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Middle Wisconsin glacial advance into the Appalachian Plateau, Sixmile Creek, Tompkins Co., NY

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ABSTRACT

Areal mapping of the middle Wisconsin varved clay site along Sixmile Creek near Ithaca, New York, has revealed a much more widespread and varied array of sediments than previously thought. Lacustrine clays, some varved, are interbedded with sands and gravels interpreted as sub-aqueous fan deposits, and both are overlain by a deformation till. Nine radiocarbon dates indicate a 34–37 ^{14}C ka BP age for the lacustrine sediment, with the deformation till less than a few thousand years younger. Beneath this sequence is a deposit dated at $\pm$42 ^{14}C ka BP. Both strata represent a tundra climate with a mean July temperature of about 10°C. The Sixmile Creek deformation till must correlate with the 35 ^{14}C ka BP till along the Genesee River, 125 km to the NW, and defines a Cherrytree stade glacial advance into the Appalachian Plateau, much further south than what has generally been accepted. Such an advance would require drainage from a proglacial lake in the western Ontario basin to flow westward instead of northeastward. The Sixmile strata suggest a colder than accepted middle Wisconsin stage. Recent data indicate that this stage is one of progressive cooling, with large climatic fluctuations.

Introduction

Existence of a middle Wisconsin varved lacustrine clay sequence along Sixmile Creek, southeast of Lake Cayuga, (Fig. 1) has been known since the work of Schmidt (1947) and Muller (1965), but since then little work has been done in, or published about that area. In fact, there had been no systematic mapping of the area until this study. Mapping of the glacial geology of the Sixmile watershed, now in progress by the first author, has demonstrated that these deposits are far more extensive and include a wider range of lithologies than previously recognized.

These middle Wisconsin sediments lie within a multistage Sixmile glacial trough that, although hanging with respect to the larger Cayuga trough, is the site of one of the larger ice streams in the Cayuga region. The trough, excavated into gently south-dipping upper Devonian siltstones and shales of the Genesee Formation, reveals evidence of at least four Quaternary ice advances into this sector of the Appalachian Plateau.

The inner and younger of these bedrock troughs (Fig. 2), now filled with Quaternary sediment, is most probably of Illinoian age, because incised into its floor is an interglacial gorge that is far larger and more extensive than the post-glacial gorges along Sixmile Creek (von Engeln, 1961). This interglacial gorge has been assumed to be of Sangamon age (e.g. Muller, 1957).

The exposures in the study area reveal pre-late Wisconsin deposits along and south of Sixmile Creek from approximately the dam that contains the Ithaca Reservoir, upstream for approximately 2 km (Fig. 1). Locally the middle Wisconsin sediments overlie a diamicton that lies on the floor of the inner glacial trough (Figs. 2 and 3). This diamicton is assumed to be a till (Schmidt, 1947, 1996), also of Illinoian age (Bloom, 1972). The middle Wisconsin deposits are overlain by late Wisconsin till (Figs. 2 and 3), characterized by a blue-gray, mildly calcareous silty clay matrix and readily differentiated from the older tills.

Of the four lithologic units comprising the middle Wisconsin deposits described in this paper, only the proglacial lacustrine sequence (our unit 1) was recognized by Schmidt (1947, 1996), who identified four series of varved clays, separated by gravel beds, and both overlain and underlain by till units. The upward thickening and coarsening of varves in his lowermost series led Schmidt (1947,1996) to interpret them as a sequence deposited in a proglacial lake south of an advancing ice front.

^{14}C ages obtained during early paleoenvironmental studies of this sequence (Ashworth et al., 1997; Miller,1996) ranged from 22 to >40 ka ^{14}C and led to uncertainty as to the true age of the lacustrine sediments and of the glacier that overrode them. At that time only the surficial till, widely accepted as late Wisconsin in age, was recognized above the varves. Because the sediments were tentatively identified as of Plum Point interstade age (Miller, 1996; Ashworth et al., 1997), the possibility that the proglacial lake was associated with the late Wisconsin glaciation could not be rejected.

Our study of these older deposits was undertaken because of the newly recognized lithologies associated with the lacustrine clays, which

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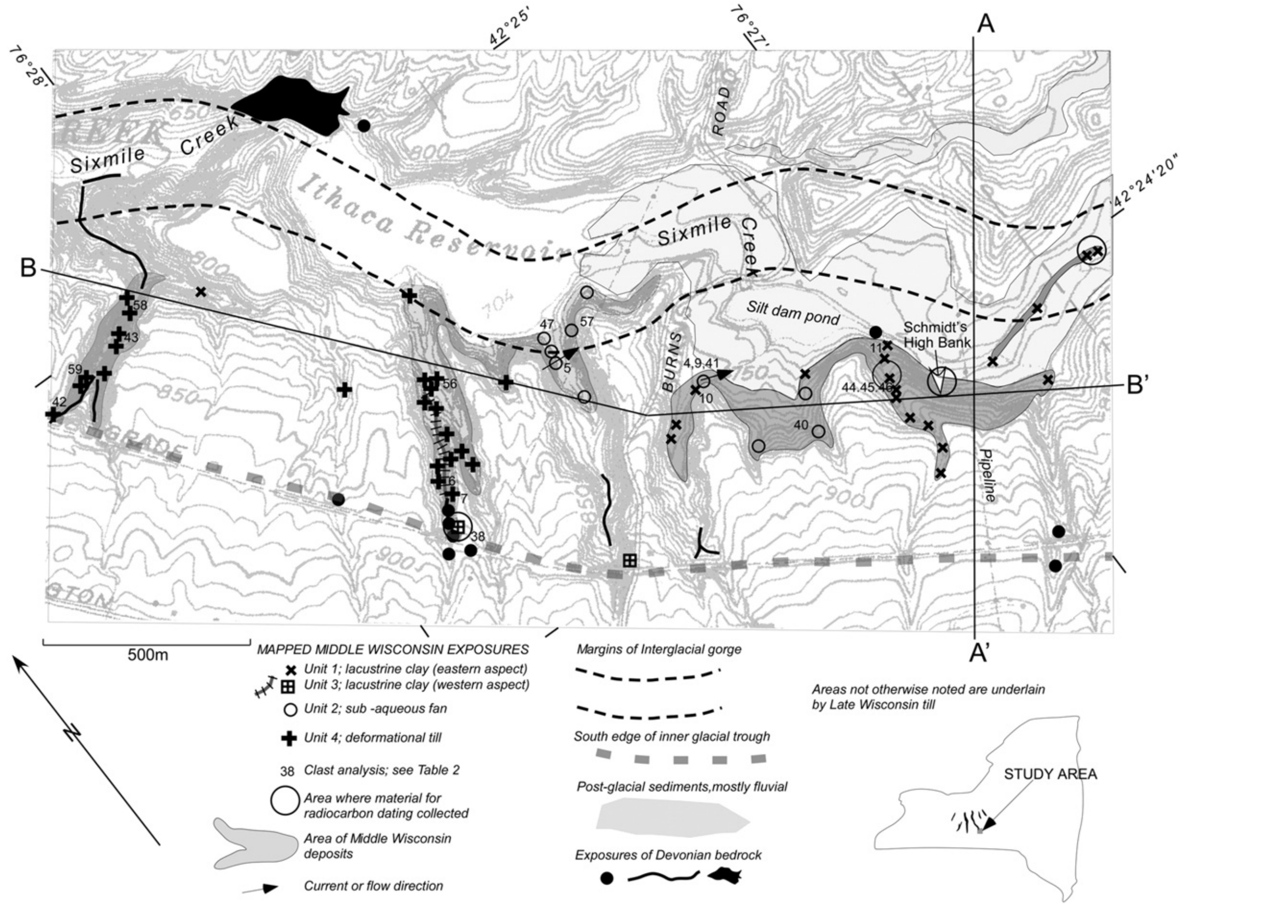

Figure 1. Geologic map of study area showing middle Wisconsin deposits along Sixmile Creek with inset location map. Contours are in feet, where 10 ft ≈ 3 m. Cayuga Lake is shown on the inset location map, just northwest of the study area.

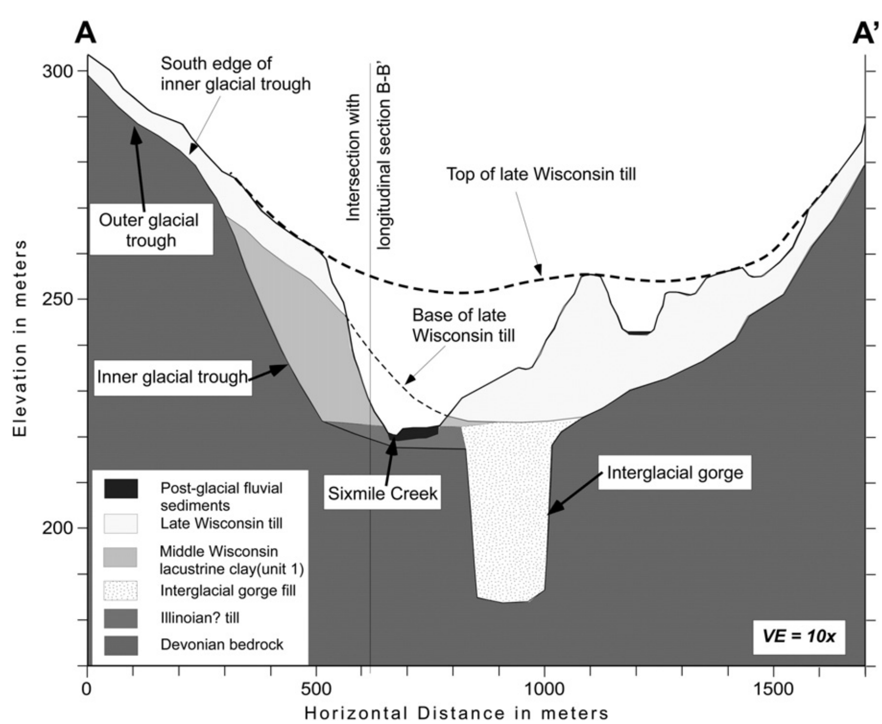

Figure 2. Geologic cross-section A-A′ across the Sixmile valley in the study area. This section emphasizes the setting of the middle Wisconsin deposits within the larger glacial framework, but shows only the lacustrine sediments of unit 1.

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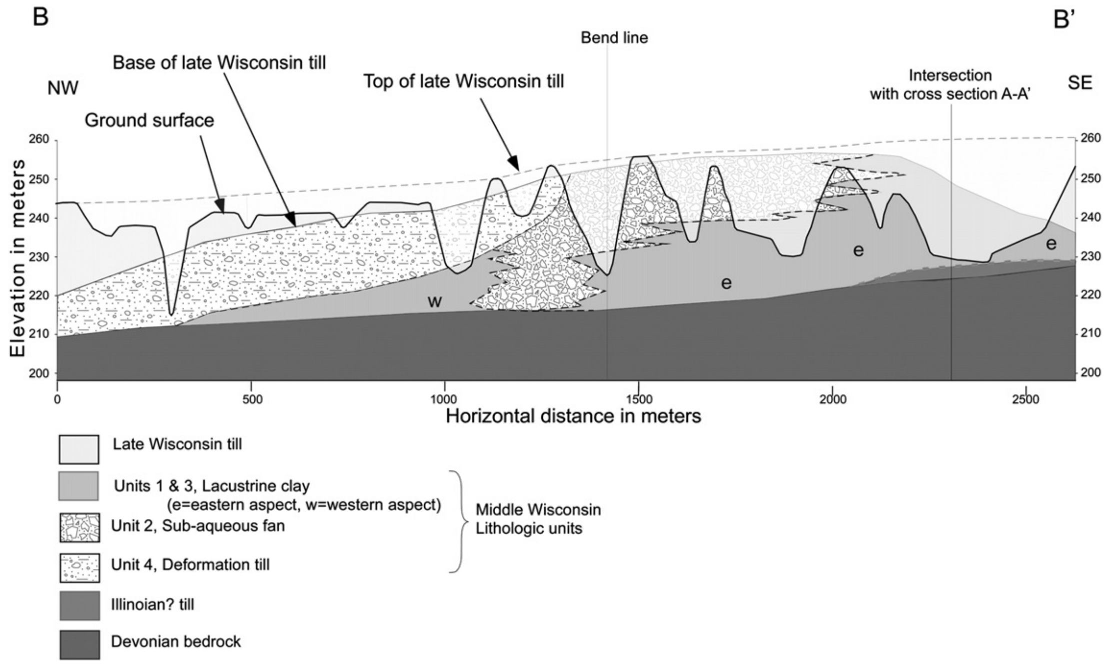

Figure 3. Longitudinal geologic section B-B′ along the middle Wisconsin deposits south of Sixmile Creek. This section is drawn so as to best illustrate the interrelationships among the units of the middle Wisconsin deposits.

were found during the more regional mapping by the first author, and involved the second author to resolve the age problem. This site was deemed particularly important because it is one of the very few middle Wisconsin sites in New York and offered the possibility of clarifying the glacial history of the eastern Great Lakes region during that period.

Methods

Because the middle Wisconsin glacial morphologies have been destroyed or buried by subsequent glaciation, this study relied primarily on lithologic observations. Some observations were made along stream banks in tributaries to Sixmile Creek, which were repeated after storm events when new exposures were created. Most observations, however, were obtained from pits dug through the colluvial cover and root zone, in locations judged to be least affected by slumping, often in slump headwalls.

Clast lithologies were investigated to determine the source of the sediments in which they were contained. The percentage of exotic clasts at a given locality increases with clast size due to their greater resistance to abrasion and breakage than the local siltstones and shales. To avoid this bias and to acquire as many samples as possible only pebbles between 1.5 and 2.5 cm in maximum dimension were collected.

Collection of samples during this study for radiocarbon dating was done from fresh surfaces, with steel tools, and packed in aluminum foil. Samples were refrigerated until being disaggregated and sieved, usually within a few weeks. Picked plant fragments were immediately freeze-dried. Individually picked plant fragments rather than bulk samples were submitted for dating.

Results

Sediments predating the late Wisconsin glaciation appear to form a large lens confined to the south flank of the inner glacial trough along the south side of the Sixmile Creek valley (Figs. 1 and 2). This lens includes both a basal diamicton and the middle Wisconsin sediments that are here divided into four lithologic units. These four units are two dominantly clay sequences, a sand and gravel unit with a significant fraction of exotic clasts and a unit composed of highly deformed sand, gravel and clay. The clay sequences occur in two separate areas and initially did not appear to be closely related. The eastern sequence is dominated by lacustrine clay, in part varved whereas the western sequence was thought to be characterized by angular platy gravels of local bedrock interbedded with clay. With further study and with additional exposures created by stream erosion it became clear that the western sequence was also clay-dominated and that both sequences represented the same water body. The four lithologic units are retained and are described from east to west, which helps clarify the contact relationships among them.

Middle Wisconsin sediments

Unit 1 (eastern clay unit)

Unit 1 is dominated by lacustrine clay and is exposed just upstream from the silt dam (Fig. 1). Creek-side exposures were formerly far more extensive than at present but major slumping and pipeline construction have destroyed or degraded most of them. Schmidt's (1947, 1996) studies focused primarily on an extensive exposure on the south side of Sixmile Creek just east of the "silt dam pond" (Fig. 1), which he termed the "high bank", but which has since slumped and is now obscured.

The remaining outcrops along the creek include only the lowest of Schmidt's varve series. A much thicker section of this suite than that mapped by Schmidt was recognized during this study in a small tributary entering the creek from the south just west of his "high bank" exposure (Figs. 1 and 4).

The first series of varves, extensively studied by Schmidt (1947), is no longer well exposed and was not closely examined in this study. He described a section up to 4 m thick in which the varves generally thicken upward from less than 1 cm to more than 5 cm and represent about 350 yr of accumulation. A typical varve in this series shows a brown silt-rich summer layer, grading upwards into a thinner winter gray clay (Fig. 5A), but there are many irregularities in grain size and relative summer- and winter-layer thicknesses.

At the base of the first varve series is a thin (up to 2 cm) and discontinuous carbonaceous layer that is overlain by sand and/or gravel in some places. This layer contains plant material and insect elytra that indicate a wet calcareous tundra meadow with snowmelt or thaw ponds and somewhat drier sites on nearby slopes in an arctic to sub-arctic landscape at the beginning of varve deposition (Miller, 1996; Ashworth et al.,

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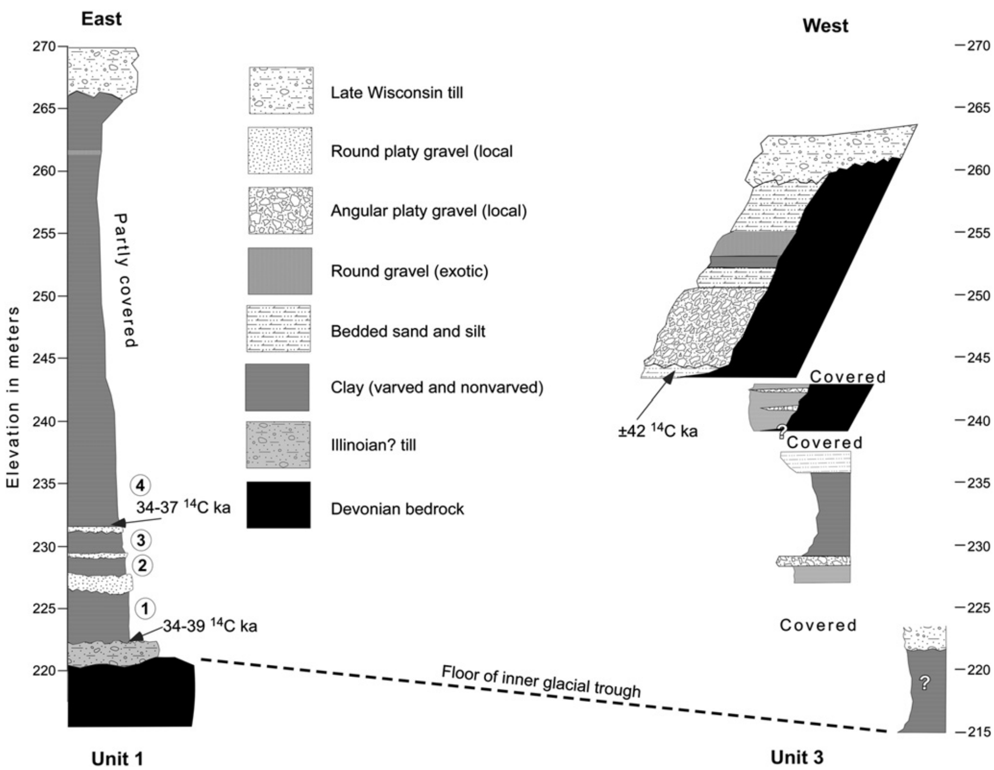

Figure 4. Comparative stratigraphic sections of units 1 and 3, both of which are clay-rich. The upper two sections of unit 3 are offset because no superposition is intended. Both parts abut a bedrock wall. The lowermost section is offset because it is in a different tributary. Locations of strata from which radiocarbon ages were obtained are shown, with details on Table 1. The circled numbers adjacent to the unit 1 section denote Schmidt's (1947) varve series.

1997; Ashworth and Willenbring, 1998). The overlap in climatic data for plants and beetles indicates a mean summer temperature of 10° to 12°C Ashworth and Willenbring (1998).

Nine radiocarbon ages have now been obtained from this bed, ranging from 22 to >40 ^{14}C ka BP (Table 1). The youngest of these ages is clearly invalid, as it would date the lake as near the peak of the late Wisconsin advance, when the ice front was far to the south (e.g. Ridge, 2003). Of the other eight ages, four lie between 34 ^{14}C ka and 39 ^{14}C ka and three lie between 40 and 43 ^{14}C ka.

The overlying section of thin-bedded to massive clay-rich sediments, separated by several sand and gravel beds, was only briefly described by Schmidt (1947), who measured a total middle Wisconsin section about

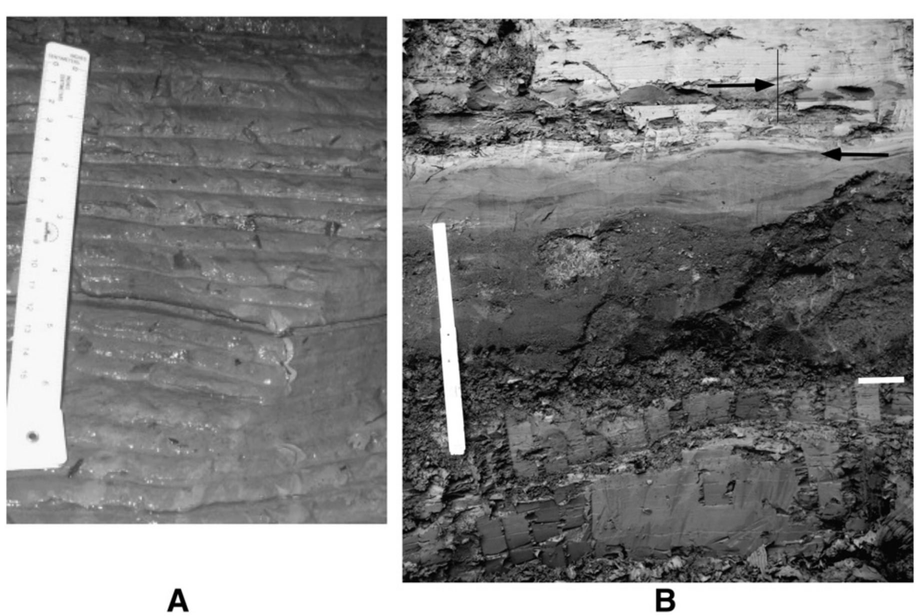

Figure 5. Unit 1 (eastern clay). A: varves of Schmidt's (1947) first series, showing summer brown phase grading upward into darker winter phase. B: Turbidite at base of Schmidt's fourth varve series showing upward fining from pebble gravel through sand to silt. Both the white horizontal bar and the base of extended scale (37 cm long) are at base of the gravel; left-pointing arrow shows black organic layer; right-pointing arrow shows zone of possible varves with alternating red and gray clay.

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Table 1
Radiocarbon ages from plant macrofossils and beetles at the Sixmile Creek site.

Site description	Age (^{14}C ka BP)	Description of sample	Source	Sample ID
Base varve series 1, unit 1				
	>39,900	Organic debris	Bloom, 1972	I-6046 (conventional)
"	27,000 ± 360	*Dryas integrifolia* leaf	Miller, 1996	Beta-27680
	33,900 ± 710	*Salix* twig	"	Beta-32973
"	21,820 ± 390	Beetle chiton	Ashworth &Willenbring, 1998	CAMS 39878
"	38,350 ± 980	Plant macrofossils	This study (Karig)	AA94456
"	41,000 ± 1900	9 *Salix herbacea* leaves	This study (Miller)	CAMS-45917
"	38,790 ± 930	6 *D. integrifolia* leaves	"	CAMS-45918
"	43,000 ± 1600	9 *Claytonia* seeds	"	CAMS-45919
"	34,510 ± 960	Beetle chiton	"	CAMS-45920
Base varve series 4, unit 1				
	33,950 ± 220	Conifer twigs	This study (Miller)	Beta-100442
"	35,190 ± 240	"	"	Beta-100443
"	37,200 ± 500	Plant macrofossils	This study (Karig)	WW 8529
Unit 3	41,900 ± 900	*Picea* knot	Bloom, 1972	Y-1401 (conventional)
Deposit below unit 3				
"	>35,000	Twigs and bark	Muller, 1965	W-504 (conventional)
"	42,300 ± 1500	Plant macrofossils	This study (Karig)	WW 8289
"	43,800 ± 4900	Plant macrofossils	This study (Miller)	OS-98037
"	40,100 ± 630	*D. integrifolia* leaves and *Salix* bud	This study (Karig, Peteet)	WW 9396

Where data are available, the labs responsible for the data are: U. Arizona (AA samples), Beta Analytic (Beta), L. Livermore (CAMS), USGS,Reston (WW). Woods Hole—NOSAMS (OS), Isotopes, Inc (I), Yale (Y). All analyses were AMS unless labeled conventional.

23 m thick at his high bank exposure (Fig. 1). The more complete section in the tributary west of the high bank exposure is overlain by late Wisconsin till at an elevation of 265 m, leading to a total thickness of at about 42 m. The difference in thicknesses is explained by the fact that Schmidt's creekside section was near the center of the inner glacial trough, where the late Wisconsin ice eroded much deeper into the pre-existing sediments (Fig. 2). The contact between the lacustrine clay section and the overlaying till is observed to be an erosional disconformity.

Schmidt's first varve series is capped by the lowest of several gravel units interbedded with the lacustrine clay. This gravel bed varies in thickness from 1.2 to 2.3 m in the high bank exposure (Schmidt, 1947, p. 85), is 1.9 m thick along the tributary where observed in this study and is composed of very poorly sorted clasts ranging in size from less than 1 cm to about 5 cm and rarely to 10 cm. The gravel has a silt to sand matrix and shows no grading. About 90% of the clasts are of local origin (Fig. 6, Table 2) and platy, but most are well-rounded. Schmidt claimed to see imbricated clasts showing flow from the east or SE and used this observation to interpret this and the other gravel units as fluvial deposits from an ancient Sixmile Creek, caused by significant and rapid changes in lake level. No clast imbrication was recognized during this study, in spite of the expectation that fluvial deposition of such platy clasts should lead to strongly developed imbrication.

This gravel unit has a sharp, clearly depositional basal contact with the underlying varved clay that is strongly deformed for 10–20 cm below the contact and is just as sharply overlain by indistinctly bedded gray silt that grades upward into thinly bedded clay. Rather than representing fluvial deposition, this gravel unit has the characteristics of a mass flow deposit, in this case a debrite (an ungraded debris flow deposit). The ungraded, unsorted character of this gravel and the preponderance of local lithologies indicate a very local source, most probably the lakeshore, perhaps at deltas. Clast rounding could have occurred either along the shore or in streams feeding the deltas.

Although the thin rhythmic bedding in Schmidt's first varve series appears to be varves, the alternating red and gray layers above the lowermost gravel bed are not as easily interpreted as such. The section above the lower gravel unit consists largely of plastic blue-gray and red clay although some of the gray layers are silty. Individual layer thicknesses are highly variable from less than 1 mm to almost 1 m (Fig. 5B). The higher parts of the section are dominated by massive beds of red to pink clay. Although the regular thin bedding in some parts of this section may represent varves, especially in the lower section of Schmidt's fourth varve series, most sections appear simply to be alternating, but seldom rhythmic, red and gray beds. Both the red and blue-gray layers are dominantly clay and the red clay is much more calcareous than the blue-gray clay, suggesting that different sediment sources, rather than or in addition to seasonal cyclicity, are the cause of this alternation. This possibility was also recognized by Schmidt (1947) and Bloom (1972), who both suggested that the red clay had a source in the Silurian Vernon and Queenston red shales at the north end of Cayuga Lake, whereas the gray clays were sourced from an ancestral Sixmile Creek, or at least more locally.

The 0.5 m thick sand and gravel bed that separates Schmidt's third and fourth varve series is almost certainly a turbidite. From a very sharp basal contact it grades upward from gravel through sand to silt (Fig. 5B). This bed has carbonaceous seams and blebs near its silty top. A distinct carbonaceous band, up to 1 cm thick, occurs within the clay about 30 cm above this turbidite (Fig. 5B). Two radiocarbon ages, of 34.0 and 35.2 ^{14}C ka BP, were obtained from conifer twigs in this band, and one sample from unidentified plant material gave an age of 37.2 ^{14}C ka BP (Table 1). The variation among radiocarbon ages both at this level and at the base of the varves is too great to provide any information about the time required for the deposition of the first three series of varves.

Schmidt (1947) measured about 12 m in his fourth varve series at his high bank section. Our mapping showed that only about 4 m of this series is continuously exposed in the tributary section but scattered exposures occur upstream that represent higher parts of the section. Exposures along this tributary include both thin-bedded and more massive red clay. At least one gravel bed composed of clasts, a large fraction of which is of exotic origin, and much more equant than in the gravels beds lower in this sequence, occurs near the top of the exposures. These upper gravel beds are quite likely tongues of the same gravels occurring in unit 2. Capping this lacustrine section is a thin (5–7 m) late Wisconsin till, (Muller and Cadwell, 1986), characteristically a blue-gray silty clay diamicton.

Unit 2 (sand and gravel)

Unit 2 consists of sand and pebble to cobble-sized gravel with a high percentage of exotic clasts. This suite is exposed along the south side of Sixmile Creek from the upper end of the impoundment behind the silt dam downstream to at least as far as the upper end of the Ithaca Reservoir (Fig. 1). At its southeastern margin these sediments are stratigraphically

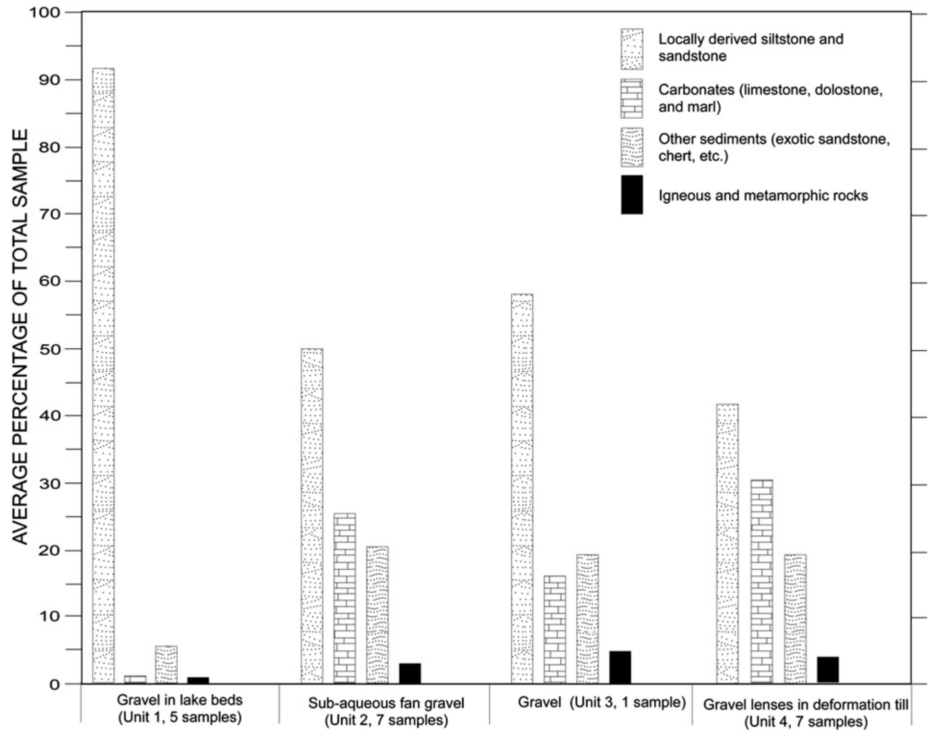

Figure 6. Histograms showing average lithologic percentages of gravel clasts in the four units at the Sixmile site. Individual sample data are shown in Table 2. The single sample from unit 3 represents a gravel lens above very angular clast gravels that were almost totally of local origin.

correlative with the upper part of the lacustrine clay of the lithologic suite 1 and overlie lacustrine clay near Burns Road.

The easternmost exposures of this unit, in several small gullies south of the silt dam pond (Fig. 1), are dominated by sands and gravels, the clasts of which are mostly granule- to pebble-size. Occasional clasts attain a diameter of 5 cm. About 40% of the clasts are of exotic origin (Table 2) and are rounder than the local clasts. Most of these gravels are matrix supported by fine to coarse sand but are without silt or clay. Some sections, especially the sands, are thin-bedded, whereas other sections show only indistinct bedding.

A large exposure of unit 2, west of those described above, but still east of Burns Road, shows similar, but significantly coarser gravels (Figs. 1 and 7A). Here, a 10 m thick sequence of crudely bedded coarse sand and gravel coarsens upward to include clasts 10–15 cm in size at its top. Gravels in this exposure tend to be clast-supported, usually with a coarse sand matrix. Exotic clasts, about half the total, are roughly equant and round to sub-round, whereas the local clasts tend to be tabular and less round (Table 2, Fig. 6). The rough but distinct bedding indicates a low ($\pm5°$) easterly dip, within which the gravel clasts are strongly imbricated (Fig. 7A), showing transport from the west.

The westernmost exposures of unit 2, at the base of the tributary west of Burns Road, are even coarser, showing clast-supported cobble gravels with clasts up to at least 25 cm (Fig. 7B). Over half the clasts are exotic and well-rounded (Fig. 6, Table 2). The more tabular local clasts highlight a strong imbrication showing eastward flow (Fig. 7B). Unit 2 clearly coarsens westward and probably upward as well. The high percentage of exotic clasts and their easterly or southeasterly transport point to a glacial source.

The exposures of this unit are too sparse and scattered to allow definition of its geometry but are sufficient to indicate that it is not a horizontal tabular body. Exposures east of Burns Road show the contact between unit 2 and the underlying clay progrades, becoming younger to the east (Fig. 3). West of Burns Road several holes drilled for a proposed dam (Hatch, 1940; unpublished drill records stored at the City of Ithaca Water and Sewer Dept) recovered no clay beneath the gravels, supporting the prograding relationship noted above. Lateral contacts are not defined but, as described in the next section, scattered beds of gravel similar to those of unit 2 occur in the upper section of unit 3. Unit 2 is disconformably overlain by late Wisconsin till along most of its southwestern exposures, which defines a section reaching at least 40 m in thickness.

Unit 2 could represent either a delta or fan but the laterally westward coarsening, with clast imbrication, more closely fits a fan or fan channel interpretation. Because this sand and gravel unit is interbedded with and overlain by lacustrine sediments, it is here interpreted as part of a subaqueous fan emanating from channels exiting at an ice front. The coarseness of the westernmost gravels would suggest that such an ice front was not far from the site of deposition. With an advancing ice front the fan facies should prograde southeasterly over the lacustrine clays. The lack of underlying clay in the drill holes west of Burns Road may be a result of erosion by channelized sub-glacial flow.

Unit 3 (western clay unit)

Adjacent to the bedrock edge of the inner glacial trough, in several tributaries between Burns Road and the Ithaca Reservoir, is a lithologic unit initially characterized by gravels consisting of very angular platy clasts of the local fissile siltstone bedrock (Fig. 8B). Associated with these gravels are beds and lenses of red or blue-gray clay, round cobble gravels with a large exotic clast component, and thin-bedded sands and silts (Fig. 8C). Unit 3 appears to combine components of units 1 and 2, with distinctly different angular platy gravels. The relationship among the three units was initially unclear but it became increasingly obvious that unit 3 consists primarily of lacustrine clay. The platy gravel occurs as lenses not only near the top of the unit but also at several other horizons (Fig. 4).

The platy gravel near the top of the unit has low dips, generally to the north and/or east, and shows clast imbrication in various directions except southwest. The source of the angular platy clasts was clearly the adjacent bedrock, but the associated and/or interbedded round cobble gravels have a high percentage of exotic clasts, again indicating a glacial derivation. Interbedded clay and silt indicate periods of deposition in a low energy environment. Unsupported pebbles found in one massive

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Table 2
Lithologic components of pebbles from gravels at the Sixmile Creek site.

Bag#	Tot peb	Local	Ig/met	Other seds	ls	Unc	% Local	Comments
								Unit 1
11	57	57	0	0	0		100	Sub ang to sub rnd; almost all platy;many broken w/ang surfaces
44	89	80	2	7	1	1	90	Local very platy;rnd–sub rnd;some broken;exotic sub ang
45	101	88	0	12	0	0	87	Local very platy;rnd–sub rnd;some broken;exotic equant and sub rnd
46	97	85	1	10	1	0	88	Local very platy;rnd–sub rnd;some broken;exotic equant and sub rnd
10	83	80	0	2	1		96	Sub ang to sub rnd;most platy
67	94	90	0	2	0	2	96	Local round and platy;some broken
								Unit 2
5	57	25	1	24	7		44	Sub rnd to rnd;larger clasts(not sampled) also rnd
9	65	42	2	5	15	1	65	Most subrnd;few broken
40	92	53	2	22	10	5	58	Exotic sub rnd;local sub rnd to sub ang;some broken;unc prob local
41	103	47	3	11	41	1	46	Rnd,subrnd;local platy;many broken surfaces on local;no red ss
57	125	56	8	22	38	1	45	Exotic sub rnd–sub ang;local mostly platy,sub rnd;few broken
47	112	44	0	26	42	1	39	Exotic rnd–sub rnd;local tabular, sub rnd;some broken clasts;1 chert,lot ss
								Unit 3
38	161	94	8	32	27	0	58	Almost all rnd/sub rnd,few broken rnd;4–5 chert
								Unit 4
56	112	50	6	15	40	1	45	Almost all rnd–sub rnd
43	102	37	5	30	26	4	36	Most rnd,subrnd;local most platy,some broken;mod amt red/white ss
58	106	43	0	23	39	1	41	Local most very ang,;ew more rnd,broken;exotic rnd,sub rnd,few ang,broken
59	114	35	5	28	46	0	31	Roughly same as 58
6	59	24	4	10	6	9	41	Sub rnd, local more tabular
7	111	74	2	15	18	2	67	Most rnd;fair # broken with sharp edges

Explanation: ig.met includes all igneous and metamorphic rocks; other seds are mostly pre-Mid Devonian sandstones; ls includes all carbonates; unc are clasts of uncertain origin.

red clay bed are interpreted as dropstones because they are 80% exotic and show glacial striae.

Distinctly different thin-bedded brown sand and silt were exposed below this platy gravel in a pit dug in 2010 near 42°24.512′N, 76°27.872′W (pebble site 38 in Fig. 1). These strata have thin layers of coarser sand and flat pebbles, and also show cross bedding, both of which indicate northward directed current action. Stringers and lenses of plant material occurring throughout this section gave three AMS radiocarbon ages of 40.1, 42.3 and 43.8 ^{14}C ka BP (Table 1), which would place these strata toward the end of the Port Talbot interstade as defined by most workers. The base of this section was not reached but it is close to an east-facing bedrock wall that trends about N 30° E. Although the contact between these strata and the overlying sediments of unit 3 as exposed in the pit can be said only to be sharp, the contrast in lithologies and the apparent difference in ages of at least 5000 yr, indicate that this lower unit is not part of the same proglacial lacustrine sequence of unit 3.

After floods late in 2011 an exposure of this organic-rich sediment was created along the stream bottom just upstream of the aforementioned pit. In this exposure very organic-rich thin-bedded silt overlies imbricated angular clasts of bedrock that indicate a northward flow. This silt also has well-rounded platy pebbles scattered throughout.

Preliminary macrofossil analysis of this ± 42 ^{14}C ka BP material indicates that it represents a tundra environment, similar to that interpreted for the plant material in unit 1 (Miller, 1996). Further analysis by D. M. Peteet (personal communication, 2013) shows that the fossil plant assemblage "includes a very flattened *Salix–Dryas* tundra mixture dominated by mosses. Prominent among the mosses are *Polytrichum juniperum* and *Drepanocladus* sp. *Claytonia caroliniana* seeds were also found. The mixture is indicative of an open, arctic–alpine environment, with both drier upland species (*Dryas integrifolia* and *Polytrichum* juniperum) as well as possibly a stream or wetland conditions, as *Salix* and *Drepanocladus* could imply. *Cenococcus*, a fungal reproductive body, indicates soil disturbance by frost action and solifluction (Birks, 2000)". *Picea* needles, cones and/or wood fragments were not found in these samples but did occur in other samples of both 34–39 and ± 42 ^{14}C ka BP ages. Nearby exposures, now obscured, of apparently similar plant-bearing sand and silt, were discovered by Fernow (1956) and a pre-AMS radiocarbon age of greater than 35 ^{14}C ka BP was reported by Muller (1965) for twigs and bark from that site.

The 2011 floods also created new exposures downstream from the pit dug during this study and significantly increased the exposed extent of unit 3 (Fig. 4). Bedrock exposures downstream from the pit demonstrate that the east-facing wall continues downstream for about 50 m, at which point the wall is abutted by an extensive exposure of thin-bedded pink-gray silt (Fig. 8A). Interbedded with this silt are gravels composed of angular bedrock clasts. These gravel beds are thickest and coarsest adjacent to the bedrock wall and thin over 30 m to become granule and coarse sand-sized. These gravel beds clearly originated from the adjacent bedrock but show current reworking. Cross-bedding, indicating a northward component of flow in some silt beds, supports this interpretation. The bedding in this exposure, which is at least 5 m thick, dips about 5° northward.

Approximately 60 m further downstream and about 4 m lower in elevation, but at approximately the same stratigraphic level, is another exposure of similar bedded siltstones and gravels that also contain fine to coarse grained sand beds. Immediately below these strata and just downstream is the top of a pink-gray silty clay section, which is nearly continuously exposed for almost 100 m along the stream channel and over an elevation range of at least 8 m. This clay is generally massive but shows faint indications of sub-horizontal layering, as defined by a few gray clay interbeds. The lowermost exposure of this sequence includes a 1 m thick bed of the angular platy gravel, with clasts ranging to more than 20 cm long.

The entire section of unit 3 in this stream is about 30 m thick, cropping out from elevations of 230 m asl to at least 260 m asl, which is approximately the same elevation range of the exposures of the lacustrine clays of unit 1 (Fig. 4). No lithologic continuity was observed between units 1 and 3. The correlation is based on the similarity of lithologies, especially in the red and red/gray clay sections. A "debarked and waterworn" black spruce knot, collected by A.L. Bloom (1972, and personal communication, 2011) at 42°24.6′N, 76°27.8′W (well within the area of exposures of unit 3) gave a radiocarbon age of 41.9 ^{14}C ka BP (Table 1). At first this age seems to negate the correlation of units 1

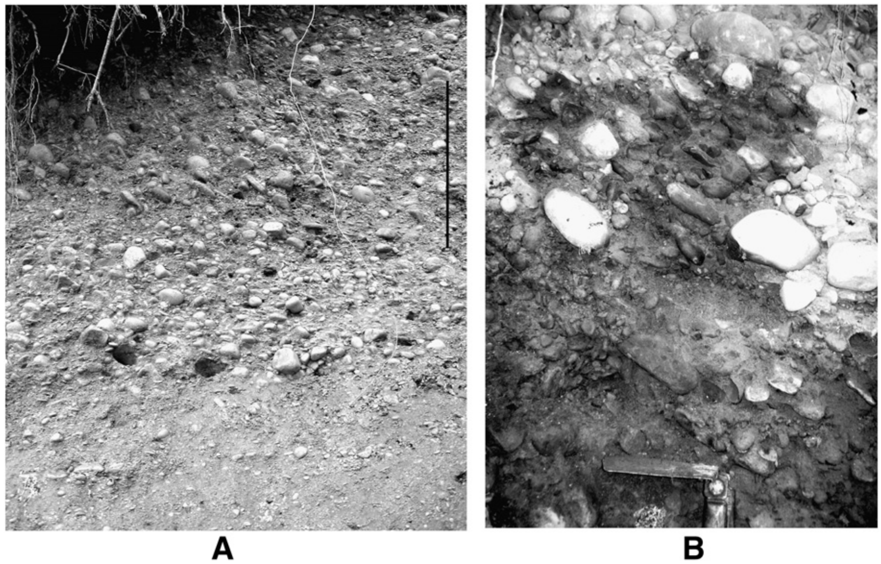

Figure 7. Unit 2. A. Cobble gravels east of Burns Road, which are grossly interbedded with coarse sand and pebble gravels. Vertical black bar (upper right) is approximately 1 m long. B. Clast-supported cobble and boulder gravels west of Burns Road. Shovel head (bottom) is approximately 20 cm long. Both exposures have strong clast imbrication showing flow from the west.

and 3 but the abraded knot was obviously transported and could be significantly older than the containing sediment. This point receives further consideration in the discussion section.

The base of unit 3 is not exposed in the section described above but interpolation of elevations of the bedrock floor of the inner glacial trough to this area indicates that about 20 m of Quaternary sediments exist below the lowest exposure. In 2013 exposures of gray silty clay with cm-scale layering were found in the next drainage to the west, close to the bedrock floor of the inner glacial trough (Figs. 1 and 4). The layering in this clay is seen only on weathered surfaces and represents differences in compaction rather than in grain size. Nevertheless, this clay may be correlative with the varved clays of Schmidt's first series in unit 1. Unit 3 is disconformably overlain along a sub-horizontal contact by the highly deformed sediments of unit 4, which are exposed along the valley slopes (Fig. 1). Unfortunately, colluvial cover and slumping prevented observation of this contact.

The disparate lithologies in unit 3 suggest intermittent deposition of the coarser sands and gravels into the low energy environment indicated by the silts and clays. Relatively deep water adjacent to shoreline cliffs that fed debris into a lacustrine environment, plus input from a subaqueous fan proposed to account for the exotic-rich gravels, would satisfy the observations. More specifically this suite could be interpreted as a facies of the proglacial lake sediments deposited close to steep bedrock scarps. These scarps were perhaps associated with a rock-walled, N30°E-trending canyon that was a tributary to the interglacial gorge, in which there was northward flow. The older, ± 42 ^{14}C ka BP, strata could have been deposited in pools or behind slump blocks in that canyon.

Unit 4 (deformation till)

Unit 4 is dominated by sand, usually very coarse-grained, in highly contorted beds. Floating in the sand are "clasts," often large irregular masses, of silt, red clay and gravel (Fig. 9). Gravel and cobbles also appear in larger masses, most often as diamictons with a coarse sand matrix. Both the matrix sands and the massive sands are uncemented but very calcareous because a significant fraction of the sand grains are carbonates. Bedding, often with high dips, occurs in some parts of these exposures (Fig. 8b), but in general the bedding is chaotic and no structural pattern is recognizable.

The diamictons have a very large exotic clast fraction, dominated by limestone and dolostone (Fig. 6, Table 2). The exotic clasts are usually quite round but some have fresh fracture surfaces. On the other hand, many or most of the local clasts are extremely angular. Some larger cobbles show glacial striae. Clasts in these diamictons are very similar in composition to those of the cobble gravels of unit 2 (Fig. 6) but show stratal disruption, clast breakage and glacial striae. It is therefore assumed that the gravels of unit 2 are protoliths for the gravels of unit 4.

Exposures of the highly deformed sediments of unit 4 are restricted to the northwestern area of the deposits that predate the late Wisconsin glaciation and extend from elevations not far above those estimated for bedrock up to at least 260 m. These deformed sediments overlie the sediments of unit 3 but their contacts with the cobble gravels of unit 2 to the SE were not exposed. To the NW the exposures of unit 4 are terminated by a northwesterly drop in elevation of the base of the late Wisconsin till (Fig. 3), which clearly overlies bedrock about 500 m NW of the area shown in Figure 1.

A number of origins for this unit were considered, such as landsliding, soft sediment fluidization and proglacial thrusting, before concluding that it was a deformation till. A landslide origin was discarded because lithologies from much lower elevations were found even at the highest of exposures of this suite. Sediment fluidization may have been responsible locally but it seems very unlikely to have been able to create such a large mass. Proglacial deformation, as described by Phillips et al. (2002), produces more coherent structure and lithologic distribution than that observed in this suite. The extensive mixing of lithologies from all elevations, the striated and fractured cobbles and the incoherent structural pattern all indicate that this suite represents a unit that was tectonized, i.e. a deformation till. Such a till would have resulted from the advance of ice from the NW into this area, deforming but only partially homogenizing the sediments deposited in front of that ice. Whatever combination of deformation beneath the ice, flowage at an ice front and secondary remobilization, the characteristics of unit 4 requires that an ice front advanced as far southward as the study area.

The preservation of undeformed lacustrine deposits to the southeast of such a till and their only partial homogenization into the till suggest that the ice front stopped here. This speculation has support in the southeastward up-ramping of the basal till contact required by the areal distribution of lithologies (Fig. 3). In such a case, the till would have included a terminal or end moraine, which could explain the local rise in elevation of the base of the late Wisconsin till that overrode and only partially removed that moraine.

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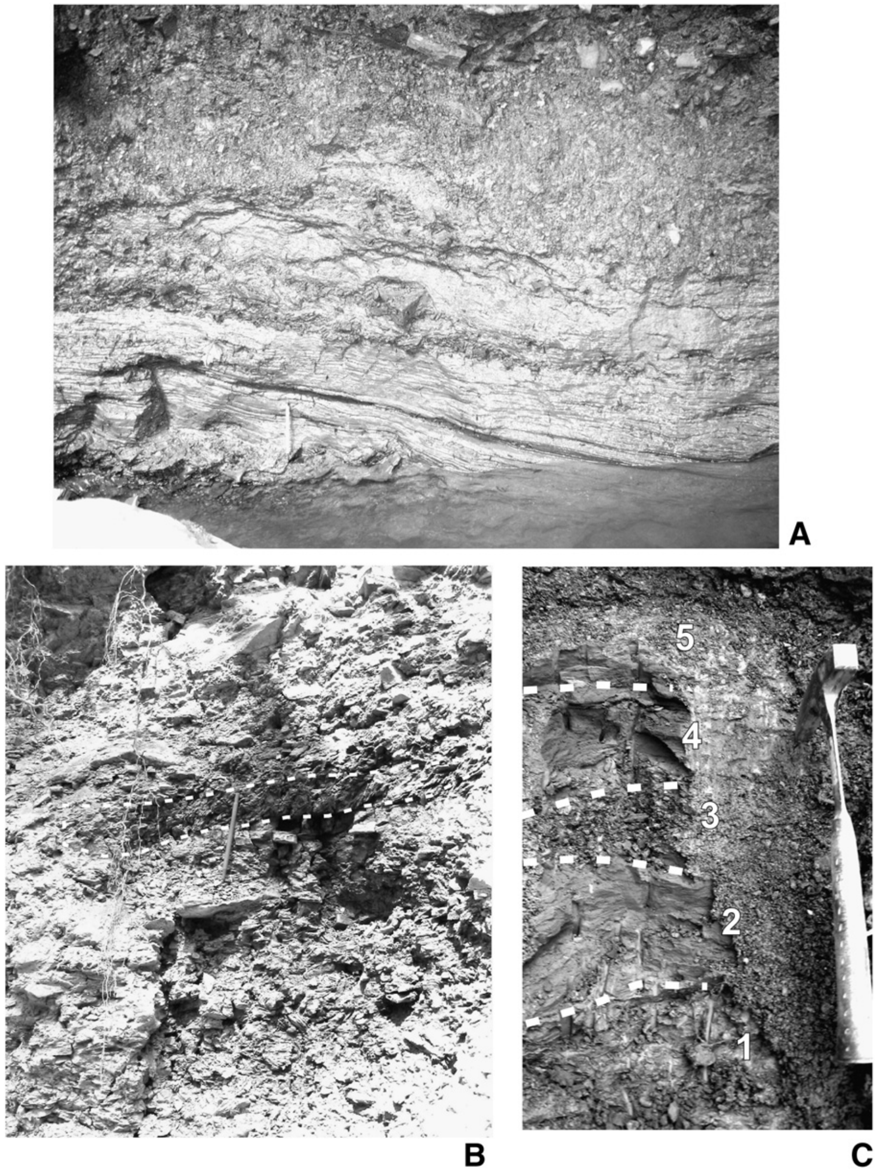

Figure 8. Unit 3. A. Thin-bedded silt with lenses of angular clast gravel that thicken toward bedrock on the left of this image. Scale is given by pen. B. Very angular platy clast gravels composed almost entirely of local bedrock, which is exposed nearby. Dashed lines outline a red clay lens within this gravel. Pen (in center) is approximately 15 cm long. C. Interbedded red (1, 5) and blue-gray (2, 4) clay and pebble gravel (3) stratigraphically beneath an angular clast gravel. Hammer is 33 cm long.

Discussion

Areal mapping and reinterpretation of the middle Wisconsin deposits along Sixmile Creek document a southeastwardly advancing ice front that trapped a proglacial lake between it and the drainage divide to the south. The lake must have had a water surface elevation of at least 265 m asl, at which the highest exposures of lacustrine sediments were observed. As the ice front approached the mapped area, this lake would have had to drain southeasterly, out the through valley in the glacial trough, but the elevation and condition of that through valley were probably different from those that developed during late Wisconsin time.

Schmidt (1947, 1996) concluded that drainage of this lake was through an outlet to the north, which may have been the case when the ice front was far from the Sixmile site, but drainage in that direction was highly unlikely during deposition of most of the lacustrine sediments in the study area, which appear to be ice-proximal. It is possible that the varves of Schmidt's first series represent distal deposition related to northward drainage and that the red clays in the overlying section, derived from the north, mark a switch in transport direction through the Sixmile site and to a southeastern lake outlet.

These middle Wisconsin lacustrine sediments were tentatively dated as of Plum Point interstade age by Miller (1996) and Ashworth et al. (1997), but the array of radiocarbon ages now available convincingly indicate an older Cherrytree stade age. Five of the radiocarbon ages from the lacustrine sequence are between 34 and 37 ^{14}C ka, BP, which is here accepted as the most likely age range of this proglacial lake.

The recognition of older ($\pm$42 ^{14}C ka BP) strata beneath the sediments of western aspect of unit 1 solves several problems concerning the radiometric ages from the Sixmile site. Given the data available, the most appealing interpretation is that local conditions at $\pm$42 ^{14}C ka BP may have been conducive to preservation of organic material, which created a “reservoir” to be reworked into younger sediment. This would explain not only Bloom's 42 ^{14}C BP ka spruce knot but also the secondary group of 40+ ^{14}C ka BP ages below the varves of

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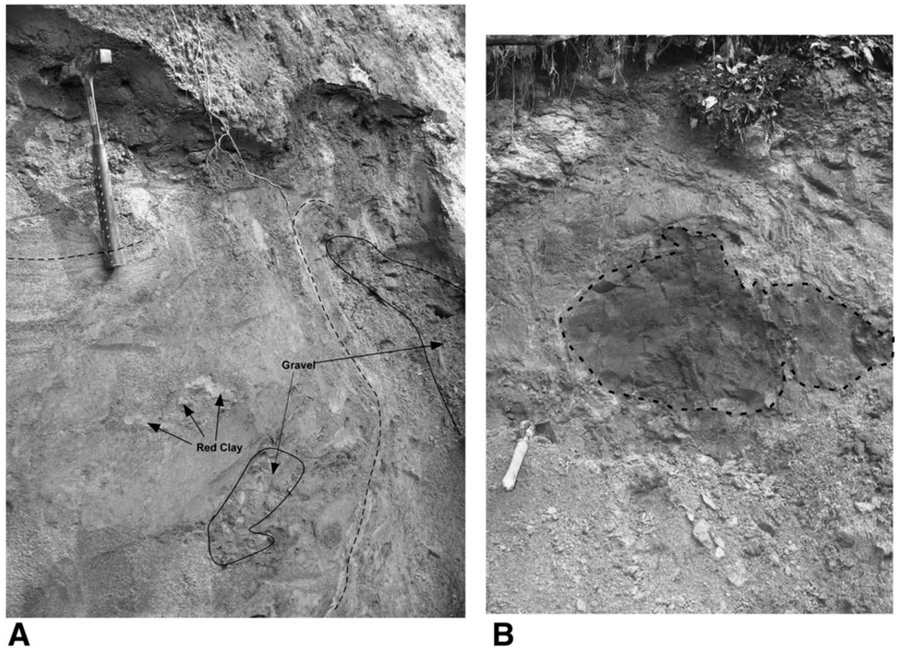

Figure 9. Unit 4. A. Highly contorted sand with lenses of gravel that closely resembles the sub-aqueous fan gravels of unit 2 and red clay that resembles the lacustrine clay of units 1 and 3. Dashed lines show the bedding that is obvious in some areas. B. Deformed sand with contorted bedding and a large floating lens of red clay. Shovel handle is 40 cm long. Both photos are examples of what is interpreted to be deformational till.

lithologic suite 1. This conclusion is supported by the fact that samples of unsorted plant macrofossils show ages intermediate between 35 ka and 42 ka, suggesting mixed source material. A tight clustering of ages around 41–42 ka and the lack of any ages older than that are evidence that even older material or sample contamination by dead carbon were not factors. A 34 to 37 ^{14}C ka, BP age would also resolve the climatic contradiction faced by Miller (1996) and Ashworth et al. (1997), who concluded that the paleoclimate at the Sixmile site was 7 °C colder than that previously interpreted from similar latitudes in the Midwest during the Plum Point interstade.

The arrival of the ice front in the study area, marked by the deformation till, is thought to be not much after deposition of the proglacial lake sediments beneath. The 1–5 cm/yr depositional rate for the varves of Schmidt's first series is most probably minimal because of the advancing ice front and would lead to the deposition of the entire 40 m lacustrine sequence in less than a few thousand years. Moreover, the coarseness of the gravels that are interbedded with the lacustrine sequence indicates that the glacial front at that time was quite close to the Sixmile site. It would be difficult not to conclude that the ice advance in question was during the Cherrytree stade of the middle Wisconsin sub-stage.

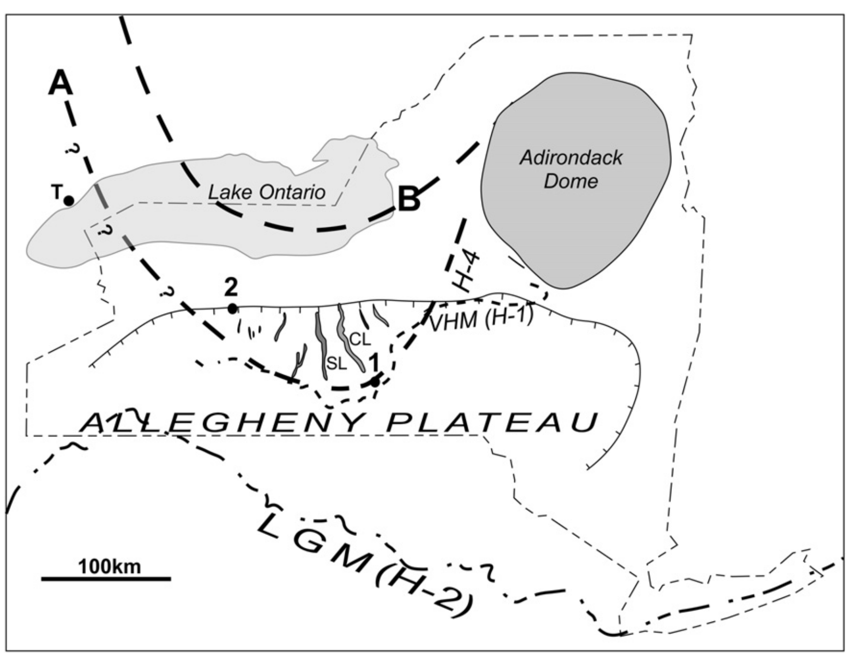

Figure 10. Regional relationships among suggested positions of the Cherrytree stade ice advance and other significant Wisconsin ice advances. The curve marked A is the generalized ice-front position proposed in this study. Curve B is that suggested by Eyles and Williams (1992). Location 1 is the Sixmile Creek site and 2 is the Genesee River site. T marks the location of Toronto. CL and SL mark Cayuga and Seneca lakes. The dashed line marked VHM is the Valley Heads moraine and the dot dashed line marked LGM is the position of the ice front at the last glacial maximum. H-1, 2 and 4 relate the ice advances to Heinrich events. The hachured line represents the northern boundary of the Appalachian Plateau.

The middle Wisconsin advance recorded in the deposits along Sixmile Creek must be the same as that reported by Young and Burr (2006) in the Genesee River valley, approximately 125 km to the northwest (Fig. 10). Young and Burr dated a double ice advance at 35 ^{14}C ka BP, which is at the young end of the range of ages determined for the pro-glacial sediments in Sixmile Creek. The oscillating glacial advance, separated by outwash gravels, that Young and Burr (2006) document apparently represents a minor intervening ice withdrawal, but no evidence for a similar dual advance was recognized in the Sixmile area. Either no such event occurred there or it was not revealed in the deposits that are exposed in the area.

In addition to the Genesee River site the most extensive and appropriate exposures of middle Wisconsin deposits with which the Sixmile site can be compared are those in south-central Ontario, mostly those around and east of Toronto. There the Thorncliffe Formation (Karrow, 1974; Karrow et al., 2001) and the Clarke beds (Brookfield et al., 1982; Brennand and Lian, 2009), its probable correlative to the east, appear to be of middle Wisconsin age. Both these units include glaciolacustrine beds, some of which are rhythmitic, fluvial sands and two diamictons, which are termed the Seminary Till and the younger Meadowcliffe Till. There is some contention as to whether these diamictons are actually tills (e.g. Karrow, 1967; Dreimanis, 1970; Eyles and Eyles, 1983) but in any case they represent ice-proximal deposition.

The age range of the Thorncliffe Formation is not well-constrained, but radiocarbon dating of peat and wood from the lower part of this section indicate an age range of 40–45 ^{14}C ka ka BP (Berger and Eyles, 1994, and references therein; Karrow et al., 2001). Radiocarbon and thermoluminescence ages (Berger and Eyles, 1994 and references therein) near the top of the Thorncliffe Formation suggest ages of 28–32 ka (23.5–28 ^{14}C ka BP, using the calibration curve of Ramsey et al. (2012)). It thus appears that the Thorncliffe Formation spans the period of time represented by the Sixmile deposits.

The sediments of the Thorncliffe Formation point to the existence of a sizeable proglacial lake in the western part of the Ontario basin trapped behind ice to the east during much of the middle Wisconsin (Eyles and Williams, 1992). Data from south-central Ontario have led to the conclusion that the trapping ice lobe did not extend southward beyond the Ontario basin (e.g. Eyles and Westgate, 1987) and that drainage from this proglacial lake was to the northeast, down the St. Lawrence River Valley (Fig. 12C in Eyles and Williams, 1992).

The evidence of a much more extensive, southward Cherrytree ice advance to the Genesee and Sixmile sites (Fig. 10) requires a significant modification of this scenario. Assuming that the Cherrytree ice front lay not far from the Toronto area, a generalized ice-front position can be drawn based on these data (Fig. 10). In reality this ice front would undoubtedly have had a much more irregular outline, with tongues extending southward into glacial troughs penetrating the Appalachian Plateau, but the paucity of data does not warrant drawing more than a very general outline at this time. This protrusion of Cherrytree ice into the Cayuga–Seneca trough sector of the Plateau might reflect both the elevation minimum of the Plateau there and a likely constraint to the east by the Adirondack dome.

Drainage from the proglacial lake trapped to the west of this ice lobe very well may have been down the St. Lawrence valley for some of middle Wisconsin time but, with the advance of the Cherrytree ice into the Appalachian Plateau, drainage could no longer have been eastward. Instead, it almost surely would have been into the Mississippi River watershed. Thorncliffe sediments lie as high as 100 m above the present Lake Ontario level (Berger and Eyles, 1994) and the proglacial lake surface could have been much higher, facilitating westward flow into the Erie basin and beyond.

The middle Wisconsin is generally accepted to have been a relatively warm part of the Wisconsin stage (e.g. Eyles and Westgate, 1987), with only a minor ice advance during the Cherrytree stade (Dredge and Thorleifson, 1987; Karrow et al., 2000). The extensive ice advance into the northern edge of the Appalachian Plateau and the cold tundra conditions at the Sixmile site both around 34–39 ^{14}C ka BP and at $\pm$42 ^{14}C ka BP seem to contradict this scenario but this contradiction is not straightforward.

The middle Wisconsin, from about 50 to 25 ^{14}C ka BP, was a period of generally progressive cooling and also was a period of pronounced oscillations in temperature (e.g. Kirby and Andrews, 1999) and in climate (Frechette and de Vernal, 2013). The two cold periods recognized at the Sixmile may have been separated by warmer intervals. Such rapid climatic oscillations during the middle Wisconsin have been interpreted using insect data (Cong et al., 1996) at Titusville, Pennsylvania, and elsewhere (Elias, 1999), and with plant data on Cape Breton Island (de Vernal et al., 1986; Frechette and de Vernal, 2013). Data from insects not dependent upon host plants were felt to reflect climatic changes more rapidly than plant data (Elias, 1999), but even pollen data show these oscillations (Frechette and de Vernal, 2013).

Karrow's (2004) review of the pre-late Wisconsin Quaternary stratigraphy of the better-known sites in south-central Ontario demonstrated that there was a wide range of paleoenvironments during the middle Wisconsin. A site near Woodbridge, northwest of Toronto (Warner et al., 1988; Karrow et al., 2001) had a tundra environment somewhere in the interval between 40.2 and 45 ^{14}C ka BP. On the other hand, a site at Waterloo (Karrow and Warner, 1984; Karrow, 2004), 100 km west of Toronto, sediments with a single age of 40.1 ^{14}C ka BP, contained plant fossils denoting a temperate climate, similar to the warm horizon at Titusville (Cong et al., 1996). Unfortunately, the age control of these deposits has not permitted development of a climatic chronology.

The cold, tundra conditions during two intervals at the Sixmile site, dated at $\pm$42 ^{14}C ka BP and somewhere in the interval 34–37 ^{14}C ka BP agree only in part with those derived from the beetle data. The warm interval dated at Titusville as between 39 and 43.5 ^{14}C ka BP and peaking near 42 ^{14}C ka BP in the areas cited by Elias (1999) seems to contradict the Sixmile data. Given the uncertainties in radiocarbon ages at both Titusville and Sixmile Creek, it is possible that the older strata at Sixmile Creek correlate with the older cold interval found at Titusville.

The middle Wisconsin glacial advance into the Appalachian Plateau, described in this study, was dated at the Genesee River site as about 35 ^{14}C ka BP and was correlated with Heinirich event H-4 (Young and Burr, 2006). Event H-4 was followed by a rapid warming, seen both in marine sediment data (e.g. Kirby and Andrews) and in the beetle data (Elias, 1999). This warming episode was used to define the end of the middle Wisconsin by Kirby and Andrews (1999), but such a boundary would place the Plum Point interstade in the late Wisconsin, which is not generally accepted. It might be logical, however, to place the boundary between the Cherrytree stade and the Plum Point interstade somewhere within this rapid warming event.

Conclusions

The two major conclusions of this study are that the middle Wisconsin sub-stage produced a colder and more variable climate in the eastern Great Lakes region than had generally been assumed and that this was associated with a Laurentian ice lobe that advanced much further south than previously recognized. One deduction from these conclusions is that such an ice lobe must have blocked eastward drainage from the large proglacial lake that has been recognized to exist at that time in the western Ontario basin and forced that drainage westward into the Mississippi system. If this ice lobe reached the Sixmile site it must have gone even further south in the larger, deeper Cayuga and Seneca Troughs, which formed the lowest section of the Appalachian Plateau front (Fig. 10).

The large climatic oscillations that seem to have occurred during the middle Wisconsin may be a principle reason for differences in interpretation of the climate during that sub-stage. These differences cannot be resolved, however, without more and better age data for middle Wisconsin

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sites in this region. Karrow (2004) has cited problems associated with radiocarbon dating at the older end of its applicable range and stressed the need for new analytical dating techniques. For the most part, however, the problem in central New York is a paucity of ages, even from known middle Wisconsin sites that are within the range of radiocarbon dating.

Although it is likely that the late Wisconsin ice advance removed most or all of the older Quaternary sediments from the northern sections of the larger glacial troughs in the Finger Lakes region (Mullins et al., 1996), it is quite possible that such older sediments remain in areas that were not so affected. These include some troughs, as the Genesee valley (Young and Burr, 2006) and the southern sections of many more. An example of the latter possibility is the recovery of wood older than 40 ^{14}C ka BP at a depth of 46 m at Millport, south of Seneca Lake (Muller and Calkin, 1993). In large part the lack of known sites pre-dating a late Wisconsin age in this region can be attributed to a lack of investigation, especially in the subsurface.

Acknowledgments

This paper was originally envisaged as a collaboration between Miller's extensive paleobotanical work on the varved clays and Karig's recent field mapping. Miller's untimely death early during this collaboration deprived the study of much of his knowledge, but many of the radiocarbon ages are his as are most of the climatic and paleoenvironmental interpretations. Richard Young, Andrew Kozlowski and Todd Miller visited the study area and provided invaluable suggestions. Correspondence with Vic Schmidt and a trip with him to his site before his death gave Karig a better idea of his thoughts. Young, Kozlowski, Paul Karrow and Jack Ridge reviewed drafts of the manuscript and greatly improved its content. Several radiocarbon analyses were funded by the USGS through William Kappel. Particular thanks go to editor Alan Gillespie, who provided far more assistance than was warranted.

References

Ashworth, A., Willenbring, J., 1998. Fossil beetles and climate change at Sixmile Creek, Ithaca, New York. American Paleontologist 6, 2–3.

Ashworth, A.C., Miller, N.G., Schmidt, V.E., Willenbring, J., 1997. The Sixmile Creek Site, Ithaca, NY, and potential problems with mid-Wisconsin regional paleoclimatic interpretations. Geological Society of America Annual Meeting, Abstracts with Programs 29, 37.

Berger, G.W., Eyles, N., 1994. Thermoluminescence chronology of Toronto-area Quaternary sediments and implications for the extent of the midcontinent ice sheet(s). Geology 22, 31–34.

Birks, H.H., 2000. Aquatic macrophyte vegetation development in Krakenes Lake, western Norway, during the late-glacial and early-Holocene. Journal of Paleolimnology 23, 7–19.

Bloom, A.L., 1972. Schedule and guidebook. Friends of the Pleistocene 35th Annual Reunion, Cornell University. 20.

Brennand, T.A., Lian, O.B., 2009. Insight into Quaternary environmental change in the Lake Ontario basin revealed through new chronological and glaciological information. Geological Society of America Annual Meeting, Abstracts with Programs 41, 641.

Brookfield, M.E., Gwinn, Q.H.J., Martin, I.P., 1982. Quaternary sequences along the north shore of Lake Ontario: Oshawa–Port Hope. Canadian Journal of Earth Sciences 19, 1836–1850.

Cong, S., Ashworth, A.C., Schwerdt, D.P., 1996. Fossil beetle evidence for a short warm interval near 40,000 yr BP at Titusville, Pennsylvania. Quaternary Research 45, 216–225.

de Vernal, A., Causse, C., Hillaire-Marcel, C., Mott, R.J., Occhietti, S., 1986. Palynostratigraphy and Th/U ages of upper Pleistocene interglacial and interstadial depositson Cape Breton Island, eastern Canada. Geology 14, 554–557.

Dredge, L.A., Thorleifson, L.H., 1987. The Middle Wisconsinan history of the Laurentide Ice Sheet. Géographie Physique et Quaternaire 41, 215–235.

Dreimanis, A., 1970. Late-Pleistocene lakes in the Ontario and Erie Basins. Conference on Great Lakes Research, 12th, Proceedings, pp. 170–180.

Elias, S.A., 1999. Mid-Wisconsin seasonal temperatures reconstructed from fossil beetle assemblages in eastern North America: comparisons with other proxy records from the Northern Hemisphere. Journal of Quaternary Science 14, 255–262.

Eyles, C.H., Eyles, N., 1983. Sedimentation in a large lake: a reinterpretation of the late Pleistocene stratigraphy at Scarborough Bluffs, Ontario, Canada. Geology 11, 146–152.

Eyles, N., Westgate, J.A., 1987. Restricted regional extent of the Laurentide Ice Sheet in the Great Lakes basins during early Wisconsin glaciation. Geology 15, 537–540.

Eyles, N., Williams, N.E., 1992. The sedimentary and biological record of the last interglacial–glacial transition at Toronto, Canada. In: Clarke, P.U., Lea, P.D. (Eds.), The last interglacial–glacial transition in North America. Geological Society of America Special Paper, 270, pp. 119–138.

Fernow, L.R., 1956. A Fossil Plant Locality in Sixmile Valley. Unpublished Senior thesis, Department of Geology, Cornell University; 12 pp.

Frechette, B., de Vernal, A., 2013. Evidence for large-amplitude biome and climate changes in Atlantic Canada during the last interglacial and mid-Wisconsinan periods. Quaternary Research 79, 242–255.

Hatch, G.E., 1940. Embankment Design for an Earth Dam on Six Mile Creek. Department of Civil Engineering, Cornell University, Ithaca, New York (M.Sc. thesis).

Karrow, P.F., 1967. Pleistocene Geology of the Scarborough Area: Ontario Department of Mines Geological Report 46.

Karrow, P.F., 1974. Till stratigraphy in parts of Southwestern Ontario. Geological Society of America Bulletin 85, 761–768.

Karrow, P.F., 2004. Late Quaternary Stratigraphic comparisons in south-central Ontario and western New York and the OIS 5E to early 3 interval. Northeastern Geology and Environmental Sciences 26, 202–210.

Karrow, P.F., Warner, B.G., 1984. A subsurface Middle Wkisconsinan interstadial site at Waterloo, Ontario, Canada. Boreas 13, 67–85.

Karrow, P.F., Dreimanis, A., Barnett, P.J., 2000. A proposed diachronic revision of Late Quaternary time-stratigraphic classification in the eastern and northern Great Lakes Area. Quaternary Research 54, 1–12.

Karrow, P.F., McAndrews, J.H., Miller, B.B., Morgan, A.V., Seymour, K.L., White, O.L., 2001. Illinoian to Late Wisconsinan stratigraphy at Woodbridge, Ontario. Canadian Journal of Earth Sciences 38, 921–942.

Kirby, M.E., Andrews, J.T., 1999. Mid-Wisconsin Laurentide Ice Sheet growth and decay: implications for Heinrich events 3 and 4. Paleoceanography 14, 211-223.

Miller, N.G., 1996. Age and paleoecology on an interstadial plant bed, Tompkins County, South-central New York. Geological Society of America Annual Meeting, Abstracts with Programs 28, 82.

Muller, E.H., 1957. Filled bedrock gorges in the drainage basin of Cayuga Lake, New York. Geological Society of America Annual Meeting, Abstracts with Programs 68, 1771.

Muller, E.H., 1965. The Finger Lakes region. In Part 2. International Association for Quaternary Research, VIIth Congress, Guidebook for Field Conference A, New England-New York State, pp. 39–92.

Muller, E.H., Cadwell, D.H., 1986. Surficial Geologic Map of New York-Finger Lakes Sheet: New York State Museum, Albany, Geological Survey Map and Chart Series #40, 1:250,000.

Muller, E.H., Calkin, P.E., 1993. Timing of Pleistocene glacial events in New York State. Canadian Journal of Earth Sciences 30, 1829–1845.

Mullins, H.T., Hinchey, E.J., Wellner, R.W., Stephens, D.B., Anderson, Jr., W.T., Dwyer, T.R., Hine, A.C., 1996. Seismic stratigraphy of the Finger Lakes: a continental record of Heinrich event H-1 and Laurentide Ice Sheet instability. In: Mullins, H.T., Eyles, N. (Eds.), Subsurface Geologic Investigations of the New York Finger Lakes: Implications for Late Quaternary Deglaciation and Environmental Change. Geological Society of America Special Paper, 311, pp. 1–36.

Phillips, E.R., Evans, D.J.A., Auton, C.A., 2002. Polyphase deformation at an oscillating ice margin following the Loch Lomond Readvance, central Scotland, UK. Sedimentary Geology 149, 157–182.

Ramsey, C.R., et al., 2012. A complete terrestrial radiocarbon record for 11.2 to 52.8 kyr B.P. Science 338, 370.

Ridge, J.C., 2003. The last deglaciation of the northeastern United States: a combined varve, paleomagnetic, and calibrated ^{14}C chronology. In: Cremeens, D.L., Hart, J.P. (Eds.), Geoarcheology of landscapes in the glaciated northeast. New York State Museum Bulletin, 497, pp. 15–45.

Schmidt, V.E., 1947. Varves in the Finger Lakes Region of New York State. Ph. D. thesis Department of Geology, Cornell University.

Schmidt, V.E., 1996. Middle Wisconsin varves near Ithaca, Central New York. Geological Society of America Annual Meeting, Abstracts with Programs 28, 97.

von Engeln, O.D., 1961. The Finger Lakes Region: Its Origin and Nature. Cornell University Press, Ithaca, N.Y.(156 pp.).

Warner, B.G., Morgan, A.V., Karrow, P.F., 1988. A Wisconsin interstadial arctic flora and insect fauna from Clarksburg, Southwestern Ontario, Canada. Palaeogeography, Palaeoclimatology and Palaeoecology 68, 27–47.

Young, R.A., Burr, G.S., 2006. Middle Wisconsin glaciation in the Genesee Valley, N.Y.: a stratigraphic record contemporaneous with Heinrich Event H4. Geomorphology 75, 226–247.