Guide to the Sedimentology of Quaternary Sediments within and adjacent western Fall Creek Valley, Tompkins County, New York

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Abstract

Late Quaternary glaciation of south-central New York State generated accumulations of sediment in Tompkins County which are still unconsolidated, now mostly hidden beneath forests, fields, and towns. Elevations of the contact between unconsolidated sediment and Devonian bedrock imply that the ancestral position of Fall Creek valley west of 76.43° longitude, prior to Quaternary glaciation, trended west-southwest across what is now the plain between modern Fall Creek and Cascadilla Creek valleys. The fill of ancestral Fall Creek Valley records a complex mosaic of sediments accumulated under time-variable and spatially variable conditions. At five locations along the north wall of Fall Creek valley west of 76.433°W longitude and at two boreholes south of Fall Creek Valley, details of the texture, fabric, and bed architectures underpin interpretations of environmental conditions during deposition. This manuscript is a field guide to those sediments, which range in thickness from 25 m (80 ft) to 60 m (200 ft) overlying Devonian rock, and are either contemporaneous with the last widespread glacial cover of this area, the Valley Heads readvance, or predate the Valley Heads readvance. Through the 2.5 km (8200 ft) long sector of modern Fall Creek Valley reported here, a till that is attributed to the Valley Heads ice readvance occupies the upper valley wall. At the westernmost valley-wall section, about 30 m of sediment include a basal till and an uppermost Valley Heads till, between which sand deposits dominate with several meters of interbedded gray muds. The sands and muds were deposited from water with high degrees of suspended sediment load, potentially in a set of small proglacial lakes or pools at the front of a retreating glacier. At the Varna High Bank, three units record distinct environmental conditions. Below the 20-m-thick Valley Heads till, a 15-m-thick unit of sands and gravels was deposited by stream flow, with an upper interval made of a laterally continuous gravel distinguished by foreset beds to 10-m-height that record the merger of a stream into a deep pool or lake. Below a contact that is interpreted as a comparatively long-lived depositional lacuna, the basal 5-m-thick brown gravel also likely formed by stream flow. At the easternmost valley-wall section analyzed, three major units of differing depositional conditions again crop out. Valley Heads till caps the section, below which occur well stratified silty sands and well sorted gravels, in turn overlying a basal clay with floating cobble clasts that lacks internal organization. In the middle unit, the sands were deposited rapidly from flowing water with a high load of suspended sediment, and the gravel is interpreted to be glacial outwash. The basal clay and cobble unit probably reflects a sequence of two environmental conditions, first lacustrine deposition and then overriding by a glacier. At these three Fall Creek locations, the lower two units differ from those at their lateral neighbors, which is interpreted to mark a high degree of lateral variation of post-depositional preservation. The two boreholes, roughly 1.2 km and 1.3 km south of the westernmost valley wall exposures, penetrate unconsolidated sediment over Devonian bedrock that is similar in thickness (24 m) to more than twice as thick (60 m) as the Fall Creek valley Quaternary sediments. In both, a surficial till that is inferred to be Valley Heads is underlain by a 5-m-thick unit of very well laminated silty clay interpreted to be lacustrine. In both boreholes the next underlying unit is a matrix-rich till that persists to bedrock in one and to at least 30 m subsurface in the other. The nature of the remaining nearly 30-m-thick unit in the borehole where bedrock is deeper is poorly documented, including both gravels and sands, some subrounded to rounded, suggesting that the stack of sediments records important shifts of depositional conditions.

Introduction

Multiple phases of Quaternary glaciation produced the unconsolidated sediment that is extensively distributed in Tompkins County. The sedimentary grains were generated by sub-glacial erosion, some within Tompkins County and some in locations farther north and northeast over which the ice had traveled before reaching Tompkins County. The sedimentary grains (hereafter, "sediment") were deposited across the hilltops, the hillslopes, and within the lower sectors of Tompkins County's Fall Creek catchment, which is a major tributary to the Cayuga Valley (Figure 1). This paper reports the sedimentology and a partial interpretation of the physical stratigraphy of sediments which underlie the walls of the modern Fall Creek valley west of 76°26' W longitude and which underlie the plain south of Fall Creek. Companion papers are Karig (2022) which places the sedimentary history of those strata into the context of advances and retreats of ice sheets, and Jordan, Crowley and Allmendinger (in preparation) which analyzes the depositional landforms of the western sector of Fall Creek and post-glacial excavation of modern Fall Creek. The sediments exposed in the walls of Fall Creek valley and underlying the southern plain are products of multiple ice advances and retreats. The upper strata exposed in Fall Creek valley's walls reflect the last ice advances over the drainage basin, e.g. the major Valley Heads ice advance and the less extensive Brooktondale readvance (Karig and Miller, 2021; Karig, 2022). The lower strata formed during older stages of ice retreat, expressed by lacustrine and fluvial sediments, and of ice advances, expressed by tills.

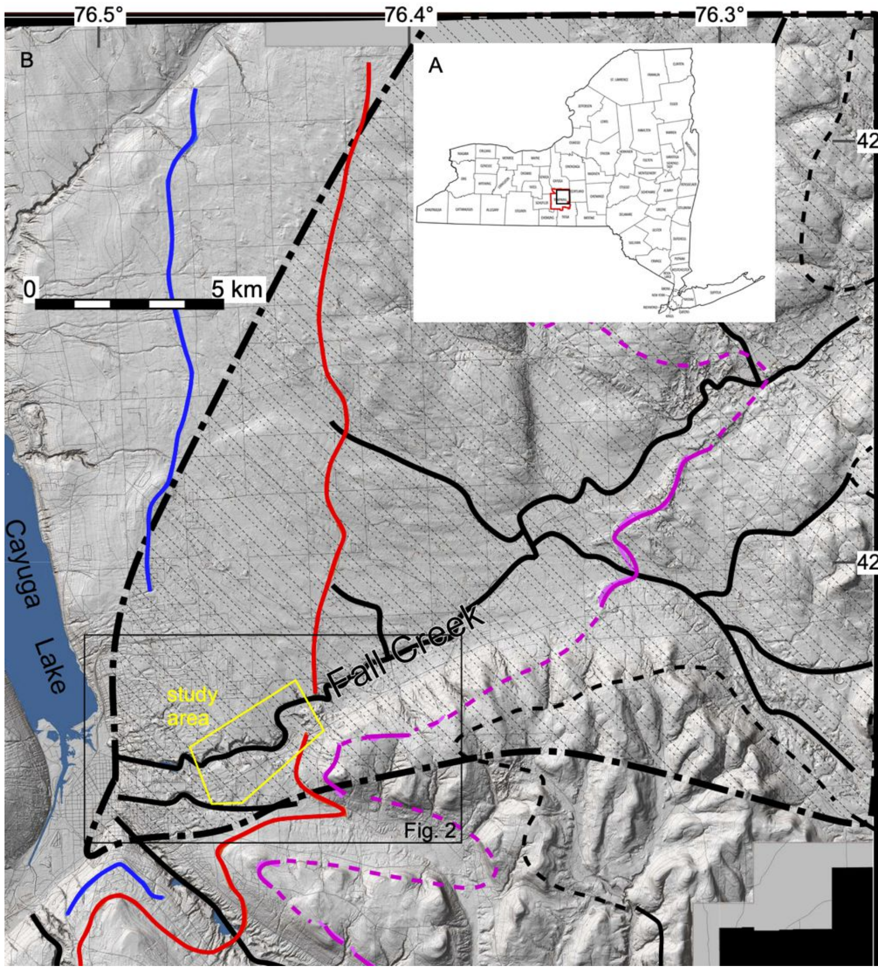

Fig 1. A) Map of New York state counties. Tompkins County outlined in red, and map B outlined in black. B) Shaded relief map with principal roads of northeastern Tompkins County, NY, showing locations of modern creeks (continuous, thick black lines). The yellow polygon encloses the outcrops and boreholes described in this paper. The heavy black dash-dot line and enclosed cross-hatched area show the approximate ancestral Fall Creek catchment, prior to the Quaternary (modified after Karig, 2022). Other lines are moraines, after Karig (2022), for which continuous lines indicate that evidence is clear and a dashed line marks where the ice margin is approximate. Consistent with Karig's color choices, black is Valley Heads moraine, magenta Brooktondale readvance moraine, and red and blue lines are minor moraines marking pauses in the ice retreat after the Brooktondale readvance.

Bloom (2018) and Karig (2022) review the history of the Fall Creek drainage. The key element of the history which sets the context for the sediments on which this paper focuses is that there were at least three distinct phases of development of Fall Creek valley. First, after Paleozoic deposition ceased, a prolonged history of denudation of the consolidated strata of the Appalachian Plateau generated a southwest-trending valley referred to here as the "ancestral Fall Creek valley" (Karig [2022] refers to this as the "paleo-valley"). Second, during Quaternary advances and retreats of ice sheets, the ancestral valley was altered radically, including splitting off and redirecting the upper catchment into the Tioughnioga drainage (Bloom, 2018; Karig, 2022). Multiple advances and retreats of ice sheets repeatedly filled the ancestral Fall Creek Valley with sediment transported below the ice sheets or which spilled from the ice front and then, during deglaciations, Fall Creek Valley was partially re-excavated with valley wall positions somewhat different than the ancestral bedrock valley walls (von Engeln, 1926). This Quaternary series of Fall Creek positions is collectively referred to here as "paleo-Fall Creek" (Karig [20222] refers to the last of these positions as "the paleo-channel"). The third phase of valley development is recorded by the landforms of modern Fall Creek which post-date the last retreat of glacial ice: the modern valley walls and terraces (Karig [2022] refers to this as the "Holocene gorge").

Revised map of ancestral Fall Creek valley

West-southwest of the crossing of Route 13 with the Fall Creek valley near 42.471°N, 76.419°W, a new detailed map is presented of the positions of the top of Devonian strata at >160 locations. The data are compiled from outcrops of Devonian rock, from Cornell University foundation engineering exploratory boreholes and water monitoring wells, and from a small number of geophysical surveys. The foundation engineering boreholes are useful but not entirely reliable records of the elevation of top of bedrock, as difficulty drilling deeper accompanied by fragments of Devonian rock can be evidence of boring into either a stiff, boulder-filled till or of true bedrock. This analysis accepted the drilling log report of bedrock top, but in some cases the true bedrock depth is likely greater than the reported bedrock depth.

I interpret the borders of the ancestral Fall Creek valley, prior to Quaternary glaciation, based on the long-wavelength variations in the top of bedrock elevation (Fig. 2a). Those elevation changes reveal that ancestral Fall Creek was several kilometers (a mile or more) wide and roughly 30 m (100 ft) deep over much of its width, with a deeper thalweg. Unlike previous authors (Bloom, 2018; Karig, 2022), I interpret the ancestral valley axis from the hamlet of Varna westward to Ithaca to be located significantly farther south than modern Fall Creek. The full span of this ancestral valley would have encompassed both the lower modern Fall Creek valley and modern Cascadilla Creek valley and its southern valley wall would be the northern boundary of Ithaca's "South Hill."

The position of the pre-Quaternary thalweg is more difficult to identify because doing so requires interpretation of shorter-wavelength variations in the elevation of the top of bedrock, and those short-wavelength variations also reflect repeated interglacial excavations of channels which created a complicated erosional deepening of narrow zones (e.g., von Engeln, 1926; Bloom, 2018). The position of the thalweg shown on Figure 2a is closer to modern Cascadilla valley than to modern Fall Creek valley because of new borehole data for the top-of-bedrock in the lowland plain between the two creeks, south and west of Varna. Even near the Cascadilla Creek valley, the top-of-bedrock beneath Quaternary sediment is at a lower elevation than it is along Fall Creek where overlain by till (e.g., Karig [2022] reports 870 ft [265 m] adjacent Fall Creek due north of boreholes where the elevation is 748 ft [228 m] and 863 ft [263 m]; Fig. 2b). Considering that the drainage basin for Fall Creek (330 km^2) is much larger than for Cascadilla Creek (35 km^2), deepest erosion of the upper surface of Devonian bedrock would be consistent with water supply by the Fall Creek drainage system rather than by the Cascadilla drainage. Given both the sparse distribution of data points between Fall Creek and Cascadilla Creek east of the main Cornell campus (Fig. 2b) and the likelihood that short-wavelength deepening was caused by interglacial erosion, alternative contouring of the top-of-Devonian is certainly possible. For example, Karig (D. Karig, 2022, personal communication) interprets the same data set to indicate that ancestral Fall Creek and Cascadilla valleys were separate.

The Quaternary fill of the ancestral Fall Creek valley is the focus of this paper.

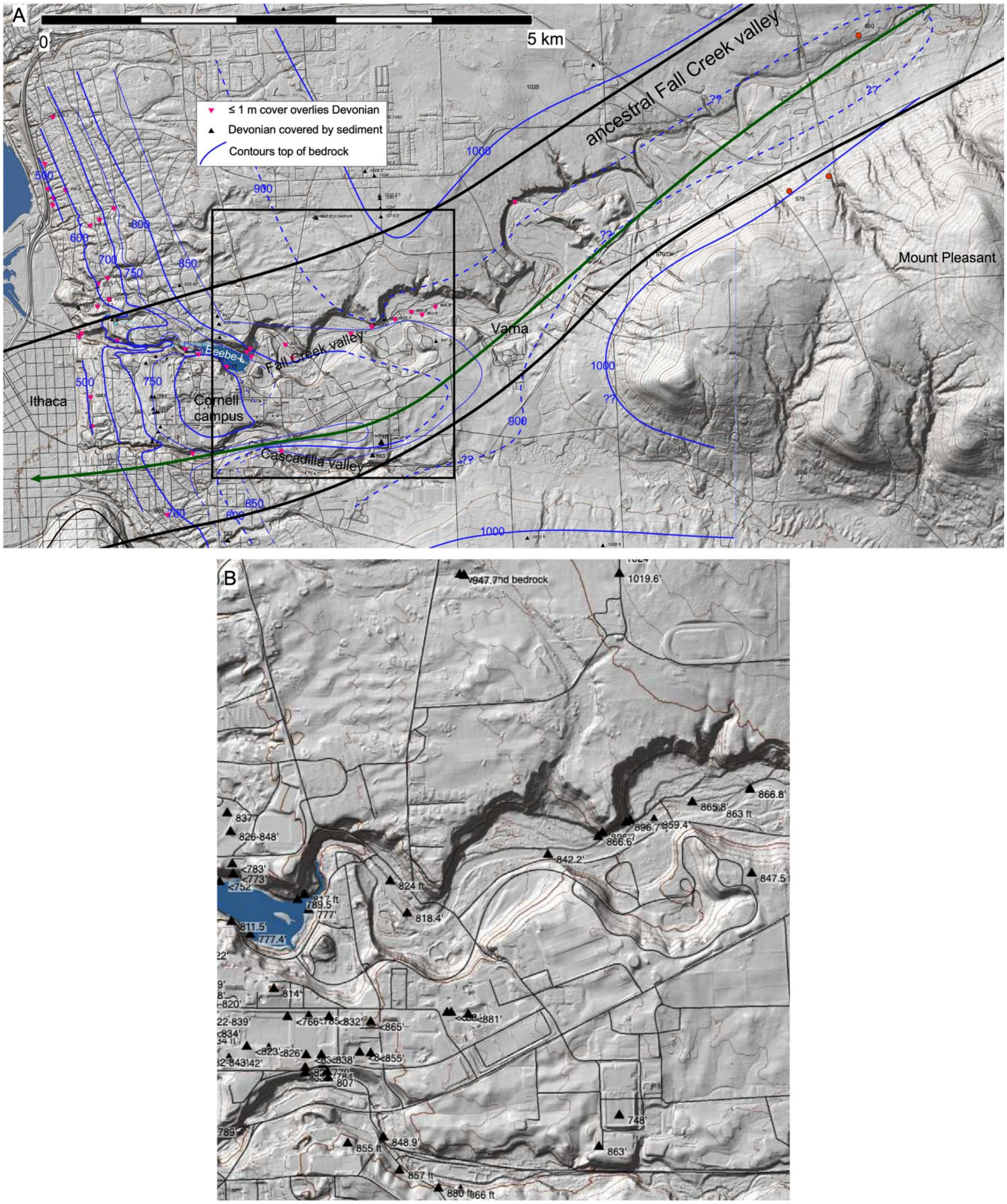

Figure 2. A) A shaded relief LiDAR image with interpreted locations of the upper valley walls of ancestral Fall Creek valley (heavy black lines). Blue contours and blue numbers are interpreted elevations (feet above sea level) of the top surface of Devonian strata in the area adjacent the western sector of Fall Creek Valley. Triangles mark point data for the top of Devonian rock; area in rectangle enlarged in B. The green line with an arrow indicates the approximate position of the valley axis. B) Enlargement of the area in a rectangle in A; elevation data in black.

Scope of paper

This paper is a field guide to the sedimentology of Quaternary sediments at three major and two minor sets of exposure along the modern Fall Creek Valley and two locations in the buried sediments below the plain south of Fall Creek. Collectively, all these sites reveal the fill of the ancestral Fall Creek valley. The natural major outcrops each exposes 35 to 40 m thickness of unconsolidated sediment. Two recently drilled boreholes in the plain between Fall Creek and Cascadilla Creek reveal general lithological and sedimentological attributes of 28-30 m thicknesses of unconsolidated sediment, and show also that poorly sampled Quaternary materials continue another 30 m deeper at one of those locations. This paper presents field and microscopic documentation of textural properties, sedimentary structures, and bedding architecture, and uses those data to develop interpretations of the depositional conditions. The paleo-environmental conditions include the water-rich base of glaciers, fluvial systems, small lakes, and larger or more persistent lakes. The lateral relationships among the facies units and Karig's (2022) chronological data permit a preliminary interpretation of the physical stratigraphic relationships among the sediments reported at individual locations.

Quaternary Sediments of the Lower Fall Creek Valley

Geology of Valley Heads-age and pre-Valley Heads Exposures Along Western Fall Creek

The ancestral Fall Creek valley was almost filled with Quaternary deposits and covered with till during the Valley Heads (VH) glacial readvance. Deep incision of the modern Fall Creek valley exposes Quaternary sediments pre-dating the Valley Heads readvance intermittently from the Forest Home neighborhood of Ithaca upstream to almost the Route 13 bridge (Fig. 3). Within the valley from Freese Road to Route 13 (2.4 km on bearing 065), fully one-quarter of that straight-line distance provides moderately good to excellent outcrop in a series of unvegetated "high banks" beginning at creek level. Nevertheless, this is a small sample of the volume of Quaternary deposits that filled the 1-2 km wide ancestral Fall Creek valley. Downstream of Freese Road, forest covers the valley walls and exposures must be sought in tributary gully bottoms and landslide scars.

The Valley Heads till is widespread, recognized as the sediment comprising the upper halves of most sectors of the Fall Creek valley walls (Karig, 2022). Although very well exposed at Varna High Bank (VHB), the material properties and clast compositions of the 20-m-thick upper gravel there are not readily characterized or sampled because of extremely steep, unstable slopes. Instead, properties of the laterally continuous gravel unit were examined in several accessible small and discontinuous outcrops spanning 500-1000 m west-southwest of Varna High Bank. These outcrops occur along the upper rim of the Fall Creek valley and in a few gullies that drain into the Fall Creek valley.

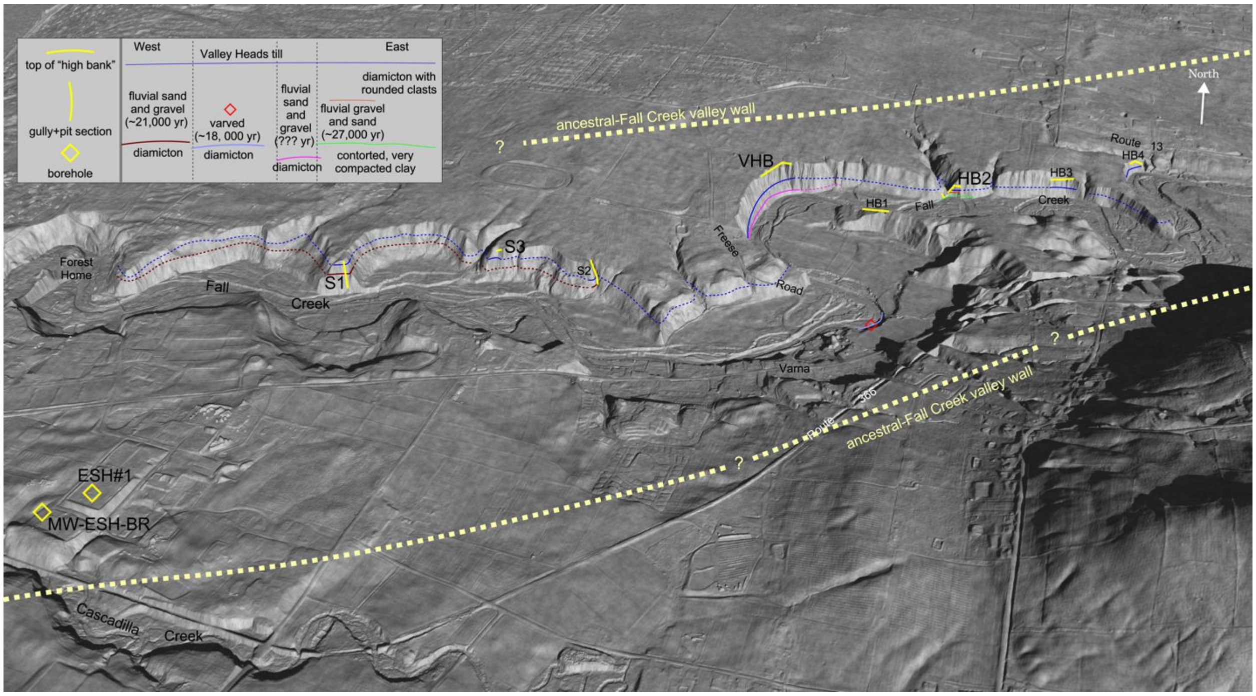

Figure 3. Perspective shaded relief image of Fall Creek valley in the 3.5 km distance from the eastern end of Beebe Lake at Forest Home (left) to ~100 m west of where it is crossed by Route 13 (right limit). Image from 1-m-resolution LiDAR-based digital elevation model, with 3X vertical exaggeration. Note the approximate positions of the ancestral Fall Creek bedrock-confined valley walls (dashed yellow lines). Labels mark positions of natural outcrops of Quaternary sediment in the eastern sector (VHB, HB2, HB3, HB4) and of vertical sections assembled from localized outcrops and dug pits in the western sector (S1, S2, S3). Colored lines on the valley wall mark approximate positions of contacts among major facies units (solid lines where constrained by outcrops or dug pits; dashed where extrapolated). Sedimentological assessments of S1, S2, S3, VHB, and HB2 are included in this paper; see Karig (2022) for separate analyses of S1, S2, VHB, HB1, HB3, HB4 and a varved section near Varna (red diamond). Yellow diamonds mark locations of two boreholes whose sediments are described (ESH#1, MW-ESH-BR). Inset shows the simplified physical stratigraphic relationship among the valley wall sections between S1 and HB2. The base of Valley Heads till is mapped throughout the length of the valley (blue line). The underlying units differ among the outcrops. Numerical dates are from Karig (2022).

S1 section at Robert Trent Jones Golf Course

The stratigraphic column referred to as “S1” is constructed from a series of 12 dug pits in a landslide scar on the north wall of Fall Creek valley, near 42.4546°N, 76.4576°W (Fig. 4). Each pit exposes between 20-150 cm of the section and, collectively, they expose a significant fraction of the total stratigraphic column – well over 80%. Karig (2022) refers to this location as “Site A”, and the 12 pits on which his descriptions are based are the same ones described here in more detail. In this report, the pits are numbered in ascending stratigraphic order although they were dug and numbered by Karig (2022) in a different order.

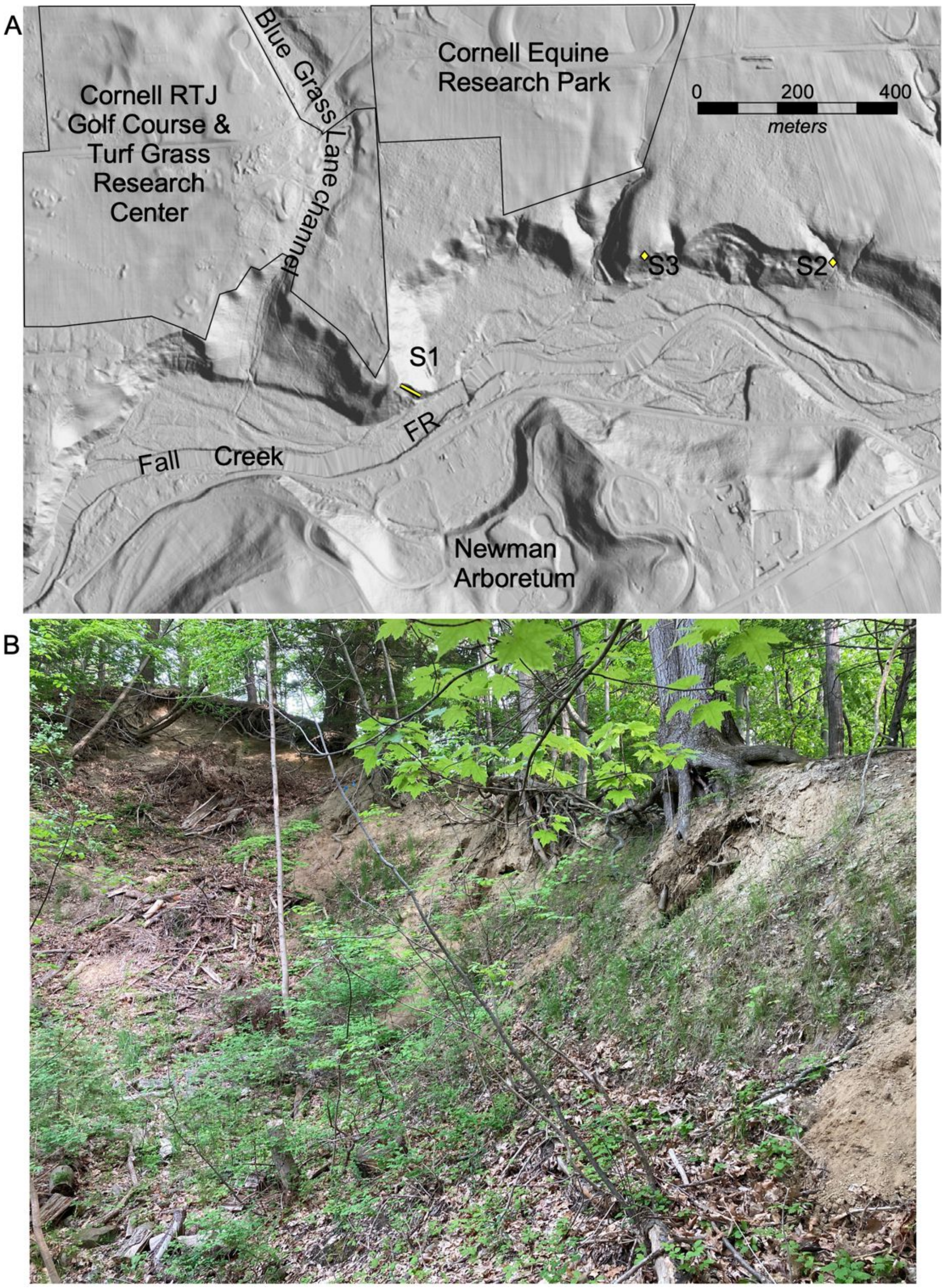

Figure 4. A) Location of the S1 section on the north wall of the Fall Creek valley adjacent to Cornell's golf course and near the Flat Rock (FR) sector of Fall Creek channel. The image is a hillshade representation of digital elevation data, with artificial illumination from the east. Note that section S1 (yellow line) occurs in a bowl-like very steep part of the Fall Creek valley wall, a form suggestive of a landslide scar. B) Photograph of the partially revegetated landslide scar, looking NW. The base of the photo is slightly above the contact of laminated muds over basal till. Animal burrows provided the initial natural exposures of sands.

Thickness data include: a) elevations from LiDAR DEM data at 2 m horizontal resolution are the basis for specifying elevations and, in turn, estimating thicknesses of major features in the stratigraphic column, b) tape measure or Jacob Staff thickness data within each pit, and c) LiDAR rangefinder data for a small set of key positions in the column. Unfortunately, smart phone geographic locations are notoriously inexact in this very protected recess in the Fall Creek valley wall, with resultant large errors on GPS locations. On the 30° slope, an error of 10-20 m horizontal results in several meters error in the assigned vertical position, hence of the corresponding elevation. The total section is about 30 m thick, and thicknesses within this section (Fig. 5) are approximate.

The Fall Creek-facing landslide scar displays four lithologically distinct units, listed in ascending order (Figure 5): A) Basal brown poorly sorted gravel, B) laminated clay and silt in alternating layers, C) sand, D) uppermost unsorted gravel diamict.

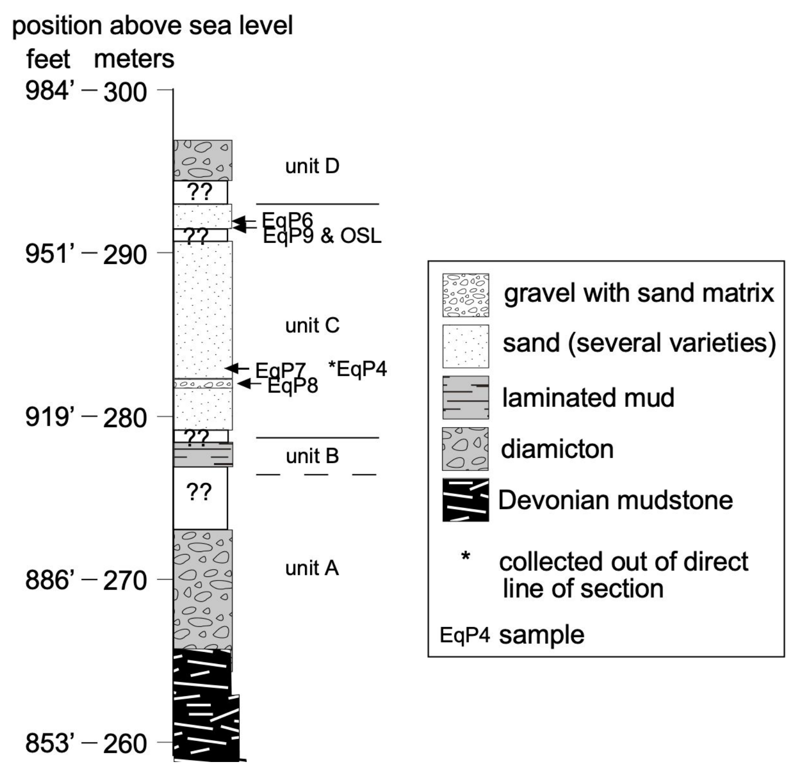

Figure 5. Stratigraphic section S1 (see Figs. 3, 4 for location). Intervals above the basal diamicton with question marks represent gaps in stratigraphic continuity between dug pits.

Sedimentology and physical stratigraphy

Unit A) brown poorly sorted gravel

Pebble, cobble, and infrequent boulder gravel in a fine, muddy matrix overlies Devonian strata, exposed to examination by D. Karig in 5 pits. This unit is at least 7 m thick, and potentially 11 m given the covered upper boundary. This is a clast-diamicton till with a fine sand to clay matrix, apparently with the fraction of matrix and sand content of the matrix increasing at higher stratigraphic levels. Cobbles with diameters of 4 to >10 cm are angular to rounded. Clasts are dominated by local lithologies. Clasts of rock types exotic to the Fall Creek catchment are more rounded. Whereas there is no visual evidence of layering, in the <0.5 m wide pits it would be difficult to recognize a weak organization into beds.

Unit B) laminated clay and silt in alternating layers

Overlying Unit A across a covered interval, Unit B displays interbedded gray clay and tan medium to coarse silt. The details were revealed in a single 1.5 m high pit face (Fig. 6a). This facies, which exceeds 1.5 m thickness, is characterized by prominent thin lamination, in both the gray clay-dominated beds and the tan silt beds. Seven clay-dominated beds are exposed, of which the lowest is thickest (23 cm) and the highest is thinnest (2 cm). These are silver-gray to slightly pinkish gray in color. The lowest of the clay intervals lacks well differentiated coarser beds. In contrast, within the second, fourth and sixth clay intervals, thin silt beds interrupt the clay. Centimeter-thick laminae are dominantly horizontal (Fig. 6b,c), yet some examples are broadly curved, mimicking the configuration of the top of an underlying silt bed. These laminae are composed of finer-scale couplets of interbedded gray clay and tan silt, which average 1-2 mm thick (Fig. 6d,e, black lines), and the silt layers display additional lamination (Fig. 3d,e, red lines). For the samples illustrated (Fig. 6d,e), the contact at the top of a gray clay lamina is sharp in nearly all cases whereas, for 80% of the laminae, the contact above a tan silt lamina is gradational.

Medium to coarse silt (0.015-0.062 mm) grains comprise the seven tan silt beds, which are 7 to 20 cm thick. At least the lower five silt intervals display complex ripple forms, which are asymmetric, preserve both lee and stoss faces, have an amplitude of 2-3 cm and wavelength of about 10 cm, and reveal a steep angle of climb toward the northwest quadrant.

Disaggregation of some of the clay-rich beds revealed abundant plant material. In the second clay bed from the bottom, the plant material is segregated into discrete laminae. In the third clay bed, plant material occurs but may be dispersed rather than in discrete layers. The organic material is largely roots (Dorothy Peteet, personal communication to Dan Karig, 2022). Karig (2022) interprets a portion of the plant material in discrete laminae to be depositional rather than entirely modern because it is fragmentary.

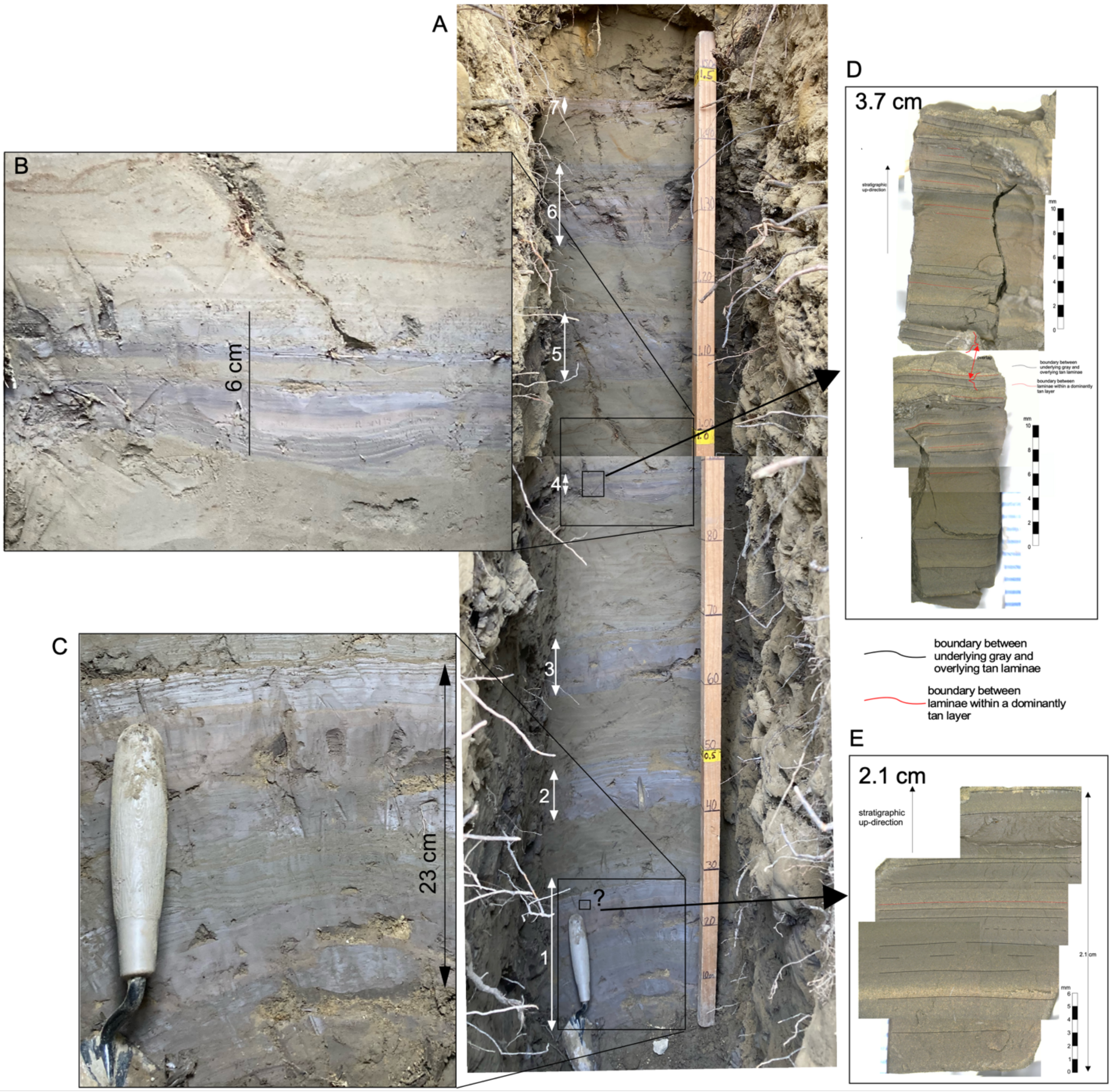

Figure 6. Photographs of unit B. A) Photomosaic of the full pit exposure reveals 7 beds of laminated clay (designated with white numbers and white double-headed arrows) and tan laminated silt interbeds. The 1.5 m long Jacob's staff is marked in 10 cm intervals. B) Closeup of the 4th clay interval and adjacent silt beds. Climbing ripples are prominent near the top of the photo. C) Closeup of the lowest clay bed. D) Photomicrograph of an interval within the 4th clay bed. Scale bar in millimeters. E) Photomicrograph of an interval within the 1st clay bed. Scale bar in millimeters.

Unit C) sand

Above unit B is a covered interval < 1 m thick, followed by sands designated as unit C. Unit C is approximately 15 m thick and exposed in 5 pits (four of which are shown in Fig. 7). The dominant characteristic is sandy coarse silt to fine sand with complex laminations. The thin laminations in the lowest meter are inclined steeply (35-80° from horizontal) and discontinuous

(Fig. 7a), suggestive of post-depositional rotation and micro-faulting rather than of primary dip. Sharply overlying the inclined lamination sub-facies is an interval nearly 50 cm thick of pebble gravel interbedded with lenses of silt, and capped by 10 cm of silt (Fig. 7b). The gravel is noteworthy for black patina on the grains. Sharply overlying the gravel-silt interbeds occurs very fine to fine sand with inclined laminae, likely in its primary depositional orientation.

Succeeding upward, next occur approximately 30 cm of thinly interlaminated clay, like in unit B, and fine sand. Large ripples in the sand display 3-6 cm amplitude and preservation of only the stoss sides of the bedforms (Fig. 7e). Successive clay and sand laminae range in thickness between roughly 0.5-3 cm. The overlying 20 cm are dominated by very fine sand in climbing ripples roughly 5 cm high with only stoss-side preservation (Fig. 7f). Karig (2022) reports that the ripple foresets face NW, indicating migration in that direction. Some of those ripple sets are capped by 1-2 cm-thick laminae, with millimeter-scale internal lamination of clay and very fine sand, which drape the form of the underlying ripple.

Above another exposure gap on the order of ≤1 m thick, sand dominates for 1.5 m thickness (Fig. 7d). The sand is moderately sorted very fine sand to fine sand (Table 1, samples EqP6, EqP9). Horizontal lamination is weakly visible.

Karig (2022) reports that a sample from Unit C yielded an OSL age of 21,425±930 years.

Table 1. Grain size data for section S1, for samples that were dry sieved. The grain size populations are expressed as percentages of the total sample. Stratigraphic positions of samples are marked in Figure 5.

S1 section	Informal Unit	< 0.063 mm	0.063-0.125 mm	0.125-0.25 mm	0.25-0.5 mm	0.5-1.0 mm	1.0-2.0 mm	>2.0 mm
		mud	very fine	fine	medium	coarse	very coarse	gravel
EqP4	C	55.6	38.9	5.6	<5	<5	0.0	0.0
EqP6	C	12.5	43.8	37.5	6.3	0.0	0.0	0.0
EqP9	C	7.1	35.7	57.1	<7	<7	0.0	0.0

Figure 7. Examples of the sedimentary structures in unit C, a sand facies. On the orange notebook is length scale in centimeters. Photos E and F are closeups of details in C, in pit DK10. Pits DK8-11 occur in ascending stratigraphic order.

Unit D) unsorted gravel diamicton

Large cobbles and boulders are prominent in the uppermost unit (Fig. 5), an unsorted gravel with a muddy matrix. As revealed in both natural outcrop and one dug pit, clasts are subangular to subrounded. An outcrop at the same elevation occurs about 400 m ENE of S1 (exposure S3, Fig. 3, 4). I interpret the materials to be the same stratigraphic interval in Unit D, and to provide more insight to the organization of this unit. Outcrop S3 is described thoroughly below.

<u>Clast provenance</u>

A sample of the pebble interval within unit C contained 46 clasts, one quarter of which had diameters of 2-7 cm, and the remainder were of diameters between 0.5-1.5 cm. The ≥ 2 cm clasts are all composed of siltstone to very fine sandstone. The set of small clasts are visually similar to the large ones. We interpret all these clasts to be derived from bedrock within the Fall Creek catchment.

As noted above and by Karig (2022), clasts within unit A, the basal diamicton, are almost entirely of local bedrock origin. Exceptions are limited to rounded clasts of exotic compositions.

Interpretations

The diamictons of units A and D are each interpreted to be glacial till.

The interlaminated clay and silt of unit B and the sands of unit C are deposited from liquid water, differing from one another in the velocity of water movement. The clay lamina, whether in unit B (Fig. 6) or in the middle sector of unit C (Fig. 7c,e,f), mark extended periods of very still conditions. In both cases, the clays appear to drape the immediately underlying bed configuration, including adopting ripple shapes where they overlie silt or sand ripples although not displaying ripple growth within internal lamina.

The rippled silts of unit B and rippled sands of unit C are noteworthy for the extent to which the ripples climb and the preservation in B of both stoss and lee sides. This preservation reflects a high degree of deposition relative to the forward translation of the ripples, which indicates that each accumulated from steadily flowing water that contained abundant silt and sand.

The environmental conditions under which unit B's laminated mud-sized material accumulated were likely very similar to the conditions under which unit C's sand-dominated material accumulated. The sharp contacts overlying each gray clay laminae in B and the upward-fining gradation of silt lamina into the superjacent clay lamina imply that water currents delivered water with suspended fine material and bedload to S1's location and then flow ceased, allowing settling from suspension.

Insight to the environmental conditions may come from examples of proglacial lakes and interconnected streams near modern retreating valley glaciers. Liermann et al. (2012) documented the distribution of bedload and suspended sediment in a small proglacial lake adjacent a retreating valley glacier in Norway. They showed that gravel-sized particles are retained in deltas between the ice front and a small pro-glacial lake, whereas sand and finer material enters and partially traverses the lake. Coarse silt and very fine sand are carried in suspension within the lake water, and about 20% of this size fraction bypasses the lake to continue down the valley's drainage. The net suspended sediment transfer is sensitive to not only seasonal glacial melt but also to heavy rainfalls in the watershed. Bogen et al. (2015) examined the hydrology and sediment transfer for three small pro-glacial lakes adjacent Norwegian valley glaciers. These lakes also act as sediment traps which effectively partition glacier-fed sediment: bedload and much of the suspended load is retained in the small lakes within over-deepened parts of a valley. However, for these examples, 16-64% of the original suspended sediment bypasses the lakes to continue downstream in the valley.

One hypothesis for the environmental conditions at S1 that delivered sediment and deposited units B and C involves a system of pools and channels downstream of a retreating ice front located near the Fall Creek paleo-valley. Seasonal variations in melt rate and rainfall events would regulate the flow into and out of pro-glacial lakes. The near absence of gravels suggest that there existed a pro-glacial lake and delta upflow of S1, which spilled downstream only the grains small enough to move as suspended load. Down-valley there may have been a series of pools with slow water flow and stream sectors with more vigorous channelized flow, and it is in that mixed fluvial environment where units B and C might have accumulated. The rippled silts and sands indicate transport as bedload of the coarser fraction of sediment which bypassed the proglacial lake, with deposition during the times of comparatively high flow velocities and high sediment supply, such as during intervals of peak melt or rainfall. In contrast, the settling of clays from suspension implies seasonal cessation of water flow and likely that deposition occurred below the frozen surface of a pool of water, in which the ice lid prevented wind-disturbance and enabled clay deposition. D. Karig (personal communication, 2022) notes that incorporation of contemporary detrital root material (Karig, 2022) is suggestive that the pools were located adjacent a stream that traversed a vegetated plain, such as in an oxbow lake. Plausibly the 7 beds dominated by clays in unit B represent 7 years, whereas the millimeter-scale alternations of clay-rich and silt-rich sediment indicate slight variations in water flow during single cold seasons. The complete freezing of the water column in the shallow pool may have disturbed the sediment bed, creating folded and fractured sediment layers.

Section S2

A series of minor natural exposures along a steep tributary on the north side of Fall Creek, spanning approximately 42.45758 N, -76.44805 W to 42.45722 N, -76.44738 W, were slightly enhanced by digging pits (Figs. 3, 4a, site S2). These are described by Karig (2022) as site B. While highly discontinuous, they reveal a basal till (Karig, 2022) in direct contact upward with a 70 cm interval of laminated clay (Fig. 8a,b,c), overlain across a narrow covered zone by >90 cm of silty sands (Fig. 8d,e; Table 2). Moving up the gully, a longer covered zone is followed by a thick upper gravel (Fig. 8f). This vertical series of facies is like that in S1, although the total thickness of fine-grained facies (approximately 2 m) at S2 is much less.

Like at section S1, the laminations in the mud unit are sub-millimeter (Fig. 8c), but they lack a strong differentiation of particle size among the laminae. The unit above the laminated mud is somewhat coarser, silt and sand, and layering is at best weakly visible. Three sampled and sieved horizons show that silt is more abundant than very fine sand (Table 2) in the lower ~50 cm, with very fine and fine sand becoming dominant upward. The position and upper contact above the sandy-silt unit is completely hidden below a wide covered zone.

The uppermost gravel facies consists of angular to sub-rounded pebbles to large cobbles that float in a matrix of mud to coarse sand (Fig. 8f). This diamicton corresponds to the till of Valley Heads readvance origin.

Karig (2022) reports that a sample from the silty sand yielded an OSL age of 20,035±835 years. He interprets this S2 series of facies to represent a basal till whose top was subsequently eroded by a stream, leaving a lag of rounded boulders, followed by a stream system in which the layered clay and silt accumulated in quiet pools, similar to and contemporaneous with section S1.

Table 2. Grain size data for section S2, for samples that were dry sieved. The grain size populations are expressed as percentages of the total sample. Positions of samples 5a, 5b, and 5c are marked in Figure 8d.

S2 section	< 0.063 mm	0.063-0.125 mm	0.125-0.25 mm	0.25-0.5 mm	0.5-1.0 mm	1.0-2.0 mm	>2.0 mm
	mud	very fine	fine	medium	coarse	very coarse	gravel
5a	29	57	14	trace	trace	0	0
5b	71	29	trace	trace	trace	trace	0
5c	67	33	trace	trace	trace	0	0


A
B
C
D
E
F
10 cm
laminated clay
boulder diamict
1 cm
~1 mm
10 cm
5a
5b
5c
10 cm

Figure 8 (preceding page). Photos of the sediments at section S2. A) In the basal meter a boulder-bearing diamict is, overlain by about 70 cm of laminated mud. B, C) Laminations within the mud interval are sub-millimeter thick, organized into centimeter-scale alterations of light brown and light gray lamina. D) A meter-thick unit dominated by sandy silt overlies the laminated muds. Samples 5a, 5b, 5c detailed in Table 2. E). Layering is weak to absent in the sandy silt unit. F) A gully-bottom exposure of the upper sediments shows angular clasts in an unsorted matrix.

Section S3 (upper gravels in Valley Heads till)

An excellent 16' (5 m) thick natural exposure of the upper till occurs 1800 ft (550 m) ENE of S1 (42.456992 N, -76.451955 W) (Figs. 3, 4, location S3). Exposed are the uppermost sectors of the till, in an overhang at the top of the valley wall. At least 30' (10 m) of covered till likely underlies this interval, expressed only by the soil parent material properties. Lateral variability of the physical sedimentology is expected, so comments are included about another nearby set of outcrops.

Sedimentology and physical stratigraphy

The gravel is weakly layered, with bed variations spaced one to several meters (Fig. 9).

The lowest exposed meter contains the coarsest boulders, accompanied by pebbles and cobbles (Fig. 9F). Its matrix contains mud, sand and pebbles.

Moderately sorted pebbles and cobbles comprise the 1.8 m thick middle unit (Fig. 9a,c). Well-developed imbrication of cobbles shows east-to-west fluid transport (Fig. 9d). A localized lens of well laminated silt is about 15 cm thick but continues only 50 cm horizontally, nested adjacent to large cobbles (Fig. 9e).

The uppermost 2.5 m unit reveals gravel clasts with sizes from cobbles to rare boulders, which are angular to rounded (Fig. 9b). Accompanying those large clasts are particles ranging in size from mud through sand and pebbles, such that, overall, the deposit is very poorly sorted with a gradation across all particle sizes, rather than bimodal.

Figure 9: Outcrop location 42.456992 N, -76.451955 W. A) Overall outcrops, with dashed lines demarcating boundaries between three beds of differing textures, designated lower (L), middle (M) and upper (U). Black gloves in foreground provide scale. In B-F, a 5-cm-long red jackknife provides scale. B) Upper gravel, unsorted, with angular to rounded clasts. C) Middle unit of moderately sorted gravel. D) Middle unit cobbles (and molds of cobbles) display imbrication corresponding to flow from right to left (east to west). E) Middle unit lens of well laminated silt (above jackknife). F) Lower unsorted unit with clasts to boulder size.

Clast provenance

A sample of clasts from the middle interval of sorted gravels establishes that the parent rock was almost entirely siliciclastic siltstone to fine sandstone like the nearby Devonian bedrock (Table 3). Infrequent clasts include weakly consolidated, rounded intraclasts of gray clay and brown sand.

Table 3. Composition of clasts in a middle interbed of moderately well sorted gravel, from location 42.456992 N, -76.451955 W. 42 clasts were collected in a size range from 1-4 cm.

number of clasts	description	lithologic class	source location
36	medium gray, or medium greenish-brownish gray, or medium brownish gray; rarely calcareous; siliciclastic grains of sizes silt, very fine sand, and fine sand	siltstone to very fine sandstone	Devonian rock available locally
1	light gray; slightly calcareous; fine to very fine grained sand	calcite-cemented quartzose sandstone	Lower(?) Paleozoic source rock, not locally available
1	medium sand size; slightly calcareous; grains of feldspar and lithics, as well as quartz	calcite-cemented lithic arkose	Middle(?) Paleozoic source rock, not locally available
4	light- to medium-gray; skeletal fragments in grainstone to wackestone	limestone	Devonian source rock, available in Cayuga Trough

Interpretations

The sedimentary fabrics are variable, some indicative of transport without liquid water and some indicating water transport. Those fabrics and the weakly developed bedding are interpreted to indicate a comparatively water-rich bed environment below Valley Heads readvance glacial ice.

Varna High Bank

Varna High Bank (VHB) is a continuous exposure which spans about 150 m length along the western wall of a meander in Fall Creek (Figs. 3, 10). The exposure is excellent although most of it must observed from the east bank of Fall Creek, because of very steep and unstable slopes. The lower sector is variably exposed year to year, due to progressive accumulation of talus followed by removal during Fall Creek high discharge events. Reportedly, a decade ago parts could be accessed by descending in some west-bank gullies (D. Karig, personal communication 2020), but in recent years erosion of vertical faces has cut access from those gullies while excessive discharge of Fall Creek also usually made the creek too deep and wide to wade. Parts of VHB were accessed on foot in June and August 2020, a season of drought and low discharge.

Six lithologically distinct units occur, listed in ascending order (VHB-Figures 10c, 11): A) brown poorly sorted gravel, B) sorted, rounded-clast gravel, C) interbedded sand and cobble-size gravel, F) gravel beds with subsidiary sand, organized in tabular inclined beds, G) interbedded gravel and sand, and T) gray diamicton. Karig (2022) treats units A-C as a single unit, units F and G as a second unit of deltaic origin, and unit T as Valley Heads till.

Sedimentology and physical stratigraphy

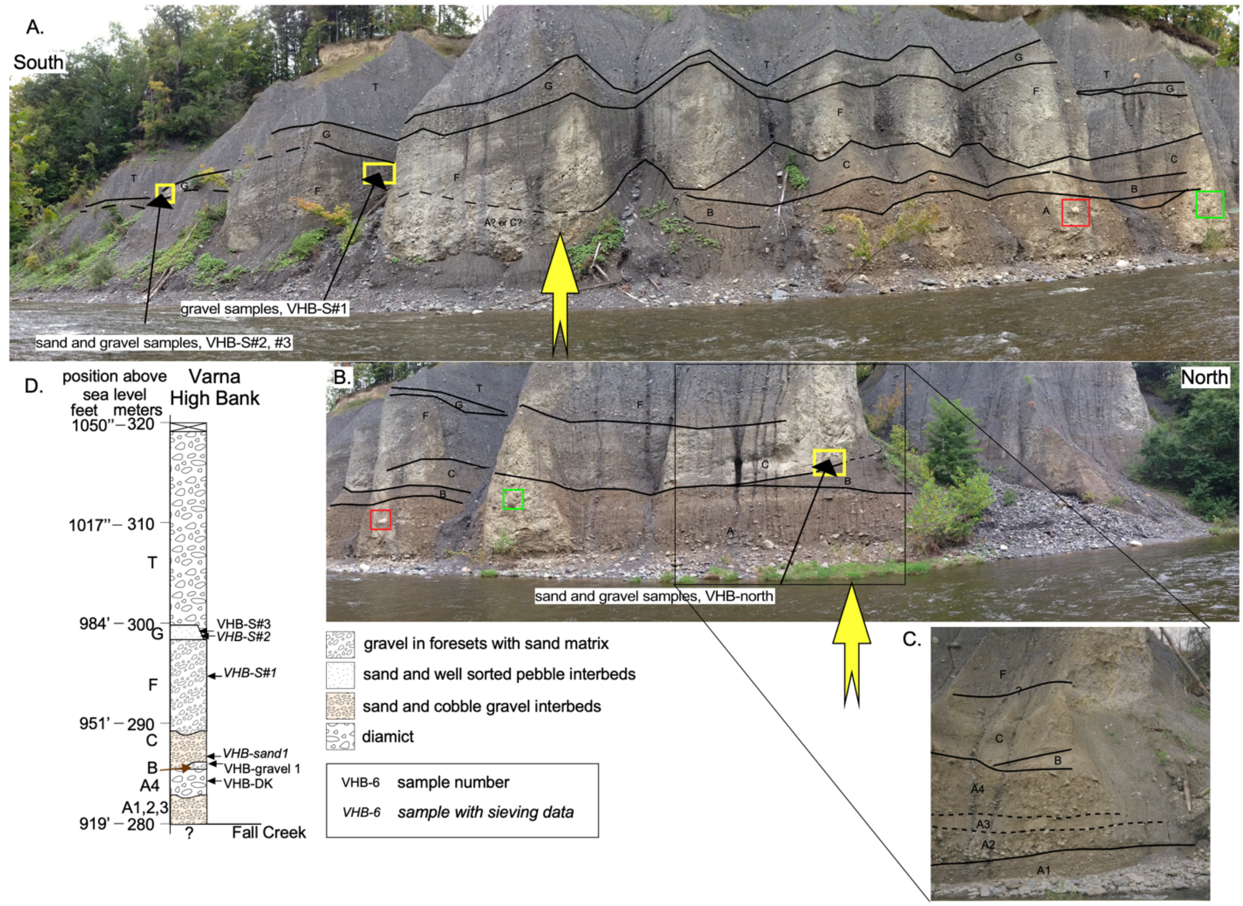

Figure 10. Panoramic views of the Varna High Bank, viewed from the eastern shore (north on right; south on left). Labeled samples are described in the text. A) Southern end, from September 2013. B) Northern end, from September 2013. The panorama southern sector (A) mates with the northern sector (B) at boulders marked by red and green squares. C) Northern end (box in B) from May 1993. D) A stratigraphic column is a composite of information about the lower units (A-C) collected at the northern end of the outcrop belt (position of yellow arrow in photo B). Information for the upper units (G, F, T) collected in the south-central sector of the outcrop (position of yellow arrow in photo A), with thicknesses measured using a Laser Range Finder.

Unit A) Thickly bedded brown gravel.

Between 2013 and 2023 this gravel unit has been partially to largely covered by scree at the base of the cliff (Fig. 10B). Yet a set of photos from the other shore of the creek dated early May 1993 shows the site cleared of scree to near creek level and reveals well the gross features of unit A (Fig. 10C), arranged in meter-scale beds of variable clast sizes and fabric. The lowest meter, A1, is a pebble to cobble gravel with inclined sub-parallel lamination. The overlying layer, A2, is variably 1-2 m thick, comprised by subrounded to sub-angular cobbles and boulders. Bed A2 has little or no fine-grained matrix and fines upward. The third differentiable layer, A3, is less than 1 m thick and appears to be a pebbly sand. The uppermost layer, A4, is 2-3 m thick, with angular to sub-angular boulders visible among cobbles. Layer A4 is moderately sorted, clast-supported, with meter-scale beds defined by variations in grain size, including some beds that appear sandy (Fig. 10B). The sharp lithologic change and color change between Units A and B suggest that the top contact is an unconformity. The unit persists much of the length of the High Bank outcrop, but is so extensively covered by scree that the downstream termination is unclear (Fig. 10A).

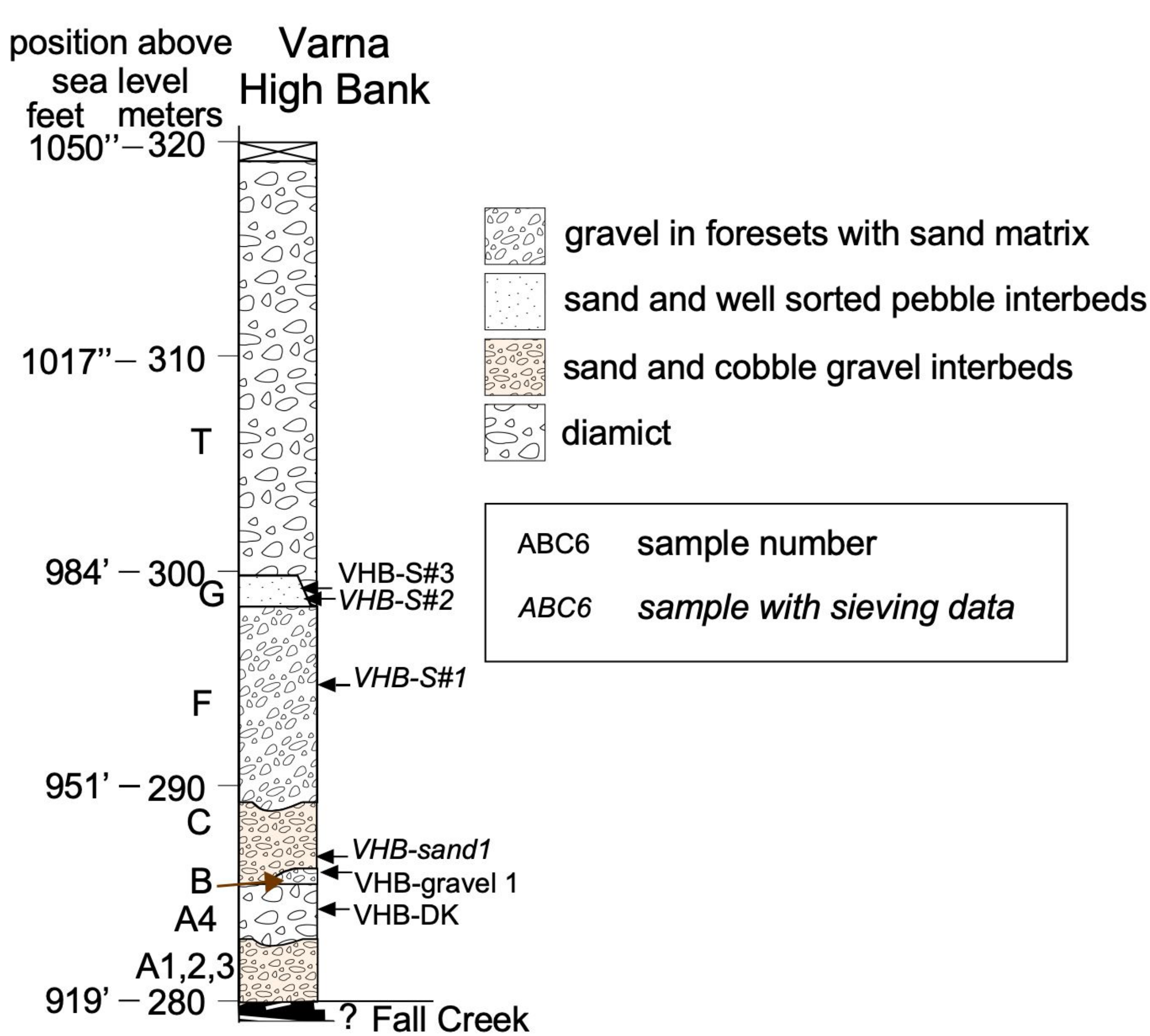

Figure 11. A composite stratigraphic column of Varna High Bank sections, based on two sections measured with a Laser rangefinder (at the upstream end of the outcrop units A-C, and in the south-central part of the outcrop units F-T, positions shown in Figure 10).

Unit B) Purplish gray to brown, sorted, rounded-clast gravel.

This unit crops out over approximately 80 m distance. It is about 2-3 m thick at the farthest upstream sector of Varna High Bank (Fig. 10b), thins over the next 15 m to pinch out entirely, and then it reappears but varies markedly in thickness (Fig. 10a). The irregularity is due to erosion of its top. Where the outcrop was visited at the north end, the dominant clasts are rounded, medium- to coarse-pebbles with a small percentage of small cobbles, of spheroidalshape. The gravel is moderately to well sorted (Figure 12). If correctly mapped (Fig. 10a), the unit includes a higher percentage of cobbles farther downstream (southward direction in outcrop).

Figure 12. Pebble to small cobble gravel of unit B, which is moderately- to well-sorted.

Unit C) Interbedded sand and cobble-size gravel.

This unit crops out over at least the same distance, ~80 m, as unit B, but its downstream termination is difficult to distinguish from Unit A where there is extensive scree and mud cover (Figure 10A). It is light brownish gray, with interbeds of gray sand and brown gravel that total about 3 m thickness. In the lower half of unit C, beds of sand 30-40 cm thick dominate (Fig. 13). The sand is well sorted, dominated by medium size sand grains (Table 4, sample VHB-sand1). Lithic grains are abundant. Laminae define gently dipping surfaces with no defined ripples (Fig. 13). In the upper half of unit C, gravel dominates in beds 30-40 cm thick where measured, but >1 m thick elsewhere in the outcrop. The dominant gravel clasts are cobbles, with less frequent boulders to a maximum diameter of 30-40 cm. The gravel clasts are sub-angular to sub-rounded. The base of unit C is generally planar, across an erosional contact with the underlying strata. The top of the unit shows erosional relief, which leads to a variation of thickness (Fig. 10a).

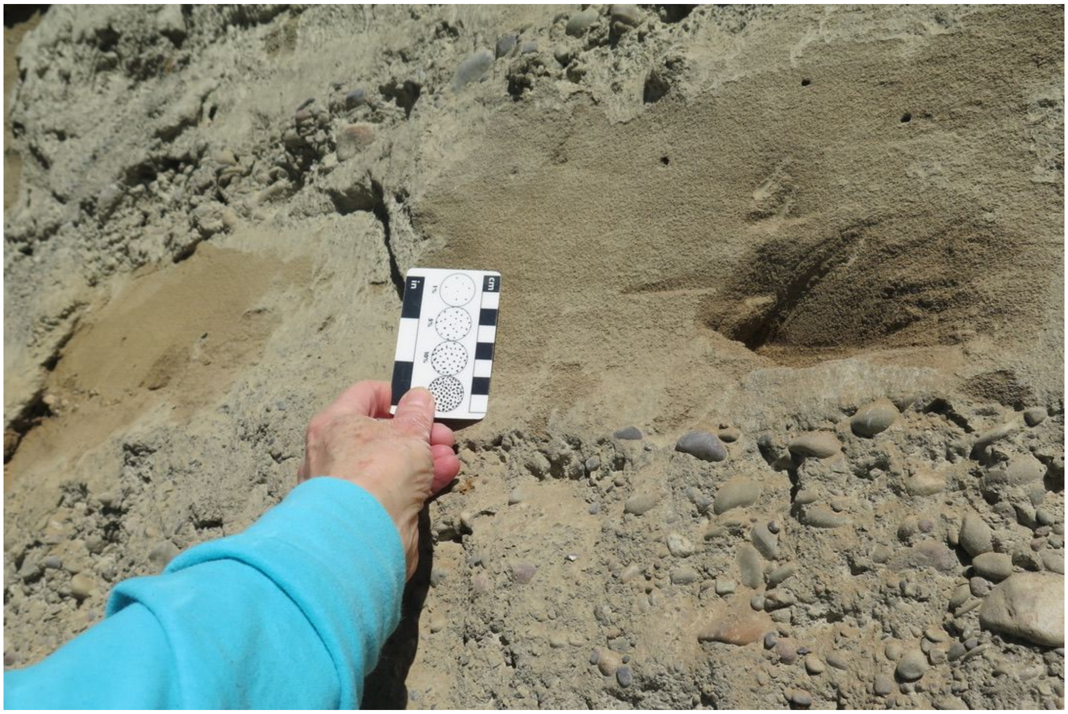

Figure 13. The lowermost bed of medium grained sand in Unit C. The gravel at the base of the photo corresponds to Unit B. The overlying gravel is an interbed within Unit C.

Table 4. Grain size data for Varna High Bank sands, which were dry sieved. The grain size populations are expressed as percentages of the total sample. Stratigraphic positions of samples are marked in Figures 10 and 11.

Varna High Bank sediment sample	Informal Unit	< 0.063 mm	0.063-0.125 mm	0.125-0.25 mm	0.25-0.5 mm	0.5-1.0 mm	1.0-2.0 mm	>2.0 mm
		mud	very fine	fine	medium	coarse	very coarse	gravel
VHB sand 1	Unit C (north end) (Figs. 11, 13)	2	2	10	84	2	trace	trace
VHB-S#2	Unit G (south end; Figs. 11, 15))	10	14	43	38	2	0	0

Unit F) Gravel beds with subsidiary sand, organized in tabular inclined beds.

Unit F is the most unusual facies of the Varna High Bank, not reproduced at outcrops either upstream or downstream. The unit varies in thickness from 9 to 10 m; a progressively lower elevation of the upper contact in the southern part of the outcrop produces thinning (Fig.

10a). Unit F is dominated by medium brownish gray gravel, whose interbeds of varying clast size define tabular, parallel, large-scale inclined stratification (Fig. 14a, b). Beds differ in texture, ranging from infrequent tan to gray thin beds of coarse sand, to much more abundant medium to thick pebble beds to bouldery cobble beds, all of which are moderately to well sorted (Figure 14c). Individual inclined beds traverse the entire thickness of the interval, up to 10 m, although the thickness of individual beds tends to increase somewhat in a down-dip direction, resulting in slightly shallower inclination near the bed toes. Orientations of the inclined beds (Fig. 14a, b), determined with a Laser range finder (Table 5), show the beds strike to the northeast and dip 10-44° to the southeast.

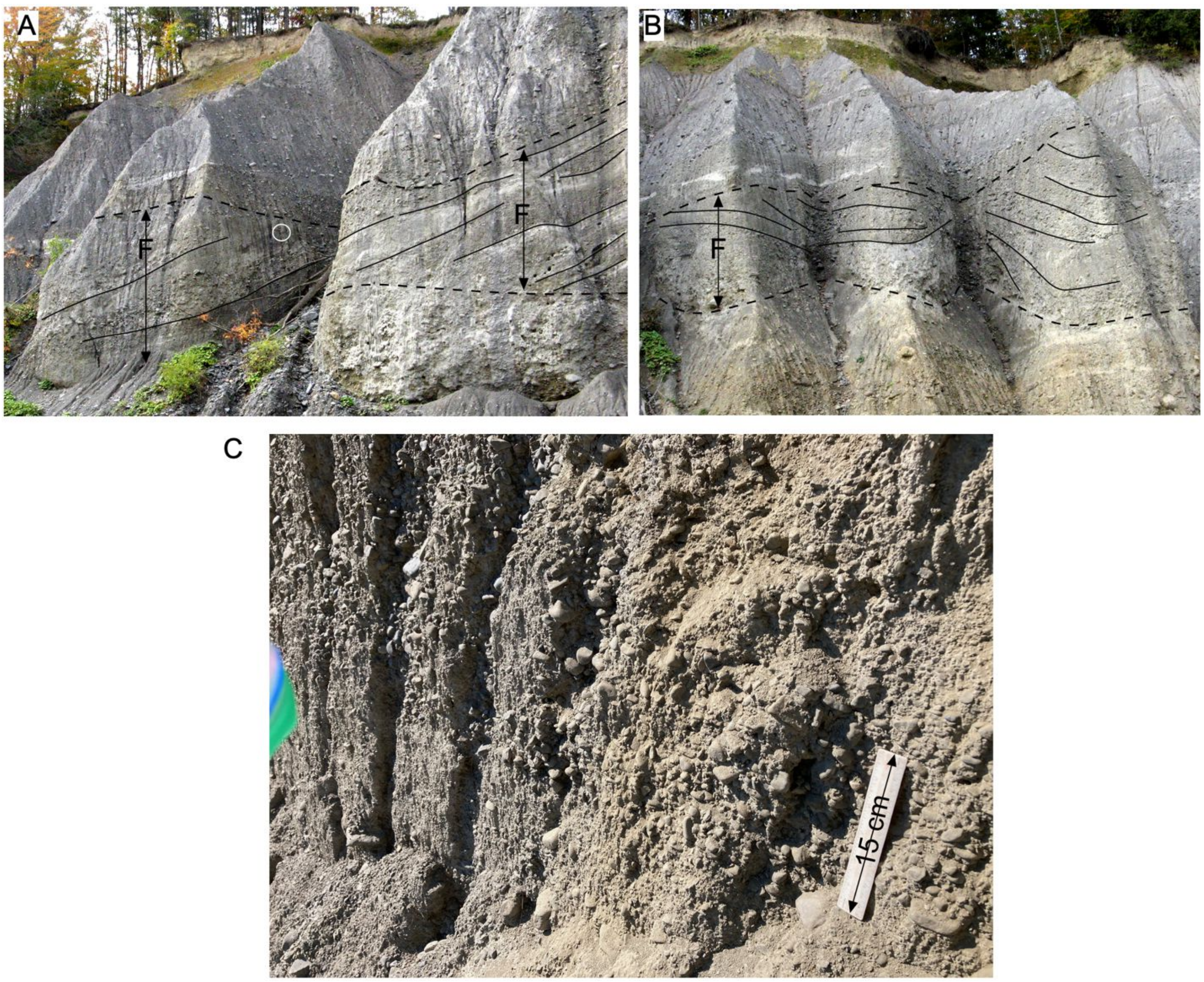

Figure 14. A) and B) Photos, with contrast enhanced, of Unit F. Dashed lines map the upper and lower contacts of Unit F, and solid lines illustrate boundaries between thick, tabular, inclined beds of interbedded gravel within Unit F. The white circle in A marks the location of photo C and sample VHB-S#1. C) A close-up of a bed of coarse pebble to cobble gravel overlying a bed of fine pebble gravel, located at white circle in A.

Table 5. Unit F bed orientations. Bedding orientations measured using Laser Range Finder operated by R.W. Allmendinger.

Example	strike	bedding inclination (clockwise of strike direction)
1	62.4	20.5
2	75.8	9.6
3	53.1	15.8
4	53.4	30.6
5	35.8	42.3
6	22.9	43.6

Unit G) Interbedded gravel and sand

Unit G is sheet-like in distribution though variable in thickness; it is approximately 1.3 m thick where measured with a Laser Range finder. Cobble-size gravel dominates, with interbedded sand beds (Fig. 15).

At the southern end of Varna High Bank, interbeds of pebble gravel and sand could be directly examined and sampled. Beds that appear white where weathered are medium brown sand in fresh exposure, forming a 40 cm thick lower sand bed and an upper sand bed exceeding 50 cm thick. There, both the fine to medium grain size sand beds and the intervening pebble bed are well sorted. The sand bed is well laminated, dominantly in sub-horizontal mm-thick laminae and also in local centimeter-scale sets of cross laminae, and rich in lithic grain compositions. The lower sand bed overlies the subjacent cobble and pebble bed of Unit F across a sharp contact that is strongly irregular at the centimeter scale (Fig. 15, base of sand), suggestive that the underlying bed was indurated prior to erosion. Pebbles are sub-angular to well rounded. One pebble bed displays imbrications (Fig. 15, above sand) indicative of south-directed paleo-flow.

Figure 15. Unit G at the south end of the Varna High Bank outcrop. A bed of gravel is interbedded with brown sand. The gravel displays imbricated, rounded clasts dominated by pebbles with scarce cobbles. The underlying sand is laminated, well sorted, and its grains are of fine to medium sand size. Below the sand, the irregular contact above gravels of Unit F is exposed.

Unit T) Gray diamicton.

The uppermost unit, a gray diamicton, is 23 m thick at the downstream end of the Varna High Bank and about 18 m thick at the upstream end (Fig. 16). The outcrop lacks vegetation or soil, yet much of it is shrouded by a thin crust of muddy sediment washed down from higher levels of the outcrop, obscuring the details of sediment texture. Because of the overhanging eroded scarp at the top and very steep slopes, close examination of the material is not possible.

The unambiguous dominant properties of Unit T at Varna High Bank are its light to medium gray color and that it is a matrix-supported cobble to boulder gravel. The lower third of the unit is relatively homogeneous with numerous dispersed boulders (Fig. 16a, d). The middle third displays vague bedding with bed thicknesses of several meters (Fig. 16a, within rectangle; Fig. 16c), in which boulders are scattered irregularly. The upper third includes better definition of beds (Fig. 16b) between zones of unsorted matrix-supported gravel and moderately sorted gravels, plus a strong oxidation overprint which turned much of this interval light brown.

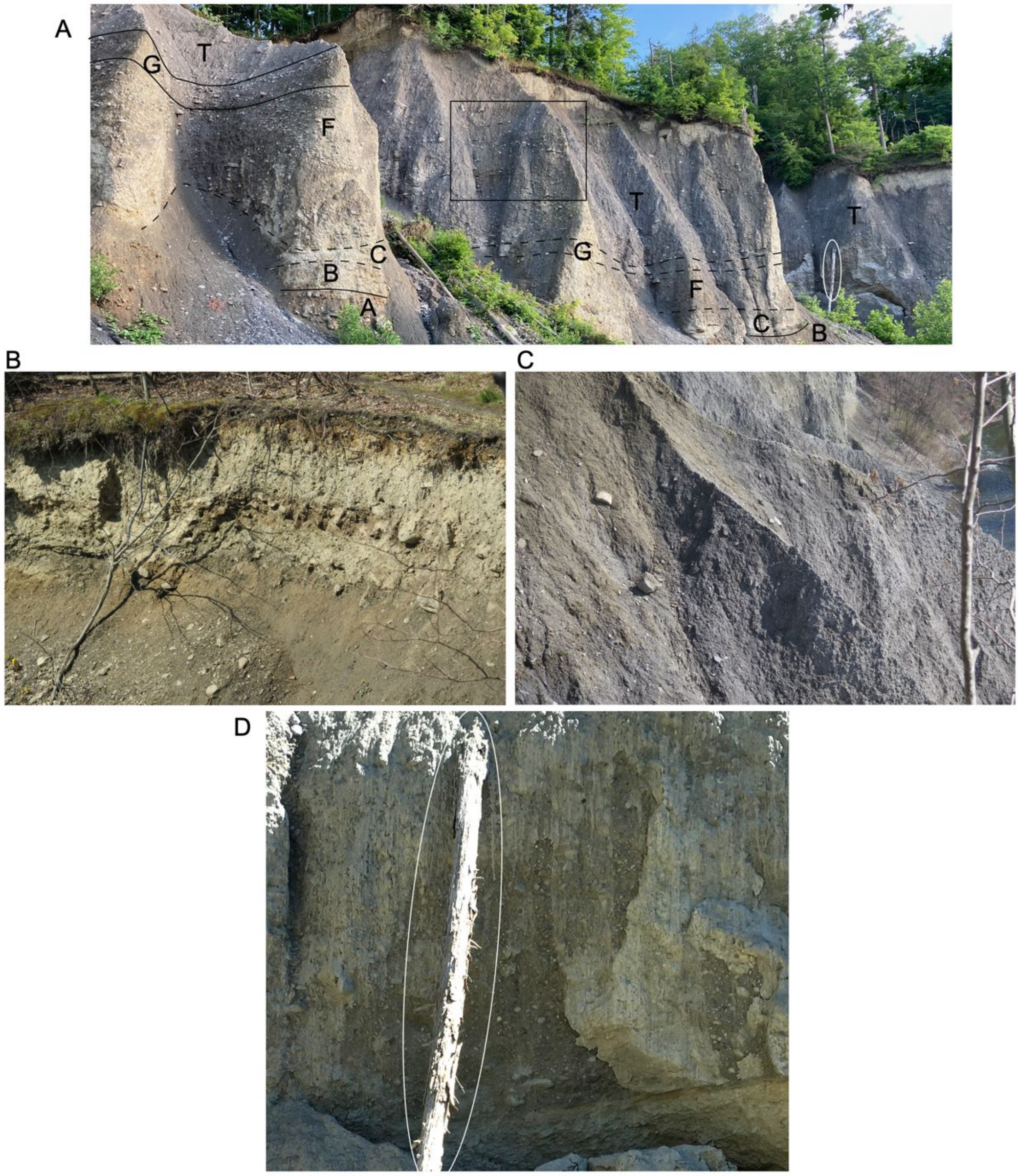

Figure 16. Unit T photographs at Varna High Bank. A) Overview of the northern (upstream) VHB outcrop, showing about 20 m thickness of unit T. Note the overall gray color and the light brown, oxidized, uppermost several meters. The rectangle marks the middle interval with weakly defined very thick beds. The white oval marks a fallen tree trunk also visible in photo D. B) View of the upper oxidized zone, with meter-thick bedding. C) Middle and lower sector of unit T. The upper horizons in the photo are roughly 5 m below the top of the valley wall. Boulders are widely dispersed in a finer matrix. D) A closer view of the lower sector of unit T, with oval around fallen tree matching oval in photo A. An overhang area is well exposed and illustrates that large cobbles and boulders float in a finer grained matrix.

Clast provenance

Unit B. The population of 75 clasts in sample VHB-gravel 1 (Figs. 11, 17a) includes 33% sandstones of types not exposed in the immediate region around Ithaca, 38% limestone or dolomite that are not exposed in the immediate region around Ithaca, and 21% very fine-grained sandstone and siltstone similar to Devonian strata that outcrop around Ithaca. Overall, roughly 80% of clasts were derived from Paleozoic strata that are not exposed in the modern Fall Creek drainage basin and yet occur several tens of kilometers north of Ithaca.

Unit F. For 110 clasts in sample VHB-S #1 (Figs. 11, 17c), 81% are very coarse siltstone to very fine sandstone like the dominant Devonian strata near Ithaca and 9% are gray limestone similar to the Tully Limestone that crops out nearby in the Cayuga Trough or about 30 km north across upland surfaces. The remaining 10% of the population are siliciclastic rocks more likely sourced from Paleozoic units lower in the section than the Devonian.

Unit G. Gravel sample VHB-S #3 (Fig. 11, 17b) has the following compositions among 60 clasts. 48% of the clasts are limestones, both light brown calcarenites and gray fine-grained limestones. Coarse siltstone to sandstone compose 50% of the clasts, with the majority yellowish brown to light gray with calcite cement, and rare quartz-dominated sandstone with quartz cement which are white to pink. A single clast is coarsely crystalline and likely an igneous rock. The parent rocks for these clasts are not today exposed in the Fall Creek catchment, although they are common Paleozoic lithologies now exposed greater than 60 km to the north.

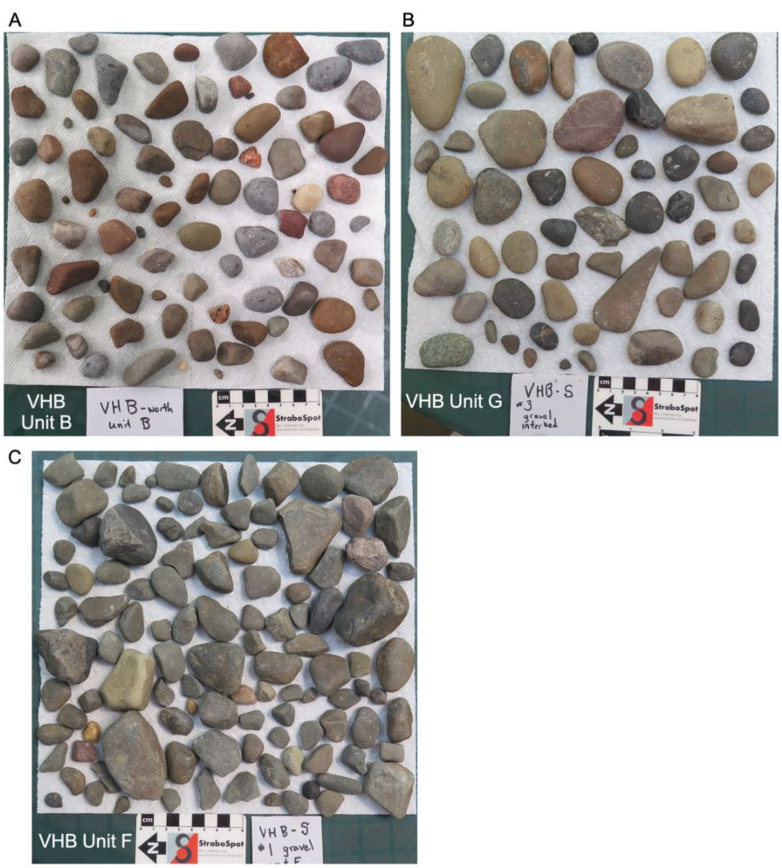

Figure 17. Clast populations for gravels in Units B, F and G. A) The clasts of Unit B are dominated by non-local lithologies (sample VHB-gravel 1). B) Clasts of Unit G are dominated by non-local lithologies (VHB-S#3). C) Clasts of Unit F are representative of the Devonian bedrock immediately underlying Quaternary sediments in Tompkins County, and hence of local source.

Interpretations

The relationship of Unit A to laterally adjacent or underlying materials is highly uncertain. Only about 20 m distant from the upstream-most cliff face there occurs at the northwestern creek bank Devonian mudstone, with layering that is near-horizontal, in a block that is about 2 m wide but only tens of centimeters thickness crops out. Despite the lack of exposure in the intervening 20 m of soil, rubble and vegetation, one interpretation of this rock body is that bedrock is immediately subjacent to the upstream limit of Unit A. Nevertheless, only 150 m farther upstream there exists at the creek shoreline a block of Devonian strata, likely Tully Limestone, that is roughly 2 m X 2 m X 5 m. If downcutting by Fall Creek had stopped at a position 2 m higher than the current creek bed and if the inclined bedding planes were not visible, one might think this block was intact bedrock. The Tully Limestone(?) block is clearly an extremely large clast rather than an outcrop of bedrock, and this same situation must be considered for the Devonian rock adjacent the Varna High Bank outcrop.

Further uncertainty about lateral and vertical relations of Unit A exists because Karig (2022) reports that, in a prior year, there was a small exposure of laminated gray clay visible on the southeast bank of Fall Creek, about 50 m distant from the upstream end of the Varna High Bank outcrops on the opposing creek bank. Karig suggests that this clay may have originally been continuous with the varved clays exposed 900 m to the southeast, where they were extensively analyzed by Karig (2022). At that downstream site, the varved clays directly overlie a till and they are interpreted to be ice-proximal lake deposits slightly younger than 18,000 years (Karig, 2002). By proximity, the layered clay unit at creek elevation at the upstream end of Varna High Bank may underlie Unit A. Or plausibly, Units A, B, and C may all be a localized erosional remnant that does not extend laterally to the area with layered clay. If so, the layered clay might be younger than Units A, B and C, and immediately predate Unit F, an interpretation advanced by Karig (2022).

The limited horizontal distance of good quality outcrop of Unit A relative to the wide range of maximum particle sizes and fabrics of its thick beds make interpretation of its depositional environment particularly uncertain. The lower half of Unit A displays relatively high degrees of sorting in beds of distinct gravel sizes. The inclined laminations in A1 are suggestive of a migrating bar in a channelized flow. These features could either be products of subglacial water flow or of outwash near the melting margin of a glacier. The upper half, designated A4 (Fig. 10C), is less well sorted but clearly stratified, compatible with a general interpretation of deposition from a sediment-laden stream, whether subglacial or subaerial. Unit A's distinctive brown color suggests it experienced oxidation at the land surface during a relatively long-lived hiatus.

Units B and C are similar in that each accumulated where there was persistent steady flow of water, under conditions of a high supply rate of sediment. An erosional unconformity separates them, yet the environmental conditions were comparatively similar between the two. A steady flow suggests that there may have been either a very large catchment which modulated variability of discharge in the stream which transported units B and C, or alternatively that spill from a water body (e.g., lake or pond) upstream in the Fall Creek drainage basin sustained steady flow in the channel that reached Varna High Bank. The mixture of non-local with local pebble clast compositions are suggestive of glacial delivery of sediment to the source of the streamflow which transported and deposited units B and C.

The top of Unit C was eroded prior to deposition of the next overlying unit. A relatively important change in environment from C to F suggests a comparatively long-duration hiatus followed cessation of deposition of C.

Unit F is distinguished by tabular inclined strata that are foresets to a large depositional landform. The interbedding of moderately to well sorted beds of slightly varying gravel particle sizes indicates water transport under conditions of slight fluctuations of flow strength. The geometries suggest a high rate of supply of sediment into the margin of a body of water at least 10 m deep. The direction of water flow was toward the southeast, which could reflect development of a short-lived delta fed by melt water from a glacier front located within a few hundred meters distance on the upland just north of Fall Creek Valley. Partially or dominantly, the southeast-flow direction expressed by the foreset beds could have been a geometrical form forced by the bedrock margin of Fall Creek valley, which was likely a steep rock valley wall proximal to Varna High bank. The pebble clasts of compositions like the nearby outcrops of Devonian bedrock could have been sourced from bedrock anywhere within the modern Fall Creek catchment or short distances to the north in the broad Cayuga Trough. Karig (2022) proposes that the foresets of Unit F indicate migration of a delta into the same lake in which varved sediments had earlier accumulated.

Unit G is much like Units B and C, deposited by persistent steady flow of water under conditions of a high supply rate of sediment. The steady flow again suggests that the regional drainage organization modulated the variability of discharge of the stream which transported unit G materials. Also, similar to units B and C, the pebble clast compositions indicate sources in sub-Devonian strata, which suggests a glacial delivery of sediment to the source of the streamflow, yet the sediment of distant origin may have been stored in the Fall Creek drainage within deposits of an older ice-advance stage.

Unit T is a glacial till. The variable extent of bed development within the unit suggests that subglacial hydrological conditions varied over the time span of till accumulation. Its position in the landscape and continuity along the Fall Creek Valley suggest that it is the Valley Heads till.

High Bank 2 (HB2)

The easternmost Fall Creek valley wall outcrop described here, referred to here as HB2 and by Karig (2022) as “high bank 2”, occurs at 42.467°S, 76.435°W. Secondary outcrops occur in the walls of the tributary valley which joins Fall Creek immediately downstream of the main Fall Creek-facing natural outcrop.

Sedimentology and physical stratigraphy

The Fall Creek-facing outcrop displays four lithologies (Fig. 18a): L-i) a basal clay with floating gravel clasts; L-ii) above a sharp, erosional contact a sand that is highly variable in thickness and well bedded; L-iii) above a sharp, erosional contact, a rounded-pebble gravel with pebbly sand interbeds; L-iv) above a locally sharp and planar contact, an unsorted but layered gravel; L-v, an angular-clast unsorted gravel. The second unit, sand, is composed of at least six sub-facies, A-E and Z (Fig. 19b).

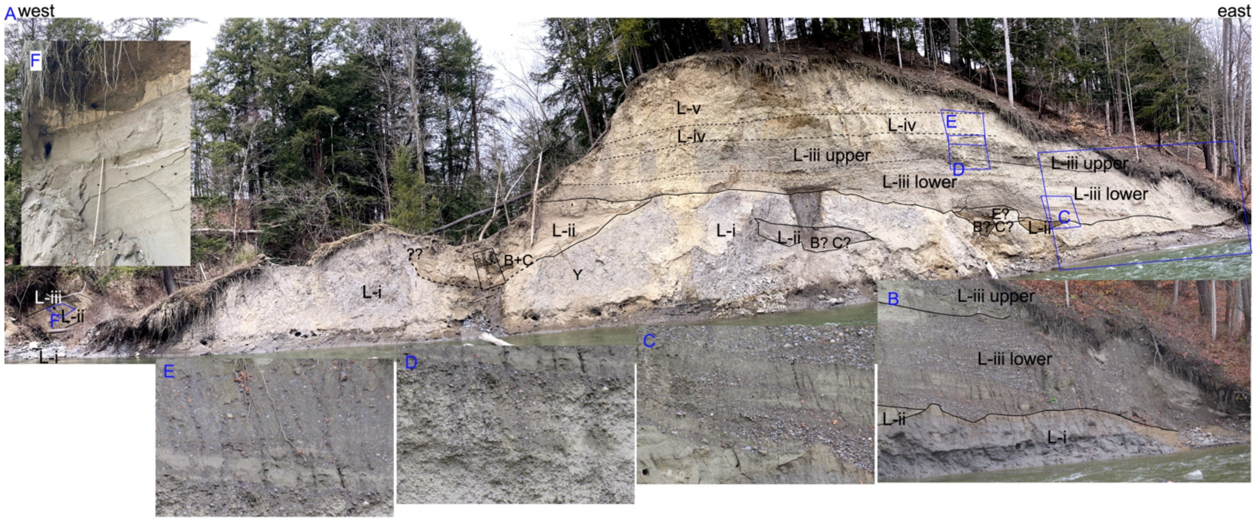

Figure 18. High Bank 2 (HB2) and representative photos of gravel and sand facies. A) Panoramic view of the north bank of Fall Creek reveals five units, whose contacts are mapped on the photo. For photos B-E, the location of each photo is indicated by a blue polygon. B) Basal clay unit, L-i, with a brown oxidized upper zone, sharply overlain by well bedded round-clast gravel and sand unit L-iii. C) Where gravel of unit L-iii onlaps the central pillar of L-i clay, beds dominantly incline east, but minor cross beds are inclined to the west. D) The upper part of L-iii is a clast-supported gravel containing sand beds that transition laterally to gravel, and appear to be more massive than in the lower part of this unit. E) Unit L-iv is a diamicton, in which rounded coarse pebbles to cobbles float in a matrix that is inferred to be muddy, based on its outcrop character. F) Unit L-ii silty sands and sands are several meters thick on the west side of the clay mound, where they include tabular inclined stratification.

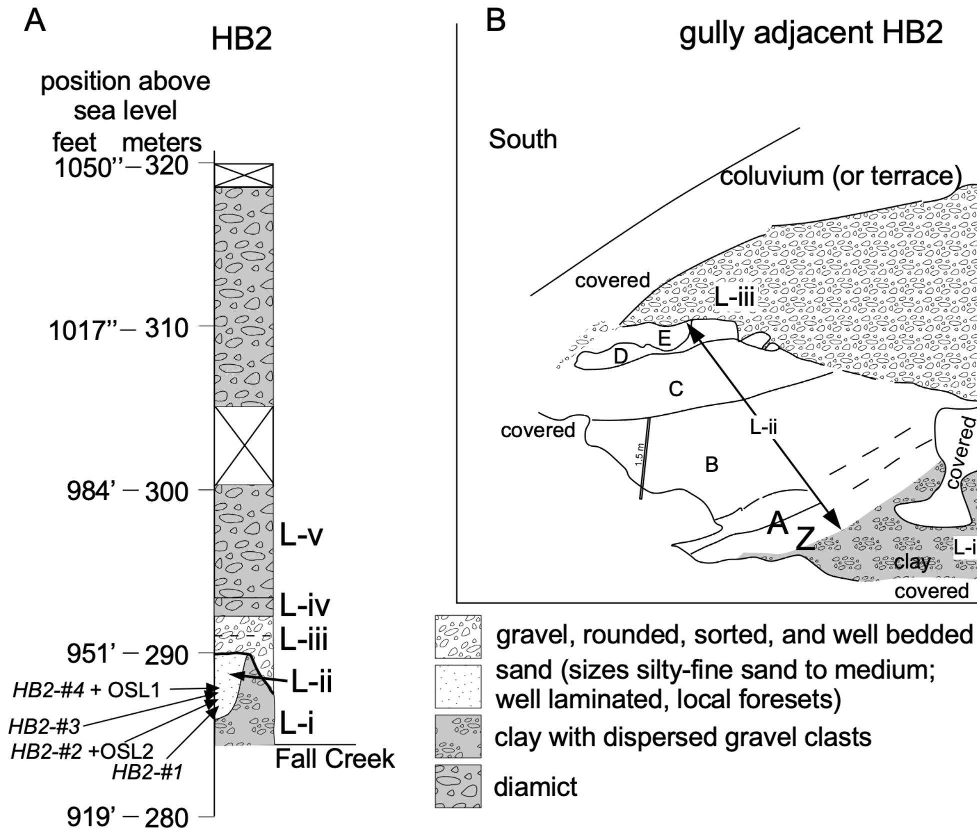

Figure 19. A) Generalized stratigraphic column for units between Fall Creek and the adjacent upland surface. B) Sketch of outcrop at junction of gully to north with Fall Creek, illuminating the six sub-facies within sand unit L-ii, defined by texture and sedimentary structures.

L-i) The clay unit forms a mound that extends about 6 m above creek level in the central sector of the outcrop (Figs. 18a, 19a), and its top declines to near water level to east and west. Contained within the pliable gray clay are dispersed pebbles, angular to well rounded, and composed of exotic as well as local Devonian rock fragments (Fig. 20b). No primary stratification is visible.

L-ii) The sand body sharply overlies the clay. On the west side of the clay mound is an accumulation of sand 3 to 5 meters thick, which onlaps the mound and yet does not extend over the top of the mound (Figs. 18a, 19a). Within an area of approximately 100 m^2, encompassing the Fall Creek-facing outcrop and two easily accessed outcrops within the adjacent gully, the sand details can be viewed from the south, east, and west, including where they lie above a smaller-scale clay mound.

Figure 19b illustrates the large-scale variations in the sand unit properties within the wedge-shaped sand body, and Table 6 reports grain sizes from sieving. Where the underlying mud stands as pillars and mounds, the lowest sand commonly occurs in localized lenses a few meters wide and roughly a meter thick, comprised by very fine to fine sand that is well laminated (subfacies Z, Fig. 19b). The lowest sand that extends widely across the paleo-topography (subfacies A), roughly 50 cm thick, is light gray, silt to very fine sand, with sparse 2-4 cm thick interbeds of medium sand, and displays planar lamination that varies between horizontal and gently inclined (Figs. 19b, 20c). The top ~6 cm of the gray subfacies A separates readily along parallel lamination planes and contains plant fragments. Where overlying a locally flat top-of-clay, these laminations are horizontal (Fig. 20c), but where overlying the flank of a clay mound the laminations dip about 20° (Fig. 20a), mimicking the form of the underlying paleo-topographic high. Conformably above are 0.5 m of light tan, very fine-grained sand, with centimeter-scale off-white horizontal laminae.

In the subsequent 2 to 4 m height of facies L-ii, the sand is light brown color, separated into two subfacies, B and C, differentiated by stratification (Fig. 19b). In subfacies B, the sands are silt-rich in the lower part, and coarsen slightly upward, with interbeds of slightly variable grain size at spacings of 1-10 cm thickness. Laminations define large scale tabular cross beds, with ripples superimposed on those large forms (Fig. 20a,d). On the Fall Creek-facing outcrop (Fig. 18), the tabular cross bed set extends at least 10 m laterally, with an apparent dip direction toward the southwest. Subfacies B overlies the inclined side of the mud mound but does not cover it. These inclined laminations parallel the top of the underlying mud mound, rather than onlapping the mound. Sand of similar bed geometry crops out about 15 m farther west in the gully wall, where lamination strikes 43E and dips 25-32° SE, there covering both the flank and crest of a small mud mound (Fig. 19b). Where distant from the crest of a mud-cored mound, the planar cross beds are inclined south and southwest more gently (12°). The superimposed ripples vary from asymmetric lee-side climbing ripples to symmetrical ripples of 20 cm wavelength in which there is very little migration of the wavecrest from one lamination to the next (Fig. 21a,b,e).

The uppermost laterally continuous sand of facies L-ii, subfacies C, is roughly 1 m thick and very friable, of very fine to medium sand. Locally, in the middle and upper parts of the sand body, pebble-sized clasts occur in sand beds and include both local bedrock material and rip-up mudstone clasts. Lamination is very well developed at millimeter-spacing scale (Fig. 20e), planar, and much gentler (6-12°) than for subfacies B, dominantly toward the south but locally in the opposed direction. The inclinations change across internal surfaces of downlap and onlap.

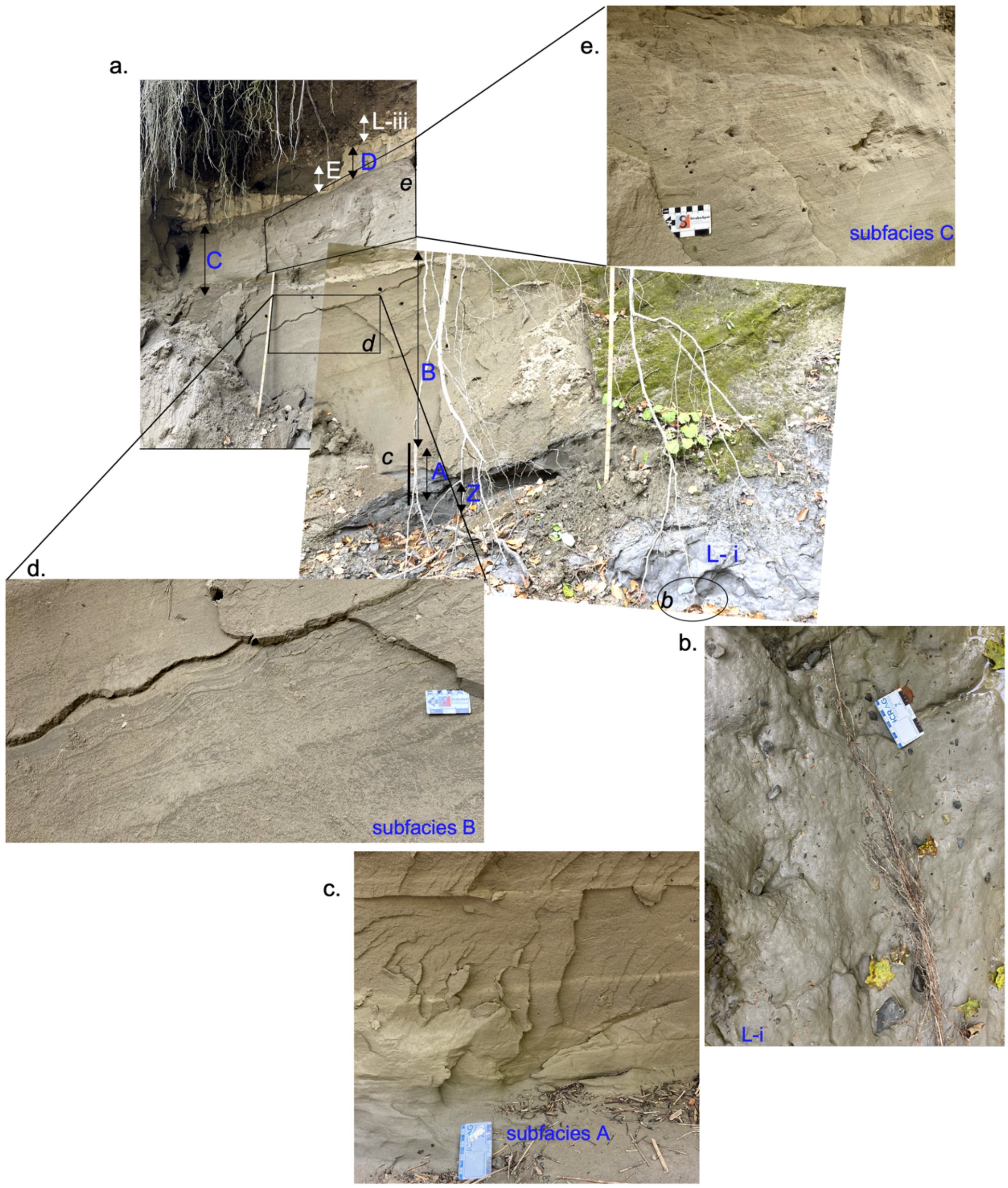

Figure 20. Photographs of the lower two units of the HB2 outcrop, L-i and L-ii. A is a photomosaic of the exposure at the junction of the northern gully with Fall Creek, looking west (see also Figure 19b). White pole is 1.5 m long. The lower-case letters (black) tie a location in the outcrop to the letters assigned to the neighboring photographs. Upper case letters Z and A-E (blue or white) indicate the subfacies of sand unit L-ii referred to in the text. B) Lower clay unit (L-i) contains dispersed pebbles (scale bar is 9 cm long) (in creek bed). C) Muddy very fine sand of the upper part of subfacies A (north wall of gully). D) Sand of subfacies B with ripples of wavelength about 20 cm superimposed on planar cross beds that are strongly inclined to the left (SW). E. Sand of subfacies C, slightly inclined to the left (SW).

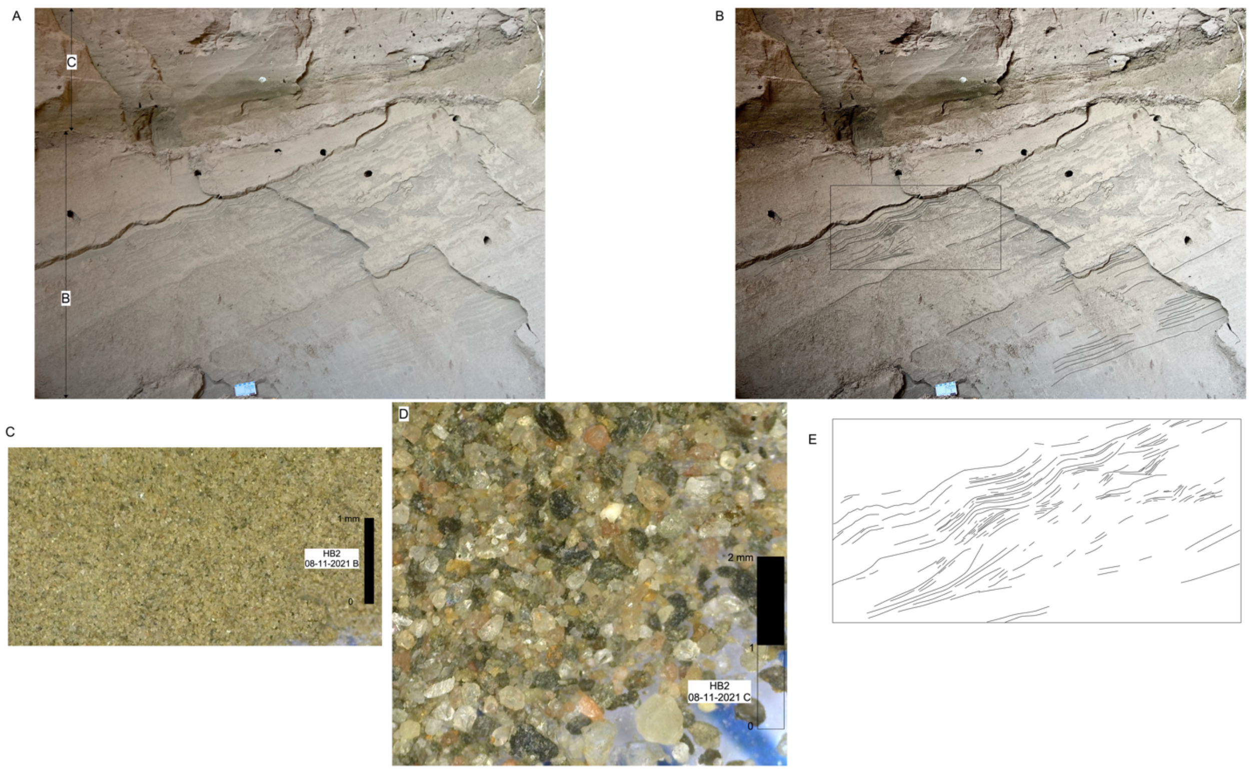

Figure 21. Details of ripple laminations in unit L-ii subfacies B and C (compare to Figure 20). A) Original photograph. B) The contrast of the photo has been enhanced and general lamination patterns traced. The rectangle marks the sub-area shown in E. C) Photograph of grains of subfacies B, with 1 mm scale bar. D) Photograph of grains in subfacies C, at same scale as in photograph of subfacies B. E) Details of the small-scale ripples (rectangle in B).

The top of the sand unit is laterally variable and includes two subfacies that is each underlain by an erosional unconformity. The lower subfacies, D, is a bed of resistant tan-colored silt that is highly variable in thickness (0-60 cm) (Figs. 18f, 20a) because it both fills erosional relief (≥ 50 cm) cut into subfacies C, and because of erosion prior to deposition of overlying subfacies E. Intraclasts within underlying unit C are of lithology similar to D, indicating that somewhere in the depositional system subfacies D was also contemporaneous with or earlier than subfacies C. The lower 10 cm display faint layering parallel the basal surface, but overall the unit is massive.

The uppermost bed of sand unit ii, subfacies E, is medium grained sand and of darker brown color than any of the others. Friable, it has parallel, subhorizontal laminations. Subfacies E occurs only locally within erosional lows that truncate the silt bed (subfacies D) (Figs. 19b, 20a).

On the east side of the Fall Creek-facing mound there is one isolated lens-shaped sand body overlying the basal clay body and underlying unit L-iii, which is only a few meters wide (Fig. 18a). Subhorizontal parallel lamination is visible. Whether this corresponds to either subfacies Z or subfacies E is not known.

Four samples of sand that were collected in the outcrop facing Fall Creek were sieved (Table 6). Each sample spans about 5 cm thickness and therefore encompasses multiple thin laminations. Samples collected in the gully outcrop where subfacies were fully described (Figs. 19b, 20a) were compared to the sieved set and grain sizes characterized visually (Fig. 21c,d). As a generality, both subfacies A and B are mixtures of coarse silt through fine sand. Subfacies C and Z (not illustrated) are very fine to medium sand, lacking silt particles. The weathering appearance of subfacies B, with gray bands interbedded with tan bands, suggests that centimeter-thick laminae of clean sand are interbedded with laminae that are rich in silt.

Table 6. Grain size data from sieving of dried samples for HB2 units, expressed as percentages of each sample. Sample locations marked in Figure 19a.

sample ID	sub-facies	height above base of sand unit L-ii	mud	sand					gravel
		meters	< 0.063 mm	0.063-0.125 mm	0.125-0.25 mm	0.25-0.5 mm	0.5-1.0 mm	1.0-2.0 mm	>2.0 mm
				very fine	fine	medium	coarse	very coarse	
HB-2 #1	A	0.2	24	48	24				
HB-2 #2	B	0.7	27	46	23				
HB-2 #3	B or C	1.1	14	43	43				
HB-2 #4	B or C	1.5	12	30	47	12			present

L-iii) The rounded-clast gravel of unit L-iii is organized into meter-scale beds, with alternations of gravel and sand (Figs. 18a, 20a, 22a). The dominant particle size of the rounded-clast gravel is pebbles (e.g., 0.2-6.4 cm diameter), with an abundance of coarse to very coarse pebbles (1.6-6.4 cm diameter) and infrequent small cobbles. Most beds are well sorted. Roughly one-third of the unit thickness is composed of pebbly sands.

Karig (2022) reports that the rounded clasts consist of carbonates and quartz-rich lithologies, which are not represented in the local bedrock, as well as locally available mudstone or siltstone.

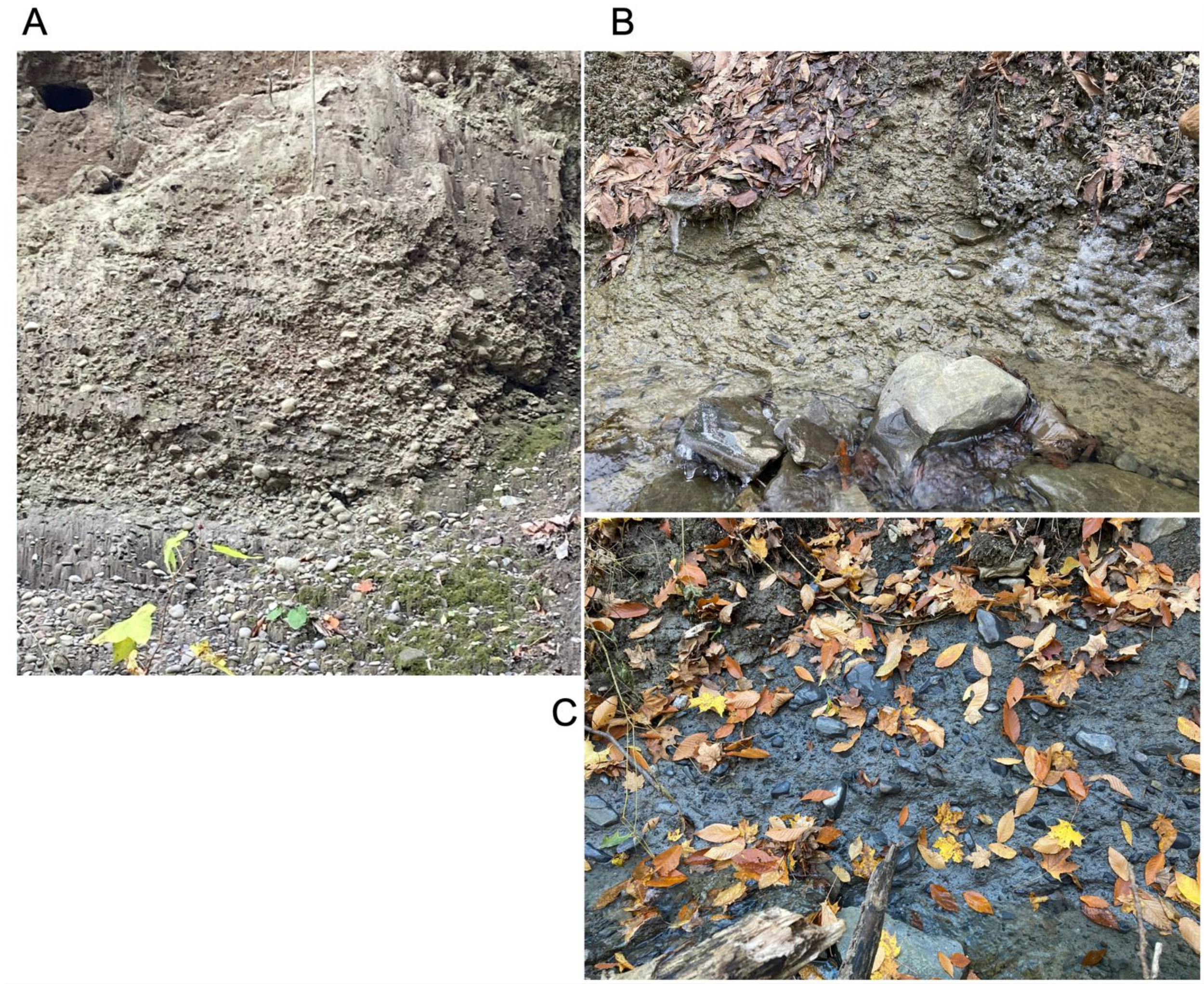

Figure 22. A) Unit L-iii, well sorted rounded-pebble gravel with sand interbeds. B) Unit L-v, diamicton exposed at 305 m elevation. C) Unit L-v, diamicton exposed at approximately 310 m elevation. Dried autumn leaves (brown) in all three photos provide relative scale indicators.

In the Fall Creek-facing outcrop, the lower L-iii gravel beds reflect the configuration of the underlying clay mound. Over the top of the clay mound, beds are subhorizontal. On the east side of the clay mound, the rounded-clast gravel is comprised by beds with long-wavelength layering inclined to the east (Fig. 18b). Individual beds are inclined variably, ranging from about 6° to about 15°. In a roughly 4-m-thick interval beginning about 2 m above the basal contact, there also is an oppositely inclined (to left) smaller scale cross lamination (Fig. 18c). Some of these west-dipping layers are the width of the dominant class size, hence finely layered. The west-facing sets of cross beds are somewhat more than 1 m thick each. In one set among these it appears that individual laminations are finer-grained gravel at the up-dip ends, with coarse grains in their down-dip halves.

The upper part of L-iii is a clast-supported gravel containing sand beds that transition laterally to gravel. This zone is either thicker bedded or more massive than the lower part of unit L-iii. The uppermost bed contains sand or mud-sized material, 0.5-1 m thick.

L-iv) No close observation of the upper gravels, units L-iv and L-v, was possible immediately adjacent to Fall Creek at HB2. In the eastern part of the Fall Creek-facing outcrop, unit L-iv begins at a sharp, approximately horizontal contact above the sand or mud bed of uppermost unit L-iii. The general lithologies above that contact are beds of gravel and beds of sand that wedge out laterally. Although these are of grossly similar lithology to the underlying beds (unit L-iii), internal organization differs markedly. The lowest gravel bed, about 2 m thick, contains rounded-pebble clasts that float in a matrix without discernable organization (Fig. 18e).

L-v) The uppermost several meters thickness of the Fall Creek-facing outcrop, above roughly 294 m elevation, consists of 2- to 3-m-thick beds with cobbles to small boulders that are mostly angular, lack visible internal stratification, and have varying proportions of fine-grained matrix. The upper extent of this exposure is estimated to be about 310 m elevation. In the deep gully which joins Fall Creek at HB2, approximately 300 m north at 305 m asl, there is a clean exposure of very poorly sorted gravel in which pebbles, both angular and rounded, float in a fine-grained matrix (Fig. 22b). This diamict texture repeats in exposures that occur sporadically to the north (Fig. 22c) at progressively higher elevations.

Age constraints

Karig (2022) reports on OSL ages determined for two samples collected from unit L-ii sand located several feet above the sand/clay contact and separated stratigraphically by about 3' (1 m) (Fig. 19a). The upper sample (HB2-1) gave an OSL age of 26,035±1200 yr and the lower (HB2-2) gave an age of 28,960±1450 yr, nearly overlapping at 27,400 yr. Karig (2022) concludes that the pre-LGM ages are relatively accurate because of the high data quality and low dispersion. He raises the possibility that a clay fraction in this sand would diminish the accuracy, as it would have impeded total bleaching. As shown in Table 6, some of the sand beds do contain high fractions of mud-sized material.

Interpretations

Unit L-i: Clay with floating gravel

Although the combination of cobble-sized clasts in a clay matrix is common of glacial tills, in this unit the clay dominates greatly (≥95%) over the large clasts. This proportion suggests that there may have existed a clay unit, likely of lacustrine origin, which was intermixed with cobbles during deformation below the bed of a moving glacier. Karig (2022) notes that the lake and the glacial advance which remobilized lacustrine deposits as till were older than Late Wisconsin, given the age constraint on the overlying unit.

The upper surface of unit L-i is noteworthy for its extreme irregularity, forming mounds and, locally, pillars with vertical or overhanging walls. Two interpretations of the relief on the top surface are possible. The first hypothesis is that extensive deformation of the clay beneath advancing ice created the preserved high-relief upper surface of the clay unit, and an alternative is that the relief of the top of unit L-i was created by gully erosion or stream erosion (Karig, 2022). In either of those cases, an implication is that much of the inclined stratification in unit L-ii would be due to deposition of beds that mimic their inclined bed.

B) Sand (unit L-ii):

Sand unit L-ii infills the relief on the top of clay unit L-i. The spatial scale and planar nature of the inclined lamination suggests that the inclined surfaces represent foresets of a large-relief feature rather than a migratory dune. The feature adjacent to which foresets develop may have been either a slowly migrating barform or a pre-existing topographic barrier (e.g., a unit L-i mud dome).

The high degree of lamination throughout the sand unit (all subfacies except D), irrespective of particle size that includes abundant silt (subfacies A, B) or only sand (subfacies Z, C, E), suggests persistent water flow with time-varying sediment concentration in the flow. Joplin and Walker (1968) describe foresets of fine silty sand with ripples in a kame delta. Their lee-side asymmetrical ripples were dominantly very fine sand with 17-35% silt, and symmetrical ripples were of comparable sand size but a higher percentage of silt (30-40%). Joplin and Walker (1968) compared the field example to flume studies and concluded that a density flow of slightly dense sediment-laden water would create these ripples through the combined action of both the very fine particle size, which generates a somewhat cohesive bed, with a fairly high rate of deposition from suspension. Cowan and Ross (1990) describe interlaminated muds and sands in an Alaskan temperate fjord fed by a subglacial stream channel. The details of mixing of sediment-laden meltwater for the Cowan and Ross (1990) case would differ from a Fall Creek case, yet a noteworthy point of reference may be that the Alaskan mud-sand couplets accumulate at a rate of several meters per hour.

For the HB2 case, we hypothesize that glacial water discharge entered a body of water (an ice marginal pool) where the meltwater stream mixed with less-sediment-laden lake/pool water. While coarse sediment was deposited in a location moderately distant from HB2, a turbid water formed by mixing flowed past HB2 as a dilute sediment gravity flow, likely decelerating on the down-flow sides of an irregular floor of the pool of water. That deceleration led gravitational settling to dominate over forward transport. Subfacies B and C may have accumulated in a single season of melt.

C) Rounded-clast, sorted gravel (unit L-iii):

The well sorted gravel and interbeds of pebbly sand that are characterized by rounded, exotic clasts is of fluvial origin. The stream flow in which it traveled was at least several meters deep, given migrating barforms that are over 1 m thick. Which way the overall water flowed cannot be interpreted with confidence. The long-wavelength inclined beds mimic the shape of the erosional surface of the underlying clay, and hence their east-facing inclination does not tell us anything about the flow direction. The superimposed west-inclined cross beds could suggest transportation to the west, but without knowing the sinuosity of the stream bed nor variability of cross-bed directions, it is premature to conclude that the overall water flow was directed toward the west. The west-directed movement of those gravel bars could have been a localized reaction to flow around the mound of clay. In this gravel at HB2, there is no direct evidence of remobilization after deposition. The combination of exotic clasts with evidence of strong flowing currents suggests that this unit was glacial outwash.

D) Rounded-clast matrix-supported gravel (unit L-iv):

The clasts of unit L-iv are the same as in the underlying unit, L-iii, yet in L-iv the clasts float in a finer grained matrix. This unit is interpreted as till formed by the flow of glacial ice across an underlying outwash deposit. Interbedding with sand-dominated beds suggests that the bed environment below the glacier was water-rich.

D) Gravel (unit L-v):

The uppermost unit exposed in HB2, L-v, is a diamicton with a clay-bearing matrix, yet differentiable from L-iv by the angularity of its cobbles and small boulders. This unit is interpreted as a glacial till. Its position as the uppermost till, with continuity to the highest positions on the north wall of Fall Creek valley, suggest that it is the Valley Heads readvance till.

Quaternary Sediments of the Plain south of the Fall Creek Valley

South of the modern Fall Creek valley there is a plain at elevations ranging between about 280 and 295 m (900-980 ft) above sea level. From the perspectives of the hill-forming Devonian rock and the contours of the elevations of the top of Devonian (Fig. 2), one plausible interpretation is that the ancestral Fall Creek valley traversed this plain from NE to SW, even though the Quaternary glacial and interglacial reorganizations of drainage has left no direct surface evidence of the ancestral valley. Because of two relatively deep boreholes recently placed in the southwestern sector of this plain as part of Cornell's investigation of geothermal energy, the Quaternary sediments below the modern plain are now available for initial study.

Sections exposed by ESH#1 and MW-ESH-BR

Boreholes ESH#1 and MW-ESH-BR occur about 150 m (500 ft) distant from one another. At ESH#1 (located 42.44362°N, -76.45776W, at 291 m [955 ft] surface elevation) occur about 63 m (207 ft) of unconsolidated Quaternary sediment above Devonian rock. MW-ESH-BR is located farther southwest (42.44246°N, -76.45879°W, 288 m [945 ft] elevation), where drilling traversed approximately 24 m (80 ft) of unconsolidated Quaternary sediment before continuing into Devonian rock (Fig. 23).

ESH#1 was bored to 33.5 m (110 ft) depth below surface with a 36-inch-diameter auger, which removed lumps tens of centimeters thick that were largely intact although commonly bent. Samples were collected and placed in small water-proof bags within two minutes after each auger-length reached the surface. Descriptions of this sector of ESH#1 rely heavily on hand-sample examination (Fig. 24), supplemented by notes about material observed that was too coarse for the sample bags. The lower 30 m (97 ft) of unconsolidated sediments at ESH#1 were drilled with a 26-inch diameter tricone bit, and sampled at 10 ft intervals by separation of cuttings from the circulating drilling mud, followed by washing away of the drilling mud. With that bit and a filter system that separated particles coarser than mud-size while recirculating the mud, all of the material extracted and sampled had been ground to particle sizes of sand or smaller or it was initially a sand (Fig. 25). Consequently, identification of sedimentary materials in that lower section is indirect and inexact, due to four major limitations. First, in the process of washing drilling mud from the sediment, primary sedimentary muds would have been lost. Second, judgement is involved in discriminating between sand-size grains created by breaking conglomerate clasts with the drill bit and those sand-size grains that existed in the original sediment. Third, the materials are assigned to a particular subsurface depth based on estimation of the lag time between drilling a given depth and the conveyance of that material to the surface by the drilling mud. Furthermore, mixing among materials from multiple depths is likely.

The lag time between the bit drilling a given depth and its cuttings reaching the surface produced a discrepancy between the apparent top-of-rock based on a caliper log registered for the borehole days after drilling through Quaternary sediment was complete, compared to the cuttings depths reported while drilling progressed. The interval drilled with a 26-inch-diameter tricone bit was continuously washed with water-based drilling mud, which led to borehole widening in the unconsolidated sediments relative to the competent Devonian rock. At all depths between 33.5 m (110 ft) and 63 m (207 ft) below surface, the borehole diameter proved to be at least 5 inches wider than the bit diameter, indicating that geological material was easily washed out by the pressure of the drilling mud. In the interval spanning 63-67 m (207-220 ft) subsurface, the borehole diameter is 1 to 2 inches wider than the bit diameter, whereas below 67 m (220 ft) there is consistently less than 1 inch discrepancy between the borehole and bit widths. I interpret the caliper data to indicate that the top of the Devonian Genesee Group occurs 63 m (207 ft) below the surface, with some weathering of the upper 4 m (13 ft) of the rock. In apparent contradiction, the drill cuttings samples estimated to be from depths of 210, 220 and 230 ft subsurface are dominated by sediments better attributed to the Quaternary than to the Devonian. I interpret that the lag time calculations were incorrect because the borehole diameter was underestimated, and that these cuttings samples correspond to shallower depths than reported. In the text that follows, “reported depth” refers to the cuttings depths reported, which are deeper than true depth or true elevation; Figure 23 reports the estimated true depths.

In the depth interval of unconsolidated sediment, water monitoring well MW-ESH-BR was drilled by a series of methods: the upper 9.1 m (30 feet) were bored with a hollow-stem auger, from 9.1-15.2 m (30-50 feet) drilled with an air-hammer, and from 15.2-24.4 m (50-80 feet) drilled with a sonic rig for which the core was collected in plastic sleeves. The samples from the upper 15 m (50 feet) were largely disaggregated, and therefore reveal texture but not the organization of the grains. The core samples from 15-24 m (50-80 ft) depth were laid in their plastic sleeves on the ground and partially photographed by Dan Karig (personal communication, 2021) two days after (2 July 2021) removal from the borehole (Fig. 26). At least 0.5 inches of rain had fallen on them. A full set of core photos and samples were collected 12 days after drilling, 12 July 2021, after at least 3 inches of rain had washed the cores (Fig. 26). The rains had partially removed mud and sand-sized matrix, although the selected samples were chosen from largely intact bulk material. The descriptions of MW-ESH-BR (Table 8) rely on notes from the drilling operation, fabric and layering expressed in the core photographs -- including comparisons of photos of the same cores on dates before and after rains -- and information about texture from examination of hand samples.

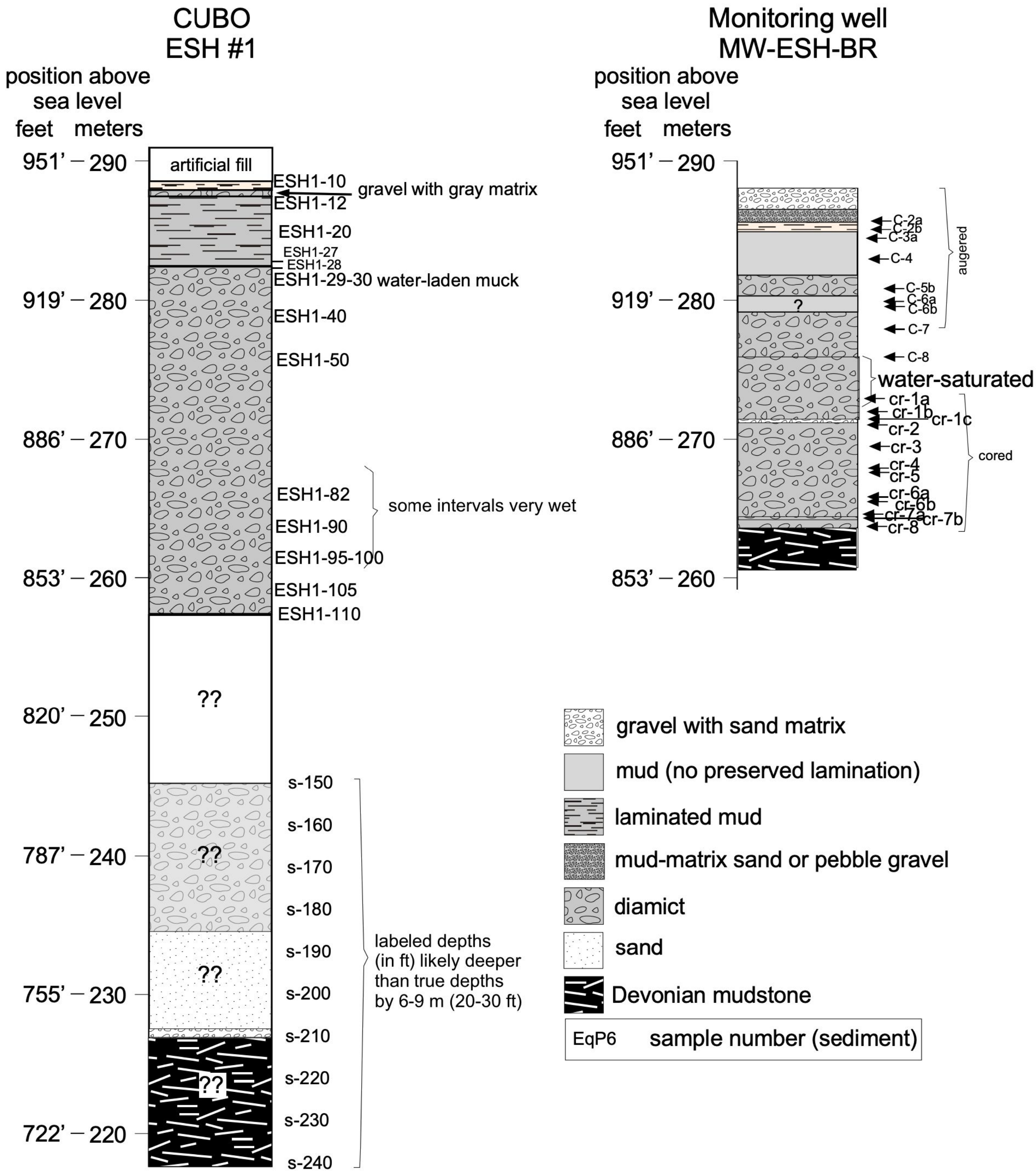

Fig. 23. Stratigraphic columns for ESH#1 (left) and MW-ESH-BR (right). Above 259 m (850 ft) elevation, borehole ESH #1 bulk samples collected by T. Jordan and O. Gustafson; deeper samples are disaggregated cuttings. Samples from water monitoring well MW-ESH-BR were collected by T. Jordan and O. Gustafson, and properties also documented by D. Karig. A pale yellow tone highlights a thin interval of light reddish brown laminated mud near the top of each borehole. In ESH#1, the comparatively poor documentation of sedimentary materials between 258-227 m (846-744 ft) elevation is expressed by faded patterns and question marks.

Hand samples (Figs. 24, 26) were hand-split to reveal natural parting surfaces, and then examined with 10-X magnification. Statements about clast compositions are based on the hand samples. Samples collected 12 July 2021 were stored in a refrigerator in closed ziplock bags until they were described 16 April 2022. The hand-sample properties of ESH#1 materials in the upper 110 ft are presented in Table 7, and those of WM-ESH-BR are presented in Table 8. Photographs of the drill cuttings for the lower part of ESH #1 appear in Figure 25.

There is a general similarity between the two vertical sections (Fig. 23). Given that similarity and their short horizontal separation, the interpretation of depositional conditions combines insight about textures and small-scale stratification best documented at ESH#1 with larger-scale bedding architecture better documented in MW-ESH-BR.

Sedimentology and physical stratigraphy

Two major lithologies were traversed by the boreholes, and a third major lithology is suggested by sparse information from the lower sector of ESH#1.

The dominant lithology between elevations of 257-282 m (926 - 844 ft) above sea level at both boreholes is a poorly sorted pebble gravel with mud-sized to sand-sized matrix (Figs. 23, 24, 26; Tables 7, 8). In most samples, there is no evidence of primary lamination. Minor interbeds are poorly sorted sands and pebbles without a mud matrix (e.g., ESH1 29-30'; ESH1-90'; MW-ESH-BR 55' and 60').

Overlying that gravel and below construction fill, the upper 6 m (20 ft) of ESH#1 and approximately 3.7 m (12 ft) near the top of MW-ESH-BR are dominantly muds. Four ESH#1 samples between depths of 3 and 8.2 m (10 and 27 ft) below the surface preserved fine lamination despite bending by the augering or while being pulled out of the borehole (Table 7, Fig. 24). These laminated muds are dominantly clay-sized particles with minor silt. The dominant color is medium gray, with localized yellow-brown discolored interbeds (Fig. 24 at 20' and 27'). One interval in which the laminations are 0.1-0.2 mm thick, near the top, is entirely light reddish brown (ESH-1 ~12 ft; Figure 24).

In the interval of ESH#1 whose samples were removed from the subsurface with a tricone bit (Fig. 25), samples from "reported depths" between 46 and 55 m (150 and 180 ft) below ground (true elevations estimated 235-245 m above sea level) contain abundant angular grains, primarily of very fine to fine sand-size, with compositions ranging from gray rock fragments to transparent quartz. These are inferred to be the broken debris of gravel-size clasts. The transparent quartz grains likely required parent-rock quartz grains or crystals larger than is common in the local Devonian mudstones, and therefore is indirect evidence of exotic clasts with a distant bedrock parent. The dark rock fragments may have been derived from the nearby Devonian siliciclastic rocks. Overall, this interval is inferred to have been conglomeratic, with no information about whether or not a matrix accompanied the gravel-sized clasts.

In the underlying major interval of materials of ESH #1, samples at "reported depths" between 58-70 m (190-230 ft) (true elevations estimated 235-228 m above sea level) (Fig. 25) are composed of grains that are fine to coarse sand, sub-angular to subrounded to rounded, and of compositions that are a mixture of gray rock fragments and translucent gray to orangish quartz or feldspar. These features are suggestive of layers of sand that were dispersed by drilling but not generally ground into smaller fragments.

The sample reported to represent 73.2 m (240 ft) depth subsurface (estimated true elevation 227 m) displays elements interpreted to be a mixture of ground rock that is exotic to the Fall Creek drainage basin (pale gray, pink and pale orange fragments, transparent quartz fragments) and of pristine Devonian bedrock (medium to dark gray fragments) (Fig. 25a, e). This suggests that a gravel layer overlies the Devonian rock, although there is no information about whether the gravel contained a matrix.

Table 7. Descriptions of samples collected by augering 36” diameter borehole at location of ESH#1. Depths reported from a surface above ~2.4 m (8 feet) of construction fill. See photos in Figure 24. Most of the description pertains to the bulk properties. The column “properties of large clasts” specifies lithology, shape, and dimensions of only the largest clasts in the sample.

Sample ID	depth (ft) below parking lot surface	color	general lithology (finger-feel and eyes with handlens)	tests of mud particle size range: finger-smear, tooth-test, and disaggregated in a container of water	fabric, layering (as visible on fresh split along natural lines [not a cut that I made])	properties of large clasts (diameter of maximum axis, Dmax)	comments	depositional interpretation
ESH1-10'	10	light brown	clay	little silt, mostly clay	lamination w/ thickness <1 mm	5 mm Dmax pebble in photo; more common clasts of 1-2 mm diameter roughly 5% volume		lacustrine
ESH1-12'	12	light brown	clay	where lacks lamina, some silt; where laminated, almost no silt	thoroughy laminated @ 0.1-0.2 mm thickness	no oversized clasts	more plastic than ESH1-10'	lacustrine
ESH1-20'	20 (?)	gray, with 10% mottles of light brown.	clay	very little silt --> clay dominates	laminated @ < 1 mm thickness	no oversized clasts		lacustrine

ESH1-MOUSEHOLE-6m	27	gray, with one 5-m-wide yellow-ish brown laminae	clay	up to about 10% silt	thor-oughly lamin-ated @ < 1 mm thick-ness	no oversize clasts		lacustrine
ESH1-28'	28	med-ium gray	unsorted silt to coarse pebbles; dominant particle size is sand and mud	little clay	no visible organiz-ation	1) 0.9 cm, subrounded; 2) 2.0 cm, subrounded, no fizz	dry (relative to overlying samples); disaggre-gates into dry lumps); depth data quality poor	till
ESH1-29-30'	29-30	light med-ium gray with yellow-ish brown mottles	sand to coarse pebbles, unsorted	clay, silt and sand all present	no visible organiz-ation	1) 2.2 cm Dmax, elongate & thin; well rounded; limestone; 2) 0.5 cm Dmax, subrounded; 3) 0.3 cm Dmax, subangular; 4) 1X0.4 cm tabular, subangular	highly mixed by the augering; slightly damp on freshly broken surfaces, and somewhat plastic	likely sub-glacial
ESH1-40'	40	light med-ium gray with yellowi sh brown mottles	unsorted, dominantly sand size and smaller, with large clasts to very coarse pebble size	cohesive-ness indicates some clay in matrix, though minor	no visible organiz-ation	1) 4.5 cm Dmax tabular (1 cm thick), subangular, likely Dev. siltstone with moderate fizz; 2) 1.1 cm, egg-shaped, brownish gray, rounded limestone	relatively dry on freshly broken surfaces	till
ESH1-50'	50	med-ium gray	unsorted, dominated by pebbles		no visible organiz-ation	1) 2 cm Dmax, subangular; 2) 1.5 cm Dmax, angular; 3)	breaks to dry lumps	till

						0.5 cm Dmax, subangular; 4) 1.5 cm Dmax, rounded; 5) 5 cm Dmax, subangular		
ESH1-82'	82	gray	very poorly sorted, coarse sand to small pebbles dominate	cohesiveness indicates some clay in matrix	no visible organiz-ation	1) 4 cm Dmax, sub-spherical, rounded to subrounded, calcareous siliciclastic; 2) 2 cm Dmax, <0.5 cm thick, angular to subangular; 3) 1.4 cm Dmax, thin, angular	somewhat damp on freshly broken surfaces	till
ESH1-90'	90	med-ium gray	poorly sorted sand and pebble mixture	fine grains are silt and sand, no clay (see notes)	no visible organiz-ation	1) 1.2 cm Dmax, subspherical, well rounded, no fizz; 2) 3.7 cm Dmax, semi-rounded in plan-view, fractured to thickness of 0.1-0.7 cm, subrounded to angular, pinkish gray, no fizz	relatively wet on freshly broken surface; placed in a container of water and fully deconstructed, the mud completely settled out of the water in 2 hours 20 minutes	fluvial (whether below ice or subaerial is unknowable)
ESH1-95-100'	95-100	med-ium gray	sand and pebbles; matrix of sand and silt	silt yes, no clay	no visible organiz-ation	1) 2.6 cm Dmax, roughly equidimensional, subrounded, gray; 2) 0.5 cm Dmax plate-shaped, angular; 3) 1cm Dmax X 0.4 cm thick, subrounded	wet surface, even on fresh breaks; placed in a container of water and fully deconstructed, the mud completely settled out of the	fluvial (whether below ice or subaerial is unknowable)

							water in 2 hours 20 minutes	
ESH1-100'	100	gray	clay, silt, sand, with infrequent cobbles	laminated zone is silty clay; unlaminated zone is silt to fine sand	in patches up to 1 cm wide, lamina @ <0.2 mm thick-ness	1) 0.15 cm Dmax, angular, plate-shaped	wet exterior but moderately damp on freshly broken surface, yet very plastic; bag label noting cobbles inconsistent with clasts within the sample	lacustrine, mixed by auger in with something else
ESH1-105'	105	gray	unsorted, dominated volumetrically by sand ≤ medium size	cohesive-ness implies signifi-cant clay	no visible organiz-ation	1) 2 cm Dmax X 1 cm thick, well rounded, gray, calcareous siltstone; 2) 1.2 cm Dmax, egg-shaped, well rounded, gray, no fizz; 3) 0.7 cm Dmax, gray, subrounded, no fizz; 4) 2.4 cm Dmax, blade-shaped, gray siliciclastic	wet exterior, interior freshly broken surfaces moderately damp	till
ESH1-110'	110	med-ium gray with hint of brown	poorly sorted silt, sand and clay	lack of cohesion pressed between fingers suggests little clay	cell-like struct-ure with elong-ated tan zones surroun-ded by gray rims	1) 1.5 cm Dmax X 0.6 cm plate shape, subangular to subrounded, light brown siliciclastic; 2) 1.8 cm X 0.5 cm thick, subrounded, calcareous siliciclastic; 3) 0.5 cm	freshly broken surfaces dry	till

						Dmax, conical, gray, subrounded; 4) 1.0 cm Dmax equidimensional but very irregular, subangular to subrounded, dark gray and polished, harder than steel, maybe chert		

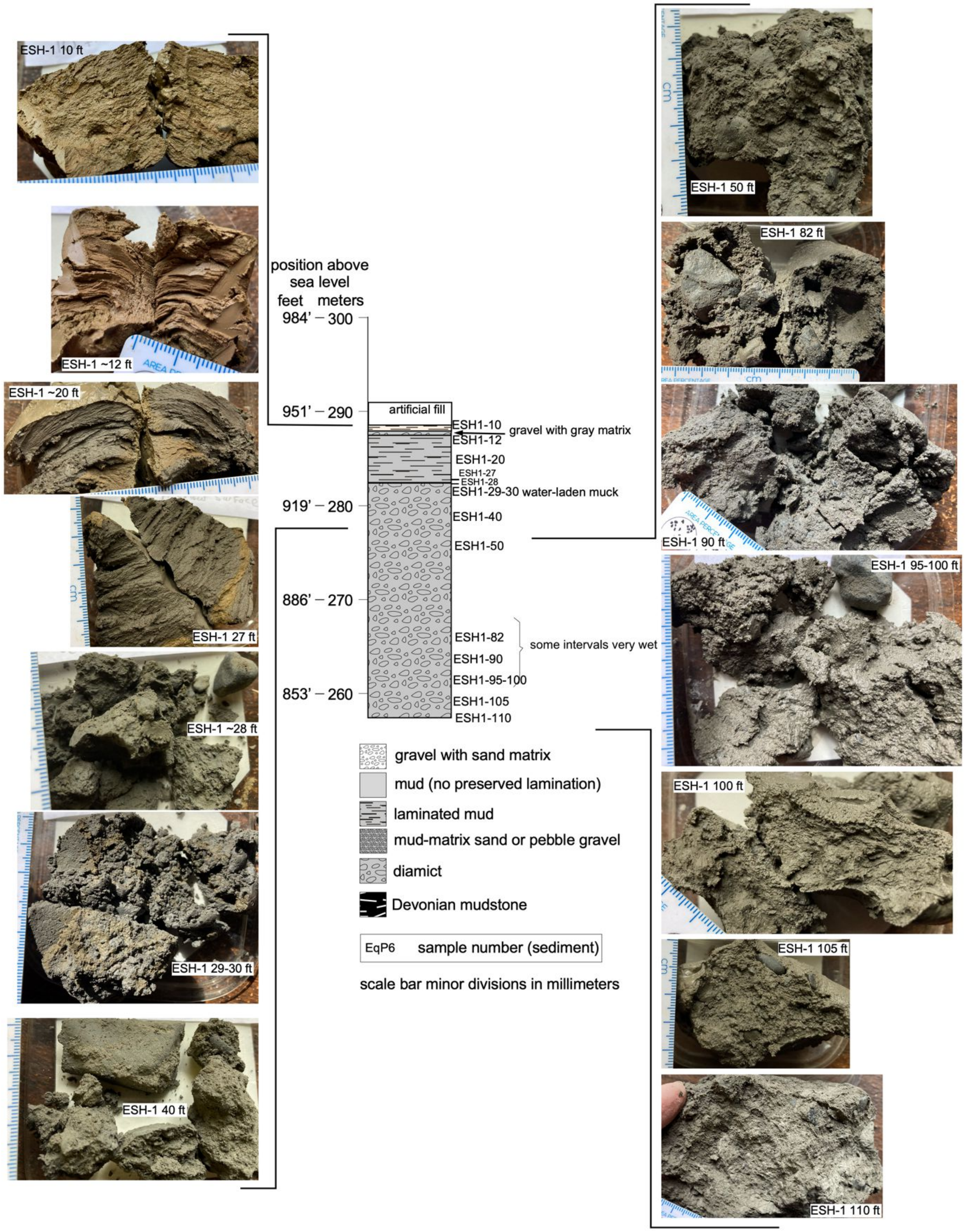

Fig. 24. Photographs of sediments extracted by augering a 36-inch-diameter borehole at ESH#1. Stated depths are sequentially accurate but not precise, as they are representative of auger-intervals 0.9 to 1.2 m (3 to 4 feet) thick. Samples were collected when an augered interval was lifted to the surface.

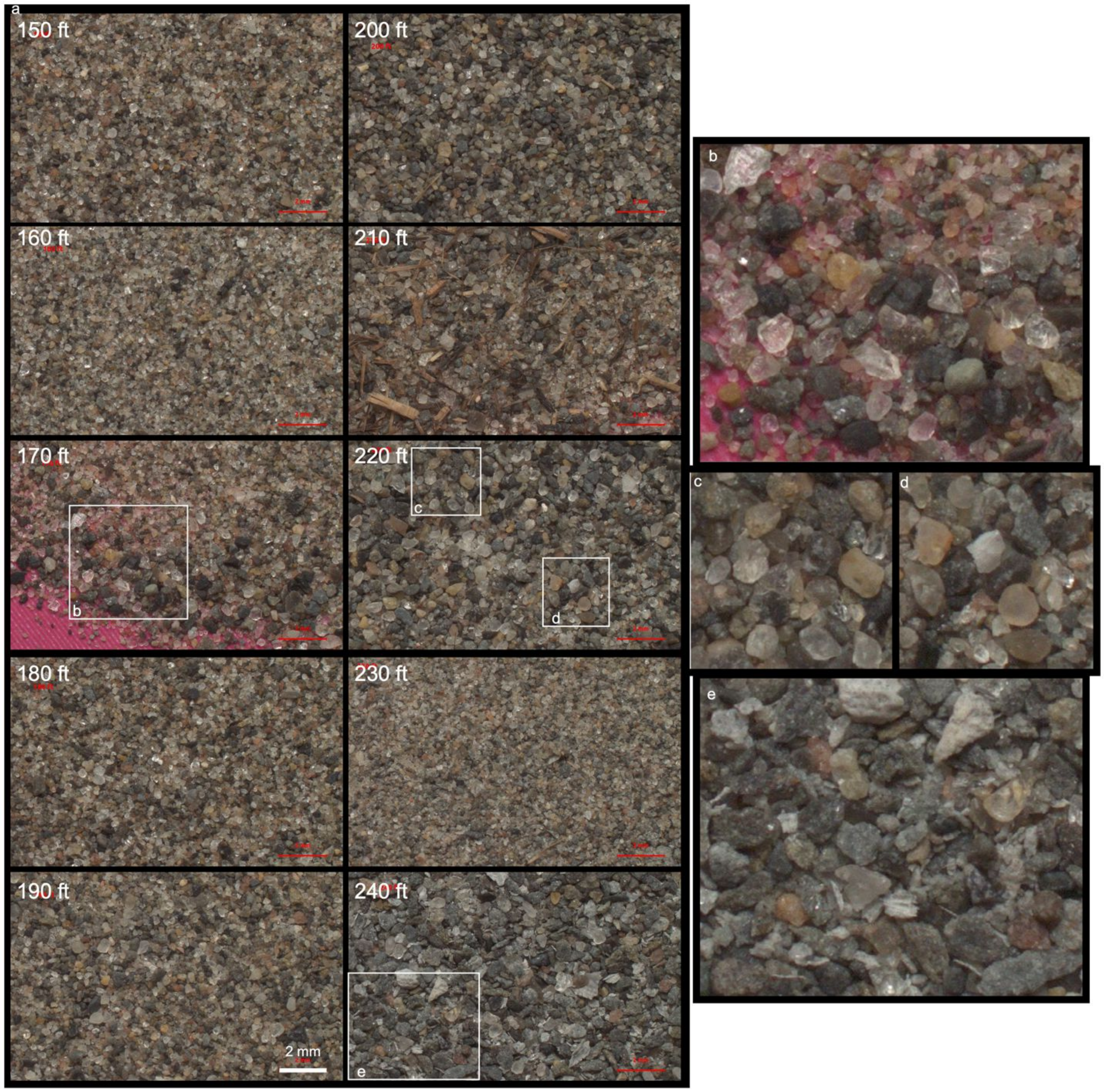

Fig. 25. Photographs of cuttings samples from the lower sector of Quaternary sediments at ESH#1. Depth labels refer to estimates that are likely 6-9 m (20 to 30 ft) overly deep. a) Photos at the same scale of all available samples; 2 mm red bar at lower right. White rectangles denote photos in b-e. Elongate brown fragments in 210 ft sample are cedar fiber, a drilling mud additive. b) Enlargement of part of the 170 ft sample shows angular grains of various compositions and transparent quartz that are interpreted to have been broken from large clasts. c,d) Enlargements of the 220 ft sample with grains of rounded sand as well as translucent quartz grains. e) Enlargement of part of the 240 ft sample showing angular lithic clasts, some medium to dark gray and some pale gray or pink or pale orange, plus transparent quartz fragments and rounded quartz grains.

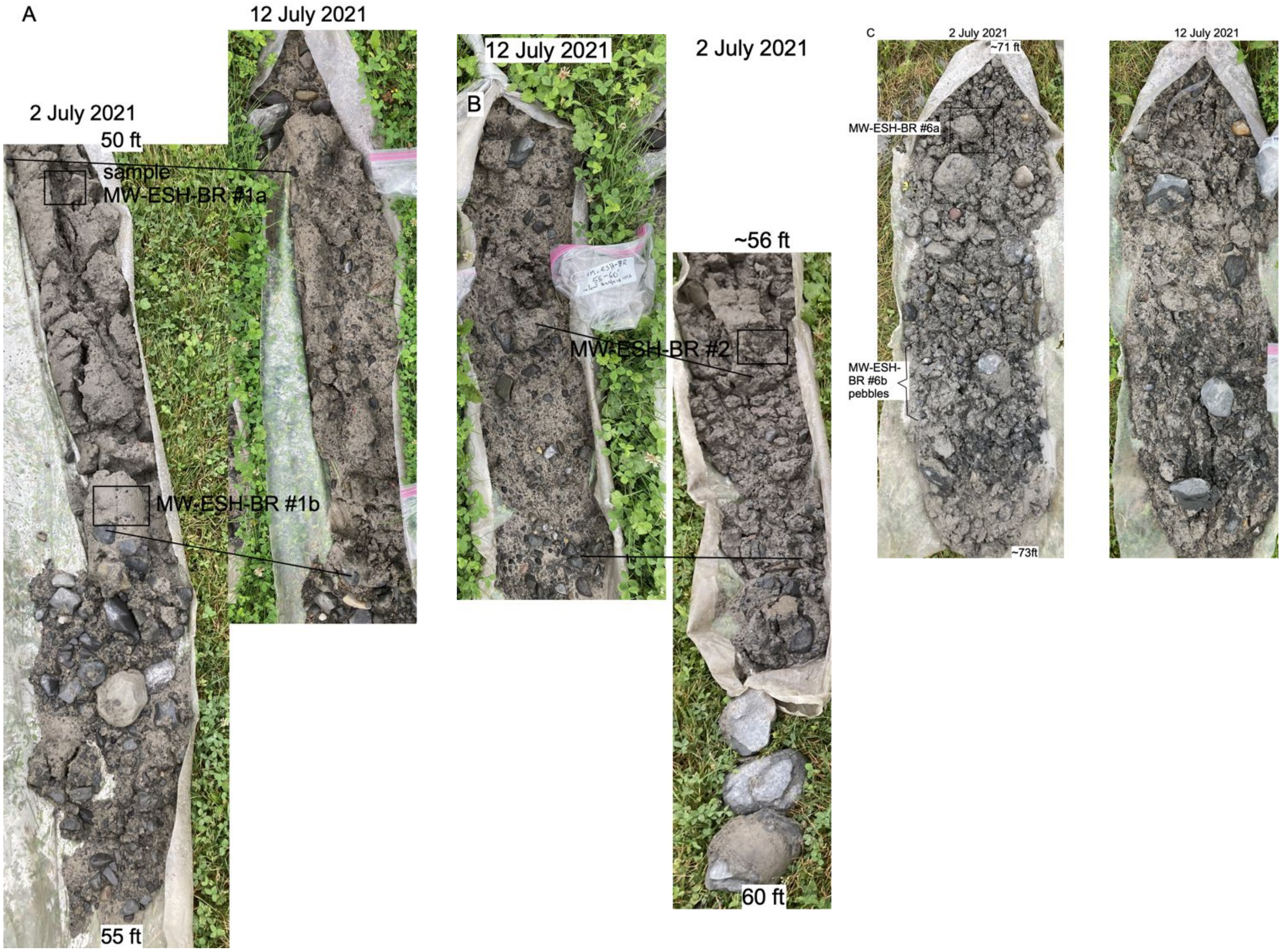

Fig. 26. Photographs of cores of sediments from borehole at WM-ESH-BR, comparing the conditions of the core on two different dates. July 1, 2021 photos by D. Karig, after a small amount of rain had fallen on the cores sleeves. July 12, 2021 photos by T. Jordan, after 3 inches of rain. A) Core spanning 50-55 ft depths. B) Core spanning about 56-60 ft depths. C) Core spanning approximately 71-73 ft. Note positions of some of the bags of samples later examined as hand samples.

Table 8. Descriptions of samples collected from WM-ESH-BR. Depths in feet below the surface divided into parts A, B and C. A) sample depths 8-28 ft bored by auger. B) sample depths 33-40 ft, drilled by air hammer. C) sample depths 51-80 ft, sonic drilled with core collected. Corresponding photographs appear in Figure 26.

Sample ID	depth (ft) below lawn surface	color	general lithology (finger-feel and visual with 10X hand-lens)	tests of mud particle size range: finger-smear, tooth-test, and disaggregated in a container of water	fabric, layering (visible on freshly split surface that followed along natural weaknesses)	properties of large clasts (diameter of maximum axis, Dmax)	comments	depositional interpretation
Part A								
MW-ESH-BR #2a	8	medium brown	poorly sorted mud + sand (in balls) and small pebbles	matrix of clay with grit	no visible organization	1) 0.8 cm semicircular X 0.3 cm thick, gray, subrounded; 2) 1.0 cm long, lumpy egg shapre, subangular to subrounded, brown	sample is mix of rounded aggregates (balls) and small pebbles	till or anthropogenic or soil-modified till
MW-ESH-BR #2b	10	light brown	clay with small percentage very coarse sand	almost entirely clay, with minor silt	no visible organization	1) 0.2 cm long, gray; 2) 0.1 cm Dmax, gray; 3) 0.15 cm Dmax, subangular, gray	needed a hammer to break this dried mass	lacustrine
MW-ESH-BR #3a	12	medium brown with medium gray pebbles	Bimodal, clay and pebbles	clay with small fraction of silt	no visible organization; the mixing of pebbles with clay likely occurred due to augering	1) 3.8 cm Dmax plate-like (1.5 cm thick), gray, subrounded-subangular, siliciclastic; 2) 3.4 cm Dmax, blade-shaped; angular; gray, limestone; 3) 3.5 cm Dmax, irregularly shaped, subangular, gray, siliciclastic		lacustrine (mixed by auger with other environment)

MW-ESH-BR #4a	17	yellowish brown	Bimodal, clay and pebbles	clay with minor % silt	no visible organization	1) 3.7 cm Dmax X 1.2 cm thick, irregular shape, subrounded dark gray, siliciclastic; 2) 2.2 cm Dmax X 0.9 cm thick, rectangular, angular to subangular dark gray, siliciclastic; 3) 2.6 cm Dmax X 1.2 cm thick, plate-shape, brownish gray, siliciclastic	notes say "18 ft" so that is label on the photo. But sketch in notebook implies it is not quite that deep, hence 17 to 18 ft is the designated depth.	lacustrine - till boundary mixed in this auger sample
MW-ESH-BR #5b	24	medium brown	mud with pebbles	clay dominates, with high fraction of silt	no visible organization	1)1.7 cm Dmax, plate-shape that is 30% missing, angular, gray, limestone; 2) 2.0 cm Dmax X 0.7 cm thick, plate-shaped, dark gray, no fizz, siliciclastic	sample of equidimensional round balls, mostly dried, plus non-spherical shapes that are pebbles	till
MW-ESH-BR # 6a	27	brownish medium gray	mud with <1% mm-size clasts, and rare pebbles	clay + silt of similar proportions	no visible organization	1) 0.5 cm Dmax, blade-shape, dark gray, subangular; 2) 1.1 cm Dmax, blade-shape, dark gray, subangular	sample still damp after >9 months in ziplock (not in refrigerator)	lacustrine?
MW-ESH-BR # 6b	28	brownish medium gray	mud and a small fraction of pebbles	clayey silt	no visible organization	1) 1.5 cm Dmax X 0.8 cm, rectangle, 0.4 cm thick, angular, dark gray, no fizz	dominated by semi-spehrical balls (aggregates)	lacustrine
Part B								
MW-ESH-BR #7	33	light gray				most rocks are angular, as if broken from a larger erratic	2/3 of light gray lumps are aggregates, other 1/3 have rock within them	till
MW-ESH-BR #8	40	light to medium gray	half pebbles,	clayey silt	no visible	1)2.3X1.7X0.3 cm, subrounded	sample is mixture of subspherical	till

			half matrix		organiz-ation	and angular, medium gray, limestone; 2) 1.7X1.5X0.3 cm, very irregular, angular, gray, no fizz; 3) 1.5X0.9X0.7 cm plate, subrounded, medium gray, no fizz	balls and irregular shaped clasts, both coated in same mud so same color	
Part C								
MW-ESH-BR core #1a	51	medium gray	unsorted mixture spanning clay to pebbles	high percentage clay	no visible organiz-ation	1) 1.2 cm Dmax, equidimensional, subangular-subrounded; 2) 2.5X2.0X1.2 cm, irregular shape, subangular, dark gray, siliciclastic; 3) 1.2 cm Dmax, equidimensional, irregular, subangular to subrounded, gray; 4) 1.0 cm Dmax, equidimensional, subangular-subrounded, gray, calcareous siliciclastic	freshly broken surfaces moderately damp	till
MW-ESH-BR core #1b	53	medium gray with slight brownish cast	unsorted, 50% matrix + 50% cobbles	little or no clay; matrix primarily sand-size	no visible organiz-ation	1) 8 cm Dmax, pie-shaped wedge, subangular, dark gray, calcareous siliciclastic; 2) 4.1 cm Dax, crudely egg-shaped, subrounded, dark gray, siliciclastic	freshly broken surfaces retain dampness	till
MW-ESH-BR core #2	56	medium gray	unsorted sand to pebbles	significant clay accompanies sand	no visible organiz-ation	1) 7.2 cm Dmax, 2 cm thick tabular, subangular-subrounded,	freshly broken surface is quite damp	till

						gray with internal parallel lamina, siliciclastic; 2) 1.8 cm Dmx, egg-shaped, subrounded, gray		
MW-ESH-BR core #3	61	medium gray	unsorted mud to pebble	primarily sand with small percent clay	no visible organiz-ation	1) 1.4 cm Dmx, wedge-shape, subangular to subrounded, gray, no fizz; 2) 1.4 cm Dmax, egg-shaped, well rounded, gray, siliciclastic; 3) 2X1.8X0.8 cm, triangular, subangular-subrounded; gray and dark red, sandstone with Fe-mineral cement on some faces, perhaps Medina or Clinton or Queenston; 4) 3X1.5X1.1 cm, irregular, subangular to angular, no fizz, gray	freshly broken surface only slightly moist	till
MW-ESH-BR core #4	66	medium gray	poorly sorted sand matrix with pebbles	very rich in clay	no visible organiz-ation	1) 6.5 cm Dmax, equidimension al cube, subangular, gray, siliciclastic	exterior very wet & muddy; freshly broken surfaces are damp; label on bag is ">63 ft", though the part of label visible in photo hides the > symbol	till
MW-ESH-BR core #5	~67	gray	pebble-rich, in unsorted matrix of sand + mud	important fraction is clay	no visible organiz-ation	1) 2.5 cm Dmax, equidimension al, irregular, subangular, gray, siliciclastic; 2) 1.8 cm Dmax,	photos have greenish hue, but this is artificial, related to camera adjusting to poor lighting	till

						equidimensional, subangular-subrounded, gray, siliciclastic; 3) 1.4 cm Dmax X0.8X0.4 cm, blade, subangular-subrounded, gray, siliciclastic	(cloud cover); freshly broken surface moderately damp; depth of label in photo was intentionally altered in this table, to better fit position in sequence of sleeves	
MW-ESH-BR core #6a	~73	medium gray	unsorted, muddy-sandy matrix with small pebbles	clay is a small fraction of matrix	no visible organiz-ation, although in Karig photo it looks clast-supporte d	1) 1.2 cm X 0.8 cm X 0.4 cm, blae-shaped, subangular, gray, siliciclastic; 2) 0.7 cm Dmax, 0.3 cm thick, plate-shape, subrounded, gray, siliciclastic; 3) 0.6 cm Dmax X 0.4 cm X 0.3 cm, subangular, gray, siliciclastic		till
MW-ESH-BR core #7a	77	medium gray	unsorted mud matrix with abundant pebbles	little clay	no visible organiz-ation	1) 3.8 X 1.2 cm thick, plate-shaped, subangular-subrounded, dark gray, siliciclastic; 2) 2.0 cm Dmax, 1.1 cm thick, plate-shaped, angular to subangular, dark gray, siliciclastic; 3) 1.2 cm Dmax X 1.0 cm X 0.6 cm, irregular form, subangular to subrounded, dark gray, siliciclastic	freshly broken surface relatively dry; depth of label in photo is slightly deeper than my final estimate based on its position in the sleeve	till
MW-ESH-	78	medium gray	pebbles to cobbles	clay is a moderate	no visible	1) 6.0 X 5.0 X 3 cm,	freshly broke surface	till that is clast-

BR core #7b			(50%) in muddy matrix (50%)	fraction of matrix	organiz- ation	subrounded, dark gray, siliciclastic; 2) 1.8 cm X 1.3 cm X 0.8 cm, subangular, dark gray, siliciclastic; 3) 1.7 X 1.0 X 0.5 cm, angular to subangular, dark gray, siliciclastic; 4) 2.2 X 1.3 X 0.8 cm, irregular, subangular, dark gray, siliciclastic; 5) 2.4 X 1.5 X 0.8 cm, tabular shape, subangular- subrounded, gray sandstone	relatively dry, and disaggregates easily	dominate d
MW- ESH- BR core #8	80	medium gray	pebbles in matrix with abundant clay (50%/50 %)	clay with minor % sand	no visible organiz- ation	1) 6.3 X 5.0 X 0.9 cm, taular, visible beds, angular, siliciclastic; 2) 5.4 X 3.0 X 1.1 cm, tabular, bedded, angular to subangular; 3) 5.5 X 4.5 X 1.2 cm, plate- shape, bedded, angular to subangular	all 3 described clasts are locally sourced Devonian siltstone; fresh surface of bulk sample is wet	the local bedrock clasts are essen- tially untrans- ported

Clast Provenance

At a depth of about 22 m (72 feet) subsurface in borehole WM-ESH-BR, pebbles were collected for compositional identification. The compositions are summarized in Table 9, and the forms of the pebbles are visible in Figure 27. Bedrock of the first two lithologies listed in Table 9, siliciclastic mudstone to very fine sandstone of gray to brownish gray color, crop out today in the Fall Creek drainage basin, indicating that 69% of clasts are of local origin. The other clasts are dominated by multi-colored sandstone and include sparse limestone. These originated from bedrock erosion beyond the modern catchment, and constitute 31% of the sample. This second set, the exotic pebbles, tends to be moderately to well rounded (Fig. 27, left side) whereas the locally sourced pebbles are commonly sub-angular to angular.

Table 9. Lithology of individual pebbles collected at a depth of about 22 m (72 ft) in WM-ESH-BR.

	N	%
dark siltstone of local derivation = 19	19	54.3
medium gray very coarse siltstone to very fine sandstone of local derivation	5	14.3
yellowish-brown sandstone, thin bedded	2	5.7
yellowish brown fine sandstone not visibly bedded	1	2.9
greenish tan and tan sandstones	3	8.6
dark reddish brown sandstone	1	2.9
light gray very fine sandstone	2	5.7
gray limestone	1	2.9
tan siltstone with calcite veins	1	2.9
sum	35	

Figure 27. Collection of pebbles from about 22 m (72 ft) depth in borehole WM-ESH-BR. Scale bar minor divisions are millimeters, and major divisions centimeters. The clasts that are exotic to the Fall Creek drainage basin are shown on the left; those of local original occur in the central and right sectors of the photo.

<u>Spatial relations among boreholes and neighboring surface exposures</u>

Across the plain between Fall Creek valley and Cascadilla Creek valley the surface sediments have been documented by digging shallow pits at about 12 locations. Within Cascadilla Creek valley, two locations provide excellent outcrop over 1-4 m heights. These constraints are combined with the two borehole lithologic columns to interpret the sub-surface distribution of unconsolidated sediments (Fig. 28). Pending additional boreholes or geophysical surveys, the cross section is speculative.

The broad pattern is that there exists an unsorted gravel above about 288 m elevation (946 ft), which likely occurs along the upper part of the Cascadilla valley wall but was not observed there. Between that elevation and about 282 m elevation (925 ft) occurs laminated muds. Below 282 m elevation, unsorted pebble to cobble gravel with a mud matrix exists, persisting to the top of Devonian bedrock at most locations. The ESH#1 samples suggest that a water-sorted sand and gravel unit underlies the lower diamicton, possibly only along the ancestral Fall Creek valley axis.

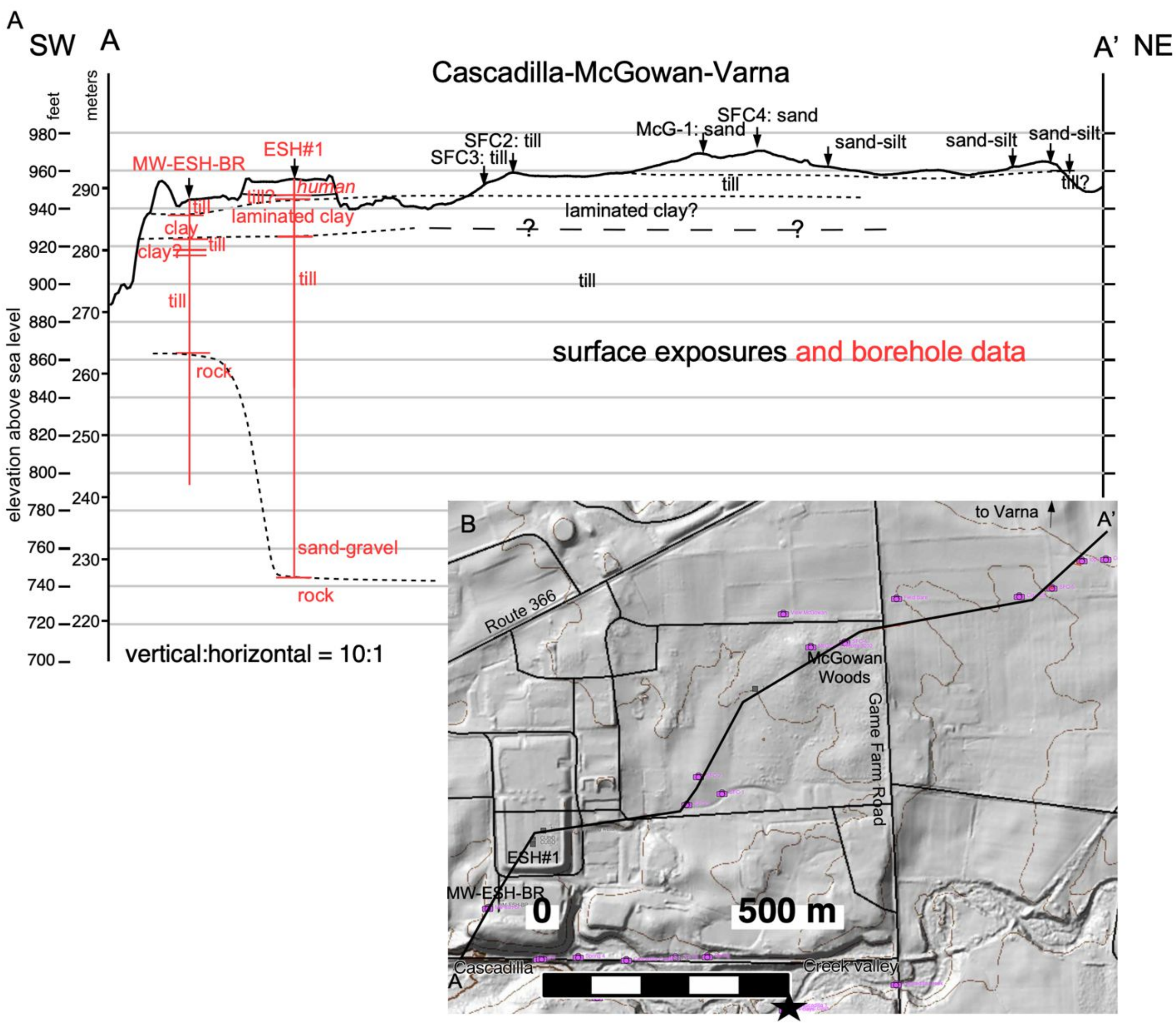

Figure 28. A cross section for the plain between Fall Creek and Cascadilla valleys (A-A') shows the physical stratigraphic relations between surface observations and subsurface materials documented in the boreholes detailed here. Surface descriptions from Jordan, Crowley and Allmendinger (in prep.). The Cascadilla Creek valley outcrops reinforce the interpretation of lateral continuity of both the laminated clay facies and a second till below 286 m (940 ft) elevation.

<u>Interpretations</u>

To a depth of 2.5 m (8 ft) (elevation 286 m [937 ft]), the sediments in MW-ESH-BR are gravels, whose organization and fabric are not known. The shallowest sector of ESH#1 is not readily interpreted, because there was known to be several feet of construction fill at the site, and immediately below that fill it was somewhat ambiguous what was natural material and what was anthropogenic. The geological cross section (Fig. 28) suggests that matrix-supported gravel, like exposed in dug pits 300 m to the northeast, is the surface material in the boreholes. Consequently, I interpret that glacial till is the shallowest unit in the two boreholes.

The underlying laminated mud, which is up to 6 m (20 ft) thick, consists of clay and minor silt that is well laminated. The lamination is throughgoing, in all cases thinner than 1 mm. The depositional conditions must have been a still body of water. The absence of coarser grain sizes implies that sediment transported to this sector was in suspension. The environment is interpreted to have been a lake. Whereas a glacier likely formed one or more margins of the water body, the absence of coarse sediment suggests that a melting glacier margin was located a long distance from the area of the boreholes.

The lower unsorted gravel, 18 to >20 m (60 to >65 ft) thick, contains a mud-rich matrix in all but a few thin horizons. This unit is interpreted as glacial till. At a position mid-way down through this unit, clasts are exotic to the Fall Creek drainage basin.

Age relations are inferred based on the physical stratigraphy. The upper till is unambiguously the surface unit 300 m northeast of the boreholes and in WM-ESH-BR. Consequently, it is interpreted to likely be part of the glacial materials generated during the Valley Heads readvance. In an outcrop along Cascadilla Creek (Fig. 29), 600 m (1970 ft) east-southeast of ESH#1 (star location in Fig. 28), a laminated mud that overlies till occurs in short wavelength (~2 m), steep-limbed folds. This suggests that this lacustrine layer was overrun by a glacier and deformed. This outcrop and the interpreted sub-Valley-Heads-till position of the lacustrine sediments in the boreholes lead to identification of the lacustrine sediments as older than the age of the Valley Heads readvance. The lower thick till may be the product of any pre-Valley Heads glacial advance, or the composite of multiple glacial advances.

Figure 29. Outcrop of highly folded, laminated mud that overlies glacial till, exposed by collapse of the bank of Cascadilla Creek (note creek at lower right). The total height of the outcrop is approximately 4 m (13 ft). At the creek margin, the linear mound over 1 m tall, with a brown top, is the collapsed material. Behind, in approximately the lower half of the outcrop, below a brown band, is a diamicton, of cobbles and rare boulders in an unorganized fine matrix. Above the brown layer and partially hidden by dangling roots are a series of chevron folds in finely laminated mud, most of which is medium or dark gray but some zones that parallel layering are orangish brown. Photograph 31 December 2021. Location 42.44066°N, 76.45136°W, elevation 283 m (927 ft) (starred location in Fig. 28).

Physical Stratigraphic Relations of the Borehole Sections to the Fall Creek Valley Sections

Caution is needed in interpretation of the physical relationships, and time sequence, of the Quaternary sediments of the boreholes on the plain between Fall Creek and Cascadilla Creek to those of the valley-wall sections adjacent modern Fall Creek. First, the correlations proposed among the sections of the Fall Creek valley wall are heavily dependent on the chronological data provided by Karig (2022), and there are no similar constraints for the borehole sediments. Second, the borehole sections occur in the southern part of the ancestral Fall Creek Valley (Figs. 2, 3) whereas the Fall Creek valley wall sections are located in the northern half of the ancestral valley. Innumerable complexities and discontinuities within the sedimentary package which fills the ancestral valley likely exist between those two zones.

Like the sections at S1, S2, S3, VHB and HB2, the shallowest sediments of the boreholes are interpreted to be Valley Heads readvance tills. Also like the Fall Creek valley-wall sites, the unit below Valley Heads till is an interval of water-transported sediment. Also in common with the Fall Creek valley-wall sites, the fluvial and/or lacustrine unit is, in turn, underlain by another unit that is either a till or was deformed beneath an ice sheet, both of which are evidence of an earlier glacier advance.

However, no strong basis exists for correlating the lacustrine mudstones of the two boreholes and the Cascadilla Creek outcrop to any specific interval of the Fall Creek valley wall. The laminated clay and silt unit (B) of S1 is one option for correlation, with an age predating 21,425±930 years (Karig, 2022). The varved clay downstream of VHB which Karig (2022) concludes are slightly less than 18,000 years old, whose physical relationship to the sediments of the VHB section remains ambiguous, is another candidate. It is also plausible that the deltaic deposits of the VHB section prograded into the lake in which the borehole lacustrine sediments accumulated. Given the numerous advances and retreats of glacial ice and the suitability of the bedrock-bounded valleys to pond water as ice fronts moved, numerous other correlations of the borehole lacustrine sections to glacial history are possible.

Conclusions

A new detailed map of the positions of the top of Devonian strata west of 76.419°W defines the ancestral Fall Creek valley across Ithaca, New York, and the lowlands east of Ithaca. The ancestral valley was wider than a kilometer and broadly at least 30 m deep. Work presented by Karig (2022) and new analysis presented here show that the ancestral Fall Creek valley was filled with sediment and partially re-excavated, multiple times, during advances and retreats of Quaternary ice sheets and during the interglacial intervals. The volume of buried unconsolidated sediment in the ancestral valley is of the order 10-15 km^3, an amount barely touched by the study presented here and by that of Karig (2022).

This study demonstrates that the sedimentary fill of the ancestral valley includes not only tills of multiple generations but also lacustrine deposits and stream-flow deposits. The chronological data provided by Karig (2022) demonstrate that there was not a single time of pooling of water to form lakes which persisted long enough to accumulate well-sorted clay, but instead that lacustrine deposits formed multiple times: prior to approximately 20,000 years (laminated sediment at sites S1 and S2), prior to approximately 28,000 years (the basal clay at HB2, which was overrun by a glacier and converted to till prior to deposition of the overlying dated unit), and also around 18,000 years (varved sediments near Varna detailed by Karig [2022]). To that set of evidence for lake formation near Ithaca can also be added the indirect record of delta growth into a >10 m deep body of water expressed by gravel foresets at VHB for which age constraints are inadequate, and the undated laminated muds of the two boreholes and the Cascadilla Creek valley outcrop.

The sedimentary fill of the ancestral Fall Creek valley offers an extensive archive of Quaternary glaciations in central New York state. However, the physical stratigraphy of the units which fill the ancestral valley are almost certainly highly complex, with lateral interruptions of continuity. To correctly interpret the sediments at any one location and maximize the value of this geological archive will require coupling extensive geophysical surveys with drilling campaigns.

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Auger at borehole ESH#1, Cornell University, 4 April 2022