GLACIAL GEOLOGY OF THE MILLER BROOK VALLEY, STOWE, VERMONT: A HEAD TO TOE TRAVERSE

By

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INTRODUCTION

The Miller Brook Valley, Stowe, Vermont, is a generally ESE-draining valley extending from a low point along the crest of the Green Mountains (Nebraska Notch, Elev. 580 m, 1900 ft) to its confluence with the Little River (Elev. 184 m, 605 ft), (Fig. 1). The objective of this field trip is to show participants the key landforms and sediments utilized to interpret the glacial history of this valley. These include large-scale cirque-like landforms visible at the head of the valley, smaller-scale erosional and depositional landforms indicative of a major subglacial drainage system, and subaqueous fan and more ice-distal sediments deposited in an arm of Glacial Lake Winooski. The field sites described in the following text are found on the “Bolton Mountain” 7.5' U.S.G.S. Quadrangle map. Shaded-relief LiDAR base maps and an extensive array of other data for this area and the entire state are available via the Vermont Agency of Natural Resources online atlas.

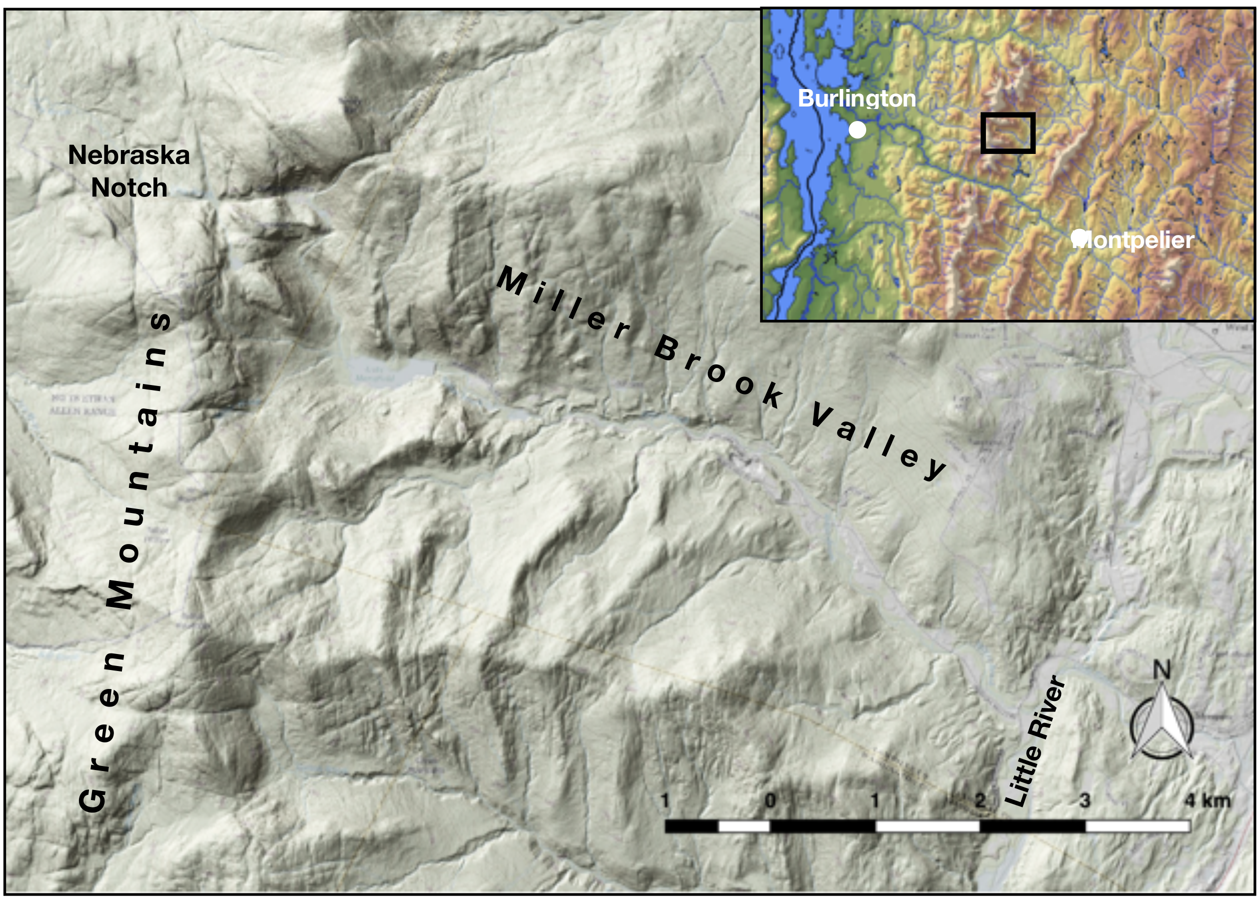


Figure 1: Box on inset location map outlines the location of the more detailed location map along the eastern flank of the northern Green Mountains. Miller Brook flows ESE until it joins the Little River which flows south to its confluence with the Winooski River.

Portions of the Miller Brook valley have been visited on previous NEIGC field trips. These include Stops 3 and 4 in Wagner and Connally (1972), Stop 4 in Wright et al. (1997), and Stop 1 in Dunn et al., 2011. This trip attempts to present an updated and integrated glacial history of the valley utilizing LiDAR imagery, recently completed mapping (Wright, 2018), exposure age dates from Mount Mansfield just 8 km north of the valley (Corbett et al., 2019), and the North American Varve Chronology (Ridge et al, 2012).

BEDROCK GEOLOGIC SETTING

The bedrock underlying the eastern Green Mountains adjacent to the Miller Brook valley consists of medium grade schists belonging to both the Hazens Notch and Fayston formations (Ratcliffe et al., 2011). The dominant foliation in these rocks (S_2) strikes N–S and dips moderately to steeply east. Resistant rock units within these formations "V" downstream and control the orientation of tributary brooks to Miller Brook as well as the orientation of Miller Brook itself upstream of Lake Mansfield (Fig. 3). The preferential weathering and erosion of brittle structures (faults, joint zones) has produced a network of lineaments that are clearly visible in the LiDAR imagery (Fig. XX). The ESE trend of the Miller Brook valley and many other river and stream valleys in the Green Mountains may also be controlled by joint zones or faults, but bedrock structures are largely masked by surficial materials in these valleys.

GLACIAL GEOLOGY OF THE MILLER BROOK VALLEY

Geographic Setting and Previous Work

The uppermost reaches of Miller Brook consist of two small tributaries, both of which head in steep-sided, bowl-shaped valleys with gently-sloping floors (Fig. 1). Below their confluence the brook enters a third similarly shaped, but much wider bowl-shaped valley. Lake Mansfield occupies this reach of the valley and is artificially dammed. Below Lake Mansfield Miller Brook lies almost entirely within surficial materials, stepping down through progressively lower lacustrine and fluvial terraces until entering the Little River just upstream from the Waterbury Reservoir.

Downstream from the Lake Mansfield dam, the valley contains several distinct ridges of surficial material lying within or adjacent to fluvial landforms and older lacustrine terraces and standing with up to 30 m of relief. Wagner (1970) described some of these ridges and interpreted these to be a lateral and end moraine produced by a tongue of ice retreating up the valley. He further conjectured that this moraine (and other moraines he identified in northern Vermont) were not produced by the waning Laurentide ice sheet, but by independent alpine glaciers that occupied the valley subsequent to ice-sheet retreat. Wagner's paper stimulated considerable discussion, mostly centered on whether or not the ridges were produced by a waning tongue of the Laurentide ice sheet or by a local glacier (Stewart, 1971; MacClintock, 1971; Wagner, 1971; Ackerly, 1989; Waitt and Davis, 1988).

Interpreting landforms in the Miller Brook Valley has always been confounded by the lack of adequate maps. The ridges that Wagner (1970) identified as moraines are crudely located on his map and his brief descriptions are insufficient to clearly locate their position or morphology. Only portions of the ridges appear on the U.S.G.S. topographic map (Bolton Mountain Quadrangle) and the position of Miller Brook and its principal tributary (Michigan Brook) from the SW are incorrectly shown. During the Fall of 1995, the area immediately downstream of the Lake Mansfield dam was mapped at a scale of 1:2,500 by two students, M. Loso and H. Schwartz, using a Total Station. This map and preliminary descriptions and interpretations of soil pits constructed by P. Bierman's geomorphology class are presented in Loso and others (1997). The mapping area was continued downstream by the author in the fall of 1996, initially using tape and compass methods (1:2,000) with parts later surveyed for elevation

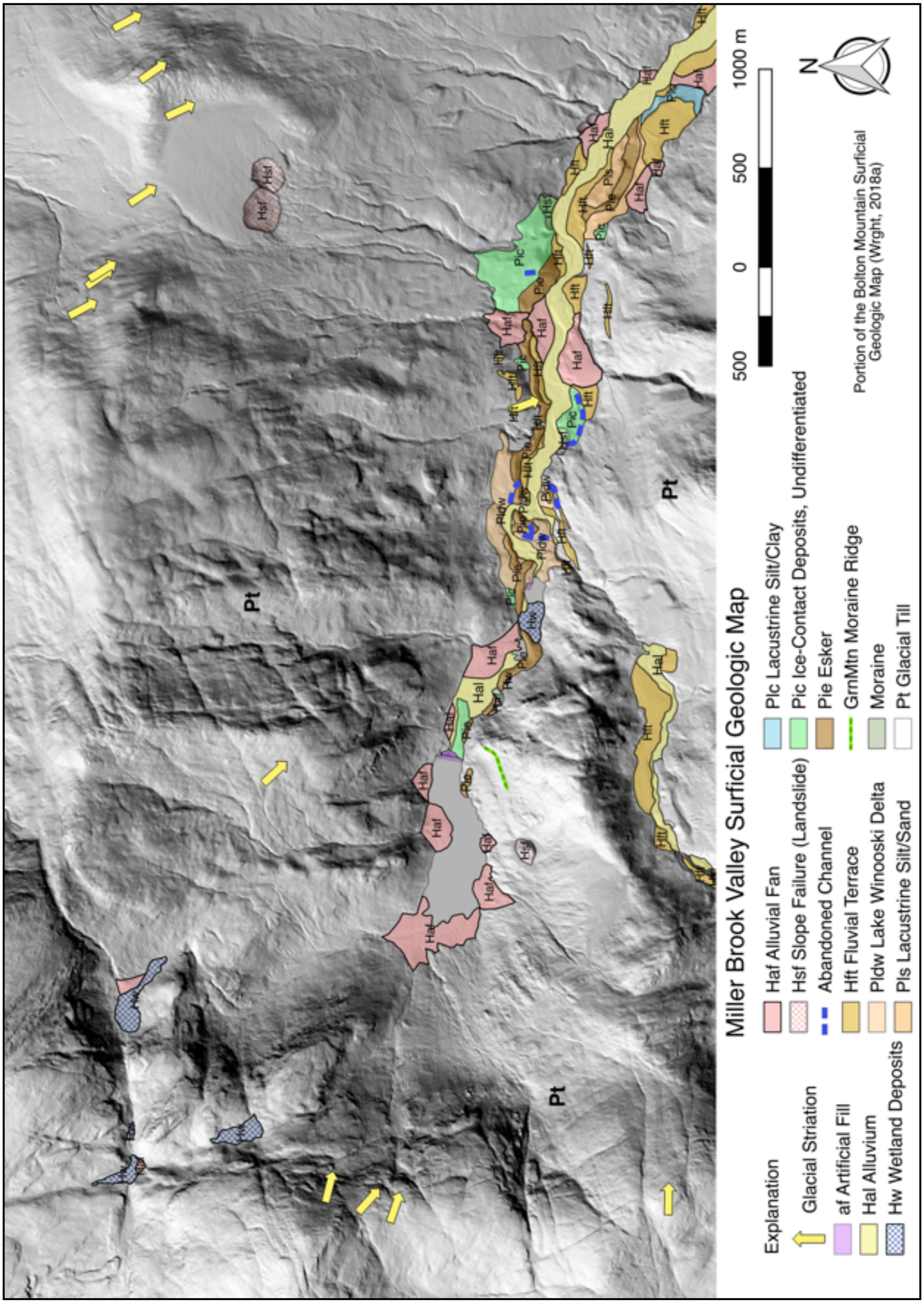

Miller Brook Valley Surficial Geologic Map
Explanation
Glacial Striation
af Artificial Fill
Hal Alluvium
Hw Wetland Deposits
Haf Alluvial Fan
Hsf Slope Failure (Landslide)
Abandoned Channel
Hft Fluvial Terrace
Pldw Lake Winooski Delta
Pls Lacustrine Silt/Sand
Plc Lacustrine Silt/Clay
Pic Ice-Contact Deposits, Undifferentiated
Pie Esker
GrnMtn Moraine Ridge
Moraine
Pt Glacial Till
500
0
500
1000 m
N
Portion of the Bolton Mountain Surficial
Geologic Map (Wrght, 2018a)
Pt
Pt
Pt

Figure 2 (Previous page): Surficial Geologic Map of the Miller Brook valley (Wright, 2018a) drawn on a shaded-relief LiDAR base map. Bedrock lineaments are prominent in the mountains surrounding the valley where the till cover is thin. Most surficial materials in the valley bottom were deposited in either ice-contact (esker and outwash fans) or lacustrine (Glacial Lake Winooski delta and deeper water deposits) environments as a tongue of the Laurentide Ice Sheet retreated up the Miller Brook valley.

the ridges described by Wagner (1970) are eskers that are overlain by a carapace of ablation till where they occur along the valley sides. Detailed surficial mapping of the valley occurred during the summer of 2017 on a LiDAR base map as part of a larger project mapping the Bolton Mountain Quadrangle (Wright, 2018a). A portion of that map appears on the previous page (Fig. 2).

High-elevation glacial striations here and elsewhere in the northern Green Mountains are generally aligned NW-SE and formed when the ice sheet was thick enough to flow obliquely across the N-S mountain range (Fig. 2, Wright, 2015). This regional NW-SE ice flow preserved in the striations was facilitated by a southeastward sloping ice sheet surface. A consequence of this slope was that hydraulic gradients in the ice sheet at this time were also sloping southeast, across the mountains. As the ice sheet thinned from south to north and the elevation of the ice surface progressively dropped below the N–S ridge of the Green Mountains, continued southeast ice flow was funneled through, from south to north, the Winooski River Valley (elev. 103 m, 340 ft), Nebraska Notch (elev. 576 m, 1890 ft), Smuggler's Notch (elev. 670 m, 2200 ft), and the Lamoille River Valley (elev. 150 m, 490 ft).. Once the ice surface elevation in the Champlain Valley west of the mountains dropped below the elevation of Nebraska Notch, ice supply to the Miller Brook valley was shut off and its glacial history ended. No landforms indicative of stagnant ice exist in the valley suggesting that the margin of the ice sheet retreated quickly up the valley and only small volumes of ice, if any, were stranded.

Timing of Laurentide Ice Sheet Retreat across the area

Glacial Lake Winooski flooded the upper Winooski River drainage basin including much of the Miller Brook valley (Larsen, 1972,,1987), (Fig. 3). The timing of ice retreat up the Miller Brook valley can be approximately determined by correlating Glacial Lake Winooski varves with Antevs' (1928) New England Varve Chronology. A nearly complete section of varves was formerly exposed along western shore of the Waterbury reservoir (~9 km southeast of the Glacial Lake Winooski delta in the Miller Brook valley) and was successfully correlated with Antevs' compiled Winooski River varve section (Fig. 4; Fig. 27 in Larsen et al., 2003). The measured section consists of classic silt/clay couplets and begins with a thick, slumped ice proximal varve partially exposed at the bottom of the section (North American Varve 6792). Along the north shore of the reservoir another section exposes between 10 and 20 thick ice-proximal varves pushing the deglaciation of the reservoir area back to North American Varve Years 6772–6782 which corresponds to a few years before 14.0 ka (Fig. 4). The measured section spans 184 years and ends where the sediment abruptly changes to thick sand/silt couplets (North American Varve 6976) deposited when the ice damming Glacial Lake Winooski was abruptly breached and water levels dropped ~90 m to the level of Glacial Lake Mansfield 1 (Wright, 2018). The lowering of Glacial Lake Winooski to the level of Glacial Lake Mansfield 1 therefore occurred at ~13.8 ka (Fig. 4). Consequently, a tongue of the Laurentide Ice Sheet must have retreated up the Miller Brook valley far enough during this 200 year time frame for a substantial delta to build into Glacial Lake Winooski.

Deglaciation of the area has been independently measured using ^{10}Be exposure-age dating (Corbett et al., 2019). Bedrock and boulder samples collected over an 800 m elevation range (1,200–400 m) on Mount Mansfield have, within the errors of the technique, indistinguishable ages and indicate rapid thinning of the ice sheet at 13.9 ±0.6 ka (Fig. 5). This date lies within the 14.0–13.8 ka date range for Miller Brook deglaciation based on the varve data. Rapid thinning of the ice sheet is also indicated by nested sets of landforms interpreted as annual recessional moraines in the adjacent mountains by Wright (2019). If this interpretation is correct, the ice sheet was thinning 9–13 m/year.

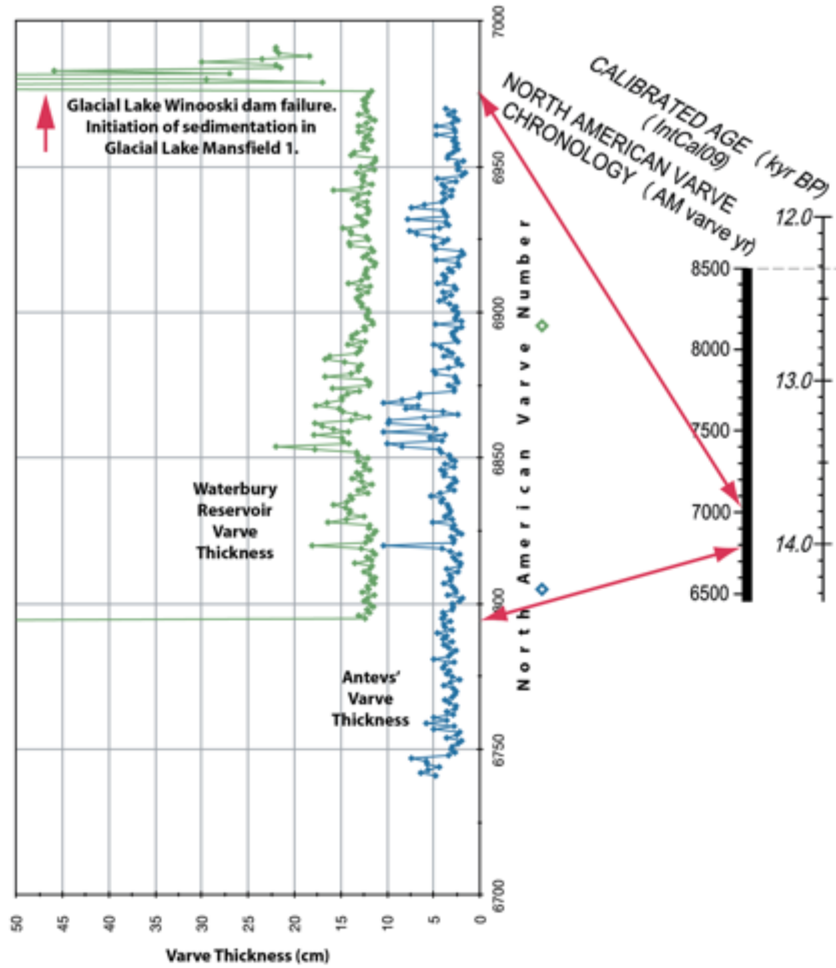


Figure 4: Correlation of varved silt/clay sections from the Waterbury Reservoir with Antevs' (1928) compiled section for the upper Winooski River valley. Antevs' original "New England Varve Chronology" has been modified by Ridge (2012) and those numbers reorganized into the "North American Varve Chronology." The thicknesses used in Antevs' curve have been normalized. To offset the two curves, 10 cm has been added to the measured thickness of varves in the Waterbury Reservoir section. Thick unit at base of section is a slumped layer. Thick units at the top of the section reflect the draining of Glacial Lake Winooski and the onset of sedimentation in Glacial Lake Mansfield.

Another point to consider here is that the area between the Miller Brook valley and the Waterbury reservoir is where the retreating ice sheet divided into three separate tongues of active ice: one funneled through the narrow Winooski River valley where it cuts across the Green Mountains (this one dammed Glacial Lake Winooski; Fig. 3), one squeezing through Nebraska Notch extending down the Miller Brook valley (the focus of this field trip), and a third coming from the north down the broad valley between the Green Mountains to the west and the Worcester Range to the east. The supply of ice feeding this last ice lobe became progressively more restricted as the ice sheet thinned limiting ice flow across the mountains. Glacial Lake Winooski sediments have been mapped in the Lamoille

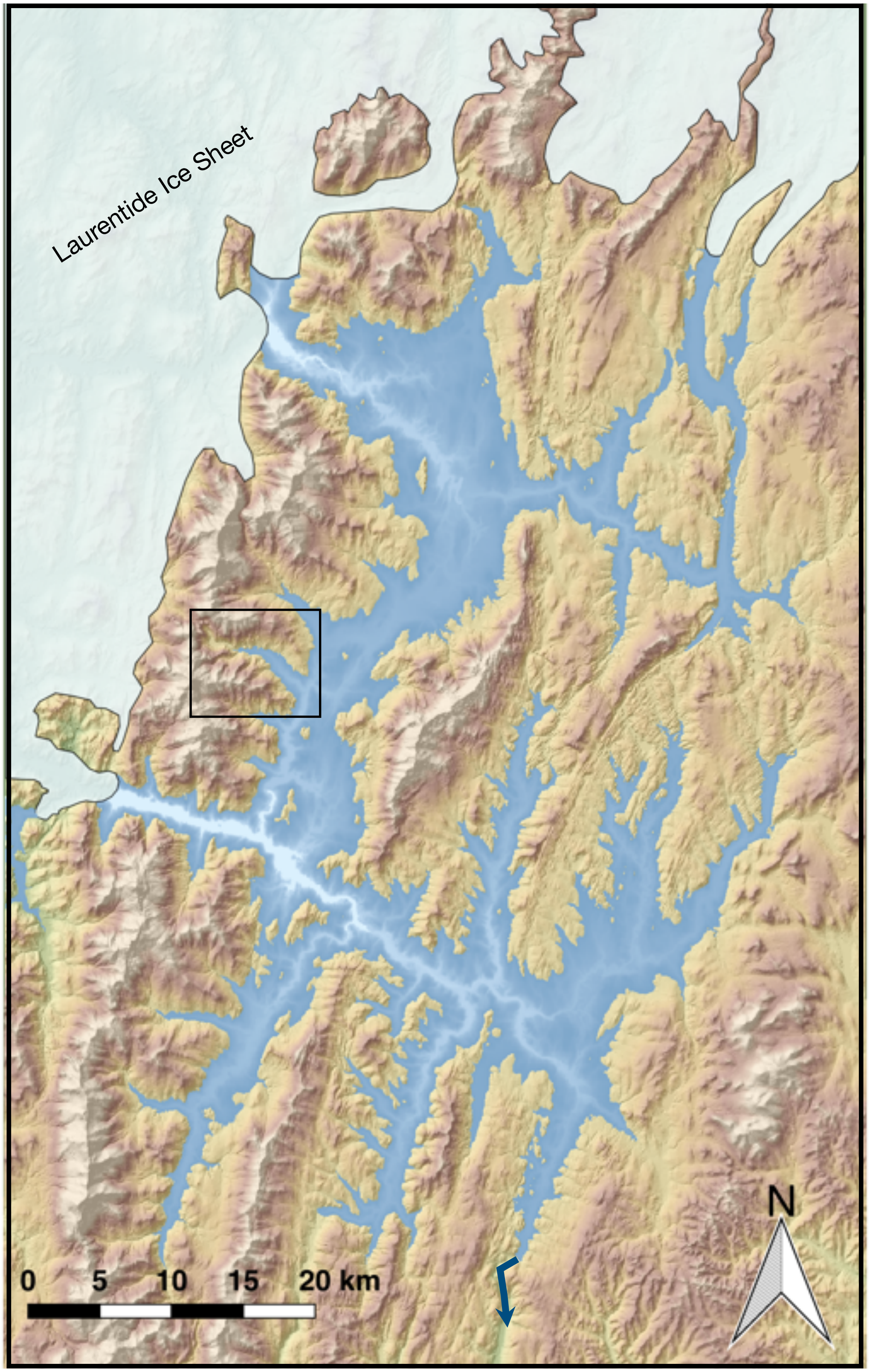


Figure 3: Glacial Lake Winooski at its fullest extent occupying the Winooski and Lamoille River drainage basins. Arrow shows the outlet of the lake through Williamstown Gulf. Box outlines the Miller Brook valley.

River valley at least 36 km north of the Waterbury Reservoir (Wright, 2001) implying that the margin of the ice sheet was retreating northwards at ~180 m/year during the ~200 year history of the lake recorded at the Reservoir.

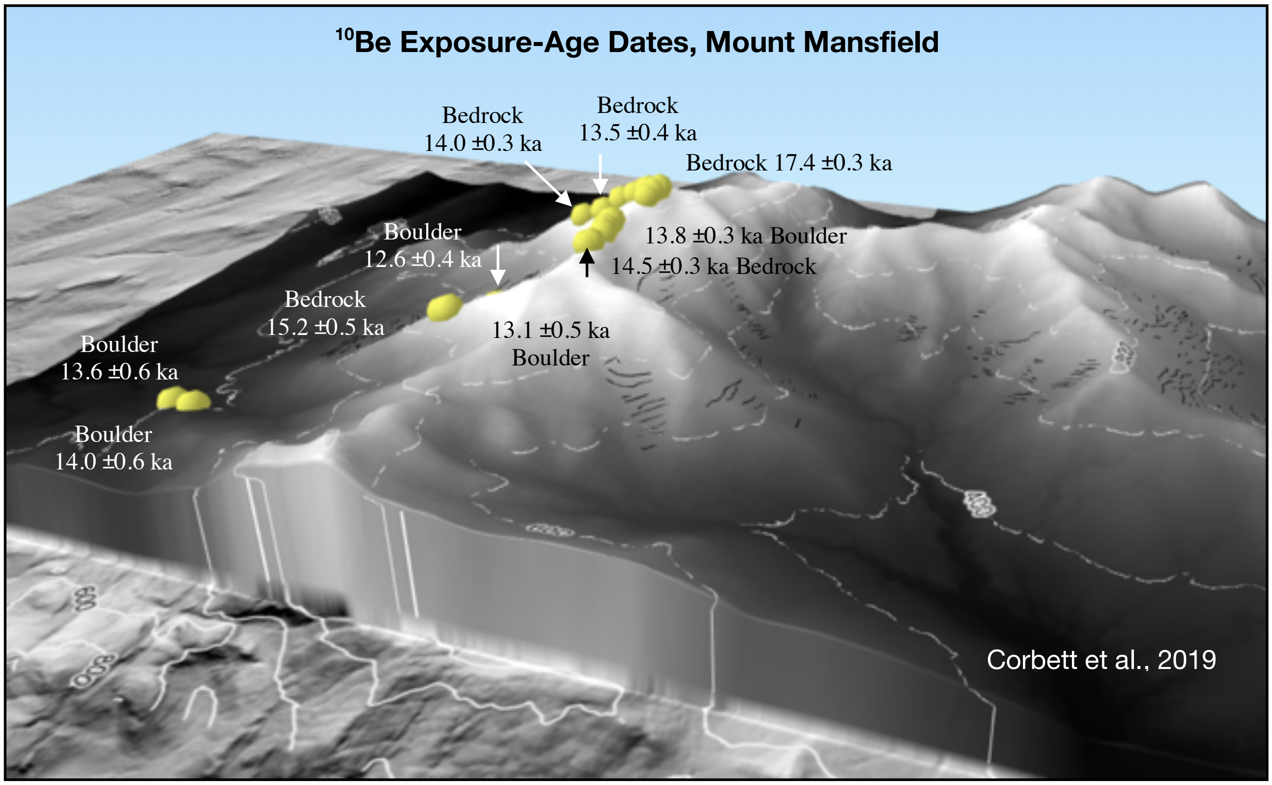


Figure 5: ^{10}Be exposure-age dates from Mount Mansfield, the highest mountains in the Green Mountain Range, indicate that, within the error of the technique, the ice sheet surrounding Mount Mansfield rapidly thinned from 1,200 to 400 m at 13.9 ±0.6 ka (Corbett et al., 2019). The Miller Brook valley lies only 8 km south of Mount Mansfield and was similarly deglaciated at the same time. Black lines on the flanks of Mount Mansfield are landforms interpreted to be recessional moraines that may record yearly thinning rates of 9–13 m/year (Wright, 2019).

ACKNOWLEDGEMENTS

My research in the Miller Brook valley would not be possible without the access generously granted by the Lake Mansfield Trout Club. In addition to granting access for my own field work, the club has allowed me and other faculty to lead countless field trips for students to this area. The geologic maps published in this guide are portions of the Bolton Mountain Surficial Geologic Map and were generated as part of a StateMap contract with the Vermont Geological Survey. Research supported by the U. S. Geological Survey, National Cooperative Geologic Mapping Program, under USGS award number G18AC00139 . The views and conclusions contained in this document are those of the author and should not be interpreted as necessarily representing the official policies, either expressed or implied, of the U. S. Government.

ROAD LOG/HIKING LOG

Meeting Place

This field trip road log begins at the Cold Hollow Cider Mill in Waterbury Center, Vermont. The Cider Mill has a large parking lot, but this can fill on busy holiday weekends. Both food and bathrooms are available in the Mill.

This field trip is designed as a two part trip. The first part is a hiking trip in the upper Miller Brook valley that will take the majority of the day. The second part of the trip is accessed via a short drive down the valley which leads to the final two closely-spaced stops.

Stops 1–6 on this field trip occur along public trails. **Stops 7–12** occur on trails maintained by and land owned by the Lake Mansfield Trout Club. While the Club has generously allowed both field work and field trips on their property in the past, please request permission before accessing the site. While most members do come to fish, many also make use of the Club's extensive trail network, including those we will use on this field trip. **Stops 13 and 14** both occur on public land and the final two stops (**15 and 16**) occur within the abandoned parts of a gravel pit owned by the Town of Stowe.

Driving Log:

Mileage

0.0 Turn Right (north) on Route 100 when leaving the Cold Hollow Cider Mill

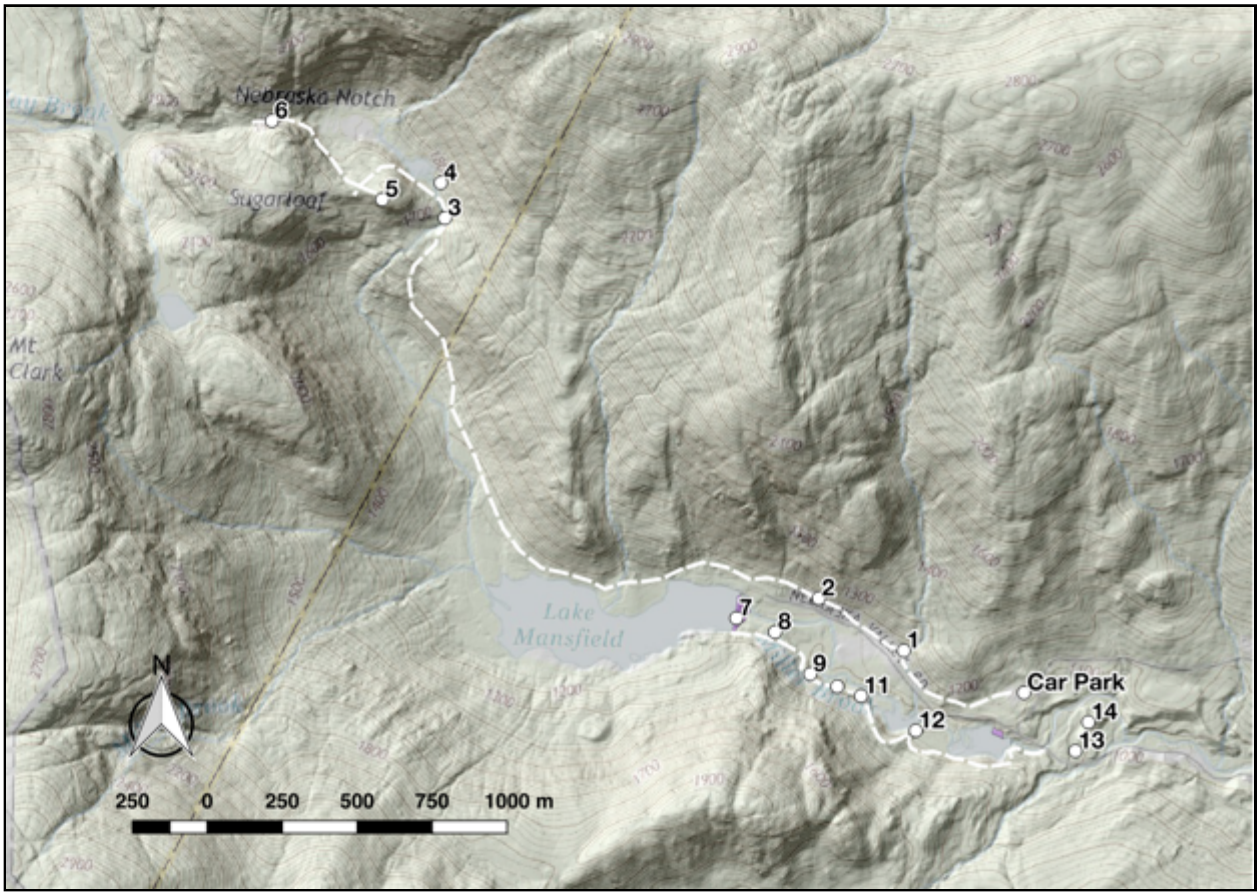
4.0 Turn Left (west) on Moscow Road and follow this through the village of Moscow. Continue along Moscow Road as it follows the Little River (Waterbury River) valley first west then south.

6.9 Immediately after crossing Miller Brook, **turn right** (northwest) on Nebraska Valley Road. Drive up the Miller Brook valley first on pavement and then on dirt. The road narrows and curves are sharp and partially blind.

10.5 Turn right (north) on Old County Road.

10.6 Turn left into the **Lake Mansfield Trailhead** parking lot. **(-72.798583, 44.469988)**

The below map (Fig. 6) shows the trails utilized and the locations of the different stops on the hiking



portion of this field trip.

Hiking Log:
Kilometers

0.0 Begin hiking west along the Lake Mansfield Trail (Fig. 5). The trail follows the north side of the Miller Brook valley and is the only public access through the Lake Mansfield Trout Club property.

STOP 1: APEX OF ALLUVIAL FAN (-72.803629, 44.471241)

0.46 Alluvial fans are common landforms in the Green Mountains and this is the first of several encountered on this field trip. Similar to alluvial fans elsewhere in the world, these fans form where steep mountain streams slow down and deposit sediments at their junction with a gently sloping trunk stream. The apex of this fan consists of diamict which includes an unsorted mixture of till which moved as a debris flow from somewhere up this tributary valley. Sediments generally fine farther down the fan as stream water plays a progressively larger role in moving sediments. This particular fan extends to the bottom of the valley and has forced Miller Brook to the south side of the valley. The unnamed tributary stream which deposited the fan is currently incising a channel along the east side of the fan.

Figure 6: Map showing the location of field stops in relation to the Car Park. White dashed lines are trails. The upper, longer "Lake Mansfield Trail" is open to the public and connects with the Long Trail.. The lower, shorter "White Trail" is on property owned by the Lake Mansfield Club and permission is needed to access this trail.

Unlike many of the huge alluvial fans in the American west, New England fans all postdate the retreat of the ice sheet. It's likely that significant volumes of sediment moved downslope in the years immediately following deglaciation when till-mantled upland slopes were free of deep-rooted vegetation. Work by Paul Bierman and his students (Bierman et al., 1997; Church, 1997; Zehfuss, 1996) has shown that fans have been active throughout the Holocene with large depositional events triggered by storms where extensive erosion is particularly likely following forest fire or disease, the large-scale land-clearing associated with European settlement, and many modern land-clearing operations on slopes where erosion has not been controlled. That said, it's also possible that many of these steep tributary valleys have lost most of the easily erodible till bordering them and are incapable of adding significant volumes of new material to the fans at their bases.

STOP 2: NORTH VALLEY SIDE LANDFORMS; LARGE ERRATIC (-72.807209, 44.472800)

0.80 The north side of the Miller Brook valley is steep and covered with a thin mantle of till. Otherwise, there are no discernible glacial landforms. When the leaves are down, large cliffs are visible well above the trail. The main point of this short stop is to contrast the (absence of) landforms here with those visible on the south side of the valley that we'll visit later. The very large boulder visible here may have been glacially transported (technically it's not an erratic as it consists of "local" rock) or it may have fallen from the above cliffs.

Continue following the trail west.

Trail crosses another large alluvial fan. This fan will be more clearly visible from the other side of the lake later in the trip.

Continue following the trail as it turns north away from Lake Mansfield and climbs first slowly (passing several cellar holes and a grove of plantation spruce) and then steeply. This steep pitch ascends the side of one tributary valley and leads to the upper tributary valley. Stop 3 is located at the top of this steep pitch where the stream makes a small waterfall.

STOP 3: LARGE POTHOLES (-72.822950, 44.484171)

3.15 Several large potholes occur where Miller Brook flows across a waterfall adjacent to the trail. Figure 7 depicts one of those visible at the bottom of the waterfall which can be accessed via a small path leading down from the main trail. Immediately upstream the bedrock has been eroded to form several large intersecting potholes. Pothole diameters are 7–10 m and are clearly out-of-scale with the small, uppermost reach of Miller Brook. Above this point the drainage basin of the brook is only 0.84 km^2, much too small to generate the water flows necessary to erode potholes on this scale. These potholes more reasonably formed by subglacial meltwater sourced from the melting Laurentide Ice Sheet in the Champlain Valley, west of the Green Mountains. As noted earlier, regional ice flow was from northwest to southeast, i.e. the ice sheet was flowing obliquely across this north-south mountain range. As a consequence, the regional hydraulic gradient within the ice sheet was also sloping to the southeast driving subglacial water across the mountains. Nebraska Notch (Stop 6) is the lowest point (Elev. 580 m, 1900 ft) along the Green Mountains between the Lamoille River valley to the north and the Winooski River valley to the south and these large

Figure 7: One of several large-scale (7–10 m diameter) potholes occurring at the bedrock lip of the uppermost reach of Miller Brook. These potholes are immediately adjacent to the trail.

potholes provide evidence that large volumes of meltwater flowed sub glacially through this notch.

Immediately above the potholes the gradient of the valley becomes very gentle. A short (~100 m) bushwhack east of the trail provides a view into this uppermost part of the valley

STOP 4: VIEW INTO THE UPPERMOST MILLER BROOK VALLEY (-72.822954, 44.484967)

3.16 The uppermost reach of the Miller Brook valley is broad and gentle, but is surrounded by a bowl of steep cliffs that are particularly high on the north side where they form the south-facing slopes of Dewey Mountain (Figs. 8, 9). Numerous beaver dams and ponds occupy the floor of the valley.

While Wagner's (1970) paper referred to the valley occupied by Lake Mansfield as being a cirque, this uppermost part of the Miller Brook valley is arguably even more cirque-like. While the floor of this valley is at a much lower elevation (544 m) than the well documented cirques in the Presidential Range of the White Mountains and on Mount Katahdin (see Davis, 1999, for a historical review of work on New England cirques), it's well above the well-developed cirques on the east side of the Baldface Range on the east side of the White Mountains (e.g. 204 m floor of "The Basin"). It seems reasonable that alpine glaciers would have formed in favorably situated, east-facing valleys in the Green Mountains during the onset of each of the glacial periods within the Pleistocene Ice Age, albeit forming later in each of those periods than alpine glaciers in New England's higher mountains. Alpine glaciers in the Green Mountains consequently had less time

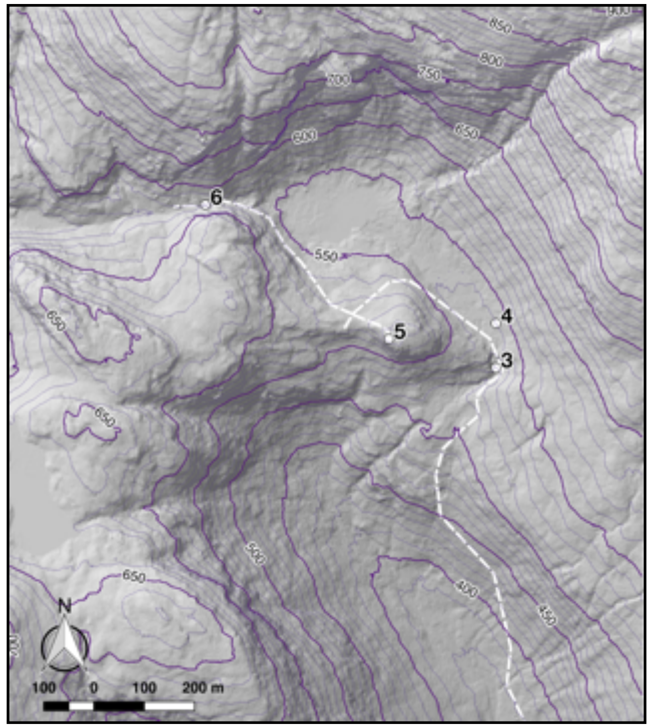


Figure 8 Detailed shaded relief LiDAR map showing locations of Stops 3–6. Contour interval is 10 m.

Figure 9: View west into the upper Miller Brook valley. Beaver ponds occupy the broad, gently sloping floor of the valley. Late afternoon March sun highlights Nebraska Notch during the snowless winter of 2016.

to erode cirques than alpine glaciers at higher elevations before these areas were overridden by the Laurentide Ice Sheet. Old exposure age dates from the summits of Mounts Washington and Katahdin suggest that cold-based, non-erosive ice covered these high alpine areas during the Last Glacial Maximum (Bierman et al., 2015) which may contribute to the preservation of cirques on these mountains.

Continue along the trail until reaching Taylor Lodge. From there a short trail leads east to a lookout.

STOP 5: OVERVIEW OF HEAD OF TRIBUTARY VALLEY TO SOUTH (-72.825630, 44.484680)

3.61 This lookout provides a good overview of the head of the valley immediately south of the one viewed at Stop 4. The valley floor slopes gradually up to the valley head where it is surrounded by an arc of steep cliffs. While this valley is less cirque-like than its neighbor to the north, the bowl shape of the upper valley still bears resemblance to valleys eroded by alpine glaciers.

Return to Taylor Lodge and follow the Clara Bow trail as it contours into Nebraska Notch. One segment of the trail leads under a large boulder and down a ladder.

STOP 6: NEBRASKA NOTCH (-72.830226, 44.487069)

4.09 Nebraska Notch is eroded along a bedrock lineament that strikes approximately E-W across the mountains (Figs. 8, 9). The lineament's straight topographic expression suggests that brittle bedrock structures (joints, faults) responsible for the lineament are close to vertical. Joint faces parallel to the notch are visible on the overlying cliffs. The notch is filled with very large angular boulders which completely hide the bedrock immediately beneath the notch. It's unclear to what extent these boulders have fallen from the above cliffs or been transported here by the ice sheet. None of the readily accessible bedrock exposures or boulders show evidence of erosion by the subglacial water hypothesized to have flowed through the notch.

Return to Taylor Lodge via the Clara Bow trail. Alternatively, continue west along the Clara Bow trail until it intersects the Long Trail. Follow the Long Trail south until it reaches Taylor Lodge

TAYLOR LODGE: LUNCH

4.51

Retrace route down the Lake Mansfield Trail to Lake Mansfield and then to the Lake Mansfield Trout Club parking lot. **NOTE**: The next part of this trip occurs on Lake Mansfield Trout Club Property. Permission is required to utilize the Trout Club's trail system.

Cross the Lake Mansfield dam to the south side of the valley. Stops 1, 2 and 7–14 are shown on Figure 10.

STOP 7: LAKE MANSFIELD DAM (-72.810659, 44.472195)

6.73 The Lake Mansfield dam was first built by the Trout Club in 1901 to provide a habitat for trout. The club owns and maintains two smaller dams downstream from here. The valley head visible to the west is what Wagner (1970) interpreted as the cirque which sourced the post-Laurentide alpine glacier that deposited the "moraines" he described farther down the valley. A lovely alluvial fan protrudes into the north side of the lake (Fig. 11).

From the dam follow the Lake Mansfield Trout Club (LMTC) "White" trail east along the south side of the Miller Brook Valley. Follow this trail to the top of a meadow that looks east, down the Miller Brook valley.

STOP 8: ICE-CONTACT DEPOSITS DOWN-VALLEY FROM THE DAM (-72.809035, 44.471783)

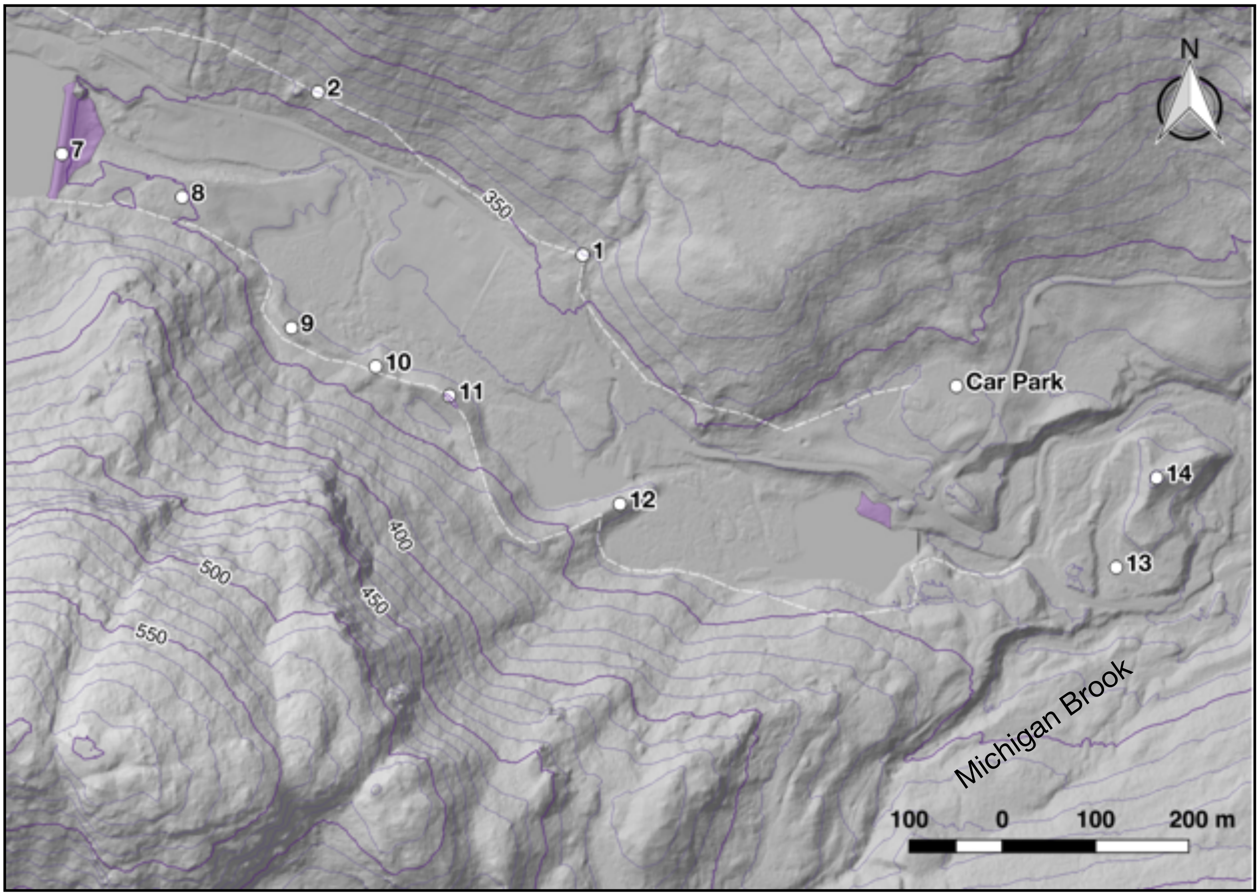


Figure 10: Shaded-relief LiDAR map of the area below the Lake Mansfield dam. Stops 9–12 occur along the ridge interpreted to be a lateral and end moraine by Wagner (1970) and reinterpreted to be an esker. CI = 10 m.

Figure 11: Alluvial fan visible from the Lake Mansfield dam. This fan is the largest and most picturesque of several that occur around the periphery of the lake (Fig. 2).

6.93 The sediments underlying this meadow were exposed in test pits dug when the this area was being considered for the Club's leach field (Fig. 12). The broad sloping ridge lying adjacent to Miller Brook consists of sand and gravel which contains one small kettle at its upper (western) end. In contrast, areas farther down the slope are underlain by silt and sand that is frequently faulted and disrupted by soft-sediment deformation. The ridge is interpreted to be the eroded remnants of ice-contact sediments deposited as a largely subaerial fan when the ice margin lay approximately where the Lake Mansfield dam currently exists. The silt and sand are ice-proximal lacustrine sediments deposited in the shallow water near the shoreline of Glacial Lake Winooski in this area, ~342 m (1,122 ft).

The broader paleogeographic picture at this time is one where the Laurentide ice sheet on the east side of the mountains had thinned and completely retreated well to the north of the Miller Brook valley. However, a tongue of ice from the much thicker ice sheet in the Champlain valley west of the mountains flowed through Nebraska Notch and down the Miller Brook valley. The sediments and landforms at Stop 8 record the recessional position of this tongue of ice at or near the shoreline of Glacial Lake Winooski. As we walk

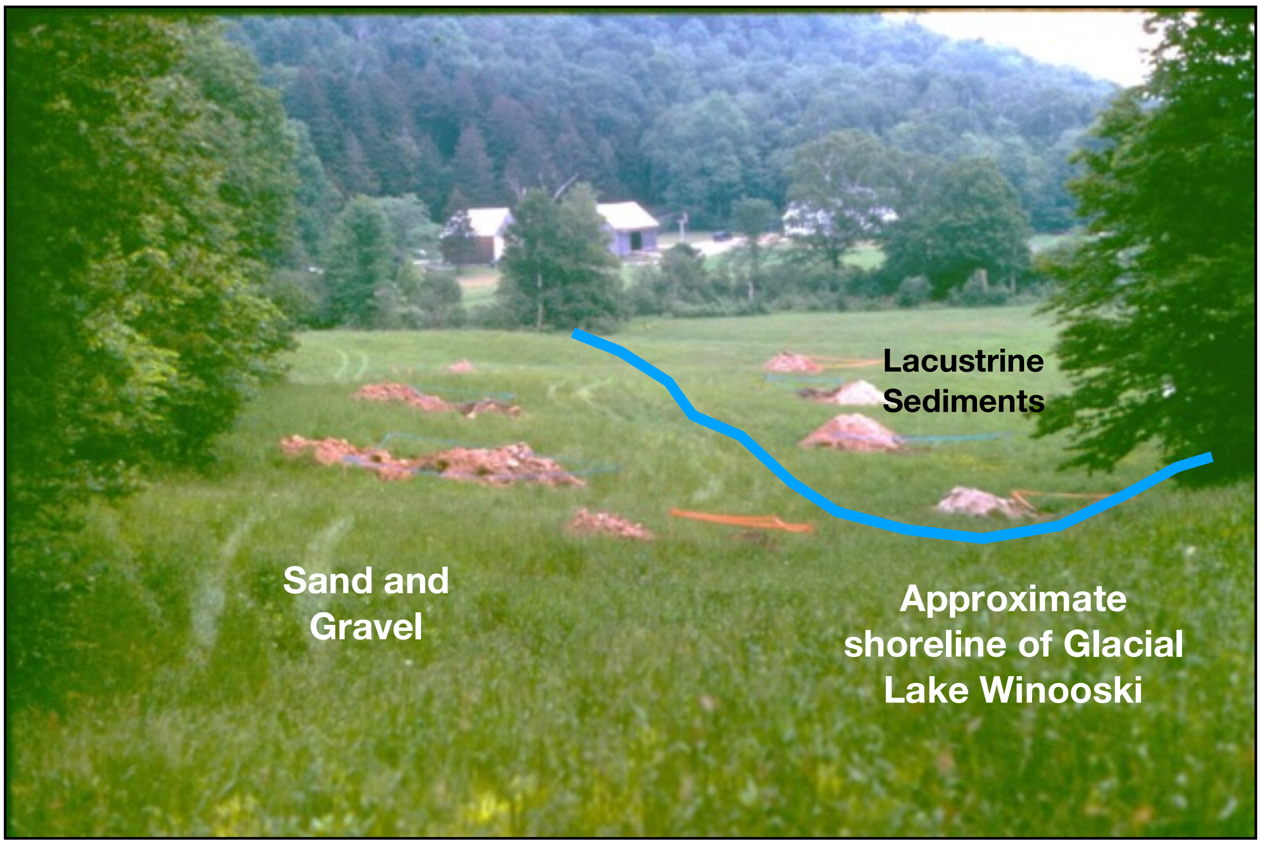


Figure 12: View looking northeast across the Miller Brook valley from Stop 8. The broad ridge to left is underlain by sand and gravel interpreted to be an apron of ice contact sediments deposited along the margin of the retreating ice sheet. The blue line shows the approximate shoreline of Glacial Lake Winooski (~342 m, 1,122 ft) and areas below that are underlain by lacustrine sediments. Modern Miller Brook alluvium overlies these sediments beyond the soil test pits.

down-valley we will be looking at sediments and landforms deposited perhaps only a few years earlier.

Return to the White trail and follow this down valley. The trail ascends a small intermittent stream valley lying between the north-facing valley side and a small ridge.

STOP 9: RIDGE ALONG SOUTH SIDE OF VALLEY (-72.807555, 44.470527)

7.22 This and the following two stops are along segments of the ridge that Wagner (1970) interpreted to be a moraine (Fig. 10). Here a distinctive ridge lies parallel to the valley wall and stands with almost 10 m of relief from the valley floor. The LiDAR imagery clearly shows the geographic form and extent of the ridge. As noted earlier, this landform is not visible on any of the published topographic maps of the area which hindered geological work here. Two small alluvial fans, deposited from ephemeral streams draining the south side of the valley, have partially filled the gap between the ridge and the valley side.

Large boulders adorn the ridge and soil pits here and at Stop 11 encountered a loose, unsorted mixture of angular rocks (Wright et al, 1997). The material littering the surface of these ridges and that accessible with hand tools is diamict. This diamict has been interpreted as till and a ridge of till parallel to a valley is logically interpreted to be a moraine (Wagner, 1970; Waitte and Davis, 1988). However, Stop 9 is nearly opposite Stop 2 on the north side of the valley where no equivalent ridge exists. If the ridge here is a lateral moraine, then (1) a correlative moraine was never deposited on the north side of the valley (unlikely!) or (2) the moraine that was there has completely eroded away.

Follow the White trail a short distance east until reaching a short ridge aligned southwest-northeast, oblique to the valley side.

STOP 10: SHORT RIDGE SEGMENT OBLIQUE TO VALLEY SIDE (-72.806416, 44.470157)

7.32 This short ridge is also mantled with large rocks but is aligned southwest-northeast, i.e it angles down valley from valley side (Fig. 10). If this ridge is largely composed of till and is a moraine, it is an erosional remnant of a small recessional moraine deposited perhaps during a winter standstill. If it used to extend across the valley then the northern end of it may be buried by the large alluvial fan existing there (Stop 1) and the middle segment has been eroded by Miller Brook. Another consequence of a moraine here is that it may have ponded meltwater from the retreating ice sheet and be the body of water the lacustrine sediments at Stop 8 were deposited in. An alternative interpretation is that the bulk of this ridge is actually composed of ice-contact sediments that were subsequently covered by diamict deposited during a debris flow down the steep valley sides although this scenario seems less plausible.

Continue east along the White trail a short distance where the trail travels along a high ridge with Miller Brook on its north side and small pond on its southwest side.

STOP 11: RIDGE AND TRAPPED WETLAND; SOUTH SIDE OF VALLEY (-72.805420, 44.469877)

7.41 Stop 11 is on a very prominent ridge that stands more than 10 m above Miller Brook and arcs to the south (Fig. 10). During most parts of the year an ephemeral peat-filled pond occupies the space between the ridge and the side of the valley. Organics, sampled from a depth of 235 cm, were dated at 9280 +/-235 ^{14}C years (10,561 +/- 327 calibrated years BP) by Sperling and others (1989) indicating that the ridge is a primary geographic feature (not produced by erosion) standing on the valley side since the retreat of the ice sheet.

The elevation profile of this ridge varies considerably. Specifically, the elevation of the ridge between Stops 9 and 11 dips down where it crosses the moraine-like landform (Stop 10) and then climbs above 350 m. Along the next stretch of trail the ridge first drops and then climbs considerably higher, reaching an elevation of ~364 m, before making a 90° turn to the northeast and steadily dropping to an elevation of ~345 m (Fig. 9). The varying elevation profile of this ridge is quite different from lateral moraines which tend to mimic the profile of the glacier that produced them dropping steadily in elevation down-valley.

STOP 12: RIDGE BELOW MIDDLE TROUT POND; CENTER OF VALLEY (-72.803116, 44.468839)

7.71 After the ridge turns northeast it protrudes out into the center of the valley. Wagner (1970 interpreted this segment of the ridge as an end moraine. Boulders are rare on this section of the ridge and even a shallow shovel hole reveals that the ridge is composed of coarse sand and rounded gravel. Similar test pits farther down valley all confirm that this ridge is composed of stream-transported gravel and not till. Consequently, this ridge is an esker and not a moraine. Inspection of the LiDAR imagery (Fig. 10) shows that the ridge is breached by Miller Brook, but continues down-valley where the access road to the Trout Club is built on it.

The till that blankets the ridge where it lies along the side of the valley is most likely an ablation till that accumulated on top of the esker when the ice sheet melted. Much of this ablation till probably consists of till that slid via debris flows from the valley side as the glacier thinned. This is the till that has led many geologists to interpret these ridges as moraines. In the center of the valley the till cover on the esker is thin and patchy and is most likely derived from englacial debris.

The White trail drops off the esker and follows the south side of the valley skirting a wetland area immediately above the lowest dammed pond on the Trout Club property. After reaching the dam, follow an old road east along the south side of Miller Brook until it intersects the road just below the bridge over Miller Brook. Walk down the road (southeast) ~90 m and then enter the woods on the north side of the road. A short walk leads to an abandoned stream channel and a series of stepped terraces above the

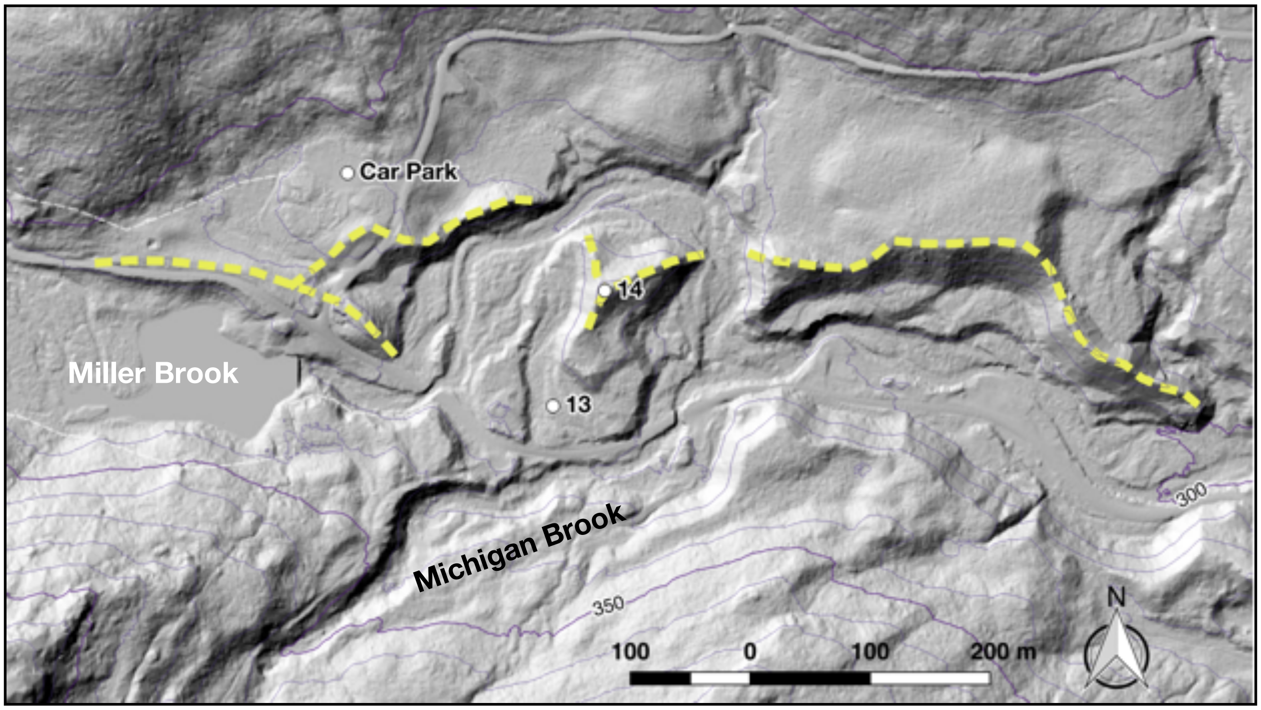


Figure 13: Shaded-relief LiDAR map of eroded Glacial Lake Winooski delta deposited by both Miller Brook and Michigan Brook. An extensive network of abandoned stream terraces and channels formed when Glacial Lake Winooski partially drained ~13,700 years BP.. Esker ridges shown with yellow dashed lines. Contour interval is 10 m.

channel.

STOP 13: ABANDONED CHANNELS; INCISED GLACIAL LAKE WINOOSKI DELTA COMPLEX (-72.796418, 44.468246)

8.43 This stop is located near the confluence of Michigan Brook and Miller Brook (Fig. 13). An abandoned Michigan Brook stream channel cuts N-S across this area. The channel is bordered by several adjacent stream terraces giving this landscape a stair-step topography. Immediately to the west (south of the parking area) the esker ridge bifurcates and is eroded by both Miller and Michigan Brooks. Stream terraces and channels situated well above the valley floor indicate that the eskers were largely buried by sediments (i.e. base level was high) prior to stream incision. Some of these sediments were deposited as subaqueous fans as the ice sheet retreated across this area. After the ice sheet retreated up the valley both Miller Brook and Michigan Brook formed deltas which merged together in this area and largely buried all but the highest parts of the esker system (Fig. 2). As noted earlier, these highest terraces are interpreted as delta tops deposited close to the local elevation of Glacial Lake Winooski, ~342 m (1,122 ft). The complex network of stream channels were incised after glacial Lake Winooski drained ~13,800 years ago.

Climb the steep slope to the north. After crossing one of the high terraces, continue climbing up the esker ridge to its high point.

STOP 14: INTERSECTING ESKERS (-72.795880, 44.469112)

8.53 This is the intersection of three esker ridges in the middle of the valley with Miller Brook flowing around this point to the west, north, and east and Michigan Brook passing to the south (Fig. 13). There is a 17 m drop in elevation to the abandoned channel to the north (Stop 13). The high esker ridge arcs from N-S to east where it has been cut by Miller Brook and then continues down the valley. The southern extension of this esker has been largely eroded away, but likely used to turn back to the west where it connected to northeast of the dam (Fig. 13). The esker extending to the north is also cut by Miller Brook and continues as a sinuous ridge below the parking area. This esker is lower in elevation and appears to be cross-cut by the higher esker. While this esker may be older, it's also possible both subglacial tunnels were active at the same time and this northern loop was just a smaller tunnel.

9.07 Return to the Lake Mansfield Trailhead parking area.

DRIVING:
Mileage

10.6 Turn Right (south) on to Old County Road when leaving the Nebraska Notch Trailhead parking area.

10.7 Turn Left (east) on Nebraska Valley Road and follow this back down the Miller Brook Valley.

12.6 Turn Right (northwest) on Beech Hill Road. Follow this road up a steep hill and park adjacent to the Stowe Solar Farm which is built on a terrace at the top of the hill. Figure 14 is a detailed map of this area.

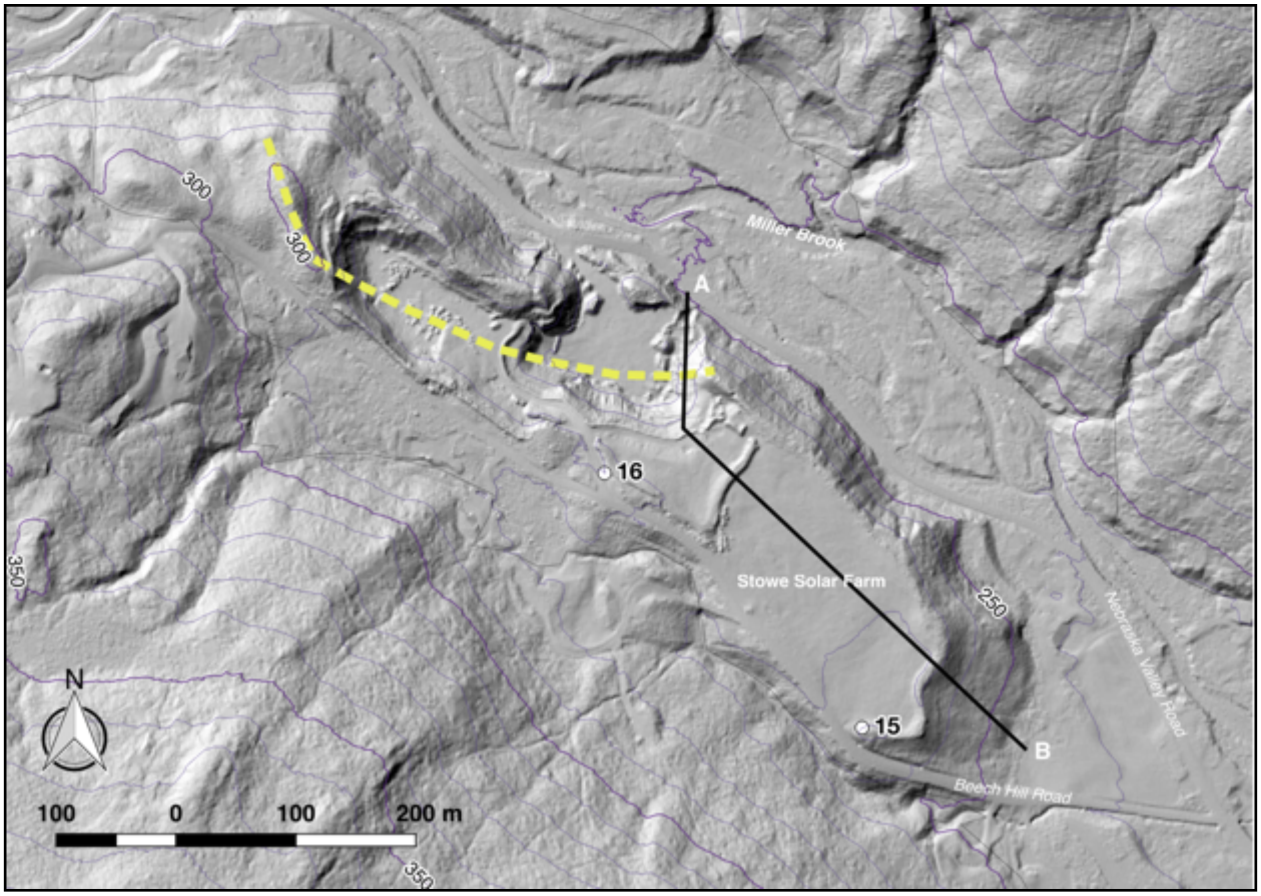


Figure 14: Detailed shaded -relief LiDAR map of the Stowe town Solar Farm and gravel pit. The terrace the solar farm is built on is underlain by a thin veneer of gravel (old Miller Brook alluvium) that in turn unconformably overlies varved silt/clay deposited in Glacial Lake Winooski. The deep pit is excavating gravel deposited in the Miller Brook esker. Dashed yellow line shows the trace of the esker. Contour interval is 10 m. A-B is location of diagrammatic cross-section (Fig. 16).

STOP 15: STOWE SOLAR FARM **(-72.769546, 44.461475)**

12.8 The Stowe Solar Farm is built on a terrace that was formerly a meadow and then a gravel pit. The berm around the perimeter of the pit shows the former elevation of the terrace (slopes gently SE 275–270 m, ~900–885 ft) and indicates that only several meters of gravel have been removed. The gravel here unconformably overlies varved silt/clay deposited in Glacial Lake Winooski. While not exposed, this material is easily accessed with a soil probe a short distance down Beech Hill Road.

The gravel that formerly covered this terrace is interpreted to be old Miller Brook alluvium deposited on the floor of Glacial Lake Winooski after the lake drained (Fig. 15). Miller Brook meandered across this terrace with a gentle gradient without incising its channel further into the underlying lacustrine sediments. This implies that the brook was close to base level which was the local elevation of Glacial Lake Mansfield 1, the lake that formed after Glacial Lake Winooski partially drained (Fig. 15).

Return to cars and continue up the road a very short distance and park at the entrance to the Stowe Gravel Pit (Fig. 14). Please do not block the gate.

STOP 16: STOWE GRAVEL PIT **(-72.774744, 44.465170)**

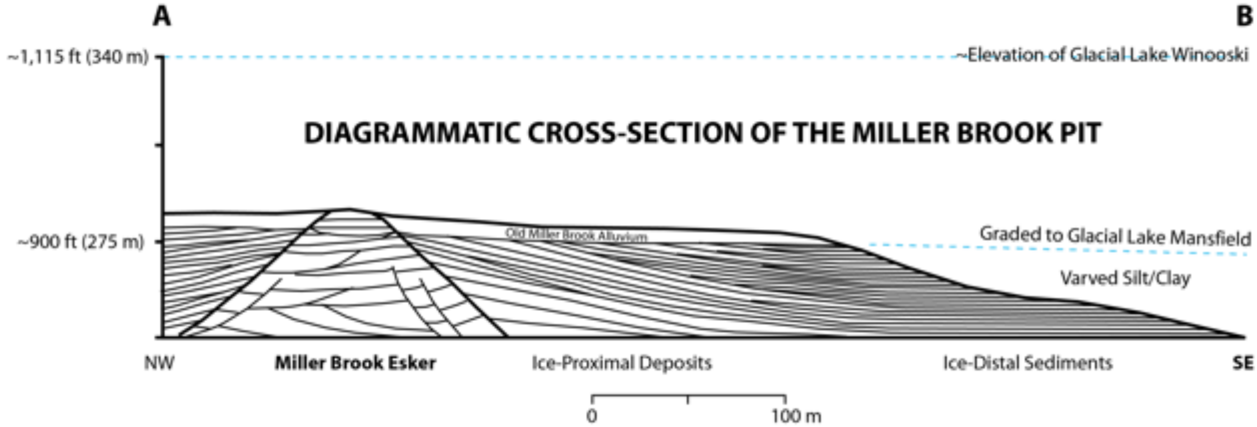


Figure 15: Diagrammatic cross-section of the Miller Brook esker, ice-proximal and ice-distal lacustrine sediments, and overlying old Miller Brook alluvium. Location of cross-section is shown in Figure 13.

13.0 The esker visited earlier in this field trip extends discontinuously from Lake Mansfield down the valley as far as this gravel pit. The objective of this stop is to observe sediments marking an almost complete transition from an esker tunnel environment to the relatively quiet waters of Glacial Lake Winooski.

The undisturbed esker ridge is prominently exposed in the woods to the northwest and can be traced across the pit floor (see dashed line in Fig. 14), although it's being actively removed and distributed across various parts of Stowe. Recent exposures of the esker sediments show bedding dipping moderately to gently to the southeast and consisting largely of coarse boulder/cobble gravel interlayered with beds of coarse sand and pebble gravel. Small scale faults, most with a normal sense of slip, are common along the exposed border of the esker.

The esker is overlain by a fining-upward sequence sediments ranging from pebble gravel close to the esker to very fine sand, silt, and clay away from the esker (Figs. 15–17). These sediments are best exposed at the northwestern end of the pit. Dropstones are common as are distinct, thin silt layers within the sand horizons. Varved silt and clay[1] layers lie at the top of the section, farthest from the esker. Spectacular folds and faults occur within these varves and were likely produced when these soft yet coherent sediments slid

Figure 16: Sheath fold in varved silt/clay along the northeast side of the pit. The axis of the fold trends to the northeast, perpendicular to the plane of the photo and to the adjacent esker. The high shear strains necessary to produce folds of this geometry likely occurred when these sediments slumped off the northeast side of the esker into deeper water.

off the northeast side of the esker into deeper water (Fig. 16). The projected elevation of Glacial Lake Winooski over this part of the Miller Brook valley is ~340 m (1,115 ft) (Fig. 16). Therefore, as the ice sheet

[1] Work by Derr (2011) has shown that the winter "clay" layers in varves collected at the Waterbury Reservoir (~8.5 km south of the Miller Brook pit) actually consist of fine silt size particles consisting largely of the minerals muscovite, clinochlore, and chlorite, common mica minerals in the surrounding rocks.

Figure 17: Cross-sectional exposure of the Miller Brook esker looking northwest along the axis of the esker.The bulk of the esker consists of thick beds of coarse boulder/cobble gravel interlayered with beds of coarse sand and pebble gravel. The right (northeast) side of the esker is mantled by a fining-upwards sequence of lacustrine sediments largely consisting of medium to fine sand with abundant dropstones.

retreated, the crest of the esker (elevation 300 m) was immediately beneath 40 m of water and and areas on either side in much deeper water. Coarse sediments ejected from the esker tunnel were deposited close to the tunnel mouth. As the ice sheet retreated farther up the valley, the average size of sediment originating from the esker tunnel gradually diminished producing the fining-upwards sequence of sediments currently draping across the esker Fig. 17).

Figures 18–21 (below) summarize the late Pleistocene through Holocene history of the Miller Brook valley.

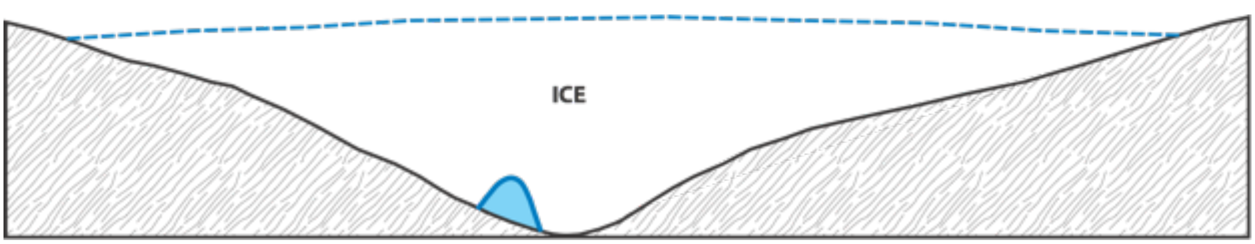


Figure 18: Shortly after 14 ka: A tongue of the Laurentide Ice Sheet flowed down the Miller Brook valley fed by ice flowing through Nebraska Notch. A large subglacial tunnel funneled meltwater, largely sourced from the ice sheet in the Champlain Valley, west of the Green Mountains, southeast, down the hydraulic gradient. Near the margin of the glacier sediments begin accumulating in the subglacial tunnel. The ice sheet in the valley between the Green Mountains and Worcester Mountains thinned and quickly retreated northwards allowing Glacial Lake Winooski to expand into that valley.

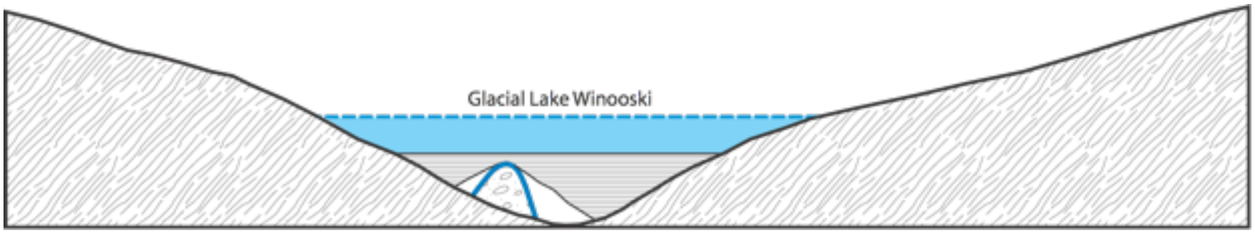


Figure 19: ~14.0–13.9 ka: Glacial Lake Winooski extends progressively farther up the Miller Brook valley as the ice sheet margin retreats exposing the esker that had formed in the subglacial tunnel. A subaqueous fan deposited sediments adjacent to the to the mouth of the subglacial tunnel. In any one place the fan deposits fined -upwards as the ice front retreated farther up-valley. Eventually, sediment accumulating on the lake bottom consisted largely of varved silt and clay. Once the ice sheet retreats above the elevation of Glacial Lake Winooski, meltwater begins depositing a delta which grows down-valley and largely buries the esker.

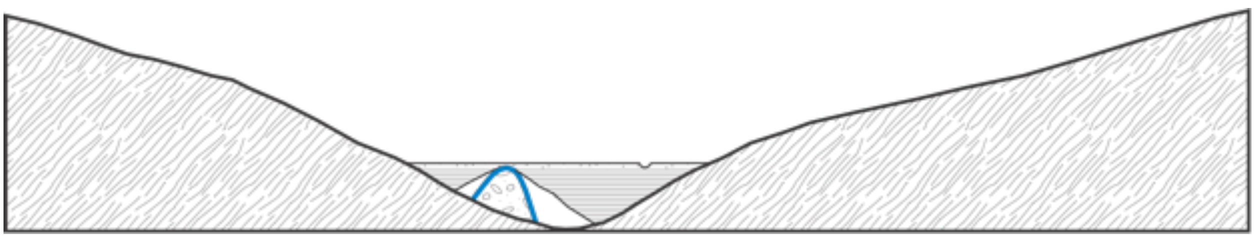


Figure 20: ~13.8 ka: At approximately 13.8 ka the Laurentide Ice Sheet in the Winooski river valley retreated westward far enough to uncover a lower outlet allowing Glacial Lake Winooski to catastrophically drain exposing the recently-deposited lake sediments. Miller Brook began incising channels through that sediment along its upstream reaches. Downstream, downcutting was limited as the elevation of Glacial Lake Mansfield 1 (local base level) was only slightly lower than the elevation of the lake bottom sediments.

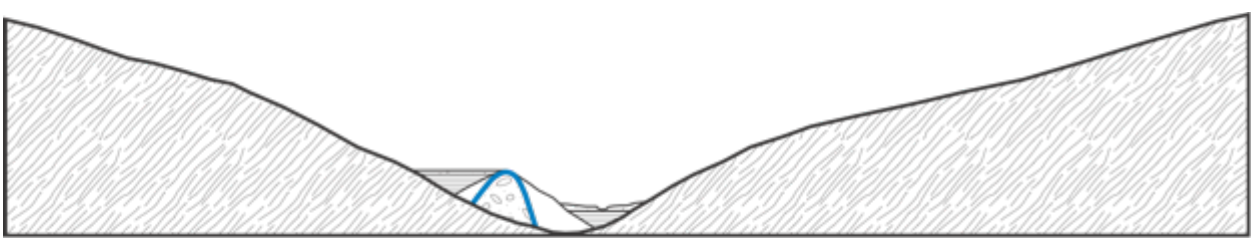


Figure 21: ~13.7 ka to Present: Glacial Lake Mansfield was a relatively short-lived lake and soon drained to the elevation of Glacial Lake Vermont with further retreat down the Winooski River valley. With this new change in base level, Miller Brook began incising its present channel through lacustrine, subaqueous fan, and esker sediments.

END OF FIELD TRIP.

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