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Surficial Geology and Groundwater Hydrology of the Richmond Quadrangle, Vermont

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Roches Moutonnée exposed along the south side of the Winooski River, ~2 km east of Jonesville. The right (up-glacier) side of the outcrop (WNW side) is glacially smoothed and incised with grooves and striations aligned approximately parallel to the Winooski River valley. The left (down-glacier) side of the outcrop (ESE side) was glacially quarried.

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Executive Summary/Significant Findings

The surficial geology of the Richmond 7.5-Minute Quadrangle was mapped during the summer of 2018 with field assistance from four geology students at the University of Vermont. Considerable detail has been added to prior maps created by Stewart (1956-1966), LaDue (1982), and Clark et al. (2005). A geologic map, cross-section, overburden thickness map, potentiometric surface map, recharge potential to surficial materials map, and bedrock hydrologic unit map are included with this report.

The Richmond 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 Champlain valley (ice west of the Green Mountains) and from WNW to ESE in the Winooski River valley.

Till mantles all of the upland areas. Most is dense lodgment till. It's unclear to what extent loose till at the ground surface is lodgment till loosened by 13,000 years of weathering or a thin discontinuous cover of ablation till.

During ice retreat large volumes of ice-contact sediments were deposited within the quadrangle. In particular, several eskers were mapped across most of the quadrangle marking subglacial drainage systems in the tinning ice. West of the mountains the eskers are all oriented north-south and are particularly well preserved within the Military Reservation. Associated with the eskers are extensive deposits of ice-contact sand and gravel that were deposited in subaqueous fans, deltas in several high-elevation lakes that existed in the Winooski River, Lee River and Mill Brook valleys. Sand and gravel deposits are also associated with ice-marginal streams and deltas that formed where the Lee River and Mill Brook entered Glacial Lake Vermont. These same ice-marginal streams eroded numerous channels that area clearly visible in the LiDAR imagery. Many of these channels are floored by till, i.e. the streams that formed the channels were primarily erosive, and some of these old channels are now occupied by wetlands.

Many of the lower elevation areas are underlain by fine-grained sediments (fine sand, silt, clay) deposited in one or more of the glacial lakes that occupied these valleys. The Lee and Mill Brook valleys hosted short-lived high elevation lakes. The Winooski River valley was occupied by two stages of Glacial Lake Mansfield and areas farther west were inundated by two stages of Glacial Lake Vermont. Erosion following lake-level drops has produced has left many abandoned river terraces. In other areas these lacustrine sediments have been incised by a dendritic drainage pattern.

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.

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 Winooksi River, the Lee River, and Mill Brook.

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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 Richmond 7.5-minute Quadrangle, northern Vermont during the summer of 2018. 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 during and immediately following ice sheet retreat. Other landforms and associated surficial materials offer insight into processes occurring during the Holocene well after the ice sheet retreated.

Location and Geologic Setting

The Richmond Quadrangle lies along the western slopes of the Green Mountains of northern Vermont and includes portions of the towns of Richmond, Jericho, Underhill, and Bolton (Fig. 1). The Winooski River valley cuts WNW to ESE across the southern third of the quadrangle and two smaller streams, Mill Brook and the Lee River, similarly occupy east-west valleys across the northern half 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 almost entirely of metasedimentary rocks that were originally deposited in the Iapetus ocean along the margin of Laurentia from late Precambrian through early/middle Ordovician time. These rocks were subsequently deformed and metamorphosed during the Taconic Orogeny and again during the Acadian Orogeny. Rock units in this area are typically bounded by north-south striking thrust faults and lesser normal faults occurring on a wide range of scales that generally mimic the north-south trend of the mountain belt (Ratcliffe, et al., 2011).

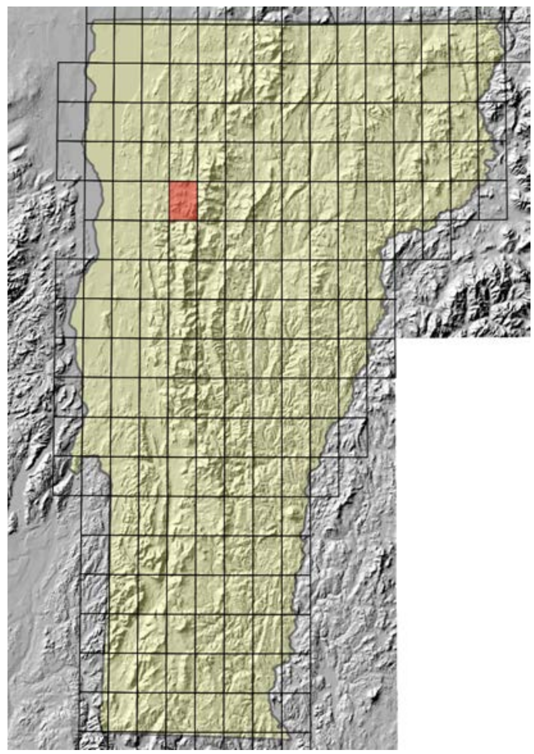

Figure 1: Shaded relief map of Vermont showing the location of the Richmond 7.5-minute Quadrangle (red rectangle) situated along the western flank of the Green Mountains.

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

Prior Work

The first systematic mapping of surficial materials in the area was completed in reconnaissance fashion by Stewart (1956–1966) and Connally (1965) using 15-minute (1:62,500-scale) base maps. These open-file maps were incorporated into the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970). A University of Vermont thesis by Ladue (1982) includes a map depicting the distribution of surficial materials in Jericho. A study by Clark et al. (2005) focused on the hydrologic setting of the Vermont Army National Guard Ethan Allen Firing Range. Their work included a surficial materials map. The principal investigator on this project has mapped a delta, esker system, and ice retreat stages in the eastern part of the quadrangle in Bolton Notch (Wright et al., 2015; Wright and Conroy, 2014), measured and interpreted a section exposed by a large landslide in the Preston Brook valley immediately southeast of the quadrangle (Wright, 2012, Wright et al., 2015), described evidence for ice readvance in West Bolton (Bierman et al., 1999), and mapped a Glacial Lake Vermont delta exposed along the Lee River (Wright et al., 2015). Wright has also interpreted the ice flow history across this part of northern Vermont from a large compilation of glacial striation azimuths (Wright, 2015) and has modeled the readvance of the Laurentide ice sheet in the Winooski River valley (the Middlesex Readvance) during the Older Dryas (Wright, 2015).

Methods

Surficial geologic mapping of the Richmond Quadrangle was completed during the summer 2018 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 2.Additional observations in the Joiner Brook valley and adjacent mountains were collected during earlier field seasons and don't appear on Figure 2, but do appear on the geologic map that accompanies this report. 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.

Four UVM undergraduate students (Timothy Quesnell, Frank Piasecki, Samuel Knapp, and Ryan Van Horn, assisted with field work for 4 weeks in June. When the weather was not suitable for mapping students were introduced to GIS mapping in the UVM Geology Department's computer lab and began digitizing their data. Student mapping efforts extended from the southern boundary of the Quadrangle (the Winooski River valley) north to the Mill Brook valley. They presented their map and cross-sections at the NEGSA meeting in Portland, Maine in March of 2019 (Quesnell et al., 2019).

Parts of the Joiner Brook valley lying within the Quadrangle were mapped during the 2017 field season with assistance from UVM graduate student Allison Waring. She compiled a geologic map of this valley and presented her map and cross-section during the 2018 NEGSA meeting in Burlington.

A significant area within the quadrangle lies within the Vermont Army National Guard Ethan Allen Firing Range. This area is used for a variety of military training activities. Permission was granted to conduct field work in a significant portion of the area during a week in August, but a large area within the General Dynamics Firing Cone was not accessible. The surficial geology within this inaccessible area was surmised based on landforms and the mapped geology to the north and south of this area.

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

Richmond 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, kettles, and water wells. During the spring of 2018 the Vermont Geological Survey developed a uniform set of mapping units which are utilized on the Richmond 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 2D surfaces that extend out-of-sight below Earth's surface. In some areas geologic contacts could be closely located in the field and these locations were recorded and used when constructing the map. However, in most

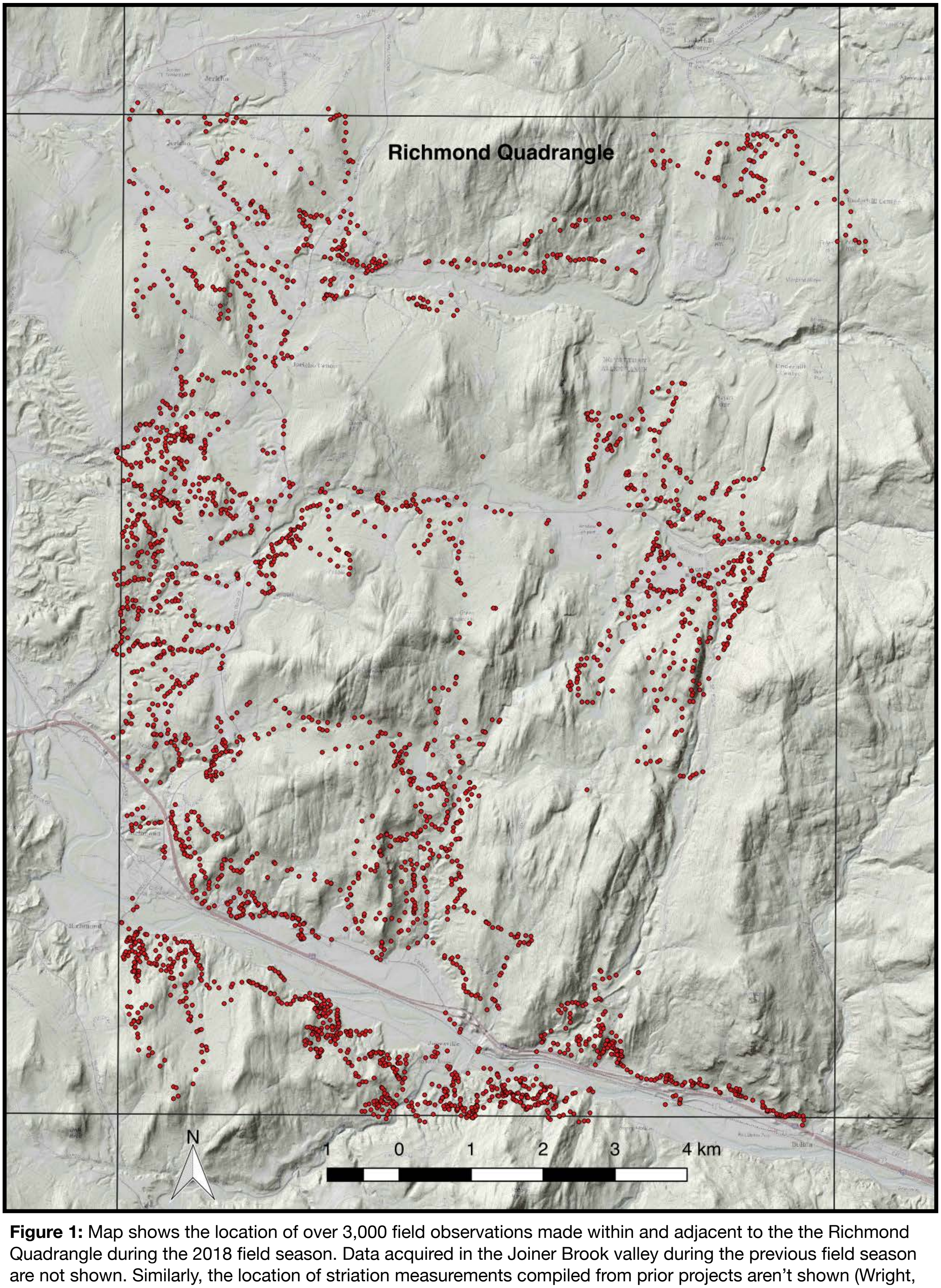

Figure 1: Map shows the location of over 3,000 field observations made within and adjacent to the the Richmond Quadrangle during the 2018 field season. Data acquired in the Joiner Brook valley during the previous field season are not shown. Similarly, the location of striation measurements compiled from prior projects aren't shown (Wright, 2015).

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 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. The following mapping units appearing on the surficial geologic map are described below in stratigraphic order, from oldest to youngest.

Bedrock Outcrops/Glacial Striations and Grooves

Bedrock outcrops were mapped when they were encountered during field traverses including most outcrops observed along town roads, state highways, and the Interstate. No attempt was made to map all outcrops, especially in the upland areas where outcrops are numerous and closely spaces. Extensive outcrops, especially along the interstate, were digitized when compiling the geologic map. Many of these outcrops still retain a smooth or polished surface produced by glacial abrasion. Where visible, the orientations of glacial striations and grooves were recorded. Roches moutonnée, erratics derived from northwest sources, and tails of uneroded rock southeast of quartz veins all indicate that the ice sheet flowed from northwest to southeast across the area. Consequently, arrows pointing in the down-ice direction are used on the geologic map to show the orientation of glacial striations and grooves.

Figure 3: UVM geology major Tim Quesnell holds his arms parallel to grooves oriented parallel to the Winooski River valley. The quarried, down-glacier side of this rouches moutonnée faces southeast. View looks south across the Winooski River valley.

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. 3). Till in the area consists of angular to subrounded pebbles, cobbles, and boulders, many with striated surfaces) suspended in a fine clay/silt/sand matrix (Fig. 3A). Most of the till occurring in this area is lodgement till consisting of materials eroded, deformed, and deposited beneath the ice sheet. Close to the ground surface frost heaving, plant roots, and animal borrows have loosened the till and surface run off has eroded some of the smaller-sized sediment (the "fines") in the till. 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 4: (A) Lodgment till with embedded rocks exposed in a small stream. This dense till ("hardpan") resists stream erosion. (B) Very large erratic near West Bolton.

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.

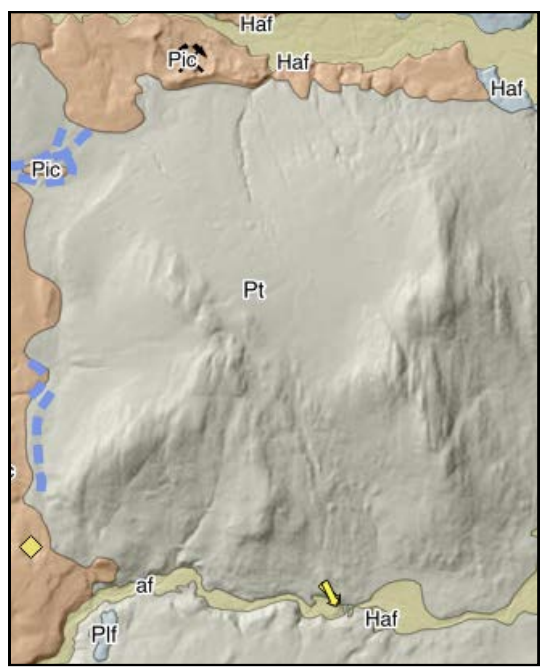

Figure 5: Clipped portion of the Richmond Surficial Geologic Map showing the till-covered (Pt) upland area immediately east of Jericho village (Lee River valley to north and Mill Brook valley to south. Within this upland area the north- and west-facing valleys are both underlain by thick till, sufficient to bury the underlying bedrock outcrops.

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. Two parallel north-south eskers extend across the quadrangle and a third, is inferred from gravel deposits along the south side of the Winooski River valley (Fig. 6). Eskers can be used to infer the hydraulic gradient in the ice sheet at the time they formed. The esker in the Winooski River valley formed when ice flow in the thinning ice sheet was funneled west-northwest to east-southeast up the valley. Similarly, the north-south eskers on the west flank of the Green Mountains formed when the ice sheet was confined by the Chaplain Valley and flowed from north to south.

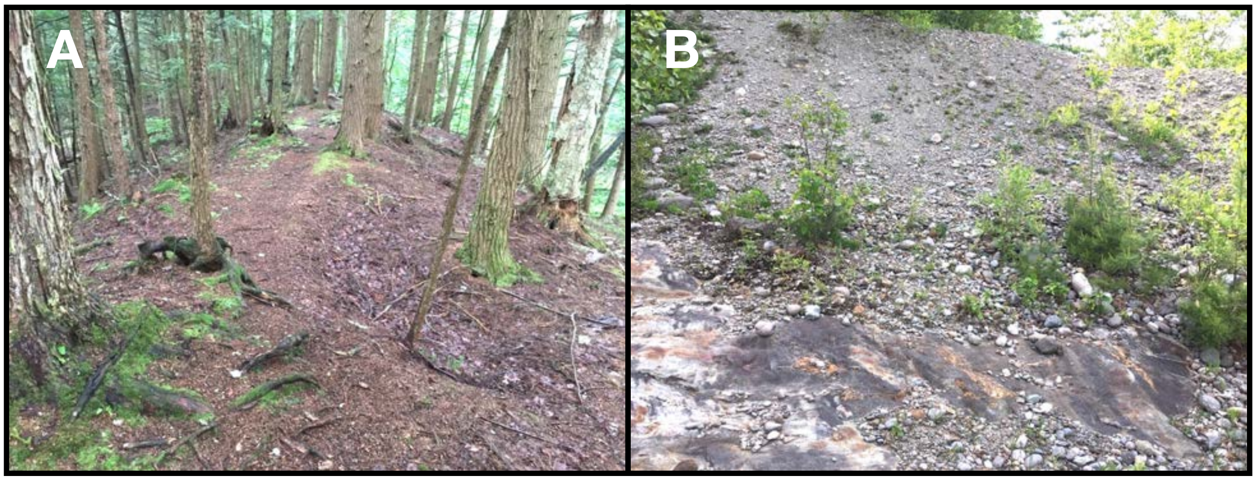

Figure 6: (A) View looks south along an esker in the Jericho Firing Range. The esker is bordered on both sides by wetlands, but the well drained sand and gravel within the esker supports a healthy mixed forest. The south end of this esker segment is a gravel pit. (B) Ice-contact gravel deposited directly on bedrock (foreground). Exposure in an abandoned gravel pit on the south side of the Winooski River between Richmond and Jonesville.

The retreating ice sheet dammed glacial lakes in most of the valleys within the mapped area (see below "Lacustrine Sediments" section). Consequently, sediments deposited as the ice sheet retreated fine upwards as the depositional environment shifted from subglacial to subaqueous fan to low-energy lacustrine. Sediments deposited in these closely-spaced and time-transgressive environments are lumped into a single mapping unit titled Undifferentiated Ice-Contact deposits (Pic). A gravel pit immediately south of Jonesville records this complete transition (Fig. 7) and pits elsewhere in the quadrangle have largely been excavating sand and gravel deposited in varying ice-contact environments.

Figure 7: Gravel pit south of Jonesville is floored by gravel and fines upward to lacustrine silt/clay. Visible section is dominated by medium to fine sand with interspersed layers of gravel and was deposited in a subaqueous fan.

Abundant abandoned channels and terraces formed along the margin of the retreating ice sheet. These are generally oriented north-south and are most commonly eroded into till although in some areas these are underlain by ice-contact gravel and are properly “kames.” These channels and terraces were eroded by both meltwater and meteoric water flowing down the west-sloping flank of the Green Mountains. This water was diverted south along the margin of the ice sheet. As the ice sheet was thinning and retreating rapidly at this period of time (~14,000–13,500; Ridge et al., 2012), the routes taken by meltwater and meteoric water changed rapidly. At the north end of the Bolton Notch valley a series of stepped terraces likely records year-by-year retreat and thinning of the ice sheet (Wright, 2011; Wright et al., 2015).

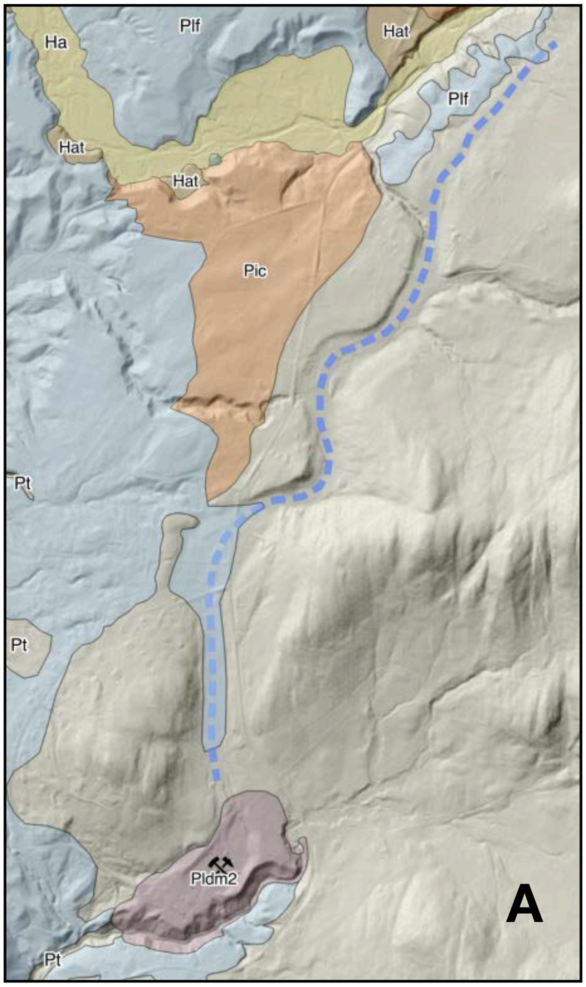

Figure 8: (A) Clipped portion of the Surficial Geologic Map showing a long ice-marginal channel (dashed blue line) extending from the Mill Brook valley south to a delta that formed in Glacial Lake Mansfield 2 (Pldm2). Meltwater was diverted south (away from the Mill Brook valley) along the margin of the ice sheet. (B) Portion of the abandoned stream channel shown in (A) visible from Browns Trace Road (arrow shows viewpoint for photograph).

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

Glacial lake deposits include both coarser-grained sediments deposited at or near the shorelines of lakes (deltas and beaches) and finer-grained sediments deposited in the deeper quiet-water parts of lakes. Lacustrine sediments are common in most of the valleys in the quadrangle. Larsen (1972, 1987) outlined the sequence of glacial lakes that occupied the Winooski River drainage basin as the retreating ice sheet dammed the west-flowing river preventing it from draining into the Champlain valley. The highest regional lake, Glacial Lake Winooski, partially drained when the ice sheet margin was near the southeastern border of the Richmond Quadrangle. As the ice sheet retreated down the Winooski River valley it uncovered in quick succession two lower outlets allowing lake water to drain through the Huntington River valley and Hollow Brook into the Champlain Valley occupied by Glacial Lake Vermont (Fig. 9). The much smaller regional lake in the Winooski River valley is called Glacial Lake Mansfield; Mansfield 1 for the higher Gillett Pond outlet and Mansfield 2 for the lower Hollow Brook threshold (Larsen, 1972, 1987). A 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 (Ridge et al., 2012) allows this drainage event to be dated to ~13,800 years ago (Wright, 2018).

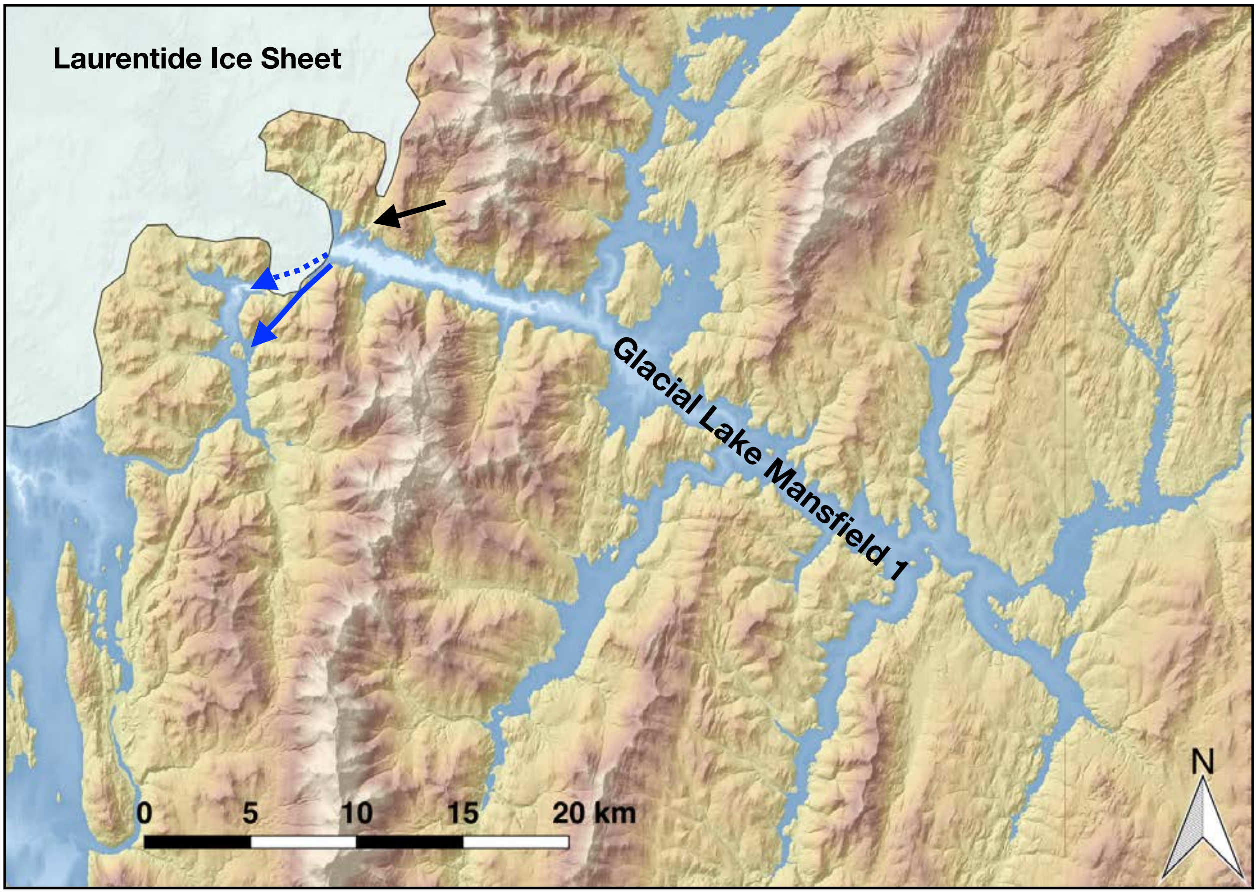

Figure 9: Map shows the extent of Glacial Lake Mansfield 1 in the Winooski River basin. The solid blue arrow shows the Gillett Pond outlet into a lake occupying the Huntington River valley (Glacial Lake Huntington). Relatively little ice retreat uncovered a lower outlet (dashed blue line) forming Glacial Lake Mansfield 2. Black arrow shows the location of a large delta built into Glacial Lake Mansfield 1 at the south end of Bolton Notch near the southeast corner of the Richmond Quadrangle.

Figure 10: Foreset and topset beds of a large Glacial Lake Mansfield 1 delta are well-exposed in a pit at the south end of Bolton Notch. Sediment in the delta was sourced from a subglacial tunnel in the tongue of the ice sheet that retreated northward through Bolton Notch.

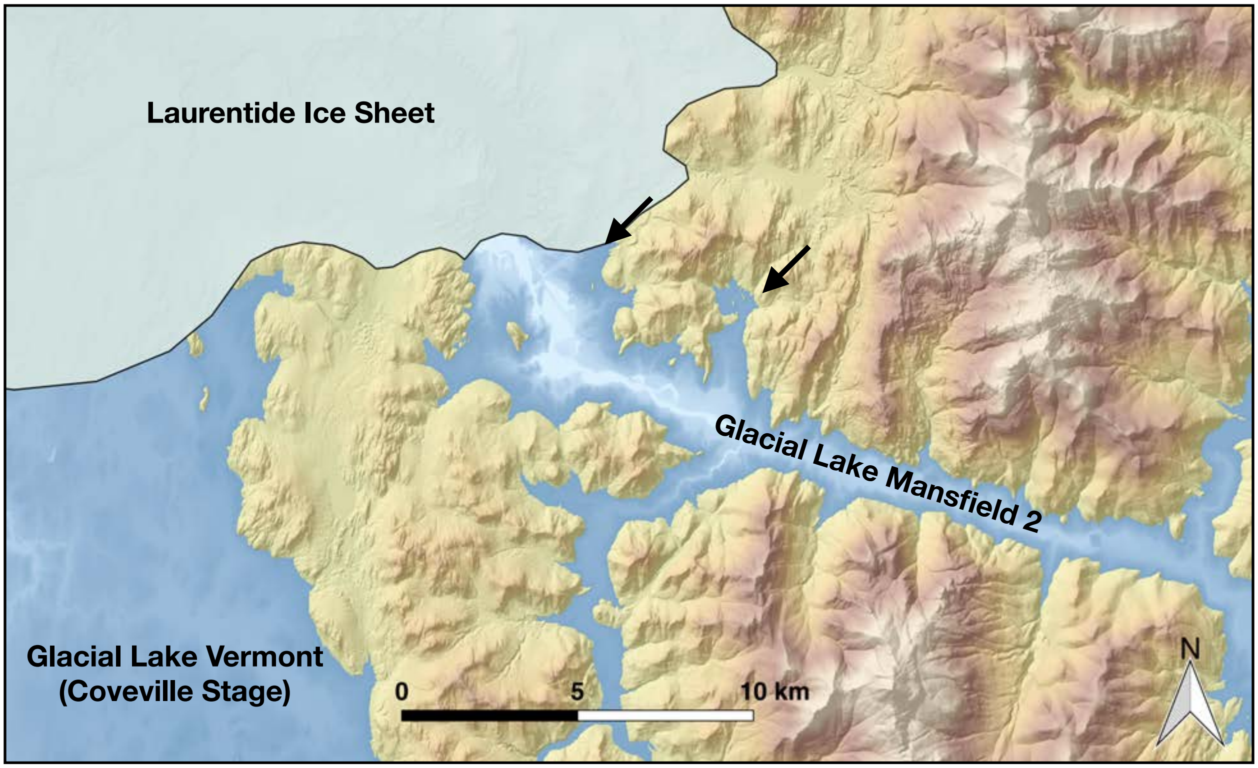

Figure 11: Map shows Glacial Lake Mansfield 2 flooding the Winooski and Huntington River valleys. The transition between the two stages of Glacial Lake Mansfield entailed an elevation drop of ~26 m. Glacial Lake Mansfield drained to the elevation of Glacial Lake Vermont when the ice retreated to the position shown on the map (see blue arrow). Deltas formed in both the Snipe Ireland valley and north of Richmond Village (black arrows, Fig. 8A).

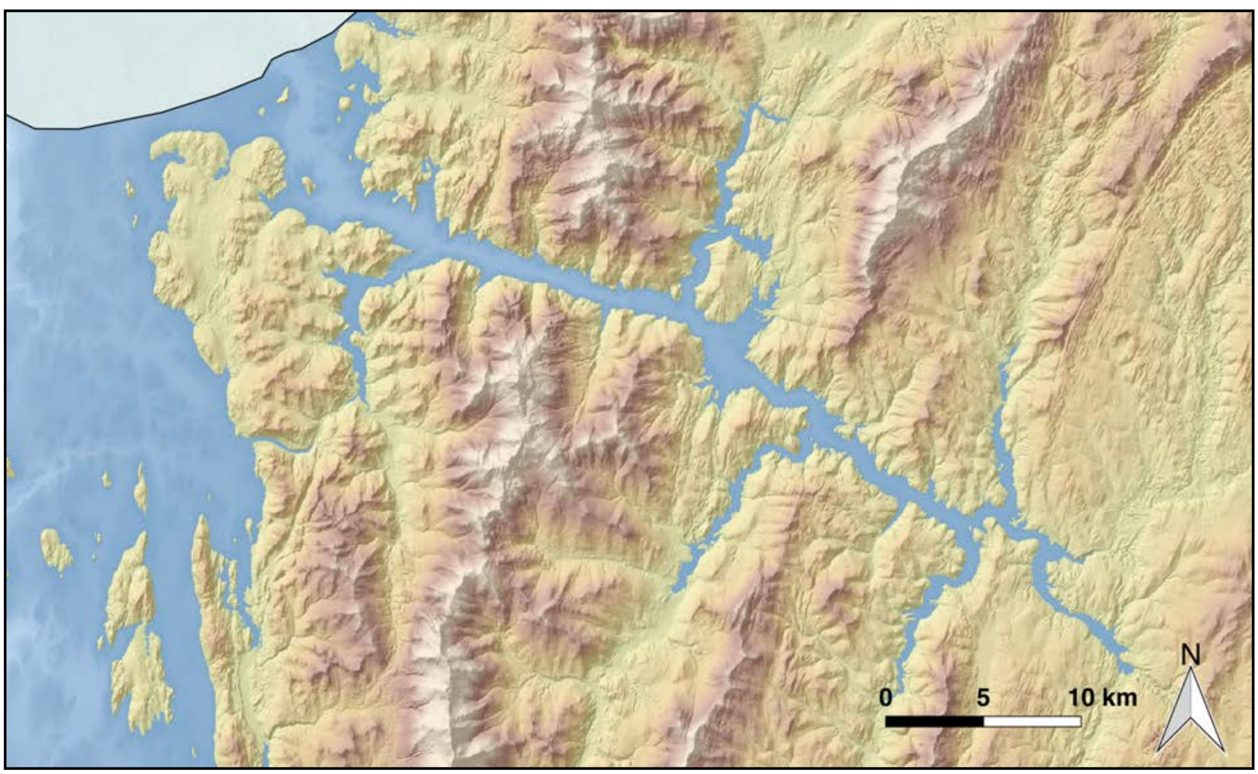

Figure 12: Extent of Glacial Lake Vermont (Coveville Stage) in the Winooski River valley and adjacent areas. Extensive areas of fine-grained lake sediment occurring along the western margin of the Richmond Quadrangle were deposits in this lake.

Several Glacial Lake Mansfield deltas were mapped in the field area. Only the southeastern corner of the quadrangle was free of ice when Glacial Lake Mansfield 1 formed. The large delta at the south end of Bolton Notch (Figs. 9 and 10) grew rapidly from sediments emanating from a subglacial tunnel beneath the tongue of ice retreating northwards up Bolton Notch. A layer of fine lacustrine sand overlies the top-set beds in this delta suggesting that the ice sheet may have temporarily advanced and pinched off the Gillett Pond outlet allowing lake water to rise for a limited period of time before the ice sheet rapidly retreated past the Huntington River valley lowering lake level to that of Glacial Lake Mansfield 2

Within the quadrangle two significant deltas were built into Glacial Lake Mansfield 2. One of these occurs in the Snipe Ireland (Island) valley adjacent to Richmond Pond. Similar to the Bolton Notch delta, this delta was also fed by sediments emanating from a subglacial tunnel that extended northeast and north. An esker deposited in this tunnel is largely buried by the deltaic sediments. Farther west, a second Glacial Lake Mansfield 2 delta formed north of Richmond. This delta was fed by water flowing along the margin of the ice sheet (Fig. 8A). This delta was utilized as a gravel pit and later developed into residential housing (Fig. 13).

Figure 13: Former gravel pit excavated in a Glacial Lake Mansfield 2 delta. Photo looks north, up the abandoned ice marginal channel that fed this delta. Approximately 12 m of sediment was excavated before the housing development was built.

As noted earlier, within most of the major valleys there is a gradual transition between coarse-grained sediments deposited in subaqueous fans at or close to the ice sheet and quiet water sediments, fine sand to clay, deposited when the ice sheet margin had retreated some distance. Fine-grained glacial lake sediments are widely distributed across the Richmond Quadrangle but can include lenses of coarser grained sediments sourced from subglacial tunnels during big drainage events (Figs. 14, 15). In most areas these sediments consist of fine to very fine sand and silt. Even finer deposits of varved slit and clay occur, but no good sections were encountered (Fig. 14). While these sediments occasionally contain large drop-stones, they generally lack large rocks, have been preferentially farmed, and erode into characteristic smooth-surfaced landforms.

Figure 14: Slumped deposit of varved silt and clay adjacent to Barber Farm Road in Richmond. These cohesive sediments can be very strong when dry, but can weaken and slump when wet.

Figure 15: Glacial lake sediment exposed in a pit east of Jericho Village on the south side of the Lee River. Sediment largely consists of fine to very fine sand with dark layers of silt. Horizontal bedding indicates that the Lee River valley was filled to at least this elevation with glacial lake sediment. Deeper parts of pit once exposed coarse-grained ice-contact sediments.

Fluvial Terrace Deposits

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

Alluvial Fans

Alluvial fans are fan-shaped deposits formed where steeply-sloping streams deposit sediment where they flow out onto a gently-sloping valley floor, e.g. a fluvial terrace or modern floodplain. 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. One fan along Cochran Road has formed within the last few years from erosion of gravel from an abandoned gravel pit (Fig. 16). Studies in the Huntington River valley ad elsewhere in northern Vermont indicate that alluvial fans have been active episodically throughout the Holocene and have often received their most recent pulse of sediment following European land clearing in the late 18th and early 19th centuries (Bierman et al, 1997, Jennings et al., 2003). Related work by Noren and others (2002) recording pulses of clastic sediment deposited in ponds and small lakes, indicates that pre-European settlement erosion has not been uniformly distributed throughout the Holocene and seems instead to be concentrated during periods of increased high-intensity storms. If climate shifts produce a greater frequency of "Irene-like" storms in the future, further sedimentation on the area's alluvial fans seems likely. In the headwaters of Mill Brook and Duck Brook older fan surfaces were mapped (Paf). Unlike the Holocene fans, these fans formed when lake levels dropped and streams eroded deep channels in older deltas and deposited aprons of sediments below these incised channels.

Figure 16: Recently active alluvial fan extends from an abandoned gravel pit consisting of ice-contact gravel to Cochran Road (south side of Winooski River valley). Road berm prevented this fan from extending farther across the Winooski River floodplain.

Alluvium

Alluvium refers to sediments deposited by modern rivers and streams. Generally 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. Organic materials are a frequent component of modern alluvium. Broad areas of alluvium lie adjacent to the Winooski and Lee rivers, and Mill Brook. In many if not most areas modern alluvium is in contact with fluvial terrace deposits (old alluvium). The contact between these two mapping units is an interpretation of how much area is flooded during high-water events. The thickness of alluvium is proportional to the size of the stream that deposited it, but generally corresponds to the depth of the modern stream channel. In the larger valleys alluvium directly overlies glacial lake deposits. In smaller stream valleys in the uplands, alluvium overlies glacial till.

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. 17). 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 17: One of many wetland areas mapped within the Jericho Firing Range. Wetland occupies a shallow basin lying between a till-covered slope (left) and esker (right).

Artificial Fill

Areas mapped as artificial fill mostly consist of road fill along the Interstate. 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.

Geologic Cross-Section

One geologic cross-section was constructed across the Winooski River valley at Jonesville (Fig. 18; See geologic map for location of section). 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 of thickness of surficial materials in most areas comes from the logs kept by drillers when completing domestic water wells. Considerable time was spent mapping the locations of water wells in the Jonesville area and then trying to match the well-log records maintained by the Agency of Natural Resources with these located wells. The most accurate information recorded by drillers is the "depth to bedrock" or "overburden thickness" as this is approximately equivalent to the length of steel casing needed for a drilled well, a length carefully recorded and charged to the home owner. Otherwise, the quality of records kept by drillers of the type and thickness of the surficial material they drill through varies enormously and frequently requires considerable interpretation when constructing a cross-section.

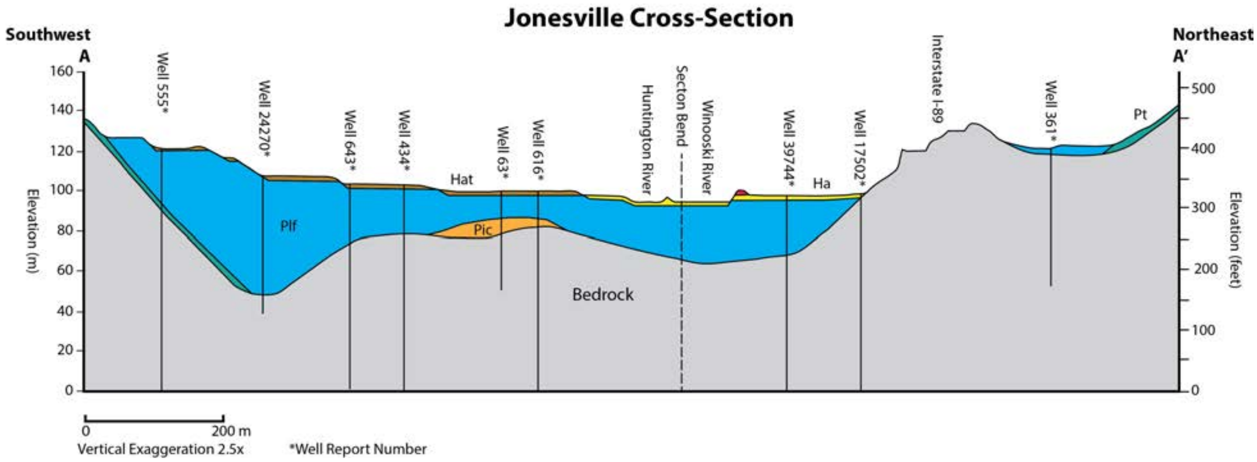

Figure 18: Geologic cross-section across the Winooski River valley at Jonesville, Vermont at it's confluence with the Huntington River. Till (green: Pt) covers the mountain slopes. Most of the section is dominated by fine-grained lacustrine sand/silt (blue: Plf). Several wells penetrate coarse sand and gravel beneath the lacustrine sediments (orange: Pic). These coarse-grained sediments are interpreted to be ice-contact gravels. A flight of abandoned stream terraces occurs where the Huntington and Winooski rivers have eroded through a thick section of lacustrine sediments that formerly filled both valleys.

Jonesville was chosen as a place to draw a cross-section as several housing developments have been built on abandoned stream terraces that extend some distance into the middle of the Winooski River valley. Glacial till is exposed on the valley sides above each end of the section but is only recorded in one of the wells. A lens of coarse sand and gravel was intersected by several wells. These sediments are interpreted to be ice-contact sediments (esker, subaqueous fan) deposited when ice was still in the valley or relatively close by. Most of the section is dominated by lacustrine sand and silt. As noted earlier, these sediments were deposited in Glacial Lakes Mansfield and Vermont) and most likely consist of fining-upward sequences deposited as the ice front retreated progressively farther down the valley (west). The lacustrine sediments have been eroded by both the Huntington and Winooski rivers. The stair-stepped fluvial terraces at the confluence of the Winooski and Huntington rivers mark the downcutting of those rivers as base-level fell following the draining of Glacial Lake Vermont.

Isopach Map of Surficial Materials

The "Isopach Map of Surficial Materials Map" 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 are missing), (2) records of overburden thickness from domestic water wells, and (3) areas visible on the LiDAR shaded-relief imagery where streams have incised through thick sections of surficial material. These data are contoured using a 20 foot contour interval between 0 and 100 feet. The state-wide compilation of bedrock outcrops (downloaded from the VCGI database) was not very helpful as most outcrops in this database occur in areas where they're clearly visible on the LiDAR imagery and many polygons falsely indicate outcrops in areas where the bedrock is overlain by thick sections of surficial materials.

Generally, areas of thick surficial materials occur in the major river valleys (see the geologic ross-section). 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.

Groundwater Hydrology

The Richmond Quadrangle includes the Towns of Bolton, Richmond, Jericho, and Underhill. Within the quadrangle area, people in these towns rely almost entirely on groundwater for their drinking water supply. Surficial aquifers are utilized by some residents, however drilled wells extending variable depths into bedrock are used by most residents. Drilled wells can also tap deeper surficial aquifers.

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

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

Water Table Contour Map with Flow Lines

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

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.

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 Richmond Quadrangle consist of the Pinnacle Formation (Cp), the Underhill Formation (Cu), and greenstone units within the Underhill Formation (Cug). These are all metamorphic rocks consisting of metamorphosed sandstones, shales, and basalts (metasandstone, phyllites, schists, and greenstones). Water wells compiled by the Vermont Agency of Natural resources are also shown on the map with well yields (GPM: Gallons Per Minute). Domestic water wells are concentrated in valleys.

There is no significant difference in well yield between the different rocks in the quadrangle. High-yield wells (>10 GPM) exist, but some pull their groundwater from coarse-grained surficial materials and others are not restricted to any one rock type. In these rocks high-yield wells are most likely correlated to the density of fractures in the underlying bedrock (specifically the number, width, length, and interconnectedness of those fractures). Extensively fractured bedrock is more susceptible to weathering and erosion than unfractured bedrock and frequently guides the location of large- and small-scale valleys that are quite linear. These linear features can be mapped and used as a guide for drilling high-yield bedrock water wells. A map of this type was not generated as part of this project.

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

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

Lacustrine very fine sand, fine sand, silt, 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 utilizing groundwater from till are common. Lacustrine fine sand, silt, and clay occurs in the valley bottoms where slopes are gentle which enhances it's ability to absorb water. Slow movement of water through these materials can recharge coarse-grained surficial aquifer materials or bedrock, albeit slowly.

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