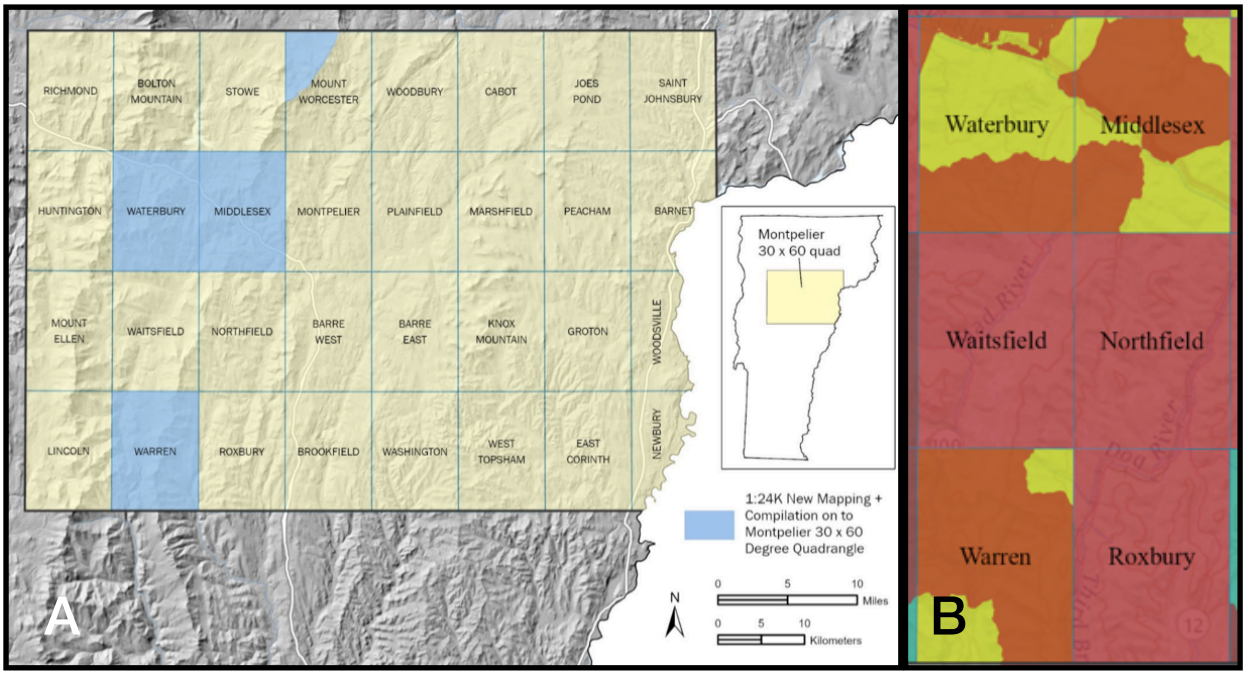

Figure 1: (A) Map shows the location of the Waterbury and Middlesex quadrangles within the Montpelier 1-dgree sheet (from the 2022 RFP issued by the Vermont Geological Survey). (B) Areas in yellow denote unmapped areas within the quadrangles that were mapped during the 2022 field season.

Location and Geologic Setting

The Waterbury and Middlesex quadrangles are both topographically rugged areas. The Waterbury quadrangle includes part of the Green Mountains whereas the Middlesex quadrangle straddles the Worcester/Northfield Range (Figs. 1 and 2). The Winooski River valley cuts WNW-ESE across both mountain ranges, bisects both quadrangles, and serves as the major transportation corridor across northern Vermont (Figs. 1 and 2). All tributary streams in the area eventually drain into the Winooski River which flows WNW and enters Lake Champlain immediately north of Burlington, Vermont.

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 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).

The surficial geologic materials occurring in this 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 this area ~14,200–13,500 years ago (Corbett et al., 2019; Ridge et al., 2012). The ice sheet in

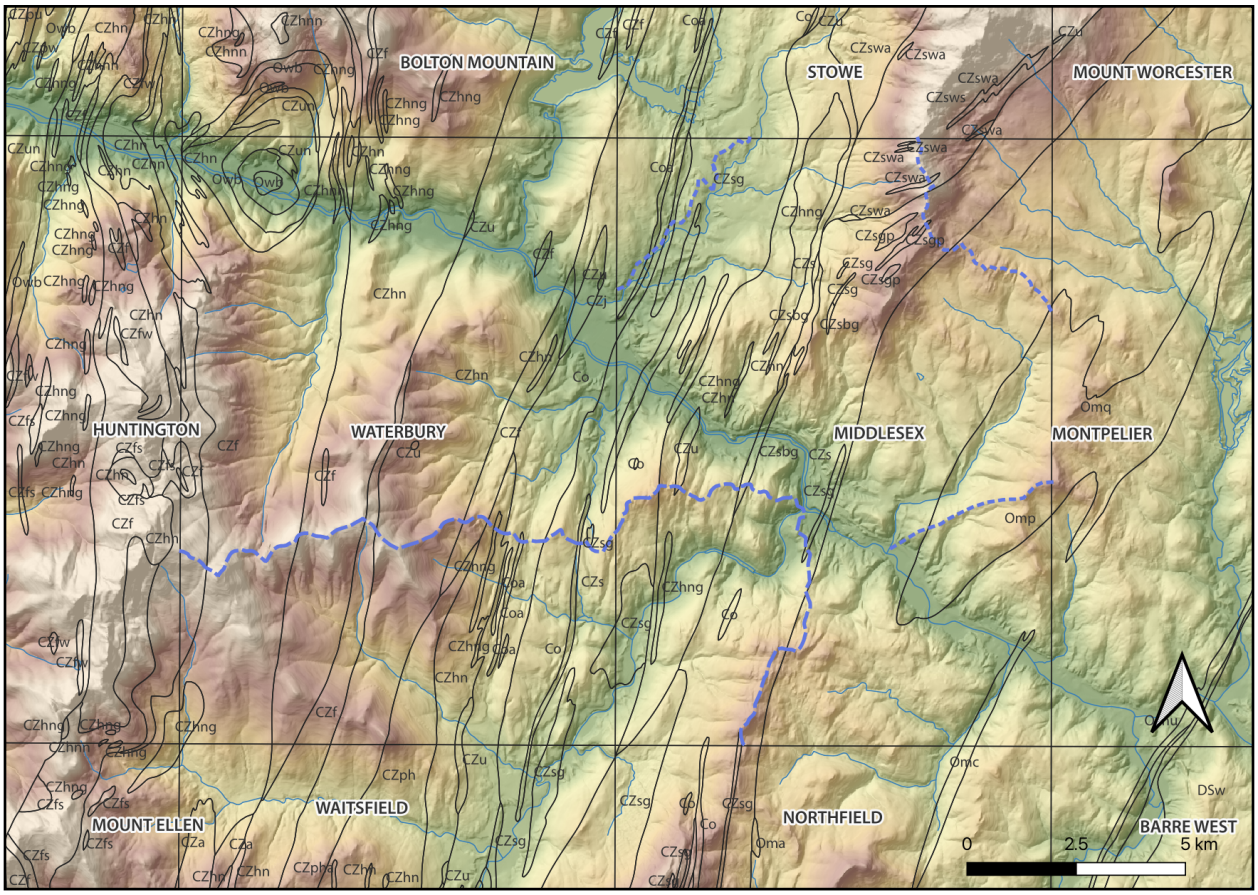

Figure 2: Physiographic map shows the locations of the Waterbury, Middlesex, and surrounding quadrangles astride the Winooski River valley in north-central Vermont. Generally north-striking bedrock rock units are dominantly metasedimentary rocks with minor metaigneous rocks. Unit acronyms are available from the Bedrock Geologic Map of Vermont (Ratcliffe et al., 2011). Blue dashed line outlines the Mad River Watershed mapped by Dunn and others (2007). Areas north of the Winooski river outlined by the blue dotted line demarcate the Southern Worcester Mountains area mapped by Springston and Dunn (2006).

northern New England was sufficiently thick to completely cover the mountains. During the time of complete ice cover, regional ice flow was generally from northwest to southeast obliquely across the north-south mountain ranges (Wright, 2015). When the ice thinned sufficiently to be topographically controlled, ice flow shifted to north-south in the valley between the Green Mountains and Mount Worcester/Northfield Range and flowed ESE up the Winooski River valley (Wright, 2015). As a consequence of this complete ice cover during peak glaciation, the mountains are largely mantled by till with isolated pockets of organics occurring in wetland areas.

As the ice sheet thinned and retreated to the north and northwest, subglacial drainage systems within the waning ice sheet deposited eskers in most of the major valleys (Wright, 2018b, 2020). When the ice sheet retreated north of the drainage divide separating the White River drainage to the southeast from the Winooski River drainage to the northwest a lake began to grow between the divide and the retreating ice front. This lake, Glacial Lake Winooski, would grow to become the largest glacial lake in north-central Vermont (Larsen, 1972b, 1987; Larsen et al., 2003; Wright, 2018a). Consequently, in most of the region's valleys older ice-contact sediments are partially or completely overlain by younger glaciolacustrine sediments. In addition to extensive deposits of fine-grained sediments deposited in the deeper waters of these lakes, deltas formed along the lake margins where streams entered. After the glacial lakes drained these same streams have eroded channels through the glaciolacustrine sediments during the Holocene

leaving abandoned fluvial terraces along their valleys. Further stream erosion in the uplands has led to the deposition of numerous alluvial fans at the base of steep slopes (Bierman et al., 1997).

Prior Work

Surficial geologic mapping in the quadrangles was undertaken during the 1950's and 1960's and these unpublished open file maps assembled into the Vermont State Surficial Geologic Map (Stewart and MacClintock, 1970). This mapping was done on 15-minute (1:62,500 scale) base maps. Due to the large areas involved, much of this work was conducted in a reconnaissance fashion. The Waterbury 7-5-minute quadrangle comprises the southeastern quadrant of the Camels Hump 15-minute quadrangle which was also mapped by Stewart (1956-1961). The adjacent Middlesex 7.5-minute quadrangle lies in the southwestern quadrant of the Montpelier 15-minute quadrangle which was mapped by Stewart (1956-1961).

Subsequent to the mapping conducted during the 1960's the general glacial geology of this part of Vermont was extensively updated by Larsen (1972b, 1987) and Larsen et al. (2003). Detailed surficial geologic mapping of portions of the Waterbury and Middlesex quadrangles occurred when the Mad River watershed was mapped by Dunn and others (2007b), (see Fig. 2). Similarly, much of the northern half of the Middlesex Quadrangle was mapped by Springston and Dunn (2006), (see Fig. 2) and this geology was outlined in a field guide to region (Dunn et al., 2011). The geologic maps of Dunn and others (2007b) and Springston and Dunn (2006) were completed using 1:24,000 topographic basemaps.

Methods

Traditional field techniques and digital mapping were employed to generate a surficial geologic map of the area. Specifically, over 3,400 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.LiDAR-derived 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

Figure 3: UVM student interns Elliott Bloom and Zoe Flanzer utilize both a soil probe (left) and auger (right) to sample and observe unweathered sediments below the soil horizon.

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.

Very limited field work was conducted in areas originally mapped by Springston and Dunn (2006) and 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). These changes were reviewed and generally agreed to by Dunn and Springston (pers. comm. 2023).

Four geologic cross-sections were constructed, two in the Waterbury quadrangle, one straddling the boundary between the two quadrangles, and one in the Middlesex quadrangle (Wright, 2023a, b). Surface observations were augmented by private water well logs to interpret the subsurface surficial geology in these areas. Two of the cross-sections (B-B': Bolton Falls, D-D': Middlesex Village) utilize depth-to-bedrock measurements acquired using a Tromino passive seismic device on loan to the Vermont Geological Survey during the fall of 2022 from the USGS. Ben DeJong, state geologist, processed the geophysical data utilized in these sections.

Six UVM undergraduate students assisted with the field mapping effort during three weeks of July and August, 2022. The author gratefully acknowledges the work of Elliott Bloom, Cora Deininger, Zoe Flanzer, Sean O'Neil, Samantha Rassias, and Tyler Sullivan.

Waterbury and Middlesex Surficial Geologic Maps

The surficial geologic maps that accompany 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 (Wright, 2023a, b). During the spring of 2018 the Vermont Geological Survey developed a uniform set of mapping units which are utilized on the Waterbury and Middlesex Surficial Geologic Maps (Springston et al., 2018). The boundaries between these different materials are geologic contacts and are shown in most places 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 generally follow the mapping units used on recently published maps by the principal author (e.g. Wright, 2022b, c). These materials and landforms fall into three groups: (1) Glacial Deposits are the 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 roughly from ice sheet retreat to the present.

Bedrock Outcrops/Glacial Striations

While surficial materials and landforms are the focus of this project, bedrock outcrops were also mapped when they were encountered during field traverses . Outcrops are abundant where glacial till and other surficial materials are thin (Fig. 4). Additionally, most outcrops occurring along town roads and state highways were also mapped. No

Figure 4: Erosion of the thin till cover by a small unnamed brook~1 km southwest of Waterbury Village exposes moss-covered outcrops of the Fayston Formation (CZf) consisting predominantly of schist.

attempt was made to map all outcrops, especially in the upland areas where outcrops are numerous and closely spaced.

The orientation of glacial striations and grooves were measured where they were observed in the field (Fig. 5). Both these and an earlier compilation by Wright (2015) are included on the geologic maps.

Figure 5: Glacially smoothed and grooved bedrock outcrop exposed along Kelley Brook in Middlesex. Arrow aligned parallel to grooves indicates SE ice flow.

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. 6). 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: lodgment till . 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.

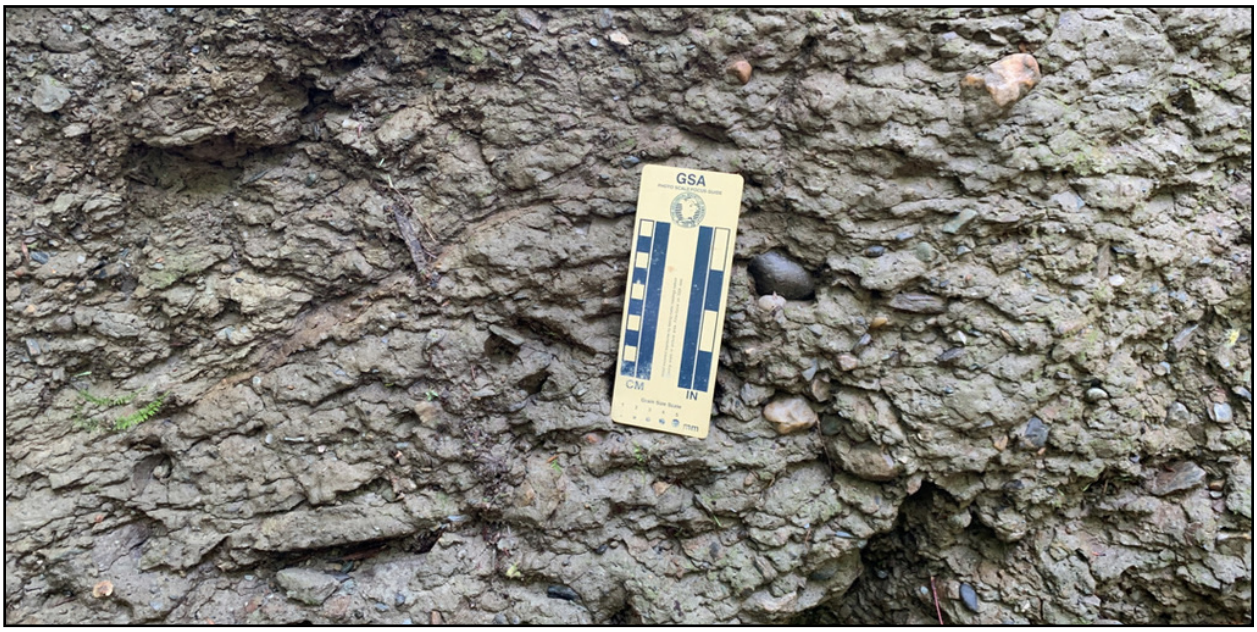

Figure 6: Dense, grey, glacial till, typical of the lodgment till in the area, exposed along Kelley Brook in Middlesex.

Ice-Contact (Glaciofluvial) Deposits: Eskers (Pie) and Undifferentiated Deposits (Pi)

Meltwater streams flowing in tunnels beneath the thinning and retreating ice sheet deposited sand and gravel in distinctive ridges referred to as eskers (Pie). Areas of sand and gravel inferred to be ice-contact deposits but not forming distinctive landforms were mapped as undifferentiated ice-contact deposits (Pi). These deposits may be the eroded remnants of eskers, kames, or may be irregular accumulations of sand and gravel deposited in subaqueous fans close to the margin of the ice sheet. Abandoned ice-marginal channels are sometimes preserved.

Lacustrine Deposits

Lacustrine deposits are those that accumulated in one of several different ice-dammed glacial lakes that occupied the Winooski river valley and its tributary valleys as the ice sheet retreated across the area. Specifically in order of occurrence, these lakes are named Glacial Lakes Winooski, Mansfield, and Vermont and the projected shorelines of critical stages of these lakes are shown on the geologic maps. The valleys that hosted these lakes contain a variety of sediments uniquely deposited in lakes.

Fine-grained lacustrine sediment (Plf) The most common lacustrine sediments mapped in the quadrangles are silt, clay, fine-, and very fine-grained sand (Fig. 7). These sediments were deposited in quiet-water environments. Despite the extensive occurrence of these sediments, good exposures were rare and small (Fig. 8); no extensive sections were discovered.

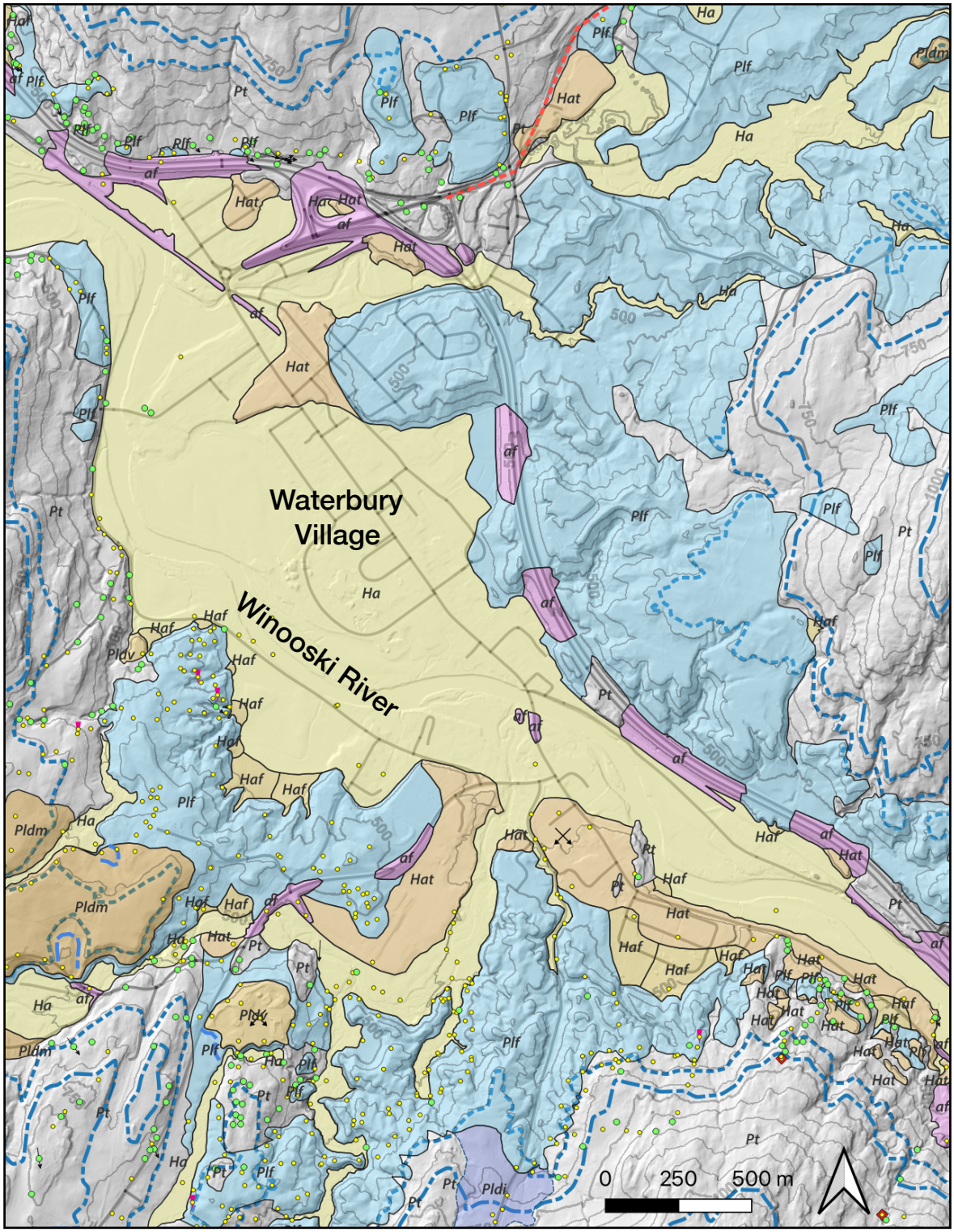

Figure 7: The Winooski River has eroded a broad channel across extensive deposits of fine-grained lacustrine sediment (Plf: silt, clay, very fine and fine sand) both north and south of Waterbury Village.

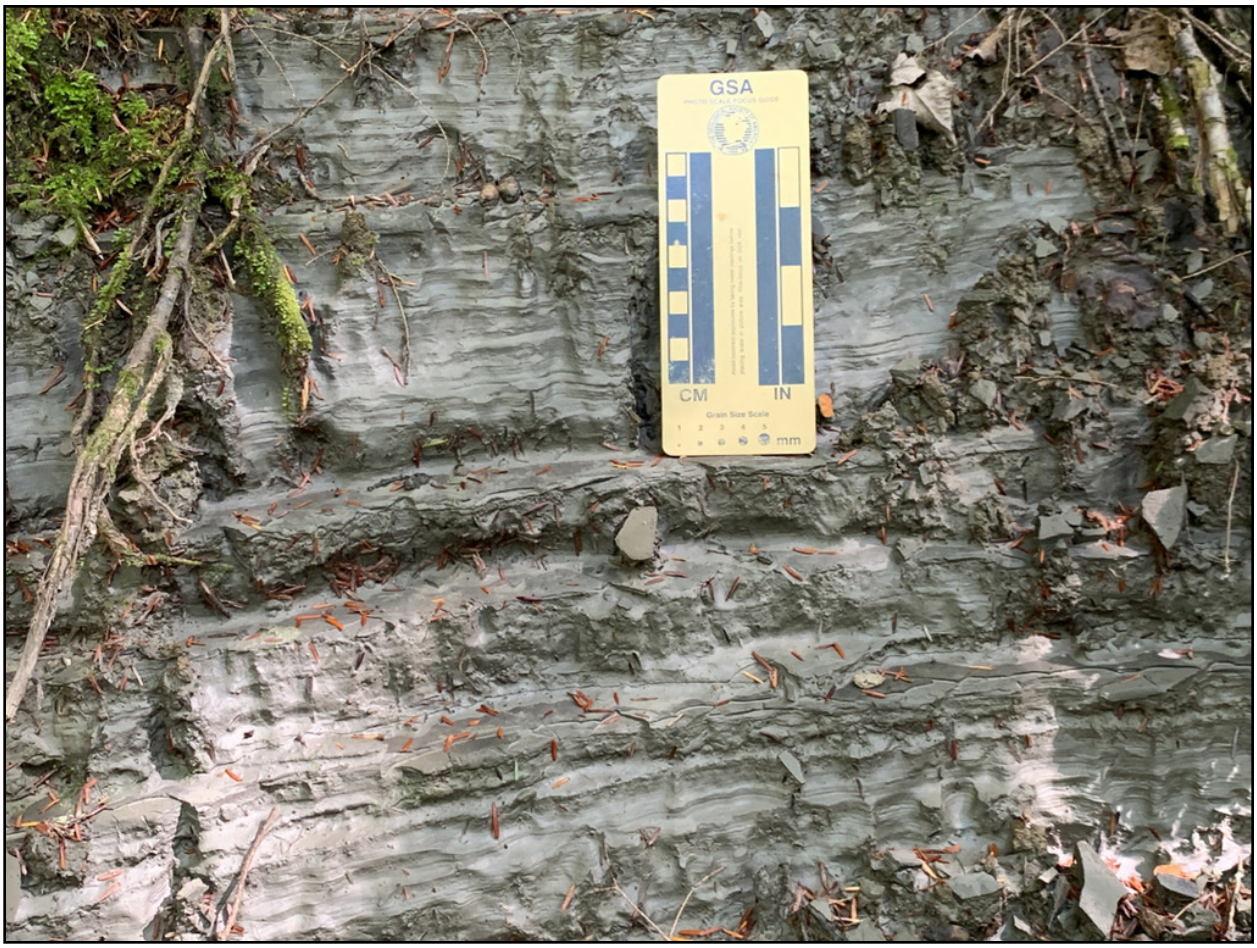

Figure 8: Horizontal beds of silt and clay exposed along a small unnamed brook ~1 km south of Middlesex village was most-likely deposited in the deep quiet water environment of Glacial Lake Winooski.

Glacial Lake Deltas (Pld) 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, Fig. 9). Gravel pits have been established in many of these deposits.

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 rare exposures (landslides) reveal the layering. Areas mapped as stratified diamict are marked by (1) thick accumulations of sediment in tributary valleys forming gently sloping surfaces, (2) surface exposures of both diamict and lacustrine sediments in close proximity, and (3) well logs similarly recording a mixture of diamict ("hardpan") and lacustrine sediments. Thick sections of stratified diamict were deposited in many of the lakes occupying the steep-sided valleys common in the mountains (Figs. 9, 10). Stratified diamict also extends above the projected lake shorelines where it consists of layers of diamict with no intervening lacustrine sediments. This indicates that landslides continued to accumulate in tributary valleys after the glacial lakes had completely filled with sediment. It is nearly impossible to accurately map this unit because it consists largely of transported glacial till and cannot be distinguished from in-place till.

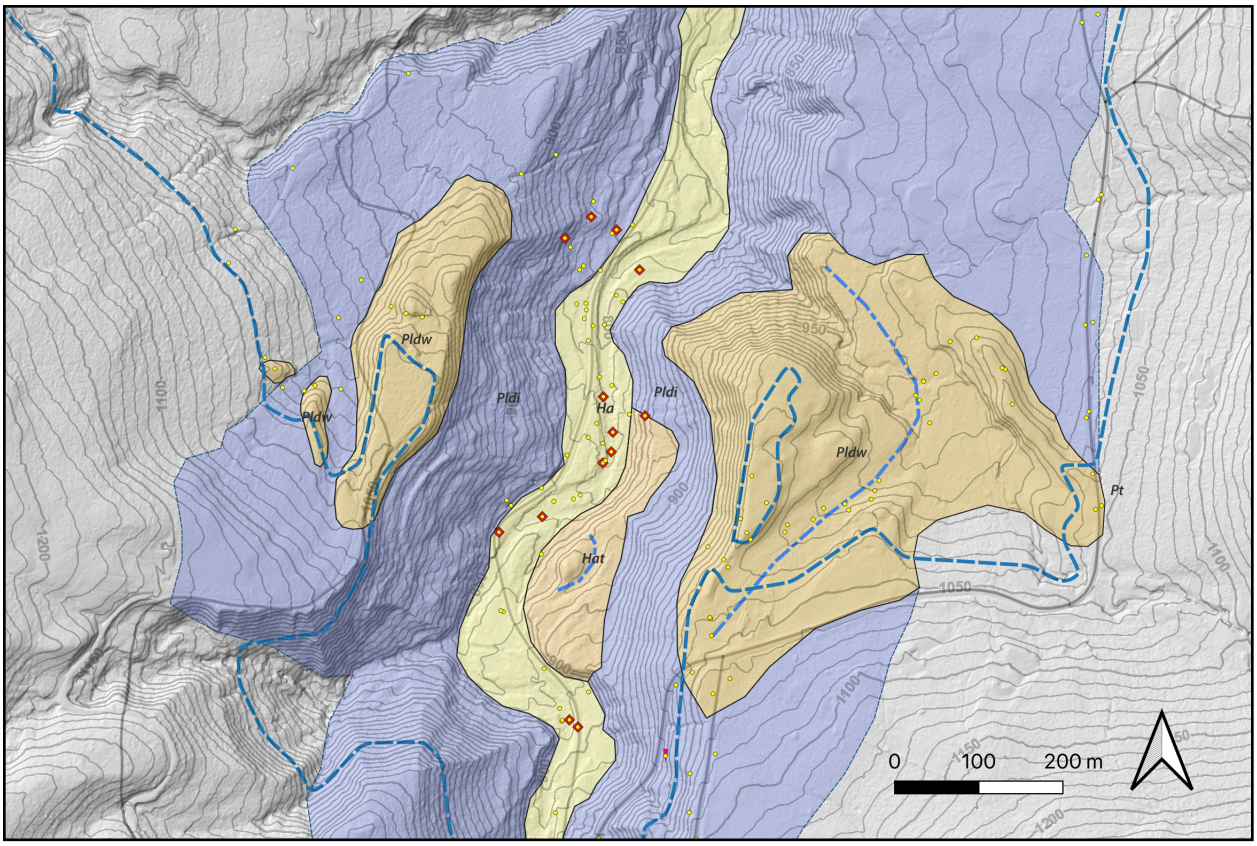

Figure 9: Eroded remnants of a Glacial Lake Winooski delta (Pldw) in the upper Ridley Brook valley on the east side of Camels Hump (Waterbury Quadrangle). Dark blue dashed line shows the projected shoreline of Glacial Lake Winooski. Lighter blue dot-dash line outlines an abandoned channel eroded across the top of the delta. Deltaic sediments are deposited on and around interlayered lacustrine sediments and diamict and mapped as stratified diamict (Pldi). Diamonds mark locations of large glacially transported boulders occurring as lag boulders in the Ridley Brook alluvium (Ha). An abandoned alluvial terrace and channel are also shown (Hat).

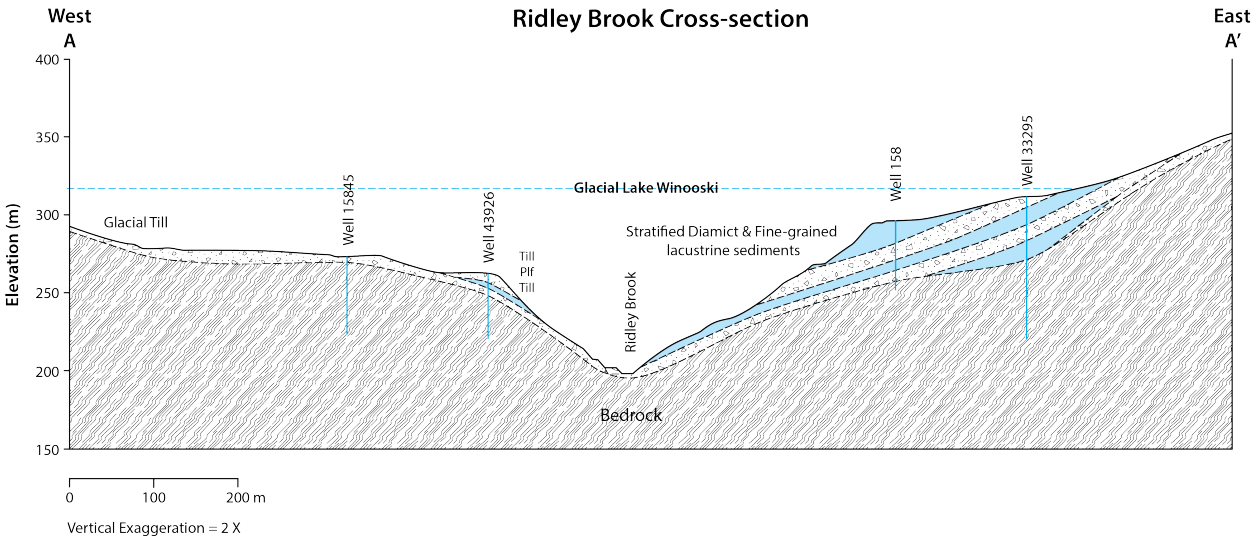

Figure 10: West-East cross-section A-A' across the Ridley Brook valley uses both well and field observations to highlight the thick accumulation of stratified diamict on the east side of the valley (see map for location).

Holocene Deposits

Alluvial Fan Deposits (Haf)

Alluvial fans form where stream-transported sediment is deposited in a fan-shaped landform where the stream gradients abruptly lessen where they flow out of the mountains onto terraces or other gently-sloping landforms.The apex of these fans frequently consists of coarse, unsorted debris flow deposits. Farther down the fan slope fan sediments consist of lenses of sand/gravel that may fine to silt at the far 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.

Alluvium (Ha)

Alluvium 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 of the tributary streams in the area are relatively small and have deposited correspondingly limited areas of alluvium. However, the alluvium transported by the Winooski River and to a lesser extent the Mad River occurs on a much larger scale and marks an almost continuous deposit extending across both quadrangles. Where the gradient is low the Winooski meanders in wide arcs and old meander scars are common (Figs. 7, 9).

Alluvial terrace deposits (Hat)

Alluvial terrace deposits are stream sediments (alluvium) occurring on terraces above but adjacent to modern streams (Figs. 7, 9). 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 commonly occur in closed basins, adjacent to low-gradient streams, and areas dammed by beaver. 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. Relatively few wetland areas were mapped in these two quadrangles and most occur in areas underlain by till.

af Artificial Fill

Artificial fill was mapped where significant volumes of material were utilized for the construction of state and federal highways, town roads and railroad grades, particularly beneath large portions of Interstate I-89. In most cases fill consists of sand and gravel. The large accumulation of refuse in the Moretown Landfill is also mapped as fill.

Glacial and Post-Glacial history of the Waterbury and Middlesex Quadrangles

The surficial geologic materials and landforms mapped in the Waterbury and Middlesex 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. The surficial geologic materials occurring in the region were predominantly deposited during the most recent (Wisconsinan) glaciation in glacial or periglacial environments. The peak of this last glaciation occurred ~25,000 years ago when the ice sheet was thickest and at its farthest extent. During the ensuing ~12,000 years the ice sheet both thinned and retreated across New England deglaciating north-central Vermont between ~14,200–13,800 years ago (Corbett et al., 2019; Halsted et al., 2022; Ridge et al., 2012).

Ice Flow History

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 11 models the ice sheet profile between Burlington, Vermont and Cape Cod, Massachusetts at a time when the ice sheet was at or near its farthest extent, the Last Glacial Maximum ~25,000 years ago. 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 ice sheets flowing across mountains. At the Last Glacial Maximum the ice sheet surface was well over 2 km above the Green Mountain ridge-line and almost 3 km above the ground surface in the Champlain valley (right side of Fig. 11).

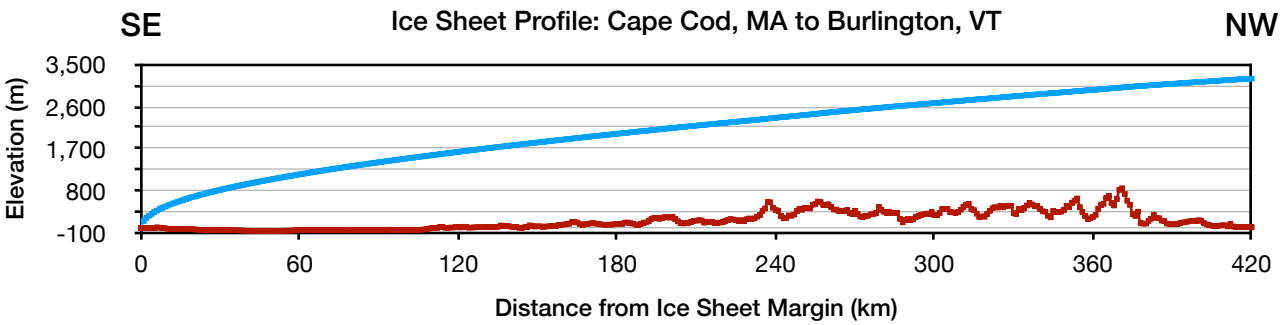

Figure 11: *Profile of modeled ice sheet surface and New England topography between Cape Cod, Massachusetts and Burlington, Vermont. Ice sheet model maintains a constant basal shear stress of 100 kPa. Between 2 and 3 km of deforming glacial ice lay above the Green Mountains and adjacent valleys. Vertical Exaggeration = 18X.*

Striations measured in the map area in addition to those compiled from other sources indicate that regional ice flow was from northwest to southeast across northern Vermont (see maps; Wright, 2015), the orientation of the Figure 11 profile. Striations in the Winooski River valley are deflected parallel to the valley indicating that the valley guided ice flow when the ice sheet had thinned sufficiently to be topographically controlled.

Ice Retreat Timeline

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. As was noted earlier, most of the surficial materials and landforms mapped in the Waterbury and Middlesex Quadrangles was deposited during this period of rapid ice sheet thinning and retreat.

Moraines

Asymmetric topographic steps, where the land surface sequentially steepens and flattens occur on some steep mountain sides (Fig. 12). These landforms are composed of till and are approximately parallel to topographic contours (Fig. 12). Similar landforms are well developed elsewhere in the northern Green Mountains and have been interpreted as recessional moraines by 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 as the ice sheet expands upslope during the winter months, and/or is squeezed out from beneath the ice sheet. Where well preserved, flights of these steps (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.,

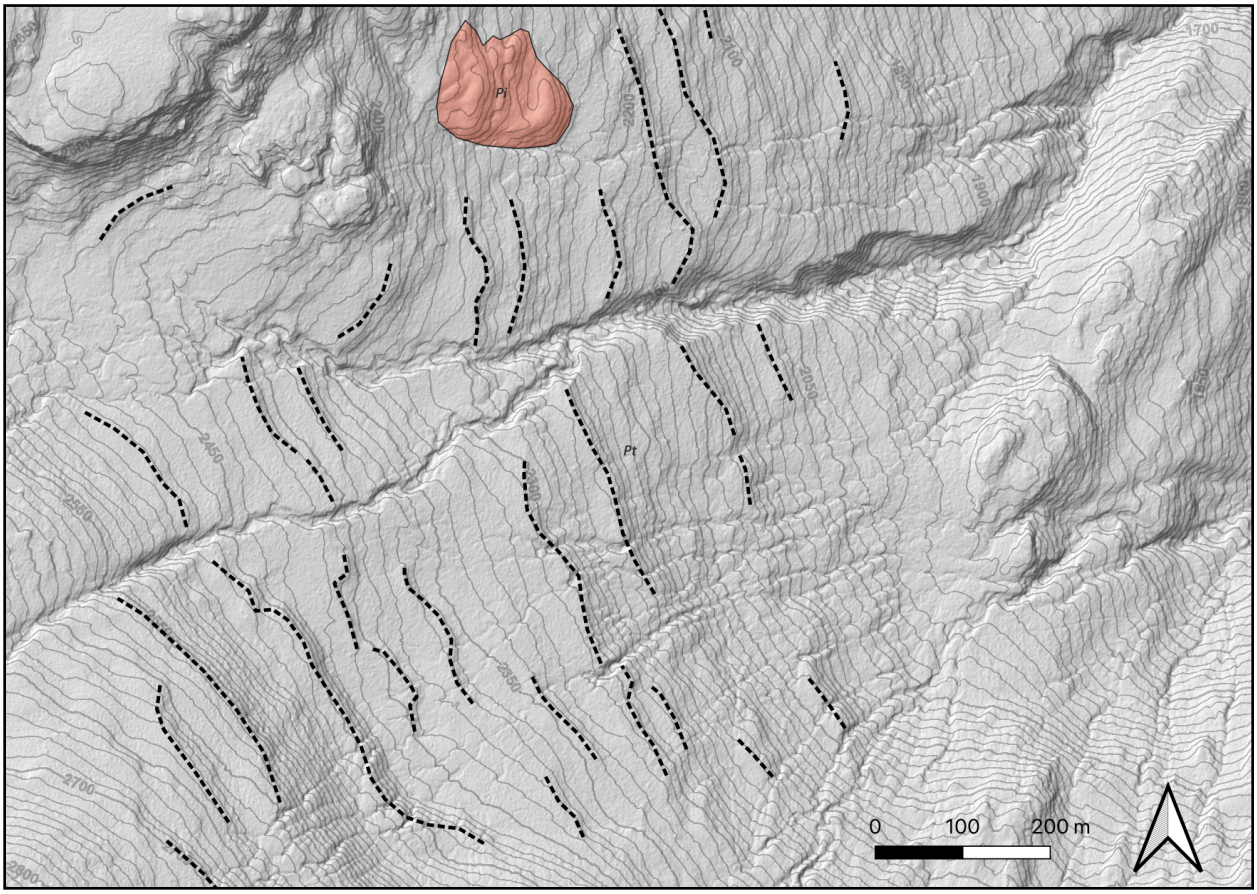

Figure 12: Asymmetric topographic steps composed of till (Pt) are highlighted with black dotted lines in the headwaters of the Ridley Brook valley (eastern flank of the Green Mountains, Waterbury Quadrangle). "Steps" are interpreted as moraines that formed along the ice sheet margin. Flights of subparallel moraines may record yearly positions of the ice sheet as it rapidly thinned. One small area of ice-contact sediments (Pi) also occurs in the area.

2019; Halsted et al., 2022) and is also a common elevation difference between adjacent ridges mapped in the Waterbury and Middlesex Quadrangles (Fig. 12).

Ice Sheet Hydrology

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.

A well-preserved set of meltwater channels occurs in the southwest corner of the Waterbury Quadrangle (Fig. 13). These south-sloping channels are parallel to the inferred margin of the ice sheet. These channels occur in subparallel 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. 13).

Most of the meltwater generated from the rapidly thinning and retreating ice sheet traveled along the base of the ice sheet in subglacial tunnels. Eskers are sinuous ridges of sand and gravel that accumulated in these subglacial tunnels. Only two eskers have been in the Waterbury and Middlesex Quadrangles. One is interpreted from a landform occurring on the western side of the Ridley Brook valley (east side of Camels Hump). Several water wells in

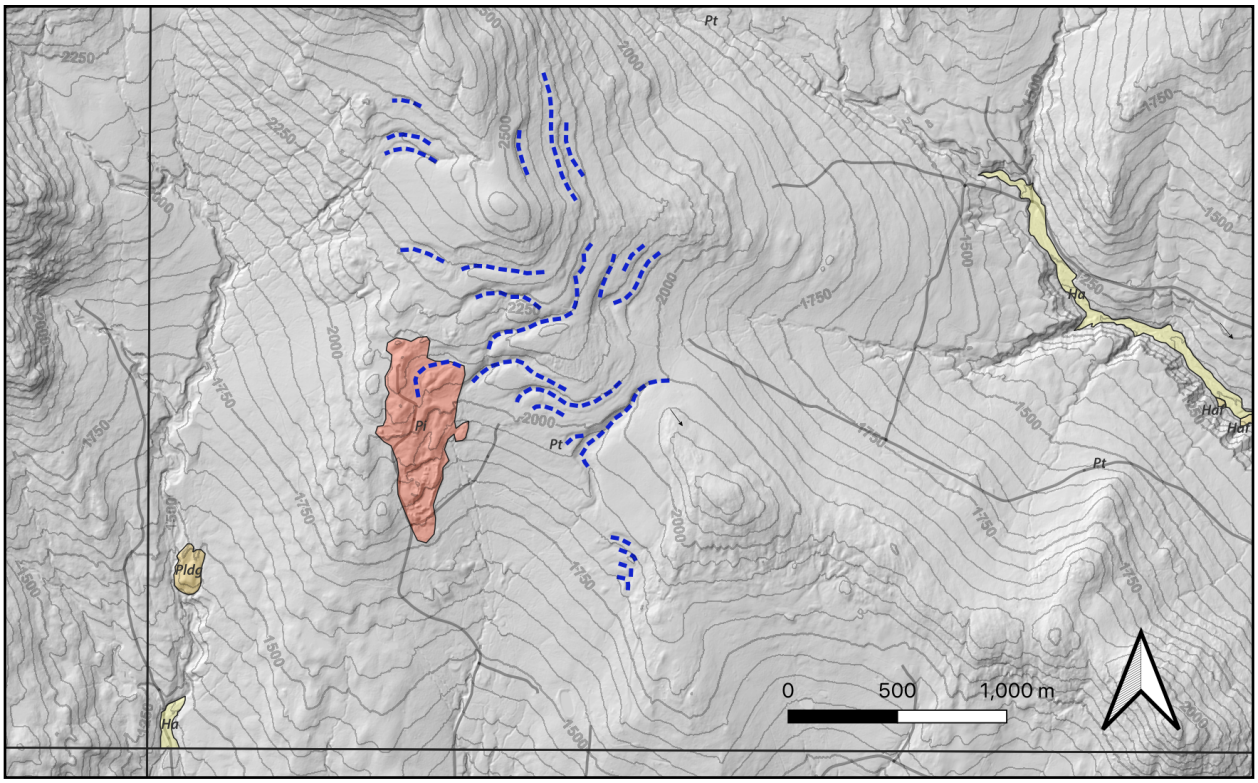

Figure 13: Dotted blue lines mark nested meltwater channels developed on the eastern flank of the Green Mountains in the southwest corner of the Waterbury Quadrangle. These channels likely record meltwater flowing along the margin of the ice sheet as it thinned from year to year. A pit is developed in ice-contact sand and gravel (Pi) deposited by these streams. A small Glacial Lake Granville delta (Pldg) is also shown.

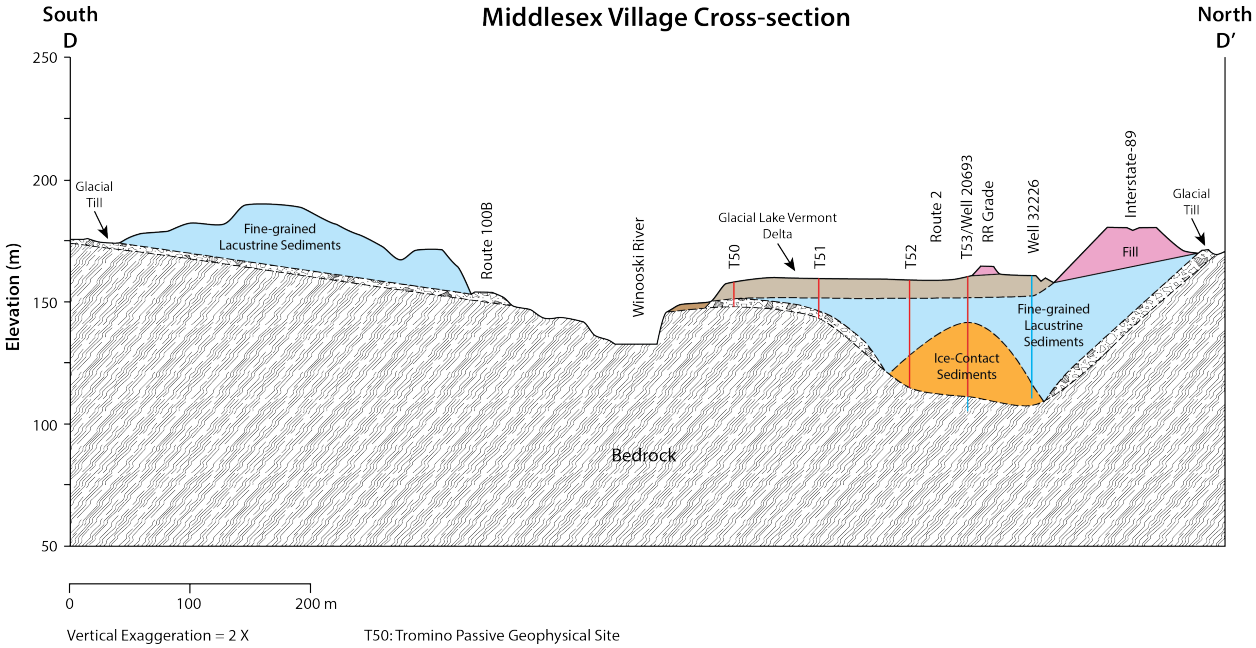

Figure 14: Cross-section across the Winooski River valley at Middlesex Village (see map for location). An old buried channel of the Winooski River is clearly outlined by both the water well and seismic data. Water well logs within the buried channel record extensive sand and gravel deposits lying beneath lacustrine sediments. These coarse sediments are interpreted as ice-contact sediments likely deposited in an esker.

the valley record sand and gravel underlying lacustrine and diamict sediments that was likely deposited in the same subglacial tunnel or subaqueous fan. A large accumulation of sand and gravel occurring in the upper reaches of Ridley Brook may also be sourced from this subglacial drainage system.

A second esker was mapped by Springston and Dunn (2006) in the Winooski River valley immediately west of Middlesex Village and is likely a continuation of the esker inferred to underlie Middlesex Village (Fig. 14). This and other limited exposures of ice-contact sediment along the Winooski River valley imply that a major subglacial drainage system routed meltwater ESE, parallel to the valley, as the ice sheet was retreating across the area.

Glacial Lake History

A series of glacial lakes were impounded by the retreating ice sheet on both sides of the Green Mountains. Larsen (1972a, 1987), 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. 15). The Mad River valley hosted Glacial Lake Granville which drained across the drainage divide at Granville Notch. One small Glacial Lake Granville delta was mapped in the southwest corner of the Waterbury Quadrangle (Fig. 13). Larsen (1972a, 1987) also recognized that the elevation of Lake Granville fell dramatically when the ice sheet retreated north of the Winooski River valley and the three smaller lakes previously restricted to the tributary valleys merged to form one larger lake, Glacial Lake Winooski. This lake drained out the lowest outlet in the basin adjacent to Williamstown Gulf (Fig. 16). 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, 1972a, 1987). Correlation of varve records indicates that Glacial Lake Winooski began ~14,170 yr BP and lasted for ~375 years (Wright, 2022b).

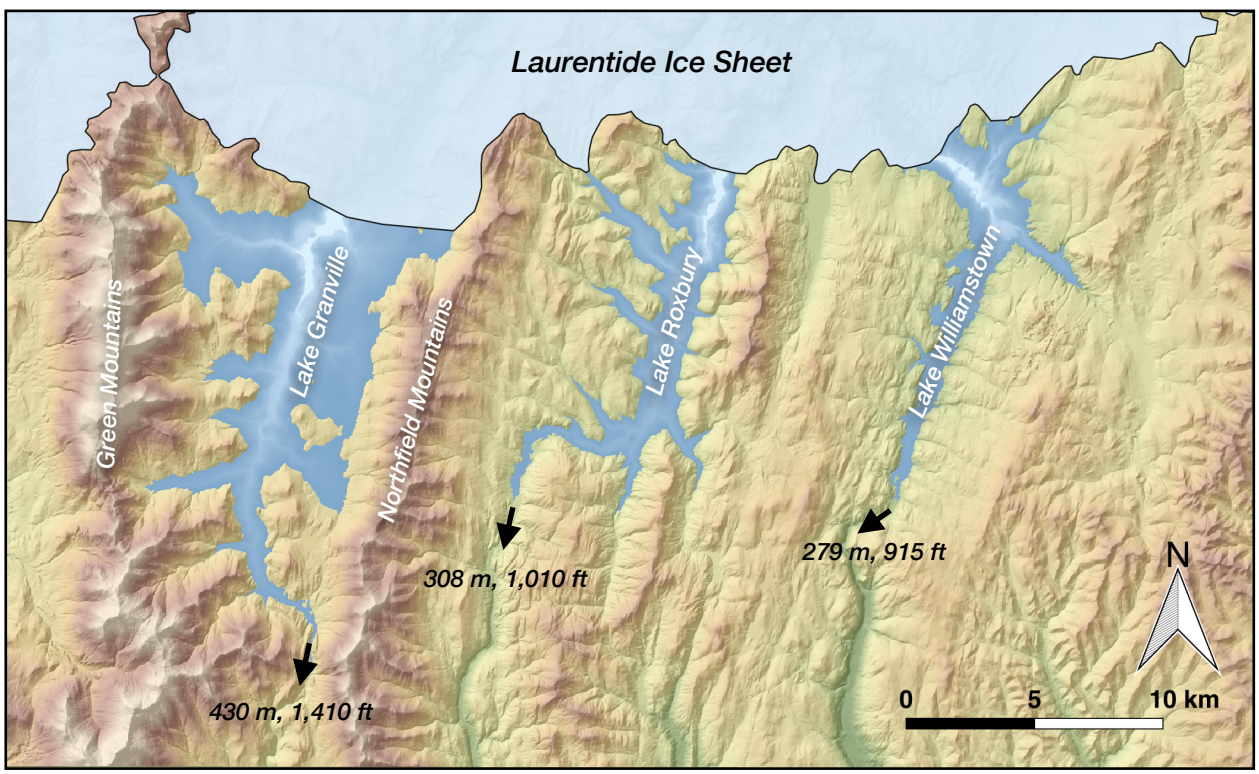

Figure 15: Configuration of glacial lakes in north-flowing tributaries to the Winooski River (Larsen, 1972, 1987; Wright, 2018). Elevations of Lake Granville in the Mad River valley, Lake Roxbury in the Dog River Valley, and Lake Williamstown in the Stevens Branch valley were dictated by the elevations of the drainage divides at the south end of these valleys.

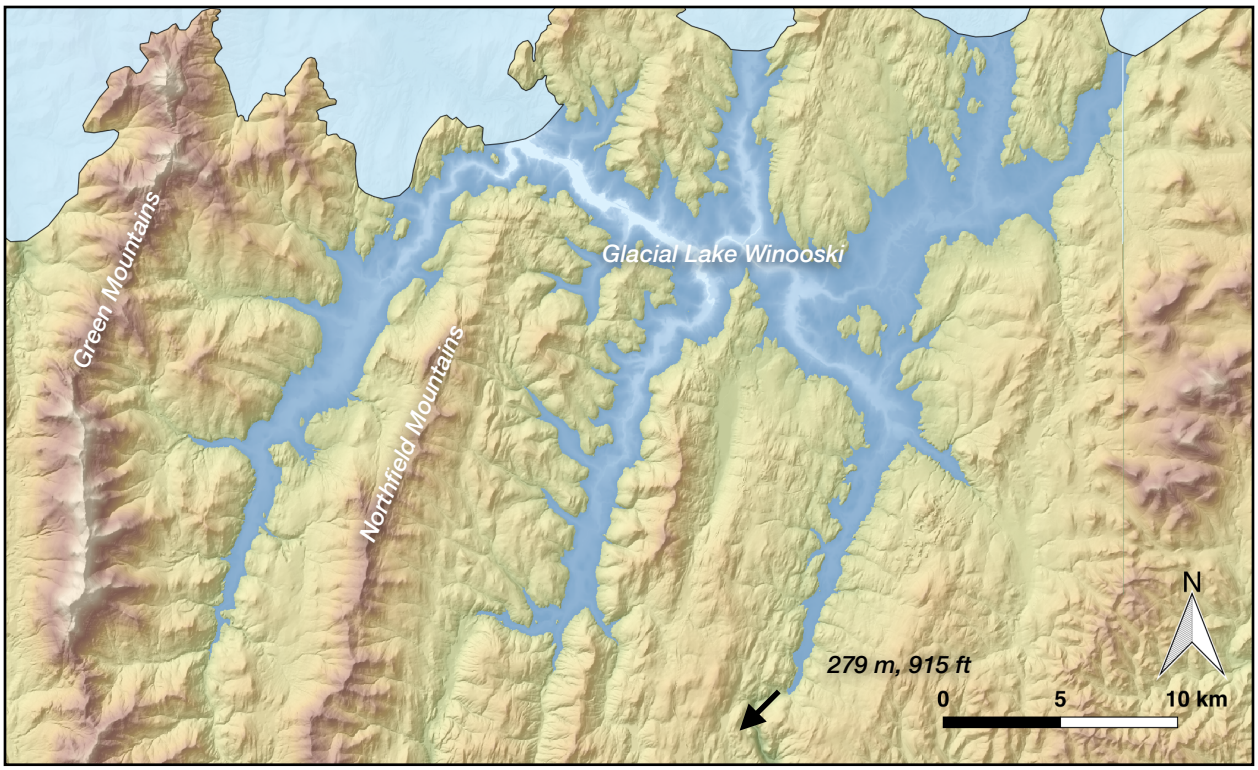

Figure 16: Retreat of the ice sheet to the north and west allowed smaller lakes dammed in the tributary valleys to merge forming Glacial Lake Winooski. This lake drained south through Williamstown Gulf, the lowest drainage divide in the basin.

Retreat of the ice sheet WNW, down the Winooski River valley, uncovered a lower outlet allowing Glacial Lake Winooski to partially drain forming Glacial Lake Mansfield (Larsen, 1972b, 1987; Wright, 2018a). This drainage event is well recorded in exposures of glacial lake sediments at the Waterbury Reservoir and correlation with the varve record dates this event to ~13,794 yr BP (Larsen et al., 2003; Wright, 2022a, b). Further ice retreat into the Champlain valley allowed Glacial Lake Mansfield to drain and the Winooski River valley was flooded as an arm of Glacial Lake Vermont, the very large lake dammed in the Champlain valley by the ice sheet.

Figure 17 shows the projection of these different lakes in the Winooski River and its tributary valleys across the mapped area. As noted in an earlier section, a wide variety of sediments accumulated in these lakes. 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. 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 away the grain size dropped to fine sand then silt and clay as the energy of this depositional system correspondingly dropped. These younger, fine-grained lacustrine sediments bury older, coarser-grained sediments in most areas and are exposed across broad areas (e.g. Fig. 18).

Deltas deposited by streams flowing off the surrounding mountains were recognized in many areas e.g. the Glacial Lake Winooski delta shown in Figure 9. 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. In several areas Glacial Lake Mansfield deltas consist of relatively thin veneers of sand and gravel deposited on top of silt and clay.

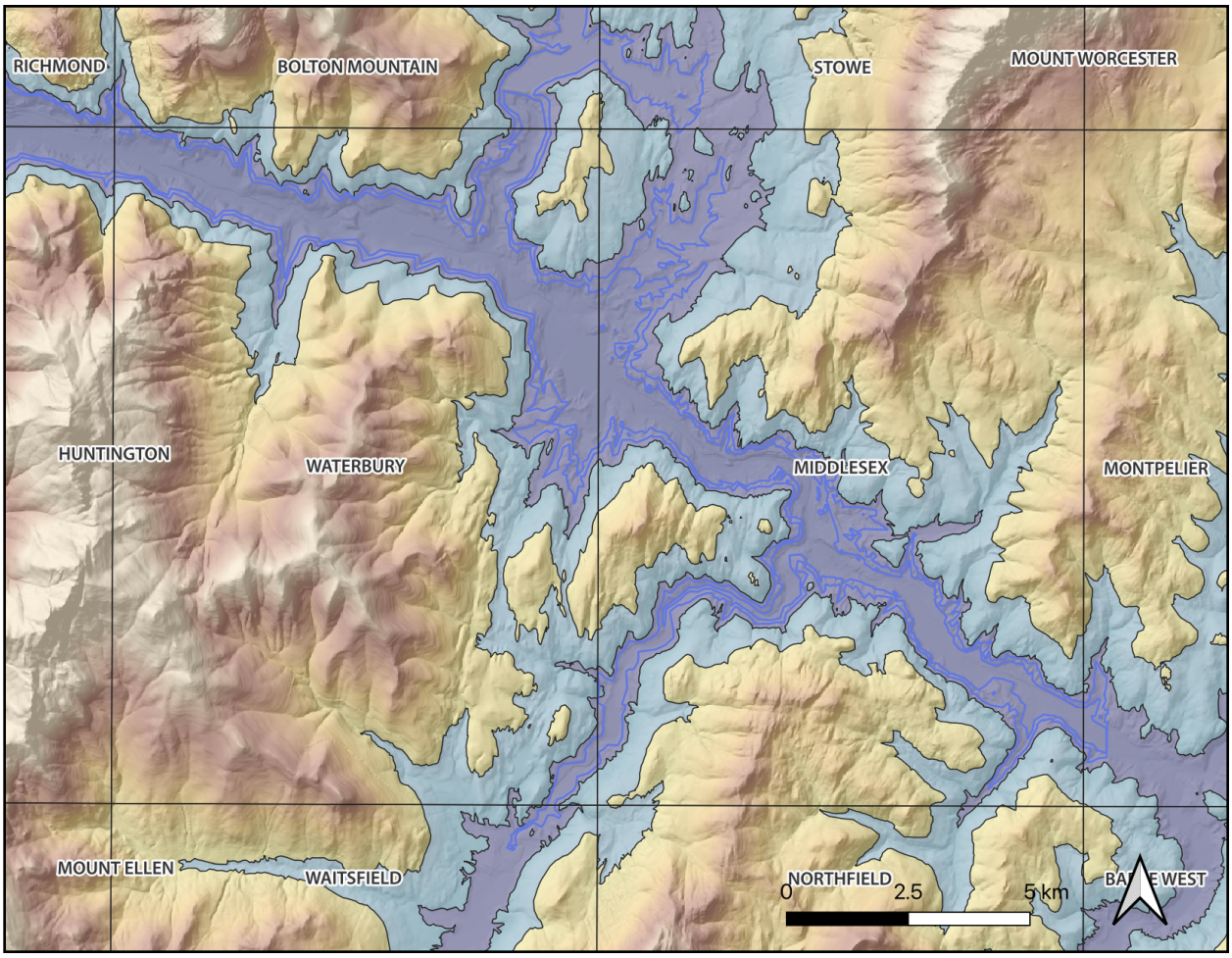

Figure 17: Projected glacial lake shorelines across the Waterbury, Middlesex, and adjacent quadrangles indicate that extensive areas were flooded and accumulated lacustrine sediments as the ice sheet retreated. Glacial Lake Winooski (light blue) is the highest-elevation lake, followed by Glacial Mansfield (grey blue). Two stages of Glacial Lake Vermont are shown with solid blue lines.

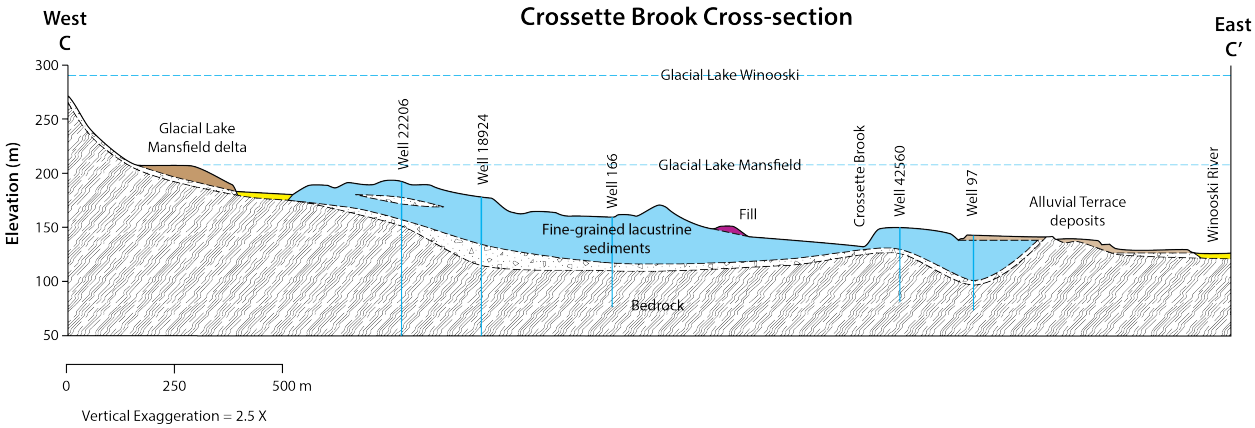

Figure 18: Cross-section C-C' is dominated by fine-grained lacustrine sediment. A Glacial Lake Mansfield delta occurs on the west side of the section. The Winooski River has eroded large volumes of glacial lake sediments from the valley and left veneers of alluvium on terraces above the modern flood plain.

This is particularly well displayed in the Thatcher Brook area (Middlesex Quadrangle, north of Waterbury Village; Fig. 19). It appears that a thick succession of fine-grained lacustrine sediments accumulated in this valley when it was flooded by Glacial Lake Winooski. When this lake partially drained the newly established lake, Glacial Lake Mansfield, was quite shallow allowing Thatcher Brook and its tributaries to quickly build thin deltas that prograded across the floor of the shallow lake. A similar situation exists south of Waterbury Village along Crossette Brook.

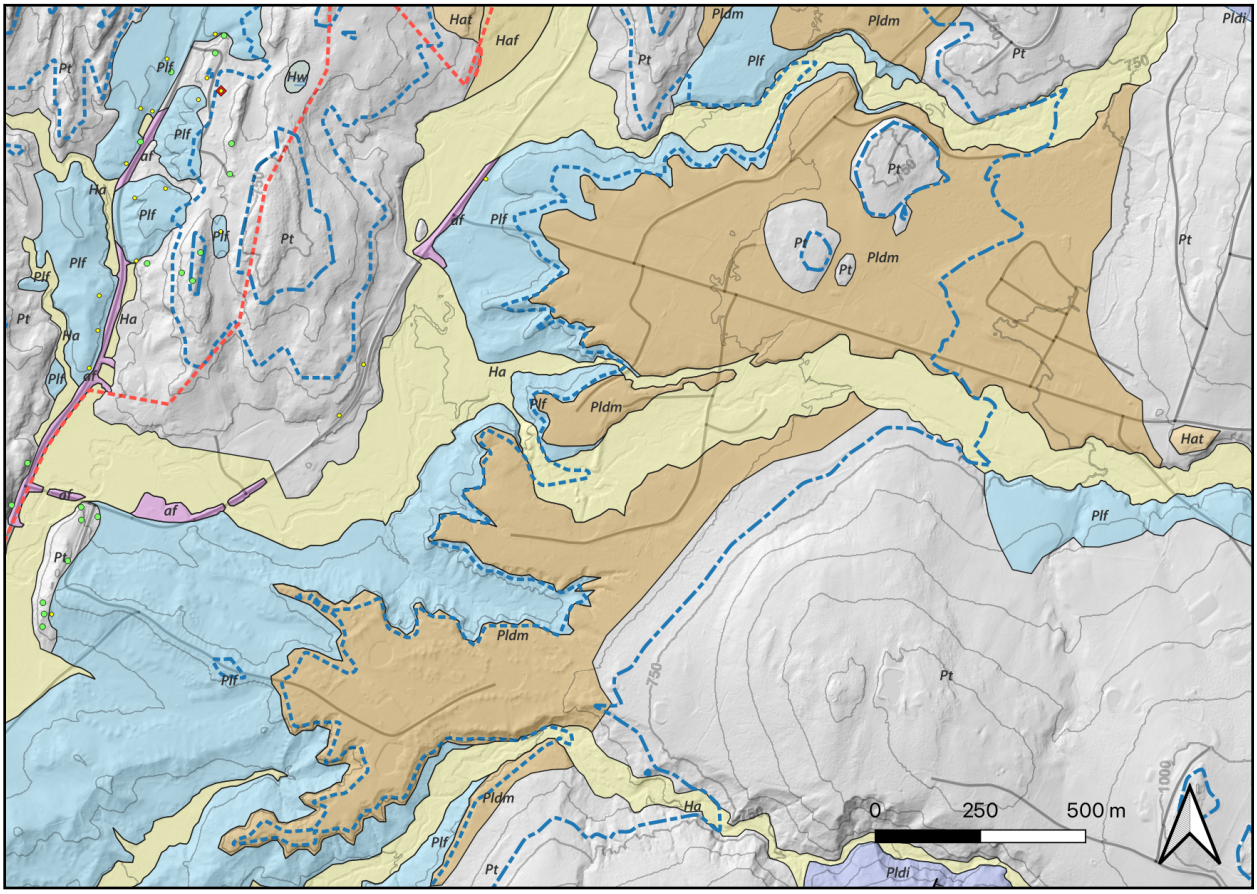

Figure 19: Broad, gently sloping terraces of sand and gravel lying between two stages of Glacial Lake Mansfield (dot-dash and dotted blue lines) are interpreted to be deltas (Pldm) deposited in Glacial Lake Mansfield by tributaries to Thatcher Brook. The modern brooks have eroded channels through both the deltaic sediments and the older, fine-grained lacustrine sediments (Plf) deposited in Glacial Lake Winooski.

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 and the last glacial lakes drained as being "post-glacial" a time interval that includes both the latest Pleistocene and the Holocene Epochs, roughly the last 13,000 years. During this time interval 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 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.
Buried Channels: The channels streams began eroding through glacial lake sediments were frequently not coincident with pre-glacial channels. This study documents two areas where the modern Winooski River is flowing

across bedrock and the river's older, much deeper channel is buried by glacial sediments. Cross-sections were drawn at both locations. Both also occur at waterfalls utilized for power production. A Tromino passive seismic instrument was used to interpret the depth to bedrock. At Bolton Falls, near the western boundary of the Waterbury Quadrangle a cross-section shows that the modern channel of the river is perched on bedrock adjacent to a much deeper bedrock channel (Fig. 20). Ice-contact sediments likely occur within this old channel, but no water well data is available to confirm this. Immediately downstream, opposite the modern falls, lies a hill composed of fine-grained lacustrine sediments. These are the materials that largely fill the old channel that the modern river has yet to find. In Middlesex Village a deeply buried bedrock channel occurs directly under the Village, north of the modern river channel. This channel is filled with both ice-contact and younger fine-grained lacustrine sediments (Fig. 14).

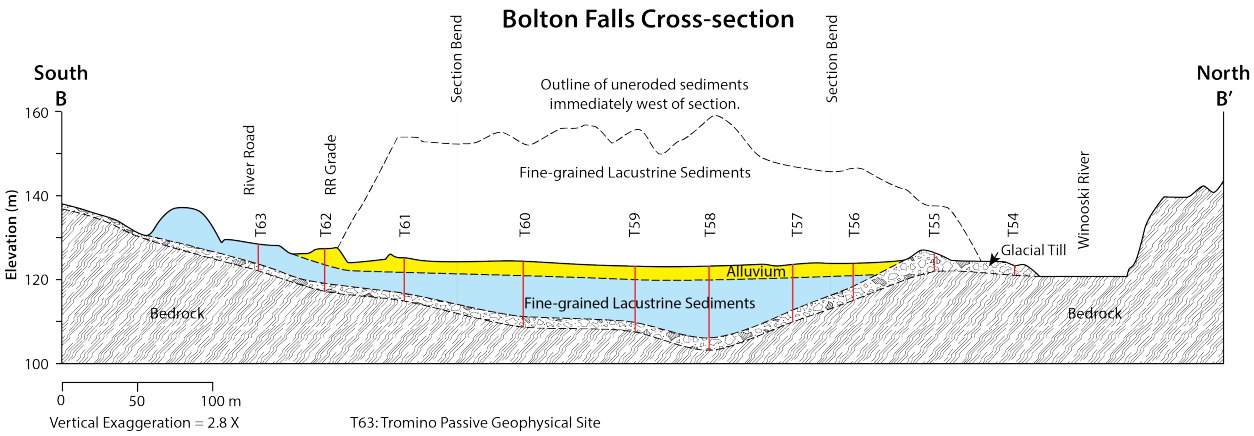

Figure 20: A Tromino passive seismic instrument was used to ascertain the depth to bedrock across the Winooski River valley just upstream from Bolton Falls (see map for location). The modern channel of the river flows across bedrock on the north side of the section. A much deeper bedrock channel to the south is buried by lacustrine sediments. Dashed line is used to outline the topographic profile of the hill of uneroded fine-grained lacustrine sediments immediately west of the section.

Alluvial fans, on a variety of different scales, are a common landform deposited during the Holocene (see earlier description of these landforms). Many small fans occur in the mapped area. 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). Large storms, forest fires, disease, land-clearing, and logging have all served to trigger sedimentation on alluvial fans.

Landslides were mapped where they were encountered on field traverses or were visible on the LiDAR imagery. Landlslides were particularly common along the east bank of Jones Brook in the SE corner of the Middlesex Quadrangle (Fig. 21). The surficial material underlying that area all appeared to be glacial till, however this area is all below the elevation of Glacial Lake Winooski and it's possible that this area is actually underlain by stratified diamict. If so, inclined beds of fine-grained lake sediment may have served as the failure planes for these landslides.

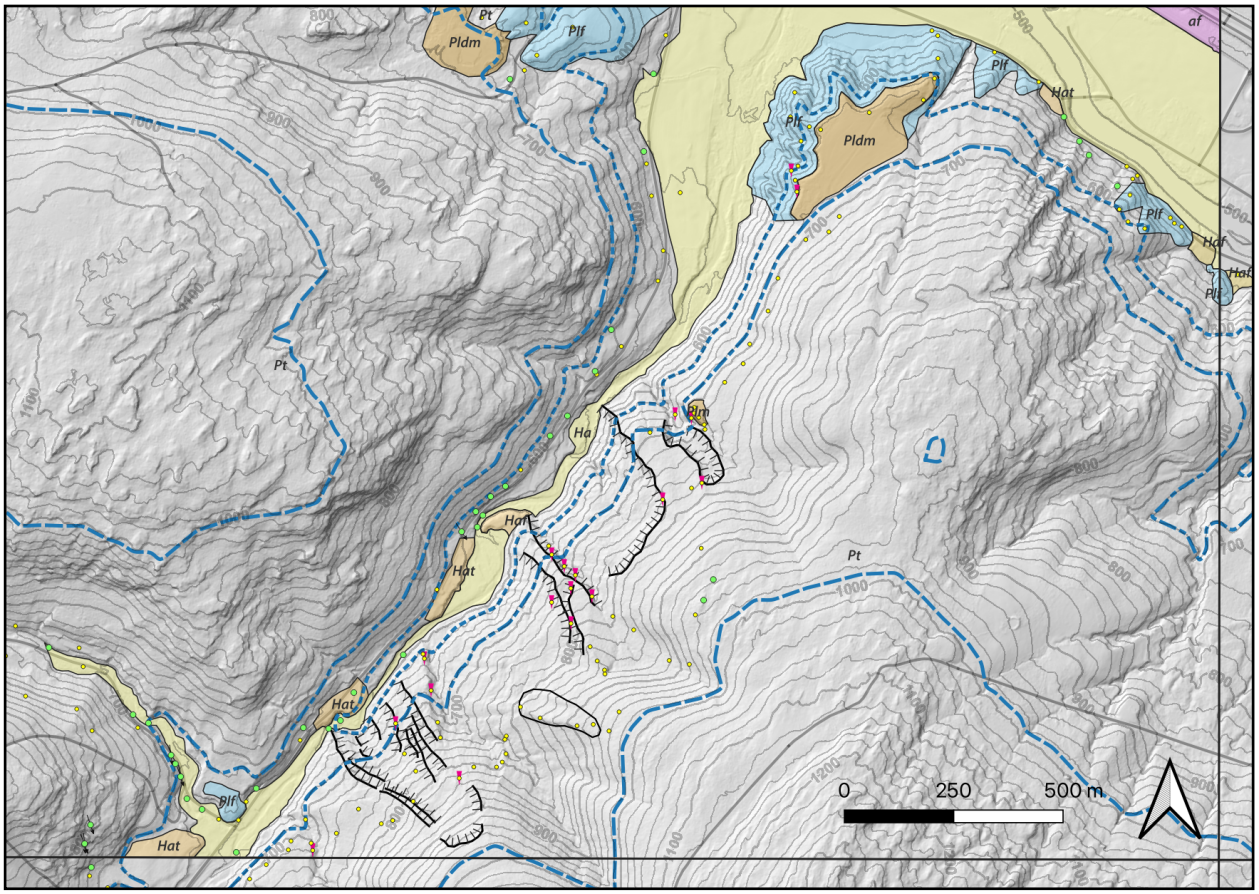

Figure 19: Landslide scarps (hachured lines) are common along the east side of Jones Brook in the SE corner of the Middlesex Quadrangle. Additionally, one debris flow is shown with dotted pattern. Failure areas all appear to be underlain by glacial till (Pt). Dashed blue line marks the projected shoreline of Glacial Lake Winooski whereas dash-dot and dotted blue lines mark the shorelines of two stages of Glacial Lake Mansfield. Uneroded remnants of a Glacial Lake Mansfield delta (Pldm) occur at the mouth of the valley deposited on older fine-grained lacustrine sediments (Plf).

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