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Surficial Geology of the Jeffersonville 7.5-minute Quadrangle, Northern Vermont[1]

Final Report

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View of the Lamoille River valley looking north from Sterling Ridge. Village of Jeffersonville is several km down-valley (SW, to the left) and the village of Waterville is just beyond the field

[1] Vermont Geological Survey Contract No: 0963581

of view, to the right. The Lamoille River meanders extensively across a broad floodplain that covers a thick section of glaciofluvial and glaciolacustrine sediments.

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Executive Summary

The surficial geology of the Jeffersonville 7.5-minute Quadrangle was mapped during both the 2000 and 2001 field seasons with help from 3 student field assistants funded by the American Association of State Geologists. Contacts between eleven different surficial geologic units were mapped using traditional geologic mapping techniques in conjunction with portable GPS meters. Bedrock outcrops have also been located within and adjacent to the mapped surficial materials and glacial striations measured where visible. Cross-sections and an isopach map of surficial materials have been constructed using water well logs and surface observations. These logs indicate that the bedrock valley of the Lamoille valley is deeply buried beneath ice-contact gravels, lacustrine sand, silt, and clay, and modern alluvial sediments between the bedrock dam in Fairfax and Ithiel Falls in Johnson. An esker system (esker ridge and associated subaqueous fan deposits) exposed in the village of Johnson continues west along the Lamoille valley, but is deeply buried. Water well logs limited surface exposures have allowed us to partially trace this esker and to document its utility as a high-yield, although hard-water-bearing, confined aquifer.

Detailed mapping within the Jeffersonville Quadrangle and surrounding areas reveals the following preglacial and glacial history. In the upper Brewster River valley we interpret a highly weathered, red-orange saprolitic diamict to be a pre-Wisconsinan till (?) weathered during at least the last interglacial period. This is overlain by a dense, unweathered gray till deposited during the late Wisconsinan by the Laurentide ice sheet. Striation measurements throughout the quadrangle indicate that regional ice-movement was from NW to SE, across the generally north-south axis of the Green Mountains. At low elevations, within both the Lamoille River and Black Creek valleys, striations indicate that the thinning ice was topographically controlled, i.e. ice flowed parallel to these valleys. As the ice sheet retreated down the Lamoille and Brewster river valleys it dammed these rivers forming a series of glacial lakes. Two observations indicate that after withdrawing from much, if not most of the quadrangle, the ice sheet readvanced up the river valleys: (1) In two sections exposed by small landslides a thin (< 2 m thick) layer of till overlies deformed lake clays. (2) The most common till observed is a sandy or clay-rich till containing abundant rounded pebbles and cobbles with few angular erratics.

Glacial lakes were dammed in both the Brewster and Lamoille River valleys during the final retreat of the ice sheet northward and westward, respectively. The earliest lake in the Lamoille valley, east of its junction with the North Branch, reached an elevation of at least 1130 ft (345 m). This lake is most likely Glacial Lake Winooski which extended north into the Lamoille River valley from its outlet south of Williamstown, and as far west as the confluence of the Lamoille and North Branch Rivers. High-elevation lacustrine sediments aren't found west of the confluence suggesting that the ice margin in the Lamoille River valley was at the confluence when the ice margin in the Winooski River valley retreated to Jonesville uncovering the Hollow Brook threshold. Younger and lower elevation lakes, originally documented by Connally (1968), [~800 ft (244 m); ~720 ft (220 m)] formed after the ice retreated west of Jeffersonville. A detailed measured section of silt/clay couplets grading into medium to fine sand/clay couplets along the Brewster River in Jeffersonville records the last 160 years of lake history recorded in the valley including a large intraformational slump that may play a key role in guiding groundwater flow at the site of the catastrophic 1999 landslides.

INTRODUCTION

This report is summarizes the surficial geology of the Jeffersonville 7.5-minute Quadrangle based on mapping completed during approximately 4 months of fieldwork in the summers of 2000 and 2001. This work was supported by the Vermont Geological Survey, Department of Environmental Conservation, and the U.S. Geological Survey, National Cooperative Mapping Program, under assistance Award No. 98HQAG2068. The author was assisted in the field by two University of Vermont undergraduate students during the summer of 2000 (Megan McGee and Andy Bosley) and one University of Vermont undergraduate student during the summer of 2001 (Matthew Guerino). All three students were supported by grants awarded from the American Association of State Geologists, part of the NSF-funded Research Experience for Undergraduates (REU) program. Fieldwork in the Quadrangle and adjacent areas completed by the author prior to the present project is also incorporated into this report.

The primary objective of this project was to make a highly detailed surficial geologic map and derivative cross-sections of the region. This work was at least partly motivated by the desire to better understand the geological and hydrogeological setting of the large landslide that occurred in Jeffersonville Village during the spring of 1999 and to identify other areas that might potentially be at risk from large catastrophic slides. The region is also key to understanding the dynamics and timing of deglaciation in the mountainous regions of northern Vermont. Additionally, the area's surficial geology has markedly affected historic settlement patterns and will continue to strongly influence land use in the future.

The following large Quadrangle-size sheets accompany this report and have been prepared as overlays to the topographic base map:

Sheet 1: Geologic Contacts
Sheet 2: Bedrock Outcrops
Sheet 3: Glacial Striations
Sheet 4: Landslides
Sheet 5: Glacial Landforms/Features
Sheet 6: Isopach Map of Surficial Materials
Sheet 7: Location of Cross-sections

Cross-sections of surficial materials are included in the text of this report.

LOCATION AND GEOLOGIC SETTING

The Jeffersonville Quadrangle is located in the Green Mountains in northern Vermont, immediately north of Vermont's highest peak, Mount Mansfield (Fig. 1). The eastern and western boundaries of the quadrangle are, respectively 72° 45' and 72° 52.5' West Longitude and the southern and northern boundaries are, respectively 44° 37.5' and 44° 45' North Latitude. The physiography of the quadrangle is one of moderate to steep relief where, with the exception of the Lamoille River, the mountain ranges and valleys are aligned approximately N–S, parallel to the structural grain of the bedrock. While the quadrangle boundaries skirt the region's highest peaks, the northern end of Sterling Ridge and Fletcher Mountain reach elevations of 2400 and 2150 ft asl, respectively, and many of the smaller mountain tops lie between 1500 and 2000 ft asl. The west-flowing Lamoille River drains the region dropping from approximately 450 to 430 ft asl from east to west and eventually flowing into Lake Champlain.

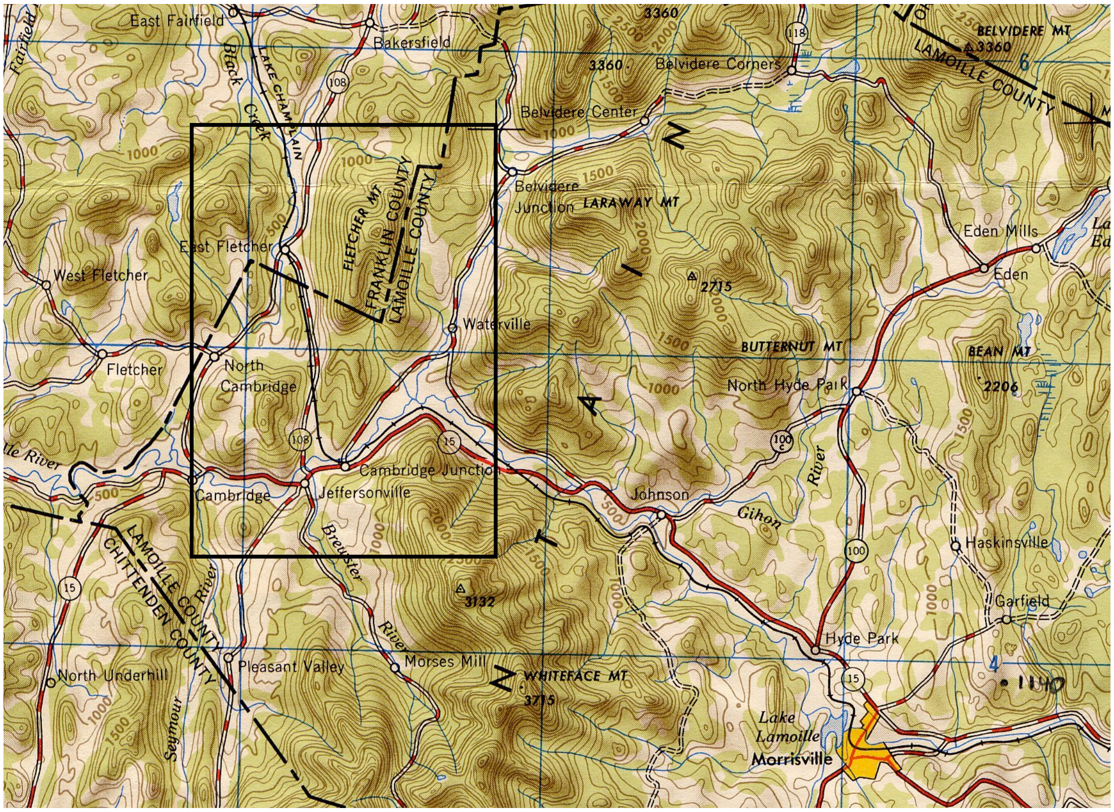

Figure 1: Shaded relief map of part of the Lamoille River valley and the Green Mountains showing the outline of the Jeffersonville Quadrangle. (Lake Champlain Sheet; original scale 1:250,000, 1950.)

The Lamoille River is the dominant physiographic feature of the quadrangle, occupying a broad valley that cuts from east to west across the mountains. Along this reach the river is graded to Fairfax Falls, 9 km west of the western boundary of the quadrangle. The river channel, as noted above, drops less than 20 ft across the quadrangle. As a consequence the channel meanders extensively oxbow lakes are common. The channel is everywhere set in surficial materials, either alluvium or glaciofluvial or glaciolacustrine sediments. The bedrock channel is buried beneath an unknown thickness of surficial materials, although seismic sections published by Stewart (1974) suggest that the bedrock channel might lie as much as 200 ft below the current flood plain. It is likely that an older and deeper channel lies north of Fairfax Falls, but is currently buried by glacial sediments. The very broad and agriculturally rich floodplain of the Lamoille River is a direct consequence of the Holocene channel placed over Fairfax Falls instead of through the deeper, buried channel.

The bedrock of the region consists of complexly faulted and folded slices of various metasedimentary and metavolcanic phyllites and schists deformed and metamorphosed during both the Taconic and Acadian orogenies. The dominant foliation and distribution of rock units strike approximately NNE–SSW and controls some of the large-scale drainage patterns. Christman (1959) mapped the Mount Mansfield 15' Quadrangle completing the first detailed bedrock map of the area (the Jeffersonville 7.5' Quadrangle is the NE corner of the Mount Mansfield 15' Quadrangle), work later incorporated into the Vermont State Bedrock Map (Doll et al., 1961). Small bodies of talc and serpentine also occur in the area, one of which has been mapped in detail by Chidester and others (1952). Much more detailed mapping has been completed by Thompson and others (1999) in the southeastern part of the quadrangle, Mock (1989) in the northwestern part of the quadrangle, and Doolan and others (1987) in the western and southwestern part of the quadrangle. These new maps reveal a much more complex assortment and geometry of thrust-bounded rock units that will not be reviewed here (see for example Fig. 4A in Thompson et al., 1999).

The broad distribution of surficial materials in the Jeffersonville Quadrangle is one where the mountainous areas above 1,100 ft are generally mantled by a thin, but variable thickness of glacial till. In contrast, most valleys are filled with a combination of ice-contact, lacustrine, and fluvial sediments although bedrock outcrops and till are also common.

PREVIOUS WORK

While comprehensive surficial mapping of the area comprising the Jeffersonville Quadrangle was not completed until the 1960's several early workers conducted studies focused on particular aspects of the area's surficial geology. In particular, Hitchcock (1861) published a map of the entire state depicting terraces, beaches, old river channels, potholes, moraines, eskers, striae, and extensive areas of "clay." He also included much more detailed maps of terraces along many of the state's major rivers, including the Lamoille where it passes the Jeffersonville Quadrangle. Merwin (1908) made one of the first attempts to work out the glacial lake history in northern Vermont and his observations in the Lamoille River valley were focused to that end. However, his publication also includes additional important observations that will be alluded to later.

Antevs (1928) published a comprehensive series of measured sections of varved lacustrine silt/clay that includes several sections within the Quadrangle. This work was an extension of his earlier work (Antevs, 1922), focused in the Connecticut River valley, that correlated sections of varved silt/clay based on distinctive patterns of thick and thin varves. While Antevs was never able to correlate the lake clays measured in the Jeffersonville area with those farther east, they nevertheless provide a valuable resource that can potentially be utilized in the future.

The Jeffersonville quadrangle is the NE corner of the Mount Mansfield 15-minute quadrangle. Christman (1959) mapped the bedrock geology of the Mount Mansfield Quadrangle, but also made important observations regarding the glacial history of the area and published a map showing his compilation of striation directions. The surficial geology of the Mount Mansfield Quadrangle was mapped by Connally (1966) and included as part of the Surficial Geologic Map of Vermont (Stewart and MacClintock, 1970). This was the only comprehensive surficial geologic mapping completed in the area prior to work reported here. While Connally's original field work was done on the same 7.5-minute base map as the current mapping, his need to cover the entire Mount Mansfield 15' Quadrangle in one field season prohibited detailed mapping. Nevertheless, Connally provided the first detailed descriptions of the surficial materials of the region and presented a geologic history based on the geometry of those materials. Connally summarized his interpretations of the glacial geology of the region in a field trip guide that emphasizes the glacial lake history of the region (Connally, 1972).

FIELD METHODS

Geologic contacts between different surficial units (see descriptions below) were mapped using traditional field techniques. Long soil probes and shovels were used to sample the surficial materials beneath the organic-rich and frequently disturbed and weathered soil horizon. Locations were plotted using UTM coordinates gleaned from hand-help GPS meters that were, in almost all places, accurate to within 30 (and usually less than 20) horizontal feet. The significantly improved accuracy over previous years resulted from the "unscrambled" signal now provided by the satellite network. Most streams were walked, but with the exception of the large landslide in Jeffersonville Village, few landslide exposures were found and these were all small.

Similarly, the area contains only one relatively small sand/gravel pit that is still being quarried. Older overgrown pits were visited, but no sedimentary structures were visible. Bedrock outcrops were mapped when they were encountered during traverses and glacial striations measured. Mapping efforts were concentrated below 1,100 feet elevation as that is the maximum height of glacial lakes in the region. Slopes higher than 1,100 feet were generally not mapped. While isolated subglacial deposits are possible at these higher elevations, past experience indicates that these slopes are usually mantled by a variable thickness of till.

The current owners of several large tracts (former farms) refused access. In these areas the contacts shown on the map are based on landforms or are taken from Connally's (1966) map.

MAPPING UNITS

Surficial materials in the Jeffersonville Quadrangle were mapped using units based on the texture of these materials: grain size and sorting. The texture of the surficial materials, in addition to bedforms and landforms provide the basis for interpreting the environment that existed at the time of deposition. For example coarse sand/pebble/cobble gravel deposits are interpreted on the map as having been deposited in one of the following environments 1) Ice-contact environment, 2) Delta, or 3) River alluvium.

Figure 2 is a generalized columnar section of surficial materials occurring in the Quadrangle showing their general age relationships. Detailed descriptions of the different mapping units follow.

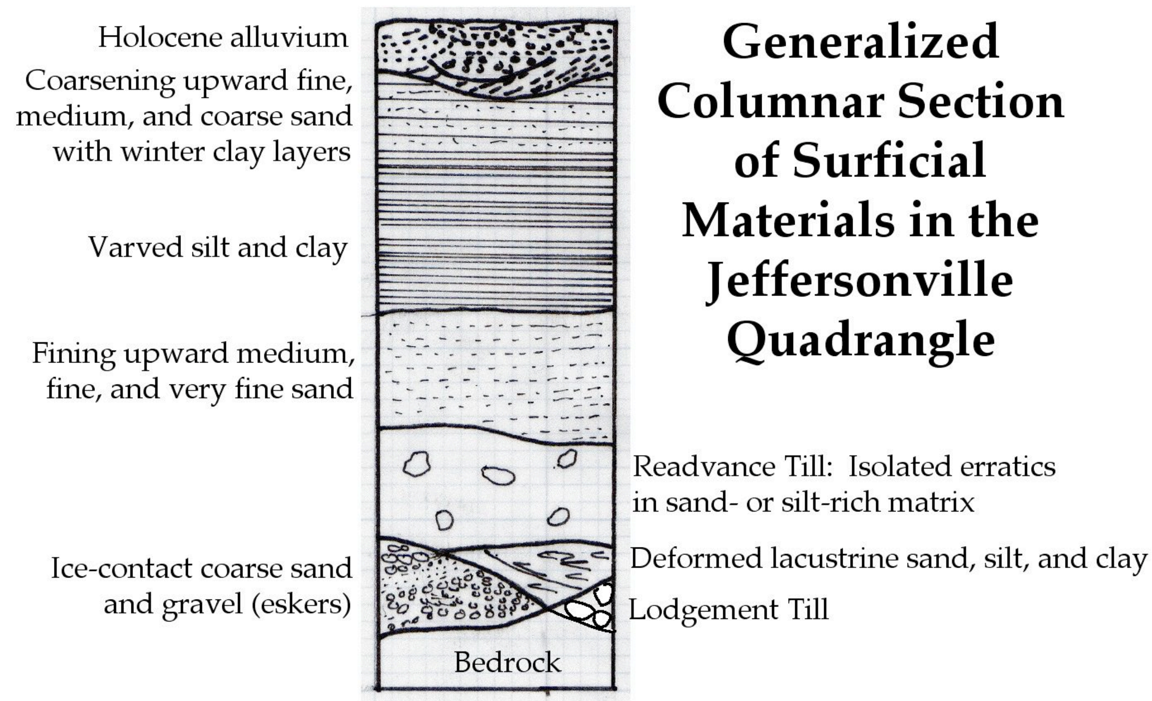

Figure 2: Generalized columnar section of surficial materials in the Jeffersonville Quadrangle.

Bedrock outcrops: Bedrock outcrops have been mapped (Sheet 2) where they lie within a mapped surficial material (e.g. "fine sand"), adjacent to contacts, or in areas that were extensively scrutinized for glacial striations (Fig. 3). Outcrops were generally not located in areas above 1,100 ft, the highest elevation of glacial lakes in the region. Bedrock lithologies and structure were not recorded as part of this study.

Figure 3: North-south trending ridge of bedrock outcrops with well-preserved grooves at the Mudgett Farm, North Cambridge. All of the surrounding pastures and meadows are underlain by lacustrine silt and clay. Till cover mantling outcrops is very thin. View is to the north.

Glacial till: Despite the occurrence of an old, pre-Wisconsinan saprolitic till in the headwaters of the Brewster River (located in the adjacent Mount Mansfield 7.5-minute quadrangle) none of this old till was discovered in the process of mapping (Wright et al., 2001). Till mapped in the Quadrangle is relatively unweathered and was most likely deposited during the late Wisconsinan by the Laurentide ice sheet. The typical basal or lodgment till in the area is grey, dense, clay-rich, and contains abundant local erratics that are frequently faceted and striated. Far-traveled erratics include Grenville gneisses from the Laurentian Mountains of Québec, basalts from the St. Lawrence River valley, also in Québec, and sedimentary rocks from the northern Champlain valley and adjacent St. Lawrence valley. Erratics are commonly quite large, > 1 m diameter. The abundant clay matrix is derived from the comminution of white mica and chlorite mica that constitute significant proportions of the underlying bedrock as well as bedrock lying to the NNW.

A second till was widely observed throughout the quadrangle, and while noted, was not mapped separately from the lodgment till. This till is less dense and most commonly light brown in color, a consequence of the high proportion of sand in its matrix, although it can also have a high proportion of silt/clay in the matrix. While not quantified in the field, erratics seemed less common and small; large > 1 m diameter erratics never occur in this till. This till has been generally interpreted to be an ablation till by Stewart (1961) and Connally (1966), but several good exposures indicate that this sandy till was produced by a readvance of the Laurentide ice sheet over previously deposited lacustrine and ice-contact deposits and is more appropriately referred to as a readvance till. One of these locations, a newly constructed log landing along the Hogback Road ~100 m south of its intersection with Route 109, reveals highly deformed lake sediments (the sandy till) overlain by undeformed lacustrine fine sand and clay. The field relationships suggest that lacustrine sediments were deposited as the ice retreated to the west, down the valley. The ice sheet then readvanced over these lake sediments before beginning its final retreat down the valley. A second location, the Mayo section (Fig. 4), is a landslide on a small creek close to the western boundary of the map where deformed varves of silt/clay are overlain by a thin sandy till. A third exposure to the south of the quadrangle in the headwaters of the Brewster river, shows similar field relationships where a loose gravely till overlies highly deformed, exceptionally dense lake clay. On the basis of these exposures, this second till is hereafter referred to as a readvance till.

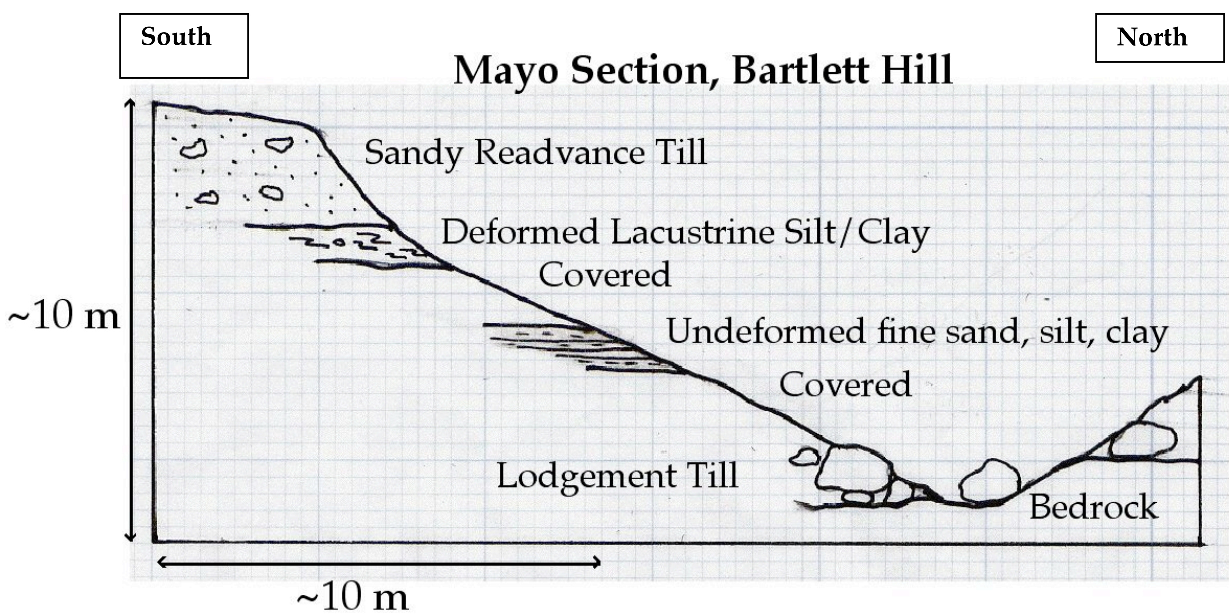

Figure 4: Mayo Section exposed in a small landslide along the western boundary of the Quadrangle (UTM coordinates: 668600/4946800). In this section a sand-rich till overlies

deformed lacustrine silt/clay sediments that were deposited over the bedrock and lodgment till. . Not visible in the cross-section is fine lacustrine sand deposited on top of the sandy till.

This sequence of surficial materials indicates that a glacial lake formed when the ice sheet first retreated from the area. Sediments in that lake were later overridden and deformed as the ice sheet advanced. The fine sand that blankets much of the surrounding area was deposited in glacial lakes that formed during the final ice retreat.

Ice-Contact Sediments: Ice-contact sediments, primarily gravel and coarse sand, are not commonly exposed at the surface within the Quadrangle, but frequently are noted in well logs, buried beneath thick sections of lacustrine sand, silt, and clay. Coarse sand and gravel deposited within ice-tunnels form eskers, whereas those deposited adjacent to the mouth of tunnels in the ice sheet create subaqueous fans. Subaqueous fans have not been recognized in the field, but thin gravel deposits at the bedrock/surficial materials interface have been noted in several well logs and may be parts of fans. The extent and thickness of the sublacustrine ice-contact gravels is shown figuratively on many of the cross-sections that accompany this report, but their distribution is too poorly constrained to show on a geological map. One small esker was mapped along the western boundary of the quadrangle along the stream draining Metcalf Pond which lies immediately west of the western boundary of the Quadrangle in the Gilson Mountain Quadrangle. A much larger esker used to exist near the drainage divide between the Lamoille River and the Missisquoi river where bedrock lies close to the surface (along Rt 108, ~3 km north of Jeffersonville village), but has been largely mined away. Well logs indicate that the esker continues both south and north from the gravel pits beneath thick sections of lacustrine sediments. Lacustrine sand exposed in a pit at the intersection of the railroad grade and Route 109 is extensively cut by high-angle faults indicating that the sand was deposited over a buried ice block presumably buried near the mouth of the esker tunnel.

Small isolated patches of gravel have also been mapped along the SE side of the Lamoille river valley NE of Jeffersonville village in areas that are otherwise underlain by till. Cross-bedding indicates water flow to the NE, up the valley. It is unclear whether these are thin subglacial deposits or “kames,” stream-deposited gravel deposited either adjacent to or on top of glacial ice.

Lacustrine Sediments and Deltas: As the Laurentide ice sheet retreated to the west, down the Lamoille river valley, it dammed the valley forming a series of lakes at different elevations as the retreating ice sheet uncovered different outlets. A thick and extensive blanket of fine to very fine lacustrine sand and varved silt and clay was deposited in both the Lamoille and its tributary valleys. While some of these sediments have eroded, especially from the steep slopes adjacent to the river valley, many areas still retain a significant cover of lacustrine sediment. The Lamoille river valley, in particular, contains a thick and almost complete section of lacustrine and underlying ice-contact deposits.

Lake sediments are derived from two very different sources. The first of these is sediment-laden water that flows into the lake from the portals of tunnels in the ice sheet. The water is derived from both melting ice and from precipitation falling on the ice sheet. The sediment is derived both from debris entrained within the melting ice and from till eroded at the base of and areas adjacent to esker tunnels. In general, aprons of coarse sand and gravel are deposited adjacent to the mouth of the ice tunnel (these are generally considered ice-contact sediments—see previous subsection), whereas the medium to fine and very fine sand emanating from an esker tunnel can travel some distance in suspension before being deposited. Bedforms visible in these deposits indicate very rapid sedimentation, In contrast, much of the silt and most of the clay pumped into the lake from the ice tunnel remains in suspension and can disperse throughout the entire lake. Much of the silt is deposited during the summer months, but the clay only settles on the lake floor during the winter when the lake is frozen and isolated from the wind.

The second source of sediment in glacial lakes is derived from erosion of recently deglaciated hillsides and transported to glacial lakes via streams. Extensive sections of sand in the quadrangle were deposited in this manner, often as turbidity currents off the front of deltas (bottom-set beds).

Extensive deposits of clay were mapped in the Quadrangle. While mapped as “clay” these deposits consist of rhythmically interbedded silt and clay (varves) that are clearly visible in good exposures. Stratigraphically the clay overlies both the ice-tunnel-derived fine sand and any coarse ice-contact deposits. It is, in turn, overlain by deltaic deposits or more recent alluvium.

The best section of exposed clay has historically been along the Brewster River at the site of the landslides during the spring and early summer of 1999.

Deltas of coarse sand and gravel have been mapped adjacent to many of the streams in the area. The elevations of these deltas record lake levels of ~800 ft and 720–760 ft. Other lower elevation alluvium terraces at approximately 640–660 ft may also be deltas. Good deltaic bedforms were only observed in one of these deltas in the northeast corner of the Quadrangle, which is the only delta that is currently being mined. Consequently, the identification of a deposit as a delta comes from its 1) landform, 2) coarse sediment, 3) location adjacent to a stream, and 4) incision of the stream through the deltaic landform. Other deltas have had pits in them in the past, but most are currently abandoned, slumped, and overgrown, but the extent of the pits provides an estimate of the thickness of the gravel

Alluvium: Alluvium consists sediment ranging from channel-deposited cobble gravels, point bar sands, and silt, fine sand, and organic matter deposited on flood plains. Alluvium in the Quadrangle occurs as a veneer comprising the floodplains adjacent to modern streams, but also on higher stream terraces. The thickness of the alluvium is proportional to the size of the stream that produced it. Old alluvial terraces in the Lamoille River valley are only 20–60 ft above the modern flood plain. However, adjacent to the Brewster River, several of these old river terraces occur ~140 ft above the modern flood plain and mark the position of the Brewster river shortly after the withdrawal of the lake from the Lamoille river valley. Alluvium along small streams was frequently of such small extent that it was not mapped.

Alluvial Fans: Several alluvial fans have been mapped. They generally occur where steep gradient streams intersect a river floodplain. Their steepness depends on the grain size of the source material: coarse-grained fans are relatively steep, whereas fine-grained fans are relatively gentle. By far the largest of these fans is one produced by the Brewster River where it flows onto the Lamoille river floodplain. The fan has "pushed" the channel of the Lamoille River up against the bedrock ledges that constitute the NW side of the valley. The village of Jeffersonville is built on this fan and currently the Brewster River has incised its channel along the eastern side of the fan. A stump, exposed by flooding along the channel of the Brewster river several years ago (> 2 m below the surface of the fan) attests to the aggradations that has occurred on the fan during the Holocene (Fig. 22). No excavations have been made in any of the fans in the quadrangle, however extensive excavations in fans elsewhere in northern Vermont indicate that they have aggraded episodically throughout the Holocene (Bierman et al., 1997).

STRIATION DATA: INTERPRETATION OF ICE-FLOW DIRECTIONS ACROSS THE QUADRANGLE

Glacial striations were usually observed on bedrock surfaces that had been stripped of their cover of surficial materials within the last 50 to 200 years, either by stream erosion or by humans. On weathered outcrops only deep grooves remain whereas freshly exposed outcrops often display many thin, shallow striations, sometimes occurring as multiple sets. Azimuthal measurements of several striations were made and the average of these measurements is shown on the map. These data are plotted on the Quadrangle map (Sheet 3) as lines emanating from a dot that indicates where the measurement was taken. Where more than one set of striations were observed, an attempt was made to ascertain their relative age and both are shown on the map. Only rarely was it possible to determine the absolute direction the ice was moving from the striations alone. However, erratics coming from outcrops only found to the northwest of the Quadrangle are reasonably common supporting the assertion that ice flow was generally from the NNW to the SSE. Striation data are also shown below as a graph plotting Azimuth vs. Elevation (Fig. 5).

Striations are generally oriented NNW–SSE across the Quadrangle reflecting the regional ice flow direction from NNW to SSE across the Green Mountains. This pattern is also clearly evident from the striations measured over the Mount Mansfield 15' Quadrangle by Christman (1959) whose map is reproduced as Figure 6. Striations measured at higher elevations were produced when the ice sheet was thicker and flowing more uniformly to the SSE (a direction parallel to the surface slope of the ice sheet) and are more tightly clustered than those at lower elevations (Fig. 5). Many of the low-elevation striations are parallel to the bedrock valleys they occur in and were formed when the ice sheet was thin enough to be guided by local topography. Where two sets of striations were preserved at low elevations in the Lamoille River valley, the older set is always the regional NNW–SSE set and the younger set is always parallel to the local orientation of the bedrock valley.

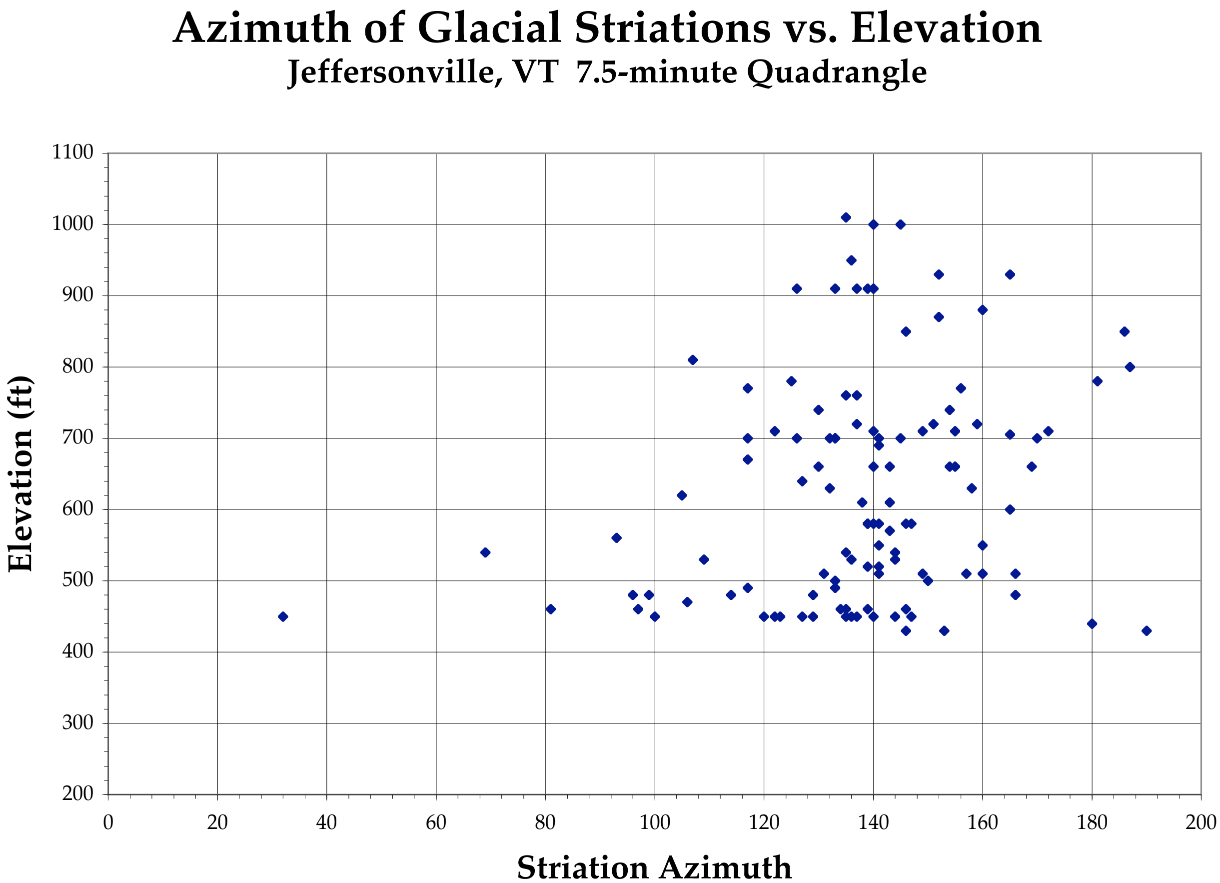

Figure 5: Graph shows distribution of down-glacier striation azimuths with elevation. Higher elevation striations reflect regional ice flow to the SE across the structural and topographic grain of the Green Mountains. Lower elevation striations are more commonly parallel to the bedrock valleys they occur in suggesting that the ice sheet was thin enough at the time they were produced to have its flow direction guided by these bedrock valleys. Note that the northeast and east-directed striations occur in the NE-SW and E-W portions of the Lamoille river valley.

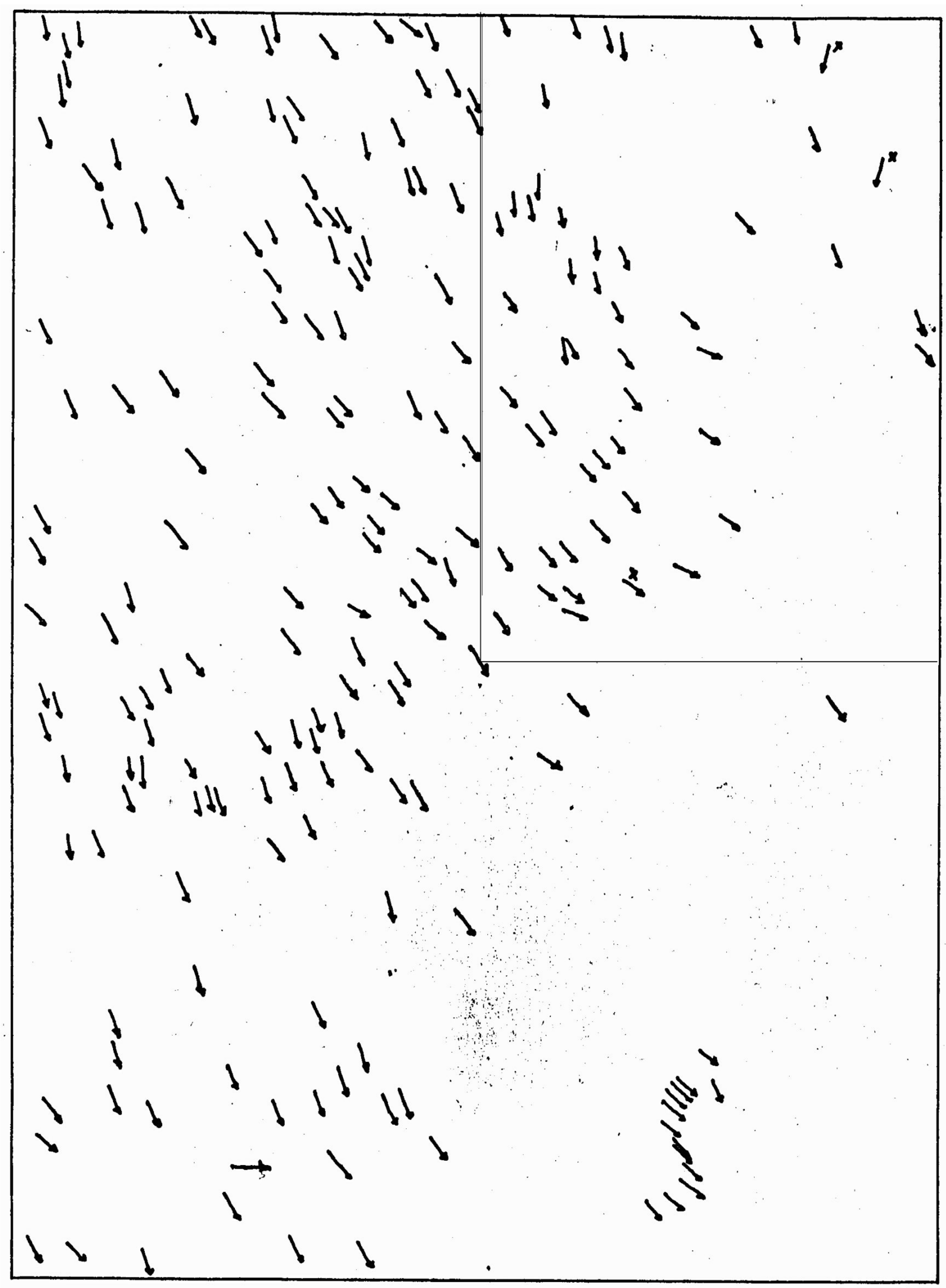

Figure 6: Map of the Mount Mansfield 15' Quadrangle showing the distribution of glacial striations measured by Christman (1959) with three additional measurements by Connally (1966) shown with 'X's' (map reproduced from Connally's 1966 report). The Jeffersonville 7.5-minute Quadrangle is outlined in the NE quarter. The dominant southeastward azimuth of striations clearly indicates regional ice flow from the northwest across the Green Mountains.

Roches moutonnée or stoss and lee structures indicating ice flow to the SSE or up-valley are common along the Lamoille river east of the Quadrangle, but none were observed within the Quadrangle.

INTERPRETIVE CROSS-SECTIONS

Seven cross-sections were constructed based on the surface geology, information gleaned from water well logs, the geometry of nearby landforms and contacts, and my current understanding of the stratigraphic relationships and glacial history of the region. The location of the cross-sections is shown on Sheet 7. Water wells located within the quadrangle are published on a separate map prepared by the Vermont Geological Survey. Many wells in the Quadrangle are not shown on the Survey map and those data were consequently not available when the cross-sections were drawn. Cross-section sites were chosen to depict critical aspects of the area's surficial geology where sufficient well data could be used to constrain the sections. All cross-sections were drawn at an original horizontal scale of 1:6,000 and an original vertical scale of 1:2,400, a 2.5X vertical exaggeration. The relatively low vertical exaggeration was chosen so as to minimize distortion yet still show sufficient detail. Individual cross-sections are reproduced and described below.

North Cambridge Cross-section 1 (A–A')

This cross-section extends across a narrow part of the Black River Valley where the valley is confined by bedrock ridges on both its west and east sides (Sheet 7, Fig. 7). Well 94, drilled in the middle of the valley, extends to a depth of 153 feet through lacustrine silt/clay, sand mixed with clay, sand, and ends in gravel. This is a typical fining upwards sequence beginning with esker gravels and ending with varved silt and clay that are exposed at the surface. The aquifer tapped by well 94 is confined; the water level in the well rising over 100 feet above the contact between the silt/clay and the first sand noted in the well log. The bedrock valley is very narrow and deep. Bedrock is exposed on both sides of the valley and extends up both sides. Till cover is very thin in this area and is not shown on the cross-section. A thin cover of lacustrine silt/clay mantles the western side of the cross-section. All of the sand and gravel deposited in the esker tunnel and adjacent to the mouth of the esker was confined to the deep parts of the Black River valley.

North Cambridge Cross-section 2 (B–B')

This cross-section is oriented almost East–West parallel to Pollander Road, the road connecting North Cambridge to Rt 108 (Sheet 7, Fig. 7). The bedrock topography is much more dramatic than the surface topography with thick sections of lacustrine sediments filling buried bedrock valleys adjacent to till-covered bedrock ridges. Many wells encountered ice-contact gravels before hitting bedrock. These deposits are all shown figuratively as esker mounds, but they could also have the

geometry of a subaqueous fan. The coarse ice-contact deposits are overlain by fine lacustrine sediments (fine to very fine sand and varved silt/clay). At the far western end of the cross-section this stratigraphy is observed in the field where a small pit along the side of a driveway exposes coarse sand and gravel beneath a cover of fine sand. In most places the fine lacustrine sediments continue to the surface.

Jeffersonville Cross-section (C–C')

The Jeffersonville cross-section is oriented approximately East-West and extends from the steep rocky knob along the west side of the Lamoille River, across both the Lamoille and Brewster rivers and their associated alluvium, across a steep, narrow hill that was the site of the 1999 Jeffersonville landslides, and then up the till-covered slope to the east (Sheet 7, Fig. 8A). The bedrock surface shown in the cross-section is constrained by the thin till cover on the east side of the section (till is not shown on the cross-section), bedrock exposed along the west side of the Lamoille river, the bedrock contact logged in one well, and a second well that extends only into ice-contact gravels that are assumed to lie within 10 m of the bedrock surface. The fining upward sequence (gravel to sand to varved silt and clay) recorded in this well is interpreted to be an esker system. The esker gravels are shown as a narrow ridge, but may in fact be much more widely distributed across the valley bottom. An extensive section of varved silt and clay extends across the valley and comprises more than half of the section that collapsed during the 1999 landslides. That section gradually coarsens upwards (see detailed description in section describing the Jeffersonville landslides) but here is shown as a single contact between the underlying silt/clay and the overlying sand. The top of this same hill is unconformably capped by alluvium.

The broad floodplain of the Lamoille and Brewster Rivers is also comprised of alluvium, mostly coarse materials, that unconformably overlie the lacustrine silt/clay. The village of Jeffersonville is built on a large alluvial fan deposited by the Brewster River as its gradient abruptly lessens where it meets the Lamoille River floodplain. The Brewster River channel is currently incised into the east side of the fan and has remained in that position for at least the last 125 years, (Beers Atlas map of Jeffersonville, 1877). A large rooted tree stump was exposed at river level by minor flooding in 1991. The stump was not dated, but nevertheless indicates that the fan has aggraded during the Holocene, similar to other alluvial fans in northern Vermont (Bierman, et al., 1997).

Brewster River Cross-section (D–D')

The Brewster River cross-section is an east-west section along the southern boundary of the Quadrangle (Sheet 7, Fig. 8B). Five well logs were used to constrain the depth to bedrock, although the position of this contact beneath the Brewster River and its adjacent floodplain is highly

conjectural. Two well logs note “rotten ledge” 20 feet above “firm ledge.” This is here interpreted to be weathered saprolitic bedrock similar to that observed farther upstream in the Mount Mansfield Quadrangle (Wright et al., 2001) and is shown as two lenses either side of the respective wells. A thick section of till is noted in several of the logs and is shown extending across the section to its intersection with the surface. Two well logs note “clay” sandwiched between till layers that is likely to be lacustrine silt and clay that was deformed during the ice sheet readvance. The varved silt/clay section lying above the till is well constrained only in the center of the section; its thickness to the east is impossible to determine from the easternmost well log. Medium to fine sand comprises the terraces on both sides of the Brewster River and is interpreted to be Brewster River alluvium. These 740–760’ terraces are interpreted to be part of a delta surface and the thickness of the alluvium adjacent to the current Brewster River channel is consequently shown to thicken, an interpretation consistent with the sands exposed on the sides of the channel cut, but unconfirmed by well data. The modern Brewster River channel is incised through the older deltaic alluvium and includes a well-developed floodplain to the east of the channel. Further down-cutting of the channel is currently prevented by the bedrock dam at the Brewster River falls ~200 m NW of the section.

Cambridge Village Cross-section (E–E’)

The Cambridge Village cross-section (Fig. 9) is oriented almost N–S across the Lamoille River valley immediately east of Cambridge Village, along the western boundary of the map (Sheet 7). The position of the bedrock contact in the section is best constrained by exposures along the north and south ends of the section and 3 well logs north of the river. Only one well lies in the river valley (the old Cambridge Village water supply well) and it bottoms in ice-contact gravel that is probably within 40–60 feet of the bedrock surface. The deepest part of the bedrock valley is unknown, but Stewart (1974) has published a seismic section taken approximately 2 km to the west that shows the bedrock contact lying only 70–80 ft bellow the floodplain at an elevation of between 350 and 400 ft. A thick section of till is shown in the well logs in the northern third of the section. This till may also include deformed lacustrine sediments observed in nearby exposures. Till thickness to the south is shown to thin based on the thin till cover noted adjacent to bedrock exposures there. As noted earlier, the Cambridge village well ends in gravel that is interpreted to be part of an esker system, here shown as a single ridge, but it may have a much more complicated geometry. The sand facies overlying the gravel is conjectural. Lacustrine silt/clay overlies both the till and ice-contact sand and gravel. On the northern end of the cross-section the section coarsens upwards to medium to fine sand. This sand has been stripped from the underlying clay at lower elevations. The floodplains of the Lamoille River and Seymour Brook are underlain by 15–20 feet of alluvium.

Cambridge Junction Cross-section (F–F')

The Cambridge Junction cross-section (Fig. 10) is oriented approximately N–S across the Lamoille River valley (Sheet 7). Six water well logs and the surficial geology are used to constrain the cross-section. The position of the bedrock valley is well-constrained by wells and thin till cover south from Cambridge Junction and two widely spaced wells north of the Lamoille River. However, the depth of the bedrock channel beneath the present river is unknown. A thick section of till is noted in two wells. If this till is accurately logged, it may include a readvance till in addition to the lodgement till, While no bedrock outcrops exist along the line of section southwards up Seeley Hill, the till section here is assumed to be thin because of its absence in the southernmost well log, the large boulders present in the surface till, and the many springs in this area. Till is not shown elsewhere on the section because it is not noted in any of the other sections and the inferred presence of esker sediments underlying the northern part of the channel. The esker system is inferred here based on the sand and gravel encountered near the bottom of the two well immediately north of the river and more direct evidence of esker sediments in well logs both up and down valley. A thick section of varved silt and clay underlies most of the cross-section. At the northern end of the section this grades up to fine sand, most likely derived from the encroaching Brewster River delta to the south. Elsewhere this sand has eroded away. Modern alluvium adjacent to the Lamoille River, and older Lamoille River alluvium occurs as thin sheets on terraces rising to elevations of approximately 490 ft, ~50 ft above the modern floodplain.

East Cambridge Cross-section (G–G')

The East Cambridge Cross-section (Fig. 11) extends SW–NE across the Lamoille River valley close to the eastern boundary of the quadrangle (Sheet 7). The section lies between 250 and 450 m SE of a seismic section published by Stewart (1974). Stewart's section includes three units here interpreted to be (1) alluvium), (2) lacustrine sediments—silt, clay, and very fine sand, and (3) bedrock. In the broad alluvial valley where no well data is available Stewart's seismic section was projected into the East Cambridge cross-section and used to ascertain the depth to bedrock. Four wells, the surficial map, and bedrock outcrops provide further control for the cross-section. A thin layer of till is shown lying between the bedrock and the lacustrine sediments based on surface exposures of till and the thickness of till shown in wells 162 and 195. Data are insufficient to distinguish the lodgment till and readvance till in this section. The cross-section depicts a very thick section of surficial material above the till. Most of this material is interpreted to be varved silt/clay and very fine sand based on the well logs and isolated exposures of varved silt/clay exposed along the banks of the river. Wells 109 and 110 both end in gravel that may be an esker or some of the coarse pebbly sand that commonly overlies the coarser esker facies. It's also possible that the wells ended in the sandy readvance till, a material with sufficient hydraulic conductivity to support a domestic well. The relatively low yields (5 and 6 gpm) support this interpretation. Isolated exposures of varved silt/clay exposed along the banks of the Lamoille River indicate that the alluvial cover is thin (<10 m thick). Alluvium also includes sections of unlayered flood diamict containing abundant woody debris and occasional pieces of sawn wood. This material is here interpreted to be materials deposited during the 1927 flood.

ISOPACH MAP

An isopach map of surficial materials (Sheet 6) was constructed based on 1) depth to bedrock recorded in water well logs, 2) depth of incision of streams, 3) relief of surficial landforms, and 4) mapped bedrock outcrops. In most areas these data are insufficient to closely constrain the location of contour lines. Therefore, the detailed patterns and placement of contour lines on the isopach map should be used with caution with focus placed on the broad patterns. Contours were drawn at 10, 30, and 50 m (~33, ~98, and ~164 ft) using solid lines in most cases, despite the poor constraints on location in most places.

The dominant feature depicted by the isopach map is the thick accumulation of surficial materials in the Lamoille River and Route 108 (Black River) valleys. The bedrock channel in these valleys is deeply buried beneath a thick section of glacial materials that have been described in detail in the previous section ("Description of the Cross-sections). A broad pattern apparent in the isopach map is that the bedrock channel of the Lamoille River valley apparently becomes shallower to the west. This is supported by the relatively shallow depth to bedrock (<100 ft; bedrock elevation ~350–400 ft asl) reported by Stewart (1974) in his seismic section taken 1.6 km west of Cambridge village at the western boundary of the Quadrangle. This is in marked contrast to Stewart's seismic section taken near the eastern boundary of the quadrangle (described earlier) which shows ~250 ft of surficial material filling the valley and the bedrock elevation at only 200–250 ft asl (Stewart, 1974). If this is true, it implies that either 1) the deep parts of the valley have been overdeepened by the flow of glacial ice through it or 2) that the paleo-drainage of the Lamoille River was locally to the east, perhaps exiting to the Winooski River valley through the Stowe valley.

In addition to the Lamoille and Black River valleys, there are two other areas underlain by a considerable thickness of surficial materials. One of these is the area adjacent to the Brewster River valley where well over 30 m of surficial material covers what may be the old bedrock channel of the Brewster River (Sheet 6). Currently the channel of the river is pinned by bedrock at the Brewster River falls. A much deeper bedrock channel lies not far to the north of the falls and east of the present channel. Much of the surficial material here consists of both till and coarse sand and gravel deposited in a delta formed where the Brewster River entered a glacial lake.

A second area with a thick accumulation of surficial materials occurs along the western boundary of the map, ~ 3 km north of the Lamoille River valley (Sheet 6). This area appears to be a buried bedrock valley that slopes southward to the buried bedrock channel of the Lamoille River, although its southern extent lies on the adjacent Gilson Mountain Quadrangle.

LANDSLIDES

Sheet 4 depicts landslides observed in the course of mapping. In general, landslides are not common in the Quadrangle and, with the exception of the Jeffersonville village landslide, all the slides shown are small, generally covering less than 250 m^2. All of the slides were produced by the failure of fine-grained glacial lake sediments (varved silt and clay) when saturated with water. All except one occurred on steep cuts above stream channels. The one exception is a small slide along the north side of Rt 15, immediately east of the eastern boundary of the map, where the slide was apparently triggered by discharge from a highway drainpipe. A detailed description of the geologic setting of the Jeffersonville landslide follows.

GEOLOGIC AND HYDROLOGIC SETTING OF THE 1999 JEFFERSONVILLE LANDSLIDES

The village of Jeffersonville was the site of three large landslides during the spring and early summer of 1999 all occurring on a steep bank directly above the Brewster River (Fig. 12). A detailed description of the dynamics of the 1999 slide is presented by Bierman and others (1999). The present discussion focuses on the geologic and hydrologic setting of the site, reviewing material originally presented in Bierman and others (1999) and presenting new observations resulting from the present mapping.

Numerous historical records indicate that the site has failed repeatedly during historic times. The landslide area is locally referred to as the “Jeffersonville clay bank,” presumably because of its frequent exposure during historic times. Old maps of the Jeffersonville area (e.g. Beers Atlas,

1877) indicate that the Brewster River has been flowing against the base of the landslide scarp for at least the past 125 years. Antevs (1928) measured two sections of varved silt/clay at the site in the 1920's indicating that landslides exposed a significant part of the section at that time. Other large landslides have occurred during historic times, the most recent during the 1950's (Bierman et al., 1999).

The Jeffersonville slides originated from a steep bank of horizontally bedded glacial and immediately post-glacial sediments occurring in a narrow, North-South oriented ridge that is currently being eroded on its west side by the Brewster River and on its east side by a small unnamed brook (Fig.12). The top of the ridge is a fluvial terrace built by the Brewster River shortly after the last glacial lake drained from the valley.

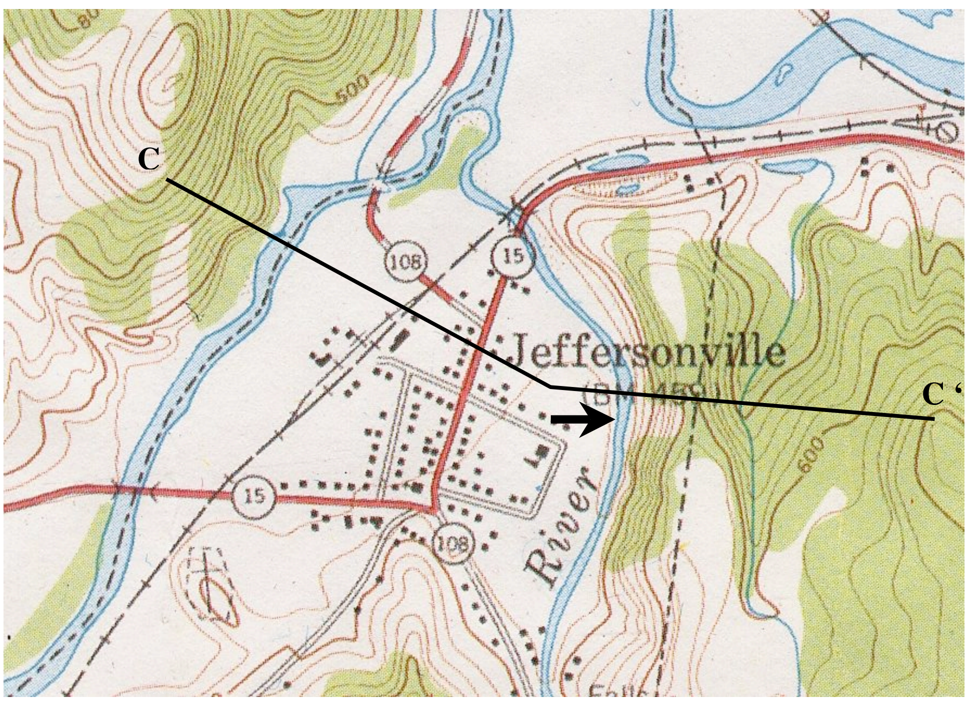

Figure 12: Topographic map of the Village of Jeffersonville taken from the Jeffersonville, Vermont 7.5-minute Quadrangle map (1948). The Village of Jeffersonville is built on a broad alluvial fan deposited on the Lamoille River floodplain by the Brewster River which enters from the south. Arrow points to site of 1999 landslides as well as site of exposed section measured during 1991 (Fig. 13). Narrow ridge is being eroded along its west side by the Brewster River and along its east side by an unnamed brook. Antevs' (1928) measured sections (his #169 and 170) lie a few 10's of meters to north of the arrow. Stump exposed during 1991 lies near head of arrow (Fig. ???). Location of cross-section C–C' is shown (Fig. 8). North is to top of figure. Map is 1.83 km (6,000 ft) across.

A detailed stratigraphic section was measured during the summer/fall of 1991 at the site of the 1999 landslides (Fig. 13). The measured section begins approximately 2 m above water level and extends to within 15 m of the top of the bank. An unknown thickness of surficial materials (most likely lacustrine silt/clay and till) lies below the exposed section. The entire measured section (29 m) consists of 143 couplets (rhythmites) consisting of varved silt/clay that become fine sand/clay couplets higher in the section. The couplets are interpreted to be yearly layers (Antevs, 1922; Ridge and Larsen, 1990), where the silt and coarser material was deposited during the summer when the lake surface was unfrozen and subject to wind-driven currents that were too strong for the clay-sized sediments to settle out of suspension. The clay layers were deposited during the winter months when the lake surface was frozen and isolated from the wind creating an environment still enough for clay to settle out of suspension. The low discharge of streams and frozen ground during the winter minimizes the amount of coarse sediment entering the lake.

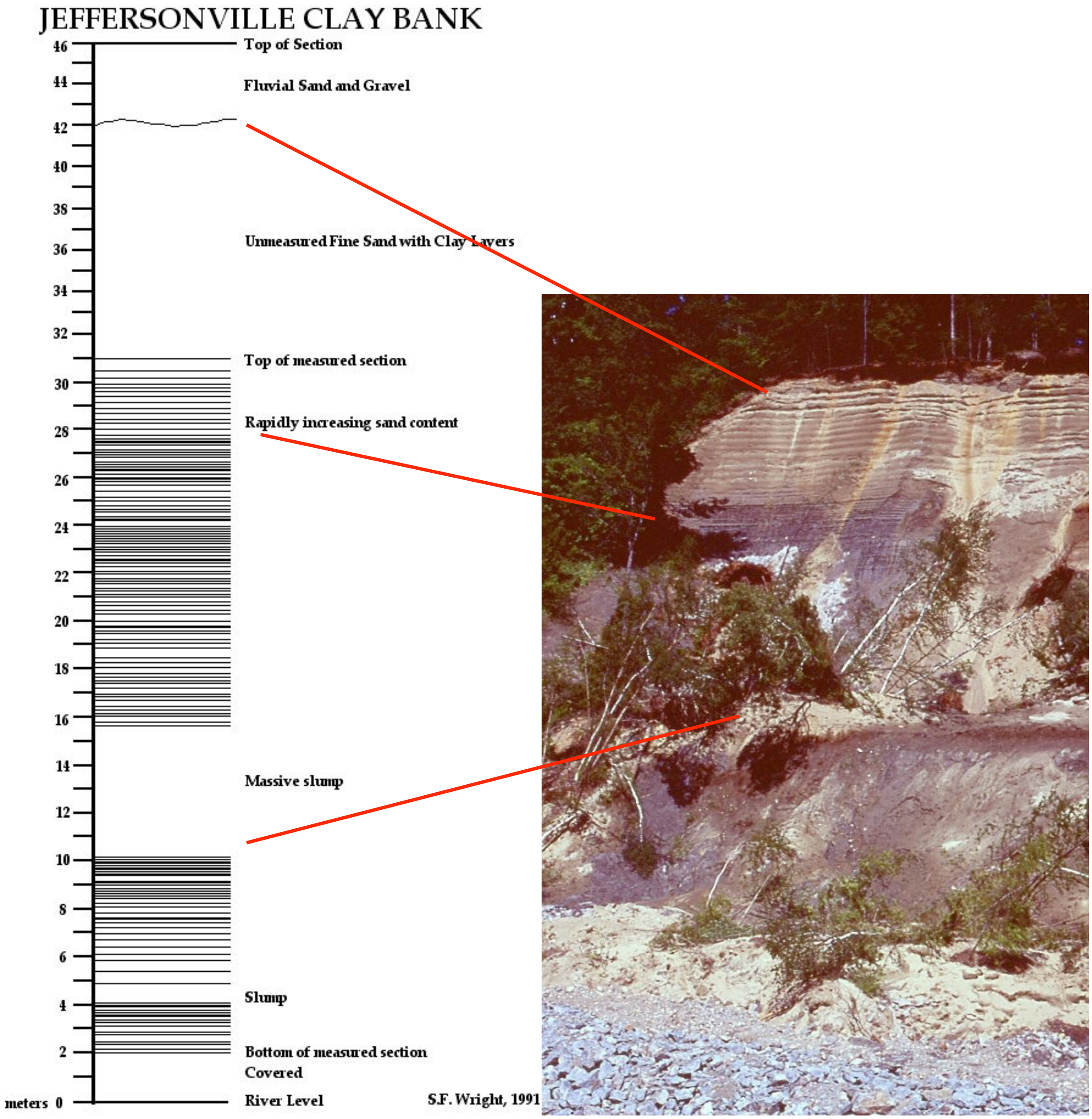

Figure 13: Columnar section of glacial sediments exposed at the Jeffersonville clay bank (Fig. 12). Except for the uppermost 2–3 m, the section consists entirely of glaciolacustrine sediments that can be divided into three distinct groups corresponding to differences in lake elevation and corresponding decreasing distance from the Brewster river delta. The lower part of the section consists exclusively of silt and clay couplets. A massive, ~5.5 m thick intraformational slump signals a change where every couplet above the slump contains at least some medium to fine sand. A second change occurs at about 28 m up the section where the amount of sand in each couplet and the corresponding thickness of each couplet increases markedly. These three packages of lacustrine sediments are tentatively assigned to 1) Glacial Lake Mansfield, 2) the Coveville state of Glacial Lake Vermont, and 3) the Fort Ann stage of Glacial Lake Vermont.

The unconformable section of fluvial sediments was deposited by the Brewster River when glacial lakes drained from the valley.

Fig. 14: Portion of the Jeffersonville clay bank as it appeared in 1991 when the section was measured. The bottom of the section consists of horizontally layered varved silt and clay. The break in slope (arrow) corresponds to the massive intraformational slump in the section which was the locus for the 1999 landslides. The intraformational slump is overlain by undeformed, horizontally bedded varved silt and clay containing some fine sand in almost every summer layer. Light-colored patch in center background is part of the upper, sandy part of the section.

Antevs (1928) measured two sections at the same Jeffersonville clay bank, one close to my measured section (his section 170) and another approximately 300 yards to the north, approximately 100 m south of the Route 15 bridge over the Brewster River (his section 169). At the time of his work the lower 11 m of the section was covered.

The stratigraphic section at the Jeffersonville clay bank accumulated quickly reflecting its proximity to deltas created by the Brewster River. The nearest delta is along the southern boundary of the Quadrangle, approximately 1.2 km south of the Jeffersonville clay bank (Sheet 1). The measured section consists of sediments deposited in four different environments, each with increasing local energy levels that are here interpreted to result from different lake surface elevations and correspondingly different distances to the Brewster River deltas.

The lowest part of the measured section consists exclusively of varved silt and clay, interrupted by one 81 cm thick intraformational slump (Figs. 13 and 14). Individual silt/clay couplets are quite thick with the silt layers in this part of the section range in thickness from 6.7 – 51.6 cm and the clay interbeds range from 0.4 – 2.9 cm. The clay layers are usually graded, becoming progressively finer grained from bottom to top. These are relatively deep water lacustrine sediments deposited in what was probably Glacial Lake Mansfield which was locally at an elevation of ~800 ft. The 800 ft Brewster River delta lies approximately 3 km south of the measured section in the adjacent Mt. Mansfield 7.5-minute quadrangle.

Figure 15: Uppermost part of the massive slump occurring between 10 and 15.5 m in the Jeffersonville clay bank section (Fig. 13). Lower part of photo shows sand layers and adjacent silt extensively disrupted by soft sediment deformation. Top part of section shows several trains of ripples moving to the left (north). Normal varved silt/clay beds begin immediately above the cleared face. Handle of scraper is 12.5 cm long.

The second part of the stratigraphic section begins with a massive 5.5 m thick intraformational slump (underwater landslide) consisting of deformed varved silt and clay and rare sand. The slump contains an impressive array of deformation structures including abundant folds, imbricate thrust faults, and soft sediment structures (Fig. 15). The disrupted beds slumped sediments are conformably overlain by trains of starved ripples, which are themselves overlain by quiet water silt/sand and clay couplets. A notable change occurring in varved sediments above the slump is that almost every summer layer now contains at least some sand, reflecting a higher energy environment, most likely the result of a drop in lake level. While landslides in lakes can result from seismic activity, storms, oversteepened slopes, or some combination of the above, the stratigraphic evidence suggests that this slump occurred when lake level dropped. This part of the stratigraphic section was most likely deposited during the Coveville stage of glacial Lake Vermont (Chapman, 1937; Wagner, 1972) when the local lake elevation was ~740–760 ft and the delta was at the southern boundary of the Quadrangle (Sheet 1).

The third group of sediments in the section begins at 27–28 m where the amount of sand occurring in each summer layer rapidly increases and silt longer occurs in these summer layers (Fig. 13). In the uppermost part of the section approximately 1 meter of medium to fine sand was deposited between each winter clay layer. Once again, this most likely represents another fall in lake level sufficient to allow the Brewster delta to prograde farther north, now only ~1.2 km from the Jeffersonville clay bank. All sedimentary structures in this part of the section indicate currents were flowing to the north and sedimentation rates were high, consistent with these sand beds forming as bottom-set beds of the delta building to the south. This part of the stratigraphic section was most likely deposited during the Fort Ann stage of glacial Lake Vermont (Chapman, 1937; Wagner, 1972) when the local lake elevation was ~680–700 ft and the delta was immediately south of the village of Jeffersonville (Sheet 1).

An erosional unconformity separates the lacustrine sand and clay couplets in the upper part of the section from fluvial coarse sand and pebble cobble gravels that comprise the uppermost ~2–3 m of the section (Fig. 13). These sediments comprise the terrace at the top of the clay bank that can be traced ~1 km to the south (Fig. 12 and Sheet 1). Cross-bedding in these sediments indicates that currents were flowing to the north. These fluvial sediments were deposited by the Brewster River shortly after glacial Lake Vermont drained from the valley and represent an early period of erosion of lacustrine materials that continues to the present day.

The entire section of lacustrine material visible at the Jeffersonville clay bank was deposited in a relatively short period of time. In addition to the 143 couplets measured in the section, the bottom 2 m of covered section contains approximately 15 couplets (extrapolating the average couplet thickness down section). In addition, the top, unmeasured ~15 m, part of the section contains another 10 –15 sand/clay couplets below the unconformity with the overlying gravels. If one interprets each couplet to represent a year's sedimentation cycle in the lake, then the measured section was deposited in 143 years and the entire exposed section in ~170 years. As noted earlier, this rapid deposition no doubt resulted from the close proximity to the Brewster River delta.

Observations shortly after the 1999 landslides indicate that the landslides occurred because the lacustrine sediments (silts and clays were locally saturated and structurally weak. Some of these

Figure 16: Run out from the 1999 Jeffersonville landslide taken looking west from the top of the slide scarp. Newly eroded Brewster river channel is visible across the bottom of the picture (river flows to the right, north). Slide debris is strewn across the terrace surface (former tennis courts) extending west from the Brewster River (see Bierman et al., 1999, for a detailed map of the slide debris). Light-colored patches along the farthest margin of the slide debris consist of liquefied silt/clay (Fig. 17).

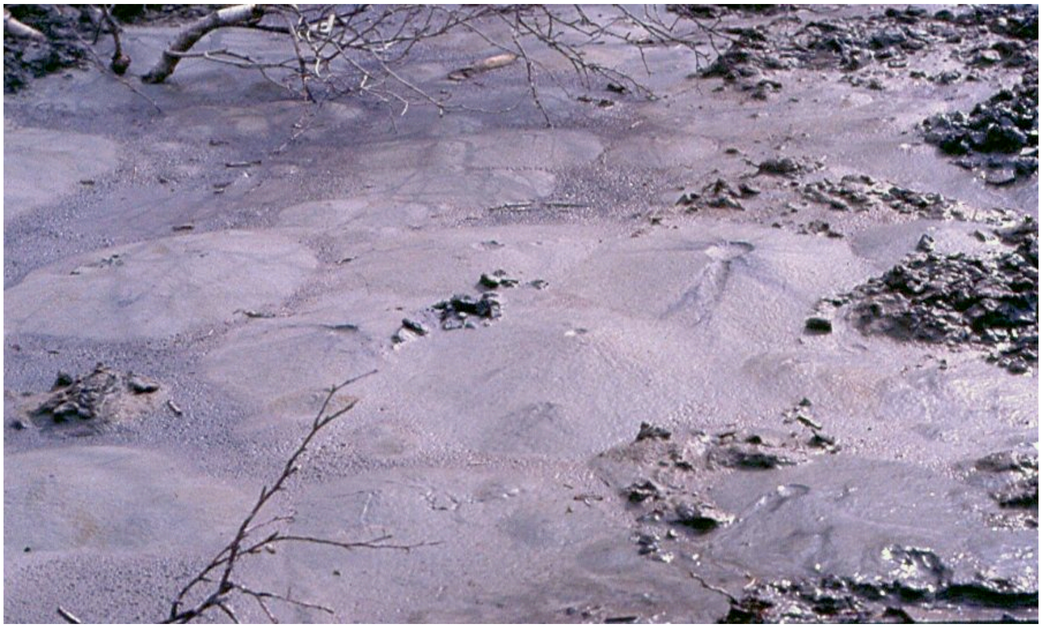

Figure 17: Mud volcanoes in liquefied silt/clay occurring at the toe of the 1999 Jeffersonville landslide. The volcanoes form as the liquefied silt/clay dewaters funneling a slurry of water, silt, and clay to the surface. These materials were most likely derived from the massive slump in the stratigraphic section (Figs. 13 and 15) which is characteristically much more water-saturated than the rest of the section.

observations include the long run out of the slide material and the soupy saturated silt/clay and associated mud volcanoes occurring at the base of the slide (Figs. 16 and 17; Bierman et al., 1999).

Two approximately East-West cross-sections depict my current understanding of the geology of the site based on field mapping, careful measurement of the section exposed in 1991, and geophysical work (Fig. 18). All indications are that the bedrock surface, mantled by a thin cover of till, slopes downwards from east to west reaching a depth of 40 to 50 feet below the alluvial fan/floodplain surface immediately west of the Brewster River. While there is no direct control on the position of the bedrock surface beneath the ridge shown in both cross-sections, I have shown the bedrock surface in cross-section Y–Y' to be closer to the surface than in X–X'. This interpretation is based on the observations that (1) till occurs at the base of the hill a short distance upstream from section Y–Y' and (2) sediments exposed in a small landslide near the top of the stratigraphic section in cross-section Y–Y' consist of interlayered silt and clay, with some fine sand, a pattern of sedimentation similar to that occurring slightly above the 500 ft level of cross-section X–X'. In other words, the alluvial unconformity, occurring in both sections at approximately 600 ft, has entirely eroded away the upper, "sandy" part of the section in cross-section Y–Y' whereas that part of the section remains intact in cross-section X–X'. Several seismic refraction lines run across the alluvium adjacent to the Brewster River on both sections indicate that approximately 40–50 feet of surficial material overlie the bedrock at this site, confirming the logs from the few wells drilled in the village (George Springson, personal communication).

In both cross-sections the lower part of the section consists of varved silt and clay that was deposited above an unknown thickness of till and ice-contact sediments. As noted earlier, this part of the section is interrupted by an almost 5 meter thick subaqueous landslide deposit consisting of extensively deformed lake clay. This layer is shown on cross-section X–X' but not in cross-section Y–Y' where only the upper part of the section is exposed. The subaqueous slump deposit may be a key stratigraphic element controlling the hydrology of the glaciolacustrine sediments and consequently their strength. Cross-section X–X' depicts the slumped horizon extending almost horizontally from where it is exposed above the Brewster River to the east where it intersects the small unnamed stream that flows along the contact between the till and the lacustrine sediments. This slumped layer could also have been drawn sloping upwards to the east, parallel to the slope of the bedrock/till surface. At the site of the 1999 landslides the slumped horizon and the varved silt and clay immediately below the slumped horizon are noticeably more saturated with groundwater than sediments above or below. This implies that the slumped horizon has a relatively high hydraulic conductivity and is acting as a conduit for groundwater flowing along or from the bedrock/till interface. Several small seeps emanating from the landslide scarp also support this

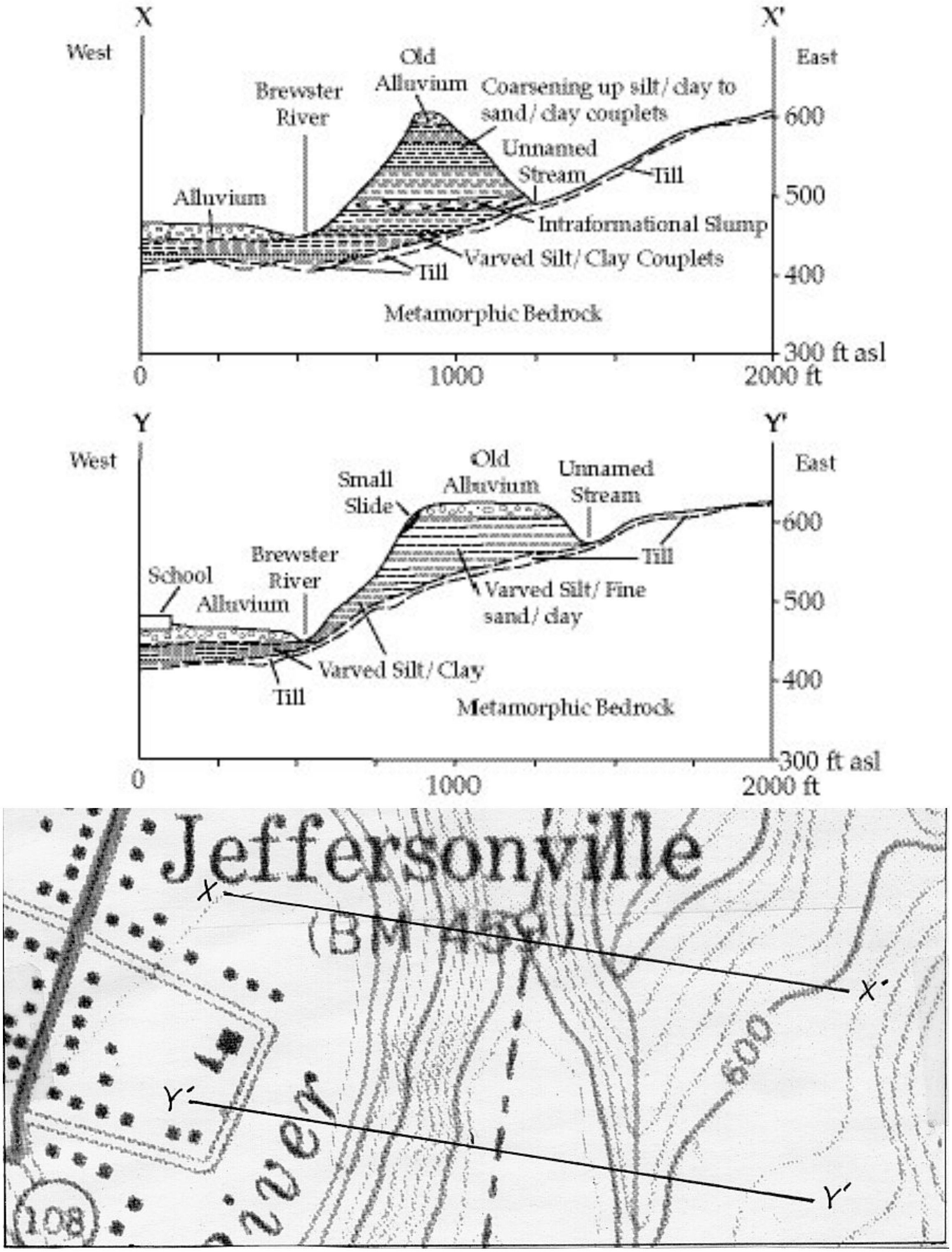

Figure 18: Cross-sections depicting the surficial geology of the site of the 1999 Jeffersonville landslides (X–X') and an area 675 ft (206 m) to the south (Y–Y'), directly above the Cambridge Elementary School. Both cross-sections have a vertical exaggeration of 2.5x. Enlarged portion

of the Jeffersonville 7.5-minute quadrangle near the village of Jeffersonville shows location of cross-sections. North is to the top of the page. Map scale is identical to cross-sections.
conclusion. While this slumped horizon is not shown on cross-section Y–Y' it is likely to exist in this section too and may influence the stability of slopes directly uphill from the school and adjacent ball fields.

SUMMARY OF THE GEOLOGIC HISTORY

This section provides a summary of the Quaternary geologic history of the Jeffersonville Quadrangle. The surficial geology of the Quadrangle is dominated by the materials deposited during the most recent advance and retreat of the Laurentide ice sheet across the area. While a highly weathered, "preglacial" saprolite has been identified in field exposures several km to the south (Wright et al., 1999) and may have been encountered in some drill holes within the Quadrangle, current mapping has not identified any areas with pre-glacial soils within the Quadrangle.

Ice Flow/Retreat History

Striation data indicate that regional ice flow was to the southeast, across the generally north-south trend of the mountains. As the ice sheet thinned its direction was guided by the orientation of the bedrock valleys it occupied. The general model for deglaciation in Vermont and throughout New England is one where the ice sheet thinned extensively as the ice margin generally retreated to the NNW. This occurred because most of the region was in the ablation zone of the ice sheet (no new ice was being added to the ice sheet in New England). As a result, the thinning ice became restricted to the valleys which were the last areas to be deglaciated.

The Laurentide ice sheet deposited till over all except the steepest bedrock surfaces. Erratics from bedrock terranes to the northwest of the Quadrangle occur in the till. As noted earlier, there is evidence that after the ice sheet's initial retreat it readvanced, deforming recently deposited lacustrine sediments and depositing a second "readvance till" in the valleys. The "common till" in most areas mapped has a very high sand or silt content with only isolated, relatively small erratics. This readvance till overlies deformed sections of lacustrine sediments and largely consists of lacustrine sediments, now mixed extensively enough that original bedding is not visible in small exposures. It is unclear at this time whether this glacial readvance is correlative with the Bethlehem Readvance (~11.8–11.9 ka ^{14}C years; 13.8–13.95 ka calibrated years, Ridge et al., 1999, Thompson, 1999, Larsen, 2001) or to another, more recent readvance.

Ice-contact sediments are rarely exposed in the Quadrangle, but an esker has been identified in the Route 108 valley and others probably exist buried beneath the Lamoille River valley. Other ice-contact sediments have been identified in water well logs and many of these are shown in the cross-sections included with this report.

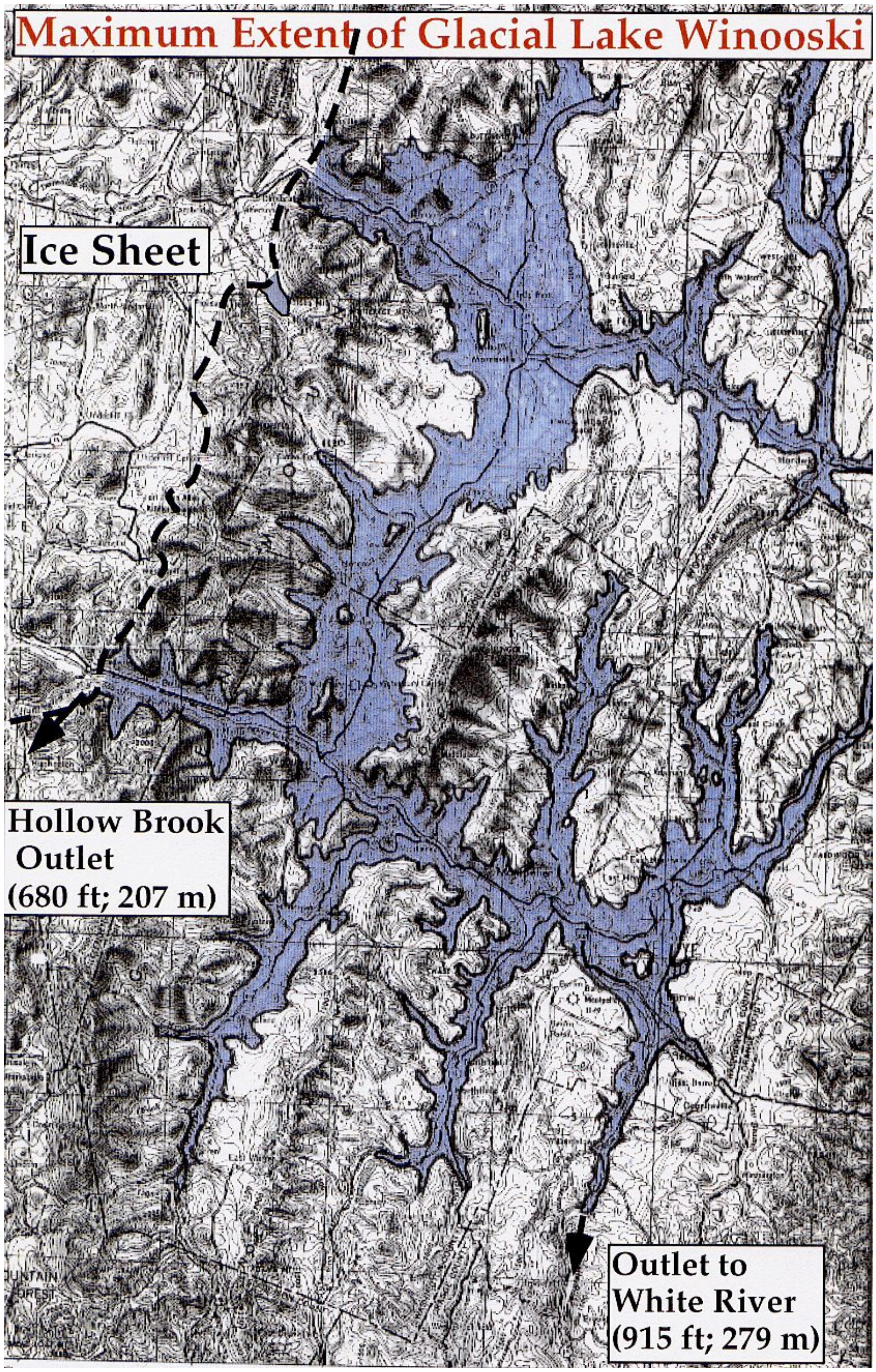

Figure 19: Map showing the maximum extent of Glacial Lake Winooski, just before the Hollow Brook outlet is uncovered. The position of the ice sheet in the Lamoille River valley is based on the most westerly occurrence of lacustrine sediments at elevations up to 1,100 feet.

Glacial Lake History

As the ice sheet retreated to the northwest, down the Lamoille River valley, it dammed a series of lakes. The highest of these was Glacial Lake Winooski whose outlet was south of Williamstown, ~20 km south of Barre, where it drained into the Second Branch of the White River (Fig. 19). As long as the Winooski and Lamoille River valleys were blocked by ice, this is the lowest outlet in central Vermont. Evidence for the existence of Glacial Lake Winooski in the Quadrangle stems

from the extensive deposits of fine lake sand occurring at elevations up to 1,030 feet in the eastern half of the Quadrangle. West of this valley, no lacustrine sediments occur above ~800 feet. For this reason I infer that the ice front was at the confluence of the North Branch and Lamoille valleys when lake level dropped from ~1,100 to 800 feet (Fig. 19). Projection of Glacial Lake Winooski from its threshold south of Williamstown to the NNW, using the isobases established for Glacial Lake Hitchcock (0.9 m/km, Koteff and Larsen, 1989), puts the surface of the lake at an elevation of ~1,115 feet, consistent with the distribution of lacustrine sediments in the Lamoille River valley.

Lake levels in the Lamoille River valley lowered significantly (~300 ft) when the ice tongue in the Winooski river valley retreated as far west as Jonesville, uncovering a lower outlet through the Huntington River and Hollow brook valleys (Larsen, 1987). This new lower-elevation lake is referred to as Glacial Lake Mansfield and is at an elevation of ~800 feet in the Quadrangle. Numerous deltas were deposited in glacial Lake Mansfield (Sheet 1) by tributary streams, most of which were previously identified by Connally (1972), although he referred to this lake level as "Lake Lamoille." Lacustrine sediments occurring in the Lamoille river valley and its tributaries west of its confluence with the North Branch were deposited in this and subsequent lakes. The detailed stratigraphic section described earlier in this report records this portion of the region's lake history.

Deltas at elevations between 700 and 720 feet record another stable lake elevation, tentatively assigned to the Coveville stage of glacial Lake Vermont (Sheet 1). It should be noted that in the northwest portion of the quadrangle no deltas higher than 700–720 feet were found, suggesting that this area was still ice covered at the time that the 800 foot lake (glacial Lake Mansfield) existed. Lake level in the valley dropped again to elevations of approximately 660–

640 ft, corresponding to the Fort Ann stage of glacial Lake Vermont. The lacustrine history of this part of the Lamoille River valley ended when Lake Vermont drained. The Champlain Sea was never high enough to flood this part of the valley.

Holocene Fluvial History

The modern fluvial history of the Lamoille River and its tributaries began with the drainage of Lake Vermont. Several observations are key to understanding the Holocene history of the Lamoille River valley. One is that the Lamoille River is pinned at Fairfax Falls approximately 10 km west of the Quadrangle boundary. Upstream of the falls the river has a very low gradient, entering the eastern side of the Quadrangle at ~455 ft asl and exiting the western side of the Quadrangle at ~435 ft asl. A consequence of this is that the Lamoille River has done little down-cutting and the bedrock valley is still filled with a considerable thickness of glacial sediments that are themselves covered by a thin veneer of alluvium (Figs. 20 and 21). The valley contains many meander scars and oxbow lakes indicating that the river channel has migrated back and forth across the floodplain. Most of the river channel is now armored with rip rap derived from the granite sheds in Hardwick in an attempt to check the lateral migration of the channel[2].

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[2] This process probably began when the St. Johnsbury and Lake Champlain Railroad was completed during the late 1870's.

Figure 20: View looking south across the Lamoille River valley near the eastern boundary of the Quadrangle. Cluster of houses visible on left side of photo (East Cambridge) are built on fluvial terraces only 20 to 40 ft above the broad floodplain of the river. Line shows approximate location of the seismic section published in Stewart (1974), Fig. 21.

Another key observation is that only a few fluvial terraces exist in the Lamoille River valley and these are less than 50 ft above the current river level (Fig. 20). There is no evidence that the Lamoille River has eroded a significant thickness of lacustrine sediments from the valley except near the confluence of the Brewster and North Branch Rivers. Specifically, nowhere in the valley are there fluvial terraces set in lacustrine sediments to indicate that the river once flowed across an old lake bottom that was significantly higher than the present elevation of the river. In other words, the Lamoille River valley today may not look significantly different than it did when the last glacial lake drained from the valley, i.e. the bottom of the last glacial lake in the valley was only a few 10's of feet above the current elevation of the river. The exceptions occur where the Brewster river delta mounded up sediments at the current site of Jeffersonville village and the North Branch similarly deposited a mound of sediments near the current site of Waterville village. The Brewster River delta in particular may well have temporarily dammed the river after Lake Vermont drained, although the duration of this easily eroded dam was probably short.

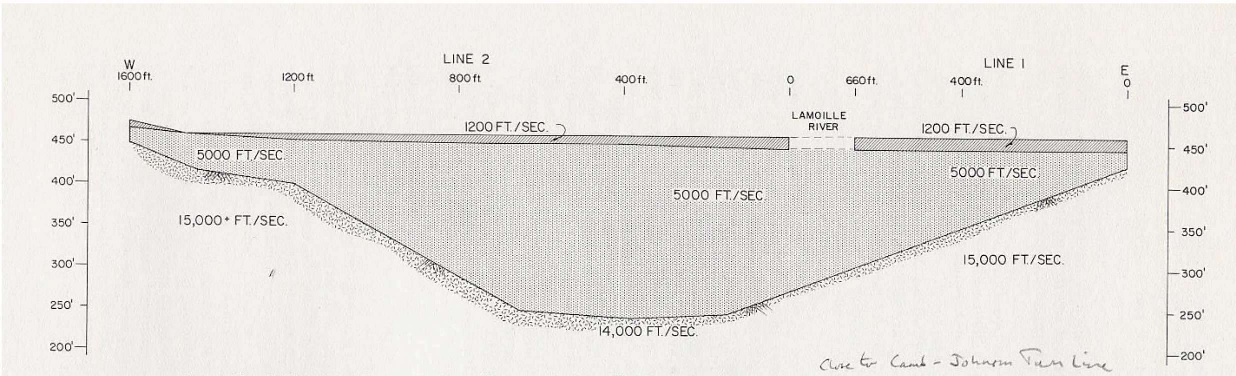

Figure 21. Northeast-southwest seismic profile across the Lamoille River valley, three and one-half miles east-northeast of Jeffersonville.

Figure 21: Seismic section across the Lamoille River valley (see Fig. 20 for approximate location) showing thick section of lacustrine sediments (5,000 ft/sec material) filling the bedrock valley (Stewart, 1974). In most places modern river alluvium (1,200 ft/sec material) is in direct contact with varved silt/clay. The East Cambridge Cross-section (Fig. 11) depicts the detailed geology of this part of the river valley.

While the Lamoille River cannot erode downward, all of the tributary streams are not so restrained. Many of these streams, both large and small have created alluvial fans where they intersect the Lamoille River valley. The largest of these is that produced by the Brewster River. The village of Jeffersonville is built on this fan. There is considerable evidence that alluvial fans in Vermont have been active throughout the Holocene (Bierman et al., 1997). A stump exposed during the summer of 1991 is clearly rooted well below the current water level, indicating that the fan surface has aggraded a minimum of 5 m of sediment since the tree was alive (Fig. 22). No attempt was made to date this tree nor have historical records been checked for evidence of aggradation during the late 18th and early 19th centuries. Elsewhere in Vermont considerable volumes of sediment were deposited by streams when the land was first cleared by European settlers (Bierman et al., 1997).

Figure 22: Stump briefly exposed during 1991 along the Brewster River at the site of the 1999 landslides. Stump is rooted well below current water level indicating aggradation of the Brewster River alluvial fan during the Holocene.

FUTURE RESEARCH

As a result of the current mapping project several directions are evident for future research:

1) A better understanding of the detailed hydrology of the lacustrine sediments that failed during the 1999 landslides is needed. Several wells with nested piezometers would allow the hydraulic gradients in these sediments to be monitored, particularly in the area behind the Cambridge town school.

2) The history of glacial lakes in the region would be greatly extended by recovering a complete core of varved sediments from the Lamoille River valley. In particular it should be possible to correlate the early history of that core with the known and dated history of Glacial Lake Winooski. The upper part of the core should record a nearly complete history of Glacial Lake Mansfield and both the Coveville and Fort Ann stages of Glacial Lake Vermont in this part of the Lamoille River valley.

3) Surficial materials mapping in adjacent quadrangles would allow the glacial history assembled from evidence here to be both tested and extended. In particular, while it is clear that tongues of

the Laurentide ice sheet extended up the Winooski and Lamoille River valleys from the Champlain valley, it is less clear what happened to the ice sheet as it retreated/thinned to the north.

REFERENCES

Antevs, E., 1922, The recession of the last ice sheet in New England, American Geographical Society Research Series No. 11, 120 p.

Antevs, E., 1928, The last glaciation with special reference to the ice retreat in northeastern North America; American Geographical Society Research Series No. 17, 292 p.

Beers, F.W., 1878, Atlas of the counties of Lamoille and Orleans, Vermont; F.W. Beers & Co.

Bierman, P.R., Lini, A., Davis, P.T., Southon, J., Baldwin, L., Church, A., and Zehfuss, P., 1997, Post-glacial pond and alluvial fans: Recorders of Holocene landscape history; GSA Today Vol. 7, No. 10, p. 1–8.

Bierman, P.R., Wright, S.F., and Nichols, K., 1999, Slope stability and late Pleistocene/Holocene history, northwestern Vermont; in Wright, S.F., ed., New England Intercollegiate Geological Conference Guidebook No., 91, p. 17–50.

Chapman, D.H., 1937, Late-glacial and postglacial history of the Champlain Valley; American Jour. of Science Vol. 34 (5th Series) p. 84–124.

Chidester, A.H., Stewart, G.W., and Morris, D., 1952, Geologic map of the Rousseau talc prospect, Cambridge, Vermont; U.S. Geological Survey Mineral Investigations, Field Studies Map MF 8.

Christman, R.A., 1959, Bedrock geology of the Mount Mansfield quadrangle, Vermont; Vermont Geological Survey Bulletin No. 12, 75 p.

Connally, G.G., 1966, Surficial geology of the Mount Mansfield 15-minute quadrangle, Vermont; Vermont Geological Survey open-file report, 33 p.

Connally, G. G., 1971, Pleistocene mountain glaciation, Northern Vermont: Discussion: Geol. Soc. America Bull., v. 82, p. 1763–1766.

Connally, G. G., 1972, Proglacial lakes in the Lamoille Valley, Vermont, in Doolan, B.L. and Stanley, R.S., eds., New England Intercollegiate Geological Conference Guidebook, No. p. 343–358.

Doll, C.G., Cady, W.M., Thompson, J.B., Jr., and Billings, M.P., 1961, Centennial geologic map of Vermont: Vermont Geological Survey, 1:250,000.

Doolan, B.L., Mock, T., and McBean, A., 1987, Stratigraphy and structure of the Camels Hump Group along the Lamoille River transect, northern Vermont; in Westerman, D.S., ed., New England Intercollegiate Geological Conference Guidebook No., 79, p. 152–191.

Hitchcock, E., Hitchcock, E., Jr., Hager, A.D., , and Hitchcock, C., 1861, Report on the Geology of Vermont—Descriptive, Theoretical, Economical, and Scenographical: 2 Volumes, Claremont Mfg. Comp.

Koteff, C. and Larsen, F.D., 1989, Postglacial uplift in western New England: Geologic evidence for delayed rebound; in Gregersen, S., and Basham, P.W., eds. Earthquakes at North Atlantic passive margins: Neotectonics and postglacial rebound: Norwell Mass. Kluwer Academic Publishers, p. 105–123.

Larsen, F.D., 1987, History of glacial lakes in the Dog River Valley, Central Vermont; in Westerman, D.S., ed., New England Intercollegiate Geological Conference, Guidebook No. 79, p. 213–237.

Larsen, F.D., 1999, Glacial history of the Montpelier 7.5-minute quadrangle; in Wright, S.F., ed, New England Intercollegiate Geological Conference Guidebook No., 91, p.286–300.

Larsen, F.D., 2001, The Middlesex readvance of the Late-Wisconsinan Ice Sheet in central Vermont at 11,900 ^{14}C years BP; Geol. Soc. America Abst. w. Prog. Vol. 33, p. A-15.

McDonald, B.C. and Shilts, W.W., 1971, Quaternary stratigraphy and events in southeastern Québec; Geol. Soc. Am. Bull. v. 82, p. 683–698.

Merwin, H.E., 1908, Some late Wisconsin and post-Wisconsin shore-lines of north-western Vermont; Vermont State Geologist, 6th Report, pp. 113–138.

Mock, T.D., 1989, Bedrock geology of the East Fletcher–Bakersfield area, northern Vermont; Vermont Geological Survey Special Bulletin No. 10, 28 p.

Ridge, J.C. and Larsen, F.D., 1990, Re-evaluation of Antevs' New England varve chronology and new radiocarbon dates of sediments from glacial Lake Hitchcock; Geological Soc. America Bulletin 102: 889–899.

Ridge, J.C., Besonen, M.R., Brochu, M., Brown, S.L., Callahan, J.W., Cook, G.J., Nicholson, R.S., and Toll, N.J., 1999, Varve, paleomagnetic, and 14 C chronologies for late Pleistocene events in New Hampshire and Vermont (U.S.A.); Géographie physique et Quaternaire, v. 53, p. 79–106.

Stewart, D.P., 1961, Glacial Geology of Vermont; Vermont Geological Survey Bulletin No. 19.

Stewart, D.P., 1974, Geology for environmental planning in the Milton–St. Albans region, Vermont; Vermont Geological Survey Environmental Geology Series, No. 5, 55 p.

Stewart, D.P. and MacClintock, P., 1969, The surficial geology and Pleistocene history of Vermont; Vermont Geological Survey Bulletin No. 31, 251 p.

Stewart, D.P. and MacClintock, P., 1970, Surficial Geologic Map of Vermont; Vermont Geological Survey, 1:250,000.

Thompson, P.J., Thompson, T.B., and Doolan, B.L, 1999, Lithotectonic packages and tectonic boundaries across the Lamoille River transect in northern Vermont; in Wright, S.F., ed., New England Intercollegiate Geological Conference Guidebook No., 91, p. 51–94.

Thompson, W.B., Fowler, B.K., and Dorian, C.C., 1999, Deglaciation of the northwestern White Mountains, New Hampshire; Géographie physique et Quaternaire v. 53, p. 59–77.

Wagner, W.P., 1972, Ice margins and water levels in northwestern Vermont; in Doolan, B.L. and Stanley, R.S., eds., New England Intercollegiate Geologic Conference Guidebook, University of Vermont, Burlington, Vermont, p. 297–316.

Wright, S.F., Bosley, A.C., McGee, M.A., Guerino, M.J., 2002, Surficial geology of the Jeffersonville 7.5-minute Quadrangle, northern Vermont; Geol. Soc. America Abstr. w. Prog., Vol. 34, p. A26.

Wright, S.F., Bosley, A.C., McGee, M.A., Hodgdon, I.A., Spangler, A.C., 2001, Glacial geology of the Lamoille River Valley near Jeffersonville, Vermont; Geol. Soc. America Abstr. w. Prog., Vol. 33, p. A15.

Wright, S.F., 1999a, Deglaciation of the Stevens Branch Valley, Williamstown to Barre, Vermont; in Wright, S.F., ed., New England Intercollegiate Geological Conference Guidebook No., 91, p. 179–199.

Wright, S.F., 1999b, Surficial geologic map and cross-sections of the Barre West 7.5-minute quadrangle, Vermont Geological Survey Open File Report.

Wright, S.F., Whalen, T.N., Zehfuss, P.H., and Bierman, P.R., 1997, Late Pleistocene–Holocene history: Huntington River and Miller Brook valleys, northern Vermont, in Grover, T. and Mango, H., eds., New England Intercollegiate Geological Conference Guidebook No. 89, p.