Surficial Geology of the Sutton 7.5-Minute Quadrangle, Northern Vermont[1]

Stephen F. Wright
Department of Geography and Geosciences, University of Vermont
March, 2025

Wetlands sediments fringe the perimeter of May Pond in the northwest corner of the Sutton Quadrangle.

Table of Contents

---

[1] Report describes Vermont Geological Survey Open File Map: VG2025-2. Research supported by the U.S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G23AC00462. 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 Sutton 7.5-Minute Quadrangle was mapped during the summer/fall of 2024. Mapping during June was assisted by eight University of Vermont students. Almost 2,500 separate field observations were recorded utilizing a digital app and LiDAR hillside imagery and contours as a base map. Considerable detail has been added to mapping conducted during the 1960's by Stewart (1956-1966a) at a scale of 1:62,500 and later incorporated into the Surficial Geologic Map of Vermont by (Stewart and MacClintock, 1970). A surficial geologic map and four geologic cross-sections compliment this report (Wright, 2025b).

The Sutton Quadrangles contains a variety of glacial landforms and sediments that formed as the Laurentide ice sheet flowed across northernVermont and then thinned and retreated from the area. Glacial striations/chattermarks are poorly preserved on the area's underlying bedrock. However, streamlined till bedforms parallel the few striations observed and are oriented generally NNW to SSE. These indicate that the ice flow indicators preserved in the quadrangle formed when the ice sheet no longer flowed across the Green Mountains, but instead formed when the ice sheet was topographically controlled and flowed generally south parallel to the regions valleys.

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. Till in the valley bottoms with many very large erratics, particularly south of Lake Willoughby, may be ablation till let down on the ground surface as the ice sheet thinned. Most of the till cover is thin, but many areas exist where local stream erosion indicates till thicknesses exceed 20 m. Most rocks occurring in the till are sourced locally from metamorphic and intrusive rocks underlying the nearby area.

During ice retreat rapid summer melting of ice and snow generated large volumes of water that flowed both along the margin of the ice sheet and sub glacially. Evidence of ice-marginal drainage are the many channels mapped across the quadrangle. While isolated channels occur, most are preserved as subparallel flights as successively lower elevations and may record yearly thinning of the ice sheet.

Eskers are well-preserved in both valleys cross the quadrangle despite having been extensively quarried from both active and disused gravel pits. These and other related ice-contact deposits of sand/gravel comprise the majority of sediments/landforms occupying these valleys particularly near the drainage divides in those valleys and SSE to the quadrangle boundary. Both the Sutton and Passumpsic River (West Branch) valleys are broad, low gradient valleys filled with minor alluvium and abundant wetlands. While no water wells exist to prove this hypothesis, it seems likely that the modern alluvium and wetlands sediments mapped in these valleys are underlain by braided outwash deposits sourced from till eroded by both ice-marginal and subglacial drainage. The valley sides are flanked by terraces composed of either outwash or kame derived stream sediments.

Limited areas within the quadrangle are underlain by several different facies of glaciolacustrine sediment. These sediments are limited to the Lake Willoughby and Willoughby Brook/Crystal Lake valleys NNW of the drainage divides in each valley. These sediments accumulated, respectively, in two ice-dammed lakes that formed when the ice sheet retreated past these drainage divides. These lakes grew and eventually merged together utilizing the lower outlet at the headwaters of Willoughby Brook (US Route 5 valley). Further northward retreat of the ice sheet uncovered an outlet that drained these lakes setting the stage for a variety of erosional/depositional processes that have dominated the post-glacial history of the area.

Stream erosion is the most significant process affecting the landscape since ice sheet retreated and the glacial lakes drained. Streams in the area are small and consequently there are relatively small volumes of eroded sediments are stored as alluvium along stream courses. A much larger volume of stream-eroded sediment is stored in alluvial fans that have formed where tributary streams flowing off the steep mountainsides deposit eroded material at the valley bottoms.

Debris flow are common below the Mount Pisgah cliffs and deposits of transported material make up large aprons of colluvium that extend between the bottom of the cliffs and Lake Willoughby. Several small debris flows occurred on this slope during the June 2024 mapping season. Small landslides are common along many of the streams in the region. Only one large landslide was mapped in the area and that occurs in an unpopulated area along the western side of the Passumpsic River (West Branch) valley.

Introduction

This report summarizes the results of mapping the surficial geology of the Sutton 7.5-minute Quadrangle during the 2024 field season (Fig. 1). This work is part of a larger project that included earlier mapping of the Newport and Newport Center Quadrangles (Wright, 2024c, 2025a). The new Sutton Surficial Geologic Map map significantly updates earlier mapping by (Stewart, 1956-1966b) and provides (1) a foundation for understanding the glacial history of the area, (2) a framework for understanding groundwater flow between recharge areas in the uplands and discharge to area rivers and Lake Willoughby, and (3) a means of assessing potential potential geologic hazards, e.g. landslides. A detailed surficial geologic map and cross-sections accompany this report (Wright, 2025b).

Location and Geologic Setting

The location of the Sutton Quadrangle is shown on the adjacent map of northeastern Vermont (Fig. 1). This quadrangle lies astride the drainage divide between the generally south-flowing Passumpsic River basin and the generally north-flowing rivers draining the Lake Memphremagog basin. The quadrangle contains the southern half of Lake Willoughby and the mountains surrounding the lake.

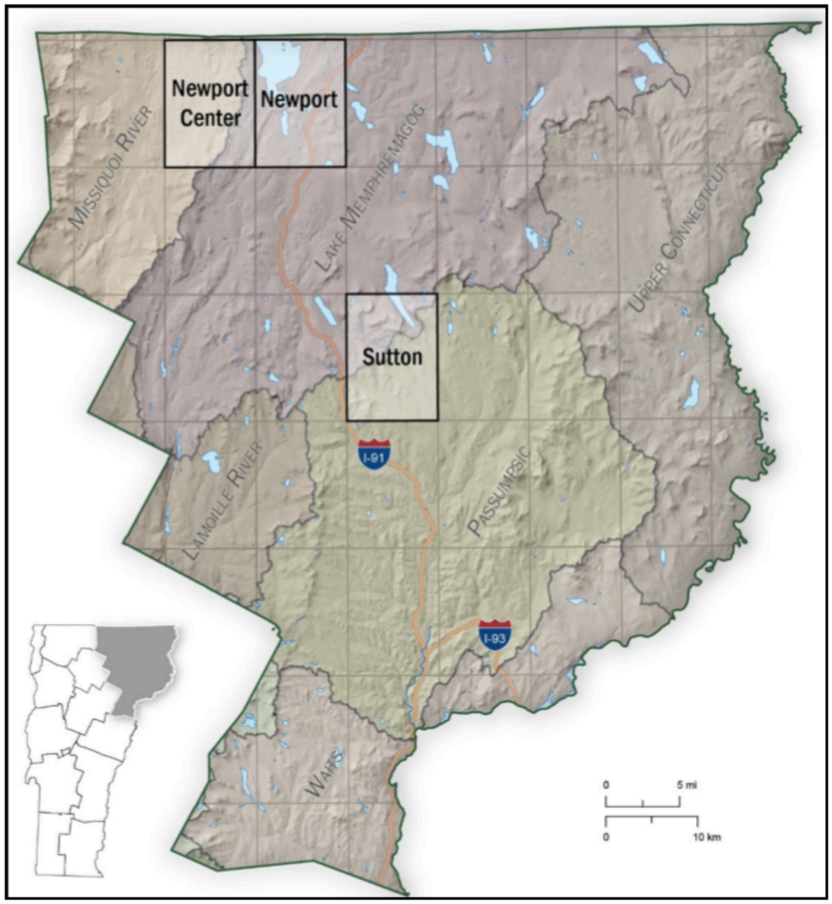

Figure 1: Map depicts the location of the Sutton quadrangle (the focus of this report) and the large-scale drainage basins in northeastern Vermont. Also outlined are the Newport Center and Newport Quadrangles mapped earlier as part of this same project (map from the 2023 RFP issued by the Vermont Geological Survey).

The bedrock geology of the Sutton area is depicted on the Vermont Bedrock Geologic Map (Ratcliffe et al., 2011; Fig. 2). Rocks underlying this area fall into two groups. The first of these consists of meta-sedimentary rocks deposited during the Silurian and Devonian time periods and subsequently deformed and metamorphosed during the Acadian Orogeny (Fig. 2). Plutonic igneous rocks, generally of granodioritic composition, comprise the second group of rocks and were intruded during the Acadian Orogeny (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 northern New England was sufficiently thick to completely cover the region's mountains. As the ice sheet thinned and retreated across the area a wide variety of sediments were deposited (1) directly by the ice sheet, (2) in contact with or adjacent to the ice sheet, and (3) in glacial lakes that formed in north-draining valleys. The geologic map that accompanies this report shows the areal distribution of these sediments and cross-sections show their vertical extent. This report describes these mapped sediments and landforms and provides an interpretation of the glacial history of this area based on those mapped materials and landforms.

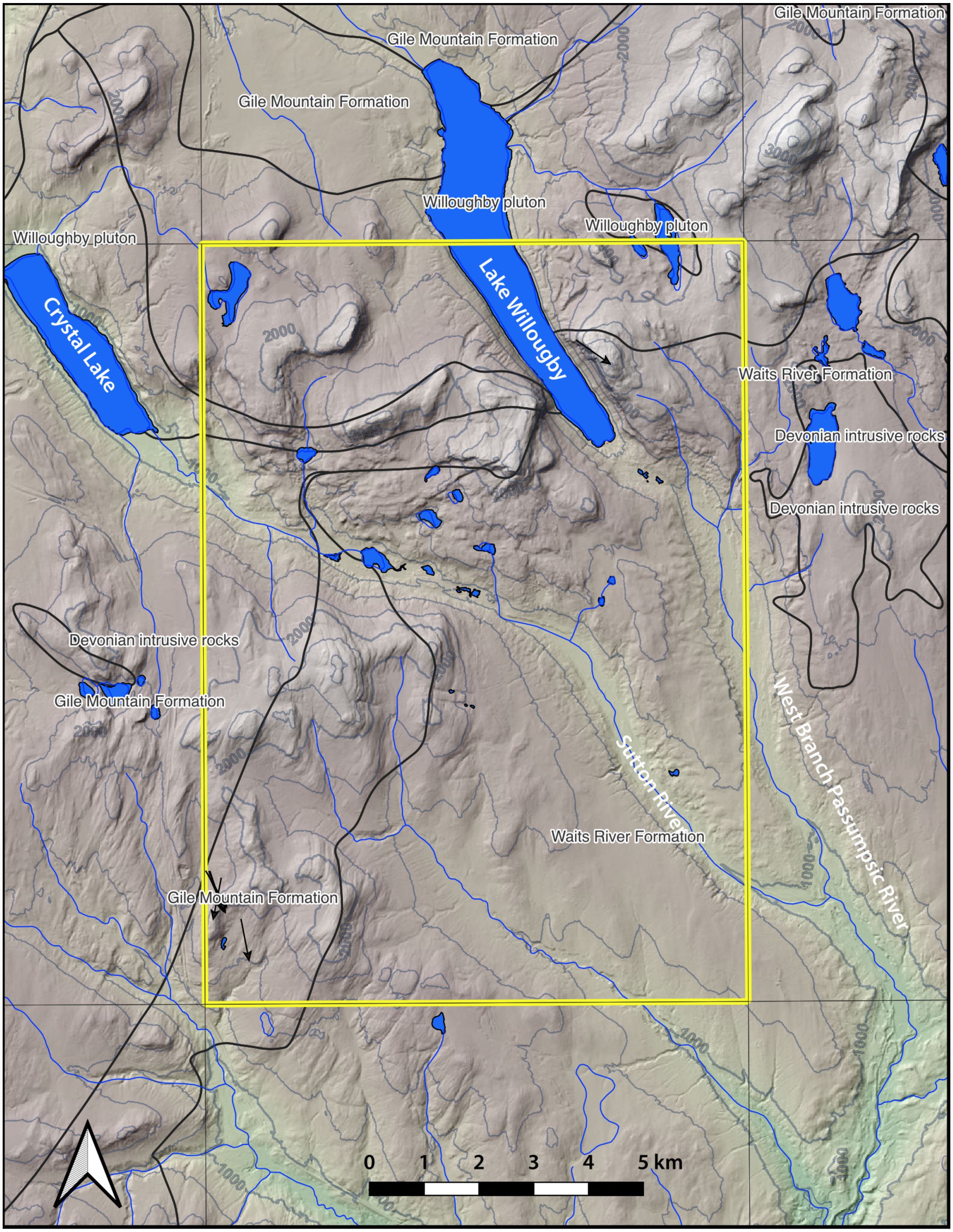

Figure 2: Bedrock geology of the Sutton Quadrangle and surrounding areas consists of deformed Silurian/ Devonian meta sedimentary rocks intruded by large Devonian plutons.

Prior Work

The Sutton 7.5-minute Quadrangle lies in the northeast quadrant of the Lyndonville, Vermont 15-minute quadrangle, the surficial geology of which was mapped by Stewart (1956-1966c; Fig. 3). Mapping was conducted at a scale of 1:62,500 on quadrangle maps published during the 1950's with topography from the 1920's. The geology depicted on this map was incorporated into the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970).

Stewart's map (Fig. 3) shows the two valleys that transverse this area are largely underlain by moraine deposits, ice contact sediments, and wetlands whereas the upland areas are covered by different thicknesses of glacial till. Earlier geological work in the area recognized that the drainage basin of the modern Lake Memphremagog once hosted a much larger glacial lake, Glacial Lake Memphremagog (Hitchcock, 1908) although this lake did not extend into the Sutton Quadrangle. Stewart and MacClintock (1969) recognized that both valleys transversing the Sutton quadrangle hosted glacial lakes following ice retreat across the drainage divides in each valley, but Stewart's map doesn't show any lacustrine sediments (Fig. 3).

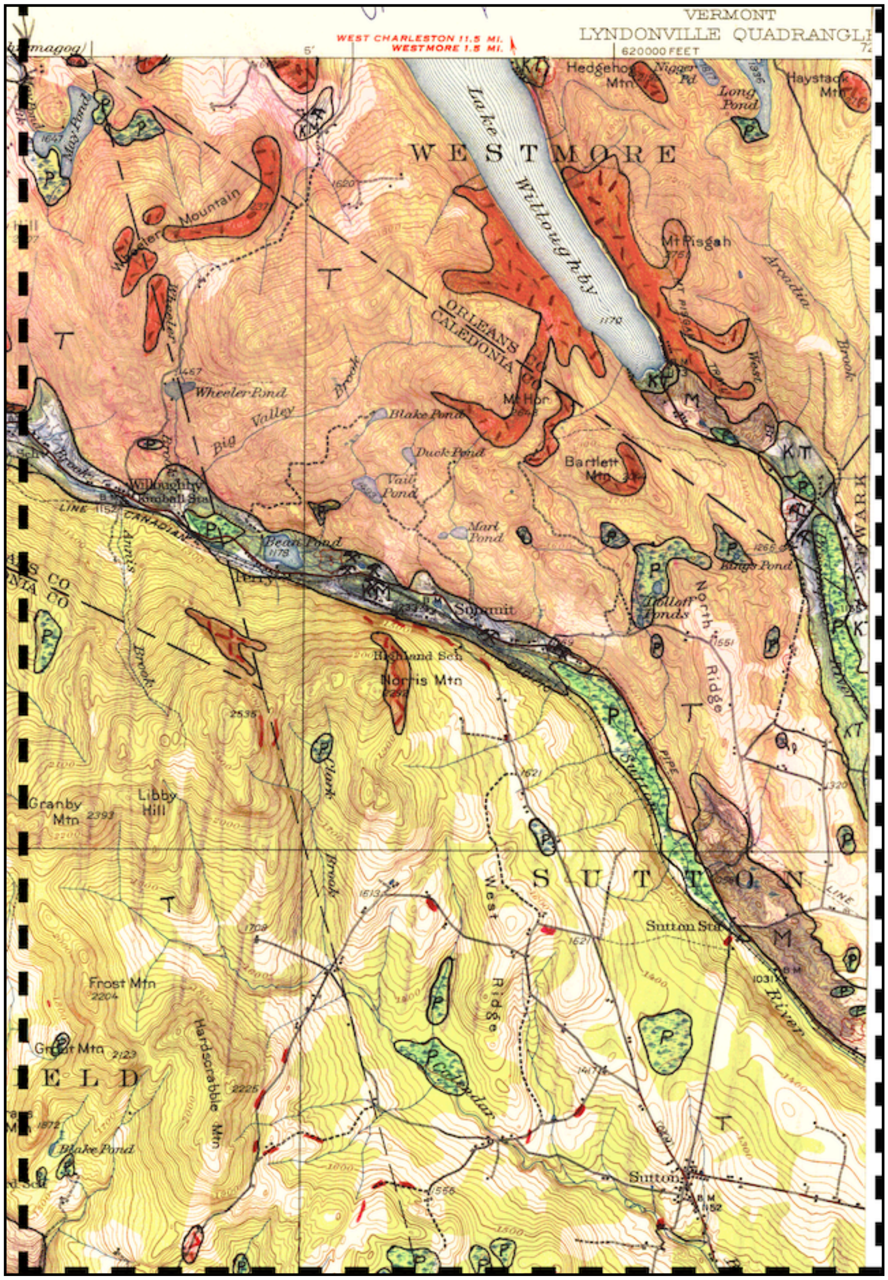

Figure 3: Black dashed line outlines the surficial geology of the northeast quadrant of the Lyndonville 15-minute as interpreted by Stewart (1956-1966).

A field guide to the glacial geology of the Lake Willoughby valley was published by Ebbett (1988). This field guide describes several features key to understanding the glacial history of the area including (1) the esker and ice-contact landforms at the south end of the lake, (2) the hummocky till landforms, also at the south end of the lake, and (3) the deeply eroded ice-marginal channels occurring above the eastern side of the lake at the quadrangle's northern border. Ebbett (1988) accurately mapped these features without the benefit of LiDAR imagery.

Sediment cores retrieved from both Duck Pond and Vail Pond in the Sutton Quadrangle were utilized by Noren et al (2002) as part of a larger project to assess storm frequency across northern Vermont. The oldest sediments dated from Duck Pond were 12,882-13119 cal. yrs BP whereas those from Vail Pond are 9,297-9,467 cal. yrs BP. These dates constrain the timing of ice sheet retreat from the area.

Methods

Traditional field techniques and digital mapping were employed to generate a surficial geologic map of the Sutton Quadrangle. Specifically, ~2,500 separate field observations recording the 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 (Fig. 4). Most field observations are located with an accuracy of 3–10 m. Field mapping utilized LiDAR hillshade imagery with LiDAR-derived contours as a base map supplemented by traditional topographic maps and satellite imagery. Field observations were imported into GIS software (QGIS) and utilized to draw contacts between different surficial mapping units using both the older LiDAR hillshade base map and a newer version that became available during the summer of 2024. Mapping units are consistent with those used on recently completed surficial geology maps within the Montpelier 1-degree sheet (e.g. Springston, 2019; Springston and Wright, 2024; Wright, 2025a) and conform to the unified set of mapping units developed by the Vermont Geological Survey.

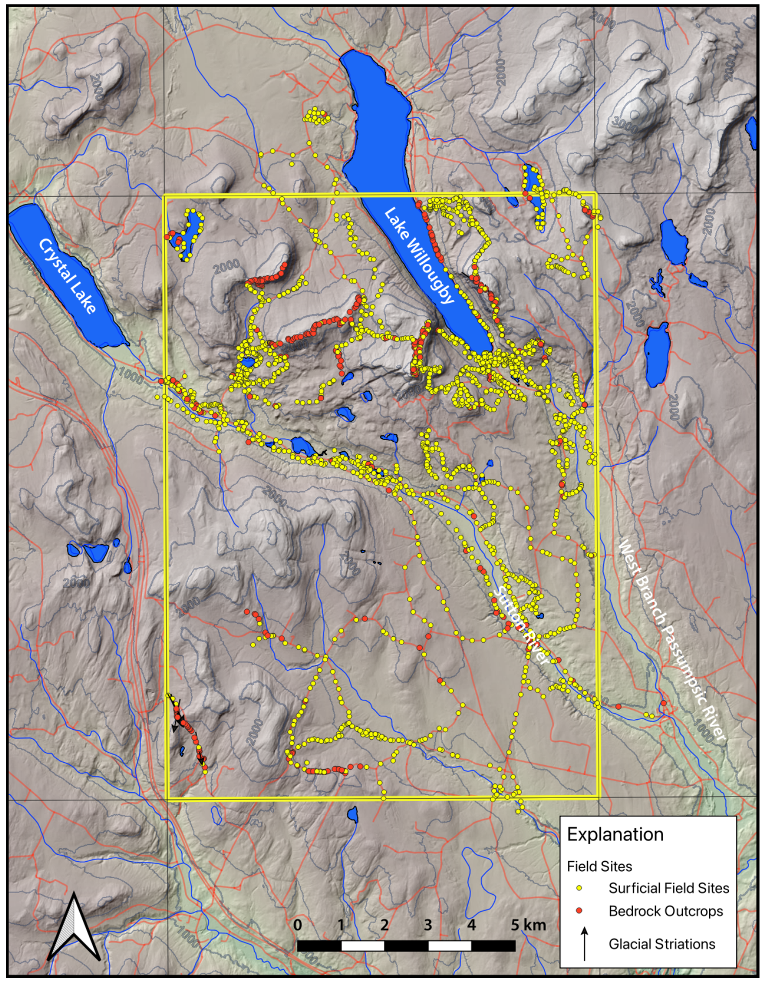

Figure 4: Map shows the location of ~2,500 field sites across the Sutton Quadrangle where observations of surficial materials, landforms, or bedrock were made.

Four geologic cross-sections were constructed and are included both on the geologic map and in this report. Surface observations were augmented by private water well logs. In the area south of Lake Willoughby several surveys were conducted using a a passive seismic device (Tromino). These seismic data were processed to determine the depth to bedrock in the surveyed area; data that was used to construct cross-sections A-A' and B-B'.

Eight University of Vermont undergraduate students assisted with the field mapping effort during the month of June, 2024. The author gratefully acknowledges the work of Amelia Bohling, Ciara Hagan, Sicilia Jantzen, Luke Jodice, MJ (Mia) Moline, Heather Morecock, Casper Vanderpoorten, and Zachary Winigrad. Assistance was also provided by Vermont Geological Survey geologist Peter Strand during several field days.

Sutton Surficial Geologic Map

The surficial geologic map that accompanies this report shows the aerial distribution of different types of surficial materials, landforms constructed of these materials, glacial striations, landslides, and other geological phenomena. During the spring of 2018 the Vermont Geological Survey developed a uniform set of mapping units which are utilized on the Sutton Surficial Geologic Map (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. However, in most areas the location of these contacts is interpreted from a combination of field observations, distinctive landforms, and aerial imagery. Every effort was made to locate these contacts as accurately as possible on the geologic map.

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, 2024c, 2025a). These materials and landforms fall into four 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 subsequently gradually thinned and retreated across the area. (2) Ice-Contact Deposits generally consist of fluvial sediments deposited beneath, adjacent to, or in the immediate vicinity of the retreating ice sheet. (3) Lacustrine Deposits were deposited in ice-dammed glacial lakes that occupied the region's valleys during ice sheet retreat. (4) Holocene Deposits largely consisting of older glacial or lacustrine surficial materials that have been eroded and redeposited by a variety of 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 (see red dots in Fig. 4). Most outcrops occurring along trails, town roads, and state highways were mapped. However, no attempt was made to map all outcrops, especially those occurring in the upland areas where outcrops are numerous and closely spaced. Outcrops are abundant where glacial till and other surficial materials are thin, generally in the upland areas. Streams in the area have also frequently eroded down to bedrock.

Figure 5: Weathered granite outcrops on Wheeler Mountain (foreground) and elsewhere in the region rarely preserve glacial striations or chatter marks. Cliffs below the west-facing side of Mount Pisgah are visible in the distance.

Despite numerous traverses across bedrock terrains and extensive bedrock exposures along some roads, well preserved glacial striations/grooves were only observed in one small area in the SW corner of the quadrangle and here they aligned NNW-SSE (Fig. 4), a direction similar to the 165 alignment of friction cracks reported on Wheeler Mountain by Ebbett (1988; his Fig. 14). However, in most areas bedrock exposures were too weathered to preserve striations/grooves/chatter marks (Fig. 5).

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 in landslides where the till texture varies from dense and silt-rich across the metasedimentary rocks and loose and sandy across the plutonic rocks. Rocks embedded within the till are angular to subrounded and can include very large boulders. Till deposited across much of the quadrangle consists of materials eroded, deformed, and deposited beneath the ice sheet as lodgment till. Within the valleys, particularly near the drainage divides, the till may be largely derived from material that accumulated on top of the thinning ice sheet via landslides from the bordering, recently exposed mountains, ablation till. The ground surface in these areas is littered with very large erratics, mostly of granitic composition (Fig. 6). No attempt was made to distinguish these types of till on the geologic map. Frost heaving, plant roots, and animal borrows have loosened the till near the surface. The thickness of till in the upland areas of the quadrangle varies considerably. In many areas, the till is thin (less than 2 to 3 meters) and abundant outcrops are present. However, in other areas the till is sufficiently thick to completely bury the underlying bedrock.

Figure 6: UVM interns Zachary Winigrad, Casper Vanderpoorten, and MJ Moline provide scale for a large angular granitic erratic occurring in the valley bottom along the Mount Pisgah trail south of Lake Willoughby. Large erratics are abundant in the surrounding area.

Streamlined Till Ridges

Streamlined till ridges/grooves are visible in some areas using the newly available high-resolution LiDAR imagery. These are inferred to have formed sub glacially and provide another means to assess at least the last direction of ice sheet motion across this area. These ridges and grooves are aligned generally north-south and parallel the orientation of the striations/grooves/chatter marks recorded in the area.

Moraine Deposits (Ptm)

Three broad areas of the Sutton Quadrangle are mapped as moraine deposits. Two occur on the north side of Route 5 and the third occurs on the NE side of Route 5A, i.e. all occur on SSW-facing slopes and equivalent landforms are not present on the opposite sides of these valleys. These areas are characterized by hummocky landforms or irregular ridges with abundant closed depressions (kettles), many of which are filled with Holocene wetlands deposits (Figs. 7, 8). Extensive field observations indicate that the hummocky terrains consist of both till and sand/gravel whereas the ridges appear to consist mostly of till. In some areas, e.g. the middle of Fig. 7, bedrock structures (E-W ridges of metasedimentary rocks) may be responsible for the dominant landform with glacial landforms superimposed. In other areas, e.g. the area east of Marl Pond in Fig. 8, the till landforms appear to result from solifluction processes, i.e. sheets of remobilized glacial till that have flowed down slope a short distance before losing enough water to strengthen and stabilize.

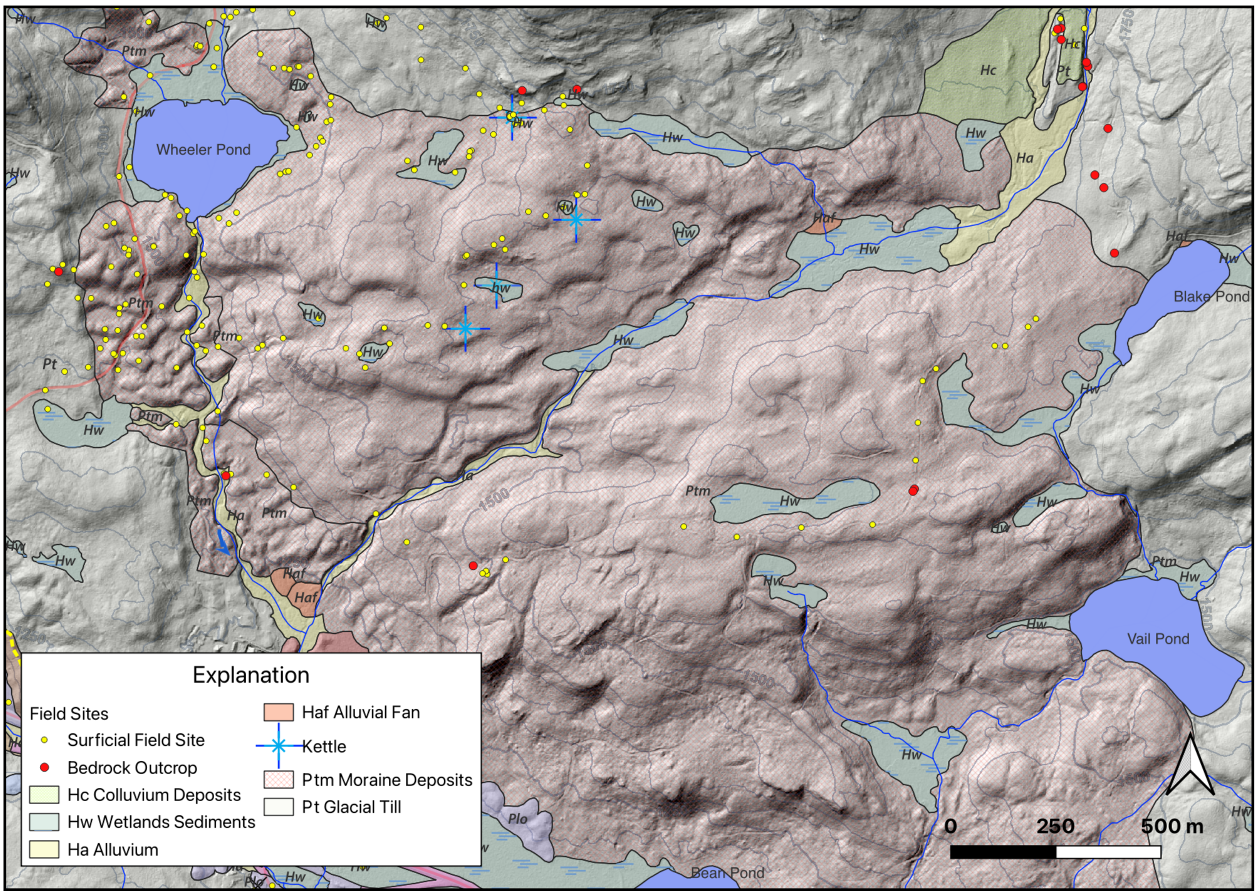

Figure 7: Map depicts the area immediately north of Route 5 that is mapped as Moraine Deposits (Ptm) that consists of both hummocky landforms and irregular ridges. Depressions, some filled with wetland deposits, are common and are interpreted to be glacial kettles. The east-west ridges in the middle of the map may owe their origin to structures in the underlying metasedimentary rocks.

Ice-Marginal Channels

Ice-marginal channels occur in many areas across the quadrangle and have been documented across northern Vermont as a result of recent mapping by the author (Wright, 2024a, c, 2025a). The most impressive array of these channels occurs on the north side of Mount Pisgah and were previously recognized and mapped by Ebbett (1988). These have a morphology similar to others mapped in the surrounding area by the author and were likely eroded by glacial meltwater flowing along the margin of the ice sheet. Flights of channels formed at progressively lower elevations as the ice sheet thinned and retreated from the area. Some closely-spaced adjacent channels may record yearly ice thinning.

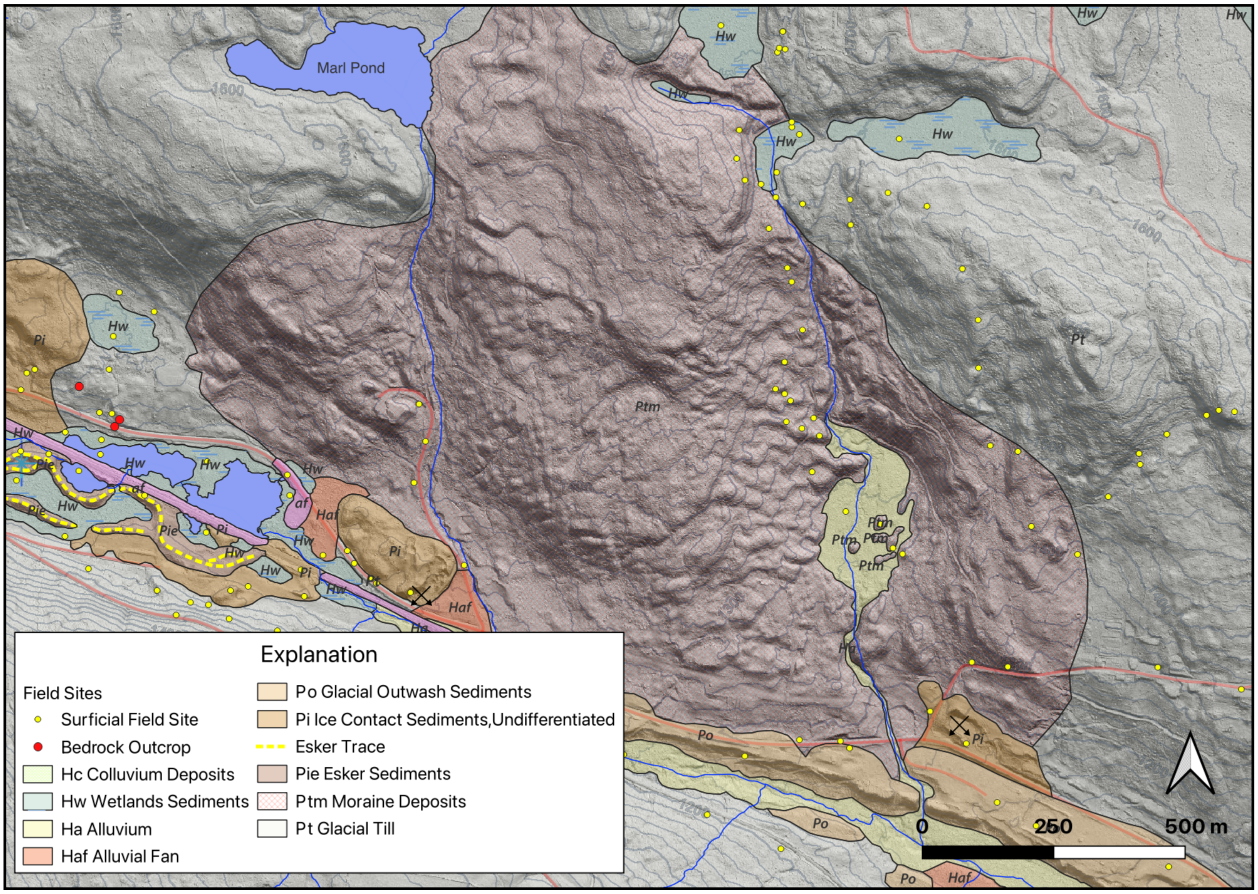

Figure 8: Area of moraine landforms immediately north of Route 5 and about 3 km ESE of Fig. 7. Ridges immediately east of Marl Pond may be solifluction sheets.

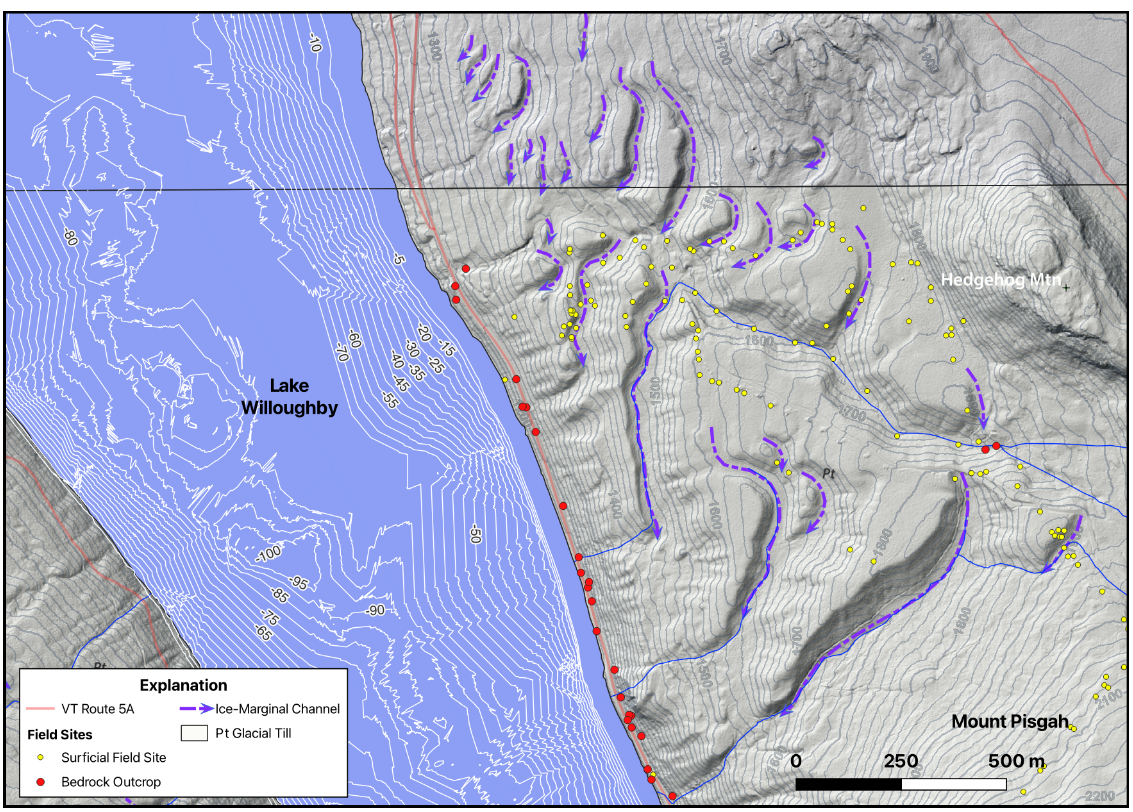

Figure 9: Ice-marginal channels cut through thick till deposits on the northern flank of Mount Pisgah. Lake Willoughby bathymetry is in meters.

Ice-Contact (Glaciofluvial) Deposits

Eskers (Pie), Kame Deposits (Pik), Glacial Outwash (Po), and Undifferentiated Deposits (Pi)

Ice-contact deposits are extensive along the two major valleys crossing the quadrangle, those utilized by Vermont Routes 5 and 5A. In addition to well-defined esker ridges these valleys also contain a variety of randomly aligned hummocks (all composed of sand and gravel) and depressions that broadly mark "kame and kettle" terrains (Fig. 10). Most of the depressions lie at or below the water table and host extensive deposits of wetland sediments. Other low-gradient reaches of these valleys are also dominated by wetlands sediments, although stream channels do meander across these areas (Fig. 11).

Multiple segments of eskers have been mapped in both valleys (e.g. Figs. 8, 10). These eskers occur in areas mapped as "Kame Moraines" on Stewart's map of the area (1956-1966a). It seems likely that portions of these same eskers have been mined away where they appear to intersect the area's many gravel pits. These eskers indicate that extensive southeast-directed subglacial drainage was funneled parallel to these valleys when the ice sheet had thinned to the point where it was topographically constrained and was similarly flowing southeast along these valleys.

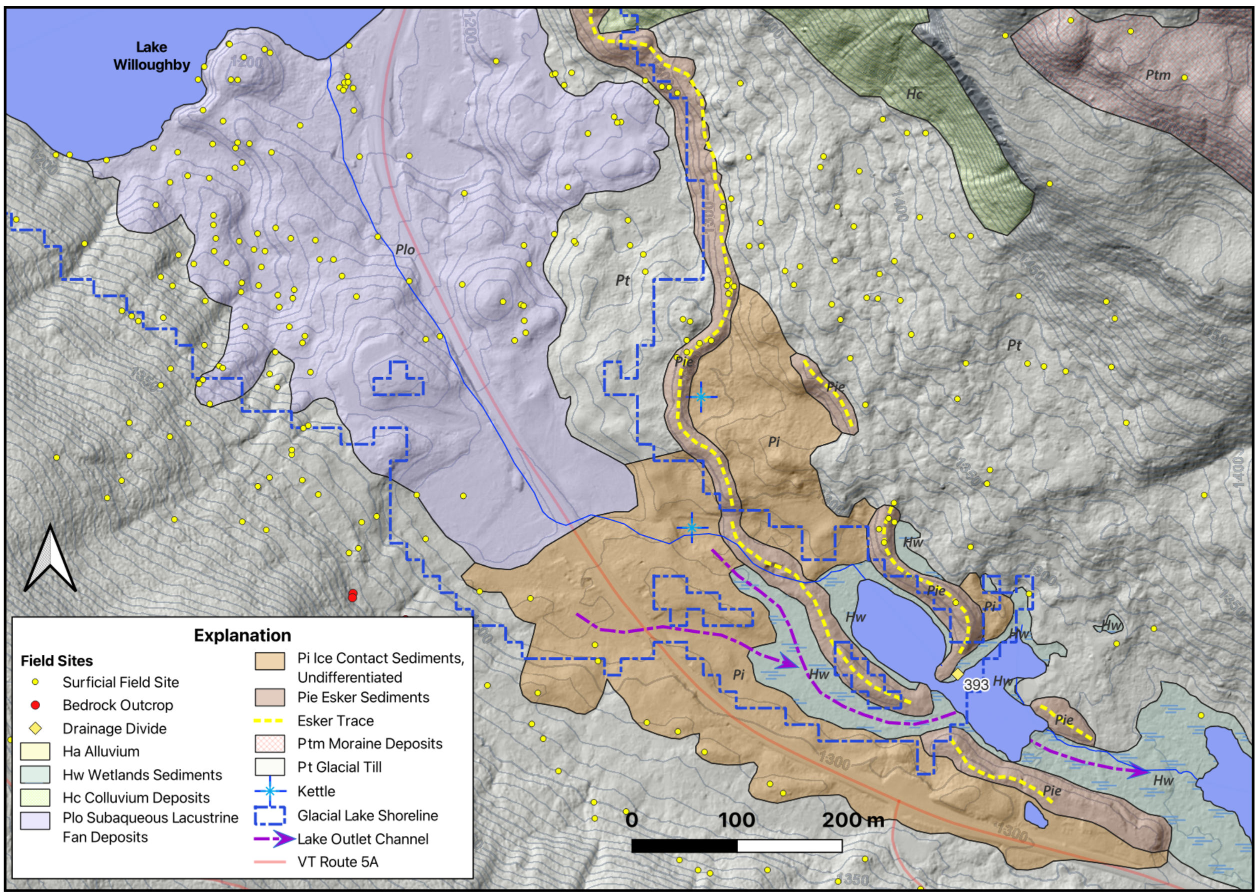

Figure 10: Map shows both ice-contact landforms and lacustrine outwash deposits that dominate the valley extending southeast of Lake Willoughby along Vermont Route 5A. Yellow dashed line highlights trace of several eskers. Interlayered fine sand and gravel is common near the southern end of Lake Willoughby and was likely deposited as a subaqueous fan in the glacial lake that extended from the ice front to the drainage divide (see arrows marking glacial lake drainage pathways).

Terraces occurring along the east side of Vermont Route 5A have been mapped as kame deposits (Pik, Fig. 11), i.e. fluvial sediments deposited between the margin of the ice sheet and the valley side. A well-developed flight of ice

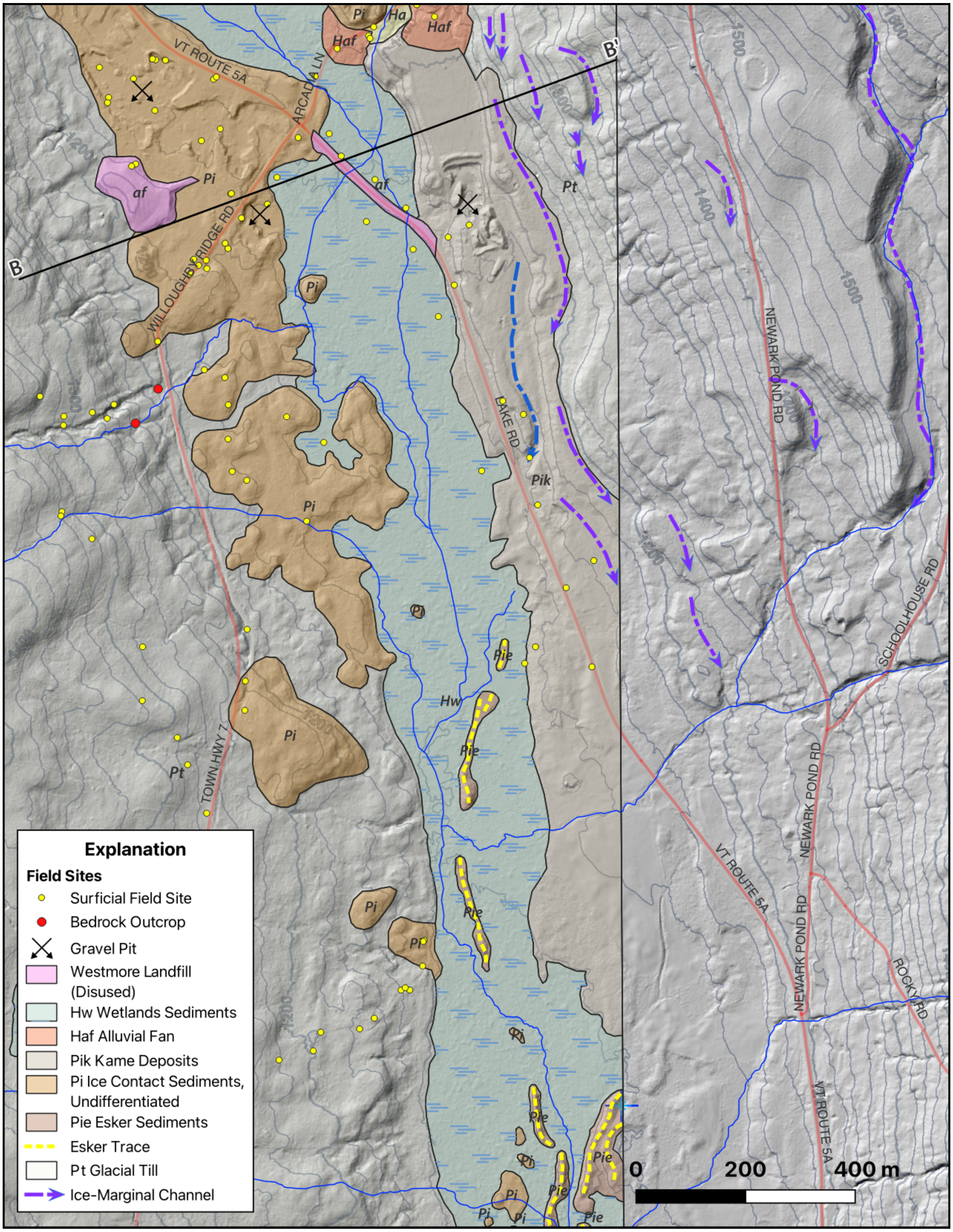

Figure 11: Map depicts ice-marginal channels, kame terraces (Pik), eskers (Pie), and other ice contact sediments (Pi) occurring in and adjacent to the south-flowing West Branch Passumpsic River valley along the eastern border of the Sutton Quadrangle. Note that most of this very low-gradient valley is dominated by wetlands sediments (Ha) as opposed to alluvium.

marginal channels occurs immediately above and parallel to these terraces indicating that a well-developed drainage system had developed along the margin of of the thinning ice sheet (Figs. 11, 12). The channels, forming earlier when the ice-marginal drainage was higher on the hillside, document a time when this meltwater was dominantly erosional. By contrast, the kame terraces formed when the ice was thinner and lower on the hillside and those same streams instead of eroding channels deposited sand and gravel (Figs. 11, 12).

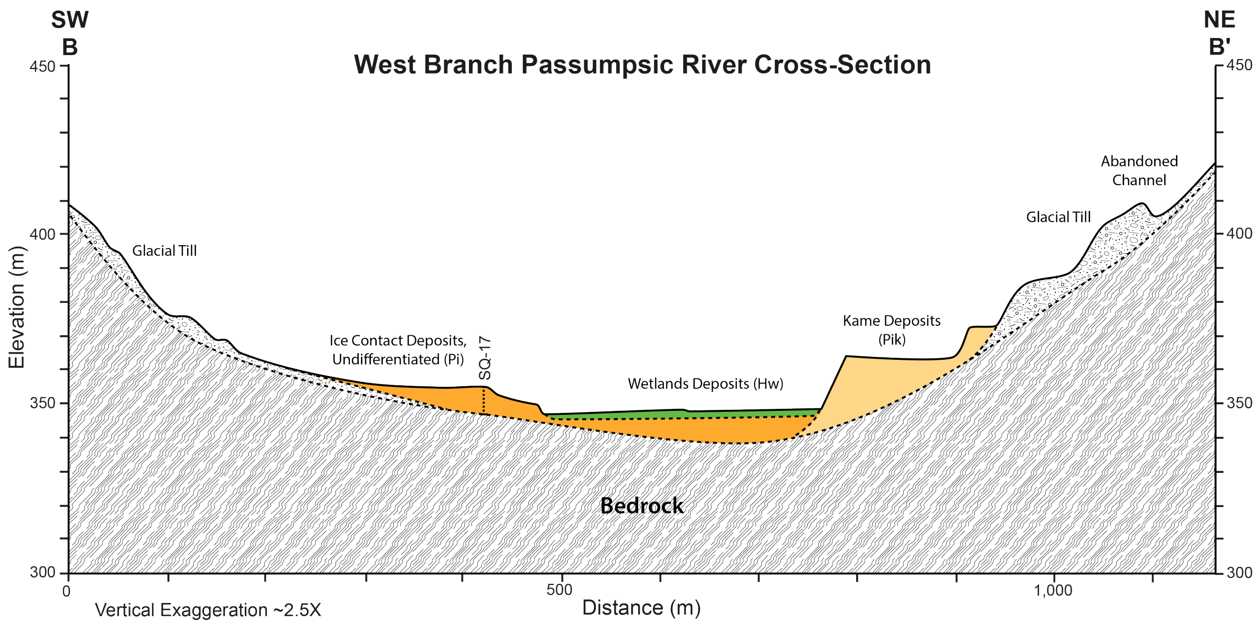

Figure 12: Geologic cross-section B-B' crosses the West Branch of the Passumpsic River approximately 2.5 km SE of the southern end of Lake Willoughby (see location on Fig. 11). Depth to bedrock is constrained by one Tromino geophysical survey point, SQ-17. Stratigraphy is inferred from surface observations. An abandoned ice-marginal channel and stepped stream terraces are visible on the east side of the valley.

Terraces along the Sutton River valley (utilized by Vermont Route 5) have been mapped as glacial outwash (Po). The reason for not mapping these deposits as kame terraces is the absence of ice-marginal channels in this valley, i.e. there isn't clear evidence of an ice-marginal drainage system here. This may indicate that most of the glacial meltwater in this valley was routed sub glacially via esker tunnels and eroded sediment not deposited in the tunnels as esker was deposited downstream of the retreating ice front as outwash.

Glacial Lake (Glaciolacustrine) Deposits

Two glacial lakes formed in the Sutton Quadrangle as the ice sheet retreated to the northwest past the respective drainage divides in both the Route 5A and 5 valleys (Fig. 13). These drainage divides mark the beginning of tributaries that flow to the northwest-into the Barton River, tributaries that were dammed by the retreating ice sheet. Both these lakes were relatively small, but they encompassed the areas currently occupied by both Lake Willoughby and Crystal Lake.

Between the south end of Lake Willoughby and the drainage divide (the southernmost part of the glacial lake that occupied the Lake Willoughby valley) fine-grained glaciolacustrine sediments are interlayered with gravel and were likely deposited in subaqueous fans near the margin of the retreating ice sheet, the "subaqueous outwash" mapping unit (Plo, Figs. 10, 14, 15). Southeast-dipping bedding exposed at the campground at the south end of the lake supports this interpretation.

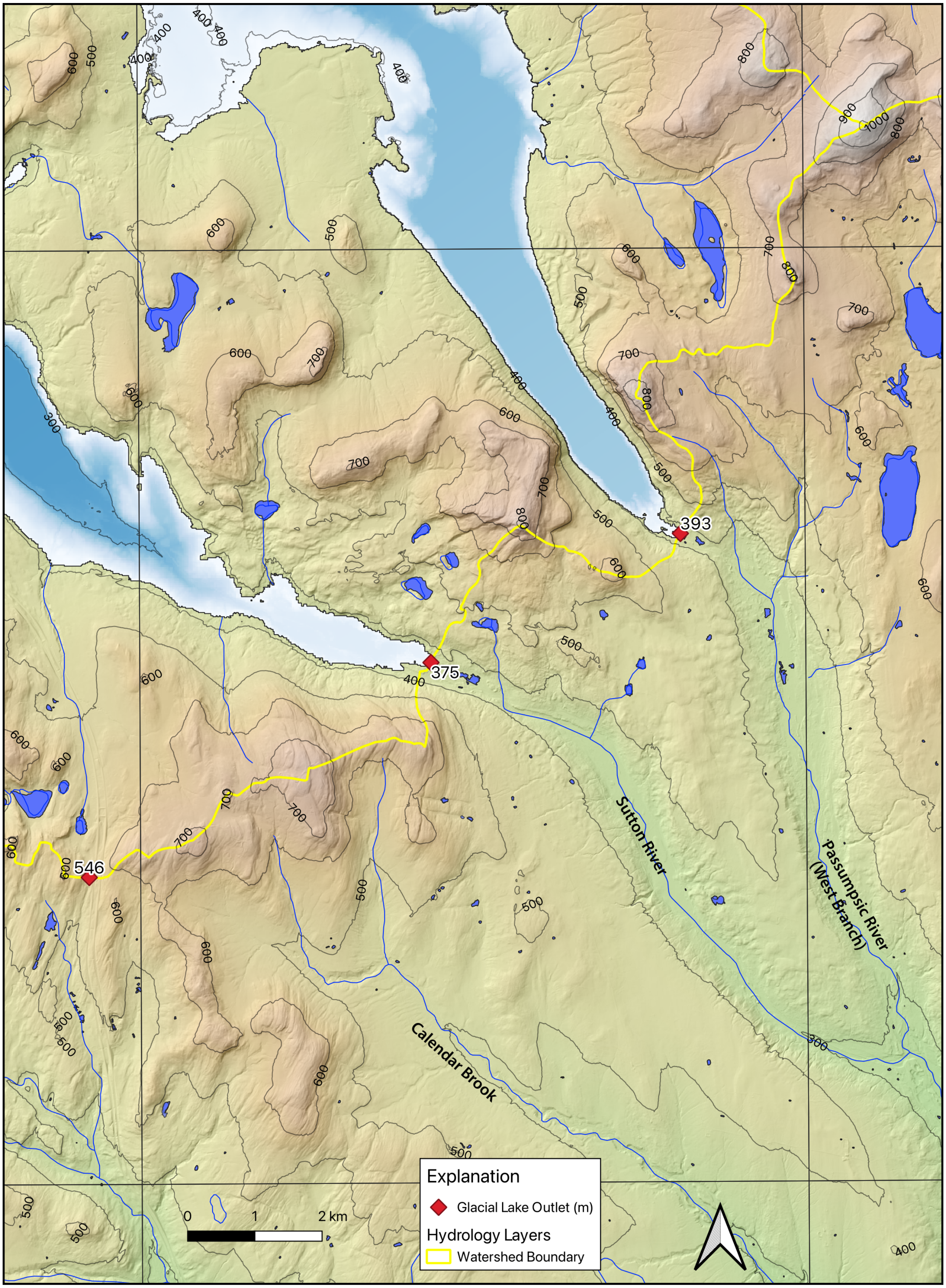

Figure 13: Glacial lakes formed northwest of the respective drainage divides in the two major valleys that traverse the Sutton Quadrangle as separate tongues of the ice sheet retreated down these valleys.

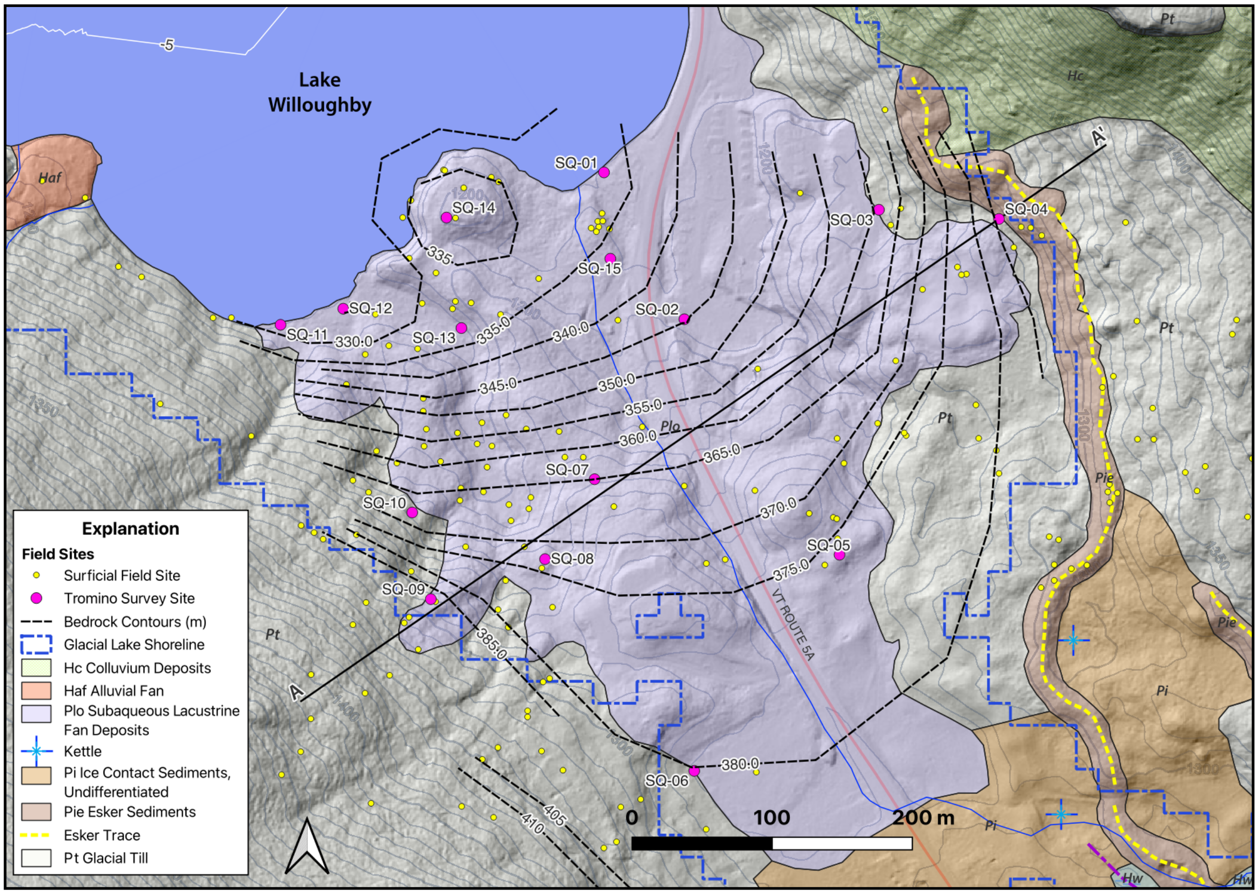

Figure 14: Map depicts the surficial geology at the south end of Lake Willoughby and the sites where passive Tromino geophysical surveys were conducted. These geophysical data were used to construct bedrock contours beneath the glaciolacustrine sediments.

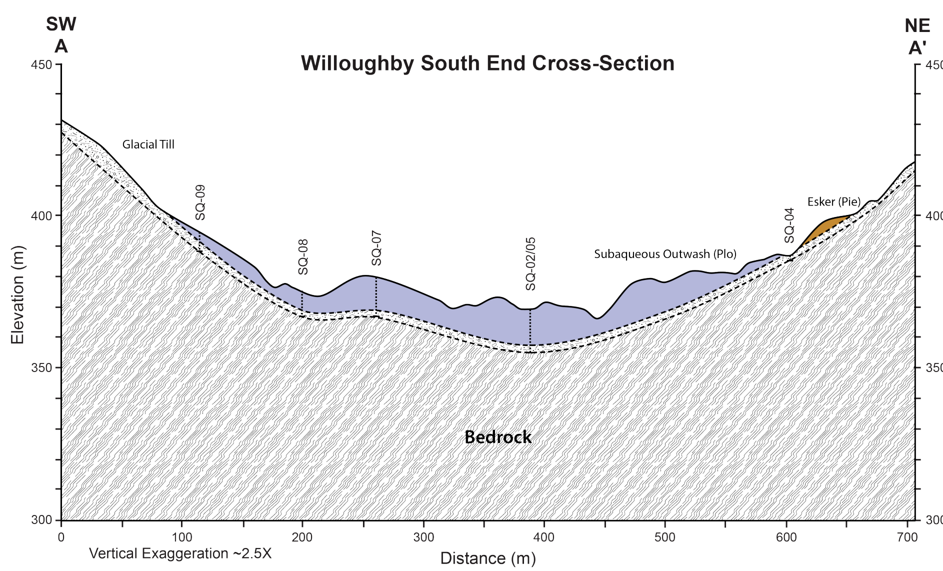

Figure 15: Geological cross-section A-A' across the area depicted in Fig. 13 utilizes Tromino passive geophysical survey data to constrain the depth to bedrock and shows the corresponding thickness of surficial sediments. The stratigraphy is inferred from surface observations.

Over the course of two days Peter Strand of the Vermont Geological Survey conducted Tromino passive seismic geophysical surveys across two areas near the south end of Lake Willoughby with help from the student interns (Fig. 14). These geophysical observations were used to determine the depth to bedrock, but could not be used to delineate any stratigraphy within the surficial sediments. The buried bedrock surface was contoured (Fig. 14) and these geophysical data were also used to constrain the depth to bedrock in cross-section A-A' (Fig. 15). The buried bedrock valley is broad and generally U-shaped, slopes northward, and lies between 25 and 30 m below the surface at the south end of Lake Willoughby (Figs. 14, 15).

Large glacially-transported boulders are common in and on these lacustrine sediments and some may be dropstones. In Google Earth satellite imagery two large boulders at the south end of the lake appear to have troughs extending NNW from the boulders into deeper water (Fig. 16, Peter Strand, personal communication). It appears they were dragged at the bottom of the ice sheet SSE, parallel to the orientation of the Lake Willoughby valley. If this interpretation is correct, it's not clear why the troughs are still visible and not covered by the same glacial lake sediments that occur just a short distance away on the shore. One possibility is that the overlying glacial lake sediments have been eroded away during the Holocene, i.e. those sediments have been washed into deeper parts of the lake.

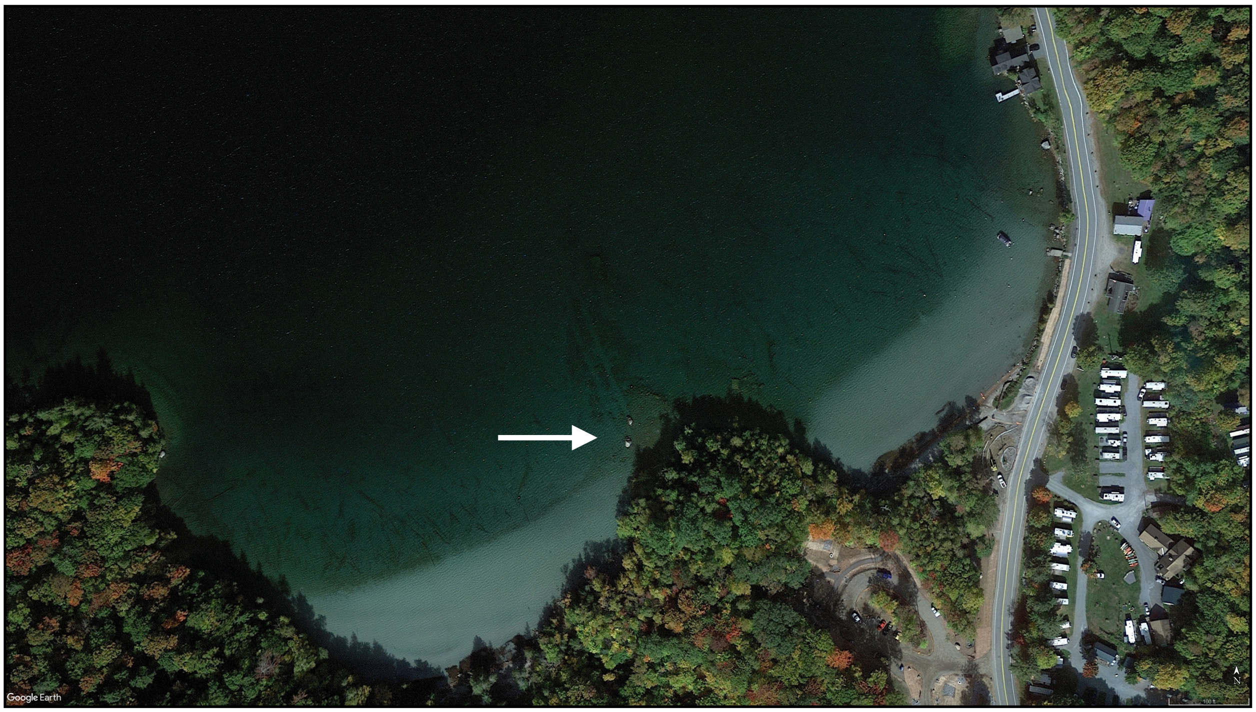

Figure 16: Google Earth satellite image of the south end of Lake Willoughby (see Fig. 14 for geologic map of the same area). Arrow points to two bright spots that are two large granite boulders that are partially emergent when lake levels are low. Faint, light-colored traces extending NNW from each boulder are interpreted to be troughs eroded into the till as these boulders were dragged SSE at the base of the ice sheet.

Glaciolacustrine sediments have also been mapped in the Willoughby Brook valley (VT Route 5 traverses this valley) northwest of the drainage divide. Similar to the sediments occurring at the south end of Lake Willoughby, these were deposited in relatively shallow lake water and consist of both fine-grained lacustrine sediment and interbedded coarser sediments. These sediments generally fine upwards reflecting the increasing distance from the retreating ice front, the dominant source of sediment in to the lake, with time. The map distinguishes dominantly fine-grained lacustrine sediments (Plf) and a mix of coarse and fine lacustrine sediments (Plo), but this distinction may reflect the density of field observations, i.e. a more conservative interpretation would lump all the mapped Plf features as Po features. Figure 17 is a cross-section of the Willoughby Brook valley and depicts older ice-contact sediments fining up through subaqueous lacustrine fan deposits and fine-grained lacustrine sand and silt.

A large active gravel pit and rock quarry occurs at the base of Wheeler Brook (Fig. 18). This is interpreted to be a delta that formed where Wheeler Brook flowed into this glacial lake. The pit is also excavating esker sediments. Wheeler Brook has eroded a channel through both the esker and the delta.

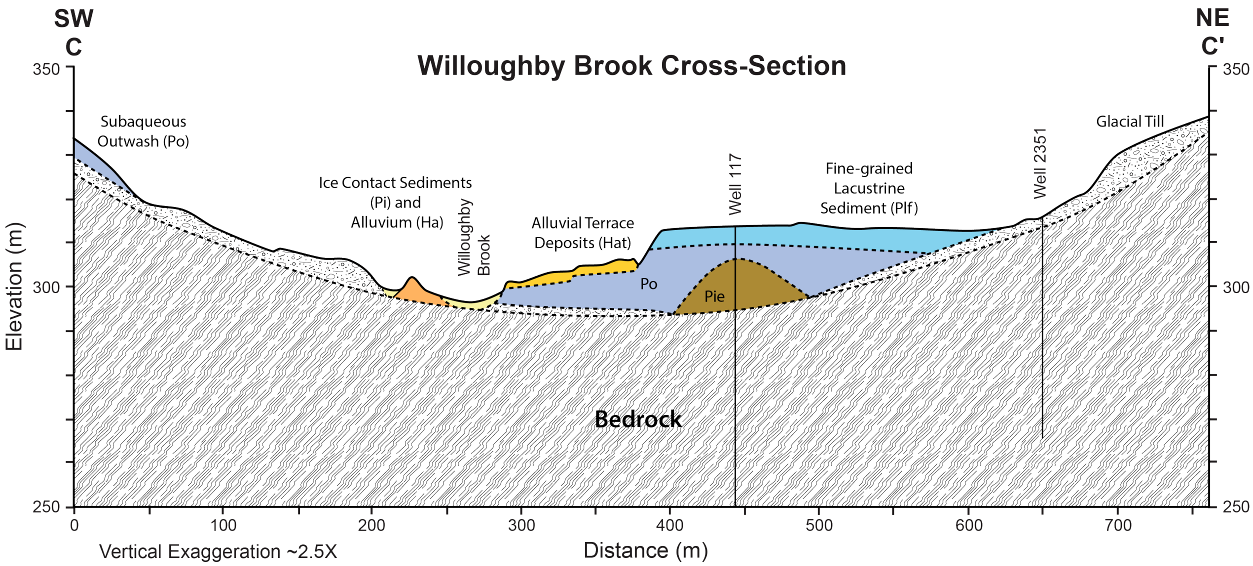

Figure 17: Cross-section C-C' traverses the Willoughby Brook valley near the western edge of the quadrangle, an area once occupied by a glacial lake that extended across where Crystal Lake lies today. Surface observations and two water wells indicate the valley is underlain by a wide variety of both ice-contact and lacustrine sediments. Facies transitions along Well 117 are inferred based on geology elsewhere in the valley.

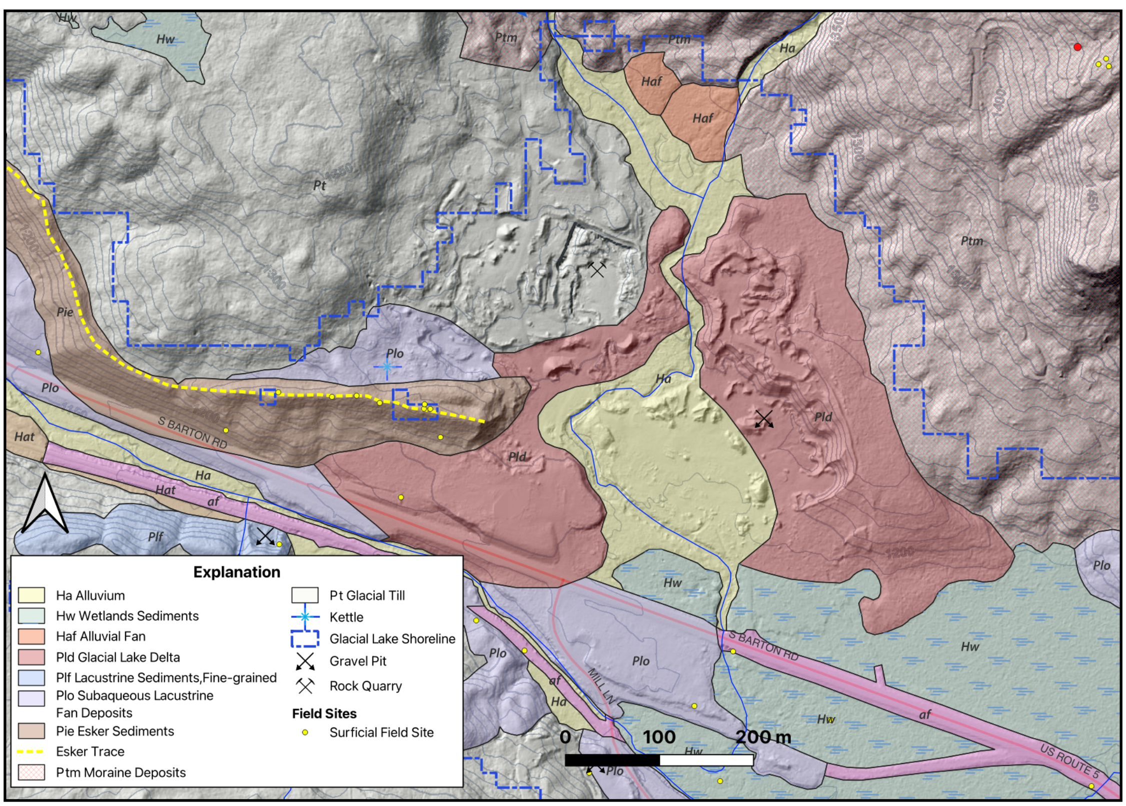

Figure 18: Deltaic sediments are mapped where Wheeler Brook once flowed into a glacial lake. The active gravel pit utilizes both these and older esker sediments. The delta and esker sediments have been bisected by Wheeler Brook following drainage of the glacial lake.

Holocene Deposits

A variety of sediments have been mapped that were deposited in the Holocene Epoch. These largely consist eroded and redeposited Pleistocene sediments transported by both fluvial and hill slope processes.

Alluvium (Ha) and Modern Delta (Hld) Deposits

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. Both the Sutton River valley and the West Branch of the Passumpsic River valley are generally broad, have very low gradients, and are occupied by extensive areas of wetland (Fig. 11). It was thus problematic whether to map these areas as alluvium or wetlands. The choices made on the map reflect the best judgement of the dominant depositional process occurring in these areas, but undoubtedly there is alluvium in areas mapped as wetlands and vice versa.

Several small modern deltas were mapped where streams enter Long Pond. Other modern deltas occur around the perimeter of other pond in the quadrangle but these sediments are masked by surrounding wetlands sediments.

Alluvial terrace deposits (Hat)

Alluvial terrace deposits are stream sediments (alluvium) occurring on terraces above but adjacent to modern streams. As streams erode channels more and more deeply through earlier-deposited sediments, older channels and adjacent flood plains are 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. Most alluvial terrace deposits mapped within the quadrangle occur where streams have been eroding through glaciolacustrine sediments.

Hw Wetlands Deposits

Wetlands commonly occur in closed basins, adjacent to low-gradient streams, and areas dammed by beaver (Fig. 19). 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.

Figure 19: Wetlands sediments lying between the RR grade and US Route 5 near the drainage divide between Willoughby Brook and the Sutton River.

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. Numerous alluvial fans have been mapped within the quadrangle. Many have formed in the Sutton River valley where tributary streams have eroded till and redeposited this till in fans (Fig. 20).

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.

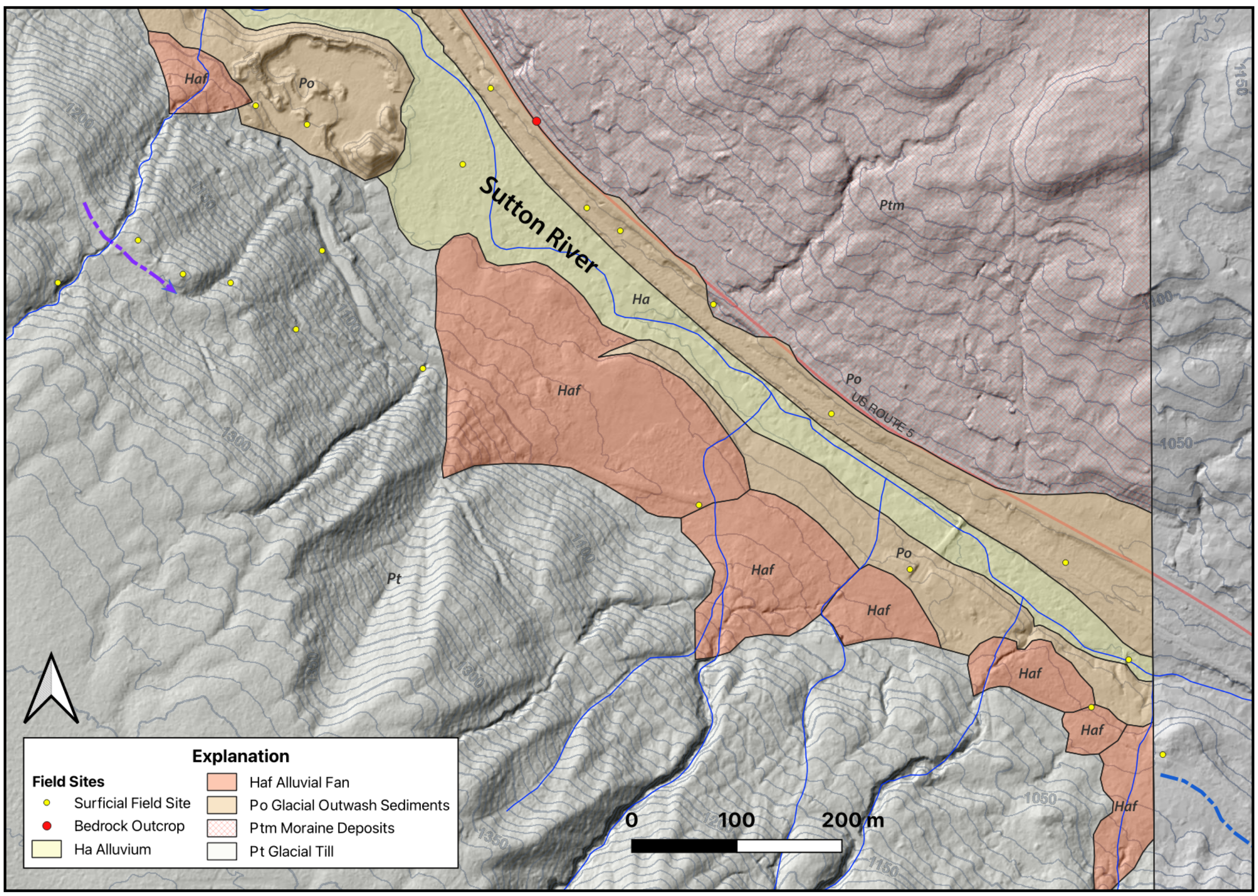

Figure 20: Alluvial fans have formed where tributary streams slow and deposit sediments in the Sutton River valley along the eastern edge of the quadrangle. Channels, deeply eroded into till, are the source of the sediments comprising the fans.An active gravel pit is situated on glacial outwash sediments (Po).

Hc Colluvium
The extensive apron of debris between Lake Willoughby and the Mount Pisgah cliffs was mapped as colluvium (Fig. 21). These deposits lie at the angle of repose and limited observations within small stream channels indicate they consist largely of diamict. Several heavy rainstorms during June of 2024 mobilized many debris flows which

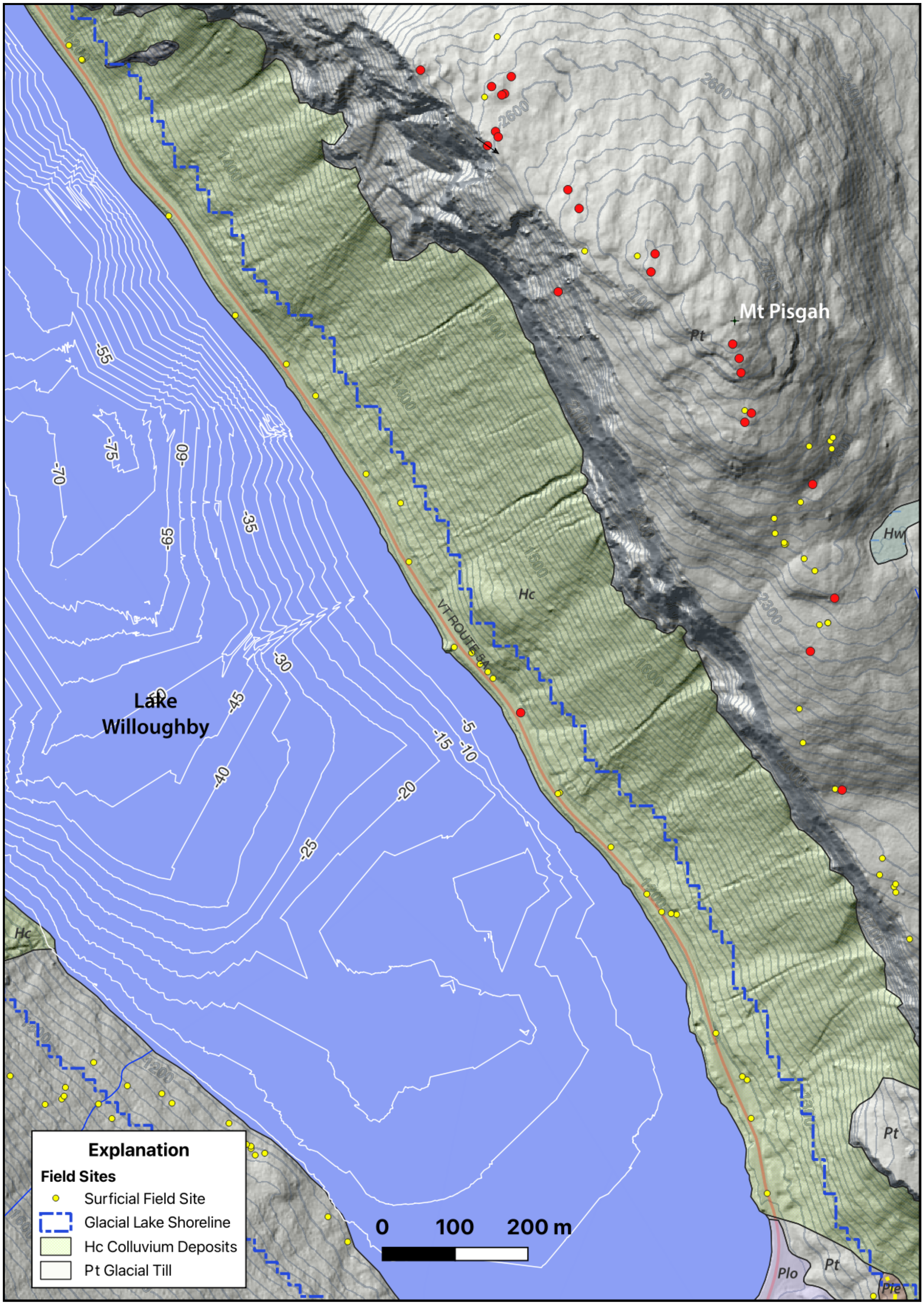

Figure 21: A thick and extensive apron of colluvium (Hc) has accumulated below the Mount Pisgah cliffs during the Holocene.

Figure 22: Fan of debris deposited along US Route 5A during one of several intense rainfall events between June 20–24, 2024. Debris is sourced from material exposed along a shallow channel that rises to the talus slopes below the cliffs on Mount Pisgah.

deposited material along the uphill side of US Route 5A and may model, on a small scale, the dominant process operating below the cliffs (Fig. 22). The debris appeared to be sourced from talus, older debris flows, and remobilized glacial till. It appears that this deposit consists of multiple debris flow deposits that have coalesced to form an apron of debris extending down to the lake. Each of the deposits we observed has a clearly defined chute extending upslope at least as far as the talus at the base of the cliffs.

af Artificial Fill
Artificial fill was mapped where significant volumes of material were utilized for the construction of federal highways, town roads, and railroad grades. In most cases fill consists of sand and gravel. Additionally, the accumulation of refuse in the Westmore Landfill is also mapped as fill.

Glacial and Post-Glacial history of the Sutton Quadrangle

The surficial geologic materials and landforms mapped in the Sutton Quadrangles as well as earlier mapping of the Newport and Newport Center Quadrangles provide the basis for the following interpretation of the glacial and post-glacial history of this area (Wright, 2024b, c, 2025a). This local history is fit within our broader understanding of northern Vermont's glacial history based on earlier work (Larsen et al., 2003; Wright et al., 2024). The surficial geologic materials occurring in the region were predominantly deposited during the most recent (Wisconsinan) glaciation in glacial or periglacial environments.

Ice Flow

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 broadly north-south in the N-S valleys lying east of the Green Mountains (Wright, 2015). Glacial striations, chatter marks, streamlined till, and boulder troughs (Fig. 16) in the Sutton area are all aligned NNW to SSE and likely formed when the ice sheet was topographically controlled.

Timing of Ice Retreat

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). The North American Varve Chronology has been utilized in the Connecticut River valley (along Vermont's eastern border) to show that the ice sheet was approaching the Québec border ~13.6 ky BP (Ridge et al., 2012). In the much larger Champlain valley to the west, the ice sheet retreated somewhat later reaching the Québec border ~13.4—13.2 ky BP (Ridge et al., 2012). Cosmogenic dating along an elevation profile on Mount Mansfield, ~60 km SSW of the field area, indicates that the ice sheet was thinning very rapidly ~13.9 ka, exposing 800 m of relief in less than 1,000 years (Corbett et al., 2019). Varve correlation work in the Glacial Lake Winooski Basin east of the Green Mountains also indicates rapid (~300 m/year) retreat of the ice sheet at this same time (Wright, 2022a).

The Glacial Lake Winooski varve record indicates that the ice sheet east of the Green Mountains was retreating northwards across the drainage divide separating the north-flowing Lake Memphremagog drainage basin from drainage basins to the south ~13,800 yrs BP and it's likely that the ice sheet retreated across this same drainage divide in the Sutton Quadrangle at about the same time (Wright et al., 2024). Sediment cores retrieved from both Duck Pond and Vail Pond in the Sutton Quadrangle were utilized by Noren et al (2002) as part of a larger project to assess storm frequency across northern Vermont. The oldest sediments dated from Duck Pond were 12,882-13119 cal. yrs BP whereas those from Vail Pond are 9,297-9,467 cal. yrs BP. These dates are consistent with estimates that the area was ice free by ~13,800 yr BP. The drainage basin north of the Sutton Quadrangle hosted a large glacial lake called Glacial Lake Memphremagog (Hitchcock, 1908; Wright, 2024b). Currently Glacial Lake Memphremagog sediments are being dated using the OSL method and these dates will further constrain the timing of ice retreat across the Sutton Quadrangle.

Ice-Contact Environment

When the ice sheet was thinning and retreating across the mountains, meltwater, flowing along the edge of the ice sheet, eroded channels in the adjacent till (Figs. 23, 24). The channels mapped on either side of Lake Willoughby formed when the thinning ice sheet was exposing the surrounding mountains and a tongue of ice was funneled SSE through the valley. During this time meltwater was flowing into the Lake Willoughby valley following the margin of the ice tongue. The channels mapped along the eastern border of the quadrangle would have formed earlier when the ice sheet was thicker and extended farther south.

The deposits of moraine mapped in the quadrangle generally do not form distinct ridges, but instead are broad areas of hummocky landforms with many interstitial depressions, some of which may be kettles. These hummocky moraines appear to consist of landforms created along the wasting margin of the ice sheet as it thinned in the valleys above the drainage divides. In this environment, ice flow would have been slow (see below paragraph) and in a climate that was rapidly warming the ice sheet would have been thinning quickly leading to the disintegration landforms that comprise these moraines. Both till and sand/gravel have been observed in these landforms indicating that stream flow was occurring around deposits of till. As noted earlier, solifluction landforms appear to dominate some of these terrains indicating that the rheology and slope of earlier deposited till was sufficient for these materials to slump.

Meltwater was also routed through subglacial tunnels as evidenced by the eskers mapped in both the Passumpsic River (West Branch) and Sutton River valleys. Much of the sediment in these eskers likely formed when the ice sheet had thinned enough that the rate of ice flow tending to close these ice tunnels was exceeded by stream erosion and sediment deposition within the tunnels. Streams flowing along the margin of the ice sheet in the valleys deposited sediment in kame terraces. Sediments exiting the esker tunnels ESE of the drainage divides deposited sand/gravel in broad, low-gradient deposits of outwash. That outwash is currently preserved in low river terraces or is overlain by

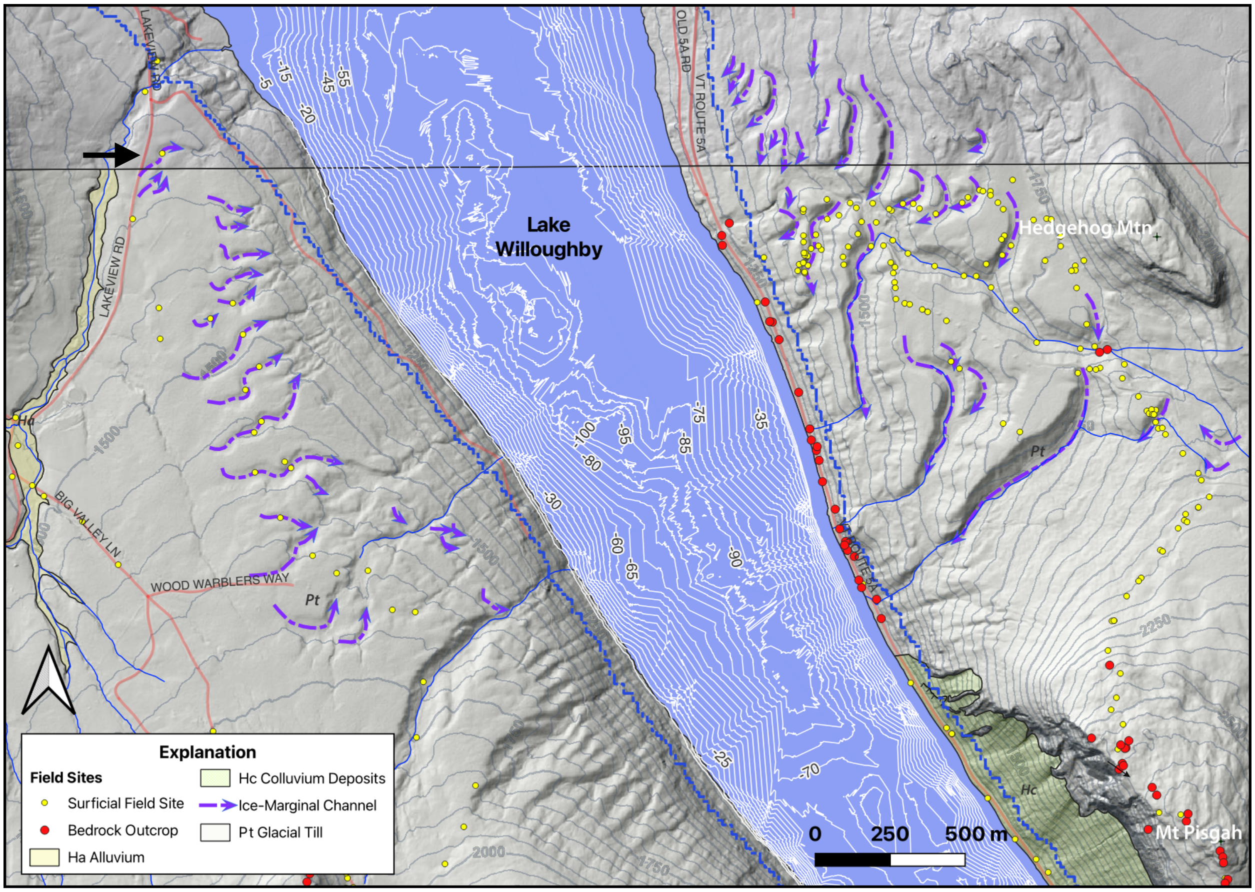

Figure 23: Channels occurring on both sides of Lake Willoughby formed as glacial meltwater flowed along the margin of the ice sheet eroding the adjacent till. Flights of channels may mark yearly positions of the ice sheet as it rapidly thinned across the area. Black arrow show the channel pictured in Figure 24 below.

Figure 24: Ice-marginal channel along Lakeview Rd at the northern border of the quadrangle.

a thin veneer of alluvium and wetlands sediments. Kettles and extensive deposits of sand and gravel in lumpy landforms (the Pi, “Ice-Contact Sediments, Undifferentiated” mapping unit) around the drainage divides in both valleys indicate that portions of the ice sheet became too thin to flow and transitioned to stagnant or “dead” ice while the active ice front continued its retreat into the Lake Willoughby and Willoughby Creek/Crystal Lake valleys, respectively. Many of these kettles and irregular basins within the Pi sediments are currently occupied by wetlands.

Lacustrine Environment

As noted earlier, glacial lakes developed in both the Lake Willoughby and Willoughby Creek/Crystal Lake valleys once the ice sheet retreated NNW of the drainage divides in these valleys. The outlets to both these lakes was across recently deposited ice-contact sand/gravel. Consequently, the elevations of these lakes likely lowered as these sediments were eroded by outflow from the lakes. These lakes grew in size as the ice sheet retreated and eventually merged to form a single lake that utilized the lowest outlet (375 m), that occurring in the US Route 5 valley. Continued northward retreat of the ice sheet allowed other glacial lakes confined to tributary valleys to merge. Each merger created a larger lake that utilized the lowest available outlet leading to the drainage of the lakes that occurred in the Sutton Quadrangle. Eventually a single large lake, Glacial Lake Memphremagog, occupied the drainage basin (Wright, 2024b, c).

Holocene 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 and animals living here.

A variety of weathering and erosional processes have affected the Sutton Quadrangle during the post-glacial period. Stream erosion/deposition and slope failures are the most widespread and persistent erosional processes and vary in scale and frequency. In the upland areas streams have incised many channels in the till and frequently the eroded sediment has been redeposited in alluvial fans. Below the Mount Pisgah cliffs debris flows appear to be the dominant process transporting both till and talus downslope to the shores of Lake Willoughby.

Small landslides are common along streams where slopes are oversteepened by stream erosion. Only one large-scale landslide scarp was observed in the LiDAR imagery, but no field observations were made. This landslide occurs along the eastern boundary of the quadrangle where thick deposits of till have failed and slumped into the Passumpsic River (West Branch) valley (Fig. 25).

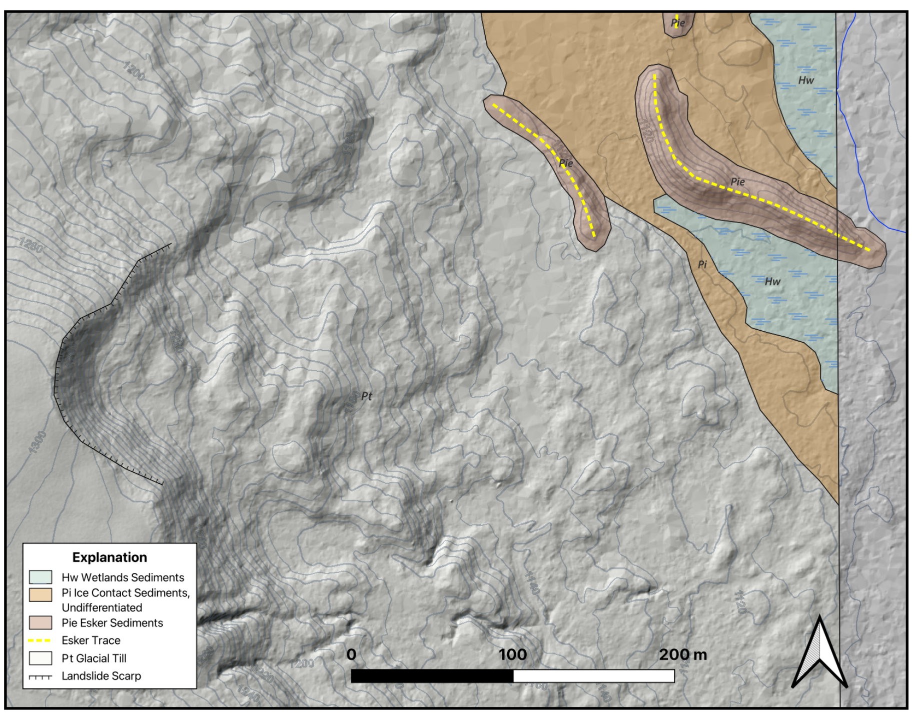

Figure 25: Map depicts a large landslide scarp and transported materials along the west side of the Passumpsic River (West Branch) valley. Esker segments and associated ice-contact and wetlands sediments are also occur in the valley.

Bibliography

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

Corbett, L. B., Bierman, P. R., Wright, S. F., Shakun, J. D., Davis, P. T., Goehring, B. M., Halsted, C. T., Koester, A. J., Caffee, M. W., and Zimmerman, S. R., 2019, Analysis of multiple cosmogenic nuclides constrains Laurentide Ice Sheet history and process on Mt. Mansfield, Vermont's highest peak: Quaternary Science Reviews, v. 205, p. 234-246.

Ebbett, B., 1988, Pleistocene glaciation at Lake Willoughby, Vermont, *in* Detenbeck, J. C., ed., Vermont Geology: Guidebook 2, Volume 5, Vermont Geological Society, p. H1-H32.

Halsted, C. T., Bierman, P. R., Shakun, J. D., Davis, P. T., Corbett, L. B., Caffee, M. W., Hodgdon, T. S., and Licciardi, J. M., 2022, Rapid southeastern Laurentide Ice Sheet thinning during the last deglaciation revealed by elevation profiles of in situ cosmogenic 10Be: Geological Society of America Bulletin.

Hitchcock, C. H., 1908, Glacial Lake Memphremagog: Geol. Soc. America Bulletin, v. 18, p. 641-642.

Jennings, K. L., Bierman, P. R., and Southon, J., 2003, Timing and style of deposition on humid-temperate fans, Vermont, United States: Geological Society of America Bulletin, v. 115, no. 2, p. 182-199.

Larsen, F. D., Wright, S. F., Springston, G. E., and Dunn, R. K., 2003, Glacial, Late-Glacial, and Postglacial History of Central Vermont, Volume 66, p. 62.

Noren, A. J., Bierman, P. R., Steig, E. J., Lini, A., and Southon, J., 2002, Millennial-scale storminess variability in the northeastern United States during the Holocene epoch: Nature, v. 419, no. 6909, p. 821-824.

Parent, M., and Occhietti, S., 1999, Late Wisconsinan deglaciation and glacial lake development in the Appalachians of southeastern Québec: Géographie physique et Quaternaire, v. 53, no. 1, p. 117-135.

Ratcliffe, N. M., Walsh, G. J., Gale, M. H., Masonic, L. M., Estabrook, J. R., Geological Survey (U.S.), Vermont. Agency of Natural Resources., and Vermont Geological Survey., 2011, Bedrock geologic map of Vermont, scale 1:100,000.

Ridge, J. C., Balco, G., Bayless, R. L., Beck, C. C., Carter, L. B., Dean, J. L., Voytek, E. B., and Wei, J. H., 2012, The New North American Varve Chronology: A Precise Record of Southeastern Laurentide Ice Sheet Deglaciation and Climate, 18.2-12.5 Kyr Bp, and Correlations with Greenland Ice Core Records: American Journal of Science, v. 312, no. 7, p. 685-722.

Springston, G. E., 2019, Surficial geology and hydrogeology of the Huntington 7.5-minute Quadrangle, Vermont: Vermont Geological Survey Open File Report VG2019-3, Report plus 1 map.

Springston, G. E., Gale, M. H., and Dowey, C., 2018, Vermont Surficial Geologic Mapping Standards, Vermont Geological Survey Unpublished Document.

Springston, G. E., and Wright, S. F., 2024, The Surficial Geology of the Montpelier 1:100,000 Quadrangle, Vermont: Vermont Geological Survey Open File Report VG2024-1.

Stewart, D. P., 1956-1966a, Surficial Geologic Map of the Lydonville 15’ Quadrangle, Vermont, Vermont Geological Survey Open-File Manuscript Map.

-, 1956-1966b, Surficial Geologic Map of the Memphremagog 15’ Quadrangle, Vermont, Vermont Geological Survey Open-File Map Manuscript Map.

-, 1956-1966c, Surficial Geologic Map of the Memphremagog 15’ Quadrangle, Vermont, Vermont Geological Survey Open-File Map.

Stewart, D. P., and MacClintock, P., 1969, The Surficial Geology and Pleistocene History of Vermont: Montpelier, Vt.,, Dept. of Water Resources, p. 251.

-, 1970, Surficial Geologic Map of Vermont: Vermont Geological Survey, scale 1:250,000.

Wright, S. F., 2024a, Ice-marginal channels and the evolution of Glacial Lake Memphremagog along Vermont’s northern border: Geological Society of America Abstracts with Programs. Vol. 56, No. 1.

-, 2024b, Ice-Marginal Channels and the Evolution of Glacial Lake Memphremagog along Vermont’s northern border.: Geological Society of America Abstracts with Programs, v. 56.

-, 2024c, Surficial Geologic Map and Cross-Sections of the Newport 7.5-minute Quadrangle, Vermont, v. Vermont Geological Survey Open File Report VG2024-1.

-, 2025a, Surficial Geologic Map and Cross-sections of the Newport Center 7.5-minute Quadrangle, Vermont: Vermont Geological Survey Open File Report VG2025–1.

-, 2025b, Surficial Geologic Map and Cross-sections of the Sutton 7.5-minute Quadrangle, Vermont: Vermont Geological Survey Open File Report VG2025-2.

Wright, S. F., Dunn, R. K., Springston, G. E., and Grigg, L. D., 2024, The Glacial, Late-Glacial, and Postglacial History of North-Central Vermont: Field Trip Guidebook for the 85th Reunion of the Northeast Friends of the Pleistocene, p. 1-58.