ICE RETREAT AND READVANCE ACROSS THE GREEN MOUNTAIN FOOTHILLS: BOLTON AND JERICHO, VERMONT

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INTRODUCTION

This field trip visits several key sites in the towns of Bolton and Jericho Vermont that shed light on the glacial, ice-contact, and lacustrine environments that existed during a relatively short period of time during the retreat of the Laurentide ice sheet across this area. This area lies on the western slope of the Green Mountains, an area dominated by steep slopes and narrow stream valleys that are cut by the broad, low-gradient Winooski River valley (Fig. 1). Stop 1 is a section displaying evidence of at least one cycle of glacial retreat followed by readvance and eventual retreat. Stop 2 visits a working gravel pit where the internal structures of a large delta formed where glacial meltwater flowing south from Bolton Notch entered Glacial Lake Mansfield which occupied the Winooski River valley. Farther north in Bolton Notch Stop 3 visits a series of nested meltwater channels and other ice-contact landforms. The trip finishes at a large landslide section along the Lee River (Stop 4) which

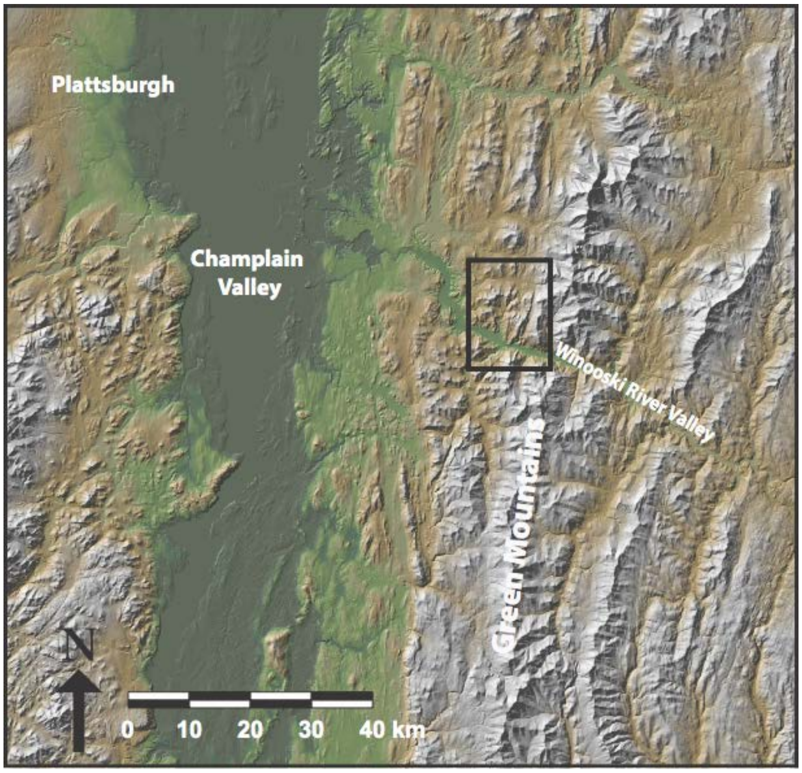

Figure 1: The field trip area is outlined with a box. See Fig. 2 for detailed map.

exposes the full transition from quiet water lake sediments through deltaic sediments where the Lee River delta prograded into the Coveville Stage of Glacial Lake Vermont. The location of all the field trip stops are shown in Figure 2 and more detailed maps accompany the road log. Many of the field stops described in this guide are located on private land. Permission from landowners, noted in the following guide, must be secured before visiting these sites.

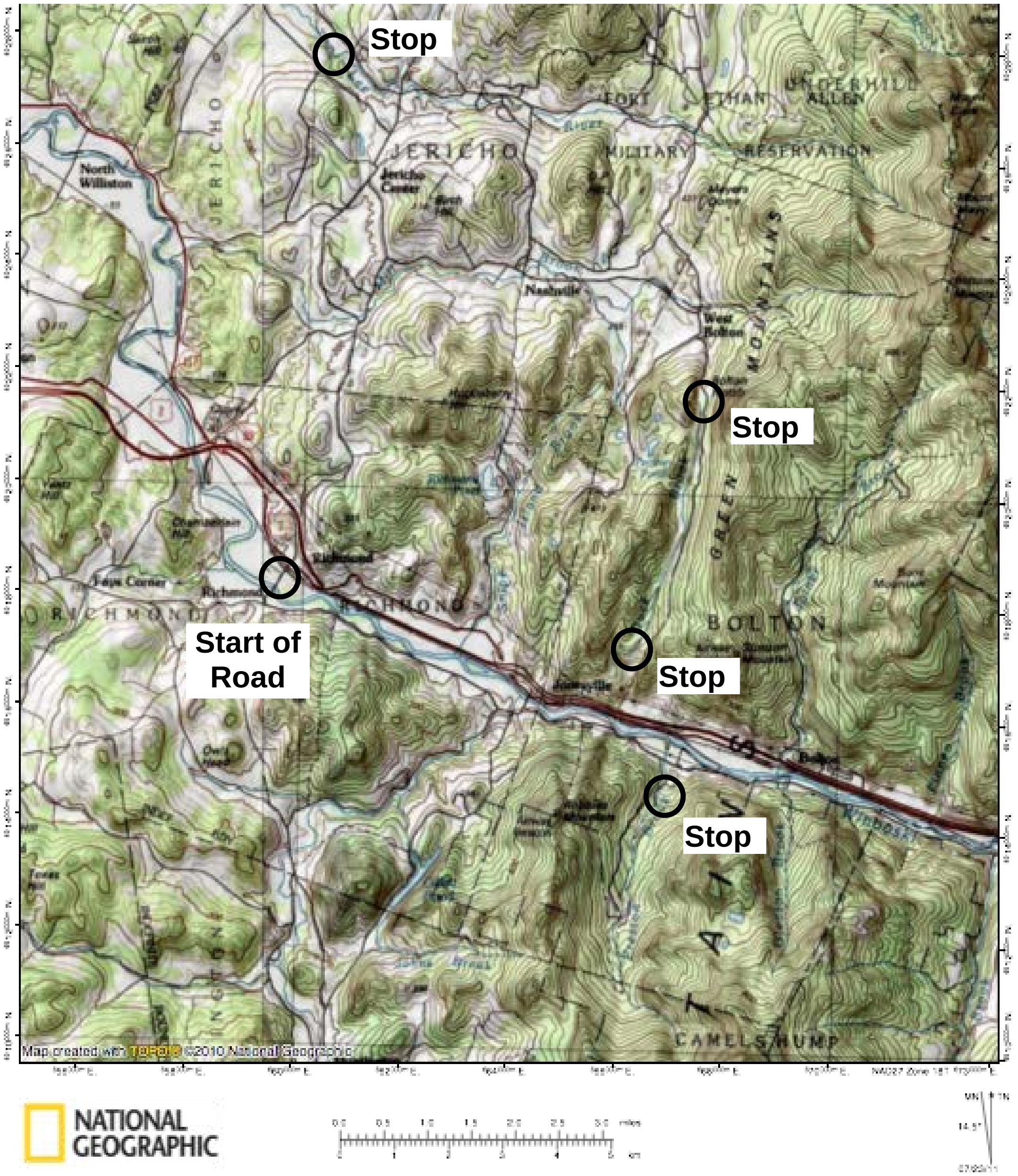

Figure 2: A topographic map showing a portion of the Green Mountain foothills cut by the Winooski River which flows WNW towards Lake Champlain. Stop locations are shown as open circles and are labeled on the map. Contours and spot elevations are in meters. Distance measurements in the road log are from the park in the village of Richmond.

GEOLOGIC SETTING

Bedrock Geology

The northern Green Mountains are composed of metamorphic rocks that were (1) originally deposited as sediments in the Iapetus Ocean along the margin of Laurentia, (2) intruded as basaltic dikes and sills through those sediments, or (3) are the now serpentinized tectonic slices of ultramafic rocks derived from Iapetus ocean mantle. The Vermont Bedrock Geologic Map published in 1961 (Doll et al., 1961) interpreted the rocks in the Green Mountains as a largely coherent, yet folded, stratigraphic section. Mapping undertaken during the last 30 years has shown that these rocks are cut by numerous thrust faults occurring on a variety of scales and active during both the Taconic and Acadian orogenies (Stanley and Ratcliffe, 1985; Thompson et al., 1999; Kim et al., 2009). In other words, most geologic contacts within the mountains have been reinterpreted to be tectonic as opposed to stratigraphic contacts. The new Vermont Bedrock Geologic Map and cross-sections (Ratcliffe et al., 2011) clearly display the results of this recent mapping and the reinterpretation of geologic structures.

Small-scale faults, isoclinal folds, and a well-developed foliation associated with the Taconic orogeny are frequently visible in good outcrops. Open upright folds and a spaced cleavage associated with the Acadian Orogeny are also easily visible in many outcrops. The hinge line of the largest of these late Acadian folds, the Green Mountain Anticlinorium, roughly follows the spine of the Green Mountains. This field trip takes place on the west side of the anticlinorium. Good summaries of recent mapping and interpretations in northern Vermont are presented in Thompson et al. (2011) and Kim et al. (2011).

West-northwest-directed thrust faults, active during both the Taconic and Acadian orogenies, and Acadian folding, have produced a mountain range with large-scale structures that generally strike NNE–SSW. These structures, in association with over 350 million years of uplift, differential weathering and erosion, have produced mountain ranges and intervening valleys that are aligned generally NNE—SSW (Fig. 1). Stops 1–3 lie in valleys with this orientation. Rocks in the Green Mountains are also cut by a well-developed joint set oriented ~WNW–ESE. The Lamoille and Winooski rivers both cut across the mountains following ~WSW–ESE courses and many smaller streams, e.g. Mill Brook and the Lee River, follow this course as well (Fig. 1).

Glacial Geology

Current dating of ice sheet retreat across the region indicates that Vermont was deglaciated from southeast to northwest between ~15,500 and ~13,200 calibrated (U-Th) years B.P. (Ridge et al., 2012). The large-scale map pattern of surficial materials in the Green Mountains consists of till-covered mountain slopes adjacent to stream valleys partially filled with variable combinations of ice-contact and/or lacustrine sediments overlain by Holocene alluvium. This pattern is readily visible on the Vermont Surficial Geologic Map (Stewart and MacClintock, 1970) where the drainage networks across the mountains are highlighted by the colors used to denote materials other than till.

The area encompassed by this field trip lies within the NW quadrant of the Camels Hump 15-minute quadrangle mapped by Stewart (1956–1966). Reconnaissance work by Wagner (1972) and detailed mapping of surficial deposits in the town of Jericho by Ladue (1982) both outline a more complex series of surficial units and a correspondingly more complex glacial history than that presented by Stewart's mapping.

Glacial striations measured across the Green Mountains indicate that the regional ice flow was generally from northwest to southeast, obliquely up and over the spine of the Green Mountains (Fig. 3, Wright, 2013). Younger cross-cutting striations in northern Vermont are restricted to the lower elevations and are parallel to the valleys they occur in (e.g. the Champlain Valley, the Lamoille and Winooski river valleys) indicating that late-stage ice-flow was guided by the orientation of the region's valleys as the ice sheet thinned (Fig. 3).

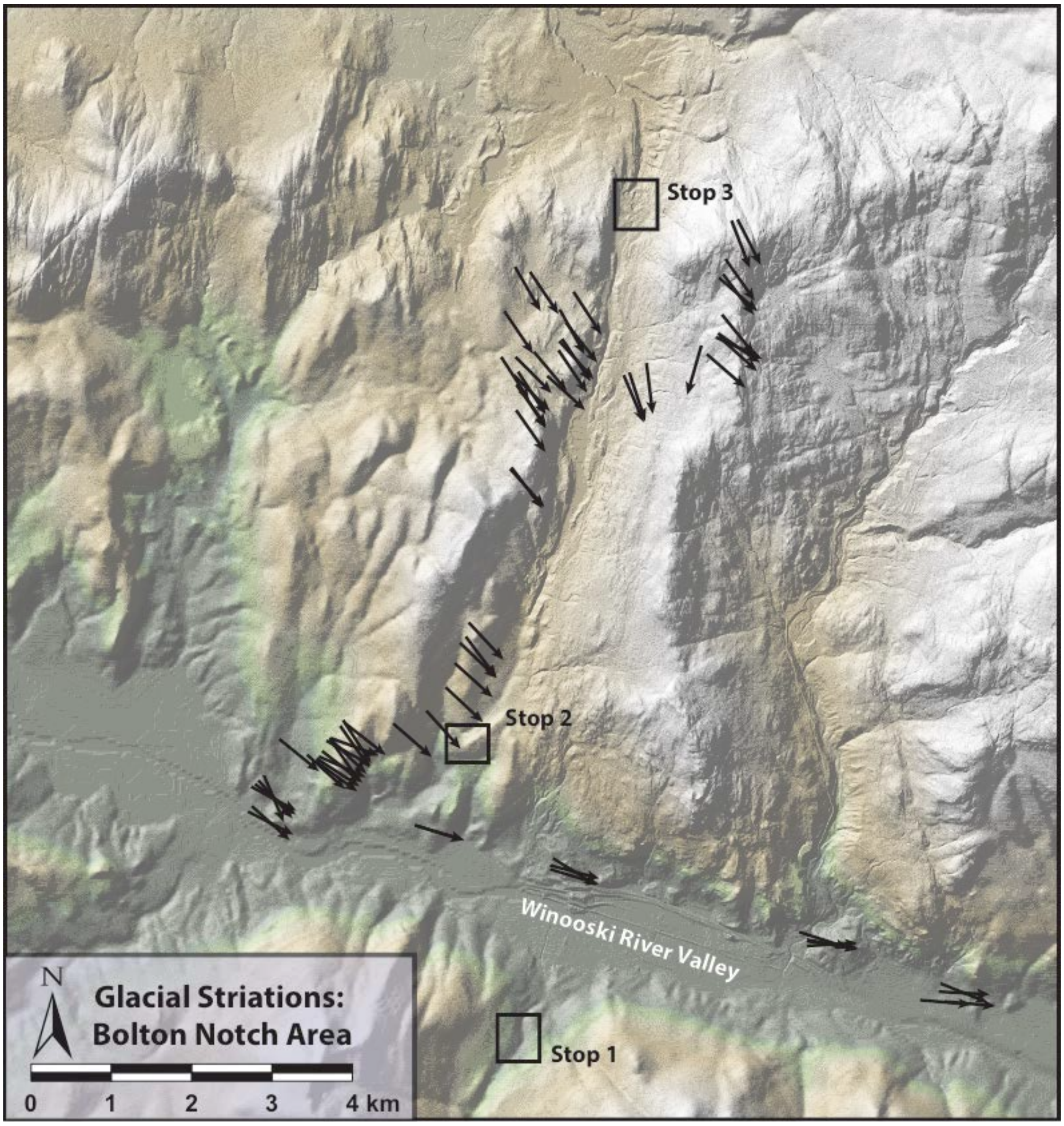

Figure 3: A shaded relief map of the Bolton Notch area showing the orientation of glacial striations. High-elevation striations are uniformly NW to SE and formed when the ice sheet was thick enough to flow obliquely across the mountains. The few striations measured within the notch show some deflection of ice flow to the south, parallel to the orientation of the notch. Striations in the Winooski River valley parallel the valley. Boxes outline the locations of Stops 1–3.

The large rivers in northern Vermont (the Winooski, Lamoille, and Missisquoi) flow generally WNW, across the mountains, and drain into Lake Champlain. As the ice sheet thinned and retreated northward and westward across the mountains, these rivers were dammed producing a series of glacial lakes that inundated these drainage basins (Larsen, 1972, 1987). The largest regional lake was Glacial Lake Winooski that occupied, at its maximum extent, much of the Winooski and Lamoille river drainage basins (Fig. 4). The outlet of this lake was at the drainage divide between the north-flowing Steven's Branch of the Winooski river and the south-flowing Second Branch of the White river, ~13 km south of Barre, at an elevation of 279 m, (915 ft). The isostatically tilted surface of Glacial Lake Winooski rises to the NNW. Based on varve counts from exposures along Muzzy Brook, the Wrightsville Reservoir, and the Waterbury Reservoir, Glacial Lake Winooski existed for no more than ~300 years (Larsen et al., 2001, Larsen et al., 2003) from ~14,090 to 13,790 yr BP,) based on current dating of the North American Varve Chronology (Ridge et al., 2012).

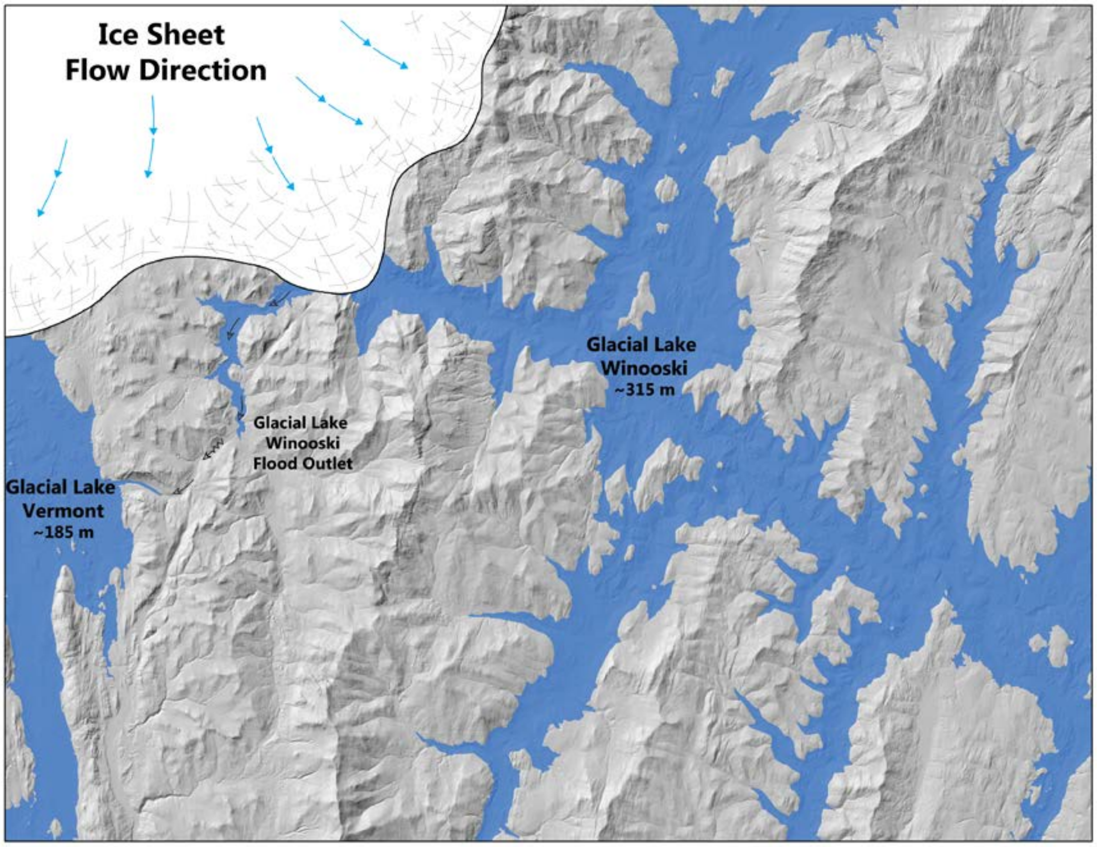

Figure 4: A shaded relief map of north-central Vermont showing the approximate configuration of the Laurentide ice sheet when it dammed the Winooski River valley flooding the drainage basin with Glacial Lake Winooski. A portion of Glacial Lake Vermont occupying the Champlain Valley is also shown. A short additional retreat of the ice sheet from the position shown on the map uncovered two successively lower outlets (the lowest Hollow Brook Outlet is shown as an arrow on the map) which allowed Glacial Lake Winooski to partially drain forming Glacial Lake Mansfield. Labeled lake level elevations are valid for the northwest portion of the map.

Glacial Lake Winooski partially drained when the ice sheet retreated down the Winooski River valley to Jonesville where the impounded water could flow into the Champlain Valley (occupied by Glacial Lake Vermont, Coveville stage) across two successively lower outlets, Gillette Pond and Honey Hollow (Larsen, 1972, 1987, Fig. 4). The ensuing lake (Glacial Lake Mansfield) also occupied much of the Winooski River basin. Continued retreat of the Laurentide ice sheet down the Winooski River valley eventually allowed Glacial Lake Mansfield to drain into the Champlain Valley which was occupied by Glacial Lake Vermont south of the retreating ice sheet. The Winooski river valley was subsequently occupied by an arm of Glacial Lake Vermont.

ACKNOWLEDGEMENTS

We wish to extend our sincere gratitude to the owners of some of the properties visited on this field trip. Specifically these include the owners of the West Bolton Golf course who have granted permission to survey parts of the Golf Course as well as the gravel pit at the north end of Bolton Notch, Sue and Dave Beckman, owners of the active gravel pit at the south end of Bolton Notch, and the McLoughlin family who has allowed this field trip and many UVM students access to the Lee River landslide site.

FIELD GUIDE AND ROAD LOG

New York Meeting Point:

Southeastern parking lot of Hudson Hall (corner of Beekman and Broad Streets), SUNY Plattsburgh campus.

Meeting Point Coordinates: 44.691°N, 73.467°W

Meeting Time: 8:00 AM

Distance				
Cumulative		**Point to Point**		
miles	**km**	**miles**	**km**	**Route Description**
0.0	0.0			Turn left out of the parking lot and head north on Beekman Street until reaching Cornelia St.
0.2	0.3	0.2	0.3	Turn right (east) on Cornelia St (NY Rt 3)
0.7	1.1	0.5	0.8	Turn left (north) on Oak St (NY Rt 22N)
1.6	2.6	0.9	1.4	Turn right to merge onto I-87 N
3.0	4.8	1.4	2.3	Take Exit 39 onto NY 314 E toward Cumberland Head. Follow NY 314 to the Plattsburgh-Grand Isle Ferry
7.5	12.1	4.5	7.2	Plattsburgh-Grand Isle Ferry
7.7	12.4	0.2	0.3	After leaving the ferry turn right (south) on West Shore Road (Vt Rt 314)
9.9	15.9	2.2	3.5	Follow West Shore until it intersects Rt 2. Turn right (south). After crossing the causeway, the road traverses part of the modern Lamoille River delta. Old distributary channels are marked by lines of trees growing on the overbank deposits adjacent to the abandoned channels.

20.1	32.3	10.2	16.4	At intersection with I-89, turn right to merge with I-89 S.
39.7	63.9	19.6	31.5	Take Exit 11 and turn right at stoplight (east) on Rt 2 heading towards Richmond.
41.5	66.8	1.8	2.9	At stoplight in the middle of Richmond, turn right (south) on Bridge Street.
41.8	67.3	0.3	0.5	Pull into village parking lot on right just before bridge. The road log that follows will begin and end here. Participants wishing to car pool may leave their cars here.

Vermont Meeting Point

Richmond Village Park, Bridge Street, Richmond Vermont

Meeting Point Coordinates: 44.413 ° N, 73.001 ° W

Meeting Time: 9:15 AM

Distance				
Cumulative		Point to Point		
miles	km	miles	km	Route Description
0.0	0.0			Turn left out of the parking lot and head north on Bridge Street until reaching the stoplight at the intersection of Route 2.
0.3	0.5	0.3	0.5	Turn right and follow Route 2 East, up the Winooski River valley to the village of Jonesville.
2.9	4.7	2.6	4.2	Abandoned oxbow of the Winooski River on right.
3.8	6.1	0.9	1.4	Jonesville. Turn right at intersection with Cochran Road crossing first the railroad tracks and then the bridge over the Winooski River.
3.9	6.3	0.1	0.2	Turn left (east) at first intersection past bridge onto Duxbury Road and continue up the Winooski River valley, now on the south side of the river.
4.8	7.7	0.9	1.4	Roche Moutonnée on right, immediately adjacent to road. Grooves and striations on the smooth, abraded top and west sides of the roche moutonnée are oriented ~095, parallel to the river valley and the east side has been quarried, indicating ice was flowing ESE, up the river valley.
5.7	9.2	0.9	1.4	Honey Hollow Road intersection: Low-water access to Stop 1 is 0.5 miles up this road.
6.1	9.8	0.4	0.6	Catamount Trail Parking Lot (“P” in Fig. 3). High-water access to Stop 1 is by hiking ~1 km up (south) along the Catamount Trail that leaves from the parking lot. Several large rouche moutonnée are visible across the valley to the north on the south side of Stimson Mountain. All have an asymmetry similar to the one exposed along the road (smooth side facing WNW, quarried side facing ESE).

STOP 1: Preston Brook Landslide

Location Coordinates: 44.371° N, 72.900 ° W

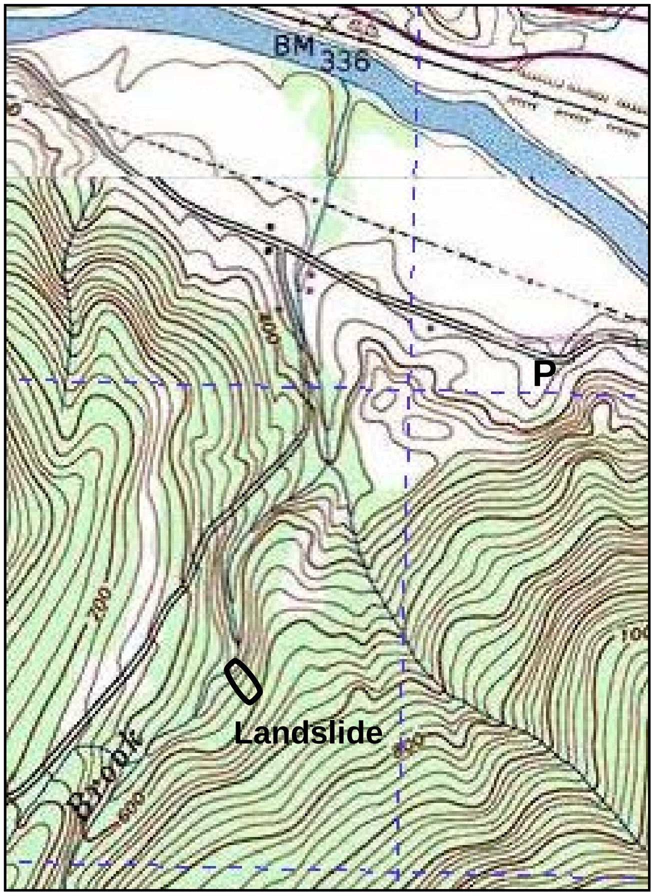

Figure 5: Topographic map showing the location of the landslide (Stop 1) above Preston Brook and the Catamount Trail parking area (“P”). The Winooski River crosses the northern half of the map.

Stop 1 is a large landslide along the east side of Preston Brook in Honey Hollow, a steep, narrow N–S valley typical of the Green Mountains (Fig. 5). There are two ways of accessing this field site. If the water level in Preston Brook is low enough, the bottom of the slide can be accessed by driving 0.5 mile up Honey Hollow road (see above road log) and parking at a small pull-off where a red iron gate blocks an overgrown logging road. The base of the slide is approximately 200 m SE of the iron gate. There is no trail. When Preston Brook is too high to cross, the top of the slide can be accessed by hiking ~1 km up the Catamount Trail to where a gently sloping alluvial terrace separates the trail from the top of the landslide.

Wright first observed this section in 2008 and as of this writing the exposures are still quite good. Please anticipate that they may not remain so in the future. Continuing slope movements change which parts of the section are visible at different times. Parts of the section are very steep and quite wet. Caution and sturdy/waterproof footwear are recommended.

The landslide exposes an approximately 30 m high section containing lacustrine sediments at three stratigraphic levels separated by both diamict and coarser-grained ice-proximal sediments (Fig. 6). The description that follows divides the section into “Lower,””Middle,” and “Upper” parts which are separated by covered intervals. Lacustrine sediments exposed in the “Lower” and “Middle” parts of the section are deformed. One objective of this stop is to ascertain whether structures in these deformed sediments formed by (1) a readvance of the ice sheet or (2) whether they formed during one or more landslides (debris flows) in this narrow, steep-sided mountain valley.

Lower Section

The lowest part of the section (stream-level) consists of fine-grained lacustrine sediments that are folded, faulted, and over-consolidated (Fig. 6). These deformed sediments are overlain by a boulder/cobble/pebble-rich diamict(?). This in turn is overlain by a boulder/cobble gravel that generally fines upwards into a sequence of sediments consisting largely of silt and very fine sand, with irregular lenses of coarser sand, pebbles, and cobbles (Fig. 6). Bedding is sometimes coherent, but also occurs as a slumgullion of lenses and irregular blebs or isolated fragments of silt/clay or rocks surrounded by finer grained sediments. The finer sediments are very compact and appear to be over-consolidated. Near the top of the lower section an approximately 10 cm thick bed of laminated silt and very fine sand has been both folded and apparently injected (dike-like) into the overlying sediments (Fig. 7). To the right (south) of the fold hinge bedding is continuous at least a short ways down section. To the left (north) of the fold hinge bedding has been pealed/delaminated away from the underlying sediment and highly deformed sediment occupies the space above the now overturned limb of the fold.

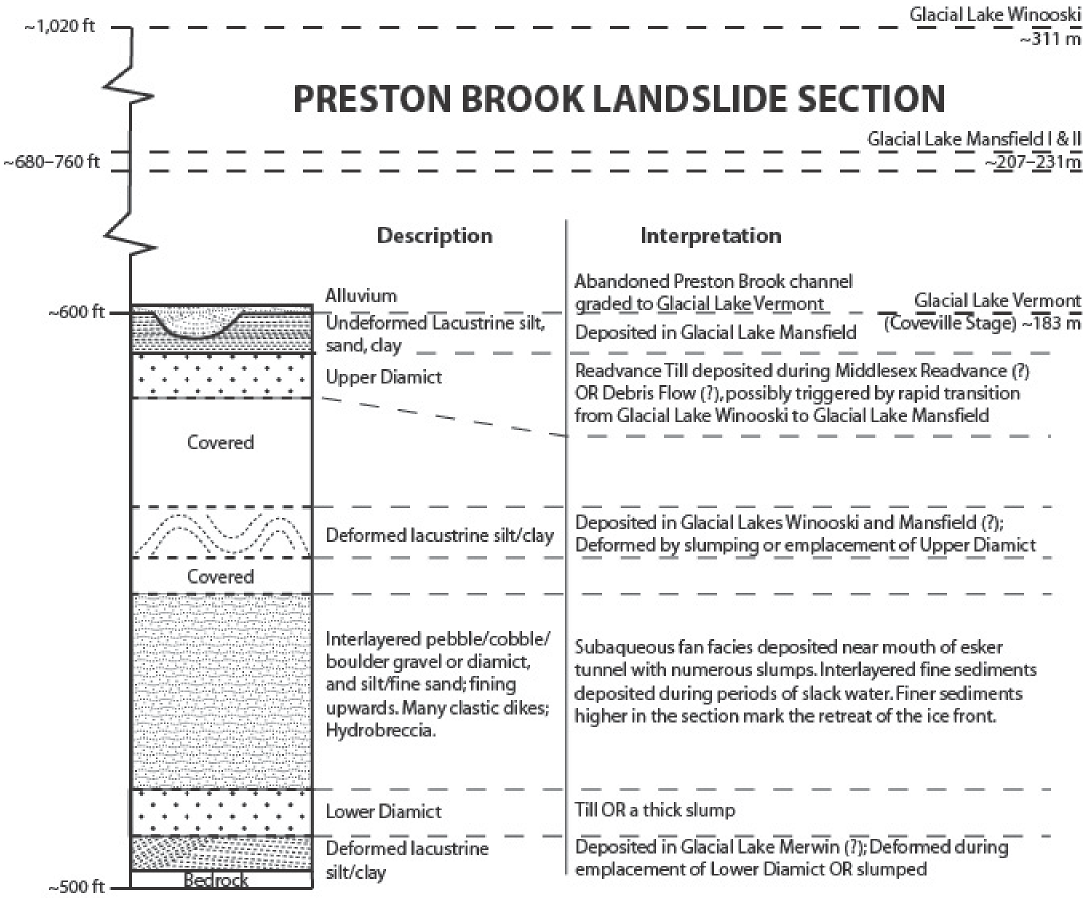

Figure 6: Description and interpretation of the Preston Brook landslide section that extends upwards from the brook to an abandoned fluvial terrace (see Fig. 3 for location). The section exposes three separate units of lacustrine sediments separated by both diamict and glaciofluvial sediments. The lower two units are deformed as a consequence of emplacement of the diamict as till during a glacial readvance or as till remobilized during an underwater landslide. The uppermost part of the section consists of alluvium deposited when Preston Brook flowed across the sediment-filled valley into Glacial Lake Vermont.

Middle Section

The middle part of the section is largely covered and water-saturated, but small exposures consist of silt and clay layers (varves) that have been deformed into meter-scale folds (Fig. 6). The present limited exposure makes it impossible to know whether (1) the entire section is deformed or (2) whether the deformation is intraformational (i.e. the folds occur only within one stratigraphic horizon and are overlain by undeformed sediments).

Upper Section

The upper part of the section consists of diamict (till?/landslide debris?) overlain by rhythmically bedded (varved) very fine sand, silt, and clay (Fig. 6). While some layers contain intraformational slumps, particularly at the base, this section is undeformed. The lacustrine sediments are overlain by a thin veneer of alluvium which extends across a gently north-sloping terrace (between the landslide headwall and the Catamount trail) and marks the top of the section. An old alluvium-filled stream channel cuts across the uppermost section of lacustrine sediments (Fig. 6).

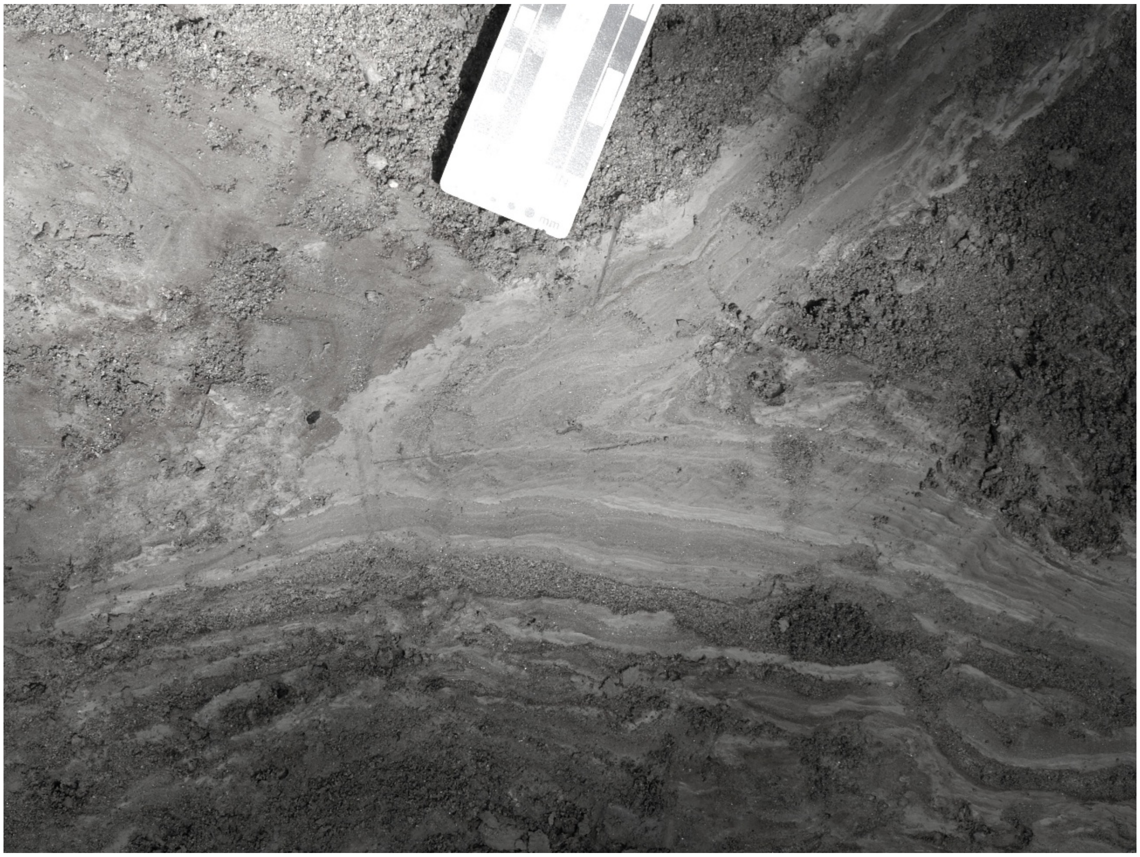

Figure 7: An exposure of folded and now overturned layer of laminated fine sand and silt that has been "pealed/delaminated" from the underlying beds. Irregular lenses and blebs of medium/fine sand, coarse sand, pebbles and cobbles occur to the left of the fold hinge in the space where the folded layer used to be.

Interpretation

The Preston Brook valley (Honey Hollow), similar to other valleys in the Winooski River basin, was partially flooded by Glacial Lakes Winooski, Mansfield, and Vermont (upper Coveville stage) as the ice sheet retreated NNW (down) the Winooski River valley (Fig. 4). The top of the landslide scarp is at an elevation of ~600 feet (~185 m) which is at or below the elevation of all these lakes (Fig. 6). It is unclear which of the lacustrine sediment units exposed in this section were deposited in which of these lakes or within a lake that may have preceded the formation of Glacial Lake Winooski. In the interpretation that follows, we have suggested a sequence of events that is consistent with the sediments exposed in this section and our understanding of the glacial history in the Winooski River valley, but other interpretations are also possible.

The fine-grained lacustrine sediments at the bottom of the section indicate that at the time these sediments were deposited, the ice sheet had retreated down the Winooski River valley west of the mouth of Preston Brook in order to flood the valley with lake water. We suggest that this lake formed in the Winooski River valley before the Middlesex Readvance that Larsen (1999) referred to as Glacial Lake Merwin. The tilted, faulted, folded, and over-consolidated nature of these sediments, in conjunction with the overlying diamict, suggest that they were overridden during a readvance of the ice sheet into the Preston Brook valley, the Middlesex Readvance. This readvance occurred during an approximately 100-year long cold period between 13,900 and 14,000 yr b2k and is coeval with the Littleton Readvance in northwestern New Hampshire (Ridge et al., 2012, Thompson, 1999). During this readvance the ice sheet reclaimed most of the Winooski River drainage basin as evidenced by sections of deformed sediments in many of the river’s tributary valleys (Larsen 1999, 2001; Larsen et al. 2003; Wright 1999, 2002, 2015).

Glacial Lake Winooski began to form at the end of the readvance when the ice once again began retreating WNW down the river valley. The coarse boulder/cobble gravels that overlie the lower diamict suggest they were deposited near the mouth of an esker tunnel as the ice sheet retreated across this area. The fining up sequence of fluvial sediments that overlie the coarse gravels were most likely deposited in a subaqueous fan that became progressively finer grained as the ice sheet retreated west of the Preston Brook valley. Continued retreat of the ice established a quiet-water arm of Glacial Lake Winooski in the valley when the varved silt/clay sediments in the middle section were deposited. However, by the time the ice retreated far enough down the Winooski River valley to expose the Preston Brook valley only 2 km of additional ice retreat allowed Glacial Lake Winooski to catastrophically drain through the Huntington River and Hollow Brook valleys across two different thresholds to form Glacial Lake Mansfield (Fig. 4). Elsewhere in the Winooski River valley this initial lake elevation drop of ~80 m is stratigraphically instantaneous and clearly recorded by an abrupt increase in grain size (Larsen et al., 2003). Very little of the middle part of the section is exposed, but we suspect that these fine grained, ice-distal, lacustrine sediments were deposited in both Glacial Lakes Winooski and Mansfield and, if better exposed, would show the transition between the two lakes.

The large folded layers of silt/clay visible in the exposed part of the Middle Section may have formed by slumping or they may have formed from shear stresses imparted when the upper diamict was emplaced. One interpretation is that the diamict formed from a debris flow (consisting of remobilized till mixed with lacustrine sediments) originating on the steep valley side that flowed into the lake-flooded valley. After entering the lake the debris flow triggered further slumping/deformation in the already-deposited sediments now exposed in the lower and middle parts of the section (Fig. 7). This slumping may have been triggered by the catastrophic drainage event associated with the transition from Glacial Lake Winooski to Glacial Lake Mansfield.

If the upper diamict is interpreted as a debris flow deposit, then the lacustrine sediments deposited on top of the diamict are most likely Glacial Lake Mansfield sediments as they were deposited in relatively quiet water and the elevation of Glacial Lake Vermont (Coveville Stage) in the valley is only slightly higher than the elevation of these sediments (i.e. when Glacial Lake Vermont occupied the valley this area would have been close to its shoreline).

Another interpretation is that the diamict is a readvance till and deformation in the underlying section was produced by movement of the overlying ice sheet. If this diamict was produced during the Middlesex Readvance, then all the underlying sediments are older than Glacial Lake Winooski and the thin section of lacustrine sediments lying above the diamict were deposited in Glacial Lake Winooski. It is also possible that this diamict records a more recent readvance of the ice sheet, although there isn't any indication in the ice core records of another cold period capable of producing a readvance during the waning stage of Glacial Lake Winooski (~13,700 yr b2k). Unlike the lower diamict, the upper diamict is overlain by sediments deposited in quiet water. If this upper diamict is a till deposited during a readvance, subglacial conduits did not funnel high-energy sediments in the valley as the ice was retreating.

The uppermost lacustrine sediments are cut by a large channel filled with a poorly sorted pebble/cobble/boulder gravel and are overlain by a thin layer of similar sediments interpreted to be historical Preston Brook alluvium. The abandoned stream terrace at the top of the section grades to the elevation of the Coveville stage of Glacial Lake Vermont (Fig. 6). This indicates that the valley was locally filled with at least 100 feet (30 m) of sediment when Preston Brook began incising its present channel when the elevation of Glacial Lake Vermont dropped from the Coveville to Fort Ann stage.

Distance				
Cumulative		**Point to Point**		
miles	**km**	**miles**	**km**	**Route Description**
6.1	9.8			Catamount Trail Parking Lot ("P" in Fig. 3).
8.3	13.4	2.2	3.5	Retrace route back west along the Duxbury Road and turn right (north) at Cochran Road recrossing both the Winooski River and the RR tracks.
8.4	13.5	0.1	0.2	Jonesville. Turn right on Rt 2 heading east along the north side of the Winooski River.
9.5	15.3	1.1	1.8	Turn left heading north on the Bolton Notch Road. Road pitches up very steeply as it ascends the face of the Bolton Notch Delta and the entrance to a large gravel pit excavated in that delta.
10.3	16.6	0.8	1.3	Bolton Notch Delta terrace on left. Park at pull-off on left (west) side of road. Pit is owned by Sue and Dave Beckman. Please request permission before visiting.

STOP 2: Bolton Notch Delta

Location Coordinates: 44.391° N, 72.910° W

The active gravel pit on the west side of the road is excavating deltaic sediments deposited by a north-flowing stream originating in Bolton Notch. This is a large delta and many of the foreset and topset beds are composed of very coarse gravels with some very large (m-scale) lag(?) boulders (Fig. 8). The size of the drainage basin is small which suggests that the high-energy stream that built the delta was fed directly by melting ice retreating up the notch and/or by drainage out a glacial lake that formed on the north side of the notch (Fig. 9). No deltas occur (or are not preserved) in other stream valleys farther east suggesting that the Bolton Notch delta formed quickly during a time span too short for significant non-glacial deltas to form in adjacent stream valleys.

Figure 8: Coarse topset beds at the Bolton Notch delta consist of poorly sorted boulder, cobble, pebble, and coarse sand gravels and indicate that a very high-energy stream fed this delta. Large boulder at top-left of photo exceeds 1 m in diameter. Similar large boulders also occur in the underlying forset beds and appear as strong hyperbolic reflectors in GPR profiles.

Well-developed foreset and topset beds are usually exposed in the pit. These are overlain by a thin (~2 m) sheet of medium to fine sand. Duck Brook has eroded a deep channel through this delta isolating an erosional remnant of this deltaic terrace on the west side of the brook. The elevation of the topset/foreset contact, measured using a Trimble GPS, is ~233 m (+/- 1 m). With ~4 m of isostatic uplift[1], this corresponds with the higher 229 m Gillette Pond outlet of Glacial Lake Mansfield (Larsen, 1987, Fig. 7).

The geometry of the ice margin at this time suggests that the Gillette Pond outlet was tenuous at best (Fig. 9).The medium to fine sand overlying the coarse topset beds of the delta was most likely deposited when the lake deepened for a short period of time, drowning the delta (i.e. the delta moved farther up the Bolton Notch valley and only fine-grained bottomset sediments here). A minor readvance of the ice sheet could easily have closed the Gillette Pond outlet allowing the lake elevation to rise for a limited period of time (Fig. 9). Similarly, a relatively small 1–2 km retreat of the ice margin uncovered a lower elevation outlet (Hollow Brook) which allowed the lake elevation to drop ~25 m.

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[1] Based on an almost due north uplift slope of 0.7 m/km (Rayburn, 2004)

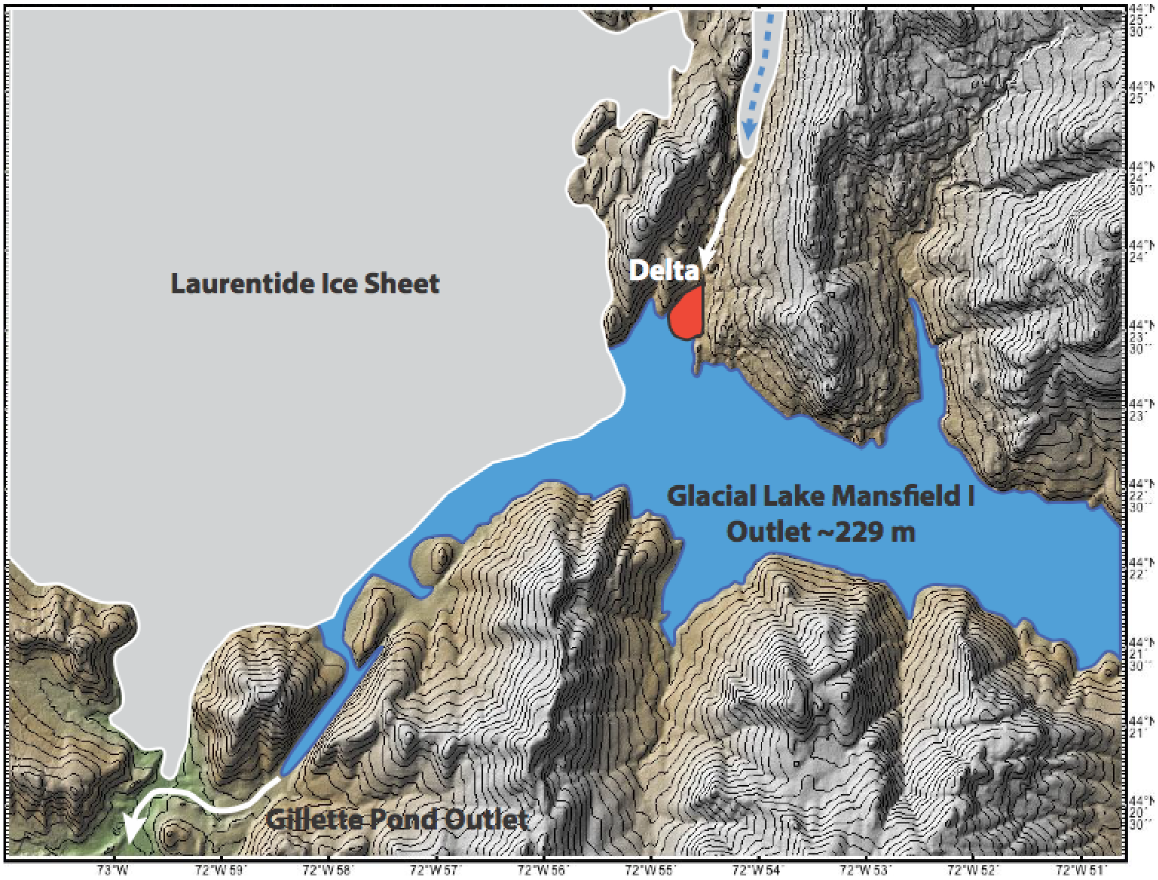

Figure 9: Map depicts the position of the ice sheet when it dammed Glacial Lake Mansfield in the Winooski River valley during the time when the lake utilized the Gillette Pond outlet. The delta at the south end of the Bolton Notch valley (Stop 2) was rapidly built from coarse sediments transported by a high-energy stream emanating from a tongue of the ice sheet in the notch.

Distance				
Cumulative		Point to Point		
miles	km	miles	km	Route Description
10.3	16.6			Stop 2: Bolton Notch Delta. Continue driving north on the Bolton Notch Road.
12.3	19.8	2.0	3.2	Long Trail crosses road. Note: During the summer of 2015 the Long Trail will be rerouted east of here on Stimson Mountain and the trail that crosses here will become an access trail to the Long Trail.
13.4	21.6	1.1	1.8	Continue driving north on the Bolton Notch Road until the road crosses from the east to the west side of the valley. Park on the right side of road just before the gate to an abandoned gravel pit.

STOP 3: Bolton Notch

Location Coordinates: 44.433 N, 72.896 W

Bolton Notch is a north-south U-shaped valley bounded by near vertical bedrock cliffs on either side of a valley floor filled with an unknown thickness of talus, lacustrine, and fluvial sediments. A poorly drained part of the valley floor marks the drainage divide at an elevation of 1180–1200 ft (~365 m) asl (Fig. 10). The objective of this stop is to observe and offer interpretations of (1) a series of terraces and channels that likely formed during ice retreat, (2) a group of kettles occurring immediately south of the gravel pit, and (3) ice-contact and lacustrine sediments exposed in the gravel pit. All of these features occur at or immediately north of the drainage divide. A detailed map of many of the small-scale landforms occurring near the drainage divide of the notch was made at an original scale of 1:4,000 using a hand-held GPS device (Fig. 11).

Striation Data

Striation measurements in the area surrounding the notch indicate a very consistent NW to SE direction of ice flow (Figs. 3, 10). Few measurements have been made on the steep valley sides; however some striations on the lower slopes show deflection to a NNW to SSE direction suggesting that ice flow rotated parallel to the valley as the ice sheet thinned, although the length of time the ice flowed in this direction was probably relatively short. Therefore, despite the distinctive "U" shape of the valley, this form may be more strongly linked to differential weathering and erosion of a relatively weak lithology underlying the valley rather than erosion by moving ice.

Terraces

A nested group of terraces occur along the eastern side of Bolton Notch, near the drainage divide. They are all aligned NE–SW, oblique to the N–S orientation of the valley, and all slope gently to the southwest (Fig. 11). The southernmost terraces are the highest and they progressively step down to lower elevations farther north. The lower-elevation terraces cross-cut adjacent higher-elevation terraces. The elevation difference between adjacent terraces typically ranges between 2–5 m. The most northerly of the terraces leads into a distinctive channel (now flooded) that occupies most of the area at the drainage divide. Farther south this pond drains and forms the modern stream channel that cross-cuts all of the higher terraces (Fig. 11). Most of these terraces are floored with till, but some also contain poorly rounded cobbles and boulders, particularly notable where these materials have been incorporated into stone walls.

These nested terraces are interpreted to be abandoned glacial meltwater channels that formed from water discharging from a tunnel beneath the glacier. This water flowed between the retreating ice front and the steep valley side or older, higher terraces. From south to north, these different terraces, at successively lower elevations, mark the position of the retreating glacier, perhaps at yearly intervals (Fig. 11). It was this glacial meltwater, flowing south through the notch and towards the Winooski River valley, that supplied most of the sediment that accumulated in the Bolton delta (see Stop 2).

Kettles

Several kettles occur in the bottom of the valley south of the gravel pit and two of the larger ones are shown on the detailed map (Fig. 11). Several of the abandoned meltwater channels abruptly drop into the pond suggesting that the pond too is a kettle or network of kettles and streams emanating from the glacier flowed directly across stagnant ice. The implication is that as the retreating ice thinned across the drainage divide, it thinned enough so it could no longer flow and became stagnant and disconnected from the thicker, still active ice front north of the divide.

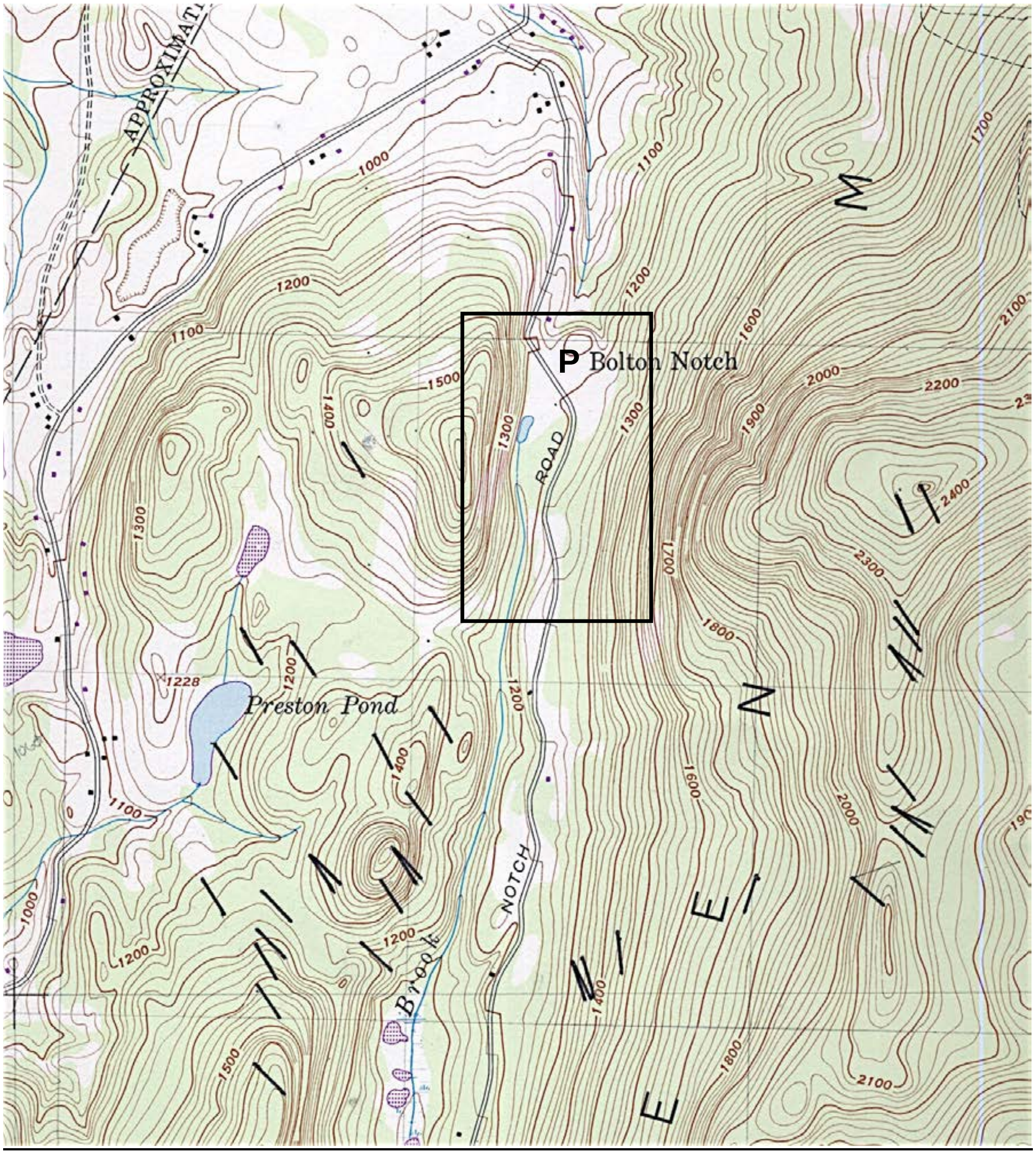

Figure 10: A topographic map of Bolton Notch and surrounding areas. Black lines represent the orientation of glacial striations. In all cases the measurement location is at the northwestern end of the line. “P” denotes the location of the abandoned gravel pit. Box outlines boundary of more detailed map (Fig. 11). Boxes are 1 km square and outline the NAD27 UTM grid. North is to the top of the page.

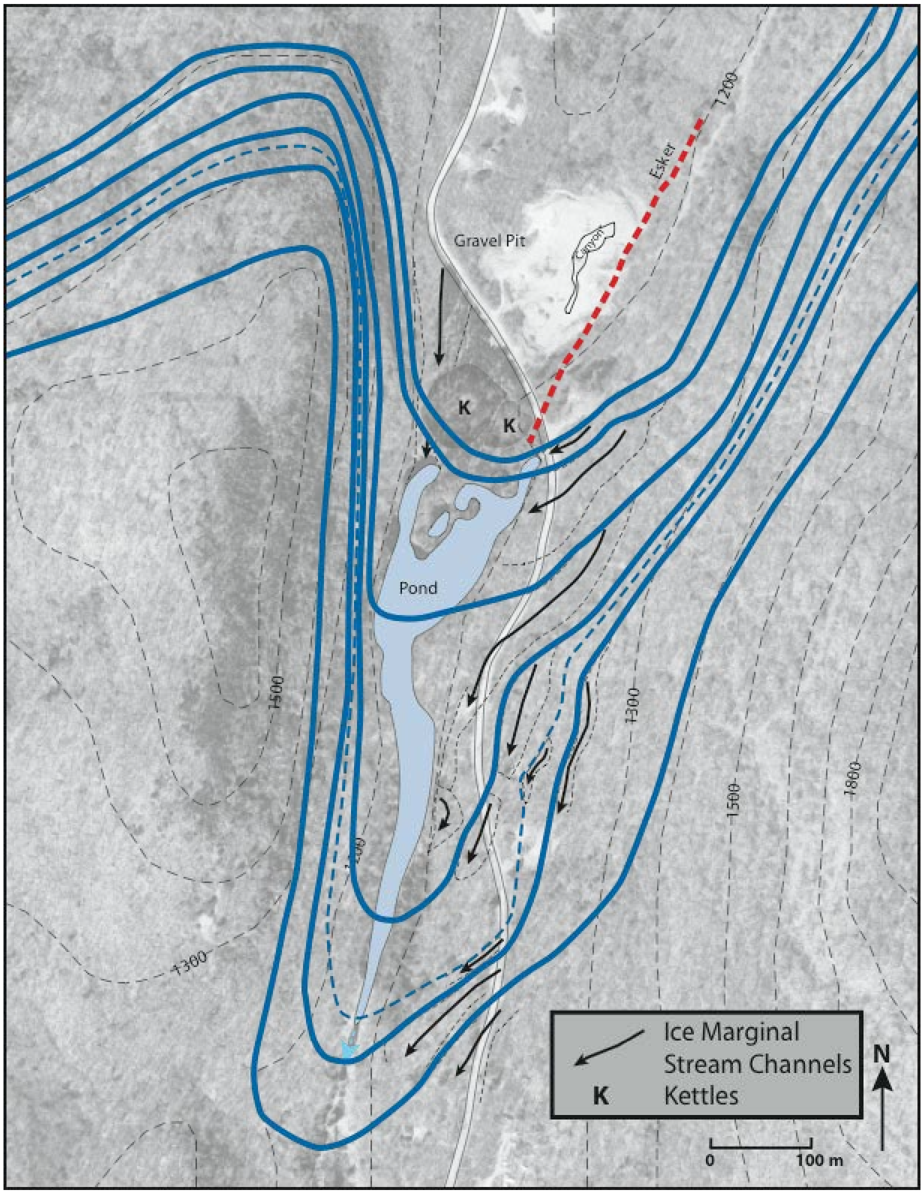

Figure 11: A detailed map of the northern end of the Bolton Notch valley. The pond marks the drainage divide. Arrows show the direction of stream flow along nested fluvial terraces. The highest (and oldest) terraces are to the south and east and progressively step down in elevation to the north and west. These are interpreted as meltwater stream terraces that formed adjacent to the retreating ice sheet as it progressively thinned and retreated to the north. Blue lines mark six different positions of the ice margin are shown and may mark annual retreat positions. Several kettles "K" occur north of the pond. Several of the channels abruptly drop into the pond suggesting that the pond too is a kettle or network of kettles and streams emanating from the glacier flowed directly across stagnant ice. A dashed line along the eastern side of the gravel pit shows the location of an esker. The esker is mantled by lacustrine sediments that accumulated in a small lake that formed when the ice sheet retreated north of the drainage divide. Contours are in feet. Vertical GPS control in this narrow valley was insufficiently precise to accurately contour this map.

Gravel Pit Geology

An old gravel pit lies along the north side of the road, at the northern end of Bolton Notch (Figs. 10, 11). The pit exposes sediments deposited in both an esker and a small glacial lake that formed as soon as the ice front retreated north of the drainage divide. The trace of the esker is shown on Figure 11. While many of the pit faces are slumped, an amazing vertical walled "canyon" has formed between two levels of the pit and offers excellent exposures of sedimentary structures (Fig. 12). Material eroded from this canyon has formed a large alluvial fan immediately below the northern end of the canyon.

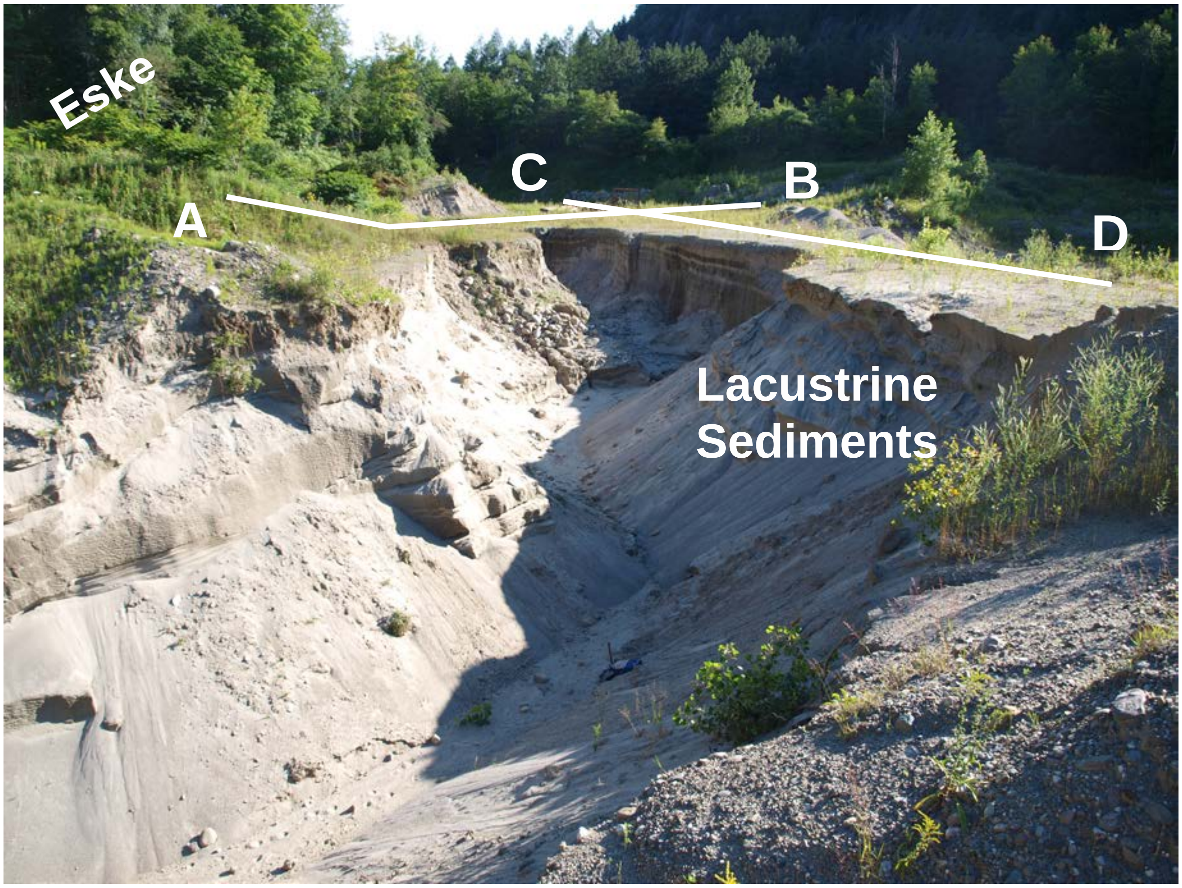

Figure 12: A view within abandoned sand/gravel pit looking south into the upper reach of a deep "canyon" eroded by ephemeral drainage into the bottom of the pit. An esker lies along the wooded left side of the photograph whereas the lacustrine sediments exposed in the canyon were deposited in a small lake whose outlet was a short distance south of the woods in top-center of the photo. White lines show the approximate location of the GPR survey transects shown in Figures 14 and 15.

Much of the esker has been quarried away, but many large rounded boulders occur on the floor of the pit at its southern end and very coarse sediment with additional boulders occurs along the pit's slumped face immediately below and northeast of the road. Many of the boulders deposited in the esker tunnel are high-grade metamorphic rocks (Grenville-age gneisses) that are distinctly erratic to northwestern Vermont and were transported here from the northern Adirondack Mountains or the Laurentian Mountains north of Montréal.

The bulk of the material currently exposed in the pit consists of medium to very fine sand and silt with occasional, relatively thin beds of coarse sand and pebble gravel. Dropstones are common. Cross-bedding and climbing ripples, frequently in beds >1 m in thickness, occur in many beds and all indicate that currents were dominantly flowing to the south, towards the notch. Structureless beds of medium to fine sand imply that these beds are slumped. Coherent blocks of bedded sediment have also slid off the steep side of the esker into deeper water (Fig. 13). There is a general fining-up pattern where the thickest beds of coarse sediment occur in the deepest parts of the pit and the finest interlayered fine sand/silt horizons occur at the uppermost part of the pit. Soft sediment deformation by slumping and/or differential loading is extensive in some beds.

Figure 13: View of faulted lacustrine sediments (fine sand) exposed in the middle of the “canyon.” A coherent block of sediment (bedding parallel to fault plane), slid from its original position higher on the flank of the esker into deeper water along the fault plane during an underwater landslide.

The fine lacustrine sediments exposed here indicate that a small glacial lake existed here once the ice sheet retreated north of the drainage divide (Figs. 10, 11). The lowest elevation channel, leading to and through the pond, marks the final outlet to this lake at an elevation of ~1,190 ft/363 m (Fig 11). This lake was likely small and short-lived as less than 1 km of further ice retreat to the northwest would have uncovered a much lower outlet to the Winooski River valley via the Indian Brook drainage (outlet elevation 920 ft/280 m).

A ground penetrating radar (GPR) survey shows that in the central part of the pit an esker is buried by a sequence of lacustrine sediments that outcrop in most of the pit (Fig. 14). Another GPR survey line emphasizes the continuity of these beds (Fig. 15). The 100 GHz antenna shows coherent reflectors to a “depth” of 300 ns (Fig. 14) whereas penetration with the 200 GHz antenna does not extend much below 150 ns (Fig. 15). However, the 200 GHz antenna shows sedimentary structures in much more detail.

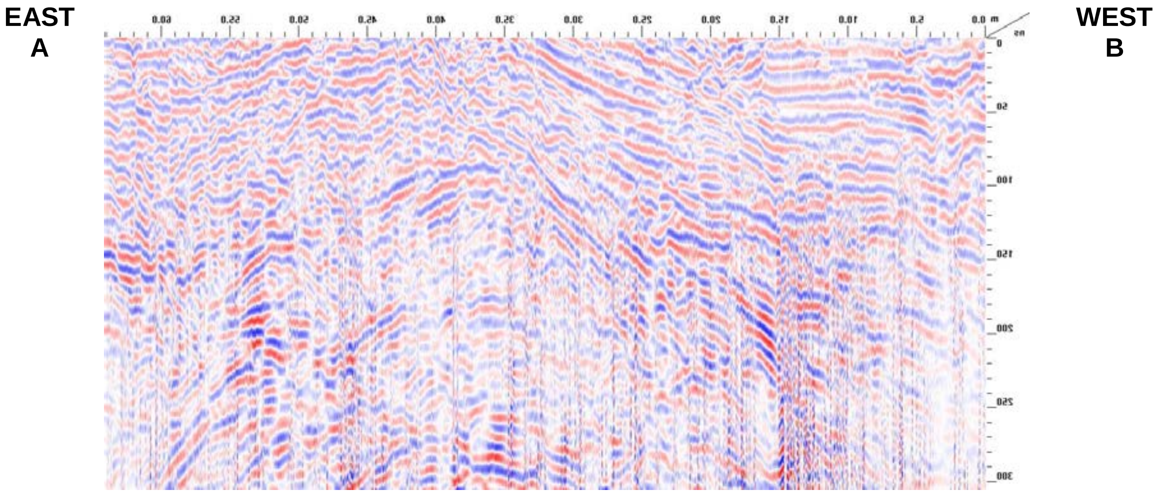

Figure 14: An East–West GPR profile across the floor of the Bolton Notch gravel pit showing the convex-up beds of an esker buried by on lapping lacustrine sediments that show an apparent dip to the west, steeply over the side of the esker and more gently in the basin to the west. 100 MHz antenna. Note that the profile was rotated about a vertical axis to correspond with the orientation of the photograph (Fig. 12) showing the location of the survey.

The large volumes of sand, frequently deposited as meter-thick beds of climbing ripples from south-flowing currents, implies that sediments in this glacial lake originated from a subglacial drainage system, i.e. meltwater and sediments discharging through a tunnel, which formed a subaqueous fan that fined upwards as the ice front receded to the north. Given the small size of the lake basin and the high sedimentation rates at the mouth of subglacial tunnel, the lake probably rapidly filled with sediment. At the northern end of the canyon a large (>15 m wide) channel filled with coarse sand and pebble/cobble gravel cuts across the finer lacustrine sand. This is interpreted to be a stream channel extending from the receding glacier to the drainage divide that was eroded through the recently deposited lacustrine sediment that largely filled the lake basin.

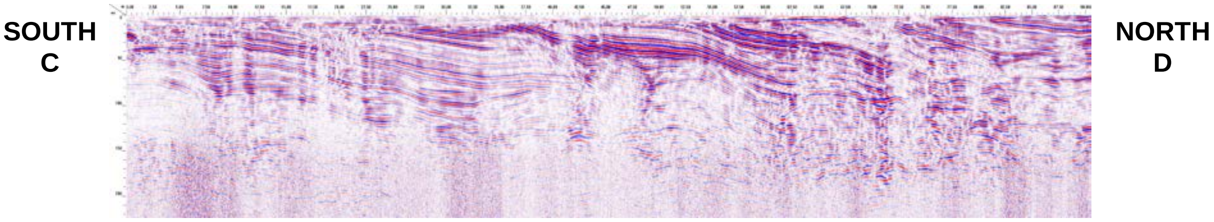

Figure 15: Gently north-dipping continuous beds of lacustrine sand (an apparent dip; real dips are to the NW) are well-imaged in this South–North GPR profile using a 200 MHz antenna (see Fig. 12 for location of survey line). Bedding is truncated by the floor of the pit. These beds were deposited on the western flank of an esker in a small ice-dammed lake when the ice margin was a short distance to the north.

Distance				
Cumulative		Point to Point		
miles	km	miles	km	Route Description
13.4	21.6			Stop 3: Bolton Notch
14.1	22.7	0.7	1.1	Continue driving north on the Bolton Notch Road until reaching a T-intersection with Stage Road. Turn right (north) on Stage Road passing along the boundary of the West Bolton Golf Course.
14.4	23.2	0.3	0.5	West Bolton. Turn left (west) at the 4-way intersection onto Nashville Road.
15.5	24.9	1.1	1.8	West Bolton Flats
18.3	29.5	2.8	4.5	Intersection with Browns Trace Road. Kame deposits with numerous kettles occur both south and west of the road intersection and were described by Wagner (1972) on an earlier NEIGC field trip. Note the many rounded cobbles and boulders in the stone walls. Turn right (north) and drive through the village of Jericho Center.
19.5	31.4	1.2	1.9	Jericho Village
19.9	32.0	0.4	0.6	Turn left (west) on Plains Road.
21.0	33.8	1.1	1.8	Follow Plains Road until its intersection with Schillhammer Road and carefully park along the side of the road so as to not block traffic. *This stop lies on private property and permission must be gained before trying to access the site.*

STOP 4: Lee River Delta (2 hours)

Location Coordinates: 44.485° N, 72.985 W

A large landslide has been recurrently active along an outside meander bend of the Lee River for at least the last 15 years revealing an almost 100 ft (30 m) high section (Fig. 16). From year to year exposures vary, but key parts of the section can be excavated where slumped. The section offers the opportunity to see the almost complete transition between relatively deep water lacustrine sediments upwards through a classic Gilbert-style delta which was deposited in the higher, Coveville stage, of Glacial Lake Vermont. This site lies on private property. Please contact the McLoughlin family (Plains Road, Jericho) for permission to visit the site.

The lowest part of the section is frequently slumped, but consists of rhythmically bedded silt and clay (varves) with occasional dropstones. Bedding is approximately horizontal. Farther up the section the summer silt layers frequently contain beds of medium to fine sand, some of which contain well-preserved asymmetric ripples. Ripples and cross-beds here and farther up the section consistently indicate current flow was to the northwest at the time these sediments were deposited, parallel to the modern course of the Lee River.

The proportion of sand in the section rapidly increases upsection. Winter clay layers are usually present and indicate that the annual accumulation of sand often exceeded 1 m/year. Asymmetric ripples, climbing ripples, and graded beds are common in these still horizontally bedded sediments (Fig. 17). Soft sediment deformation resulting from differential loading has produced folds and flame structures in some layers. Calcite-cemented concretions are also common. These are the bottomset beds of a delta encroaching from the east, fed by the Lee River.

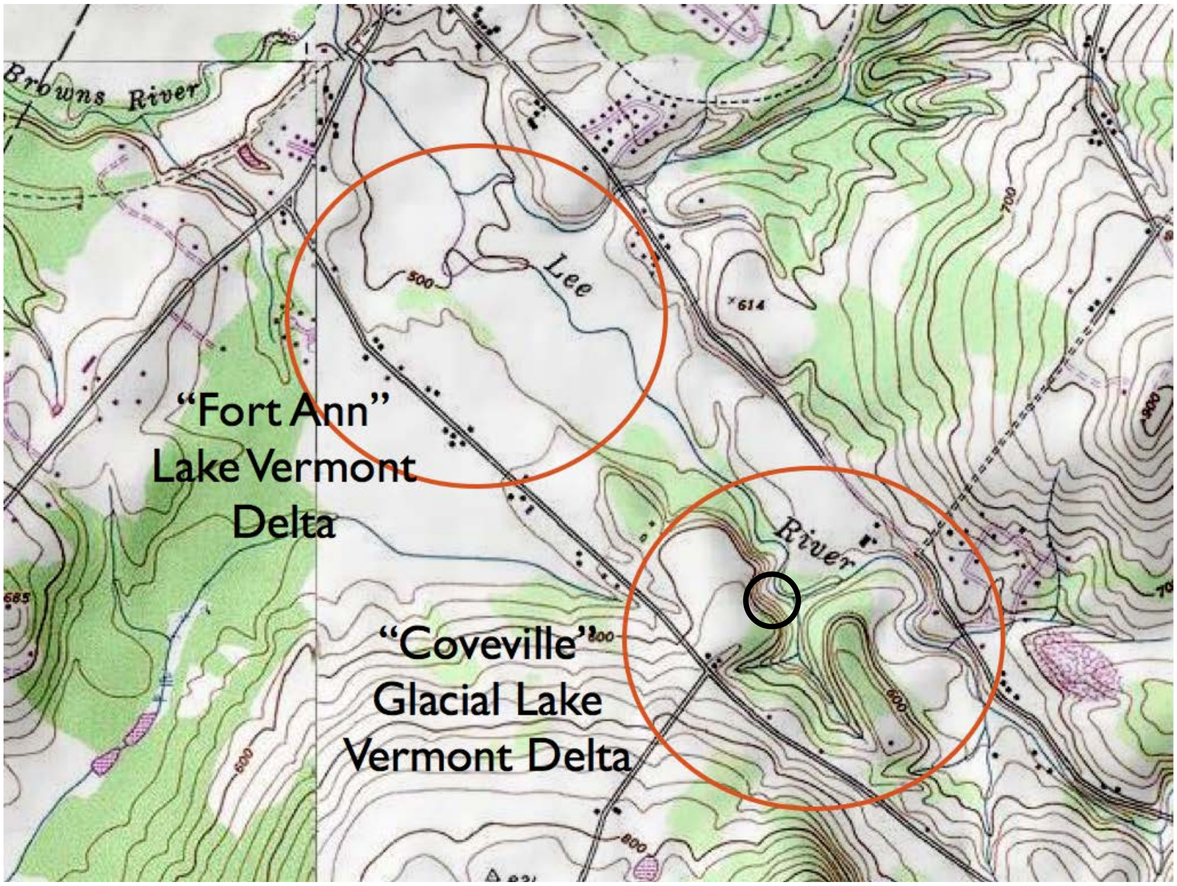

Figure 16: A topographic map of a portion of the Lee River valley. The location of the landslide (Stop 3) is shown with a small circle. Access to the site from the road is via the small stream. The upper Lee River delta marking the Coveville Stage of Glacial Lake Vermont and the lower Lee River delta marking the lower Fort Ann Stage of Glacial Lake Vermont are both circled.

Higher in the section the first beds containing coarse sand and pebble gravel appear bedding is inclined to the west northwest. The average grain size continues to increase in these foreset beds. The very top of the section consists of horizontal beds of coarse pebble/cobble gravel, the topset beds of the delta. Poor exposure usually makes it difficult to ascertain whether the transition between the foreset and topset beds is smooth or truncated. The topset/foreset contact lies ~2 m below the terrace at the top of the landslide. The elevation of that terrace has not been surveyed, but lies between 620–640 ft (189–195 m) asl based on the topographic map and pins the elevation of the Coveville Stage of Glacial Lake Vermont in this part of Vermont (Fig. 18).

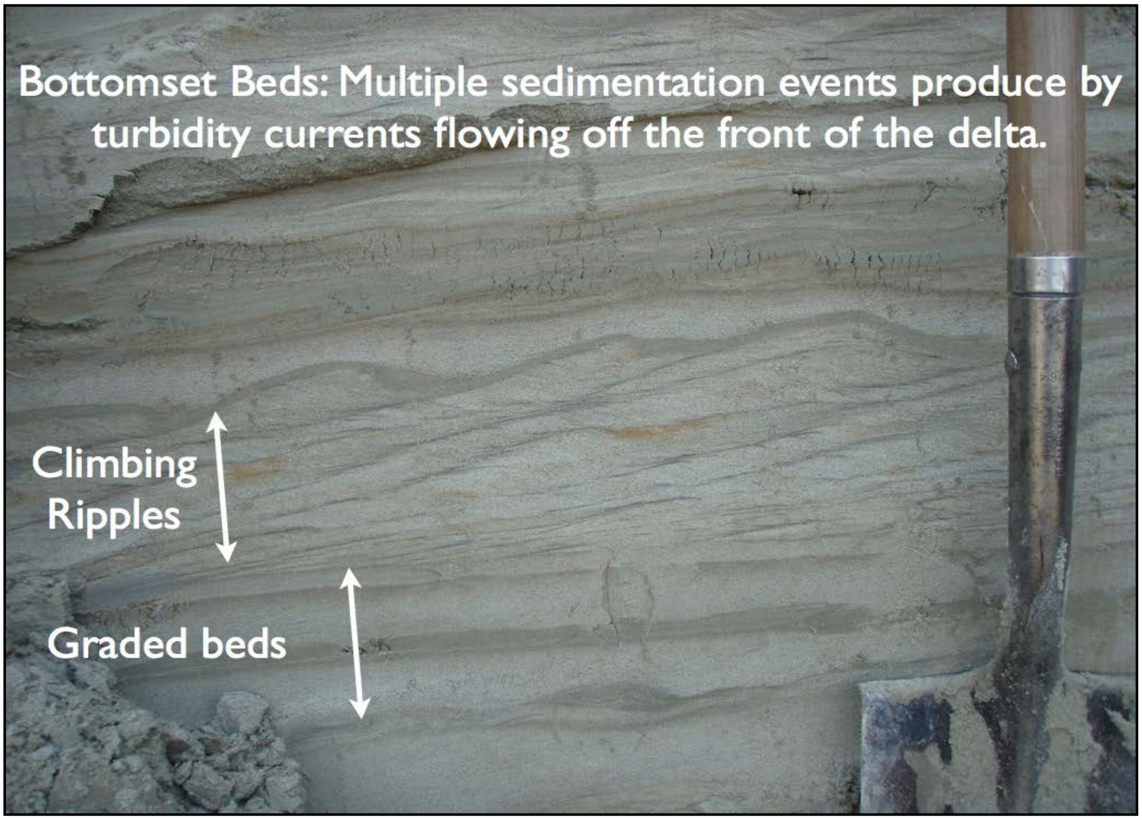

Figure 17: Bottomset beds of the Lee River delta exposed approximately midway up the section. Horizontal beds of graded sand and silt are overlain by climbing ripples capped by silt. Current flow was from left to right, from ESE to WNW

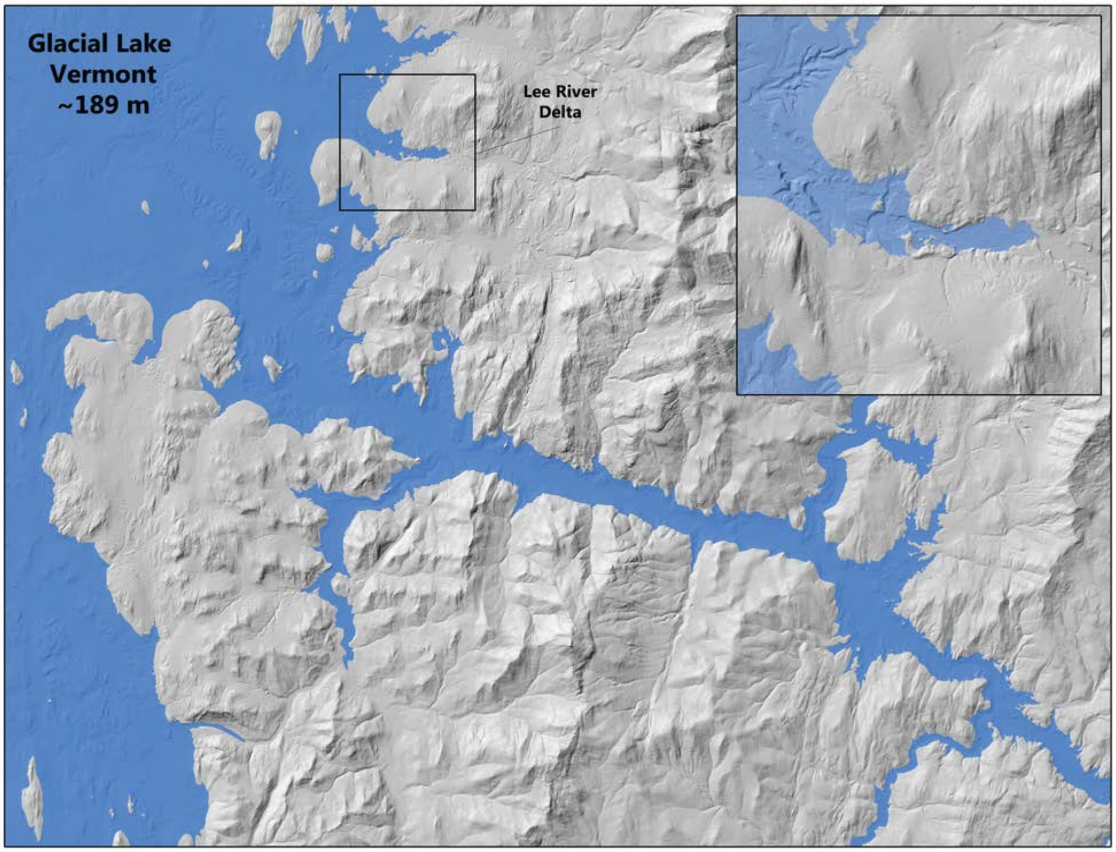

Figure 18: A shaded relief map of the lower Winooski River valley and adjacent Champlain valley shown flooded to the elevation of the Lee River delta (see detailed inset map), the Coveville Stage of Glacial Lake Vermont.

Distance				
Cumulative		Point to Point		
miles	km	miles	km	Route Description
21.0	33.8			Stop 4: Lee River Delta
22.1	35.6	1.1	1.8	Reverse direction and return east on Plains Road until its intersection with Browns Trace Road. Turn right (south) and follow Browns Trace Road to Richmond Village.
24.4	39.3	2.3	3.7	Mill Brook crosses road.
27.7	44.6	3.3	5.3	Intersection with Route 2 in Richmond Village (stoplight). Turn right (west) to return to the Interstate or continue straight through this intersection to return to the town park/bakery parking lot.
28.0	45.1	0.3	0.5	Town Park/Bakery parking lot. End of trip.

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