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Surficial Geology and Groundwater Hydrology of the Stowe7.5 Minute Quadrangle, Vermont[1]

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Figure 1: Glacially striated erratic perched on a larger erratic on land owned by the Green Mountain Club between Stowe Village and Waterbury Center.

Table of Contents

[1] Vermont Geological Survey Contract # 38392

Executive Summary/Significant Findings

The surficial geology of the Stowe 7.5-Minute Quadrangle was mapped during the summer of 2019 with field assistance from four geology students at the University of Vermont. Considerable detail has been added to prior map created by (Stewart and MacClintock, 1970). A surficial geologic map, four geologic cross-sections, an overburden thickness map, potentiometric surface map, recharge potential to surficial materials map, and a bedrock hydrologic unit map are included with this report.

The Stowe Quadrangle contains a variety of glacial landforms and sediments that formed as the Laurentide ice sheet first flowed across the Green Mountains and then thinned and retreated from the area. Glacial striations are almost universally oriented NW-SE. The asymmetry of roches moutonnée (smooth abraded side to the NW, quarried side to the SE), glacial erratics sourced from the northwest, and small-scale stoss and lee bed-forms on outcrops all indicate that ice flow was to the southeast when the ice sheet was sufficiently thick to cover the mountains. When the ice sheet thinned, its flow was guided by topography, from north to south in the Little River valley.

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 extensive areas exist where the till is thick enough to completely mask the underlying bedrock topography. The surface till in these areas may overlie older glacial deposits consisting of till or glaciolacustrine sediments.

During ice retreat ice-contact sediments, originating in subglacial tunnels or in subaqueous fans, were deposited in some of the valleys. These are only evident via water well logs where they occur at the bottom of deep valleys and are overlain by younger glaciolacustrine sediments. Nevertheless, they comprise a significant aquifer confined by and protected by those same fine-grained glacial lake sediments.

The retreating ice sheet dammed two different glacial lakes that filled the Little River valley to different elevations. Glacial Lake Winooski formed first and grew as the ice retreated west and north across the area. With the onset of the Older Dryas cold period, ~14,100 years ago, the ice readvanced down the Little River valley and then up the Winooski River valley. This readvance of the ice sheet deposited a second “readvance till” across some parts of the quadrangle and formed at least one moraine that was recognized while mapping in the quadrangle. At the end of the Older Dryas the ice sheet began retreating again and Glacial Lake Winooski once again grew and eventually occupied most low-lying areas east of the mountains. Glacial Lake Winooski partially drained when the ice sheet retreated as far west as Jonesville creating another lower-elevation lake, Glacial Lake Mansfield. Deltas that formed in both these lakes occur within the quadrangle, however the majority of the glacial lake sediments consist of medium to fine sand, silt, and clay that accumulated in the deeper parts of these lakes, i.e. the Little River valley and its tributaries.

Well data was utilized to contour the overburden thickness. Similar to most valleys in Vermont, thick sections of surficial materials accumulated in the valleys whereas the high and steep mountain slopes are overlain by a discontinuous cover of till. An old buried channel of the Little River was discovered in the valley parallel to Barrows Road. The current channel of the river is relatively new which is why the bedrock that underlies the waterfall between Stowe’s upper and lower villages still exists. This bedrock lip has severely limited upstream erosion by either the West Branch or the Little River. As a result, these rivers have meandered back and forth across these broad, flat valleys that are still largely filled with glacial lake sediment, but have not eroded deeply into them. These areas have historically provided some of the best agricultural land in the area.

The abundance of coarse grained surficial materials in many of the valleys constitute both good areas for groundwater recharge and good surficial aquifers. In areas where ice-contact sediments are overlain by thick sections of fine-grained lacustrine sediments, these become nicely protected confined aquifers. No systematic association exists between well yields and the mapped bedrock units within the quadrangle. This is because all these units are metamorphic rocks with no primary porosity. Groundwater accessed by wells within the quadrangle occurs within the secondary porosity of these rocks, the fractures.

The water table across the map largely mimics the ground surface topography. Large-scale groundwater flow is towards the major rivers that drain the area: the Little River and its tributaries.

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Introduction

This report describes the results of mapping surficial geologic materials and landforms at a scale of 1:24,000 in the Stowe 7.5-minute Quadrangle, northern Vermont during the summer of 2019. Numerous observations have been used to create a geologic map of the area and these observations underlie the interpretations presented here. This report also describes several derivative maps generated for this project that focus on the area's groundwater hydrology. A major objective of this work was to describe the three-dimensional distribution of surficial materials in the mapped area. These surficial materials, in addition to measurements of glacial striations, provide the basis for an interpretation of the different environments that existed as the Laurentide Ice Sheet was flowing and subsequently retreating across this area. Other landforms and associated surficial materials offer insight into processes occurring during the Holocene well after the ice sheet retreated.

Location and Geologic Setting

Much of the Stowe Quadrangle lies in a broad valley between the Green Mountains to the west and the Worcester Range to the east, but also includes a portion of the high Worcester Range ridge in the southeastern corner (Fig. 1). The south-flowing Little River and its tributaries drain most of the area which flows into the Winooski River a short distance south of the quadrangle. The bedrock geology of the area is summarized on the Vermont Bedrock Geologic Map (Ratcliffe et al., 2011). Rocks underlying this area 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, mafic igneous rocks intruded these sediments or erupted as lava flows or pyroclastic deposits across the ocean floor. All of 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 generally north-south striking thrust faults and lesser normal faults occurring on a wide range of scales that generally mimic the north-south trend of the mountain belt (Ratcliffe et al., 2011).

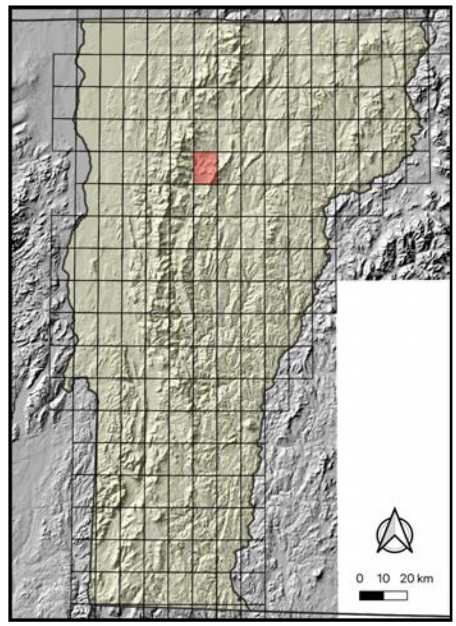

Figure 1: Shaded-relief map of Vermont showing the location of the Stowe7.5-minute quadrangle (red rectangle) situated immediately east of the Green Mountains.

The surficial geologic materials occurring in the region were predominantly deposited during the most recent (Wisconsinan) glaciation in glacial or periglacial environments existing during or shortly after the Laurentide ice sheet retreated across this area ~14,000–13,500 years ago (Corbett et al., 2019; Ridge et al., 2012). A variety of surface processes have redistributed these materials during the Holocene. The Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970) shows the general distribution of these sediments based on reconnaissance mapping completed during the 1960's (Fig. 2).

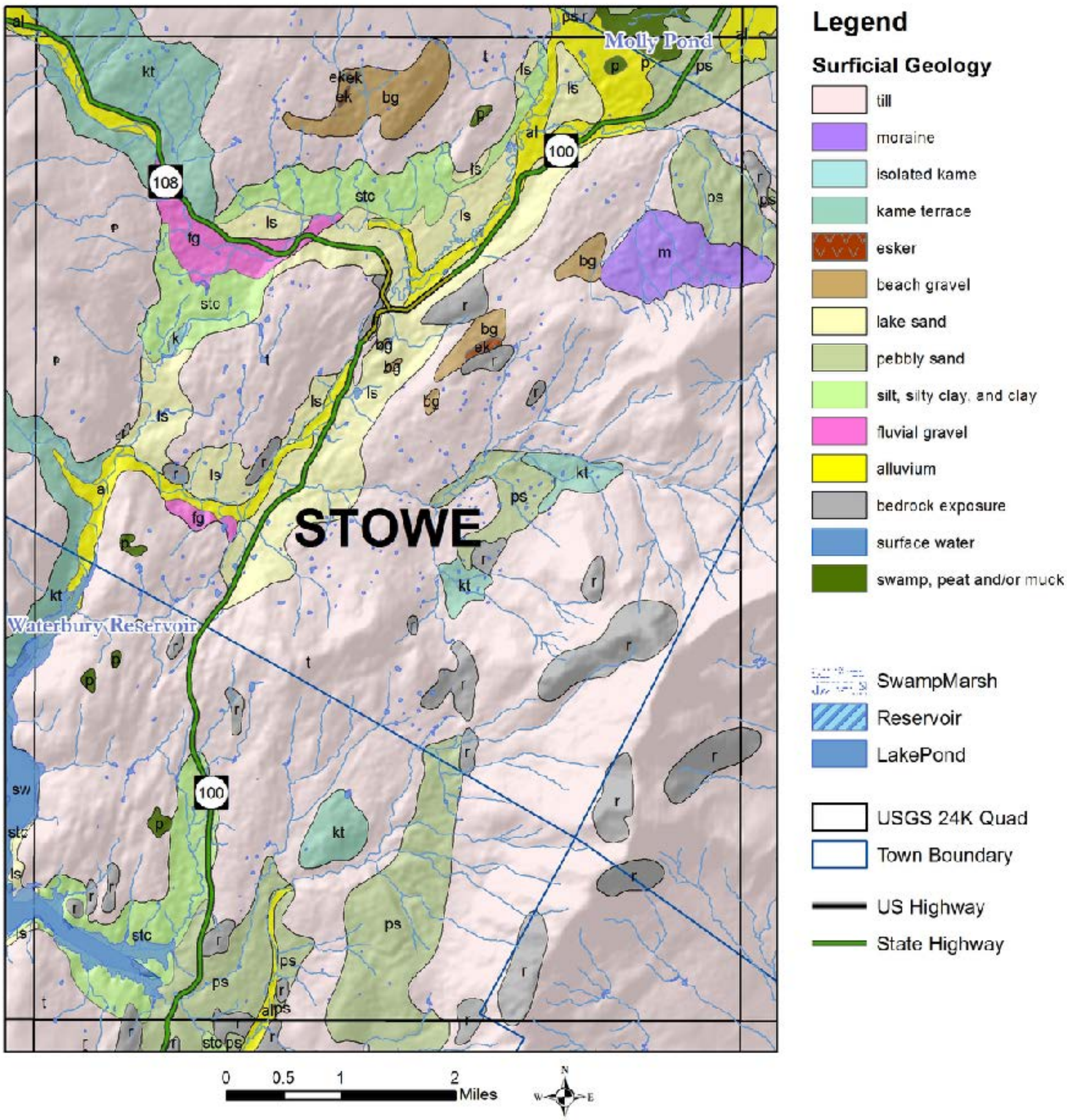

Figure 2: Map shows the distribution of surficial materials within the Stowe Quadrangle based on reconnaissance mapping utilized to complete the Vermont Surficial Geologic Map (Stewart and MacClintock, 1970).

The ice sheet in northern New England was sufficiently thick to completely cover the mountains. Consequently, the mountains are largely mantled by till with isolated pockets of organics occurring in wetland areas. Ice-contact sediments, deposited beneath or adjacent to the retreating ice sheet, are found in many of the major river valleys. These ice-contact sediments are largely overlain by glaciolacustrine sediments deposited in several ice-dammed glacial lakes that flooded the valley (Larsen, 1972, 1987; Wright, 2018a). The largest of these was Glacial Lake Winooski which formed when the retreating ice sheet dammed the Winooski River (Fig. 3A). A lower elevation lake, Glacial Lake Mansfield, formed when the retreating ice sheet uncovered a lower outlet (Fig. 3B).

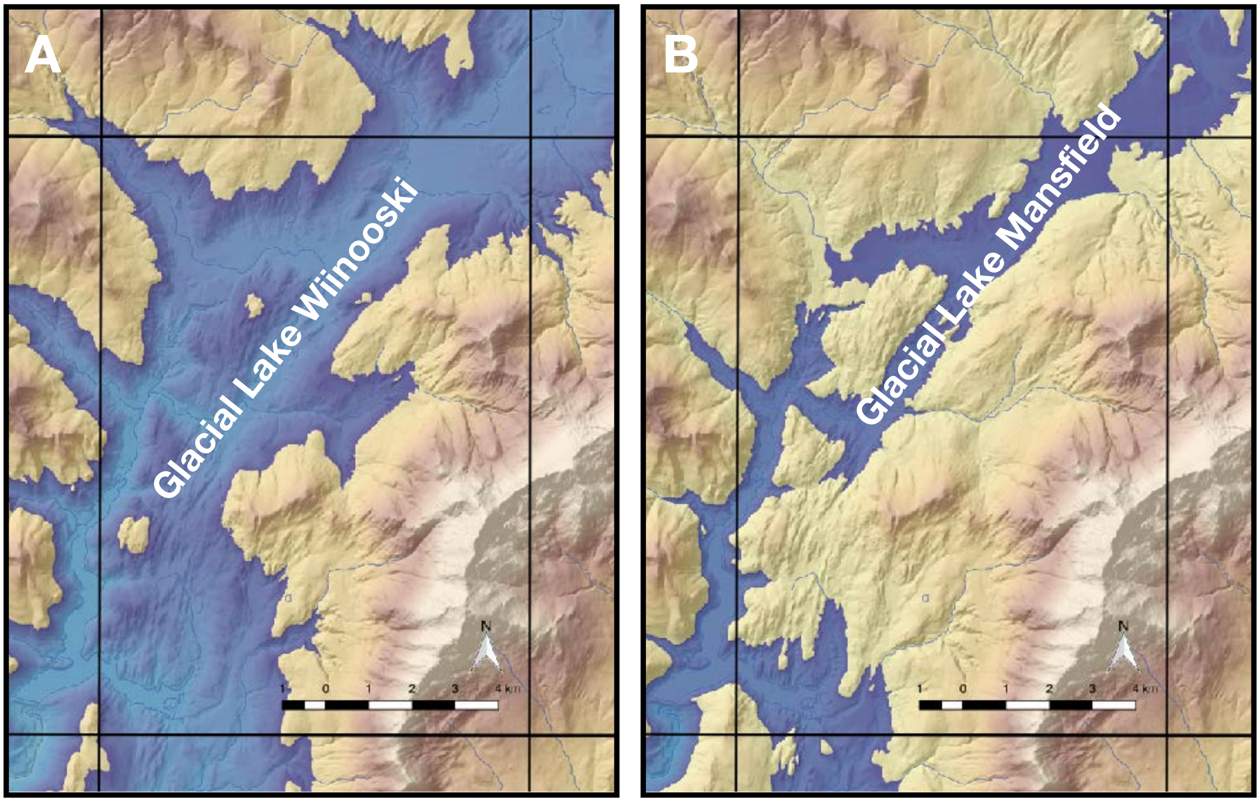

Figure 3: (A) Extent of Glacial Lake Winooski in the Stowe Quadrangle (lake elevation ~323 m). (B) Extent of Glacial Lake Mansfield in the Stowe Quadrangle (lake elevation ~235 m). The Worcester Range is the prominent ridge in the southeastern corner of the quadrangle.

In addition to extensive deposits of fine-grained sediments deposited in the deeper waters of these lakes, deltas formed where streams entered these glacial lakes. After these glacial lakes drained these same streams have eroded channels through the glaciolacustrine sediments during the Holocene leaving abandoned fluvial terraces along these valleys. Further stream erosion in the uplands has led to the deposition of numerous alluvial fans at the base of steep slopes.

Prior Work

The Stowe 7.5-minute quadrangle is the NW quadrant of the Montpelier 15-minute quadrangle which was mapped in reconnaissance-fashion by Stewart (1956–1966) using 1:62,500-scale topographic base maps. These open-file maps were incorporated into the Surficial Geologic Map of Vermont which is the source for the map presented in Figure 2 (Stewart and MacClintock, 1970). Springston and Dunn (2006) mapped a portion of the southern quadrangle encompassing the drainage basins of Bryant and Thatcher Brooks as part of a larger project mapping the southern Worcester Mountains watershed. Wright (2018b) mapped the western side of the Little River valley north of the Waterbury Reservoir when mapping the Bolton Mountain Quadrangle, the quadrangle lying immediately west of the Stowe quadrangle. Wright (2015b) has interpreted the ice flow history across this part of northern Vermont from a large compilation of glacial striation azimuths and has modeled the readvance of the Laurentide ice sheet in the adjacent Winooski River valley (the Middlesex Readvance) during the Older Dryas (Wright, 2015a).

Methods

Surficial geologic mapping of the Stowe Quadrangle was completed during the summer 2019 field season. Field observations were recorded using a Fulcrum data collection App modified for surficial field mapping. During this time over 3,000 separate field observations were recorded using the (1) shaded-relief LiDAR imagery, (2) topographic map, and (3) aerial photography as base maps. The locations of these observations are shown on Figure 4. Additional observations along the west side of the Little River valley immediately north of the Waterbury Reservoir were collected during an earlier field season (Wright, 2018b). A shape file detailing the location and geological observations recorded at each site was generated by the Fulcrum mapping app. These field data, the LiDAR imagery, and topographic contour lines generated from the LiDAR DEM's provide the basis for generating the surficial geologic map that accompanies this report.

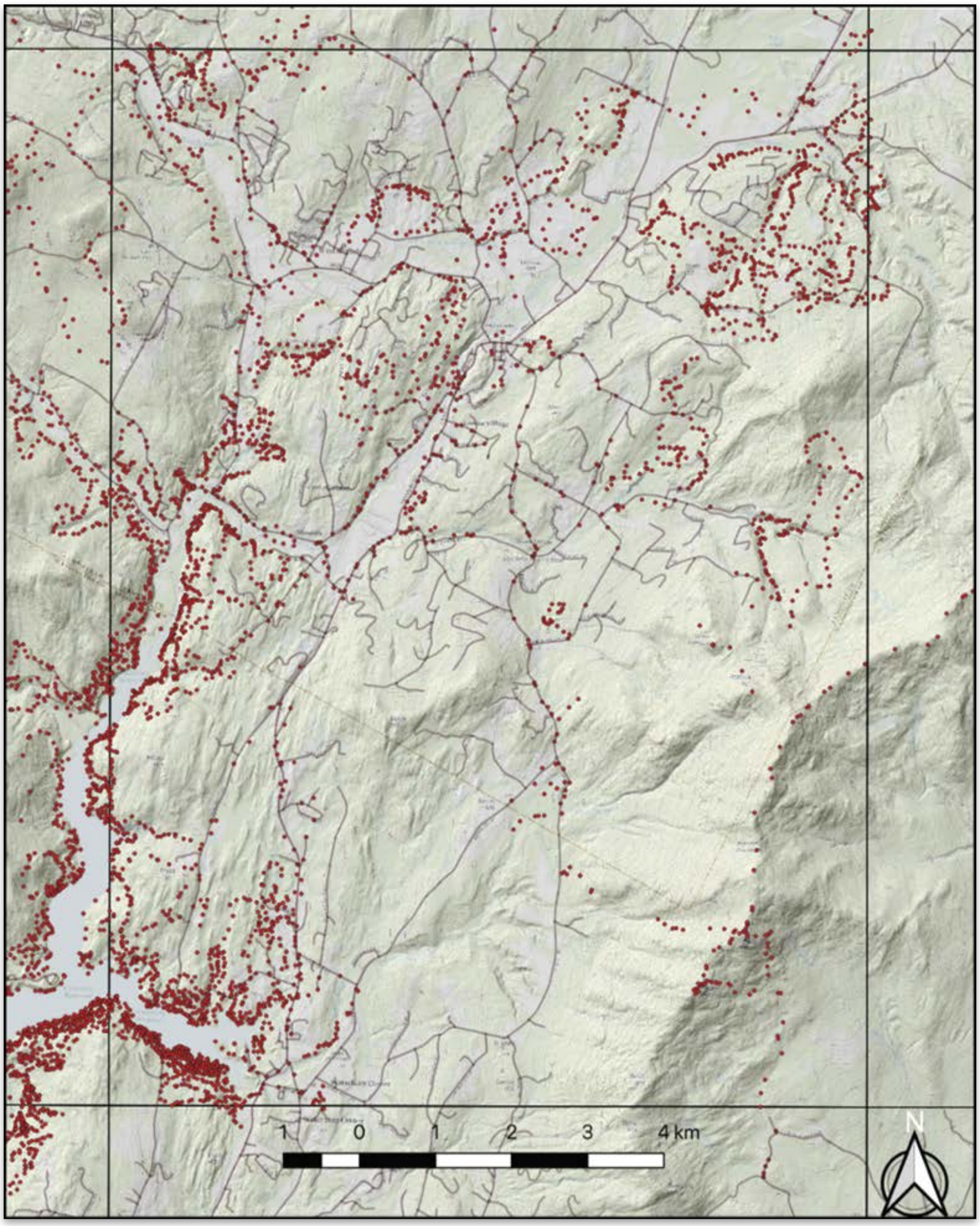

Figure 4: Red dots show locations of field observations within the Stowe and adjacent quadrangles.

Four UVM undergraduate students, Caleb Bogin, Sarah Powers, Abby Zani, and Corey Beutel, assisted with field work during 4 weeks in June. The students also assisted with 2 days of field work on the Cotton Brook landslide, a large landslide that occurred during May of 2019 just a few kilometers west of the Stowe Quadrangle boundary (Springston et al., 2020). When the weather was unsuitable for mapping students were introduced to GIS mapping in the UVM Geology Department's computer lab and began digitizing their data. Student mapping included most areas within the quadrangle west of Route 100 south of Stowe village and then west of a north-south line extending north from Stowe village. Students also collected outcrop locations and glacial striations along the trail up Stowe Pinnacle and the trail between Stowe Pinnacle and Mount Hunger/White Rocks. The students presented their map, cross-sections, and interpretations on a poster (Bogin et al., 2020). While the combined Northeast/Southeast Geological Society of America meeting in Reston, Virginia was canceled because of the Corona virus, the students' poster will be eventually be accessible via the Vermont Geological Society website.

Only limited field work was conducted in the Thatcher Brook valley as this area had been recently mapped (Springston and Dunn, 2006). Consequently, geologic contacts and materials mapped in this area broadly follow those on the earlier map, but have been modified in some areas based on the stratigraphy described in water well logs and limited field observations.

Stowe 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, large erratics, and water wells. During the spring of 2018 the Vermont Geological Survey developed a uniform set of mapping units which are utilized on the Stowe Surficial Geologic Map (Springston et al., 2018). The boundaries between these different materials are geologic contacts and are shown as solid lines on the geologic map. It's important to realize, however, that these contacts are non-planar 2-D surfaces that extend out-of-sight below Earth's surface and their extension above Earth's surface has eroded away. In some areas geologic contacts could be closely located in the field and these locations were recorded and used when constructing the map. However, in most areas the location of these contacts is interpreted from field observations, distinctive landforms, and aerial imagery. Every effort was made to make these contacts as accurate as possible, but there is an element of interpretation in the placement of these contacts.

Surficial Geologic Mapping Units

The different surficial materials mapped within quadrangle are described below, in stratigraphic order, from oldest to youngest. Most of the surficial materials in the area were deposited by or adjacent to the Laurentide ice sheet as it flowed across and then gradually thinned and retreated across the area.

Bedrock Outcrops/Glacial Striations and Grooves

Bedrock outcrops were mapped when they were encountered during field traverses. Additionally, most outcrops occurring along town roads and state highways were also mapped. No attempt was made to map all outcrops, especially in the upland areas where outcrops are numerous and closely spaced. Some of the mapped outcrops still retain either or both glacial striations or grooves produced by glacial abrasion. Where visible, the orientations of linear features were recorded. In northern Vermont roches moutonnée, erratics derived from sources northwest of erratic locations, and tails of uneroded rock southeast of quartz veins all indicate that the ice sheet flowed from northwest to southeast across the area (Wright, 2015b). Consequently, arrows used on

Figure 5: Grooved bedrock outcrop on the east side of Mount Hunger.

the geologic map to show the orientation of glacial striations and grooves point generally southeast and south in the inferred down-ice flow direction.

Glacial Till

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 gray to light brown 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 (Fig. 3A). Most of the till occurring in this area is lodgement till consisting of materials eroded, deformed, and deposited beneath the ice sheet. Close to the ground surface frost heaving, plant roots, and animal borrows have loosened the till and surface run off has eroded some of the smaller-sized sediment (the "fines") in the till. Ablation till was undoubtedly at least locally deposited on top of the lodgment till, but its texture is similar to lodgment till loosened by frost heaving etc. No attempt was made to systematically measure the composition of the till by either grain size or composition nor were any till fabric measurements made.

Figure 6: Dense, grey glacial till exposed in a small stream-cut along an empheral tributary to Miller Brook. Most clasts in the till are small, but large boulders are not uncommon.

The thickness of till in the upland areas of the quadrangle varies considerably. Generally, the till cover is thin (less than 2 to 3 meters) and abundant outcrops are present. However, the till across extensive areas in the upland valleys is sufficiently thick to completely mask the underlying bedrock. No wells exist in these areas, but tributary streams frequently incise through more than 10 m of till. Large (>4 m diameter) erratics, composed of locally derived metamorphic rocks, are common and were mapped where encountered (Fig. 7).

Figure 7: Exceptionally large erratic along a small tributary east of the Waterbury Reservoir. Erratic diameter exceeds 15 m.

Readvance Till

A stratigraphically continuous, albeit thin layer of diamict was mapped by Springston and Dunn (2006) across a high-elevation terrace in the Thatcher Brook valley. This diamict overlies glaciolacustrine sediments and was interpreted to be a readvance till deposited when the ice sheet readvanced across a recently deglaciated landscape in response to climatic cooling, the Middlesex Readvance (Wright, 2015a). A cross-section illustrates the geometry of the readvance till and other glacial materials in this area (Fig. 8). Another diamict comprised largely of structureless silt/sand mixed with rocks was mapped southwest of Moss Glen Brook in the northeastern corner of the quadrangle where it occurs in a landform interpreted to be a moraine. This material is similarly interpreted as a readvance till produced as the ice sheet advanced across recently deposited glaciolacustrine sediments and pushed these materials into a moraine. Stewart and MacClintock (1970) mapped this moraine, but show it extending far beyond what is shown on the current map (Fig. 2).

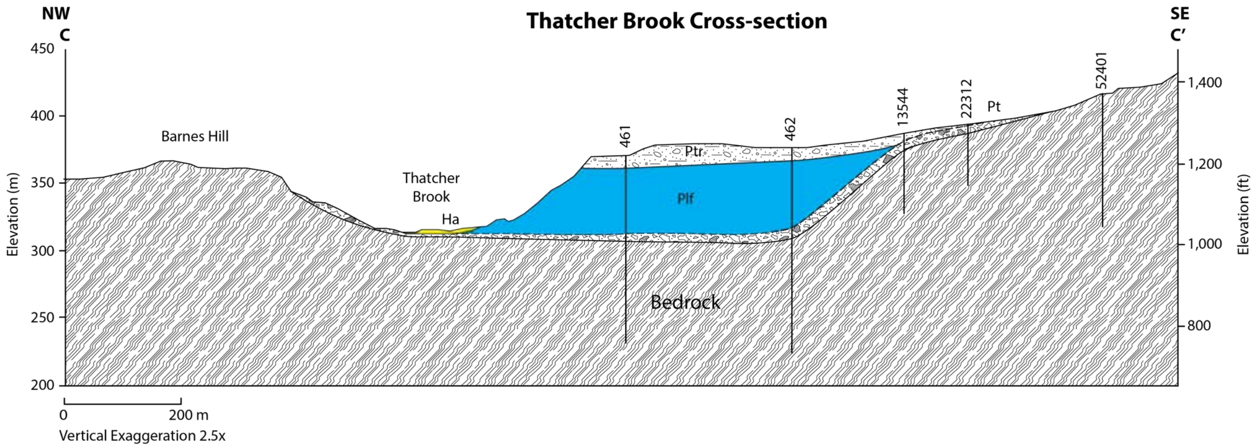

Figure 8: Cross-section C-C' showing the vertical distribution of glacial sediments in the Thatcher Brook drainage. Well logs document the thin readvance till (Ptr) overlying a thick section of fine-grained glaciolacustrine sediment (Plf: silt/fine sand). The lacustrine sediments overlie the widely distributed basal till (Pt) that extends across Barnes Hill and the highlands to the southeast. See geologic map for location of section.

Ice-Contact Deposits

Ice-contact deposits largely consist of fluvial (stream-deposited) sediments deposited under, adjacent to, or in front of the retreating ice sheet. These streams are generally fast-moving and therefore carry and deposit coarse-grained sediment, dominantly sand and gravel. Sediments deposited in subglacial tunnels form ridges of sand and gravel (eskers) once the glacier melts away. No ice-contact sediments were mapped in the Stowe Quadrangle. However, well logs indicate that coarse-grained sediments underlie fine-grained glaciolacustrine sediments in the Little River valley north of Stowe Village (Fig. 9). A cross-section (B-B') illustrates the vertical distribution of sediments in the valley. Well 400 taps a confined sand and gravel aquifer here interpreted as an esker although this could also be part of a subaqueous fan deposited near the mouth of an esker tunnel.

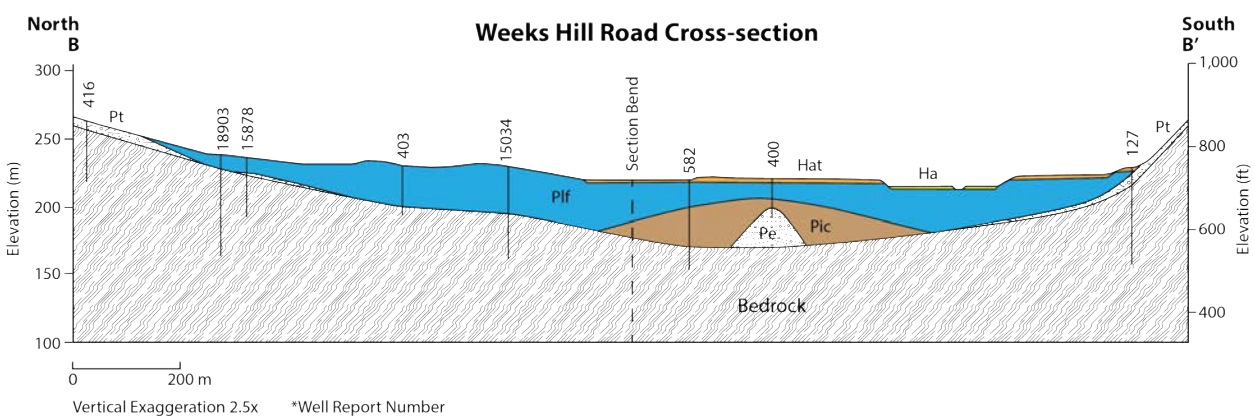

Figure 9: North-south cross-section across the Little River valley north of Stowe village (see geologic map for location). Thin alluvial terrace (Hat) and alluvim (Ha) deposits overlie a thick section of fine-grained glaciolacustrine sediments (Plf). These fine-grained sediments overlie coarser, more permeable sediments that serve as the aquifer that feeds wells 582 and 400.

Lacustrine (Glacial Lake) Deposits

Glacial lake deposits include both coarser-grained sediments deposited at or near the shorelines of lakes (deltas and beaches) and finer-grained sediments deposited in the deeper quiet-water parts of lakes (Fig. 10). Fine-grained lacustrine sediments are common in most of the valleys in the quadrangle (see Plf unit on the geologic map and in Figs. 8 and 9) and several deltas have also been mapped. Larsen (1972, 1987) outlined the sequence of glacial lakes that occupied the Winooski River drainage basin as the retreating ice sheet dammed the west-flowing river preventing it from draining into the Champlain valley. The highest regional lake, Glacial Lake Winooski, extended across the Little River valley as well as tributary valleys in the quadrangle (Fig. 3). The geologic map traces a projection of the shoreline of this lake across the quadrangle[2]. As the ice sheet retreated down the Winooski River valley it uncovered lower outlets allowing Glacial Lake Winooski to partially drain through the Huntington River valley and Hollow Brook into the Champlain Valley. The lower-elevation regional lake that formed is called Glacial Lake Mansfield and the designators 1 and 2 are used to refer to two outlets of that lake at slightly different elevations (Fig. 3; Larsen, 1972, 1987). The geologic map also includes the projection of the shoreline of this lake at its higher elevation, i.e. Glacial Lake Mansfield 1. A stratigraphic section exposed along the Waterbury Reservoir in Little River State Park records the transition from Glacial Lake Winooski to Glacial Lake Mansfield 1 (Larsen et al., 2003). Correlation with the well-dated Connecticut Valley varve sequence allows this drainage event to be dated to ~13,800 years ago (Ridge et al., 2012; Wright, 2018a). Glacial Lake Winooski varve counts indicate that this lake evolved over a time span of less than 300 years and likely only existed in the Stowe Quadrangle area for less than 200 years. Glacial Lake Mansfield lasted for a much shorter period of time as the ice sheet needed to retreat only a short distance for this lake to merge with Glacial Lake Vermont, a lake too low in elevation to flood any of the valleys in the Stowe Quadrangle (Wright, 2018a).

Figure 10: Fine-grained glaciolacustrine sediments (Plf) exposed (A) near the north shore of the Waterbury Reservoir and (B) in Stowe Hollow. Sediments in both photos consist of yearly layers of silt and clay (varves). Soft-sediment deformation is evident near the shovel blade and resulted when weak unconsolidated sediments flowed in response to a density inversion (sand over water-saturated silt) or slumping along a sloping lake-bottom surface.

Several glacial lake deltas were mapped in the area. Significant areas of sand and gravel were deposited as deltas in Glacial Lake Winooski in (1) the northwest corner of the quadrangle where the West Branch of the Little River flowed into the lake (the bulk of this delta lies near Stowe Fork), (2) in the northeast corner of the quadrangle where Moss Glen Brook entered the lake, and (3) in Stowe Hollow where Gold Brook entered the lake. Similarly, streams flowing into the lower-elevation Glacial Lake Mansfield also deposited deltas. The best preserved of these lies northeast of the intersection of Gold Brook Road and Route 100. The broad terrace that Stowe High School is built on may also

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[2] The shoreline projection of both Glacial Lake Winooski and Glacial Lake Mansfield 1 are from work by George Springston. Calibration, based on recent detailed mapping, is ongoing.

be a Glacial Lake Mansfield delta. A third Glacial Lake Mansfield delta occurs where Moss Glen Brook partially eroded its older Glacial Lake Winooski delta and redeposited these sediments in both a fan (see below) and a delta.

Alluvial Fans (Pleistocene and Holocene)

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

Alluvial fans of different sizes and age are shown on the geologic map. Pleistocene alluvial fans have been mapped in areas where Glacial Lake Winooski deltas were incised by streams immediately following their abandonment when the lake partially drained forming Glacial Lake Mansfield. The eroded delta sediments were deposited as fans that graded into Glacial Lake Mansfield deltas.

Holocene fans are also common in the area. Studies in northern Vermont indicate that alluvial fans have been active episodically throughout the Holocene and have 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 climate shifts produce a greater frequency of high-intensity storms, further sedimentation on the area's alluvial fans seems likely.

Fluvial Terrace Deposits

Fluvial terrace deposits are stream sediments (alluvium) occurring on terraces well above modern streams (Fig. 11). Most commonly these sediments were deposited when streams began flowing across and incising into sediment-filled valleys after the glacial lakes drained. As streams eroded channels more and more deeply through earlier-deposited sediments, older channels were abandoned. Consequently, in many areas mapped as fluvial terrace deposits there are several terrace levels and old abandoned channels are visible in many of these terraces. In most areas these fluvial terraces are underlain by a veneer of sand and gravel corresponding in thickness to the depth of the stream channel that deposited the sediment. In some areas gravel on these terraces has been partially or largely mined away revealing the underlying sediments. For geological consistency, terraces where the alluvium has been mined were still mapped as fluvial terrace deposits.

Figure 11: Abandoned fluvial terrace (Hat) along River Road, west side of Little River valley. Meadow is underlain by sand and gravel deposited by the Little River before it eroded ~10 m down to its current level to the right of the photograph.

Alluvium

Alluvium refers to sediments deposited by modern rivers and streams. Alluvium includes sand and gravel deposited in river channels and point bars, but also includes sand and silt deposited on floodplains that are frequently forested or farmed (Fig. 12). Organic materials are a frequent component of modern alluvium. Broad areas of alluvium lie adjacent to the Little River and its tributaries.

Figure 12: Alluvium exposed along a reach of the Little River lying between River Road and Route 100. Pebble/cobble gravel is exposed on the bar at right whereas finer-grained sand/silt/organics are exposed in the cutbank at left.

As soon as the glacial lakes that once occupied the valleys drained, streams began flowing across the sediment deposited in these lakes. In most areas at least some of the underlying glacial lake sediments were eroded before alluvium was deposited. Figure 13 shows a rare exposure of Little River alluvium in contact with the underlying glacial lake sediments. In smaller upland stream valleys, alluvium commonly is deposited directly on glacial till.

Figure 13: Approximately 2 m of alluvium is deposited directly on fine-grained glacial lake sediments exposed near the waterline. When the last glacial lake drained from the valley the Little River began flowing across and eroding the recently deposited lake sediments. Mayo Farm property, Stowe.

In many if not most areas modern alluvium is in contact with fluvial terrace deposits (old alluvium). The contact between these two mapping units is an interpretation of how much area is flooded during high-water events. The thickness of alluvium is proportional to the size of the stream that deposited it, but generally corresponds to the depth of the modern stream channel.

North of the confluence of the West Branch and the Little River the Little River valley becomes very broad where it's joined by Sterling Brook (Fig. 14). This wide area has almost no relief and is most likely the little-eroded bottom of Glacial Lakes Winooski and Mansfield mantled with a thin veneer of alluvium and alluvial terrace deposits. The alluvium across much of this area dominantly consists of fine-grained sediment as that was the material Sterling Brook and the Little River were eroding and transporting in this area. A diffuse drainage divide crosses this area separatig water flowing north into the Lamoille River from water flowing south into the Winooski River (via the Little River). Several large kettles occur in this area indicating that blocks of the ice sheet detached where the ice sheet thinned over this drainage divide. They were likely quickly buried by ice-contact sediment emanating from one or more subglacial tunnels in the ice sheet and/or sediment deposited by the Moss Glen Brook Delta.

Figure 14: View looking south across a broad area of alluvial terrace deposits (Hat) lying between the Little River and Sterling Brook. A thin veneer of alluvium overlies fine-grained glacial lake sediments deposited on the bottom of both Glacial Lakes Winooski and Mansfield.

Swamp/Wetlands

Wetland areas generally occupy closed basins and display varying amounts of open water depending on the season and the water table elevation (Fig. 15). The dominant surficial material in wetland areas consists of both living and partially decayed organic materials but also includes inorganic clastic sediment washed into these areas by streams and overland flow. The borders of wetland polygons were mapped using satellite imagery, but the boundaries shown on the geologic map should not be used for regulatory purposes.

Figure 15: Wetland area near northern boundary of the quadrangle. Sediments accumulating here consist of both organics and silt/sand washed in from the surrounding area.

Artificial Fill

Areas mapped as artificial fill often consist of materials used to fill stream valleys crossed by roads but also include materials used for construction where the water table is close to the surface. Fill is shown on the geologic map where it could be mapped using the LiDAR imagery. Materials comprising fill are generally sand and gravel, but can also include broken and crushed rock, concrete, and other waste materials.

Geologic Cross-Sections

Four geologic cross-sections were constructed for this project. All of them are included on the geologic map sheet where their locations are also shown. Two were described earlier in this report and the remaining two are described below. Cross-sections present an interpretation of the different surficial materials lying beneath Earth's surface and their thickness. The best information available about the type and thickness of surficial materials in most areas comes from the logs kept by drillers when completing domestic water wells. The most accurate information recorded by drillers is the "depth to bedrock" or "overburden thickness" as this is approximately equivalent to the length of steel casing needed for a drilled well, a length carefully recorded and charged to the home owner. Otherwise, the quality of records kept by drillers of the type and thickness of the surficial material they drill through varies enormously and frequently requires considerable interpretation when constructing a cross-section. Many well logs are so poor that they provide no useful geological information. Geologic cross-sections were generally drawn where a reasonable number of water wells with good logs were aligned across major valleys. All are drawn with a 2.5x vertical exaggeration making slopes appear steeper than they actually are and units thicker.

The Little River Farm Road Cross-section (A-A', Fig. 16) displays a distribution of surficial materials that is common in the region. Glacial till (Pt) mantles the steeper slopes above the valley whereas most of the materials filling the valley consist of fine-grained lake sediment (Plf). The silt/clay was most likely deposited when Glacial Lake Winooski occupied the valley whereas the sand was likely deposited in the much shallower Glacial Lake Mansfield. These lake-bottom sediments were eroded into a series of terraces by the Little River once the glacial lakes drained. Each terrace is underlain by river alluvium (Hat) including those adjacent to the modern river channel (Ha).

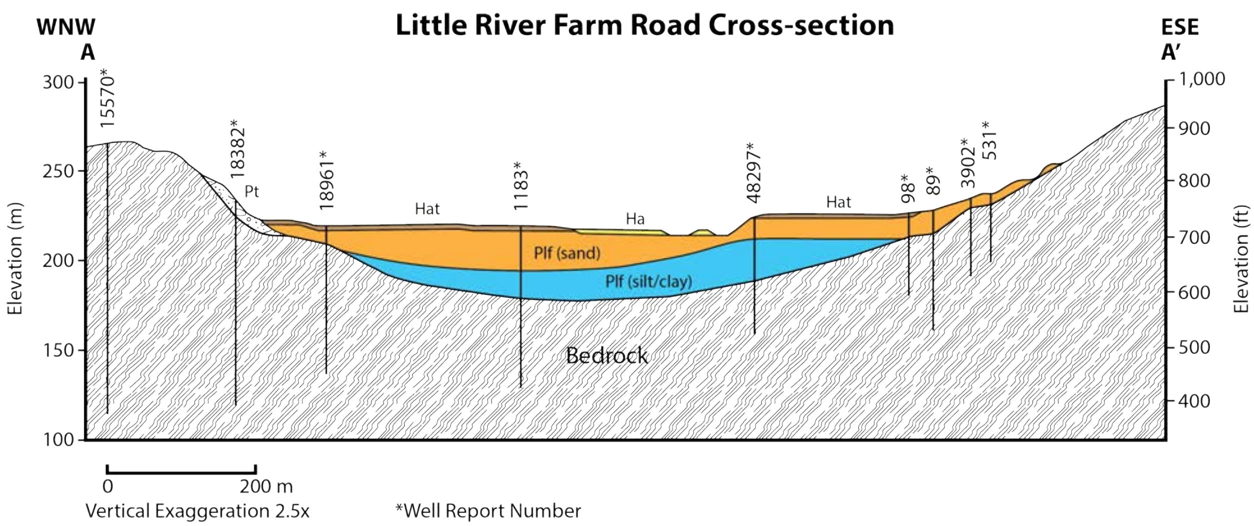

Figure 16: Approximately West-East geologic cross-section across the Little River valley northeast of Stowe Village. Most surficial sediment occurring in the valley consists of fine sand, silt, and clay deposited in the relatively deep parts of Glacial Lakes Winooski and Mansfield. Terraces on either side of the river are underlain by "old" alluvium deposited when the Little River was flowing across the underlying lake-bottom sediments.

The Waterbury Center Cross-section (D-D', Fig. 17) extends almost north-south through Waterbury Center and across the Bryant Brook valley not far upstream from where it enters the Waterbury Reservoir. Numerous wells indicate that the valley is filled with fine-grained glacial lake sediment. The terrace which the village of Waterbury Center is built on is underlain by sand. This is interpreted to be sand also deposited in a glacial lake (Glacial Lake Mansfield) but it may be sand that was eroded from farther upstream and deposited as the fine-grained toe of an alluvial fan. Coarser grained sediments penetrated by some wells are interpreted to be ice-contact sediments (Pic).

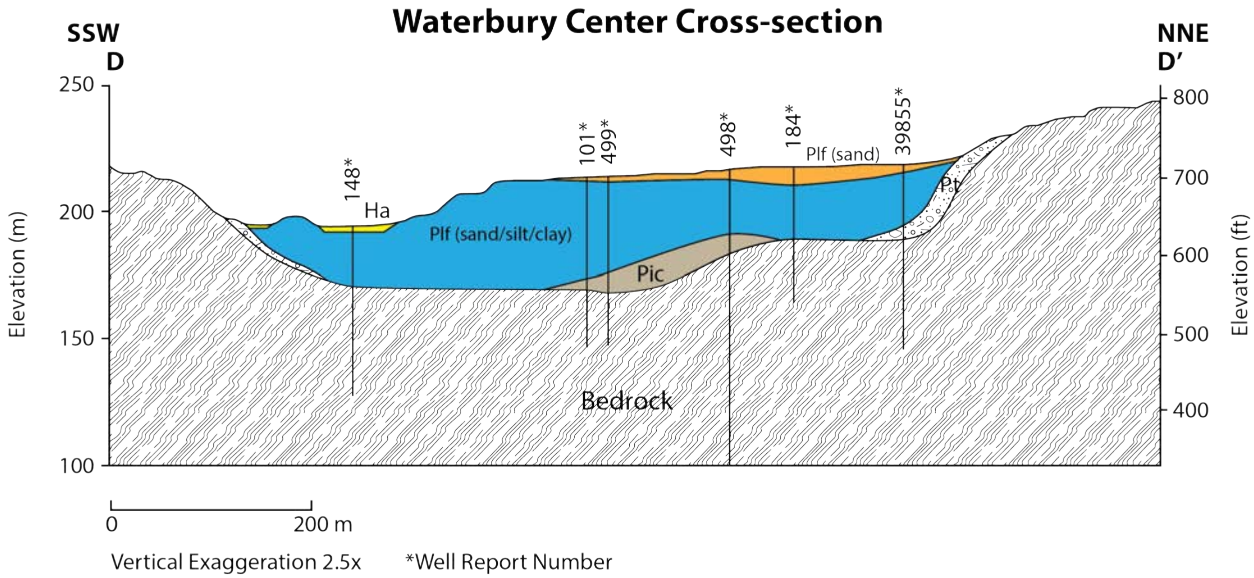

Figure 17: Cross-section through Waterbury Center and Bryant Brook (view looks west). The bedrock valley is well constrained by water wells and is filled with both coarser ice-contact sediments (Pic) and fine-grained glacial lake sediments (Plf). Terraces mark former positions of Bryant Brook as it has eroded through the glacial lake sediments.

Isopach Map of Surficial Materials

The "Isopach Map of Surficial Materials" contours the thickness of surficial materials (overburden) within the quadrangle. The data used to generate this map are (1) bedrock outcrops recorded from this study (which indicate areas where surficial materials don't occur), (2) bedrock outcrops visible on the LiDAR shaded-relief imagery, and (3) records of overburden thickness from domestic water wells. The well locations were not checked and errors, some significant misplacements of wells, occur which affect the accuracy of these contours. These data are contoured using a 20-foot contour interval between 0 and 100 feet and 100-foot contours in areas where surficial materials exceed 100 feet. Contouring algorithms applied to the overburden thickness data produced geologically unrealistic contours, so these data were contoured by hand. In general, isolated wells reporting thick surficial materials were ignored, i.e. bullseyes were not drawn around these isolated wells.

Generally, areas of thick surficial materials occur in the major river valleys (see the geologic cross-sections described earlier in this report). The valleys have accumulated not only the till that's also present in the uplands, but all of the ice-contact (e.g. esker) and glacial lake sediments that accumulated as the ice sheet was retreating across this area. In many parts of these valleys sediment fill exceeds 100 to 200 feet indicating that preglacial erosion was substantial and in many areas these preglacial valleys are largely hidden by the glacial sediments that currently fill them. One striking example is the thick accumulation of sediment lying beneath the terrace that Stowe High School is built on. A deep buried bedrock channel extends south from here to the modern channel of the Little River. This is the paleo-channel of the Little River and its current channel across the waterfall between the lower and upper village of Stowe is new (see discussion in below section). The bedrock channel beneath the Little River valley north of Stowe Village is also deep and may indicate a preglacial channel that extended north into the Lamoille River valley.

Surficial Geological History of the Stowe Quadrangle Area

The observations gathered during this mapping project combined with many other studies provide the basis for interpreting this area's surficial geologic history. The highest mountains in the area are marked by glacial striations and contain remnant patches of glacial till. These observations indicate that the last ice sheet completely covered the mountains. Modeling by the author suggests that at the peak of glaciation, ~25,000 years ago, the ice surface over the northern Green Mountains was at an elevation of almost 2,200 m, i.e. ~840 m of ice (~2,750 ft) covered

Vermont's highest peak, Mount Mansfield. Glacial striations across both the Green Mountains and the Worcester Range are oriented NW-SE indicating that the ice sheet was flowing to the southeast, obliquely across the mountains and intervening valleys (Wright, 2015b). As the ice sheet thinned its flow direction became topographically controlled by the orientation of the large valley lying between the Green Mountains and the Worcester Range, the valley which occupies most of the Stowe Quadrangle. Glacial striations in the valley are dominantly oriented parallel to it and formed when the thinning ice sheet was flowing approximately south.

As the ice sheet was retreating, most meltwater generated at its surface flowed through the ice to its base where it collected in large subglacial tunnels. Sediments eroded from the underlying till as well as from the ice were carried in subglacial streams and eventually discharged at the margin of the ice sheet. As noted earlier, no ice-contact sediments were mapped at the surface of the Stowe Quadrangle, but coarse sand and gravel encountered at depth in drill cores are interpreted to be ice-contact sediments (Figs. 9, 17).

When the margin of the ice sheet retreated across north-central Vermont the drainage divide separating water flowing east and south into the Connecticut River from water flowing north and west into Lake Champlain was uncovered. As the ice sheet retreated north of this divide, water that would normally flow north and west into the Winooski River instead pooled up forming a glacial lake, Glacial Lake Winooski (Larsen, 1972, 1987). This lake grew in size as the ice sheet retreated and eventually covered all of the Winooski and Lamoille drainage basins east of the Green Mountains (Fig. 3A; Wright, 2018a). However, there is good evidence that while Glacial Lake Winooski was expanding northward, the ice sheet reversed its retreat and began advancing back across areas it had recently uncovered. This event is locally referred to as the Middlesex Readvance and likely occurred during a ~100-year-long cooling period referred to as the Older Dryas, ~14,100 to 14,000 years ago (Ridge et al., 2012; Wright, 2015a). During this time a thin layer of till was deposited on top of sediments recently deposited in Glacial Lake Winooski and locally moraines formed along the ice margin (See northeast corner of the geologic map; Springston and Dunn, 2006). The extent of this readvance till indicates that the ice front advanced back up the Winooski River valley well beyond Montpelier before it withdrew again allowing Glacial Lake Winooski to regrow (Wright, 2015a).

After the Middlesex Readvance, Glacial Lake Winooski lasted for less than 200 years. As the ice sheet retreated down the Winooski River valley it uncovered lower outlets allowing Glacial Lake Winooski to partially drain, albeit catastrophically, through the Huntington River valley and Hollow Brook into the Champlain Valley. This transition can be accurately dated and occurred 13,820 years ago. The lower-elevation regional lake that formed is called Glacial Lake Mansfield and the designators 1 and 2 are used to refer to two outlets of that lake at slightly different elevations (Fig. 3B; Larsen, 1972, 1987). The transition from Glacial Lake Winooski to Glacial Lake Mansfield is evident stratigraphically where parts of the lake floor that previously only received silt and clay size sediment abruptly began receiving coarser sand.

As noted earlier, coarse sand and gravel was deposited in deltas where streams entered Glacial Lake Winooski. One delta occurs near the northwest corner of the quadrangle at Stowe Fork, another near the northeast corner of the quadrangle where Moss Glen Brook enters the quadrangle, and a third in Stowe Hollow where Gold Brook formed a delta. Streams flowing into Glacial Lake Mansfield also formed deltas that have been described earlier. However, the majority of the sediments deposited in these lakes consist of medium to fine sand, silt, and clay. These fine sediments were suspended in the high-velocity water emanating from beneath the retreating ice sheet and eventually settled on the lake floor. These fine sediments were also sourced from streams eroding the recently deglaciated, steep mountain slopes that were free of vegetation as well as the older Glacial Lake Winooski deltas.

Further retreat of the ice sheet WNW down the Winooski River valley allowed Glacial Lake Mansfield to drain and merge with Glacial Lake Vermont, the large lower-elevation lake that occupied the Champlain valley (Van Hoesen et al., 2016; Wright, 2018a). When this occurred, the low-relief, sediment filled lake bottom was quickly exposed and streams began to flow across them eroding new channels and depositing alluvium along their courses. Pre-glacial stream channels were filled with glacial sediments. In most areas the modern streams re-excavated those old channels, but in some areas modern streams eroded new channels. In the Stowe Quadrangle, the old Little River channel remains buried beneath over 200 ft of sediments that currently extend south from Stowe High School along Barrows Road. Formerly, the West Branch joined the Little River just north of the high school and joined rivers flowed south from there to rejoin the modern channel where Barrows Road intersects Moscow Road. The “new” channel that the Little River eroded crosses bedrock in Stowe Village. This bedrock is the source of the water fall that powered the mills critical for Stowe’s early development. This bedrock has also prevented the Little River from eroding the glacial lake sediments from the valleys upstream of the village. Instead, both the West Branch and Little Rivers have meandered back and forth across the glacial lake sediments that filled the bottom of the glacial lakes that once existed here. These wide, low-relief valleys with a thin cover of river sediments have historically provided the best agricultural land in the area.

Groundwater Hydrology of the Stowe Quadrangle

Within the Stowe Quadrangle, people rely almost entirely on groundwater for their drinking water supply. Most households utilize private water wells, but the villages of Stowe and Waterbury Center operate municipal water systems that also are sourced from groundwater wells. Surficial aquifers are utilized by some residents (shallow dug wells or deeper drilled wells in surficial materials), however drilled wells extending variable depths into bedrock are used by most residents.

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

The largest useful groundwater aquifers occurring in the quadrangle are found in the coarse-grained surficial materials (sand and gravel) where those materials extend below the water table. The sand and gravel deposited in deltas that were deposited in both Glacial Lakes Winooski and Mansfield are one of these aquifers. The second large group of aquifers are the ice-contact sediments (sand and gravel) that lie buried beneath fine-grained glacial lake sediments in many of the area’s valleys. These sediments, while buried and only discoverable via drilling or geophysical work, are confined and consequently isolated from contamination from human and agricultural sources.

Water Table Contour Map with Flow Lines

A map contouring the elevation of the water table is included with this report. The data used to construct these contours comes from the topographic map of the area and domestic water wells where the depth to the water table was recorded. Specifically, groundwater discharges to the surface in streams, ponds, lakes, and wetlands so these are areas where the elevation of the ground surface and the elevation of the water table are equal. In areas between these groundwater discharge points the water table is, by definition, at an elevation below the ground surface. Streams are common in the upland areas implying that even in these areas the water table is relatively close to the ground surface. For the groundwater wells, the water table elevation was calculated by taking the surface elevation of the well (garnered from the LiDAR DEM) and subtracting the depth to the static water table. The calculated water table elevation (in feet above sea level) is labeled adjacent to each well where these data are available.

Drainage basin outlines were downloaded from the VCGI database and denote both surface water and groundwater divides. In this mountainous terrain water table contours were drawn at 500-foot intervals across the quadrangle.

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

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

Recharge Potential to Surficial Aquifers Map

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

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

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

Alluvium, Alluvial Fan sediments, Fluvial Terrace sediments, Deltaic sediments, and Wetlands are all materials that readily absorb surface water. They all consist of coarse-grained surficial materials and lie in valleys where slopes are gentle. Where these materials overlie moderate- to low-permeability materials, they have the capacity of soak up surface water allowing it to slowly seep into these underlying surficial materials. With the exception of the wetlands areas, these materials make excellent surficial aquifers where they extend below the water table. Wetlands uniquely serve as good recharge sites because they occur in closed depressions where surface water collects. Even if the surficial materials underlying wetland have a low permeability, they will have a near constant flow of well-filtered surface water through them into the underlying groundwater system.

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

Lacustrine very fine sand, fine sand, silt, most till and artificial fill (commonly covered with pavement) all have moderate to low permeabilities. Till mantles most upland areas and usually directly overlies bedrock, so till itself is the surficial aquifer that's being recharged. As noted earlier, animals, vegetation, and frost heaving enhance near surface infiltration and dug wells utilizing groundwater from till are common. Lacustrine fine sand, silt, and clay occurs in the valley bottoms where slopes are gentle which enhances its ability to absorb water. Slow movement of water through these materials can recharge coarse-grained surficial aquifer materials or bedrock, albeit slowly.

Bedrock Hydrologic Units Map

A “Bedrock Hydrologic Map” was generated using the bedrock map units utilized for the Bedrock Geologic Map of Vermont (Ratcliffe et al., 2011). Rock units within the Stowe Quadrangle include several members of the Stowe Formation (CZs, CZsg, CZswa, CZsws), the Jay Peak Formation (CZj), two members of the Hazens Notch Formation (CZhn, CZhng), the Fayston Formation (CZf), and two members of the Ottauchechee Formation (Co, Coa). These are all metamorphic rocks consisting of siltstone, shale, and basalt metamorphosed to produce a variety of metamorphic rocks, e.g. phyllites, schists, greenstones, and amphibolites). Water wells from the database compiled by the Vermont Agency of Natural resources are also shown on the map with the size of the well symbol correlative with the well yield (GPM: Gallons Per Minute).

Water wells were grouped by rock type and statistics (maximum, minimum, median, mean, and total count) were calculated for both well depth and well yield. These statistics include all wells occurring within each rock unit. Most of these are drilled wells in bedrock, but some are deep wells that tap surficial aquifers. High-yield wells occur in all rock units, but some of these may be deep wells tapping surficial as opposed to bedrock aquifers. There is no significant difference in well yield between the different rocks in the quadrangle reflecting the fact that the yield of any drilled well in metamorphic rocks is most likely correlated to the density of fractures in the underlying bedrock (specifically the number, width, length, and interconnectedness of those fractures) and not its mineralogy. Extensively fractured bedrock is more susceptible to weathering and erosion than unfractured bedrock and frequently guides the location of large- and small-scale valleys that are quite linear. These linear features can be mapped and used as a guide for drilling high-yield bedrock water wells. A map of this type was not generated as part of this project.

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