11-17-2020

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Research Paper

GEOSPHERE

GEOSPHERE, v. 17, no. 1

https://doi.org/10.1130/GES02257.1

22 figures; 3 tables; 1 supplemental file

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CITATION: Young, R.A., Gordon, L.M., Owen, L.A., Huot, S., and Zerfas, T.D., 2021, Evidence for a late glacial advance near the beginning of the Younger Dryas in western New York State: An event postdating the record for local Laurentide ice sheet recession: Geosphere, v. 17, no. 1, p. 271–305, https://doi.org/10.1130/GES02257.1.

Science Editor: Shanaka de Silva

Received 13 March 2020
Revision received 28 July 2020
Accepted 26 September 2020

Published online 17 November 2020

Evidence for a late glacial advance near the beginning of the Younger Dryas in western New York State: An event postdating the record for local Laurentide ice sheet recession

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ABSTRACT

Widespread evidence of an unrecognized late glacial advance across preexisting moraines in western New York is confirmed by 40 ^{14}C ages and six new optically stimulated luminescence analyses between the Genesee Valley and the Cattaraugus Creek basin of eastern Lake Erie. The Late Wisconsin chronology is relatively unconstrained by local dating of moraines between Pennsylvania and Lake Ontario. Few published ^{14}C ages record discrete events, unlike evidence in the upper Great Lakes and New England. The new ^{14}C ages from wood in glacial tills along Buttermilk Creek south of Springville, New York, and reevaluation of numerous ^{14}C ages from miscellaneous investigations in the Genesee Valley document a significant glacial advance into Cattaraugus and Livingston Counties between 13,000 and 13,300 cal yr B.P., near the Greenland Interstadial 1b (GI-1b) cooling leading into the transition from the Bölling-Alleröd to the Younger Dryas. The chronology from four widely distributed sites indicates that a Late Wisconsin advance spread till discontinuously over the surface, without significantly modifying the preexisting glacial topography. A short-lived advance by a partially grounded ice shelf best explains the evidence. The advance, ending 43 km south of Rochester and a similar distance south of Buffalo, overlaps the revised chronology for glacial Lake Iroquois, now considered to extend from ca. 14,800–13,000 cal yr B.P. The spread of the radiocarbon ages is similar to the well-known Two Creeks Forest Bed, which equates the event with the Two Rivers advance in Wisconsin.

INTRODUCTION

The late glacial history of the southern Great Lakes in western New York State lacks a detailed chronology for the final recession of the Laurentide ice sheet. The inadequate documentation of the precise ages of moraines younger than ca. 16,900 calendar year (cal yr) B.P. has prevented an accurate correlation of the western New York history with the better established record exposed in the upper Great Lakes, including deposits such as the Two Creeks Forest Bed of Wisconsin. We present detailed evidence for a previously unrecognized late glacial advance and recession that is compatible with the documented climatic fluctuations near the Bölling-Alleröd to Younger Dryas transition and permits an improved correlation of more regional events. Our comprehensive comparison and reevaluation of the late glacial stratigraphy at four key western New York sites (Fig. 1) are based on 16 new and 24 previously acquired calendar-corrected ^{14}C ages (Table 1) and several new optically stimulated luminescence (OSL) ages (Tables 2 and 3). Most of the unpublished ^{14}C ages, excluding the recent Enviro Compliance Solutions, Inc. study (ECS, 2018), were acquired randomly in the Genesee Valley from tills and glaciolacustrine sediments containing wood from forests that flourished throughout the Late Wisconsin Bölling-Alleröd (B-A) warm interval, potentially extending into the beginning of the Younger Dryas (YD) cooling. The diverse data are the result of specimens collected during many years of informal university teaching, research, and consulting. The majority of the uncorrected conventional ^{14}C ages are in the 11,000–12,000 ^{14}C B.P. year range, an interval where calendar-year corrections now provide revised ages that are ~1700–2000 calendar years older.

Recent improvements in the dating of major glacial events, such as the history and demise of glacial Lake Iroquois (Anderson and Lewis, 2012; Lewis and Anderson, 2020), and the accurate calibration of the classic Antevs (1922) varve study in the Connecticut Valley (Ridge et al., 2012; Ridge, 2018) permit a more realistic evaluation of the timing of a limited number of Late Wisconsin events across New York State. Our revised interpretation is strengthened by several engineering test wells (Alpha Geoscience, 2002); these wells allow construction of a detailed north-south cross section of the glacial stratigraphy along the axis of the Genesee Valley stretching 14 km north of Geneseo (Fig. 2). The compilation of ^{14}C ages and stratigraphy (Tables 1–3) provides evidence for a previously unknown glacial advance ca. 13,300–13,000 cal yr B.P., close to the Bölling-Alleröd/Younger Dryas (B-A/YD) boundary (12,900 cal yr B.P.;

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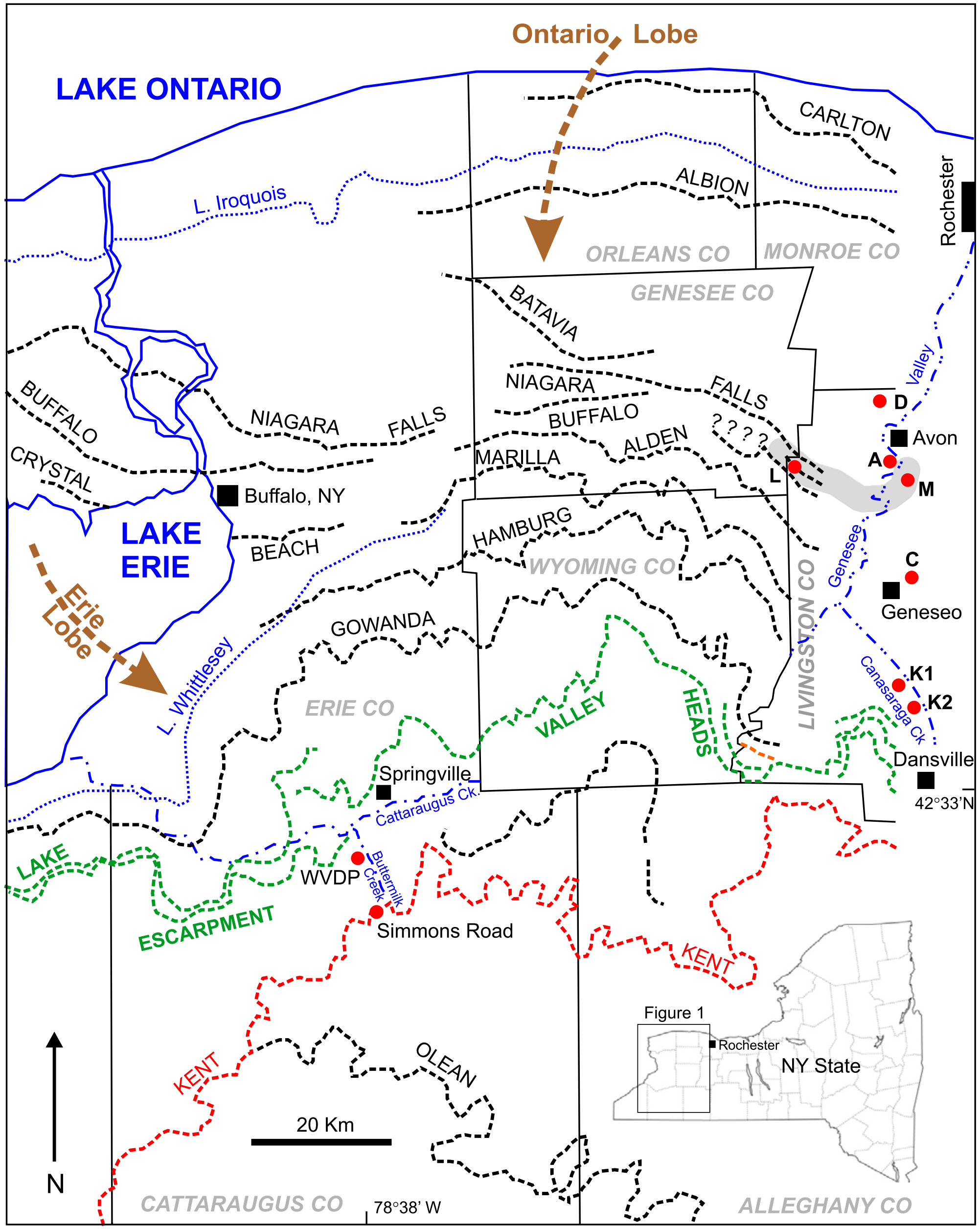


Figure 1. Regional map of selected major named moraines correlated by Muller (1977). Dashed lines are moraines with the most relevant landforms colored red and green; dotted blue lines are selected glacial lake shorelines. Rivers are dash-dot patterns for clarity. Large brown arrows are generalized flow directions of Ontario and Erie ice lobes. Gray italics are counties. Squares are towns and cities. Red circles are radiocarbon date sites: A—Avon; L—Linwood; D—Dugan Creek; C—Carter Pond; K1, K2—Keshequa-Canaseraga Creek; M—mastodon; WVDP—West Valley Depression Pits at Western New York Nuclear Service Center. Thick gray curve is approximate location of Fowlerville moraine of Bölling-Alleröd/Younger Dryas (B-A/YD) age; correlation westward uncertain.

TABLE 1. RADIOCARBON AGE DATA FROM THE GENESEE VALLEY REGION AND BUTTERMILK CREEK SITES

No.	Laboratory ID number	Material	Site location	Enclosing strata	^{14}C age B.P.	Cal yr B.P.	2σ range	$\delta^{13}C$	Comment and/or interpretation	Latitude/longitude (NAD27)	Figures
		Duplicate = (X)	WNYNSC			**2σ median**					
1	B 437410	Wood	Abandoned meander bog	Till	11,630 ± 40	13,462	13,379–13,568	–26.1	Youngest ice advance; Tamarack[†]	42.45768/78.65031	15, 16, 17D
2	B 444820	Wood	Abandoned meander bog	Till	11,940 ± 40	13,767	13,700–13,865	–27.0	Youngest ice advance	42.45768/78.65031	15, 16, 17
3	B 437409	Wood	Abandoned meander bog	Till	12,280 ± 40	14,192	14,041–14,451	–25.7	Youngest ice advance	42.45768/78.65031	15, 16, 17
4	B 437408	Wood	Abandoned meander bog	Till	12,220 ± 40	14,114	13,984–14,255	–25.8	Youngest ice advance	42.45768/78.65031	15, 16, 17
5	B 437407	Wood	Abandoned meander bog	Till	12,250 ± 50	14,155	13,986–14,407	–24.9	Youngest ice advance	42.45768/78.65031	15, 16, 17
6	*B 329701**	*Wood*	*Abandoned meander bog*	*Clay or till?*	*12,260 ± 50*	*14,170*	*13,999–14,446*	*–25.4*	*Youngest ice advance*	*42.45768/78.65031*	*
7	*B329702**	*Wood*	*Abandoned meander bog*	*Clay or till?*	*12,250 ± 50*	*14,155*	*13,986–14,407*	*–25.9*	*Youngest ice advance*	*42.45768/78.65031*	*
8	*B329703**	*Wood*	*Abandoned meander bog*	*Clay or till?*	*12,360 ± 50*	*14,380*	*14,120–14,719*	*–25.2*	*Youngest ice advance*	*42.45768/78.65031*	*
			WNYNSC (offsite)								
9	B 442543	Wood	Simmons/Town Line Road	Till or peat above?	11,080 ± 30	12,955	12,824–13,056	–24.8	Stratigraphic position uncertain	42.37919/78.62615	Offsite pond
10	B 442542	Wood	Simmons/Town Line Road	Till	11,280 ± 40	13,130	13,061–13,223	NA	Advance onto Kent moraine	42.37919/78.62615	14, 15, 19, 20
11	B 442541	Wood	Simmons/Town Line Road	Till	12,140 ± 30	14,030	13,904–14,152	–25.9	Advance onto Kent moraine	42.37919/78.62615	14, 15, 19, 20
12	B 442540	Wood (x)	Simmons/Town Line Road	Till	11,940 ± 50	13,770	13,588–13,964	–24.3	Advance onto Kent moraine	42.37919/78.62615	14, 15, 19, 20
13	B 444821	Wood (x)	Simmons/Town Line Road	Till	11,900 ± 30	13,728	13,583–13,783	–24.0	Advance onto Kent moraine	42.37919/78.62615	14, 15, 19, 20
14	B 442539	Wood	Simmons/Town Line Road	Till	12,390 ± 40	14,438	14,162–14,751	–24.7	Advance onto Kent moraine	42.37919/78.62615	14, 15, 19, 20
15	B 442538	Wood	Simmons/Town Line Road	Till	12,370 ± 50	14,402	14,128–14,739	–24.6	Advance onto Kent moraine	42.37919/78.62615	14, 15, 19, 20
			Genesee River, Avon								
16	B 462893	Plant	Genesee River, Avon	Lacustrine	10,520 ± 40	12,486	12,391–12,613	–28.2	Postglacial lake above varves	41.91197/77.76374	1, 2, 3, 4
17	AA52255	Wood	Genesee River, Avon	Lacustrine	10,630 ± 59	12,612	12,523–12,712	–51.4	Proglacial lake varves above till	41.91197/77.76374	1, 2, 3, 4
18	AA52256	Wood	Genesee River, Avon	Till	12,003 ± 62	13,862	13,726–14,050	–26.4	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
19	AA52257	Wood	Genesee River, Avon	Till	11,997 ± 69	13,857	13,707–14,074	–25.0	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
20	AA52258	Wood	Genesee River, Avon	Till	11,971 ± 69	13,824	13,690–14,023	–24.6	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
21	AA52259	Wood	Genesee River, Avon	Till	11,966 ± 69	13,817	13,594–14,015	–26.1	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
22	AA52261	Wood	Genesee River, Avon	Till	11,983 ± 86	13,841	13,589–14,056	–25.6	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
23	AA52262	Moss	Genesee River, Avon	Till	12,486 ± 78	14,676	14,246–15,076	–32.4	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
24	B 462892	Wood	Genesee River, Avon	Till	12,200 ± 40	14,092	13,965–14,223	–24.8	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
25	AA52306	Wood	Genesee River, Avon	Till	11,788 ± 56	13,623	13,478–13,741	–24.8	Till, with deformed peat and wood	41.91197/77.76374	1, 2, 3, 4
26	AA52260	Wood	Genesee River, Avon	Till with gravel	12,166 ± 71	14,044	13,788–14,239	–24.6	Till with gravel lenses	41.91197/77.76374	1, 2, 3, 4
27	AA52263	Wood	Genesee River, Avon	Till with gravel	11,640 ± 73	13,469	13,295–13,596	–25.6	Till with gravel lenses	41.91197/77.76374	1, 2, 3, 4
28	AA52264	Moss	Genesee River, Avon	Till with gravel	11,804 ± 85	13,632	13,457–13,775	–27.3	Till with gravel lenses	41.91197/77.76374	1, 2, 3, 4
29	AA52265	Wood	Genesee River, Avon	Till with gravel	11,845 ± 69	13,660	13,535–13,785	–25.5	Till with gravel lenses	41.91197/77.76374	1, 2, 3, 4
			Linwood, New York (Peccary)								
30	CAMS14612	Bone collagen	Federal Road, moraine	Sand under till	11,460 ± 60	13,307	13,162–13,437	NA	Outwash sand; leaching issue?	42.88792/77.92034	5, 6, 7
31	CAMS17132	Bone collagen	Federal Road, moraine	Sand under till	11,180 ± 70	13,045	12,830–13,174	NA	Outwash sand; leaching issue?	42.88792/77.92034	5, 6, 7
32	AA8641	Bone	Federal Road, moraine	Sand under till	11,145 ± 80	13,002	12,796–13,147	–21.2	Outwash sand; leaching issue?	42.88792/77.92034	5, 6, 7
33	AA9878	Bone	Federal Road, moraine	Sand under till	11,041 ± 95	12,907	12,732–13,072	–22.8	Outwash sand; leaching issue?	42.88792/77.92034	5, 6, 7
			Genesee Canaseraga								
34	I-9972	Wood	Keshequa Creek at Railroad	Peat (9.8 m deep)	11,160 ± 160	13,012	12,724–13,293	NA	Near peat/lacustrine contact, 10 m	42.70213/77.82597	1
35	I-9952	Organics	Pioneer Road at Railroad	Silty clay (9.4 m deep)	10,730 ± 150	12,641	12,170–12,990	NA	Sieved organics from 9.4–10.6 m	42.68510/77.80180	1
			Dugan Channel								
36	I-9829	Plant debris	Lacy Road near Dugan Creek	Peat (2.7 m deep)	11,040 ± 160	12,917	12,668–13,203	NA	Peat above till contact, 2.7 m	42.97631/77.79277	1

(*continued*)

TABLE 1. RADIOCARBON AGE DATA FROM THE GENESEE VALLEY REGION AND BUTTERMILK CREEK SITES (*continued*)

No.	Laboratory ID number	Material	Site location	Enclosing strata	^{14}C age B.P.	Cal yr B.P.	2σ range	$\delta^{13}C$	Comment and/or interpretation	Latitude/longitude (NAD27)	Figures
			Carter Pond								
37	B 486058	Wood	North Road, Geneseo	Peat with shells	11,030 ± 30	12,893	12,784–13,010	–27.0	Near contact peat over dune sand	42.80939/7775092	1, 2, 10
38	B 459189	Organic debris	North Road, Geneseo	Lacustrine gyttja	13,710 ± 40	16,545	16,330–16,786	–26.4	Organic debris, layer below dune	42.80939/7775092	1, 2, 10B, 10C
			Irondequoit Bay								
39	AA8632	Compact gyttja	Bay Outlet Bridge B2	Silt and sand	11,790 ± 80	13,621	13,461–13,761	NA	High-strength organic black clay	43.23474/77.53436	12, 13
40	AA8636	Compact gyttja	Bay Outlet Bridge B3	Silt and sand	11,340 ± 90	13,194	13,052–13,378	NA	High-strength organic black clay	43.23474/77.52436	12, 13
			Fowlerville moraine								
41	AA7397	Bone	Fowlerville moraine	Bog under water	11,565 ± 105	13,395	13,164–13,584	NA	Kettle in moraine; mastodon	42.88545/77.76440	1, 2, 11

Abbreviations: B—Beta; AA—University of Arizona; cal—Calendar; CAMS—Center for Accelerator Mass Spectrometry, Lawrence Livermore; I—Teledyne Isotopes; NA—not available; WNYNSC—Western New York Nuclear Service Center.

*Italics—Beta dates from Gordon et al. (2013).

†Tamarack ID by C. Griggs, Cornell University.

Rasmussen et al., 2014), a discovery that may permit significantly revised correlations across the broader Great Lakes region.

METHODS AND GOALS

This analysis involves the recalibration of a substantial amount of unpublished ^{14}C data collected over a 50-year interval during which time the Late Wisconsin chronology in western New York State has undergone only limited improvement. The new perspective is prompted by a detailed field study including 15 new ^{14}C and 2 new OSL ages obtained at the Western New York Nuclear Service Center (WNYNSC) along Buttermilk Creek near Springville, New York (ECS, 2018), as well as two new ^{14}C and two new OSL ages at a recently excavated kettle pond near Geneseo, New York (Figs. 1 and 2; Table 3). The focus of the Genesee Valley analysis is a description and reevaluation of randomly collected samples from a variety of studies and informal field observations as reevaluated with respect to inconsistencies posed by the published literature. Supportive ^{14}C data derived from several old highway engineering borings in the Genesee Valley are more relevant than originally realized. The scattered observations originally compiled at seven locations throughout the Genesee Valley attain renewed significance when compared to the unanticipated results of the ECS (2018) field studies at two new sites along Buttermilk Creek in Cattaraugus County (Fig. 1).

Two of the most critical initial interpretations at the Avon and Linwood sites on Figure 1 (Young et al. 1978; Young, 2003, 2012) in the Genesee Valley were erroneously influenced by an imperfect understanding of the incomplete chronology of Late Wisconsin deglaciation in western New York State for the events following the glacial recession from the Valley Heads moraine at the southern ends of the Finger Lakes, now estimated at ca. 16,900 cal yr B.P. (Ridge, 2018). The Valley Heads moraine, formed during Heinrich stadial H1.1 (17.1–15.5 k.y.; Hodell et al., 2017), was followed by the oscillatory glacial recession northward to Lake Ontario that created the numerous moraines shown on Figure 1, an interval spanning ~4000 years. The final Laurentide recession has long been assumed to have ended gradually with the demise of glacial Lake Iroquois, currently revised to have occurred ca. 13,000 cal yr B.P. (2σ range 12,779–13,218 cal yr B.P.; Lewis and Anderson, 2020). The present analysis reevaluates the widespread chronologic evidence and suggests a model to account for the field evidence that is similar to published references describing deposition by partially grounded, floating ice shelves in the same region (La Fleur, 1979, 1980), as well as a proposed similar re-advance coincident with glacial Lake Iroquois (Calkin, 1982; Calkin et al., 1982).

The new Buttermilk Creek ^{14}C ages and the randomly acquired older data sets in the Genesee Valley included in Table 1 are converted to calendar-corrected ages (cal yr B.P.) using the calibration program, Calib 7.1 (Reimer et al., 2013; Stuiver et al., 2018). Calendar-corrected ages cited in the text are mostly the 2σ mean calendar-corrected ages listed on Table 1, expressed as cal yr B.P. However, in some cases, an uncorrected conventional published age (^{14}C yr B.P.) is substituted to clarify why initial assumptions raised issues that now conflict with older uncorrected presumed chronologies. The compilation of the calendar-corrected ages from both valleys in Table 1 provides a total of 41 glacially linked ^{14}C ages with 35 of the calendar-corrected wood (27) and plant (8) ages falling between 14,438 and 12,955 cal yr B.P., entirely within the B-A warm interval (14,700–12,900 cal yr B.P.) as defined in Rasmussen et al. (2014). The reader is referred to Table 1 for the 2σ ranges and supporting data for the ^{14}C ages (cal yr B.P.) cited throughout the text. The overall purpose of this discussion is to demonstrate there is compelling evidence for a late glacial advance that correlates closely with the established ice-core climatic history of the Northern hemisphere, including scattered localities in Wisconsin, the Canadian Maritimes, Ireland, and Scandinavia.

TABLE 2A. HISTORIC CHRONOLOGY AND NAMES OF MAJOR GLACIAL EVENTS IN WESTERN NEW YORK FROM LITERATURE SOURCES

Event or feature	References	^{14}C age	Calendar corrected age (cal yr BP)
Valley Heads moraine (=Lake Escarpment Moraine)	Muller and Calkin (1993)	13,865–14,100	16,630–16,489
	Franzi et al. (2016)	(Varve chronology)	16,900
	Ellis et al. (2004)	Lake core	~17,000
	Ridge (2018)	Varve; ^{14}C	16,900
Lavery moraine	Crowl (1980)	14,500–14,300	16,840–17,140
Erie Interstadial	Muller and Calkin (1993)	16,000 (est.)	18,144 (est.)
	Karrow et al. (2000)		
	Ridge (1997)	16,000–14,500	19,300–17,700
	Owen (this paper)	20.1–17.9 kyr (OSL)	
	Huot (this paper)	19.4–14.5 kyr (OSL)	
Kent moraine	Miller and Calkin (1992)	<24,180	<28,350
	Karrow et al. (2000)		
	LaFleur (1980)		
	Muller et al. (1988)	24,430 ± 5000	28,331 ± ?
Plum Point Interstadial	Mörner (1971)	32,000–28,300	35,914–32,162
	Miller and Calkin (1992)	24,900–24,180	29,060–28,350

TABLE 2B. CHRONOLOGIC SEQUENCE OF CLASSIC WISCONSIN TILL AND/OR MORAINE NAMES FROM HISTORIC LITERATURE

Ohio, Pennsylvania (White et al., 1969; White and Totten, 1979)	Western New York (Muller, 1977; *this report)
No till younger than Ashtabula in NE Ohio, Pennsylvania	B-A/YD or Younger Dryas(?) This report*
Ashtabula till (mapped across Pennsylvania to New York border)	Valley Heads moraine (Lake Escarpment?)
Hiram till (Defiance moraine)	Hiram till (Defiance moraine)
Lavery till	Lavery till
Erie Interstadial	Erie Interstadial
Kent moraine and till	Kent moraine and till
Plum Point Interstadial (Middle Wisconsin)	Plum Point Interstadial

Note: White and Totten (1979) state the Ashtabula moraine in Ohio is eroded by shoreline features developed in Lakes Maumee and Whittlesey at elevations as high as 760 to 770 feet. If correct, this would indicate the Ashtabula till is significantly older than the proposed B-A/YD event. B-A/YD—Bölling-Alleröd/Younger Dryas.

WISCONSIN STAGE GLACIAL CHRONOLOGY AND LANDFORMS

Finger Lakes to Cattaraugus-Buttermilk Creek Basin

Despite the existence of more than a dozen named moraines between the Pennsylvania border and Lake Ontario (Fig. 1), as depicted on the Niagara Sheet of the Surficial Geologic Map of New York (1st edition, Muller, 1977), there were no unambiguous ages directly associated with these prominent glacial features. Thus, there was no precise chronology for the events accompanying the uneven recession of the Late Wisconsin ice sheet from western New York. In contrast, there is limited control for the Late Wisconsin glacial chronology of east-central New York (Ridge, 2003, 2004, 2018; Ridge et al., 2012) as well as for Middle Wisconsin events in the central Finger Lakes and the Genesee Valley (Young and Burr, 2006; Karig and Miller, 2013). Kozlowski et al. (2018) make a case for locating the Port Huron Phase maximum at 14,300–16,000 cal yr B.P. north of the eastern Finger Lakes. Early Wisconsin deposits are preserved at Great Gully on the east side of Cayuga Lake (Kozlowski et al., 2014). A few ages for Early or Middle Wisconsin events are available farther to the west at the

TABLE 3. OPTICALLY STIMULATED LUMINESCENCE AGES (THOUSANDS OF YEARS: KYR) FROM CARTER POND, WNYNSC LANDSLIDE, AND MEANDER SITES

Location and material	CAM (k.y.)	W_{ase}	N_d	MAM (k.y.)	Latitude/longitude (NAD27)
Carter Pond*					
Dune sand A (Owen)	13.9 ± 0.9	14.8 ± 1.4	29	12.7 ± 0.9	42.811/77.750
Dune sand B (Owen)	12.3 ± 0.8	13.2 ± 1.0	26	12.6 ± 0.8	42.811/77.750
Landslide (WVDP)					
Erie sand (Owen)	20.1 ± 1.3	26.8 ± 2.8	18	17.9 ± 1.2	42.450/78.644
Erie sand (Huot)	19.4 ± 1.2	NA	43	14.5 ± 1.5	42.450/78.644
Meander (WVDP) sample 9a					
2010 gully sand (USDOE)	17.1 ± 1.39	NA	NA	17.07 ± 1.1	42.458/78.648
2018 gully (ECS) Revised	19.3 ± 0.9	NA	NA	19.1 ± 0.9	42.458/78.648
Meander channel (Huot)					
Trench 1 samples (ECS, 2018)					
WV T1 S2 gravel over till	16 ± 3	NA	29	11.2 ± 0.8†	42.458/78.644
WV T1 S1 till	22 ± 4	NA	21	15.6 ± 1.6†	42.458/78.644
Meander kettle pit P2 (Huot)					
WV-MD-Pit2a (ECS, 2018)	29 ± 5	20.5 ± 1.5	47	12.8 ± 1.2†	42.457/78.650

Abbreviations: CAM—Central age model (weighted average or mean for equivalent doses); ECS—Enviro Compliance Solutions, Inc.; W_{ase}—average and standard error for equivalent doses of all aliquots; N_d—Number of replicated equivalent doses or aliquots; MAM—Minimum age model (†—best age estimate for specific analysis); NA—not available from report; USDOE—U.S. Department of Energy; WVDP—West Valley Demonstration Project.

*Carter Pond: Calculated optically stimulated luminescence ages for two sand dune samples collected from trench and pond excavation, close to dune base and ~10 m horizontally apart. Overlap of spread for two age calculations suggests 12.9 to 14.2 k.y. is reasonable time span for likely minimum range of Carter Pond active dune development (Young and Owen, 2017).

Nichols Brook, Lord Hill, Otto, and Gowanda Hospital sites in the Cattaraugus Creek basin (Miller and Calkin, 1992; Muller and Calkin, 1993). However, attempts to accurately date or extrapolate the ages of the most prominent moraines on Figure 1 into western New York from mapping to the east or the west have not yet produced a definitive Late Wisconsin glacial chronology for the western New York region. Excluding these few recent improvements in the glacial chronology, the most detailed and comprehensive review of the western New York Wisconsin Stage of the Pleistocene remains that by Muller and Calkin (1993).

Reconstruction of the glacial history for this region is limited by the fact that no morphologically distinct Late Wisconsin moraines within the Genesee Valley or the Buttermilk Creek basins are dated precisely by included organics. The published mapping studies with limited chronologic or stratigraphic control in the Genesee Valley are those by Fairchild (1904, 1923, 1928), Young et al. (1978), Wilson (1981), Braun (1988), Muller et al. (1988), Young (1988, 2012), and Mansue et al. (1991). One of the more detailed studies (Young and Burr, 2006), based upon 68 radiocarbon samples, documents a Middle Wisconsin site in northern Livingston County that matches the age of Heinrich event H-4 (Bond and Lotti, 1995; Hemming, 2004; Andrews and Voelker, 2018) and is supported by the description of a similar advance by Karig and Miller (2013) in the southern Cayuga Lake basin near Ithaca, New York.

The best dated regional landform, the Valley Heads moraine (Fig. 1), located near the southern ends of the Finger Lakes and passing near Dansville in the Genesee Valley, extends westward through Springville, New York, and was initially estimated to have formed ca. 17,200 cal yr B.P. (Ridge, 2003, 2004; Ridge et al., 2012). This projection is based on the correlation of Valley Heads moraine segments farther to the east in New York with the Hinkley–St. Johnsville re-advance north of Utica, New York. Ridge recently revised the Valley Heads age to 16,900 cal yr B.P. after minor recalibration of the New England varve chronology (Ridge, 2018; J.C. Ridge, 2018, personal commun.; Kozlowski et al., 2018, their figure 3 therein).

Muller's (1977) first edition of the Niagara Sheet of the Surficial Geologic Map of New York correlates the Valley Heads moraine with the Lake Escarpment (Defiance) moraine system farther to the west (Fig. 1). The Lake Escarpment moraines of western New York were formed during a late phase of glacial Lake Maumee ca. 14,100 ^{14}C B.P. (17,153 cal yr B.P.), as cited in Muller and Calkin (1993). More recently, Fisher et al. (2015) present OSL ages suggesting

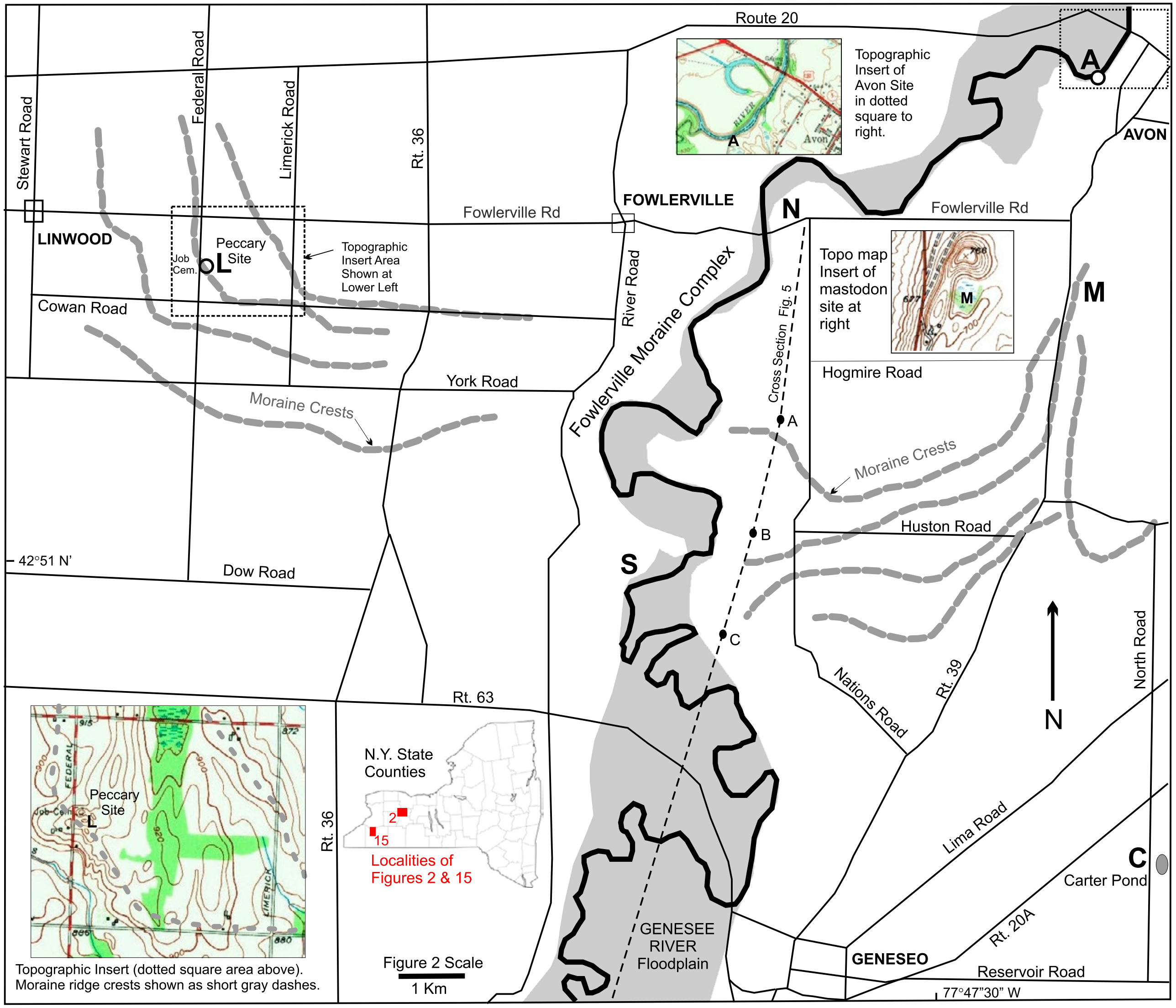


Figure 2. General map of Genesee Valley: Avon (A), Linwood (L), Carter Pond (C), and Farview mastodon (M) locations with topographic inserts for key sites. Approximate width of the larger Fowlerville (Bölling-Alleröd/Younger Dryas [B-A/YD]) moraine indicated by the distance between N and S along the Genesee River. Subsidiary moraine crests of low relief are indicated by the thick dashed gray lines. Cross section dashed line for Figure 5 shows wells A, B, and C, which intersect Fowlerville moraine.

that glacial lakes Maumee, Whittlesey, and Arkona in the Erie basin simply record a series of continuously falling lake levels beginning with Maumee at 16.8 ± 1.1 k.y. and ending with Arkona ~15 k.y. These Erie basin OSL age assignments are consistent with the proposed position and estimated age of the Valley Heads–Lake Escarpment moraine system.

The geology of the Buttermilk Creek basin in Cattaraugus County (Fig. 1) is the focus of several studies with limited ^{14}C ages completed to characterize the former Western New York Nuclear Service Center (LaFleur, 1979, 1980; Albanese et al., 1983, 1984; USDOE, 2010; ECS, 2018). The published glacial stratigraphy of this portion of extreme western New York (Lake Erie Basin), including the WNYNSC site, was tentatively established by extrapolation of the names of till sheets and moraines (Fig. 1; Tables 2A and 2B) as mapped in Ohio and adjacent northeastern Pennsylvania (Shepps et al., 1959; Muller, 1977; Thomas et al., 1987; Fleeger, 2005; Braun, 2011). Starting at the Plum Point Interstadial, this includes the Kent, Lavery, and Hiram tills in ascending order (Tables 2A and 2B).

Western Lake Ontario and Eastern Lake Erie Shoreline Stratigraphy

Summaries of the most relevant glacial stratigraphy exposed north of our sites in eroding bluffs along the shores of western Lake Ontario and eastern Lake Erie are by Calkin (1970, 1982), Salomon (1976), Calkin et al. (1982), Muller and Calkin (1993), and Muller et al. (2003). The stratigraphy exposed along the Lake Ontario shoreline west of Rochester, New York, includes a stony red basal till and overlying purplish till, separated by a glaciolacustrine unit (Calkin et al., 1982). Above these two widespread glacial tills is a sequence of rhythmites, sands, and till lenses, capped by thinly bedded to massive glaciolacustrine silts and clays. Neither of the lower till units along the lake shore west of Rochester has been correlated with the named tills farther to the west, such as the Kent, Lavery, or Hiram; the formal names projected eastward through the Lake Erie basin from Ohio and Pennsylvania. The uppermost glaciolacustrine unit along the western Ontario shoreline includes dropstones and encloses discontinuous ice-marginal deposits in several places, and rests on a boulder lag at the glaciolacustrine-till interface. Calkin interprets these youngest ice-marginal deposits as including subaquatic flow till from an active glacial stand or short glacial re-advance and oscillatory retreat that occurred during the existence of glacial Lake Iroquois (Calkin et al., 1982). Given Calkin's observations and the currently proposed calendar-corrected age for the demise of Lake Iroquois as ca 13,000 cal yr B.P. or slightly younger (Lewis and Anderson, 2020), the implication is that glacial ice or a partially grounded, floating ice shelf apparently did impinge on the southwestern Lake Ontario shoreline (glacial Lake Iroquois) at a time that overlaps the evidence for the B-A/YD advance that is the focus of this analysis and discussion.

In Erie County, New York, along the southern shore of eastern Lake Erie, Calkin (1982) describes the region north of Cattaraugus Creek (Fig. 1) as blanketed by "glaciolacustrine and ice-contact drift, and traversed by subdued, water-laid end moraines." Calkin (1982) states that ten stages of proglacial Great Lakes are recorded in the New York portion of the Lake Erie lowland during Late Wisconsin time with only the Whittlesey (Fig. 1) and Warren strands strong enough to be traced southward or westward to their type areas.

Calkin (1982) believed the Port Huron advance (ca.15,500 cal yr B.P.; Blewett et al., 1993) continued far enough south to potentially override or build the Gowanda moraine (Fig. 1), the most prominent glacial feature immediately north of the Lake Escarpment (Valley Heads) moraine. The significant findings by Calkin that are most relevant to our current analysis are his observations that superficial glacial re-advances across one or two older subdued moraines did occur. Calkin proposes that the ice must have been thin during such events and the advances short lived. Calkin discusses the ^{14}C ages of these events within the context of ^{14}C ages available in 1982, especially the ages of the major glacial lake stages, and the Port Huron advance. Although Calkin's comments on the nature of glacial mechanics during this interval are encouraging with regard to our proposed evidence for a potentially younger advance, he did not expand upon the evidence for a partially grounded, floating ice shelf in as much detail as did LaFleur (1979, 1980) in his Cattaraugus-Buttermilk Creek studies.

LOCATION OF NEW SITES IN THE CURRENT ANALYSIS

The four major surface sites in this analysis include two in the Genesee Valley, near Avon and Linwood, New York, and two in the Buttermilk Creek basin, one on the WNYNSC property and the other along Simmons Road in the southeast corner of the Ashford Hollow 7.5 min topographic quadrangle (Figs. 1 and 2). Buttermilk Creek is a 12-km-long, north-flowing tributary to Cattaraugus Creek, which forms the northern boundary of Cattaraugus County (Fig. 1). The Buttermilk Creek sites are associated with the orientation of the Erie lobe of the Laurentide ice sheet, whereas the Genesee Valley sites reflect the orientation of the contemporaneous Ontario Lobe; the two lobes having slightly different flow directions (Fig. 1). However, the major moraines associated with the two contiguous lobes are correlated continuously across western New York (Fig. 1; Muller, 1977; Cadwell, 1988). Three of the four main sites in these two valleys contain abundant, well-preserved wood in glacial till; the fourth (Linwood) preserved a complete peccary skeleton at a subsidiary crest of a moraine complex composed of ice-contact outwash sands overlain by a thin till (Young et al., 1978; Young and Owen, 2017). A fifth site, Carter Pond, provides supportive evidence relevant to both the B-A/YD event and the Valley Heads recession.

The cluster of late Wisconsin radiocarbon ages (ca. 14,438–12,955 cal yr B.P.) obtained from tills along Buttermilk Creek during the ECS (2018) fieldwork in 2015 and 2016, and by Gordon et al. (2013) (Table 1, samples 1–15), initiated a reconsideration of the more extensive and overlapping Genesee Valley data, especially where glacial tills are directly associated with well-dated organic remains; wood near Avon, New York (Fig. 3) and a complete peccary skeleton near Linwood, New York (Figs. 1 and 2). Given that the majority of the ages

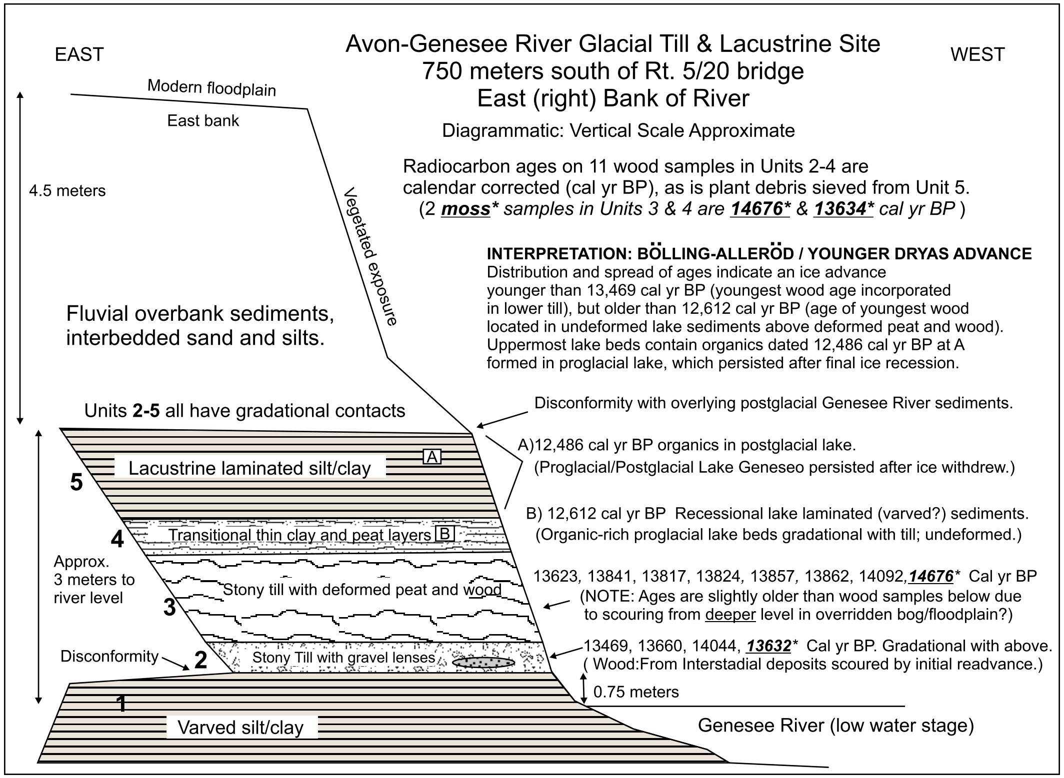


Figure 3. Diagrammatic stratigraphic section of till between glaciolacustrine sediments at Genesee River site near Avon. Horizontal contacts are intended only to indicate contrasting textures of subunits 1 through 5, whereas boundaries between designated subunits are somewhat gradational and slightly irregular. Aquatic mosses may give erroneous older ages as explained by MacDonald et al. (1987).

represent trees presumably toppled or reworked by glacial scouring of deadfalls from B-A forests, swamps, and floodplains, it follows that the proposed glacial advance must be younger than the youngest relevant ^{14}C calendar-corrected age at each location.

Avon Site at Genesee River

Figures 3 and 4 depict the most comprehensively dated stratigraphic section of till sandwiched between two sets of lacustrine sediments exposed on the east (right) bank of the Genesee River ~0.75 km south of New York Routes 5 and 20 (Young, 2003). Based on the range of the eight youngest uncalibrated ^{14}C wood ages (11,997–11,640 ^{14}C B.P.), their apparent conflict with the previously uncorrected age estimates for the demise of glacial Lake Iroquois (>11,600 ^{14}C B.P.; Calkin, 1970; Terasmae, 1980), and the apparent lack of such young tills elsewhere in western New York, Young initially felt compelled to assume the diamict (Fig, 3, layers 2 and 3) must represent a landslide (Young, 2003, 2012). A large landslide (3.6 ha, 8.9 ac), locally exposing till overlying varved sediments within the nearby Fowlerville moraine, occurred 3 km south of the Avon site in 1972 (Young and Rhodes, 1973, their figure 3 therein). However, it is notable that the 1972 landslide did not bury trees; rather the trees were carried atop the large slide as it advanced and temporarily blocked the Genesee River.

In hindsight, Young's (2003) premature landslide designation of the diamict at the Avon site is hereby redefined as a glacial till sandwiched between two sets of undeformed, laminated, lacustrine sediments with near-horizontal, conformable contacts (Figs. 3 and 4). The seven youngest recalibrated calendar ages from wood in the Avon site till fall between 13,857 and 13,469 cal yr B.P. (Table 1), a range of less than 400 years, and extend close to the upper limit of the oldest peccary bone date (13,307 cal yr B.P.) at the Linwood moraine site. The wood-bearing Avon till and overlying lacustrine deposits formed entirely during prolonged or repeated submergence of the site. This is inferred because ice advances to that latitude would automatically create a wide proglacial lake 107–137 m (350–450 ft) deep by damming of the Genesee River with an elevation control at the older Lake Hall outlets nearby. Such a lake would form

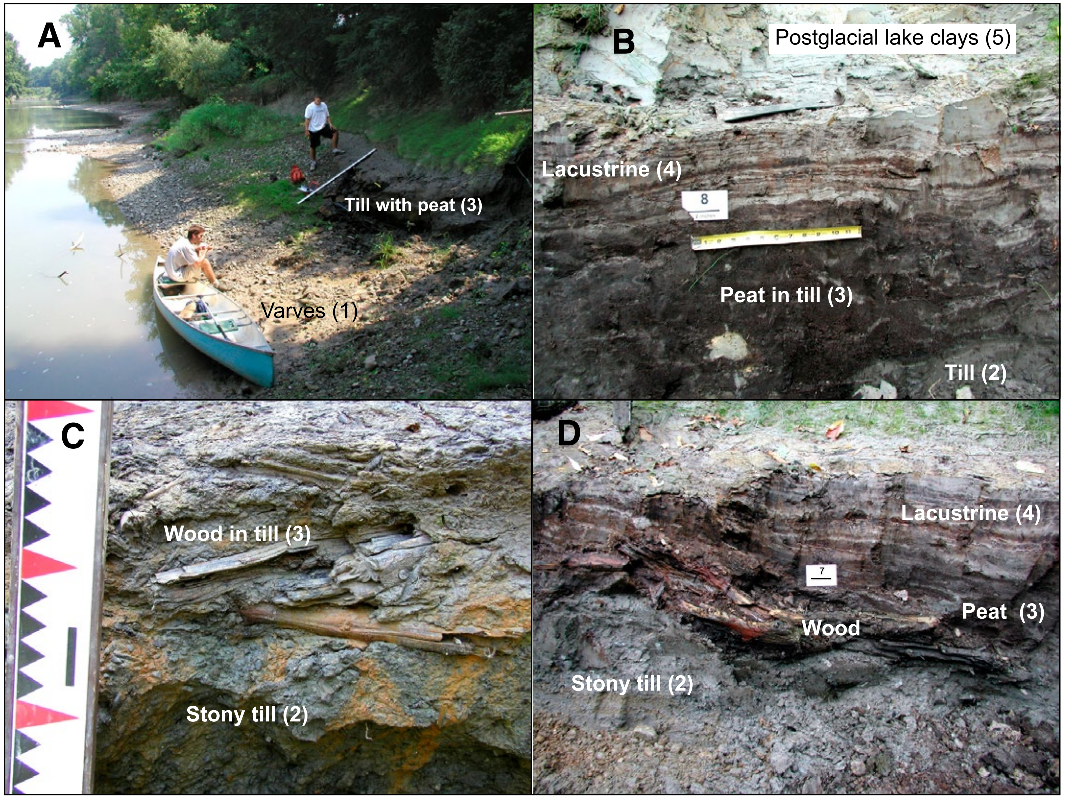


Figure 4. Views of Genesee River outcrop at Avon with layers labeled as in Figure 3. (A) Overview looking upstream. (B) View of subunits 2–5 emphasizing laminated (varved) nature of organic-bearing lacustrine unit 4 (ruler is 1 ft.; 30.5 cm). (C) Fragmented, abraded log sections in till indicating glacial removal of bark and branches as well as suggesting N-S parallel ice flow direction. Red arrows on stadia rod are 0.5 feet apart. (D) View of wood and peat interval near top of stony till (bar at #7 label is 5 cm long).

initially when the lobate ice front first encountered the restrictive confines of the valley sides a short distance north of the Avon location (Muller et al., 1988).

The discovery of the till exposures containing wood with atypically young ages in the Buttermilk Creek basin (ECS, 2018), and their conspicuous overlap with the calendar-corrected ages in the Genesee Valley, motivated the present reconsideration of the premature landslide designation near Avon (Young, 2003). In addition to the overlapping age criteria for the samples in the Genesee and Buttermilk Valleys, reconsideration of the stratigraphic details, as well as the orientation and condition of the logs at the Avon site confirm that the revised glacial designation is more appropriate. The numerous severed log segments preserved in the diamict (i.e., till) at the Avon site are completely stripped of branches and bark, and are partially intertwined with their long axes aligned parallel to the presumed north-south ice flow (Figs. 4C and 4D). Living trees buried by a local subaerial landslide should be less disarticulated, would have preserved bark and branches, and would have more random orientations, similar to trees observed in a prehistoric landslide examined during the WNYNSC trenching studies (ECS, 2018, Trench FT-26, their figure 4.9 and appendices F and G therein), as well as in two very recent landslides along the Genesee River. In addition, small stones from the enclosing till at the Avon site are strongly impressed into the logs by overriding ice pressure, similar to details observed at the Simmons Road site. Nevertheless, the relatively young wood ages, and the inferred age of the B-A/YD advance must be reconciled with the apparently overlapping age of glacial Lake Iroquois, as discussed in a subsequent section.

Interpretation of Avon-Genesee River Site

The Genesee River site near Avon (Fig. 3) exposes a sub-lacustrine basal till deposited during the glacial advance to the nearby Fowlerville moraine (Figs. 1, 2, and 5) based on the following evidence. There are older undated varved lakebeds associated with a proglacial lake of pre–Bölling-Alleröd age at the

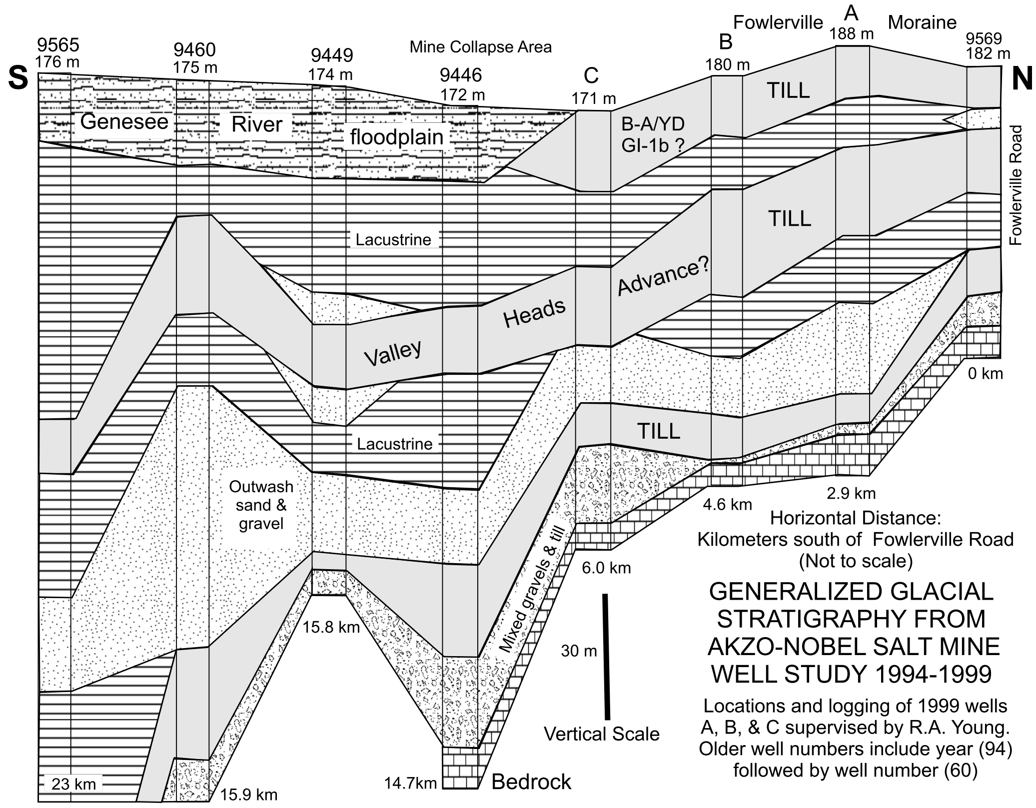


Figure 5. North-south cross section along the thalweg of the buried bedrock Genesee Valley constructed from key exploratory wells drilled through Fowlerville moraine following the collapse of the Akzo-Nobel (Retsof) salt mine (Nieto and Young, 1998). Wells A, B, and C drilled in 1999 for aquifer characterization (Yager et al., 2001). The abrupt termination of the Fowlerville moraine (Bölling-Alleröd/Younger Dryas [B-A/YD] event) advance ending ca. 6 km south of Fowlerville Road and transition to floodplain is clear. Location of cross section for wells A, B, and C shown as dashed line on Figure 2.

base of the Avon exposure, overlain by the wood-bearing diamict (inferred till), which was followed by continued deposition in a similar proglacial lake (Fig. 3). The depth of the younger proglacial lake (107–137 m) is constrained by the elevations of the nearest glacial Lake Hall outlets, located a few kilometers to the southwest, as defined by the features depicted along the 1000- and 950-foot topographic contours on the Leicester 1:24,000-scale quadrangle map (Muller et al., 1988, their figure 6 therein; Fairchild, 1904, 1928). The youngest wood in the till (13,469 cal yr B.P.) exposed at the Genesee River site is assumed to provide the nearest estimate for the minimum age of the forest cover that was buried by the ice advance. However, it is unlikely that the limited number of random samples preserved at the Avon site would have fortuitously included the absolutely youngest specimens growing in the B-A forest.

The older of two ages located at intermediate intervals within the thin proglacial lacustrine deposits overlying the till at the Avon site indicates that ice recession was under way shortly before 12,612 cal yr B.P. (Fig. 3; Table 1). This is based on the assumption that the date represents input of contemporaneous fluvial debris to a proglacial lake either from the north-flowing, obstructed Genesee River or from debris washed off local slopes. Miscellaneous plant detritus sampled from a bit higher within the uppermost lacustrine layers at the Avon site indicate that the lake persisted through a recessional proglacial "Lake Geneseo" stage (Muller et al., 1988) lasting until shortly after 12,486 cal yr B.P. (Table 1, sample 16), after which time the Genesee River became incised through the broad moraine dam near that location. Most of the critical wood samples at all sites (Table 1) were extracted from the interiors of logs 12–25 cm in diameter. Therefore, the true age of some of the trees at death could be easily 50 years younger than the measured ^{14}C ages, independent of the standard measurement uncertainties. This observation is supported by the 40-year age difference between duplicate samples 12 and 13 (Table 1), specimens sent to the same lab from inner and outer sections of the same log. Overall, the Avon samples must represent the felling or reworking of B-A–generated forest growth, which was overridden leading to the emplacement of the Fowlerville end moraine complex described in the following section.

The ^{14}C results indicate that a proglacial lake persisted for more than 126 years following the Fowlerville moraine advance, thus placing an approximate limit on the rapid initiation of local incision by the Genesee River. This estimate of the initial postglacial incision age is supported by a separate Genesee River study, which includes 53 radiocarbon ages on Genesee River point bar and overbank sediments (Young, 2003). The oldest ^{14}C age in the 2003 river channel sample set was 10,930 ± 63 ^{14}C B.P. (12,793 cal yr B.P.) obtained from a point bar at low river stage within 1.5 km of Avon (Young, 2003, their table 2, sample 43 therein). This age indicates that the Genesee River became incised relatively rapidly through the moraine to its current elevation. Although the point bar 2σ mean age is ~300 years older than the youngest proglacial lacustrine sample (Table 1, sample 16), this is readily accounted for by noting that point bar debris derived from upstream in the modern Genesee River basin often includes older reworked detritus that has been growing for hundreds of years in the forest beyond the southern limit of the proposed ice advance Young (2003).

Fowlerville Moraine Complex

The Fowlerville moraine complex is a broad, low-relief, drift plug filling the Genesee Valley; the plug ends 3 km north of Geneseo and is further characterized by at least four low subparallel and curvilinear ridges (Fig. 2), which are distributed over a north-south distance of 2 km (Muller et al., 1988). The total width of this broad moraine with its subtle multi-ridge topography (Fig. 2) is ~6 km, as measured from its northern margin near Fowlerville Road (Fig. 2, N and S; Fig. 5). The Fowlerville moraine complex marks the end of the re-advance that deposited the till incorporating the wood at the Avon-Genesee River site, which is 2 km behind the northern edge of the moraine. The subsurface evidence for the nature and extent of the till forming the bulk of the moraine is verified by the exploratory drilling program (Fig. 5) that resulted from the 1994 collapse of the Akzo-Nobel salt mine (Nieto and Young, 1998). Detailed logs for the test wells on Figure 5 were obtained during studies of the resulting widespread dewatering of local aquifers. Sites for wells A, B, and C on Figures 2 and 5 penetrate the moraine, were chosen by R.A. Young, and were installed in 1999 to characterize the northernmost subsurface stratigraphy being modeled by the U.S. Geological Survey (Yager et al., 2001, 2009). The detailed till stratigraphy recorded in these three well clusters (shallow, intermediate, and deep monitor wells installed at each location) was logged independently on site by R.A. Young during installation by Alpha Geoscience (2002). The termination of the youngest ice advance (uppermost till) at the Fowlerville moraine is clear on Figure 5, which includes two additional tills associated with older advances. The shallow "Fowlerville" till in wells A, B, and C is described as "faintly laminated" and "reworked lacustrine till" in the consultant's official logs (Alpha Geoscience, 2002). The cross section clarifies that the youngest till is the major surficial glacial unit corresponding to the Fowlerville (B-A/YD) advance and clearly removes any concerns over its initial misidentification as a landslide in the stratigraphically equivalent position at the Avon-Genesee River site (Fig. 3).

Linwood Peccary Site

One subsidiary Fowlerville moraine ridge crest on the west side of the Genesee Valley includes the abandoned Job Cemetery south of the junction of Fowlerville and Federal Roads (Fig. 2). The well-preserved skeleton of a juvenile peccary (Platygonus compressus) was collected in 1978 on the eastern edge of the cemetery in an excavation dominated by ice-contact, ripple-laminated sands overlain by a thin till (Figs. 2, 6, and 7; Young et al., 1978). The lengthy 6-m-high outcrop exposed two narrow, vertically disturbed "quicksand" zones within the outwash sands (proglacial, ice-contact fan?), one of which contained the peccary bones (Fig. 6). The narrow quicksand zones mark locations where the upward flow of groundwater eradicated or deformed the original layering by partial to complete liquefaction (Figs. 7C–7F). These vertical flow-induced structures formed during the escape of glacial meltwater that saturated the marginal proglacial sediments and was discharged vertically, close to the ice margin. Such discharge, driven by the over-pressurization of subsurface meltwater issuing from outwash near the base of an active glacier terminus, was possibly enhanced by an added head of meltwater discharging through ice fractures. Evidence of similar "quicksand" phenomena near modern glacier margins can be appreciated by inspecting the vast collection of online internet glacier images such as illustrated in Young and Owen (2017, their figure 9 therein). These proglacial discharges vary from vigorous fountaining above the existing surface to a more subtle upwelling that is typical of the relatively invisible quicksand conditions in modern fluvial environments. Evidence that similar ice-marginal meltwater discharge conditions are present elsewhere in the region is preserved in nearby borrow pit exposures (Fig. 8; Young and Briner, 2006; Young and Owen, 2017).

An approximate, 10-month juvenile age for the peccary skeleton is inferred from the incomplete eruption of the secondary tusks and posterior molars (Young et al., 1978; Young and Owen, 2017, their figure 8 therein) from data on modern species of javelina (collared peccary) by Kirkpatrick and Sowls (1962). The amazingly well-preserved peccary skeleton at the Linwood site was enclosed in the homogeneous (liquefied) quicksand on a narrow "shelf-like" margin of the irregularly shaped quicksand conduit (Fig. 7D). It is inferred that the inexperienced juvenile wandered into a proglacial environment where subtle groundwater upwelling masked the unstable conditions. The unusually complete skeletal preservation attests to the rapid burial and isolation of the animal's remains from normal disintegration, weathering, or predation. The presence of a juvenile peccary near an active ice front indicates that a breeding population with an adequate food supply must have been present. This supports an ice advance into an existing forest, rather than a regional recession, which would leave a sparsely vegetated landscape. The stratigraphy at the location, moderately dipping, ripple-laminated sands overlain by thin

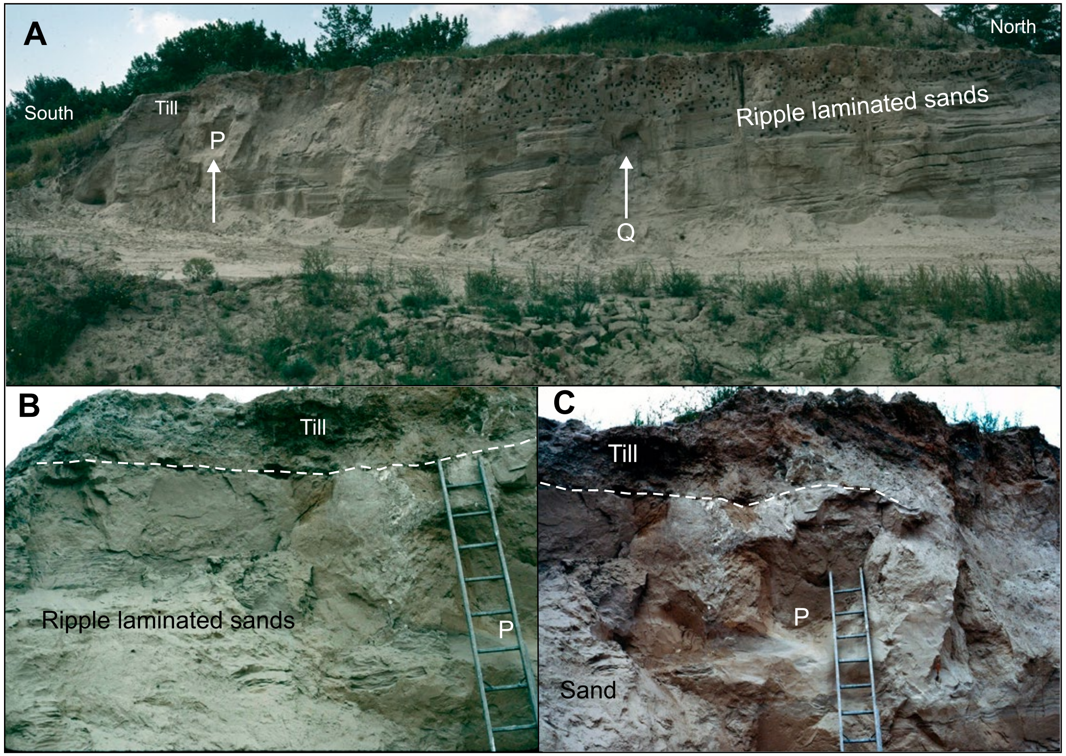


Figure 6. Views of Linwood peccary site. (A) Moderate south dip of ripple laminated sands indicates deposition (proglacial delta or fan) off nearby ice front. P is location of peccary skeleton. Q is second vertical quicksand structure with detail shown on Figure 7. Exposed section is 6 m thick at highest point. (B) Closer view of area immediately south of peccary location (P) showing surface till. Twelve-foot ladder rungs are 1 foot apart. (C) View overlapping B showing complete cavity (P) where peccary bones were removed.

glacial till on a topographic high at the crest of a secondary morainal ridge (Figs. 2 and 5), also implies that the demise of the peccary occurred close to an active ice front. The preserved quicksand structures, indicative of an upward groundwater gradient, could only occur at the crest of such a moraine if the ice front were nearby and at an elevation rising above the peccary location. This is supported by the burial site being subsequently overridden by a minor glacial advance as documented by the conformable till-outwash contact visible in Figures 7A and 7D.

The initial peccary bone date (Table 1, sample 32) provided an uncorrected ^{14}C age of 11,145 ± 80 yr B.P. (13,002 cal yr B.P.). This previously unpublished ^{14}C age was obtained before the radiocarbon calendar-correction curve had been extended to this limit. Given that the uncorrected age in 1977 for the presumed demise of glacial Lake Iroquois with its well-preserved shoreline at Rochester was considered at the time to be ca. 11,600 ^{14}C B.P. (Calkin, 1970; Terasmae, 1980), Young et al. (1978) initially assumed that the age of the peccary bone, located at the more southern latitude, was too young to represent a glacial advance, possibly due to groundwater contamination. Upon reconsideration of the calendar-corrected ages of the many wood-in-till samples from all the sites in this analysis, it is notable that the oldest accelerator mass spectrometer (AMS) collagen age on the four peccary bones (13,307 cal yr B.P.) is close to the age of youngest wood preserved in till at the Avon site (Fig. 3; Table 1, sample 27) as well as at the Buttermilk Creek sites. The range of all four peccary ages (12,907–13,307 cal yr B.P.) at the Linwood site also overlaps the age estimates for the demise of Lake Iroquois, possibly as young as 12,800 cal yr B.P. (Lewis and Anderson, 2020). A plausible chronology might involve a short-lived re-establishment of an Iroquois shoreline at Rochester following a relatively rapid ice surge and withdrawal ca. 13,000 cal yr B.P. or slightly earlier. The uncertainty concerning the precise sequence of events is due to the fact that ages on trees buried in till at all four sites must be somewhat older than the associated ice advance, as compared to the age of a short-lived peccary trapped and instantly buried in a dynamic ice-marginal environment. Given the conclusions regarding the demise of glacial Lake Iroquois as revised by Lewis and Anderson (2020), and the slight uncertainty over the exact age of the B-A/YD advance, there could be a few hundred years available for wave action to reestablish the preserved Lake Iroquois strand near Rochester following a rapid ice recession or an in situ floating ice-shelf disintegration.

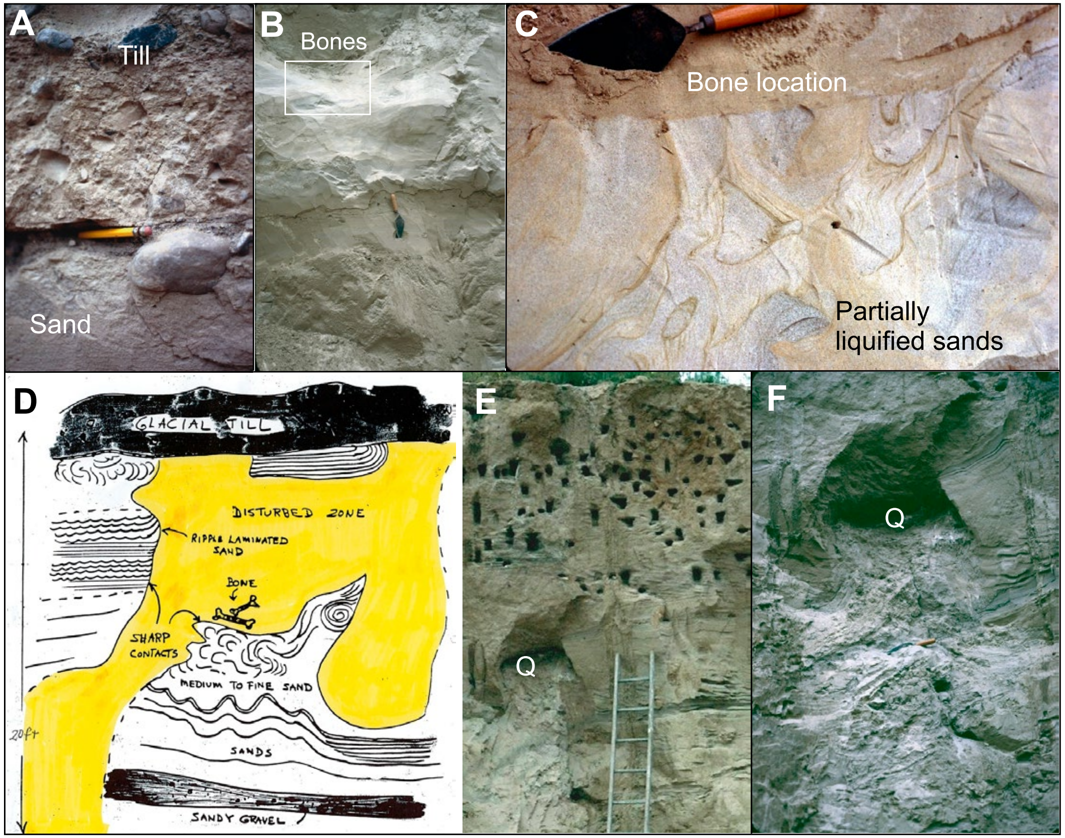


Figure 7. (A) Close-up view of till/sand contact (at pencil) near center of Figure 6B. (B) "Shelf" within quicksand conduit where bones were located with rectangle indicating location of cleaned view in C (trowel is 24 cm). (C) Enlarged view of shaved section and liquefaction texture present in rectangle of B. (D) Field sketch of quicksand zone as interpreted during original site visit. (E) Top of second quicksand structure (Q) located 20 m north of peccary location as marked on Figure 6A at Q. Holes are swallow nests. (F) Closer view of E showing detail of upturned bedding near center trowel at edge of vertical, upward-flowing quicksand conduit.

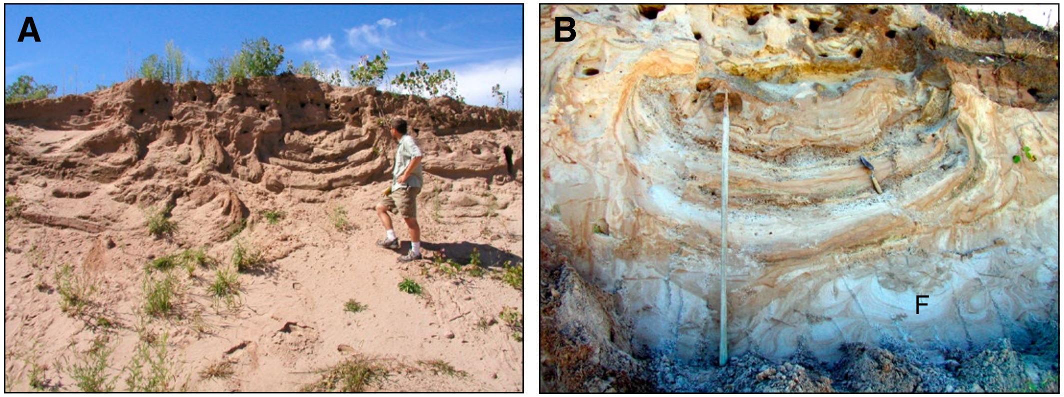


Figure 8. Sand and gravel borrow pit locality near Albion, New York, 40 km northwest of Linwood site. Albion site has similar ripple-laminated sands as Linwood site, dipping moderately southward away from a nearby ice front position. (A) Weathered surface outcrop of quicksand liquefaction structures. (B) Exposure of quicksand structure scraped clean with 1.5 m hoe for scale. Note similarity of liquefaction textures at F to Figure 7C. Numerous deformational structures in this large borrow pit imply that liquefaction structures created by quicksand conditions may be relatively common at ice-marginal sites where upward groundwater pressure gradients exist.

GENESEE VALLEY SUBSURFACE DATA

Canaseraga Creek Borings

There are three additional B-A/YD-linked ^{14}C ages obtained from isolated bore-hole samples elsewhere in the Genesee Valley proper that are compatible with the chronology proposed for the Avon and Linwood sites. The boring locations shown on Figure 1 are: (1) Two locations beneath the Canaseraga Creek floodplain, 10.4 and 13.2 km south of Geneseo near the Keshequa Creek bridge (Fig. 1, K1) and at the Pioneer Road crossing along the Erie-Lackawanna railroad (Fig. 1, K2); and (2) A hand-cored boring 8 km northwest of Avon (Fig. 1, D, Dugan Creek outwash channel; Muller et al., 1988; Table 1, sample 36). The better of the two Canaseraga Creek samples (Fig. 1, K1) is a 10-cm-long, 2.54-cm-diameter, piece of wood with intact bark and branch stubs collected at a depth of 9.7 m at Keshequa Creek, a small Canaseraga Creek tributary, from a peat layer resting on laminated glaciolacustrine sediments. R.A. Young collected the wood in 1977 during drilling of test borings by the New York State Department of Transportation (NYSDOT) for the I-390 Interstate highway (Mansue et al., 1991). This sample age (Table 1, sample 34, 13,012 ± 160 cal yr B.P.) falls within the age range of the Linwood peccary samples. This wood is reevaluated as recording a sample of the B-A forest cover potentially floated to that location while the existing valley was occupied by proglacial Lake Geneseo (Muller et al., 1988). A composite stratigraphic section at the K1 location, based on seven closely spaced borings all located within a 100 m radius of the Interstate I-390 centerline near Keshequa Creek, is depicted on Figure 9. The dated wood is from the most prominent, 30-cm-thick, peat layer near 9.7 m. Samples 34–36 on Table 1 by Teledyne Isotopes are the only ages using pre-AMS technology.

Prior to our current evidence for the relatively young B-A/YD advance to the Fowlerville moraine, Young (Mansue et al., 1991) originally assumed the thick peat layer at K1 (Figs. 1 and 9) represented the postglacial reestablishment of Holocene vegetation along the Genesee River floodplain deposited after Lake Geneseo had drained by erosional breaching of the undated moraine dam (Muller et al., 1988). However, because Lake Geneseo is now considered as forming due to the damming of the Genesee River by the B-A/YD advance, wood with a 13,012 cal yr B.P. age would have been deposited within Lake Geneseo sediments before this proglacial lake created by the Fowlerville moraine drained. Given the age of the Keshequa Creek wood sample, it could be either B-A debris flushed into the former lake from beneath the advancing ice front, or B-A wood derived from the contemporaneous forest that flourished south of the ice front and delivered by the evolving ancestral Genesee River system. The age of the wood provides additional evidence that the B-A/YD advance and short-lived proglacial lake record events close to the B-A/YD boundary, within the 2σ limits listed on Table 1.

A second ^{14}C age obtained from beneath the Canaseraga Creek floodplain within the lacustrine silty clay immediately below the same thick K1 peat horizon is located 2.78 km farther to the southeast in a separate test boring for the I-390 Interstate highway near the intersection of the railroad with Pioneer Road (Fig. 1, K2). The stratigraphic section (NYSDOT log) at the Pioneer Road site is virtually identical to the generalized stratigraphy shown on Figure 9. The basal contact of the thickest peat horizon with the underlying lacustrine sediments is at a depth of 9.3 m. A 1.2 m section of the silty clay immediately below the peat was sieved, and the organic residue was dated at 12,641 cal yr B.P. (Table 1, sample 35). This is a few hundred years younger than the age of the wood in the overlying peat at the nearby K1 boring (sample 34) but close to the age of the lacustrine beds at the Avon site. It is likely that the sieve residue sample K2 from the lacustrine beds simply records an intermediate composite age for proglacial debris delivered to Lake Geneseo from the ice and the surrounding forest. The slight age reversal, by comparison with the overlying K1 sample at Keshequa Creek, is likely the result of the slightly older wood being discharged into the lake somewhat later from beneath the advancing ice, or as slightly older debris washed down from the lake border or Genesee River, as proposed above. Both Canaseraga Creek boring ages (samples 34 and 35) are compatible with an ice advance damming the valley between 13,300 and 13,000 cal yr B.P. The two randomly located lacustrine sample ages near the top of the Avon section (samples 16 and 17) only record a partial record of proglacial sedimentation in the valley for ~126 years. However, Glacial Lake Geneseo would have formed prior to the ice actually reaching the latitude of

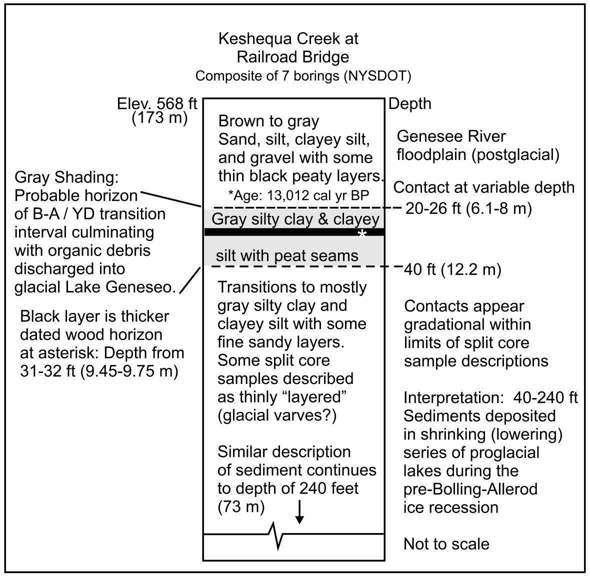


Figure 9. Composite section (K1 site on Fig. 1) based on seven test borings near intersection of Keshequa Creek with Erie-Lackawanna Railroad bridge, near Interstate Rt. I-390 centerline. Fine-grained lacustrine sediments (proglacial) below peaty beds continue to 73 m (240 ft) without encountering till or bedrock. Asterisk is location of thickest peat layer (black) and dated wood specimen (Table 1, sample 34). B-A/YD—Bölling-Alleröd/Younger Dryas.

the Fowlerville end moraine, because the Genesee River would have been ponded as soon as the advancing ice blocked the narrowing mouth of the Genesee bedrock valley some distance north the Fowlerville moraine.

Dugan Creek Boring

The Dugan Creek sample northwest of Avon (Fig. 1, D; Table 1, sample 36) is woody plant debris from 2.7 m depth at the basal peat-till contact, which was hand cored by R.A. Young near the former railroad stop at Lacy Road. The site is within one of a series of subparallel Late Wisconsin outwash channels that discharged sequentially southeastward into the Genesee Valley, as depicted on figures in Muller et al. (1988), Young (1988), Fairchild (1904), and Young and Burr (2006). The age of the Dugan Creek basal peat (12,917 cal yr B.P.) is intermediate between the two Canaseraga/Keshequa Creek samples (Table 1, sample 36). The simplest assumption when the uncorrected Dugan Creek age first was acquired by Young in 1977 was that it also marked the approximate time of early Holocene forest (bog) recovery following ice withdrawal. The several subparallel outwash channels mapped by Fairchild (1904) and depicted in Young and Burr (2006), including Dugan Creek, probably formed sequentially along the progressively receding margin of the B-A/YD ice. The B-A/YD advance would have a lobate shape where it entered the narrowing Genesee Valley, and it is reasonable to conclude that the Dugan Creek organic sample could have come from remnants of B-A forest cover that persisted on the ice-free uplands adjacent to such an ice tongue. Thus woody debris seemingly slightly younger than the wood in the till could be fluvially transported from higher elevations along the ice margin and deposited within the marginal outwash channels during deglaciation.

Carter Pond Site, Geneseo, New York

Excavation of a shallow kettle bog in 2016 to create a small pond on North Road, 5 km northeast of Geneseo, exposed thick cross-bedded dune sand overlying organic-bearing lacustrine clay (Fig. 10B). The new pond is surrounded by

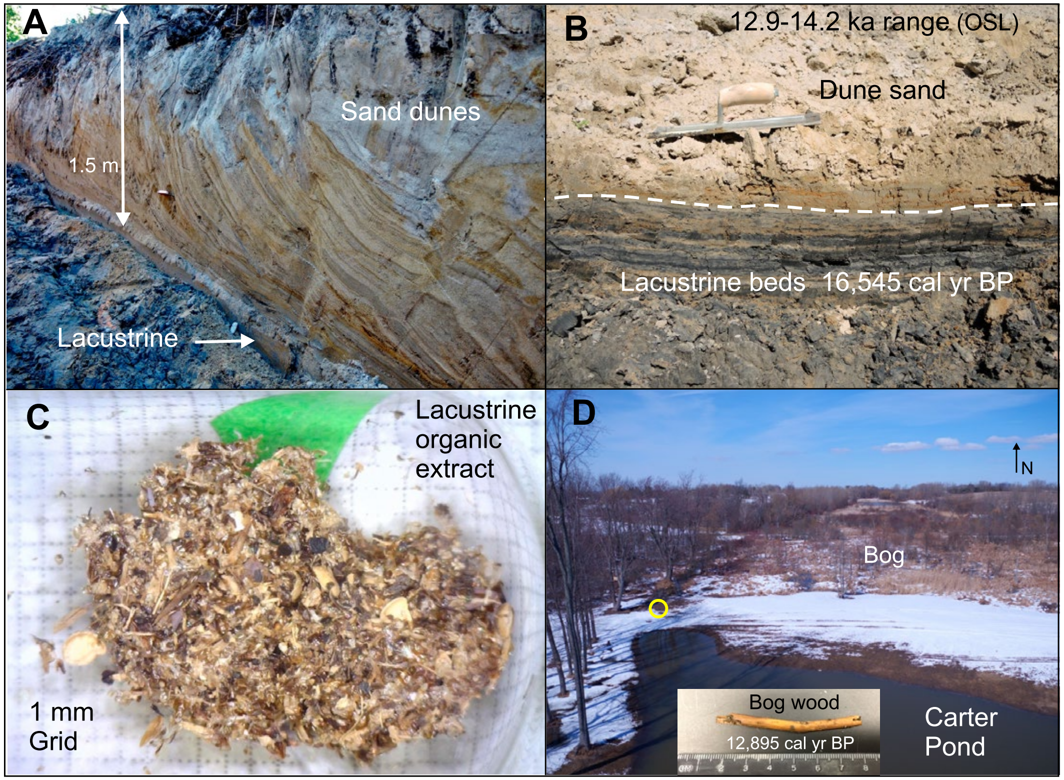


Figure 10. Carter Pond site. (A) Trench through surface sand dunes exposed by pond excavation. (B) ^{14}C calendar-corrected age (Table 1, sample 38) and optically stimulated luminescence (OSL) ages (Table 3) on organics and dune sands at top of underlying lacustrine beds. (C) ^{14}C laboratory extract of dated organic debris from top of lacustrine beds in B. (D) North-looking view over finished pond with yellow circle indicating where dated wood sample at base of bog above dune sands was located. Wood is from 1.2 m depth in peat near base of bog, and calendar-corrected ^{14}C age (Table 1, sample 37) is consistent with OSL ages from dune sand shown in A and B.

the remnants of the postglacial bog deposit; these remnants vary from ~10 cm to 1 m in thickness (Figs. 1 and 10). The organic-rich layers (Figs. 10B and 10C) collected within the topmost beds of the postglacial lacustrine sediments (shallow kettle fill) immediately below the dune sand have an age of 16,545 cal yr B.P. (Table 1, sample 38). This age is consistent with the proposed timing of the pre–Bölling-Alleröd recession from the Valley Heads moraine near Dansville as beginning ca. 16,900 cal yr B.P. (Ridge et al., 2012; Ridge, 2018). Taken at face value, the age difference between the Valley Heads moraine position at Dansville and the Carter Pond composite kettle age records a recession rate of 240 ft/yr, the exact rate reported by Ridge (2004, their table 3 therein) for his Connecticut Valley studies at the same approximate time.

Two OSL ages from near the base of the Carter Pond dunes (Table 3; Young and Owen, 2017) suggest the dunes were active between 12.9 and 14.2 k.y. B.P., bracketing the age of the proposed B-A/YD advance. A second radiocarbon wood age (Fig. 10D, inset) near the base of the Carter Pond bog, immediately above the bog-dune contact, is 12,893 cal yr B.P. (Table 1, no. 37). This conformable OSL and ^{14}C age sequence at the Carter Pond site is compatible with the B-A/YD age of the nearby Farview mastodon described below (Fig. 2, M), including the evidence that the mastodon site was also overwhelmed by aeolian dune deposition (Fig. 11). Dune sands at these two sites appear to record glacially produced katabatic winds, at a time that is consistent with the age of the advance to the Fowlerville moraine. The potential wind speed at the Carter Pond site based on the median grain size, is estimated to have been in the range between 7 and 60 m/s, based on the experimental research of Eastwood et al. (2012).

Farview Mastodon Excavation

In January 1991, a nearly complete mastodon skeleton was recovered from a shallow bog in a kettle immediately adjacent to one of the most prominent Fowlerville moraine ridges (Figs. 1 M and 2 M). The Farview mastodon skeleton (Fisher, 2009) was hurriedly retrieved by hand from peaty muck at the flooded site by hastily assembled State University of New York at Geneseo faculty and students during a brief January thaw. Because of the challenges posed by the cold temperatures and the high water table, there was insufficient time to document the precise relationship of the mastodon skeleton to the enclosing sediments. During the following spring, coauthor Young evaluated the stratigraphy immediately adjacent to the mastodon location from fresh exposures provided by the ongoing landscaping activity. The main sedimentary unit surrounding the bog containing the mastodon bones consists of cross-bedded dune sands extending below the visible exposures (Fig. 11). These dune sands record a surficial sedimentary record similar to that preserved at the Carter Pond site, located 8 km to the south. Sieve analyses of the dune sand produced a typical aeolian graphical probability phi plot with a narrow grain-size distribution (medium sand to coarse silt; 0.35–0.044 mm) with 65% of the sediment composed of fine to very fine sand (Directed Study analysis by former student and current Geneseo faculty member, Dr. A. Sheldon).

Figure 11. Aeolian cross-bedded dune sand at Farview mastodon kettle site (Fig. 1, M), 10 km (6 mi.) NNE of Geneseo, New York. Wind direction was northerly as inferred from limited two-dimensional exposures.

The age of the Farview mastodon is 13,395 cal yr B.P. (Fisher, 2009; Table 1, sample 41). This is very similar to one of the collagen ages obtained on the Linwood peccary (13,307 cal yr B.P.), as well as close to the age of the youngest wood date from till at the Avon Genesee River site (13,469 cal yr B.P.; Table 1, sample 27). This similarity in ages and the close association with the Fowlerville moraine provide additional evidence that the B-A/YD ice advanced into a forested region, which contained a population of mammals that could inhabit such an interstadial landscape. The mastodon age implies that the individual was living near the ice front at or close to the time that the B-A/YD advance occurred.

Taken as a whole, the overlapping and limited range of ages for the Fowlerville moraine advance (Avon site), the Linwood peccary, the Farview mastodon, the Canaseraga-Keshequa Creek samples, the Dugan Creek sample, and the Carter Pond stratigraphy all are compatible with an ice advance and retreat culminating between ca. 13,300 and 13,000 cal yr B.P. or slightly younger.

Irondequoit Bay Barrier Sandbar Borings

Irondequoit Bay near Rochester, New York, is the location of a buried bedrock gorge created by inferred multiple occupations of an ancestral (interglacial) Genesee River, which currently enters Lake Ontario 6 km to the west (Kappel and Young, 1989). Two borings, one to bedrock, along the Irondequoit Bay barrier bar were completed in 1991 for construction of a new bridge at the entrance to the Bay (Figs. 12 and 13). Borings B-2 and B-3, completed to depths of 119 m and 81 m, respectively (Erdman et al., 1991), both encountered

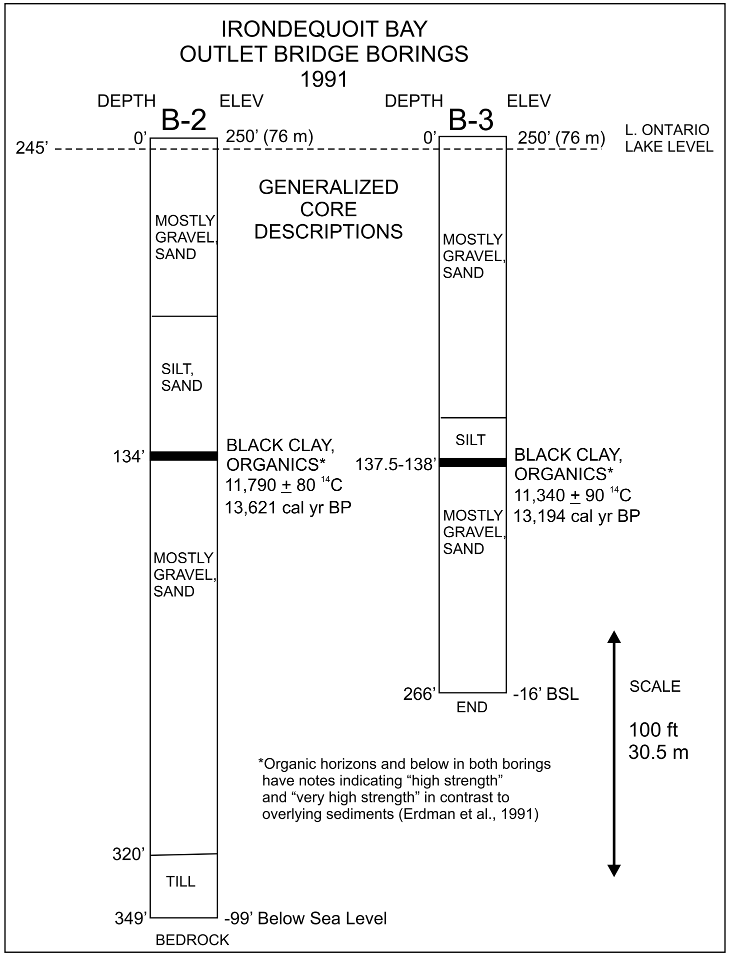


Figure 12. Generalized and simplified sedimentary sequence from boring logs in Irondequoit Bay test holes for new bridge to emphasize location and age of most prominent dense organic horizon and similar ^{14}C ages. Depths in feet as on original logs. Locations on Figure 13.

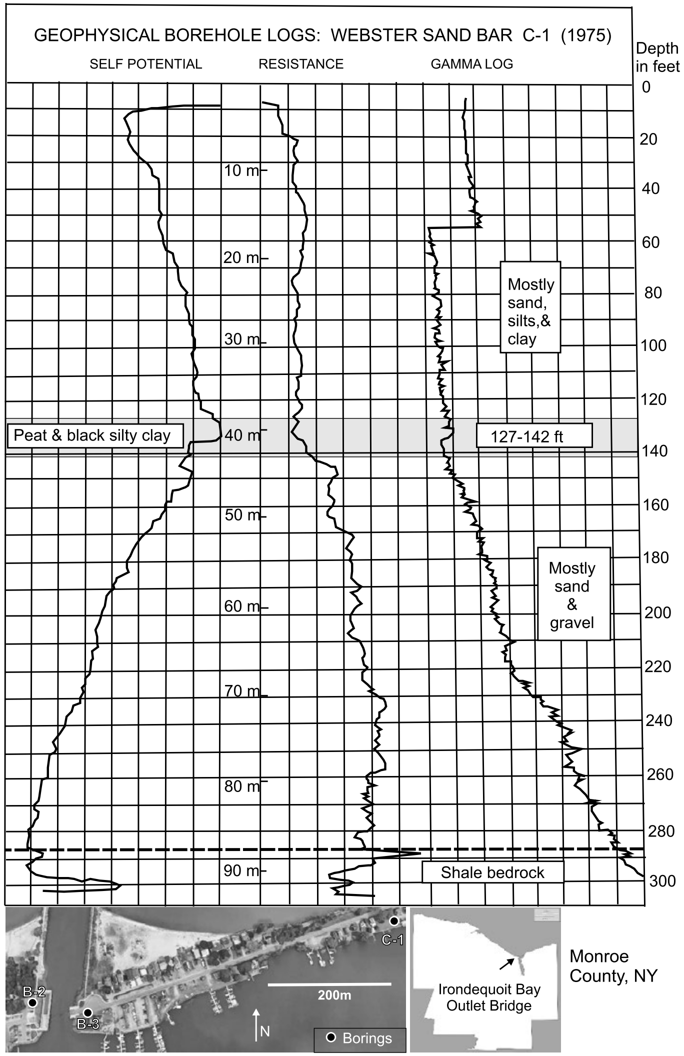


Figure 13. Irondequoit Bay 1991 boring locations (Fig. 12, B-2, B-3) and geophysical logs from representative 1975 boring (C-1) completed for study of aquifer potential of bay-mouth sandbar (Morrison, 1975). Drillers logs shown simplified here that denote "sand and gravel" as identified from drill cuttings could include till, especially at depths below organic horizon. Geophysical logs are traced directly from Morrison report and had no scale units other than depths.

a prominent organic horizon at depths between 40 and 41 m. R.A. Young collected organic-bearing, split-spoon samples on site from various depths. The thickest organic horizon provided similar calendar-corrected ages in the two borings of 13,621 and 13,194 cal yr B.P. (Fig. 12; Table 1, samples 39 and 40). Standard penetration resistance (N-values) more than doubled beginning at the top of the dated organic horizon and continued downward in both borings at equally high values (Erdman et al., 1991).

Several older borings completed during a 1975 aquifer investigation along the eastern arm of the same sand bar intercepted organic intervals at similar depths, between 38 and 43 m (Morrison, 1975). The same prominent organic horizon encountered in the 1975 borings clearly marks the beginning of an abrupt change in the logged geophysical properties, including self-potential, resistance, and gamma logs (Fig. 13), which are assumed to record an abrupt increase in density attributable to glacial compaction (Morrison, 1975).

The overlap of the two Irondequoit Bay bridge core sample ages with the many similar ages described in this study is unlikely to be coincidental. It is not obvious how this early Lake Ontario lacustrine(?) organic horizon is related genetically to the glacially linked samples with similar ages farther south in the Genesee Valley. Anderson and Lewis (2012) describe in detail the postglacial fall and rise of Lake Ontario, which experienced a precipitous drop in lake level of ~134 m between 13,500 and 13,000 cal yr B.P., followed by a gradual rise to its current level (age revised to 13,000 cal yr B.P. by Lewis and Anderson, 2020). Our theorized B-A/YD ice re-advance could have scoured organic-rich sediment from the Ontario lake floor and compacted the organic-rich sediment accumulated during the B-A ice-free interval. The apparent failure of the Erdman et al. (1991) engineering logs to specifically record identifiable till textures above this organic horizon in the Irondequoit Bay barrier bar borings, as well as the lower density of this overlying apparently "lacustrine" sequence at Rochester, could be explained by the rapid advance and retreat of an intermittently or partially grounded ice shelf during the B-A/YD event. This type of semi-floating, glacial ice-shelf advance might not produce a typical basal till texture that would be readily identifiable in small-diameter, split-spoon core samples. These findings also demonstrate that the ice during the B-A episode retreated north of the current Lake Ontario southern shoreline prior to the proposed B-A/YD advance (Dalton et al. 2020). Such a sequence of events also is consistent with the ice advance during the existence of Lake Iroquois as inferred by Calkin et al. (1982).

BUTTERMILK CREEK SITES, CATTARAUGUS COUNTY, NEW YORK

Local Interpretive Complications

The geologic studies of LaFleur (1979, 1980), Boothroyd et al. (1979), and Albanese et al. (1983, 1984) and references therein describe in extensive detail the Buttermilk Creek geology following the Kent advance (Fig. 1; Table 2) and based upon numerous detailed geologic and engineering reports prepared during evaluation of the NYSNSC and surrounding region (Fig. 14). However, these older studies were unable to establish an accurate ^{14}C chronology of glacial events. In addition to the extrapolated western New York glacial stratigraphy summarized previously, this section provides the details that are essential to an understanding of our revised interpretations, based on the extensive trench excavations in the Phase 1 Erosion Studies completed during field work in 2015 and 2016 (ECS, 2018). Table 2 provides a synopsis of the key historic literature references upon which the incomplete chronologic information was based prior to the ECS (2018) study. The basic stratigraphy following the Plum Point Interstadial includes the Kent, Lavery, and Hiram tills in ascending order along with their associated moraines as extrapolated from mapping in Ohio and Pennsylvania, and as presented on the New York maps of Muller (1977) and Cadwell (1988).

The predominant Kent and Lavery tills at the WNYNSC site are separated by a variable but maximum of 9 m of stratified outwash and lacustrine sediments presumed to represent the post-Kent recession leading into the Erie Interstade (LaFleur, 1980, p. 30). These undated interstadial sediments, which separate the two undated tills, are well exposed at a large active landslide on the left (west) bank of Buttermilk Creek (Fig. 15, LS). The stratified sediments include a mixed sequence of silty clays, sands, gravels, and proglacial lacustrine sediments; this sequence coarsens northward along the 200 m exposed width of the landslide. We (coauthors L.A. Owen and S. Huot) acquired two OSL ages from a sand bed within these sediments that provide an age range potentially extending from 14.5 k.y. to 20 k.y. (Table 3). This range closely parallels estimates by several researchers for the age of the Erie Interstade elsewhere in New York State. Our results indicate that the basic stratigraphic extrapolations of the Ohio and Pennsylvania stratigraphy eastward into New York are appropriate for this inferred interstadial interval. However, the post-Lavery history is more complex than previous studies imply, as described in this revised stratigraphic analysis.

There is uncertainty in the voluminous older WNYNSC geologic literature over whether the youngest Hiram(?) glacial advance as defined in Ohio and Pennsylvania actually extends into lower Buttermilk Creek, and whether the Defiance moraine (Fig. 14), immediately north of Cattaraugus Creek, marks its terminal position. The new data in our study complicate these issues insofar as it is unclear whether the B-A/YD ice advance proposed herein is a previously unrecognized and totally separate advance, or if it was confused previously with either the presumed Hiram till and/or the uppermost, slightly deformed sediments observed at the top of the Lavery till as described by LaFleur (1979). Albanese et al. (1983, 1984, p. 6) considered that Hiram(?) till might, in fact, overlie the Lavery till at the WNYNSC site. An additional issue is whether the Defiance moraine simply is part of the Lake Escarpment moraine system, which Muller (1977) equated with the Valley Heads moraine (Fig. 1), or part of a more complex event.

WNYNSC Kettle Site

The most informative area at the WNYNSC site excavated during the ECS (2018) study is a shallow glacial kettle adjacent to an abandoned postglacial

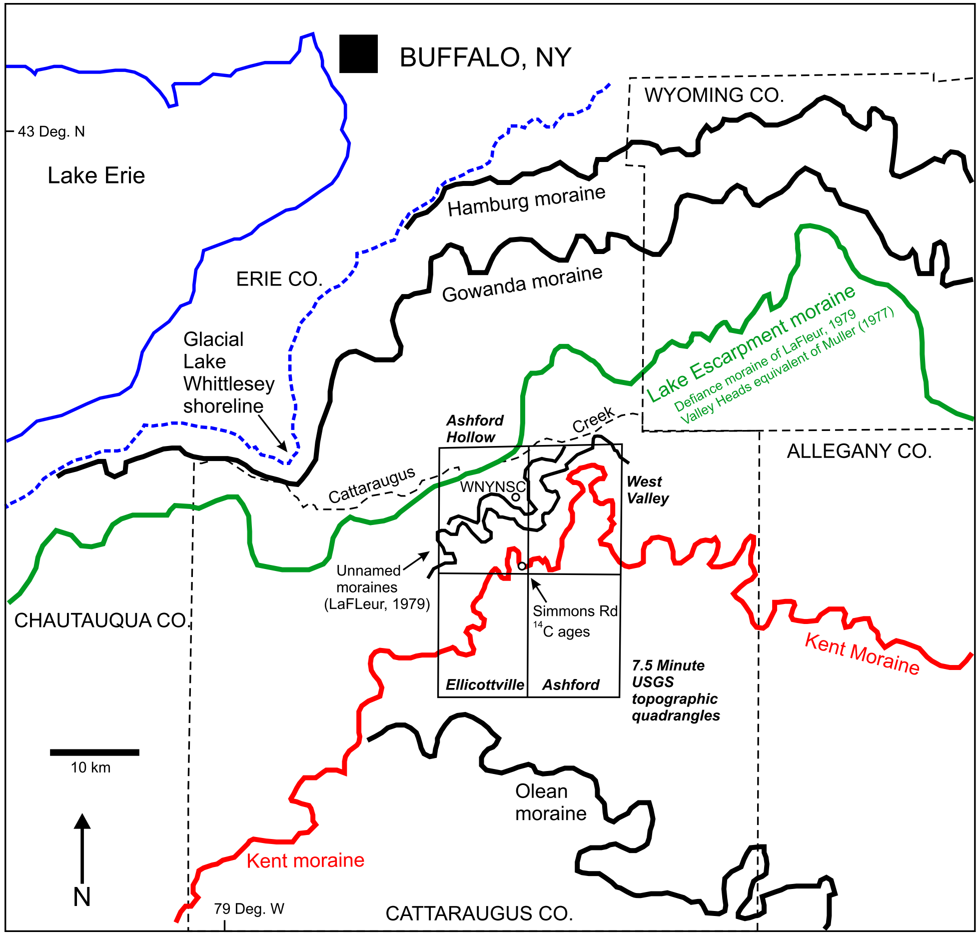


Figure 14. Solid black and colored lines are simplified locations of selected moraines near Western New York Nuclear Service Center (WNYNSC) and Simmons Road sites (small open circles) with names of 7.5 min geologic quadrangle maps by LaFleur (1979) in italics. Red and green moraine designations match moraines on Figure 1. For simplification, small black moraines on Ashford Hollow Quadrangle are two of several minor ice positions between Lake Escarpment and Kent moraines mapped by LaFleur (1979, 1980).

meander, referred to as the "racetrack," which is currently stranded 30 m above the modern Buttermilk Creek channel (Figs. 15, W; 16, M; and 17). The broad kettle depression in the glaciated surface abuts the southwestern margin of the younger meander (Fig. 16, K). The shallow depression fill consists mainly of clay-rich till containing discontinuous and irregularly shaped gravel pods or lenses and is covered by a thin postglacial bog with a semi-perched water table. The rim of the formerly enclosed glacial depression is breached by a headwardly eroding postglacial gully, which forms a small alluvial fan within the abandoned meander channel (Fig. 16F).

Gordon et al. (2013) originally obtained three ^{14}C ages (14,170; 14,155; 14,380 cal yr B.P.) from wood that they described as contained within "meltwater/backwater" sediments in the same glacial depression (Table 1, samples 6–8). The clay sediments first described by Gordon et al. (2013) also included undated "thin horizontal leaf mats." The more numerous trenches and test pits examined by Young and Wilson (ECS, 2018) labeled on Figures 15 and 16 encountered mainly clay-rich till and interbedded irregular pods of ice-contact gravels in the depression, except at pit, P4, where a large rotated clump of reworked varved sediments was encountered. Contiguous test pits P1 and P2 exposed a shallow, horizontal, organic-rich till layer, which contained noticeably compressed wood specimens, thoroughly impregnated with the enclosing clay till (Figs. 16 and 17).

Young and Wilson (ECS, 2018) submitted four wood samples from the shallow organic till layer (Fig. 17) in pits P1 and P2 that produced a range of ages from 13,462–14,192 cal yr B.P. A portion of one sample (Table 1, sample 1;

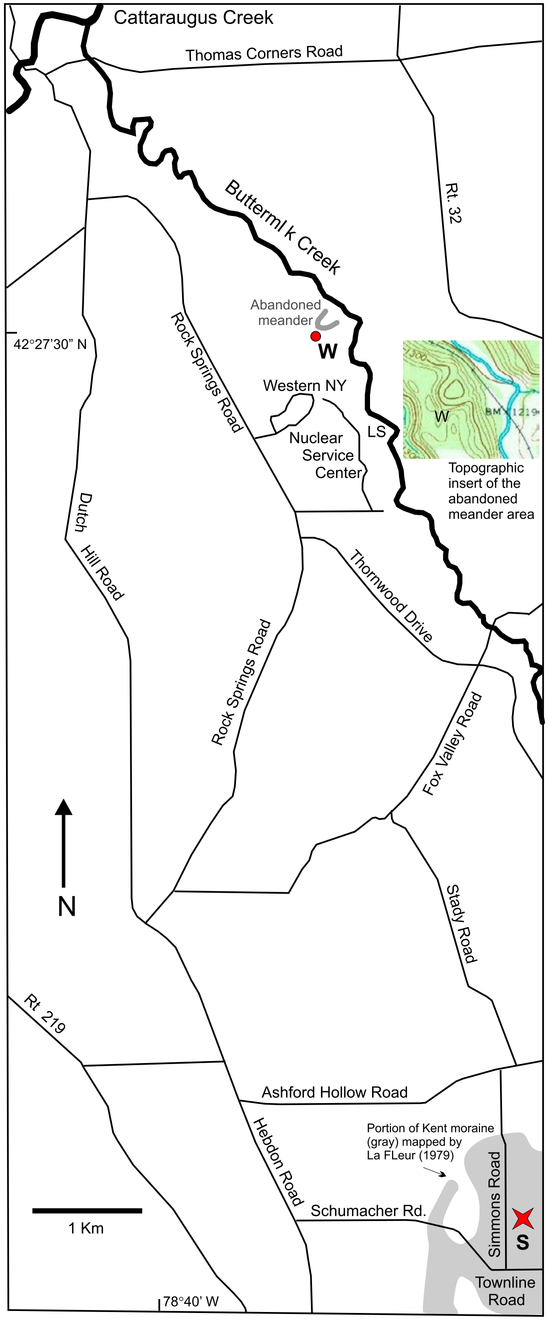


Figure 15. Expanded location map for Western New York Nuclear Service Center (WNYNSC) and Simmons Road sites. Gray pattern is mapped segment of older Kent moraine with star at location of Simmons Road trenches that exposed logs in till superimposed on older landform. LS = Active landslide exposing Erie Interstade sediments at WNYNSC site. W at red circle marks glacial kettle location at abandoned meander indicated by gray curve. Location of area relative to other sites shown on Figure 2.

Fig. 17D) was submitted to Carol Griggs at the Cornell University Tree-Ring Laboratory. Griggs identified the specimen as Larix laricina (tamarak or larch), "a species common to the boreal and northernmost temperate climatic zones, and one of the first tree species to return to this region following the retreat of the Laurentide Ice Sheet" (Griggs and Kromer, 2008; Griggs, 2016; Griggs et al., 2017). Griggs confirmed that thin sections of the wood show obvious signs of compression. An OSL age from a thin sand layer in the same till 60 cm below the wood-bearing layer in Pit 2, produced an age of 12.8 ± 1.2 k.y. (Table 3, minimum age model), which brackets the YD/B-A boundary, currently accepted as 12.9 k.y. (ECS, 2018, their appendix G, Meander Depression Pit 2; their appendix K, sample 454).

The older Gordon et al. (2013) excavation was located closer to the center of the glacial depression but contained organics at similar shallow depths of 0.5–1 m. The relatively soft, gray, clay-rich till exposed within depression pits P1 and P2 is saturated and is less compact than the more typical Kent and Lavery tills seen elsewhere at greater depths. If the proposed B-A/YD advance, including a partially grounded floating ice shelf, is correct, it appears that the Gordon et al. (2013) and the ECS (2018) observations regarding the kettle sediment origins are compatible. The sediments containing the wood and leaves described by Gordon et al. (2013) also appear to be a reworked (lacustrine-based) clay till deposited by the B-A/YD advance. Such an advance would have deformed and dragged a range of sedimentary proglacial materials and overridden B-A organics into the depression at the same time that loosely compacted saturated tills and ice contact gravels were being deposited unevenly beneath a semi-floating ice shelf. Several younger fluvial terraces near the abandoned meander are surfaced with postglacial fluvial gravels (ECS, 2018), which may account for a single younger age reported by Boothroyd et al. (1979) as described below.

Boothroyd et al. (1979) reported a single ^{14}C age of 9920 ± 240 yr B.P. on a wood fragment from a depth of 50 cm at an unspecified location near or within the same glacial depression, which they assumed to be a river terrace. Their relatively young ^{14}C age has three possible 2σ median calendar-corrected ages of 11,468, 12,291, or 12,356 cal yr B.P. The ^{14}C analysis by R. Pardee at Queen's College, which is cited in Boothroyd et al. (1979), is omitted from the Table 1 samples due to uncertainty with regard to the reliability of results from that source, as well as the fact that the favored (underlined) calendar-conversion age (Stuiver et al., 2018) is younger than the YD-Holocene boundary. It is likely this relatively younger wood sample came from a postglacial fluvial terrace. It could represent wood introduced during an early Holocene pre-meander

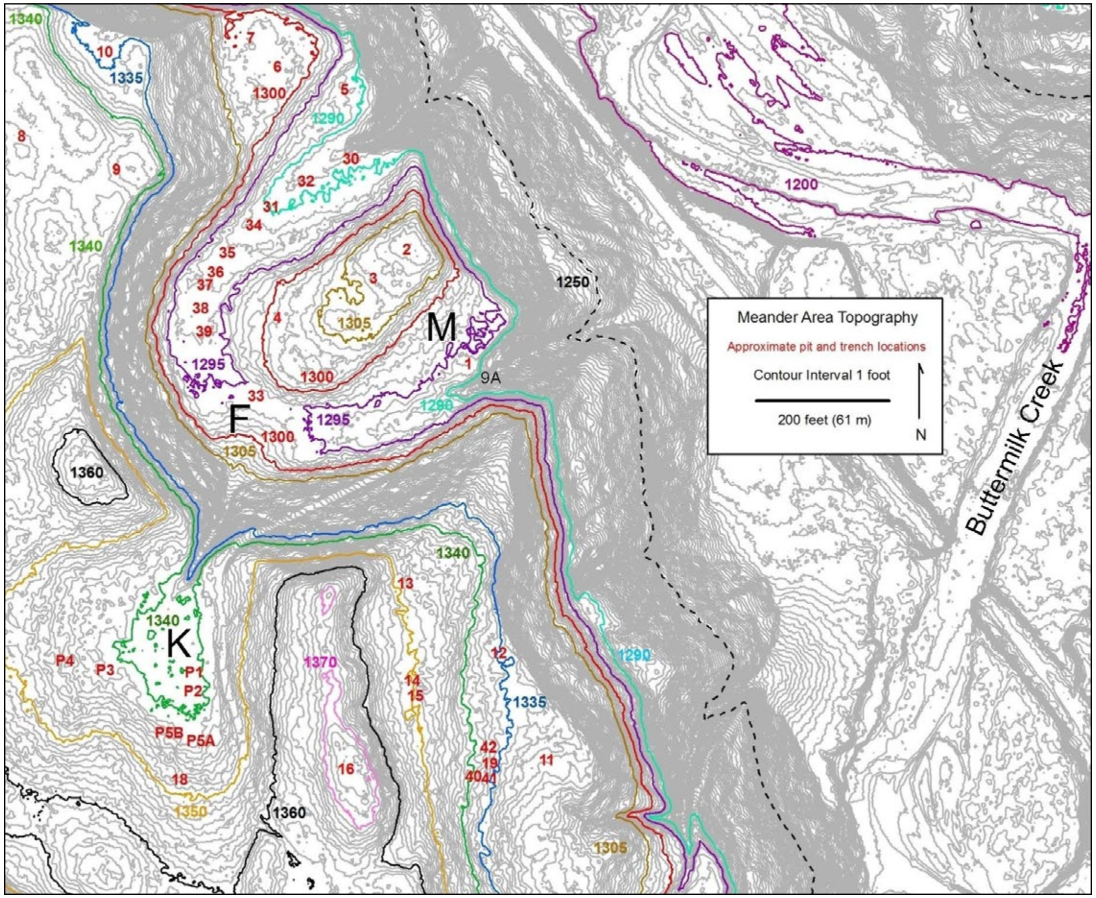


Figure 16. Light detection and ranging (Lidar) generated, 1-foot contour map of abandoned meander (M), alluvial fan (F), and glacial kettle (K) at Western New York Nuclear Service Center (WNYNSC) "racetrack" site (map units in ft as on original ECS study using U.S. Geological Survey standard topographic quadrangles). Selected 5-ft index contours are labeled in matching colors for clarity. Red numbers are pits (P#) or trenches (#1–44) completed for WNYNSC study (ECS, 2018). Important ^{14}C sample locations are pits P1 and P2 in glacial kettle immediately south of "K" as imaged on Figure 17.

flood-stage event along Buttermilk Creek or by a local tree fall before the adjacent meander channel became incised to its current elevation, which is currently 13.7 m below the floor of the adjacent kettle depression (Fig. 16). Partially buried tree falls are common in the modern bog.

The relict ancestral Buttermilk Creek meander (Figs. 15 and 16) was abandoned ca. 5600 cal yr B.P. (ECS, 2018) based on dated wood samples collected from postglacial fluvial gravels scattered throughout trench numbers 30–39 (Fig. 16) along the axis of the meander channel. The data obtained from all of the trenches shown on Figure 16 and along the modern floodplain document an irregular incision history for the modern Buttermilk Creek between ca. 13,000 cal yr B.P. and ca. 2500 cal yr B.P. (ECS, 2018, their figure 4.10-4 therein).

Overall, the 2018 ECS field studies and accompanying high-resolution, light detection and ranging (Lidar) imagery indicate that the detailed relief preserved on the uplands adjacent to Buttermilk Creek closely reflects the original glacial topography, modified to a limited degree by postglacial alluvial fans, numerous small slumps, and limited postglacial gullying. It appears that the thin surficial tills, such as those encountered in the kettle site at the abandoned meander, were deposited under atypical conditions, which resulted in thin, loosely consolidated clay tills, reworked varves, sand lenses, and irregularly shaped gravel pods being draped across the preexisting late glacial relief. A reasonable model for such heterogeneous deposition is a relatively thin, partially grounded, floating ice shelf. The clast-poor clay till probably was derived from clay-rich sediments deposited somewhat erratically in a contemporaneous or preexisting proglacial lake, then subsequently overridden and reworked into the existing heterogeneous glacial deposits, along with pockets of coarser basal debris sporadically released from the overriding ice.

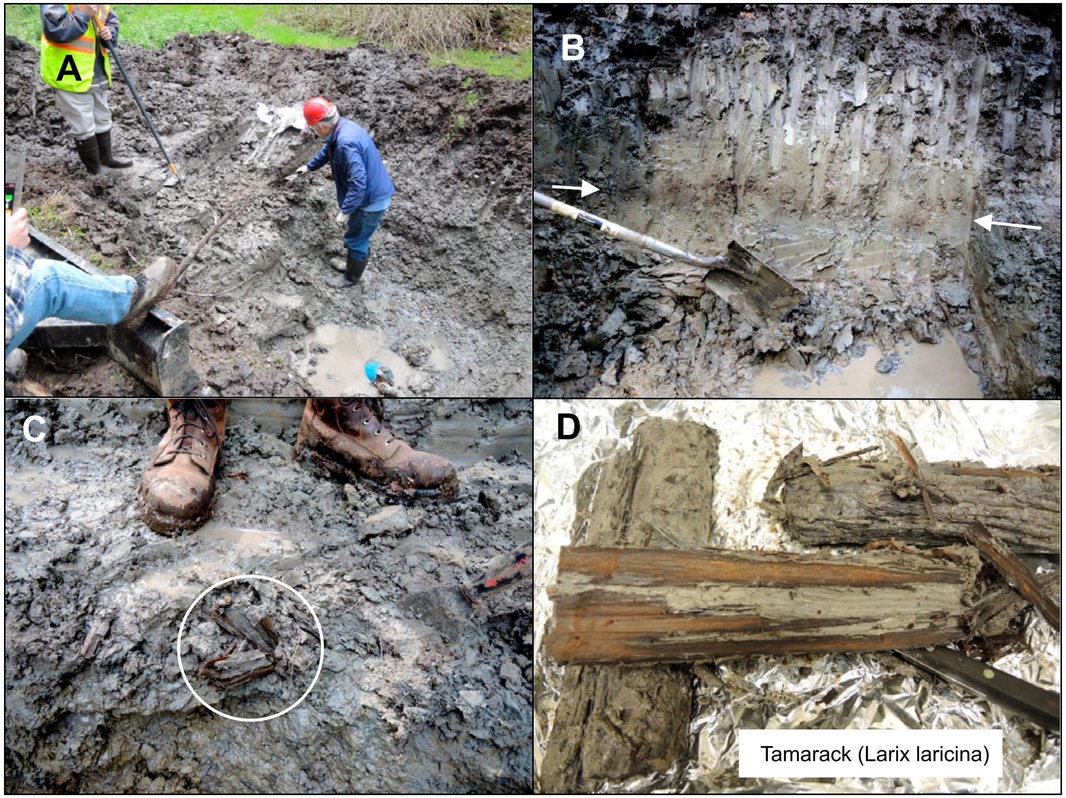


Figure 17. Kettle excavations at Pit 2 as located by number on Figure 16. (A) Removal of Tamarack wood samples onto aluminum foil. (B) Dark organic and wood layer in shallow clay-rich till zone between arrows. (C) Close-up of Tamarack wood fragments prior to removal from organic layer. (D) Compressed Tamarack wood specimens after splitting to show impregnation by clay extending through interior of samples due to inferred ice pressure. Knife handle is 1.5 cm wide.

The identification and dating of this thin, clast-poor clay till raises the obvious issue of whether it was originally mistaken elsewhere for part of a late-stage Lavery oscillatory advance, was lumped together with younger Hiram(?) deposits described by LaFleur (Table 2), or whether it simply was overlooked as a separate, younger unit as was speculated to be present at the WNYNSC site (LaFleur, 1979; Albanese et al., 1984). Given the relative lack of accurate age data at the time of the older studies, previous investigators presumably assumed that any textural deformation at the top of the Lavery till might be related either to a minor oscillatory Lavery re-advance or to the younger Hiram(?) event, presumably associated with the Defiance moraine. It is still unclear following the recent ECS project whether the B-A/YD advance, presumed to have occurred between 13,000 and 13,300 cal yr B.P., previously was confused with the locally inferred Hiram(?) event, or whether it is a distinctly different advance. It is not clear whether the Hiram till, as traced eastward into western New York from Ohio and Pennsylvania, was correctly identified at the WNYNSC site by previous investigators, using the terminology extrapolated from Pennsylvania and Ohio. If the Hiram till is present in the Cattaraugus Creek basin, does it also have the characteristics of a grounded ice-shelf event? Does the Defiance moraine north of Cattaraugus Creek simply mark a recessional phase of the Hiram advance, as opposed to being an end moraine formed at its furthest limit? It is clear that the B-A/YD event we have dated is definitely younger than the classic Lavery till. However, at present it appears to have an uncertain relationship to the presumed "Hiram" deposits as discussed briefly in the studies by LaFleur (1979, 1980) and by Albanese (1983, 1984).

Age of Erie Interstade Sediments at WNYNSC Landslide and Meander Sites

Verification of the Erie Interstade is critical to accurately identifying the overlying Lavery advance. The OSL ages on the two samples from a fine sand layer in the intertill sediments (Erie Interstadial) at the aforementioned landslide (Fig. 15, LS) were completed by two independent laboratories (coauthors Owen and Huot) following completion of the ECS (2018) study (Fig. 18; Table 3). The fluviolacustrine section sampled for OSL dating at the landslide fines upward (sands to silty clay), exhibits cross-bedding and localized liquefaction structures (Fig. 18), and has a conformable contact with the Kent till below. The stratigraphy suggests that the bulk of the interstadial sediment probably records deposition during ice withdrawal following the Kent advance, rather than during the subsequent Lavery advance. The OSL age (Table 3) measured at the University of Cincinnati (L.A. Owen, this study) ranges from 20.1 ± 1.3 k.y. (weighted mean) to 17.9 ± 1.2 k.y. (minimum age model), whereas the OSL age by the Illinois State Geological Survey (S. Huot, this study) on the same layer (Fig. 18B) ranges from 19.4 ± 1.2 k.y. (weighted mean) to 14.5 ± 1.5 k.y. (minimum age model). The overlapping ranges of the two measurements are consistent with an Erie Interstadial age, previously estimated to have occurred between 14.5 and 19.3 k.y. (Fullerton, 1980; Lewis et al., 1994; Ridge, 1997; Monaghan et al., 2016).

Additional OSL ages at the abandoned meander site were included in an older Final Environmental Impact Statement (USDOE, 2010). One of the OSL samples from that 2010 study (USDOE, 2010, their appendix F, Table F-3, sample 9A) is located on the northwest side of a prominent postglacial gully, which is eroding the southeast edge of the abandoned meander (Fig. 16 at 9A; Table 3). The 2010 OSL age ranged from 17.1 ± 1.39 k.y. (central age model) to 17.07 ± 1.1 k.y. (minimum age model). In the 2010 USDOE report, this sandy gravel sample in the gully wall apparently was assumed to be a fluvial deposit related to the abandoned meander, whose age was unknown at that time. The fact that the meander was abandoned ca. 5600 cal yr B.P. (ECS, 2018) precludes a genetic relationship of the sandy gully gravel as a postglacial fluvial deposit within the meander. The 2010 OSL gully site was reexamined during the ECS study in 2015, and a completely separate trench at a similar elevation was excavated within the meander channel a few meters northwest

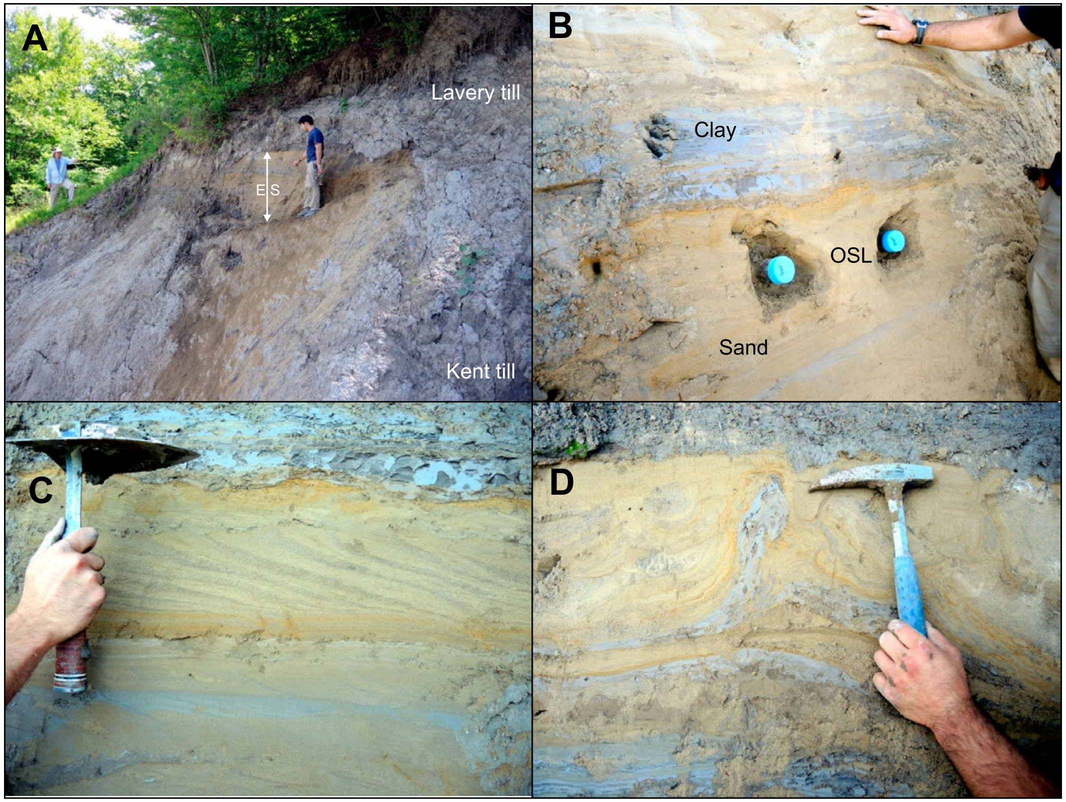


Figure 18. Landslide exposure along Buttermilk Creek near Western New York Nuclear Service Center (WNYNSC) (LS on Fig. 15). (A) Two-meter-thick interval (ES) of Erie Interstade fluvio-lacustrine sediments between Lavery and Kent tills located at person, ca. 15 m below original glaciated surface. (B) Optically stimulated luminescence (OSL) sampling tube locations (Table 3) in fine sands located between gray silty clay layers within interval ES. (C) Cross bedding in fine fluvial and/or lacustrine sands within interval ES. (D) Flame structures in ES suggesting penecontemporaneous fluidization deformation in lacustrine environment.

of the gully edge (Fig. 16, Trench 1). The older sediments exposed in the side of the postglacial gully at location 9A are more complexly stratified, thicker, and somewhat finer grained than the younger, relatively coarser, meander channel sediments encountered resting on till in the nearby meander Trench 1 exposure (ECS, 2018, their appendix C, Activity Notes for 11-17-15 and 11-18-15). The gravel-dominated sample from the new ECS channel trench was sufficiently coarse that the OSL sample was extracted by hand (not cored) in total darkness (Fig. 16, Trench 1). This coarser trench sample gave an age of 11.2 ± 0.8 k.y. (minimum age model) for gravel resting on till (Table 3; ECS, 2018, their appendix K), but an average age of 16 ± 3 k.y. (central age model). All these OSL ages are significantly older than either the apparent origin or the abandonment ages determined for the meander in the ECS (2018) report (p. 107, their figure ES-1 therein).

The postglacial erosion by the gully adjacent to the meander has exposed the same Erie Interstadial horizon as sampled at the nearby landslide (Table 3). The gully sediments represent an undisturbed outcrop of Erie Interstadial sediments, whereas nearby Trench 1 within the meander channel may be a mixture of younger meander channel deposits, which may include reworked Erie interstadial sediment. The till immediately below the meander gravel in Trench 1 has OSL central age model and minimum age model values of 22 ± 4 k.y. and 15.6 ± 1.6 k.y. (Table 3), which are reasonably consistent with Lavery till age estimates from the published literature (Table 2).

The Erie Interstade OSL samples at both the abandoned meander gully and at the landslide are located at comparable vertical distances below the preserved glaciated surface, allowing for the minor irregularities common to glacial topography. It is clear that the gully adjacent to the abandoned meander has exposed stratified sediments from the Erie Interstadial, rather than representing fluvial sediments associated with the demonstrably younger abandoned meander. Assuming the abandoned meander originally formed within the less compact Erie Interstadial sediments between the Lavery and Kent tills, the fortuitous location appears to have facilitated the ability of the evolving postglacial Buttermilk Creek to erode laterally more easily and thus create the singular meander preserved at the level of the less compact, sandy, interstadial horizon.

H.J. Gray of the U.S. Geological Survey reanalyzed several of the 2010 OSL ages near the meander from the older USDOE report (USDOE, 2010) by applying improvements in the statistical tools currently used to calculate OSL ages. Gray's reanalysis of 2010 gully sample 9A (Table 3) produced a slightly older OSL age ranging from 19.3 ± 0.9–19.1 ± 0.9 k.y., representing standard central and minimum age model calculations (ECS, 2018, their appendix L). Although older than our landslide age for the Erie Interstadial, Gray's (ECS, 2018, their appendix L therein) recalculated values still overlap the estimated older end of the Erie Interstadial proposed by the authors previously cited. A second OSL sand sample from the 2010 USDOE study acquired from the presumed interstadial sediments on the opposite (north) side of the abandoned meander provided a similar recalculated age ranging from 19.2 ± 0.7 k.y. to 18.6 ± 1.4 k.y. (USDOE, 2010, their appendix F, Table F-3, sample 8A).

The age of the Erie Interstadial (Erie Phase of Karrow et al., 2000) elsewhere in New York from the work of Ridge (1997) on the Shed Brook discontinuity near Little Falls is estimated to extend from 16,000–14,500 ^{14}C B.P., which translates to ca. 19,300–17,700 cal yr B.P. Thus it appears that the sediments between the Kent and Lavery tills at the WNYNSC do represent the Erie Interstadial as presumed by LaFleur (1979). The exact age of the Lavery advance is unclear. The next youngest well-documented ice advance is the Valley Heads event close to 16,900 cal yr B.P. (Ridge et al., 2012; Ridge, 2018), which is clearly younger than the Erie Interstadial. It is possible that the post-Kent, Lavery advance, which LaFleur (1979) mapped as ending with a prominent moraine a short distance south of the WNYNSC, may be closely related to the Valley Heads event, perhaps a related surge that sent ice lobes a bit farther south than the prominent moraine normally associated with the edge of the Valley Heads ice (Fig. 14).

Simmons Road Site

Three closely spaced trenches were excavated in slightly undulating morainal topography located 5 km south of the WNYNSC property boundary near the Buttermilk Creek headwaters on the east side of Simmons Road (ECS, 2018). The location is one that both Muller (1977) and LaFleur (1979) mapped as part of the older Late Wisconsin terminal Kent moraine (Figs. 14 and 15; Table 2). All three trenches encountered abundant log segments imbedded in clay-rich, clast-poor gray till that is overlain by 1–2 m of a massive heterogeneous layer of peat-bearing debris (Fig. 19). The "peat"-till contact varies from nearly horizontal to clearly irregular and interfingering within the three trenches (Figs. 19 and 20). Locally, the "peat," logs, and till are complexly comingled by obvious glacial deformation, which is best exposed in the easternmost Simmons Road trench (Figs. 19C and 19D). In the horizontal exposures at the westernmost trench (Figs. 19A and 19B), the main mass of the organic debris does not appear to be an orderly sequence of slowly accumulated, internally layered peat, such as would be expected in an isolated postglacial bog. It more closely resembles a relatively homogenized mass of well-macerated organic remains, including small wood fragments, randomly oriented broken twigs, and small intercalated stones (Fig. 20). The texture suggests reworking of the heterogeneous organic mass by glacial overriding. The organic mass is in direct horizontal contact with the logs imbedded in the top of the till (Fig. 19B), but the units are clearly interpenetrating (Fig. 20F). The lack of a more distinct contact or the presence of glacial outwash sediment between the till-enclosed logs and the overlying peaty debris implies no passage of time or meltwater event, such as might be indicated by stratified sediment from a typical recession prior to the establishment of vegetation and the gradual formation of a postglacial bog. One possibility would be glacial reworking of the organic mass from a thick floating vegetation mat upon draining of a proglacial lake associated with a partially grounded ice-shelf depositional model. Such a floating depositional model also is implied by the position of

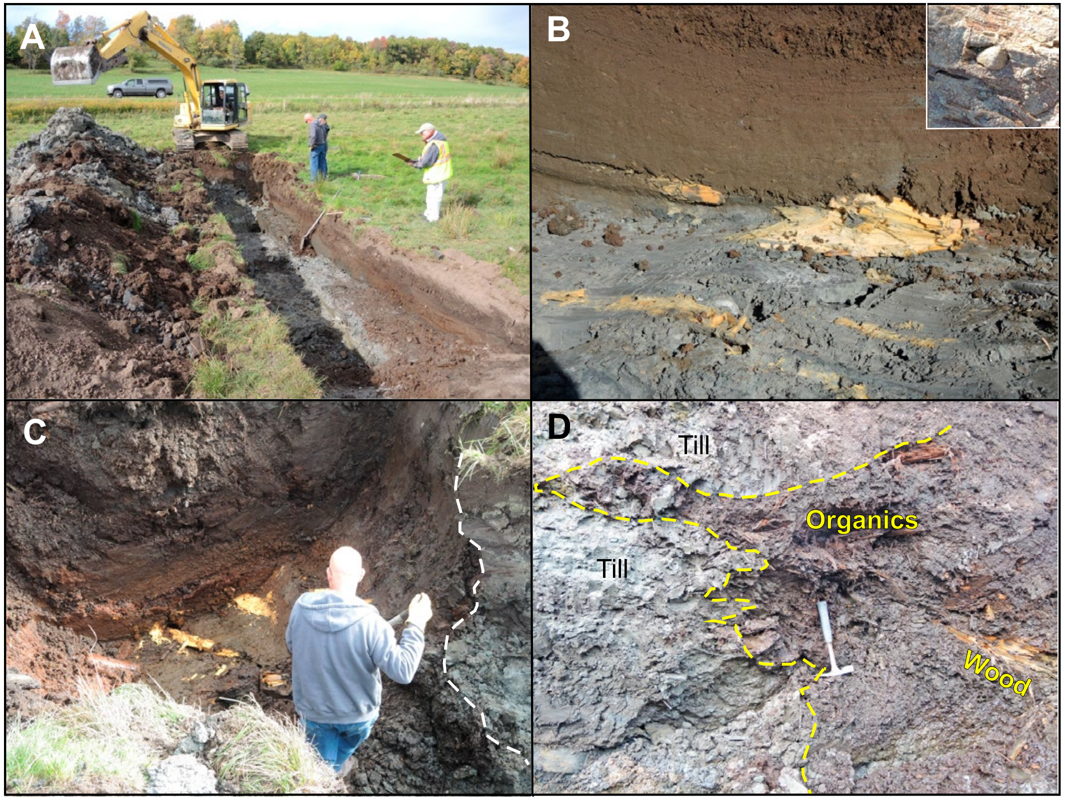


Figure 19. Simmons Road trench site. (A) Exposure of gray, clay-rich till beneath well-macerated organic debris indicative of ice reworking in westernmost trench (view looking west). (B) Tree fragments imbedded in top of till exposed in trench floor of A. Inset shows 2 cm stone impressed into log. (C) Tree fragments complexly intermingled in peaty groundmass at deeper level in separate trench located 60 m east of trench shown in A. Note abnormal near-vertical till-organic contact (white dashed line) to right of individual. (D) Lateral interfingering (dashed contact) of till and organic debris in vertical wall of second trench exposed in excavation directly behind individual standing in C; overall texture indicates complex glacial reworking.

the logs in the till that caps the Kent moraine in the westernmost trench at Simmons Road (Figs. 19A and 19B). The numerous logs in this trench are all imbedded at or immediately below the surface of the relatively soft, clay-rich till. In a partially grounded ice-shelf model, this could be explained as the result of semi-waterlogged (partially submerged) logs being pressed into the soft lacustrine-derived till during the intermittent grounding of the ice shelf as it temporarily dragged floating B-A debris onto the higher ground associated with the preexisting relief.

Seven log segments collected from the three trenches (Figs. 19 and 20) and one older pond excavation adjacent to the Simmons Road site produced calendar-corrected ages ranging from 12,955–14,438 cal yr B.P. (Table 1). The youngest 12,955 cal yr B.P. age (Table 1, sample 9) is less well documented than the other six, because that wood fragment was saved from the pond site excavated by the landowners several years earlier. It is unclear whether this wood sample was enclosed within the clay till as opposed to being located at or immediately above the organics/till contact. In either case, it is indicative of the potentially youngest age of the event, and it is close to the age of the two youngest peccary ages at the Linwood site (samples 32 and 33). This wood fragment, preserved from the older pond excavation, was several cm thick, and the sample submitted for dating was extracted from the unexposed interior.

The relatively unweathered, fragmented, log segments encased in till at the three trench exposures are uniformly stripped of bark, branches, and extended roots (Fig. 20). Some logs are impregnated with small stones from the pressure of the overriding ice (Figs. 19B [inset] and 20B), similar to logs at the Avon site. If the underlying Simmons Road morainal topography is essentially the product of the Kent advance, as mapped by Muller and by LaFleur (1979), the superposition of the clast-poor, log-bearing till and thick organic mat by a younger ice advance had a limited effect on the older landscape. The morphological expression of the Kent moraine is traceable for a long distance as described in the available literature and as depicted on the Muller (1977), LaFleur (1979, 1980), Cadwell (1988), and Braun (2011) maps. In further support

Figure 20. Additional Simmons Road Trench details. (A) Two-cm-diameter stones firmly impressed into butt end of fragmented log. (B) Stone deeply impressed into side of log fragment after till was washed off. (C) Root end of broken stump illustrating amputation of extended root ends and rapid oxidation (darkening) of exterior following brief exposure to atmosphere. (D) Naturally fragmented log as removed from trench with till scraped off to expose relatively unweathered interior. Splintered end (S) is condition as uncovered, not caused by excavation. Inset shows 1 cm oxidation front penetration (dark rind) of split log fragment after one day of exposure. (E) Irregular contact between organic debris and gray, wood-bearing till. Circles (broken stem fragments) and square (2.5 cm stone) highlight specific examples of the numerous disaggregated materials randomly strewn throughout organic debris. (F) Same contact as E, illustrating log fragment (W) completely enclosed in till below contact showing obvious diffuse interpenetration of organic debris and clay till near X.

of a floating ice shelf model, LaFleur (1979) states, "Overridden Kent kame deltas experienced only minor alteration from the partly buoyant Lavery ice and retained much of their original sedimentary structure and landform beneath the Lavery till." The clear record of younger glacially derived material spread over what is mapped as a Kent-age landform provides convincing evidence of the complexity of the glacial history, including a relatively young B-A/YD or early YD advance extending well south of Lake Erie, similar to the situation observed in the Genesee Valley with respect to Lake Ontario.

DISCUSSION OF RELATED ISSUES

The Bölling-Alleröd/Younger Dryas Boundary

The age of the YD cold interval (Fig. 21) is well defined by published studies (Carlson, 2013), especially the INTIMATE (Integration of Ice-core, Marine and Terrestrial records) event stratigraphy. The INTIMATE time scale uses a 20-year averaging method to define Dansgaard-Oeschger climatic events (stadials and interstadials) during the Wisconsin Stage for its entire 123 k.y. length (Svensson et al., 2008; Rasmussen et al., 2014). The YD interval is currently defined on the calendar-corrected INTIMATE time scale as extending from ca. 12,900–11,700 cal yr B.P. (actual INTIMATE interval: 12,896 ± 4–11,703 ± 4 cal yr B.P.). This 1200-year-long cold period was immediately preceded by the Bölling-Alleröd warm interval (Fig. 21), which lasted from ca. 14,700–12,900 cal yr B.P. (actual INTIMATE interval: 14,692 ± 4–12,896 ± 4 cal yr B.P.). Adolphi et al. (2017) improve some issues relating to the 14,700–14,000 cal yr B.P. interval of the B-A portion of the calibration curve. Numerous studies show that the Northern hemisphere atmospheric, oceanic, and Greenland ice-core records are in close agreement concerning the position of the YD and B-A intervals most relevant to this discussion (Brauer et al., 2014; Rasmussen et al., 2014). Thus, the 1200-year-long YD cold event was preceded by ~1800 years of warmer B-A temperatures accompanied by ice withdrawal from central and western New York. However, the irregular cooling trend at the end of the B-A warm interval includes a relatively sharp temperature decline near 13,300 cal yr B.P. (Fig. 21), immediately prior to the actual INTIMATE-defined B-A/YD boundary as determined in the Greenland ice cores (Rasmussen et al., 2014). The short cold event is designated as Greenland Interstadial 1b, abbreviated as "GI-1b." This short GI-1b episode between 13.3 and 13.1 cal k.y. is recognized by Ridge (2018) in the varve chronology of New England and is recorded in the Canadian Maritimes as the Killarney Oscillation (Levesque et al., 1993). Similar cool events are reported for Ireland (Van Asch et al., 2012) and for Scandinavia (Lohne et al., 2007; Mangerud et al., 2016).

Given these constraints, it follows that immediately preceding the newly proposed B-A/YD ice advance, there was a nearly 1800-year-long warm B-A recessional period, when forests, bogs, swamps, and floodplain environments had adequate time to develop in western New York. Therefore, any ice advance close to the B-A/YD boundary would incorporate logs from trees, both living and fallen, with B-A ages in the 14,676–13,130 cal yr B.P. range, as compiled on Table 1 (Fig. 21). If the glacial advance culminated between 13,300 and 13,000 cal yr B.P., but the B-A warm period did not end "officially" until ca. 12,900 cal yr B.P., the most obvious question is whether there is a reasonable case for a direct relationship between the slightly earlier sharp temperature decline (GI-1b) near the end of the B-A and our proposed B-A/YD advance.

It is tempting to associate the onset of the YD cold interval with our glacial advance as cause and effect. However, several Northern hemisphere studies describe discrepancies between the INTIMATE-defined onset of the YD and glacial advances that seem to support a relationship to the slightly older GI-1b event. Mangerud et al. (2016) report the Scandinavian ice sheet "re-advancing at 13.5–13.0 cal kyr." Lohne et al. (2007) conclude that the "so-called YD

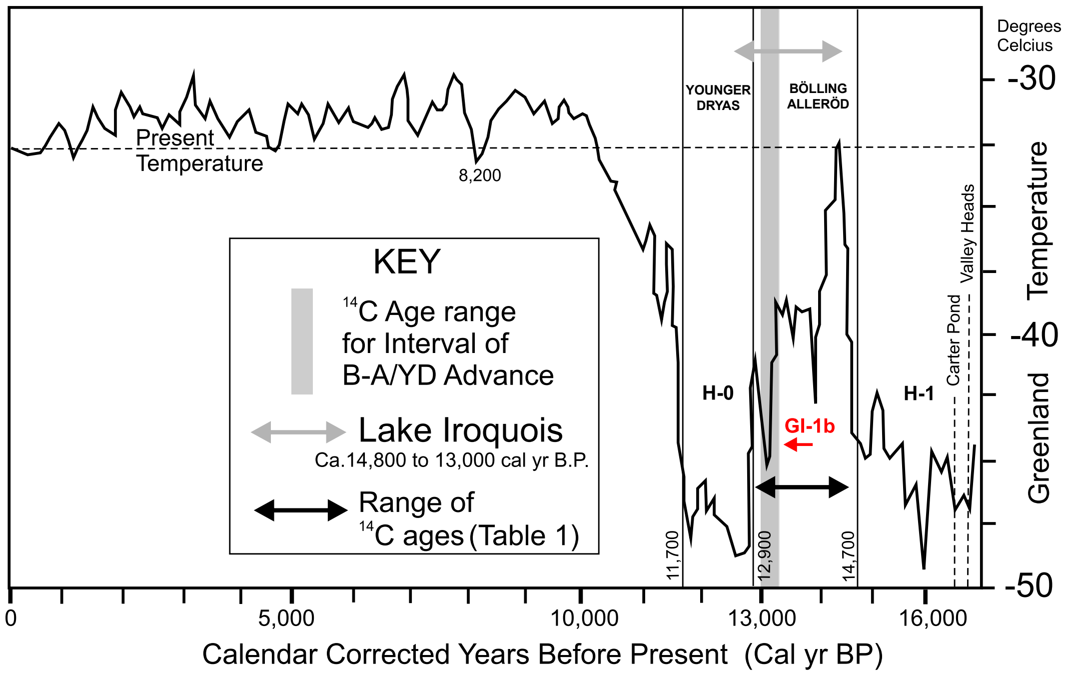


Figure 21. Bölling-Alleröd and Younger Dryas (B-A/YD) intervals modified from Williams and Farrigno (2012, figure 21 therein) with generalized Greenland paleotemperature curve and additional data as discussed in text from Rasmussen et al. (2014). Red GI-1b marks approximate location of Greenland Interstadial-1b cold interval of Killarney Oscillation in Canadian Maritimes (Levesque at al., 1993) that closely parallels the proposed timing of the B-A/YD event ca. 13.3–13.1 k.y. B.P.

ice-sheet advance in western Norway started during the Alleröd, possibly more than 600 years before the Alleröd/YD transition." van Asch et al. (2012) describe a cooling of similar age in Ireland. Levac et al. (2015) observe that "sea-surface and air temperatures started cooling 250 and 110 years before the start of the YD" in the northwest Atlantic. The lack of a more definitive match between the apparent ages of the New York ice advance and the INTIMATE-defined beginning of the YD cold period is consistent with these other studies. The simplest assumption would be that the somewhat erratic temperature decline into the YD cold period created conditions conducive to a short-term ice advance as the B-A warm interval declined.

Partially Grounded, Floating Ice-Sheet Model

The glacial history of the Buttermilk Creek region as mapped by LaFleur (1979, 1980) is based on the tentative extrapolation of moraines and associated till sheet ages from Ohio and Pennsylvania into New York as mapped by Muller (1977) and sources listed in the Table 2 references. LaFleur also mapped minor recessional moraine positions within the Buttermilk Creek basin as shown on Figure 14. The second (revised) edition of the Niagara Sheet of the Surficial Geologic Map of New York by Cadwell (1988) substitutes different local names for a couple of the landforms in Muller (1977), including the Kent moraine, which for unexplained reasons is relabeled locally by Cadwell (1988) as the Randolph moraine. There were no ^{14}C ages for the Lavery and Kent tills at that time within western New York. LaFleur's description of the Lavery advance makes clear that a younger floating ice-sheet model is physically plausible. LaFleur (1979) describes conditions during Lavery till deposition at the WNYNSC as follows:

> In Buttermilk Creek Valley, the pro-Lavery glacial lake was controlled by the summit of the Kent moraine, which is 1,710 ft in altitude. The top of the Lavery till now lies at an altitude of about 1,380 ft at the latitude of the waste-burial site, so the Lavery glacier must have been buoyed up by a hydrostatic head approaching 400 ft as it overrode a saturated and muddy substrate. It emplaced a stony, clayey, silt till with minor interbedded silty clay.
>
> During advance, the glacier sole seems to have periodically floated free from the substrate and allowed space for rapid accumulation of poorly bedded pebbly silt and clay. Regrounding of the ice on the lake floor and renewed movement could be responsible for the till deposition as well as the structural deformation observed throughout both till and lacustrine subunits. The overridden Kent kame deltas experienced only minor alteration from the partly buoyant Lavery ice and retained much of their original sedimentary structure and landform beneath the Lavery till. Disjointed lenses of badly deformed sand and fine gravel, exposed in trenches on the waste-burial site, are overlain by the uppermost 9 feet of Lavery till and might indicate a major ice withdrawal and readvance equivalent to the Defiance glaciation. However, there is no lithologic, textural, or weathering evidence to warrant separation of the uppermost till from the Lavery beneath. Withdrawal of Lavery ice from Buttermilk Creek Valley seems to have been rapid and accompanied by erosion by upland streams. (LaFleur, 1979, p. 7–9)

Had LaFleur the advantage of the numerous AMS radiocarbon ages available in Table 1, he probably would have drawn a different conclusion about whether there is "evidence to warrant separation of the uppermost till from the Lavery beneath." In other words, there was a younger B-A/YD and/or Hiram(?) ice advance culminating between 13,300 and 13,000 cal yr B.P. following the main phase of Lavery till deposition as proposed herein. LaFleur's comments about the overridden Kent landforms experiencing only minor alteration from the partly buoyant Lavery(?) ice support our observations concerning the apparent glacial overriding as far south as the Kent moraine, as mapped by Muller (1977) and by LaFleur (1979), at the Simmons Road site. These observations are consistent with the weakly compacted heterogeneous nature of the shallow till and gravel lenses excavated in Pits 1 and 2 at the WNYNSC abandoned meander kettle site (Fig. 16), as well as by the unusual textures exposed in the Simmons Road trenches. The Fowlerville moraine also is capped by reworked lacustrine till (Fig. 5).

LaFleur (1979) seemed convinced that the Defiance (Lake Escarpment or Valley Heads) advance, which was assumed to have produced the Hiram till, was not present as far south as the WNYNSC site proper. However, in the 1980 Friends of the Pleistocene fieldtrip guidebook, LaFleur (1980) recognized that the Hiram till was present south of Cattaraugus Creek in more westerly locations and stated, "Extending eastward along the south side of the Cattaraugus Valley are correlatives of the Lavery till and the overlying Hiram till, with its associated Defiance moraine" (LaFleur, 1980, p. 3). He further states that, "both the Lavery and the Hiram tills are thin, and the latter, in particular, is rich in clay presumed to have been derived from proglacial lake deposits." In LaFleur's 1979 report he states, "Lavery subfacies include a predominant stony, clayey silt till, minor deformed massive lacustrine clay and silt, and, in the uppermost Lavery only, fragments of overridden sandy pebble gravel and clay beds," and, "A lodgement mode of deposition beneath a periodically buoyant ice lobe advancing through a preglacial lake is proposed for the Lavery till." In addition, Albanese et al. (1984, their table 1 therein) list the youngest till unit as "Lavery (with overlying Defiance?) till" as occurring in the "NY State Licensed Area" of the WNYNSC. These slightly contrary interpretations suggest it was unclear to those individuals whether the Lavery or Hiram(?) till was the youngest unit at the WNYNSC, with an upper, deformed, clay-rich member, or whether various researchers were actually describing our unrecognized B-A/YD till, either of which may have been associated with a "periodically buoyant ice lobe."

Figure 22 depicts the topographically controlled position of the two glacial lake shorelines described and mapped by Fairchild (1904) for slightly older glacial Lakes Hall and Vanuxem. Fairchild mapped the Lake Hall shoreline as declining from an elevation of 1000 ft (305 m) to 900 ft (275 m above sea level) in the Genesee Valley, and Lake Vanuxem was slightly lower. The composite strand depicted for these two recessional shorelines in Figure 22 is a close match for the topographic setting that would likely develop as a partially grounded floating ice front advanced down the Genesee and Cattaraugus Valleys between 13,300 and 13,000 cal yr B.P. The locations of the major sites described herein, relative to this projected older shoreline, demonstrate that a short-lived advance, such as might accompany a partially grounded, floating ice-shelf model, would not involve an unrealistic spatial distribution of glacial deposits as indicated by the locations of the four major localities described in this discussion—Avon, Linwood, WNYNSC, and Simmons Road.

Further evidence for the timing of recession comes from two studies that provide bog bottom or basal organic ages that are compatible with our B-A/YD or GI-1b time frame. The well-documented Hiscock site (Laub, 2003) just north of the Batavia moraine (Fig. 1) has a basal organic age of 11,450 ± 50 yr B.P. ("$\delta^{13}C$ corrected" age) or 13,296 cal yr B.P., which is reasonably compatible with our 13,300–13,000 cal yr B.P. bracketed advance. The Hiscock site also has seven closely grouped ^{14}C ages from mastodon tusks (3) and bone collagen (4), whose oldest 2σ mean ages are 12,594 and 12,716 cal yr B.P. (2σ error 12,650–13,100 cal yr B.P.) (Boulanger and Lyman, 2014). The Devil's Bathtub kettle site 9 km south of Rochester (Clark et al., 1996) has a basal age of 11,230 ± 80 yr B.P. ("$\delta^{13}C$ adjusted" age) or 13,098 cal yr B.P., equally compatible with our proposed late glacial event. Thus, the general area was ice free ~300–400 years after our proposed youngest limit of the advance ca. 13,000 cal yr B.P.

Correlation with Upper Great Lakes Stratigraphy

The B-A warm episode in western New York, as documented by the wood ages in Table 1, is clearly time-equivalent with the range of wood ages from the classic Two Creeks buried forest of Wisconsin (McCartney and Mickelson, 1982; Kaiser, 1994; Panyushkina et al., 2008). Numerous studies have examined and re-dated wood from several additional Two Creek Forest Bed exposures in Wisconsin (Mickelson et al., 2007; Mickelson and Socha, 2017). The Two Creeks radiocarbon ages generally fall between 14,000 and 13,000 cal yr B.P., with a mean age close to 13,500 cal yr B.P. (Mickelson et al. 2007). Thirty-five of the relevant ages listed in Table 1 (14,676–12,917 cal yr B.P.) fall within the same officially designated B-A time interval (14,900–12,900 cal yr B.P.), with a median age close to that of the samples from the Two Creeks beds. Therefore, the youngest ice advance in the Buttermilk and Genesee Valleys was apparently synchronous with the post–Two Creeks forest advance of the Green Bay Lobe, currently designated as the Two Rivers advance, which reached its maximum extent shortly before 13,000 cal yr B.P. in Wisconsin (Mickelson and Socha, 2017).

Glacial Lakes Agassiz and Iroquois

There has been much discussion in the literature concerning the possible causes of the relatively sudden return to cold conditions during the YD interval (Fig. 21). The major arguments center around the effects of the drainage of Lake Agassiz on North Atlantic Deep Water (NADW) circulation, as well as speculation concerning a proposed impact event ca. 12,900 cal yr B.P. Controversy surrounds both types of hypotheses, especially with regard to the

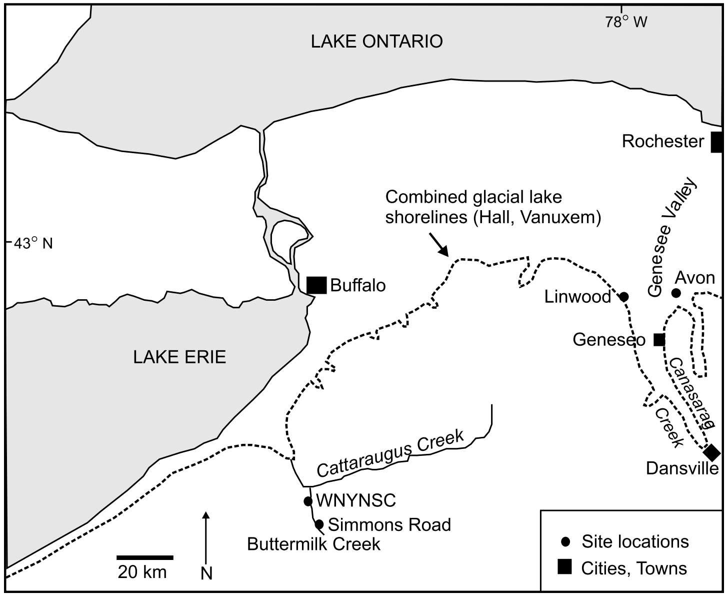


Figure 22. Dashed line is the approximate composite location of shorelines for glacial Lakes Hall and Vanuxem as traced by Fairchild (1904). This approximates the shoreline that would form during the proposed Bölling-Alleröd/Younger Dryas (B-A/YD) ice advance along Genesee Valley and Buttermilk Creek. The suggested topographic control is consistent with the apparent "simultaneous" occupation of the four key locations as marked and proposed in the partially grounded, ice-shelf model. WNYNSC—Western New York Nuclear Service Center.

poor matching of dating for the various types of evidence, such as ice margin positions (Larsen et al., 2016), the evidence for impact (van Hoesel et al., 2014), the range of ^{14}C ages of critical events, and the directions of Lake Agassiz discharge (Tarasov and Peltier, 2006). The impact hypothesis has been criticized by van Hoesel et al. (2014) and by Holliday et al. (2014), but Moore et al. (2020) recently describe convincing evidence for such an event.

The issues of the effects of changes in NADW circulation revolve largely around how Lake Agassiz drained during its demise—south via the Mississippi, east via the St. Lawrence, or north through the Arctic Ocean. Tarasov and Peltier (2006) make a lengthy and detailed case for Arctic drainage as the most important meltwater pathway. They point out that a large pulse of meltwater through the Gulf of St. Lawrence basin is in conflict with salinity data (de Vernal et al., 1996), which record reduced freshwater input during the YD. However, Levac et al. (2015) use more detailed data from the Laurentian Channel to refute the conclusions of de Vernal et al. (1996). Rayburn et al. (2011) discuss evidence for two closely spaced outflows through the St. Lawrence estuary near the beginning of the YD, estimated to have occurred between 13,200 and 12,900 cal yr B.P. Ages of invertebrate fossils indicate that freshening of the Champlain Sea occurred only after 10.5 k.y. (Rodrigues and Vilks, 1994).

Klotsko et al. (2019) document several major discharge events from sedimentary seismic profiles along the Beaufort margin of the Arctic Ocean between 13.0 and 11.3 k.y., which they associate with the YD interval. In addition, Condron and Winsor (2012) use a high-resolution circulation model to support the idea that meltwater discharge from the Arctic was more likely to be a greater factor in Atlantic Meridional Overturning Circulation (AMOC) than discharge from the St. Lawrence Valley. Alternatively, Leydet et al. (2018), relying on ^{10}Be surface exposure ages, propose that drainage switched from the St. Lawrence to a northwestern route partway through the YD at ca. 12.2 k.y. Gang Li and Piper (2015) provide evidence for the enhancement of the Labrador Current flow during Heinrich Event 1 and the YD, with the greater flow occurring during the YD event. They date the onset of the ocean current enhancement at ca. 13 cal k.y. B.P., which they point out preceded the enhanced ice-rafted deposition in Hudson Strait by about a thousand years. Breckenridge (2015) argues that neither the eastern nor the northwestern outlets for Lake Agassiz were ice free at the beginning of the YD. He concludes that although a northwestern outlet for Agassiz is more effective at weakening the AMOC, episodic and short-lived eastern drainage could explain the anomalous fluxes of freshwater in the Champlain Sea and St. Lawrence Estuary at the beginning of the YD.

Our evidence suggests the existence of a temporarily(?) ice-covered Lake Iroquois estimated to have culminated ca. 13,300–13,000 cal yr B.P. or slightly later and lasting for an unknown interval. Such a scenario could support the arguments of Tarasov and Peltier (2006), Condron and Winsor (2012), Breckenridge (2015), and Klotsko et al. (2019) that a major portion of discharge near the start of the YD was more likely to the Arctic Ocean and on to the Greenland-Iceland-Norwegian Seas. Alternatively, if the Lake Ontario basin (Lake Iroquois) was only temporarily ice covered during a brief, partially grounded ice-shelf advance, as suggested by our ^{14}C data, such an event might be relevant to an explanation of the apparent complexity in the St. Lawrence discharge history reported by various researchers. Such complexities would include the suggestion in Levac et al. (2015) that subglacial meltwater drainage (base flow) suggested by several researchers could help explain the lack of evidence for large floods and associated sedimentary deposits.

The occurrence of such a Late Wisconsin ice advance, extending southward across the positions of moraines previously considered to be older, presents issues regarding the mechanism of the advance and the apparent lack of significant modification of older landforms. Similar ice advances, which did not obliterate landforms created by older events, are reported from Pennsylvania and Ohio (Totten, 1969; Fleeger, 2005). Sharpe and Russell (2016) describe the sedimentary evidence in the Halton till, which laps onto the Oak ridges moraine near Toronto and supports the presence of a "subglacial lake with a floating ice lid over Lake Ontario and grounded ice along the basin margin" at some indeterminate time after ca. 16,000 cal yr B.P. (Sookhan et al., 2018). Hardy (1977) describes conditions along the southeast margin of the Laurentian ice cap in the James Bay lowlands of Canada during the Cochrane advances where till was sporadically deposited by a partially grounded floating ice shelf that extended more than 100 km into glacial Lake Ojibway, a potential eastern extension of Lake Agassiz (Roy et al., 2015). Livingstone et al. (2013) analyze the mechanisms that relate to subglacial drainage and show the likely distribution of glacial ice underlain by significant meltwater with the southern margin of Lake Ontario shown as the prime location for such subglacial lakes in striking contrast to the other Great Lakes.

CONCLUSIONS

The 34 best documented calendar-corrected radiocarbon ages on wood supporting a regional ice advance and recession stretching from the Genesee Valley westward to the Buttermilk Creek basin fall between 14,438 and 12,955 cal yr B.P. (Table 1, omitting samples 23, 28, 32, 33, 35, and 38). This is consistent with a previously unrecognized regional ice advance culminating sometime between 13,300 and 13,000 cal yr B.P. or possibly slightly younger, as best constrained by the measurement uncertainties, the stratigraphic evidence, and the record of decreasing ages descending toward 13,000 cal yr B.P. in the Genesee Valley and Buttermilk Creek localities (Table 1). The precise length of time occupied by the advance and subsequent recession is unknown. The overall event might have culminated a couple of hundred years more recently than 13,000 cal yr B.P., if the 2σ standard deviation ranges are included. A rapid glacial retreat might involve a sudden breakup and disintegration in place, given an ice-shelf scenario, as opposed to the typically assumed slow back wasting of a terrestrially grounded ice sheet associated with more conventional basal till deposition. Several ages near the bases of two bogs in the region provide a reasonable calendar-corrected mean approximation for the time of local plant and animal recovery in the range between 12,600 and 13,100 cal yr B.P. (using 2σ limits).

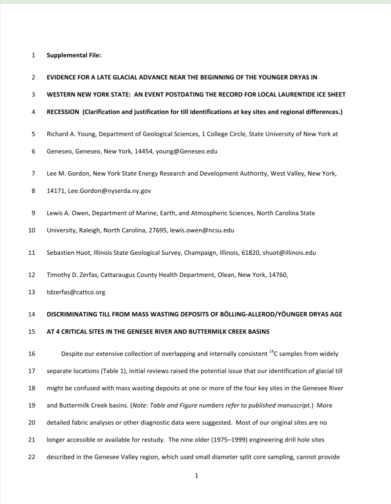
Assuming the ice advance across the B-A "interstadial" landscape reached its southernmost position close to 13,000 cal yr B.P., it is understandable why a mixture of log samples as much as 1400 years older than this limit is included within the tills and lacustrine deposits at three of the four major surface sites discussed herein. The evidence supports an ice advance through a recessional forest of B-A age that would have incorporated and mixed living trees with the remains of slightly older buried debris scoured from contemporaneous forest, bogs, and floodplain deposits.

Regardless of whether a floating ice shelf is the most credible model, as described by several geologists for similar settings in the region, the evidence for such a widespread Late Wisconsin event in western New York is compelling, given the number and distribution of well-preserved and relatively unweathered wood samples and their decreasing ages approaching the B-A/YD boundary. Whether it is designated as a YD-triggered event or a B-A/YD boundary event corresponding to the slightly older Greenland Interstadial (GI-1b) is unresolved, given the scattering of a few ages close to the YD boundary, and the likelihood that the very youngest trees in the B-A forest were not sampled at any of the wood-bearing sites in our study (Table 1). The compelling evidence for the young age of the advance has some unresolved implications, and obvious limitations, for current views of glacial Lake Iroquois and Lake Agassiz histories. The agreement between the ages of the New York glacial advance and the Two Rivers event in Wisconsin is obviously relevant to reexamining and improving the reconstruction of the Late Wisconsin history throughout the broader Great Lakes region.

ACKNOWLEDGMENTS

Numerous individuals were tangentially involved in the diverse ECS (2018) studies at the WNYNSC site between 2014 and 2016. The main scientists who comprised the formal ECS "Erosion Working Group" for the various components of the project are (alphabetically): Sean J. Bennett (SUNY, Buffalo), Sandra G. Doty (Consulting Geological Engineer), Robert H. Fakundiny (New York State Geologist, Emeritus), Gregory E. Tucker (University of Colorado), Michael P. Wilson (SUNY Fredonia, Emeritus), and Richard A. Young (SUNY Geneseo, Emeritus). Geology student and field assistants for Young and Wilson during the onsite fieldwork were: David Butzer, Alex de Silva, Zakkary Hess, and Eraklis Hristodoulou. Timothy Zerfas doubled as senior geologic field assistant and ECS staff member for miscellaneous logistics and offsite excavations. M.P. Wilson shared jointly in the collection of ^{14}C samples and stratigraphic analysis at the WNYNSC site. Contributions of the other Erosion Working Group scientists to the companion studies are detailed in the final report (ECS, 2018). Appreciation is extended to Michael Wolff, ECS Study Area Manager, and Daniel Feldman, who served as the ECS onsite logistics manager. Acknowledgment is extended to John Ridge, Andrew Kozlowski, William Kappel, Shanaka de Silva and two anonymous reviewers for critical reviews of submitted drafts of the manuscript. Michael Lewis and Serge Occhietti provided useful suggestions during preparation of earlier drafts.

An extended discussion relating to the identification of glacial tills at the critical sites in this investigation is provided as a Supplemental File[1] to eliminate any concerns that the exposures might be landslide debris as opposed to primary glacial till. The supplement also speculates as to why the advance in western New York State may not have been obvious in the extensive research published for the St. Lawrence Valley.


Supplemental File:

EVIDENCE FOR A LATE GLACIAL ADVANCE NEAR THE BEGINNING OF THE YOUNGER DRYAS IN WESTERN NEW YORK STATE: AN EVENT POSTDATING THE RECORD FOR LOCAL LAURENTIDE ICE SHEET RECESSION (Clarification and justification for till identifications at key sites and regional differences.)

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DISCRIMINATING TILL FROM MASS WASTING DEPOSITS OF BÖLLING-ALLEROD/YÖUNGER DRYAS AGE AT 4 CRITICAL SITES IN THE GENESEE RIVER AND BUTTERMILK CREEK BASINS

Despite our extensive collection of overlapping and internally consistent ^{14}C samples from widely separate locations (Table 1), initial reviews raised the potential issue that our identification of glacial till might be confused with mass wasting deposits at one or more of the four key sites in the Genesee River and Buttermilk Creek basins. (*Note: Table and Figure numbers refer to published manuscript.*) More detailed fabric analyses or other diagnostic data were suggested. Most of our original sites are no longer accessible or available for restudy. The nine older (1975–1999) engineering drill hole sites described in the Genesee Valley region, which used small diameter split core sampling, cannot provide

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[1]Supplemental Material. Extended discussion relating to the identification of glacial tills at the critical sites in this investigation. Please visit https://doi.org/10.1130/GEOS.S.13011614 to access the supplemental material, and contact editing@geosociety.org with any questions.

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