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Athens Subepisode (Wisconsin Episode) non-glacial and older glacial sediments in the subsurface of southwestern Michigan, USA

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ABSTRACT

We describe the first complete sediment core to bedrock in southwestern Michigan of a radiocarbon defined sequence of Michigan Subepisode (Marine Oxygen Isotope Stage [MIS] 2) glacial sediments, Athens Subepisode (MIS 3) non-glacial sediments, and two older tills using sedimentological, lithological, and radiocarbon analyses. Organics from Athens Subepisode lacustrine and palustrine sediments yield radiocarbon ages of 41,920–42,950 and 43,630–45,340, and >43,500 ^{14}C yr BP. We propose the name Port Sheldon Formation for these organic-bearing sediments. We interpret the underlying diamictons as two basal tills separated by glaciolacustrine fines. The youngest till (Hemlock Crossing till) lying below the Port Sheldon Formation is a dark gray, gravel-poor clay loam to loam with a mean kaolinite–illite ratio of 0.98 ± 0.04. The oldest till (Glenn Shores till) is a dark grayish brown, gravel-rich, clay loam to sandy loam with mean kaolinite–illite ratio of 1.22 ± 0.08. About 130 water-well records demonstrate that organic sediments and underlying diamictons are common in the subsurface of Ottawa County. These tills are likely Illinois Episode (MIS 6) or older, but an Ontario Subepisode (MIS 4) age cannot be ruled out. Deep bedrock basins in Lower Michigan provide an untapped archive of pre-Michigan Subepisode history.

Introduction

The Great Lakes region of North America contains one of the thickest terrestrial glacial archives in the world, with areas in Lower Michigan covered by >300 m of diamicton, gravel, sand, and fines (Soller, 1998; Kehew et al., 2012). Of this, only Michigan Subepisode glacial sediments (Wisconsin Episode), or Marine Oxygen Isotope Stage (MIS) 2, have been described in detail (Larson, 2011), even though it has been known for some time that older sediments are present in the subsurface (Leverett and Taylor, 1915; Zumberge and Benninghoff, 1969; Farrand and Eschman, 1974; Kapp, 1978; Eschman, 1980; Rieck and Winters, 1980, 1982; Eschman and Mickelson, 1986; Monaghan et al., 1986; Winters and Rieck, 1991).

Terrestrial records of glaciation are critical because they provide a direct record of former ice sheets. A dated terrestrial record is needed to calibrate and test coupled climate-ice sheet models of ice extent and volume (Clark et al., 1993). Ice-sheet reconstructions are needed for defining sea levels derived from marine oxygen isotope records (Clark et al., 2009; Hughes et al., 2013). Despite this, relatively little is known about pre-Michigan Subepisode events (>30 ka) in the Great Lakes, a key region in reconstructing the Laurentide ice sheet and its earlier incarnations.

Here, we describe a complete core to bedrock of a radiocarbon-dated sequence containing Michigan Subepisode, Athens Subepisode, and older sediments. We show that below the Michigan Subepisode tills are Athens Subepisode non-glacial sands and organic silts, which in turn overlie older tills. We then document the distribution and lateral continuity of the organic unit and underlying till in the subsurface of Ottawa County, Michigan and demonstrate that they are common and laterally continuous. Finally, we argue that the two tills underlying the organic unit were likely deposited during the Illinois Episode (MIS 6) or pre-Illinois Episodes, although we cannot eliminate an Ontario Subepisode age (MIS 4).

Regional geologic and geomorphic setting

Rovey and Balco (2010) provide evidence for ice-sheet advance into northern Missouri, south of the Great Lakes by 2.47 ± 0.19 Ma, based on cosmogenic radionuclide burial dating methods. Roy et al. (2004) provide evidence for at least seven pre-Illinoian glaciations just southwest of the Great Lakes. In Wisconsin and Illinois, at least four glaciations are recorded, with the oldest occurring before ~0.78 Ma (Eschman and Mickelson, 1986; Syverson and Colgan, 2004, 2011; Curry et al., 2011). Based on these studies, Michigan was probably glaciated multiple times during the Quaternary.

In Lower Michigan (Fig. 1), glacial sediments cover the land surface except in a few small areas of exposed bedrock (Soller, 1998; Larson, 2011; Kehew et al., 2012; MDEQ, 2015). Sediments older than Michigan Subepisode are not exposed at the surface as in adjoining states of Wisconsin, Illinois, and Indiana where ice sheets extended farther

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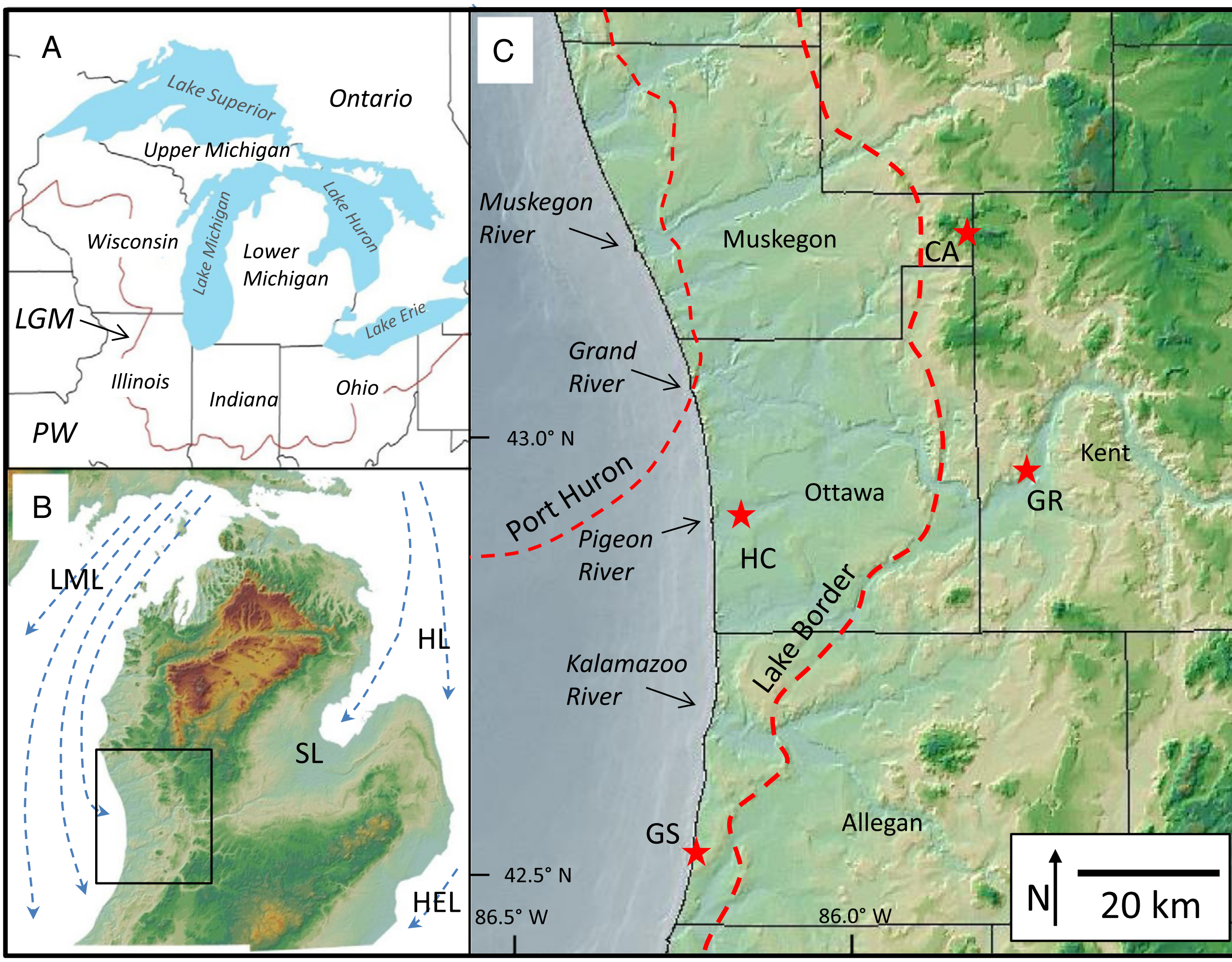

Figure 1. A. The western Great Lakes region of the United States. LGM — Approximate last glacial maximum limit. pW — Areas covered by pre-Wisconsin Episode glaciations. B. Lower Michigan and major ice lobes during the Michigan Subepisode (MIS 2) deglaciation. LML — Lake Michigan lobe, SL — Saginaw lobe, HL — Huron lobe, HEL — Huron-Erie Lobe. Black square outline is location of Fig. 1C. C. Location of study area Ottawa County, Michigan and important glacial sections mentioned in the text. HC — Core OT-12-01 located at Hemlock Crossing County Park, Ottawa County. GS — Type section for named tills in southwestern Michigan at Glenn Shores, Michigan (Monaghan et al., 1986). GR — John Ball Park Section at Grand Rapids, Michigan (Zumberge and Benninghoff, 1969). CA — Water well with Athens Subepisode organics at Casnovia, Michigan (Kapp, 1978).

south and west during older glaciations (Fig. 1). The Laurentide ice sheet reached its last glacial maximum position between 33.0 and 26.5 ka, and began its retreat by 24 to 19 ka (Clark et al., 2009; Curry et al., 2011, 2014; Hughes et al., 2013; Ullman et al., 2015). As in the last deglaciation, Michigan was a center of deposition during older deglaciations because of its low elevation, north of the drainage divide between the Great Lakes and Mississippi River drainages (Larson and Schaetzl, 2001).

Quaternary sediments in Ottawa County, Michigan are underlain by late Mississippian sedimentary rocks, which dip at low angle to the northeast (Fig. 2). The bedrock surface slopes to the northwest. The overlying Quaternary sediments range from 20 to >100 m in thickness. Bedrock is shallowest in the Grand River Valley where sediment and bedrock were eroded during glacial lake outburst floods that cut the valley during deglaciation (Bretz, 1953; Kehew, 1993). Dominant landforms are till plains, end moraines, outwash valley trains, lake plains and lake deltas, modified and overlain by Holocene aeolian and fluvial sediments (Fig. 2). Till plains and end moraines are of the Lake Border system (Leverett and Taylor, 1915). Two Lake Border ridges are present and were deposited between 18.2 and 16.8 ka during the Crown Point Phase (Curry et al., 2011, 2014; Larson, 2011). The low-relief topography in western Ottawa County is a relict lacustrine plain that was formed by Glacial Lake Chicago after retreat of the Lake Michigan lobe. The Allendale and Zeeland deltas (Leverett and Taylor, 1915) are graded to this surface and mark the highest water levels of Glacial Lake Chicago. Inland and coastal aeolian dunes modified and overprinted the lacustrine surface since deglaciation (Hansen et al., 2003, 2006).

Wisconsin and pre-Wisconsin Episode stratigraphy of Lower Michigan

We employ a diachronic classification for the Great Lakes region when discussing the event stratigraphy of Lower Michigan (Johnson et al., 1997; Karrow et al., 2000). We adopt the term Athens Subepisode for MIS 3 non-glacial sediments and organics in southwestern Michigan. This is because our area was dominated by the Lake Michigan lobe and is part of the western Great Lakes, which includes central Illinois, the type area for the Athens Subepisode. The material referents for the Athens Subepisode are bounded on top by Michigan Subepisode tills and by the Sangamon Geosol below (Hansel and Johnson, 1996; Johnson et al., 1997).

Lithostratigraphic units in Lower Michigan are informal and limited to the Michigan Subepisode, except for the Glenn Shores till of southwestern Michigan (Monaghan et al., 1986). Michigan Subepisode tills deposited by the Lake Michigan lobe are the Ganges and Saugatuck tills described at coastal exposures near Glenn Shores, Michigan and from inland pits and surface exposures (Monaghan et al., 1986; Larson and Monaghan, 1988). The older Glenn Shores till underlies an organic-rich silt and sand. Seven radiocarbon ages between 37,150 ±

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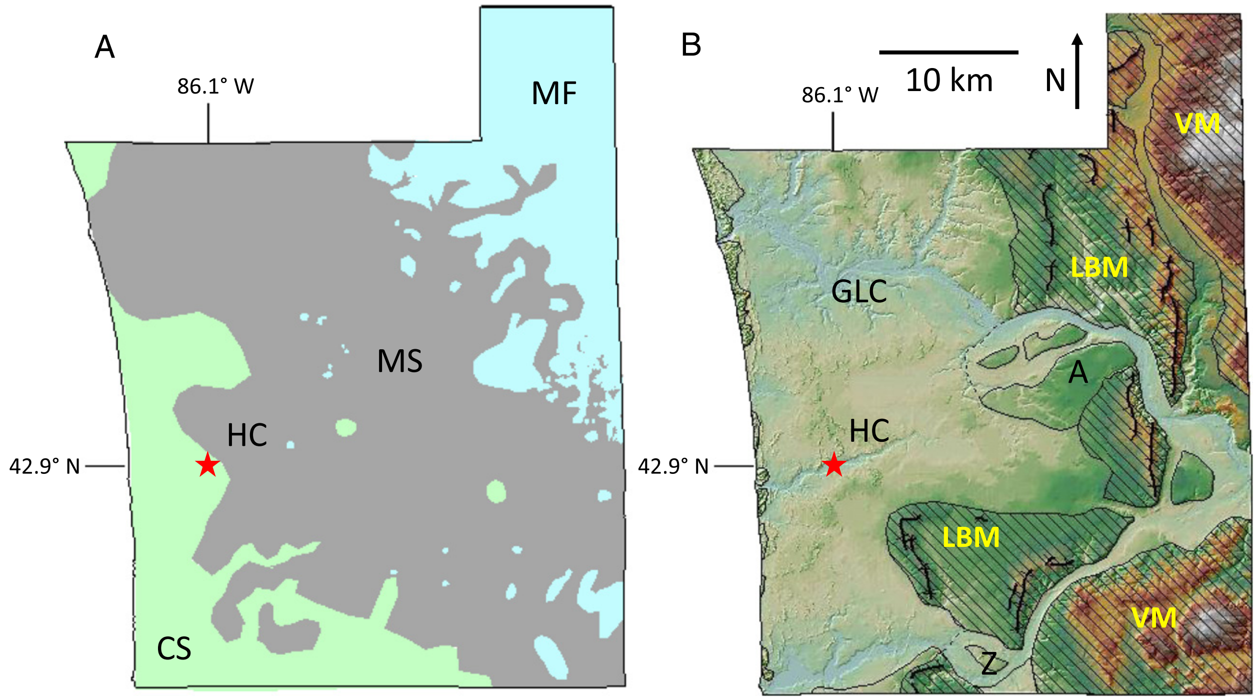

Figure 2. Surface geomorphology and subsurface geology of Ottawa County, Michigan. A. Bedrock units in Ottawa County, CS — Coldwater Shale, MS — Marshall Sandstone, MF — Michigan Formation. HC — Hemlock Crossing Park core site. B. Principle landforms of Ottawa County. GLC — Relict lake plain of Glacial Lake Chicago. Most of this surface is covered with a sheet of aeolian sand as well as inland dunes. LBM — Lake Border moraine system ground moraine and moraine ridges. VM — Area traditionally mapped as the Valparaiso moraine system, the area is actually a complex upland of ground moraine and isolated areas of drumlinized ground moraine (Kehew et al., 2005). A — Allendale delta and Z — Zeeland delta (Leverett and Taylor, 1915). Location of core site is 42.91531°N/86.14762°W.

540 and 64,500 ± 1000 ^{14}C yr BP were obtained on wood and peat from this organic silty sand, and underlying gravel (Table 1). Monaghan and Larson (1986) describe two tills in south-central Michigan deposited by the Saginaw lobe, that they named the Fulton and Bedford tills. A third Michigan Subepisode till underlying these is recognized in St. Joseph County, Michigan and is named the Sturgis till (Nicks, 2004). Additionally, a pre-Wisconsin Episode till (unnamed formation) underlies the Sangamon Geosol in St. Joseph County (Gardner, 1997; Flint, 1999; Nicks, 2004).

Previous descriptions and ages of buried organics in Lower Michigan

Water-well records demonstrate that wood and other pre-Michigan Subepisode organic materials are buried in the subsurface of Lower Michigan (see references to the pre-1960 literature in Eschman, 1980; Rieck and Winters, 1980, 1982). More than two dozen buried organic samples have been radiocarbon dated in Lower Michigan (Table 1). Zumberge and Benninghoff (1969) reported three non-finite conventional radiocarbon ages (>36,000 and >40,000 ^{14}C yr BP) from a peat- and wood-bearing layer lying between tills near Grand Rapids, Michigan (Fig. 1, Table 1). They also describe pollen and macrofossils from the organic unit and infer that the climate was cool and the region was covered by boreal forest. Similar organic sediments are described in a well in Casnovia, Muskegon County (Fig. 1, Table 1) and in Clinton County, Michigan (Miller, 1973; Kapp, 1978). Both organic units contain similar pollen as described by Zumberge and Benninghoff (1969), but the Casnovia organics produced a radiocarbon age of 25,050 ± 700 ^{14}C yr BP (~29,860 ± 850 cal yr BP).

Eschman (1980) and Rieck and Winters (1980, 1982) compiled and described sites and radiocarbon ages for organics underlying Michigan Subepisode glacial sediments. Eschman (1980) provides detailed site information and section descriptions for the organic sites known at the time (Table 1). Rieck and Winters (1980, 1982) mapped the location of water wells in Lower Michigan that contain organic deposits underlying till or outwash. They grouped these sites into clusters and interpreted that they were evidence of multiple buried surfaces from previous ice-free events. Many of the buried organic units are below 200 m above modern sea level (amsl). One of the clusters described as the Grand Haven–Holland cluster outlined areas in Ottawa County, which contain buried organic deposits. They concluded that buried organics indicate that lake levels and the surrounding landscapes progressively increased in elevation with each successive glaciation, even though lake basins were being deepened during each successive ice advance (see Fig. 5 in Rieck and Winters, 1982). Winters and Rieck (1991) described another buried and radiocarbon-dated organic layer in northern Lower Michigan (Table 1) overlain by two tills, interbedded outwash and lacustrine deposits (>100 m thick). They argued that this demonstrated the dramatic increase in surface elevation during the last glacial advance. Karrow et al. (1997) describe floral and faunal evidence in sediment below Michigan Subepisode till at the Mill Creek site near Port Huron, Michigan, and provide one radiocarbon age of 48,300 ± 800 ^{14}C yr BP (Table 1), a thermoluminescence age of 57 ± 9 ka, and amino acid analyses suggesting that organics were deposited in during Elgin-Athens Subepisode, or perhaps the Sangamon Episode. Sediments underlying the organic beds include glaciolacustrine silt and clay. Bedrock is not exposed, so it is not known how thick the sediment is below the organic interval or if older till is present (Karrow et al., 1997). Wood and other organic materials incorporated into Michigan Subepisode tills have been described and radiocarbon dated in southwestern Michigan (Kehew et al., 2005).

The oldest finite radiocarbon ages in Lower Michigan on wood below till are 48,300 ± 800 ^{14}C yr BP (QL-1215, 52,310 ± 2020 cal yr BP) and 64,500 ± 1000 ^{14}C yr BP (QL-1949) from the Mill Creek Site in St. Claire County and the Glenn Shores section in Allegan County, respectively (Table 1). The youngest ages reported (Table 1) are also from St. Claire County, on organic clay and peat below till, range from 17,450 ± 600 to 36,200 ± 4400 ^{14}C yr BP; the youngest being too young and probably due to contamination by younger material (Eschman, 1980). The youngest wood age of 25,050 ± 700 C^{14} yr BP (29,860 ± 850 cal yr BP) is from Muskegon County (Kapp, 1978). Taking all of these ages into

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account suggests that Lower Michigan was probably ice-free between ~65 ka and ~29 ka.

Materials and methods

A ~42.5 m-long core to bedrock was obtained at Hemlock Crossing County Park (Fig. 1) using a rotosonic method, which provided excellent core recovery (>90%). The core was taken as part of a hydrogeology field camp and subsequent groundwater study, and is archived at the Michigan Geological Repository for Research and Education at Western Michigan University as Core OT-12-01 (Lingle, 2013). The core was photographed, described for Munsell color, texture, sedimentary structures, and contacts (Tables 2 and 3). We sampled fine organic silt with visible wood and plant fragments for three radiocarbon analyses. Bulk organic sediment was sieved for plant material and treated using the acid/alkaline/acid wash method by Beta Analytic Inc. before analysis by accelerator mass spectrometry (AMS).

Texture was determined using hydrometer and sieves on samples taken at ~0.5 m intervals and near unit contacts (Lewis and McConchie, 1994). Our analyses produced continuous grain size curves for the <2 mm fraction, from which we determined the matrix mean grain size, sorting, and percentage sand, silt, and clay (<2 μm). Samples were not large enough to determine gravel content quantitatively, so percentage gravel is used for qualitative comparison. We measured

Table 1
Athens Subepisode radiocarbon ages in Lower Michigan.

Site location (elev. of sample)	Sample #	Radiocarbon age ^{14}C yr BP	Calendar age[a] cal yr BP	Material dated, sample stratigraphy	References
Clinton Co. (<183 m)	W-2182	>32,000	–	wood, peat and organic clay under till NE of Hubbardston, NW, Sec. 6, T8N, R4W	Sullivan et al. (1970) and Miller (1973) Eschman (1980)
Kent Co.	W-1293	>36,000	–	organics in sand under till units II and III	Zumberge and Benninghoff (1969)
John Ball Park	W-1292	>40,000	–	wood in peat under till units II and III	" "
Grand Rapids	W-1294	>40,000	–	wood in peat under till units II and III	" "
(205–207 m)	W-1300	>40,000	–	wood in till unit II	" "
	GrN-4614	>51,000	–	wood in sand under till	Farrand and Eschman (1974) and Eschman (1980)
Kent Co. (201 m)	I-4900	>39,900	–	wood in red brown till, in SW Grand Rapids, SE, NW, Sec. 34, T7N, R12W	Buckley and Willis (1972) and Eschman (1980) Rieck and Winters (1980, 1982)
Kent Co. (198 m)	I-5078	33,300 ± 1800	38,080 ± 2190	wood under gravel in pit northwest of Grand Rapids, S1/2, Sec. 1, T7N, R12W	Buckley and Willis (1972) and Eschman (1980) Rieck and Winters (1980, 1982)
Gratiot Co. (204 m)	M-879	>30,000	–	buried wood, may be contaminated with coal	Rieck and Winters (1982)
Ionia Co. (220 m)	M-653	>30,000	–	buried wood under till	Crane and Griffin (1961) Rieck and Winters (1980, 1982)
St. Clair Co.	GX-4975	>37,000	–	wood in sand under two tills exposed	Eschman (1980)
(186 m)	QL-1215	48,300 ± 800	52,310 ± 2020	along Mill Creek, sec. 7, T7N, R16E	Rieck and Winters (1980, 1982)
St. Claire Co.	GX-3436	17,450 ± 600	20,920 ± 820	organic mud, peat, and clayey peat	Eschman (1980)
(180–183 m)	GX-3435	22,200 ± 700	26,620 ± 990	respectively, in three closely spaced	
	GX-3447	36,200 ± 4400	40,030 ± 4090	borings, sec. 27, T8N, R12E	
Sanilac Co. (201 m)	GX-5104	>37,000	–	buried spruce log in outwash under till sec. 31, T9N, R16E	Eschman (1980) Rieck and Winters (1982)
Midland Co. (220 m)	M-2145	24,000 ± 4000	27,930 ± 4240	mammoth tooth in stream gravel Sec. 22, T16N, R2W	Kapp (1970), Farrand and Eschman (1974) Rieck and Winters (1980, 1982)
Sanilac, Co. (191 m)	W-3667	24,480 ± 700	29,310 ± 800	wood under two tills from well driller near Mill Creek, SW, sec. 25, T11N, R15E	Eschman (1980) Rieck and Winters (1980, 1982)
Muskegon Co. (230 m)	W-2897	25,050 ± 700	29,860 ± 850	wood in clay under till in Casnovia SE, SE, SE, Sec. 24, T10N, R13W	Holman (1976), Kapp (1978)
Manistee Co.	QL-963	45,800 ± 700	49,100 ± 1850	wood under till exposed along the	Stuiver et al. (1978) and Eschman (1980)
(232 m)	I-8735	>40,000	–	Pine River NW, sec. 23, T21N, R13W	Rieck and Winters (1980, 1982)
Allegan Co.	Beta-3311	37,150 ± 540	41,930 ± 410	wood in gravel-sand under two tills	Monaghan et al. (1986)
Glenn Shores	Beta-3310	38,130 ± 740	42,700 ± 690	" "	" "
(177.5–179.5 m)	GX-8193	>37,000	–	" "	" "
	ISGS-948	>48,000	–	" "	" "
	SI-5183	>43,000	–	peat in gravel–silty sand under two tills	" "
	QL-1949	64,500 ± 1000	–	wood in gravel–silty sand under two tills	Larson and Monaghan (1988)
	Beta-22153	>37,310	–	" "	" "
Hillsdale Co. (unknown)	W-3823	39,500 ± 1000	43,510 ± 800	spruce wood above and below till NW, NW, Sec. 29, T6S, R2W	Eschman (1980) Rieck and Winters (1980, 1982)
Kalamazoo Co. (unknown)	Beta-17891	33,810 ± 750	38,880 ± 1510	wood under till	Winters et al. (1988)
Kalkaska Co.	Beta-9046	34,200 ± 1320	38,870 ± 1740	wood in sand under two tills	Winters and Rieck (1991)
(170–180 m)	Beta-9273	36,300 ± 2450	40,280 ± 2440	wood in sand under two tills	
Van Buren Co. (177 m)	W-108	30,000 ± 800	34,230 ± 780	wood fragments in contorted silts near South Haven	Eschman (1980)
Van Buren Co. (213 m)	GX-28748	32,480 ± 1850	37,420 ± 2280	wood in lowest lacustrine between tills in core VB-01-09	Kehew et al. (2005)
Van Buren Co. (186 m)	GX-27991	38,390 + 2290 − 1780	42,699 ± 1530	wood in till from water well NE,SE,SW, sec.31, T2S R14W	Kehew et al. (2005)
Van Buren Co. (198 m)	GX-27990	30,720 + 2370 − 1830	35,620 ± 2340	wood in till from water SE,SE,SW, sec.30, T2S R15W	Kehew et al. (2005)

[a] Calibrated ages are cal yr BP (1 sigma uncertainty). Calibration done with CalPal online calculator tool (http://www.calpal-online.de/cgi-bin/quickcal.plwas).

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low field mass magnetic susceptibility using a Bartington MS-3 system with a MS-2 sensor for air-dried samples in plastic boxes (Dearing, 1999). Loss on ignition (360°C, 2 h) was determined for the organic interval on samples taken approximately every 10 cm between ~13.4 and 20.7 m depth. Pebble (2–8 mm) counts were completed for the upper, middle, and lower diamictons by combining all pebbles from the texture analyses. Pebbles were classified under a binocular microscope into three classes: felsic crystalline, mafic crystalline, and local sedimentary.

Clay mineralogy of diamictons was determined using a semi-quantitative method of X-ray diffraction with a Rigaku Miniflex 600 system. The clay size fraction (<2 μm) for each sample was obtained in a 25 ml aliquot at 10 cm depth after settling for ~8 h. Subsamples were pipetted onto glass slides and allowed to settle out and air dry to produce oriented clay samples. Slides were then exposed to ethylene glycol vapors in a sealed chamber for at least 24 h. Each slide was analyzed from 2° to 15° 2θ with a sampling interval of 0.02° of 2θ. Measurement geometry included a Soller 5° incident parallel slit, 1.250° incident slit, 10 mm length limiting slit, 1.25° receiving slit #1, no filter, 5° receiving parallel slit, and a 0.3 mm receiving slit #2. No slit correction was applied in order to compare our data with older datasets that probably did not use a slit correction for variable beam widths at low 2θ angles. Enabling the slit correction option with the Rigaku Miniflex 600 system produced higher peak counts than older systems that did not maintain a constant beam width (set to 20 mm). We found empirically that 7 Å to 10 Å ratios (not slit-corrected) could be slit-corrected by multiplication by 0.724 ($r^2 = 0.954$). Baseline-corrected peak counts were determined using Rigaku PDXL software at 7 Å (~7.1 Å, 2θ = 12.5°), 10 Å (10.1 Å, 2θ = 8.8°), and 14 Å (14.1 Å, 2θ = 6.3°). Relative percentage of the three clay mineral phases were determined by dividing the peak height counts for each phase (7 Å = kaolinite + chlorite, 10 Å = illite, 14 Å = chlorite + vermiculite) by total counts for the three phases. Ratios of kaolinite + chlorite (7 Å) to illite (10 Å) were calculated and are referred to as kaolinite–illite ratios. Fifteen samples were heated to 550° C to determine if chlorite added to the 7 Å peak since the 002 reflector plane of chlorite is the same as the 001 plane of kaolinite. No statistically significant peaks remained after the heat treatment in all 15 samples. Because of this we assumed that 002 chlorite peaks were not increasing 7 Å peaks significantly even though chlorite is present in the samples (~10%). Later, after it became apparent that weathering might be present in diamictons, a completely new set of oriented samples were prepared and analyzed from 2° to 30° 2θ in order to determine the 002 illite peak (~5.0 Å, 2θ = 17.9°), and 003 chlorite peak (~4.75 Å, 2θ = 18.8°). The ratio of the 4.7 Å peak to the 5 Å peak was determined to see if chlorite weathering had occurred in any of the units (Hughes et al., 1994).

Water-well records were examined to determine the distribution of organic units and underlying sediments in Ottawa County. We examined records in the Wellogic Database (MDEQ, 2012) and older scanned copies of well records (MDEQ, 2009). We searched Wellogic lithology files for "wood" or "muck" or "peat" in MS Excel and manually for older scanned records. Paper records were checked for location accuracy, and the well lithology was entered into ArcMap 10.1.

Table 2
Lithofacies classification used in this study.

Code	Lithofacies description	Depositional processes
Fl	laminated fines	gravitational settling from suspension
Fr	rhythmites in fines of clay and silt couplets	gravitational settling from suspension
Fm	massive fines, with sand	various, and as above
Sm	massive sand, well sorted with few fines	traction
Sm (gr)	massive sand, with gravel	traction
Dmm	massive diamict , striated and wedge-shaped clasts common	subglacial lodgement, deformation, or basal melt out
Dms	weakly stratified diamict, striated and wedge-shaped clasts not as common as in Dm facies	subaqueous mass flow, and rainout

Results

Sedimentary lithofacies

Figure 3 and Table 3 present lithofacies and lithologic data for the Hemlock Crossing core. Three diamicton units are interbedded with sand and silt beds, some containing organics. Above the organic unit is a sequence of massive (Dmm — lithofacies codes are adapted from Eyles et al., 1983) to weakly stratified matrix-supported diamicton (Dms) overlain by laminated fines (Fr and Fm). The organic interval contains medium sand and organic fines. Below the organic interval are two diamictons with interbedded silts and sands. Bedrock is late Mississippian Coldwater Shale.

Unit 1 – Sandy diamicton (Dmm) – A reddish brown to dark grayish brown sandy loam to clay loam, diamicton is present from 29.0 to 40.5 m depth. The upper ~2 m of this unit is reddish brown becoming dark grayish brown at depth. Large gravel clasts are common with mean percent gravel of ~6%. Small pebbles are 9% felsic crystalline, 3% mafic crystalline, and 88% sedimentary (n = 1094). Many larger clasts are striated and or wedge shaped. The unit contains a sand and gravel layer ~20 cm-thick. The contact with the underlying Coldwater Shale is sharp.

Unit 2 – Sandy silt (Fm) – Unit 2 (26.8 to 29.0 m depth) is a grayish brown to dark gray, massive loam with rare gravel (≪1%).

Unit 3 – Middle diamicton (Dmm) – A grayish brown to dark gray, silty diamicton is present from 21.5 to 26.8 m depth. The upper contact with the overlying organic silt is sharp. Mean matrix texture is a clay loam or loam (Fig. 4) containing >3% gravel. The unit is massive and dense with a wide variety of clasts up to ~5 cm in diameter. Small pebbles (2–8 mm in diameter) are 13% felsic crystalline, 4% are mafic crystalline, and 83% sedimentary (n = 221). Many clasts are striated and/or wedge-shaped.

Unit 4 – Organic interval (Sm, Fm, and Fl) – Unit 4 (13.4 to 21.5 m depth) is composed of finely laminated organic sandy silt interbedded with well-sorted and massive sand beds (Figs. 3 and 5). Well-sorted sand beds are found at the upper and lower portion of this unit. Fine to medium sand (Sm) is present in the upper sand, and finer sand in the lower sand; neither contains gravel. Underlying the sand units is light brown to dark brown, massive to laminated organic silt (Fm-Fl) containing ostracods, wood and plant fragments (Fig. 6). Percentage loss-on-ignition values vary from ~1% to ~12% (Fig. 5). Textures of the organic silts vary from sandy loam to clay loam (Fig. 5). In sand units there are small euhedral crystals of calcite. Many of the sand grains have coatings of calcite or are weakly cemented with calcite cement. The mean grain size varies from 0.24 to 0.30 mm in the upper sand and 0.18 to 0.25 mm in the lower sand; both units are well sorted with sorting coefficients varying from 1.8 to 2.4.

Units 5a and 5b – Massive to weakly stratified diamicton (Dmm and Dms) – Units 5a (5.8 to 10.4 m depth) and 5b (10.4 to 13.4 m depth) are light gray to gray, massive diamictons (Dmm) with silty clay, silty clay loam, and clay loam matrix textures. The diamictons are separated by a weakly stratified zone (Dms) at the base of unit 5a from 9.2 to 10.4 m depths (Fig. 3). Unit 5a is finer than unit 5b and contains less sand (Fig. 4). Both diamictons contain polymictic gravel up to 3 cm in diameter. Unit 5a contains <1% gravel and unit 5b contains slightly more than 1% gravel (Fig. 3, Table 3). The contact of unit 5b with the underlying sand is sharp. Small pebbles (2–8 mm in diameter) are 13% felsic crystalline, 3% are mafic crystalline, and 84% sedimentary clasts (n = 82). Larger clasts are striated and wedge-shaped.

Unit 6 – Laminated clay and silt couplets (Fr and Fm) – Unit 6 (3.4 to 5.8 m depth) is gray to very dark gray, fine sandy silt and silty clay

Table 3
Lithological data for Hemlock Crossing core sediment units.

Lithologic unit/ Munsell color	n[a]	%sand	%silt	%clay[b]	kaolinite/illite[c] (n[d])	K + C/I/C + V	MS ($\times 10^{-6}$ m^3/kg)(n[e])
Unit 7 (med. to coarse sand w/gravel) (10YR 3/2–10YR 6/2–6/4)	4	95.6 ± 0.7	4.4 ± 0.7	–	–	–	8 ± 4 (4)
Unit 6 (silt and fine silty sand) (10YR 3/1–10YR 6/)	5	6.8 ± 2.9	73.0 ± 8.8	20.2 ± 6.4	1.00 ± 0.04 (4)	44–44–11	167 ± 8 (4)
Unit 5a (upper diamicton) (10YR 5/1 7/1)	9	14.8 ± 2.9	46.6 ± 3.4	38.6 ± 3.9	0.88 ± 0.08 (6)	42–48–10	112 ± 13 (4)
Unit 5b (upper diamicton) (10YR 5/1 7/1)	5	32.7 ± 15.9	40.0 ± 12.9	27.4 ± 4.1	0.79 ± 0.03 (4)	41–48–11	167 ± 8 (6)
Unit 4 (organic silt and sands)	–	see Figure 5 for texture data		–		–	Figure 5
Unit 3 (middle diamicton) (10YR 5/1 5/2 10YR 4/1 4/2)	13	31.0 ± 5.7	38.4 ± 4.2	30.7 ± 4.6	0.98 ± 0.04 (12)	44–45–12	109 ± 43 (12)
Unit 2 (middle silt and sand) (10YR 5/1 5/2 10YR 4/1 4/2)	5	39.2 ± 1.8	47.0 ± 1.8	13.8 ± 2.6	1.05 ± 0.05 (4)	47–44–9	195 ± 10 (5)
Unit 1 (lower diamicton) (5YR 5/3 10YR 5/2 5/3)	30	45.7 ± 4.8	32.9 ± 4.9	21.4 ± 3.7	1.22 ± 0.08 (36)	49–41–10	158 ± 36 (30)

[a] Number of matrix texture samples analyzed for each unit.
[b] Clay fraction is defined as <2 microns (USDA. textural triangle) uncertainty is one sigma for n values.
[c] Mean kaolinite-illite ratios for ethylene glycol treated samples with no slit correction. These values can be converted to slit corrected values by multiplying by 0.723 ($r^2 = 0.9541$). Uncertainty is one sigma for n values.
[d] Number of interval samples for clay mineral analyses.
[e] Number of interval samples for magnetic susceptibility analysis (3 sample replicates for each interval sample). Uncertainty is one sigma for n values.

couplets (Fr), and massive sandy silt (Fm). Texture is silt loam or silty clay loam (Table 3, Fig. 4) and contains rare pebbles (<0.2%, <4 mm). Millimeter- to centimeter-scale couplets of fine sandy silt and silty clay (Fr) are present throughout with thicker massive sandy silts (Fm) near the base. Many of the couplets are deformed or convoluted, especially at the top of the unit, but it is unclear if this is an original sedimentary structure from loading and dewatering, or due to deformation from coring. Yellowish red (5YR 4/6) shale intraclasts are present in

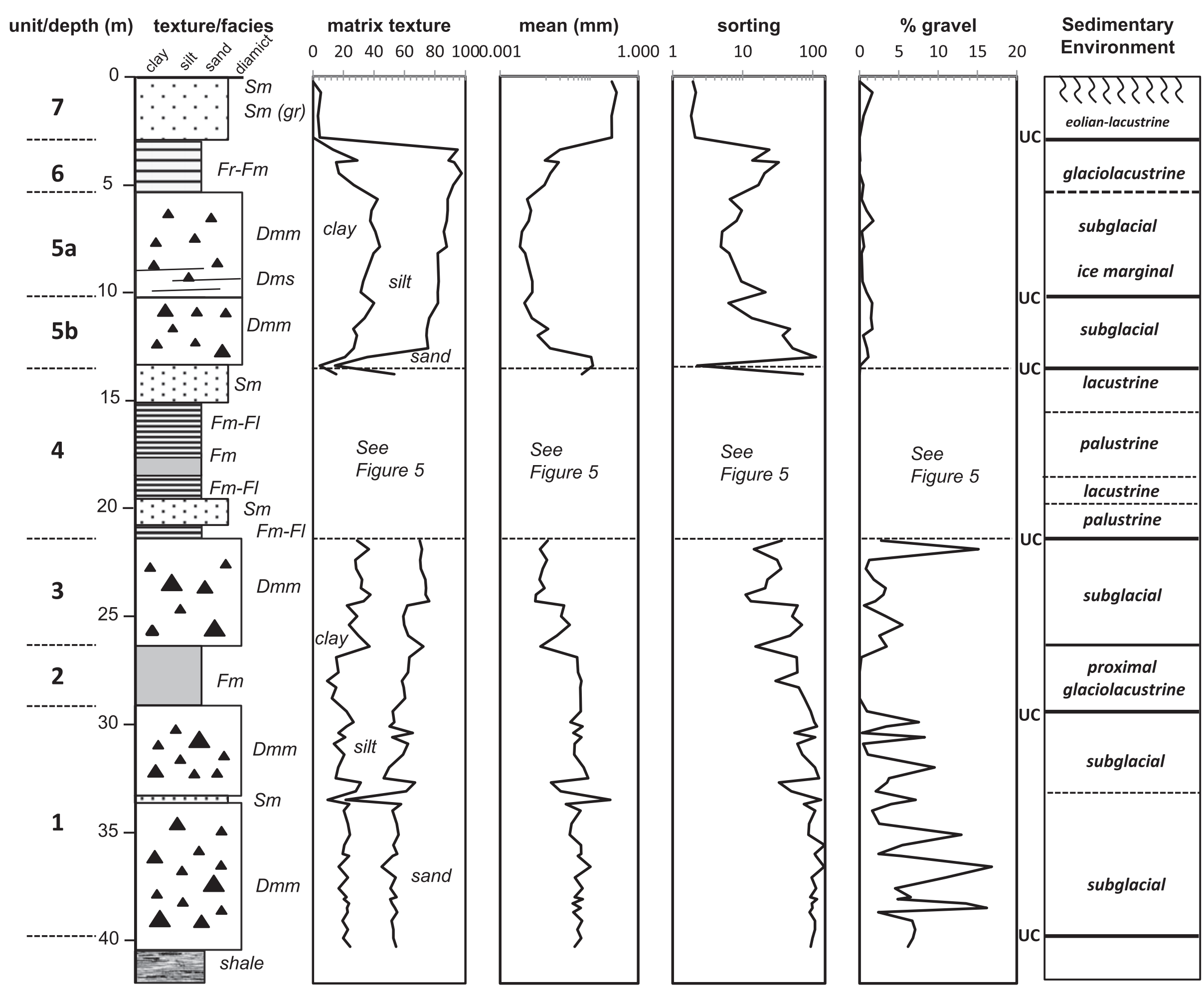

Figure 3. A graphic sedimentary log of the Hemlock Crossing core. Lithofacies codes are explained in Table 2. Core interval of unit 4 is shown in Fig. 5. Sorting coefficient is calculated as D_{40}/D_{90}.

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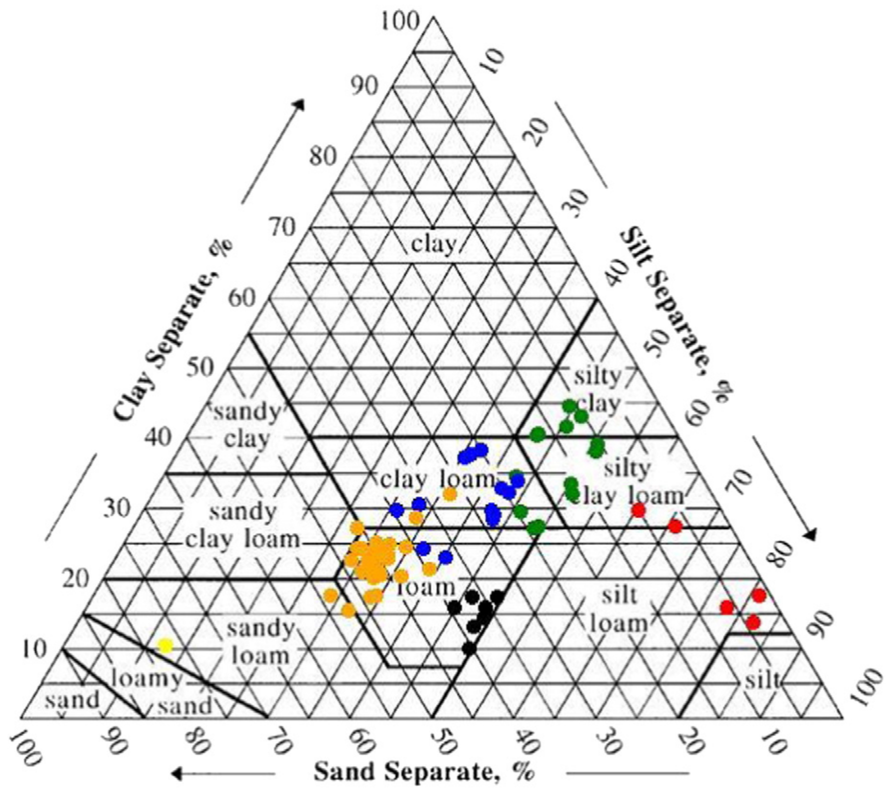

Figure 4. USDA textural triangle for sediments in the Hemlock Crossing core. Orange — unit 1 lower diamicton, Yellow — intra-diamicton sand in unit 1, Black — unit 2 massive fines, Blue — unit 3 middle diamicton, Green — unit 5 upper diamicton, Red — unit 6 laminated rhythmites. Natural Resources Conservation Service, Soil texture calculator application (accessed at http://www.nrcs.usda.gov/wps/portal/nrcs/detail/soils/survey/tools/).

the upper part of the unit. The contact with the underlying diamicton is sharp. No fossils were found in the small sediment samples available, but sieving of larger sediment volumes might find ostracods and other fossils.

Unit 7 – Sand with gravel (Sm) – Unit 7 (0 to 3.4 m depth) is a very dark grayish brown to light yellowish brown, medium to coarse pebbly sand with an Inceptisol developed in it. The sand contains sub-rounded to sub-angular grains with local and non-local pebbles. The upper

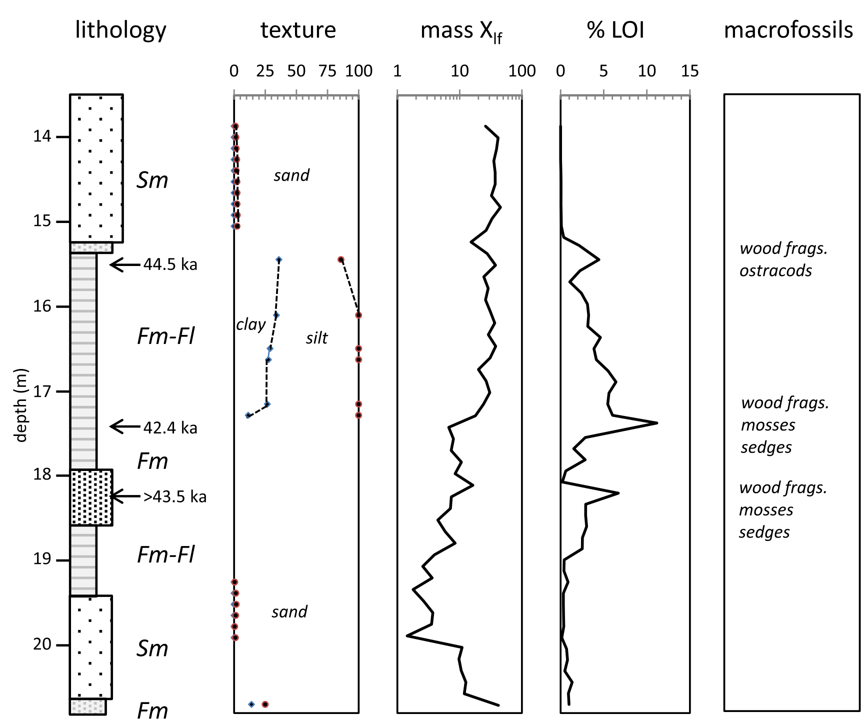

Figure 5. A graphic sedimentary log of the organic interval (unit 4) of the Hemlock Crossing core.

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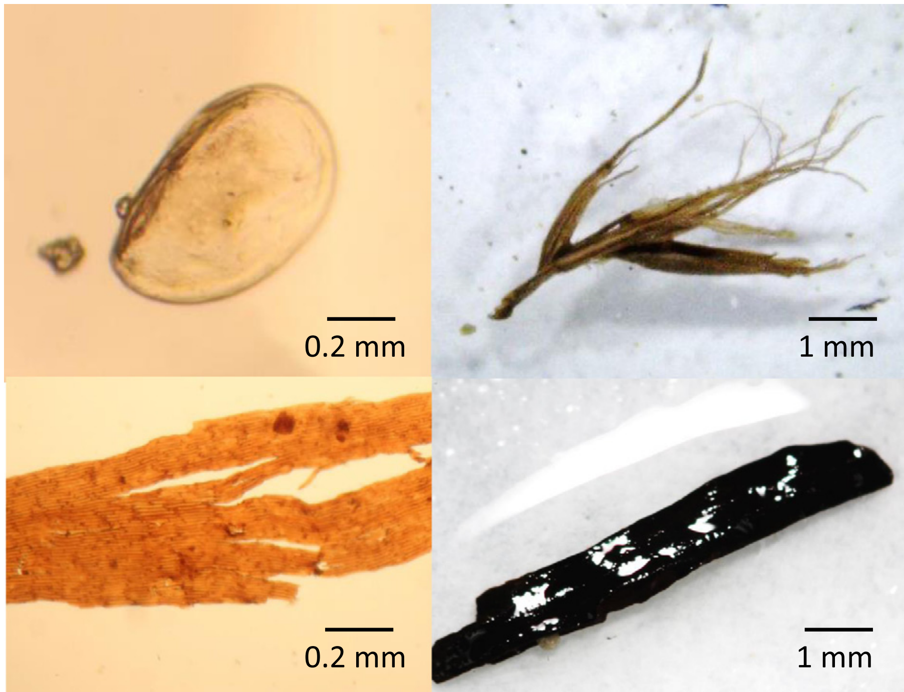

Figure 6. Examples of organic materials found in the silt lithofacies (Fm-Fl) of unit 4. Ostracod test (upper left), sedge fragment (upper right), wood fragment (lower right), and fragment of brown moss (lower left).

70 cm is medium sand whereas the lower part of the unit is medium to coarse pebbly sand. The contact with the underlying laminated clay and silt unit is sharp.

Macrofossils and radiocarbon analyses

Organic materials in the sandy silt are wood fragments (up to 10 mm) and other detrital plant materials such as brown moss (bryophytes such as sphagnum moss species) and sedge fragments (Figs. 5 and 6). Pollen, plant fragments, and ostracods are also present. Three AMS radiocarbon analyses of wood and plant macrofossils yield ages of 41,920–42,950 and 43,630–45,340 cal yr BP, and >43,500 ^{14}C BP (Table 4).

Clay mineral analyses

X-ray diffraction analyses of oriented clays produced well-defined peaks for kaolinite + chlorite, illite, and chlorite + vermiculite. Some replicate samples did not produce significant peaks for chlorite + vermiculite. This was especially common in the upper parts of units 2, 5, and 6. We found no samples with significant amounts of chlorite in the ~7.1 Å peak after heating samples to 550°C. Our samples contain primarily illite and kaolinite with lesser amounts (generally ~10%) of chlorite + vermiculite (Fig. 7, Table 3).

Kaolinite–illite ratios (Fig. 7) vary from ~0.75 to ~1.5 with a mean of ~1.1. The lowest kaolinite–illite ratios (~0.75) are in the lower portion of the upper diamicton (unit 5b) below the contact with the stratified diamicton facies (unit 5a), and highest ratios (~1.2–1.5) are found in the lowest diamicton (unit 1). Diamicton units above the organic unit have means < 1 and diamicton units below the organic unit have means of ~1 or greater. Both upper and lower fine units (units 6 and 2) and the middle diamicton have similar mean values of ~1. Mean chlorite (003)–illite (002) ratios (Fig. 7) vary from no detection (N.D.) of chlorite to ~0.9 with a mean of ~0.6. The lowest chlorite–illite ratios (as N.D. of chlorite) are in units 2, 3, and 6.

Spatial distribution of organic sands and silt in Ottawa County, Michigan

Figure 8 plots locations of ~130 water-well records in Ottawa County, Michigan that contain “wood” or “muck” or “peat”, which lie below “clay” and “clay and gravel” units. The most common sequence in these wells is “sand, clay, clay and gravel, sand with wood” (in descending order). Below the organic sand is commonly a descending sequence of “sand, sand and gravel and clay and gravel” overlying bedrock. Wells with organic bearing sand are clustered in two areas with other scattered sites (Fig. 8). Nearly all are associated with sediments described as “sand” or “silt.” Only a few report organic material in “sand & gravel” or “clay” or “clay and gravel” units. Thicknesses of these organic sands vary from 0.3 to 14.0 m and the mean thickness of the bed is 3.5 ± 2.4 m (1 σ uncertainty). The depth to the top of the bed varies from 8.5 to 66.1 m below the land surface with the mean depth of 26.7 ± 8.0 m.

About two dozen occurrences of buried organic bearing silt and sand are located near Hemlock Crossing Park. Organic silt and sand in this

Table 4
Radiocarbon ages from the organic interval.

Sample number	Laboratory ID	Sample material	Depth (m)	^{14}C Age (^{14}C yr BP)	2-sigma calibrated range[a] (cal yr BP)	Median age (cal yr BP)	^{13}C/^{12}C
HC3	Beta-353120	wood/plant fragments	15.4	40,790 ± 400	43,630–45,340	44,490	−26.7
HC1	Beta-329000	wood/plant fragments	17.4	37,840 ± 400	41,920–42,950	42,440	−23.0
HC2	Beta-353122	wood/plant fragments	18.6	>43,500	na	na	−29.7

[a] radiocarbon calibration uses INTCAL09.

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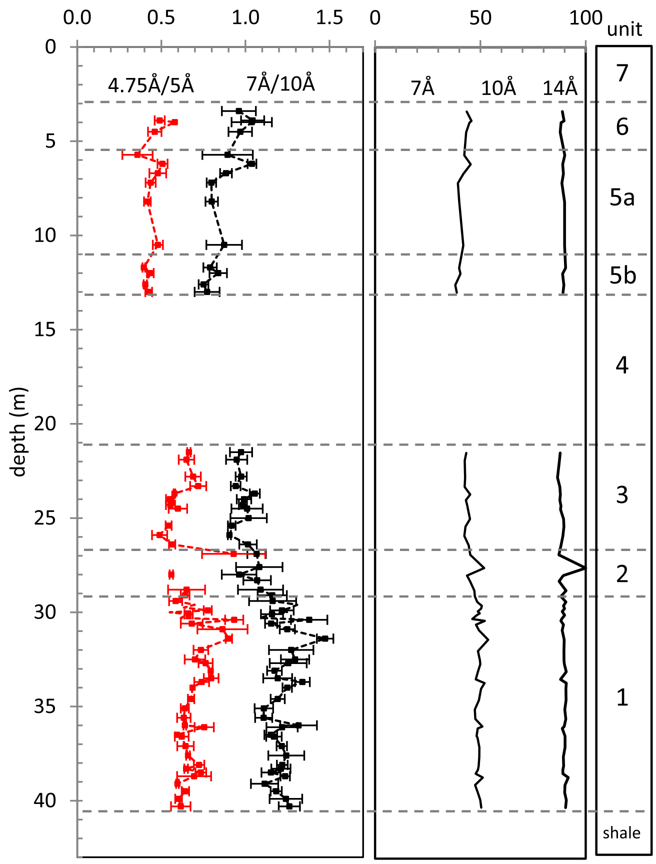

Figure 7. Results of the clay mineral analyses plotted versus depth in the core. Ratios of chlorite (~4.75A) to illite (~5A) in red, and kaolinite (~7 Å) to illite (~10 Å) in black (left panel). One sigma uncertainty between sample replicates (n = 2 to 6 for each interval) is shown with horizontal uncertainty bars. Relative percentage kaolinite + chlorite (~7 Å), illite (~10 Å), and chlorite + vermiculite (~14 Å) (middle panel).

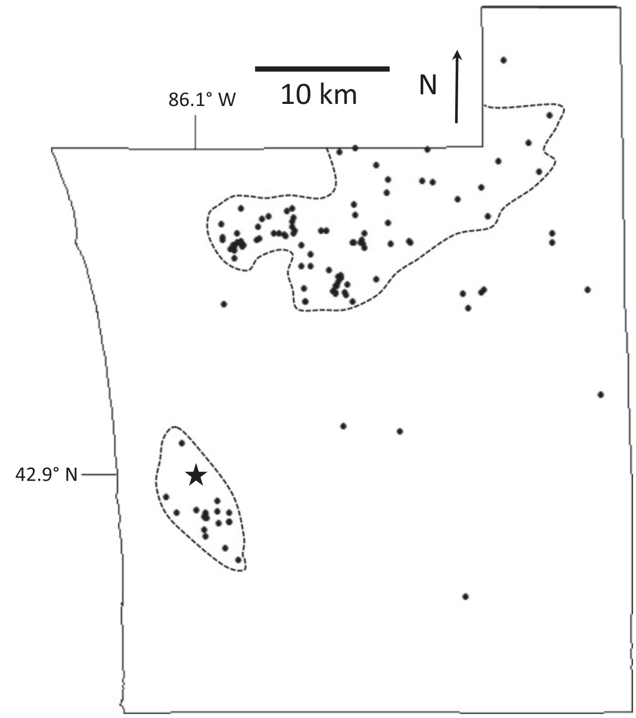

Figure 8. Water wells in Ottawa County, Michigan that report organics in sand and silt underlying thick sequences of clay and clay and gravel.

cluster varies from 0.6 to 6.4 m thick, with a mean thickness of 3.3 ± 1.3 m and the elevation of the top of the unit varies from 166 to 177 m with a mean of 170 ± 3 m. This is ~7 m below the current mean elevation of Lake Michigan (~177 m). Mean values are similar to unit 4 where organic silt is ~3.0 m-thick (all of unit 4 is ~8 m), and the elevation of the top of unit 4 is ~168 m amsl. This is about 9 m below mean Lake Michigan water level. The largest cluster of occurrences is north of the Grand River. The average thickness of the organic sand in this cluster varies from 0.3 to 14.0 m and the average depth to the top of an organic bearing unit is 28.6 ± 7.8 m. The mean elevation of these organic beds is 164 ± 8 m. This is about 13 m below the mean level of Lake Michigan.

Thickness and continuity of pre-late Wisconsin sediments

Figure 9a is a cross section, constructed through Hemlock Crossing Park that runs approximately parallel to flow of the Lake Michigan lobe during the Crown Point Phase (18.2 to 16.8 ka). The topographic profile shows the abandoned surface of Glacial Lake Chicago and the prominent ridge of the inner Lake Border moraine. Figure 9B is a west to east cross-section through the Glacial Lake Chicago plain and the inner Lake Border moraine and demonstrates that thin sand lies over thick sequences of clay and clay and gravel. Organic sands and silts are present in many wells and bedrock depth varies from ~50 to ~100 m. Sediments below the organic sand in most wells are "clay" and "clay and gravel."

Discussion

Depositional environments

Sediments in the Hemlock Crossing core were most likely deposited in subglacial and glaciolacustrine environments, except for the sands and fines in the organic unit, which were deposited in non-glacial lacustrine and palustrine environments. In the following, we briefly discuss our interpretations of depositional environments.

Unit 1 – Subglacial (Dmm) – This unit is one or more basal tills based on massive and dense structure and wedge-shaped and striated polymictic clasts. It has more gravel than the overlying diamicton units 3 and 5. An interbedded layer of sand and gravel is probably an intra-till sorted unit, common in subglacial till sequences (Eyles et al., 1983).

Unit 2 – Proximal glaciolacustrine (Fm) – A lack of sedimentary structures makes interpretation of this facies difficult, but this unit is likely proximal glaciolacustrine sediments formed by rainout and underflows. The unit is enriched in silt compared to the tills above and below it and this supports a lacustrine origin. Gravel is rare (≪1%) so it must have been deposited far enough from the ice margin that energy was not high enough to transport gravel.

Unit 3 – Subglacial (Dmm) – This is basal till based on its massive and dense structure, and striated wedge-shaped polymictic clasts. The contact at the top of the unit is sharp and shows no indication of weathering such as color, leaching, or chlorite depletion. Because of this it was either deposited directly before deposition of the overlying sand, or it was eroded before the deposition of the overlying unit 4.

Unit 4 – Lacustrine (Sm) and palustrine (Fl, Fm) – The organic interval contains both lacustrine and palustrine sediments. Well-sorted, fine to medium sands probably formed as beach sediments or in the near shore zone of an open body of water. Fine organic sandy silts were deposited in a much lower-energy environment based on the silt and fine organic matter. Organic silts contain plant macrofossils such as brown mosses, sedge fragments, aquatic plant fragments, small intact wood pieces, and poorly preserved ostracods. Euhedral calcite present

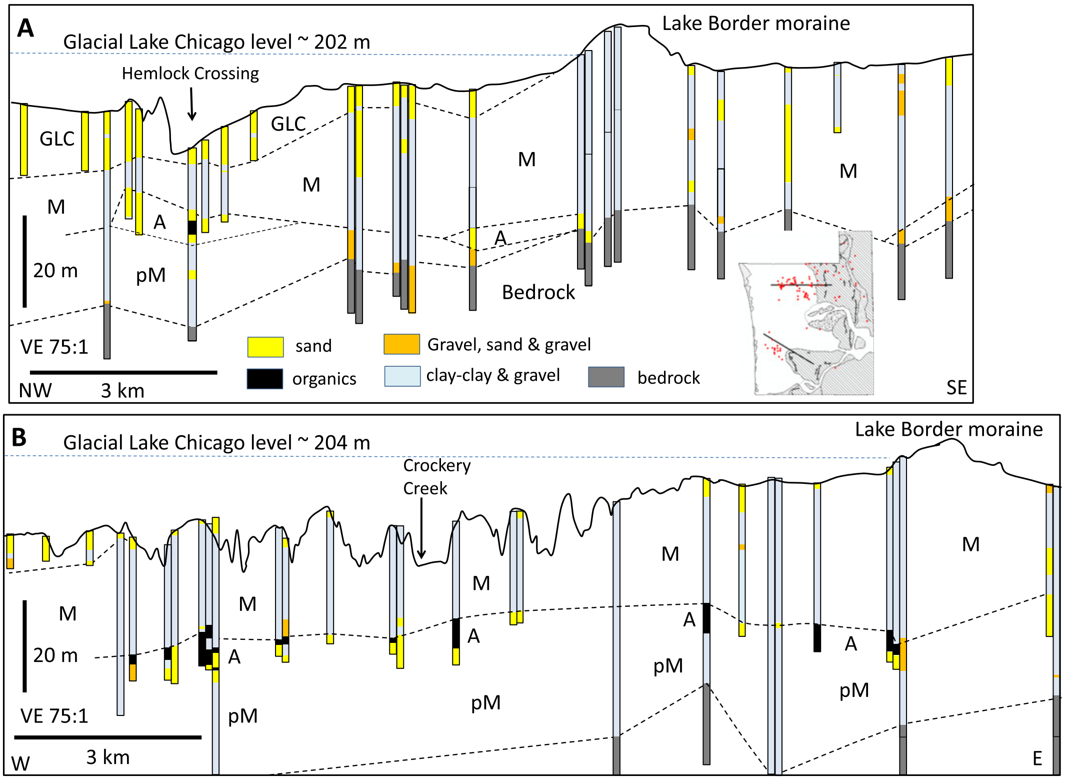

Figure 9. Two geologic cross sections showing the continuity of organic bearing sediments in Ottawa County, Michigan. A — Cross section including Hemlock Crossing core site. B — East to west cross section through well in the northern half of Ottawa County. M — Michigan Subepisode clay and diamict overlying organic sand unit. A = the Athens Subepisode organic bearing unit correlated with unit 4 in the Hemlock Crossing core. pM = pre-Michigan Subepisode clay and diamict underlying Athens Subepisode organic unit.

in the sands suggests carbonate-rich groundwater was discharging into small wetlands and marl lakes near a larger lake shoreline.

Unit 5 – Subglacial (Dmm) and proximal glaciolacustrine (Dms) – Units 5a and 5b are interpreted to be basal tills based on their massive texture and striated clasts. Weakly stratified diamicton (Dms) at the base of unit 5a is similar to debris flows and rainout tills described by Howard (2010) in southeastern Michigan. The sharp contact between unit 5a and the underlying diamicton (unit 5b) suggests erosion or a break in sedimentation.

Unit 6 – Proximal to distal glaciolacustrine (Fr and Fm) – This unit contains glaciolacustrine rhythmites deposited in Glacial Lake Chicago during the retreat of Lake Michigan lobe following the Crown Point Phase (~18.2 to 16.8 ka). Similar rhythmites are common overlying the Saugatuck till in Ottawa, Muskegon, and Allegan Counties. Rhythmites probably formed during individual discharge events due to rainout in Glacial Lake Chicago or could reflect annual deposition as varves (e.g. Benn and Evans, 2010). In Ottawa County, we estimate lake level to have been between 202 and 204 m amsl based on the highest elevations of the Allendale and Zeeland deltas (Fig. 2b). During retreat from the outer Lake Border moraine there would have been a proglacial lake fronting the retreating terminus. A similar sediment glaciolacustrine sequence has been described in southeastern Michigan during retreat of the Huron lobe (Howard, 2010).

Unit 7 – Lacustrine-eolian sand (Sm) – We correlate this unit to similar mixed lacustrine and aeolian units widespread in Ottawa County as lacustrine sands at the surface, which were reworked by the wind after exposure.

Chronology of organic sediments

Radiocarbon ages suggest that deposition of the organic unit occurred between 41,920 to 45,340 ^{14}C yr BP, and >43,500 ^{14}C yr BP (Table 4). The three ages do not fall in the correct stratigraphic order as the youngest age is from ~17.4 m depth (41,920–42,950 cal yr BP) and an older age at ~15.4 m depth (45,340–43,630 cal yr BP). The non-finite age of >43,500 ^{14}C yr BP is from the deepest interval. This returned a non-finite age perhaps because the sample size was small (~9 mg). The organic matter is detrital based on its fragmentary nature, but large intact macrofossils of sedges and moss suggest minimal transport distance. We argue that the organic material is not reworked from older sediment and is not significantly older than the enclosing sediments. The organic interval was likely deposited during the Athens Subepisode. Our two finite radiocarbon ages (Fig. 10) overlap with the 2 σ uncertainty of the two finite AMS radiocarbon ages from the organic interval at Glenn Shores (Beta-3310 and Beta-3311) reported by Larson and Monaghan (1988). This suggests they are the same age.

Extent and continuity of Athens Subepisode and older units in Ottawa County

We propose the name Port Sheldon Formation (Fig. 11) for the sorted sands and interbedded organic silts after Port Sheldon Township, Michigan where they are commonly found in the subsurface as in core OT-12-01 (unit 4). At least two areas in Ottawa County preserve glacial sediment underlying similar organic beds, which we correlate to the Port Sheldon Formation (Figs. 8 and 9). Both clusters were likely preserved because they were at low elevations, and just west of the inner Lake Border moraine system, which was pinned by the Marshall Sandstone escarpment buried in the subsurface (Fig. 2A). Scattered occurrences to the east of both of these clusters suggest that the Port Sheldon Formation is more extensive, but perhaps was eroded during or before the Crown Point Phase (18.2 to 16.8 ka) or occurred as small discontinuous environments. In many wells, “sands” and “silts” are described between “clay” and “clay and gravel” units, but organics are not described in these units. Both clusters, as well as sands at the same stratigraphic level demonstrate that pre-Athens Subepisode units are common in the subsurface of Ottawa County. Based on our cross-sections, 10 to 30 m of "sand," "sand and gravel," and "clay and gravel" lie below the Port Sheldon Formation in both clusters (Fig. 9). The Port Sheldon Formation is present at a consistent elevation (~164–169 amsl) and this suggests that organic sediments were deposited in wetlands surrounding a larger lake with a surface elevation below ~164–169 m amsl. The Port Sheldon Formation and older glacial deposits are likely truncated to the west by the erosional basin of Lake Michigan since the current lake bottom falls off very quickly to elevations much lower than the mean elevation of the Port Sheldon Formation.

The Port Sheldon Formation extends north into Muskegon County and it is also present in scattered individual outcrops and wells in Kent County (Zumberge and Benninghoff, 1969; Eschman, 1980; Rieck and Winters, 1980, 1982). A similar organic unit has been described in a well located in Casnovia, Michigan in Muskegon County (Fig. 1, Kapp, 1978). We have also found over two dozen well logs with organics in similar stratigraphic position in southeastern Muskegon County. The extent of the Athens Subepisode Port Sheldon Formation and older tills is probably greater than shown by our data because most modern well-drilling methods and lack of concern by drillers suggests that most of the time they would never notice thin organic materials, when drilling a 30 to 100 m-deep well using modern rotary drilling methods. This is especially true if their target aquifer was in bedrock (as in the Marshall aquifer). An observation supporting this argument is that ~80% of the water-well records which report "wood" and "muck" and "peat" used older and much slower cable tool methods of well drilling (wells in Fig. 8).

Correlative Athens Subepisode units in the western Great Lakes region

The Port Sheldon Formation correlates with the Roxana Silt in Illinois (Fig. 11). The Roxana Silt is primarily loess and suggests ice was able to introduce outwash and glacial rock flour into the Illinois and ancestral Mississippi drainage basins during the Athens Subepisode (Grimley, 2000; Curry et al., 2011). Calibrated radiocarbon ages for the Roxana Silt range from about 48 to 31 ka (Curry, 1989; Curry et al., 2011); the oldest ages are similar to ages for the Port Sheldon Formation in the Hemlock Crossing core. Outwash terraces and slackwater lacustrine sediments of the Equality Formation in Illinois (Fig. 11) have produced optically stimulated luminescence (OSL) and calibrated radiocarbon ages from 60 ka to as late as 21 ka (Curry et al., 2011; Curry and Grimley, 2006). The glacial source for the Roxana Silt is likely to be the southwestern lobes of the Laurentide ice sheet such as the Superior, Des Moines, and Wadena lobes. These lobes delivered silt to the ancestral Illinois–ancient Mississippi River valleys before ~21 ka. After ~21 ka the Peoria Silt sourced its silt from the Green Bay and Lake Michigan lobes via the Illinois and modern Mississippi River Valleys (Grimley, 2000). The non-glacial nature of the Port Sheldon Formation confirms that Lower Michigan was unglaciated at ~65 to 29 ka, even though it is possible that Upper Michigan was glaciated at this time since no sites of pre-Michigan Subepisode organics have been reported from there. Some of the silt in the Port Sheldon Formation may have come via either a direct glacial source as meltwater, or was blown or washed into lake and wetland environments from sources similar to those of the Roxana Silt. Interestingly, wood ages from the Casnovia site in Muskegon County and Mill Creek in Sanilac County yield radiocarbon ages (~29 ka) that correlate with ages in northern Illinois for the Robein Silt Member of the Roxana Silt. This suggests that Michigan Subepisode ice advanced into Lower Michigan after ~29 ka at about the same time as in northern Illinois (Curry et al., 2011).

The Plymouth sediments (Fig. 11) are described in several cores from Sheybogan County in southeastern Wisconsin and they have yielded AMS radiocarbon ages of 39,530 ± 410 and 34,610 ± 390 ^{14}C yr BP from interbedded diamicton, sand, and silt units (Carlson et al., 2011). The calibrated ages for these samples (~43,500 to 39,800 cal yr BP) correspond to the Athens Subepisode and similar in age to those in the Port Sheldon Formation. The Plymouth sediments themselves must be younger than the Athens Subepisode since they contain detrital wood of Athens Subepisode age in sands and diamictons. This suggests they are from an early Michigan Subepisode advance that eroded Athens Subepisode sediments and probably correlate in age with the Tiskilwa Till Member of the Zenda Formation of southeastern Wisconsin (Fig. 11).

In southern Ontario, MIS 3 age organics have also been found in numerous borings and in quarry overburden exposures (Bajc et al., 2015). Seven AMS radiocarbon ages ranging from 50,500 to 42,900 ^{14}C yr BP have been obtained from organic sediments at the Zorra Quarry just east of London, Ontario. As in the Hemlock Crossing core, organic sediments underlie two Michigan Subepisode tills, and overlie two older tills (Bajc et al., 2015). These sediments suggest boreal vegetation at this site. Organic sediments of MIS 3 age are also described in Iowa ranging in age from >50 to ~23.3 ka (Baker et al., 2009). The Iowa sites suggest open prairie and parkland environments with interspersed marshes, and cooler temperatures. Loess began to fill these wetland environments in Iowa after ~29 ka (Baker et al., 2009). In summary,

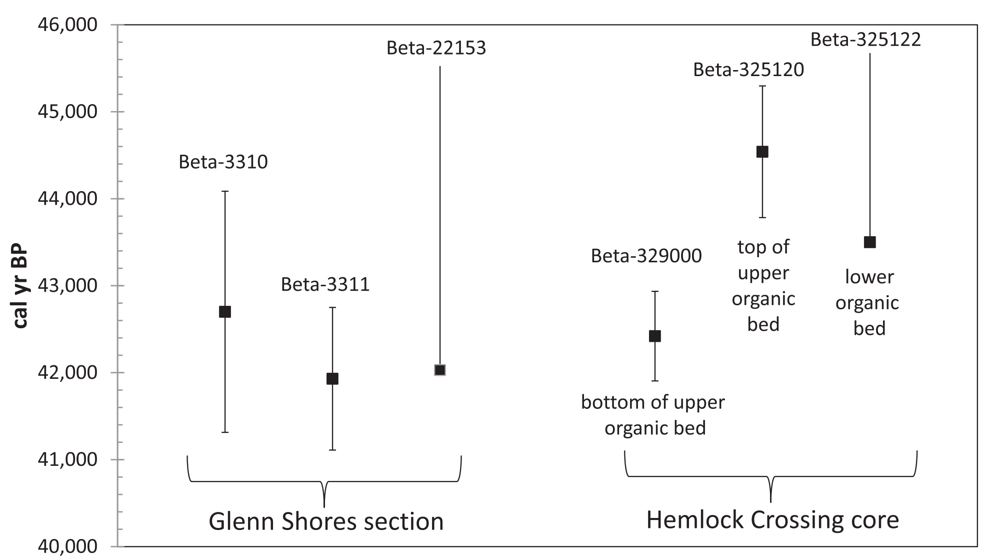

Figure 10. A comparison of radiocarbon ages with 2 σ uncertainties of the Glenn Shores (Larson and Monaghan, 1988) section and the Hemlock Crossing core. The Glenn Shores radiocarbon ages were calibrated using CalPal radiocarbon calibration program.

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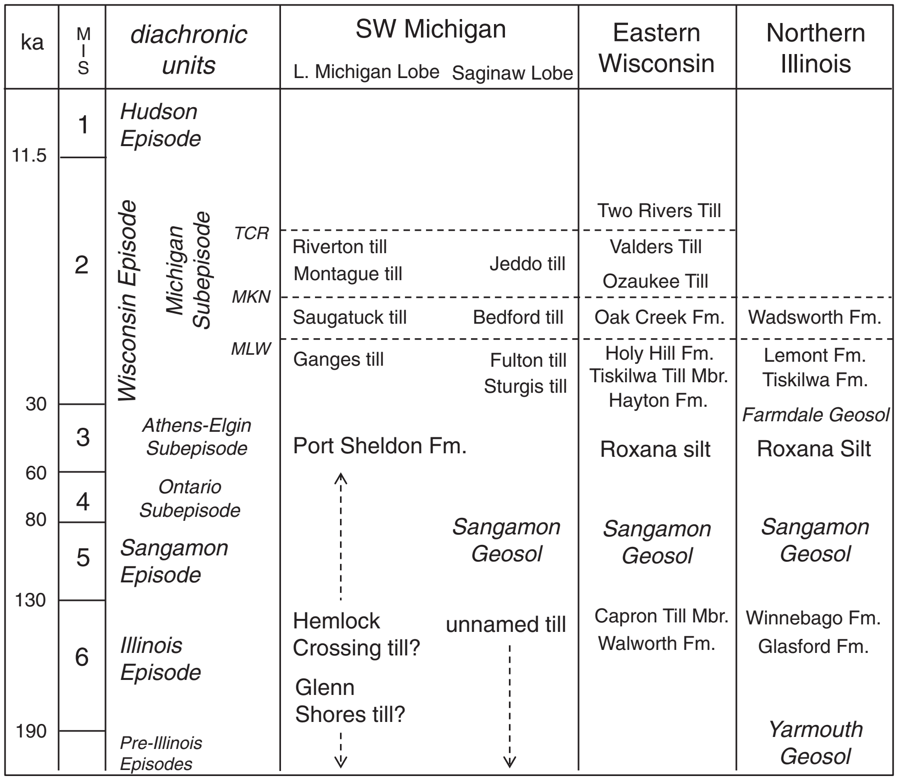

Figure 11. Stratigraphic units of southwestern Michigan (Larson, 2011 and this study) compared to those in Illinois (Curry et al., 2011) and Wisconsin (Syverson and Colgan, 2004, 2011). Regionally correlated phases of ice lobe recession of during of the Michigan Subepisode are *TCR* — Two Creeks Phase, *MKN* — Mackinaw Phase, and *MLW* – Milwaukee Phase (Larson, 2011).

there is widespread evidence in the Great Lakes and Central Lowlands for an ice free period of cool and moist conditions during most of MIS 3 between ~65 and 29 ka.

Correlation to till units in southwestern Michigan

Both the Glenn Shores till at the type section and unit 1 have loam to sandy loam textures, high stone contents, and high kaolinite–illite ratios (Table 5). We propose that the lowest till in the core is correlative to the Glenn Shores till. The Glenn Shores section is ~55 km south of Hemlock Crossing and is in a similar geomorphic position behind the inner Lake Border moraine. Unlike the Glenn Shores till, the reddish brown color at the top of unit 1 suggests some weathering after deposition, or alternatively a change in provenance. Such coloring is common in thin cambic B horizons with partial carbonate leaching. Arguing against weathering, chlorite–illite ratios (Fig. 7) show no decrease in chlorite relative to more stable illite as would be expected in a B horizon (Hughes et al., 1994). At the Glenn Shores section a gravel bed is described on top of the Glenn Shores till, so this could be interpreted as evidence of wave erosion at this site. We suggest that the reddish coloring in unit 1 is evidence of at least a minor unconformity, perhaps as a truncated paleosol. Well-preserved paleosols in subglacial till successions are rare, because these soils are commonly truncated by the next glaciation. Also, lowland sites of important marker soils like the Sangamon Geosol do not always have bright colors in horizons or major clay mineral alterations (e.g. Jacobs et al., 2009). Unit 1 was probably deposited during the Illinois Episode or during a pre-Illinois Episode, but we cannot rule out an Ontario Subepisode age (MIS 4) because the Sangamon Geosol is lacking in the core.

The sandy texture, gravel content, local pebble lithology, and high kaolinite–illite ratios of the Glenn Shores till are similar to some of the Saginaw lobe tills described in central Lower Michigan (Rieck et al., 1979; Monaghan and Larson, 1986). Because of this we infer that the Glenn Shores till likely has a Saginaw lobe provenance. Rieck et al. (1979) found that Saginaw lobe surface tills in southeastern Michigan have kaolinite–illite ratios of 0.91 or higher, and are significantly different from Huron–Erie lobe tills that have lower ratios. They also found that bedrock samples traversed by the Saginaw lobe also have high kaolinite–illite ratios (>1). High kaolinite–illite ratios in Saginaw Lobe tills may reflect incorporation of Pennsylvanian fluvial and deltaic

Table 5
Comparison of Hemlock Crossing core diamicton units and defined till units in southwestern Michigan.

Hemlock Crossing diamictons and fines (unit #)	%sand-%silt-%clay	Kaolinite/illite ratio	Previous studies[b]	%sand-%silt-%clay[a]	Kaolinite/illite ratio
subglacial till (5a) and debris flow/rain out	15-34-51	0.88 ± 0.08	Saugatuck till	36-42-22	0.58 ± 0.04 (25) 0.57 ± 0.19 (46) 0.32 ± 0.16 (8)
subglacial till (5b)	33-29-38	0.79 ± 0.03	Ganges till	59-22-19	0.85 ± 0.11 (39) 0.84 ± 0.18 (16) 0.64 ± 0.22 (22)
middle till (3)	31-31-38	0.98 ± 0.04	Glenn Shores	46-34-20	1.21 ± 0.16 (21)
lower till (1)	46-27-27	1.22 ± 0.08			

[a] Clay size is defined as b4 μm in order to facilitate a comparison to these previous studies, which use 4 μm as the clay-silt break.
[b] Matrix texture and clay mineral data are from compilation of Monaghan (1990) Table 2 for first value, Beukema (2003) for second values, and Wong (2002) for third value.

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sandstone units that generally contain more kaolinite than the illite-rich Mississippian shale or older marine sequences.

Unit 3 is rich in fines and gravel-poor and different from the Glenn Shores till in kaolinite–illite ratio. It is similar to Lake Michigan lobe tills of the Michigan Subepisode, but it has a slightly higher kaolinite–illite ratio than either the Saugatuck or Ganges tills (Table 5). As such, we propose unit 3 as a new unit called the Hemlock Crossing till after the location of core OT-12-01 in Hemlock Crossing County Park, Ottawa County, Michigan. The Hemlock Crossing till likely has a Lake Michigan lobe provenance based on its fine texture, high illite content, and local gravel content. The finer mean texture probably reflects greater incorporation of glaciolacustrine fines perhaps from the proglacial lake in which unit 2 was deposited.

Like the Glenn Shores till at the type section, unit 3 shows no evidence of weathering in its upper portion based on a lack of soil colors, leaching, or low chlorite–illite ratios (Fig. 7). A lack of weathering in the Glenn Shores till has been cited as evidence that it may have been deposited during the Ontario Subepisode or MIS 4 (Johnson, 1986). A lack of a paleosol developed in the Hemlock Crossing till also does not rule out deposition during MIS 4, but it is more likely that a paleosol was eroded before deposition of the overlying Athens Subepisode sands and organic silts. As with the Glenn Shores till, the Hemlock Crossing till was probably deposited during the Illinois Episode or during a pre-Illinois Episode, but we cannot rule out an Ontario Subepisode age (MIS 4).

In southwestern Michigan there are few pre-Michigan Subepisode sites for us to compare our observations to besides the Glenn Shores section. Zumberge and Benninghoff (1969) demonstrated that sandy till, near Grand Rapids, Michigan underlies organic beds, which probably formed during the Athens Subepisode or an older ice-free interval. This till (their unit T1) has similar texture and pebble lithology as Saginaw lobe tills, which are dominated by sedimentary clasts (Anderson, 1957), but this would have been an older advance of the Saginaw lobe based on the till's position below Athens Subepisode sediments. Also, tills in the Hemlock Crossing core have small pebbles dominated by local sedimentary clasts. The upper (unit 5) and middle (unit 3) tills in the Hemlock Crossing core contain ~85% sedimentary pebbles, while the lower till (unit 1) contains ~90% sedimentary pebbles. Based on their description and pebble count data, we suggest it is likely that the lowest till (T1) at Grand Rapids also correlates to the Glenn Shores till, but more research would need to be done to confirm this and to trace the units laterally in the subsurface.

Gardner (1997) and Flint (1999) describe a sandy till underlying a weathered zone in the subsurface of St. Joseph County, Michigan lying just above bedrock of Coldwater Shale. Gardner (1997) describes the till as underlying a paleosol near Sturgis, Michigan in western St. Joseph County and having a mean texture of 40% sand, 33% silt and 27% clay, and a kaolinite–illite ratio of 0.45 ± 0.07. Texturally this is similar to our lowest till (Glenn Shores till), but is very different in kaolinite–illite ratio even though both tills rest on the same illite-rich Coldwater Shale. This ratio was based on analysis of a weathered sample so probably does not reflect the unaltered ratio, or reflects local enrichment of illite from the Coldwater Shale. The pre-Wisconsin Episode till described by Flint (1999) in eastern St. Joseph County was leached of carbonates, heavily weathered, and so thin that both the texture and clay mineral analyses were limited to a single sample. Both researchers interpreted these weathered zones as a correlative to the Sangamon Geosol (Curry and Follmer, 1992; Jacobs et al., 2009). Both sites are in upland zones with elevations ~260 to 280 m above sea level and the top of the paleosol would have been between ~200 and 215 m above sea level. In comparison, the upper surface of the lowest till at Hemlock Crossing (Glenn Shores till) is ~150 m amsl (and about 25 m below current Lake Michigan level) so we would not expect to find a heavily leached and weathered zone in such lowland sites as at Hemlock Crossing and Glenn Shores.

We correlate the uppermost basal till (unit 5a) and glaciolacustrine fines (unit 6) to the Saugatuck till, the surface till in the area, and overlying Glacial Lake Chicago sediments respectively (Fig. 11). Texture of unit 5a is finer and clay is enriched with kaolinite compared to the Saugatuck till at Glenn Shores (Table 5), but this probably indicates a greater incorporation of lacustrine fines into this unit. This would increase fines and the kaolinite–illite ratios since lacustrine sediments have higher amounts of fines and kaolinite (Table 3, Fig. 7). Alternatively, it is also possible that both units 5a and 5b correlate to the Ganges till and this section does not contain Saugatuck till. This is unlikely because this site lies just a few kilometers behind the inner Lake Border moraine (Fig. 9), which is primarily composed of the Saugatuck till (Monaghan et al., 1986; Kehew et al., 2005). We correlate unit 5b to the Ganges till as it has a similar kaolinite–ratio (Table 5). The texture of unit 5b is also finer than the Ganges at the type section. The stratified diamicton (Dms) between massive diamictons of units 5a and 5b is probably proximal lacustrine formed by rainout and debris flows near the terminus. Additionally, the sharp contact and weakly stratified diamicton between massive diamictons suggest a break in sedimentation between units 5a and 5b.

In eastern Ottawa County there is a thick sequence of glaciolacustrine sands and clays between the surface till (Saugatuck till) and the underlying Ganges till. This glaciolacustrine sequence was likely deposited in Glacial Lake Milwaukee (Schneider and Need, 1985), or in an earlier proglacial lake. Kehew et al. (2005) described these sediments in Allegan and Van Buren Counties exposed in pits and in rotosonic borings. Well records and exposures show that up to 30 m of possible Glacial Lake Milwaukee sediments occur in eastern Ottawa County. At other sites such as at the Glenn Shores section the thickness of these glaciolacustrine sediments vary from zero to a few meters thick (Monaghan et al., 1986; Kehew et al., 2005). The Hemlock Crossing core is likely sampling a sequence similar to that at the Glenn Shores section where Glacial Lake Milwaukee is represented by stratified diamicton and thin lacustrine sediments interbedded between the Saugatuck and Ganges tills.

Till correlation based entirely on texture or clay mineral ratios is equivocal because of variability of these properties within basal tills, and the varying analytical methods used by different researchers. For example, Wong (2002) analyzed the clay mineralogy of Saugatuck and Ganges tills at the Glenn Shores type section, and found lower kaolinite–illite ratios for both units compared to the original study by Monaghan et al. (1986). The differences are probably related to the differing machine geometry of the XRD analysis, such as incident and receiving slit size and if a slit correction was applied to compensate for variable beam widths (and therefore intensity) at low 2θ angles. We found significant differences in whether or not we used a variable slit size to maintain beam width (and intensity). Slit corrected kaolinite–illite ratios were about 72.4% of the uncorrected values ($r^2 = 0.954$, $n = 41$). This perhaps explains the differences in kaolinite–illite ratios between the Wong (2002) and Monaghan et al. (1986) datasets, neither of which indicates whether a slit correction was applied.

Correlative pre-Athens Subepisode tills in the western Great Lakes region

Without numerical ages for the Hemlock Crossing and Glenn Shores tills it is impossible to determine their age more precisely than older than Athens Subepisode (Fig. 11). The tills could have been deposited during the Ontario Subepisode (MIS 4), Illinois Episode (MIS 6), or one of numerous pre-Illinois Episodes (pre-MIS 6).

In Wisconsin, the Merrill member of the Copper Falls Formation of northwestern Wisconsin is one of few tills of possible MIS 4 age that has been described in the western Great Lakes region (Syverson and Colgan, 2004, 2011). Numerical age data for this unit is a single non-finite radiocarbon age of >40,800 ^{14}C yr BP (IGS 256) on peat directly overlying the till (Stewart and Mickelson, 1976). The surface of the Merrill member still has recognizable glacial landforms, but is not as extensively eroded as Illinoian tills are in Wisconsin and Illinois

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(Syverson and Colgan, 2004, 2011). The surface morphology was used by early workers to classify glacial sediments in the Great Lakes as early Wisconsin or MIS 4 (Goldthwait, 1992). There are also other eroded moraine segments such as the Arnott moraine which lie outside of the Green Bay lobe of central Wisconsin, which may be older than the Michigan Subepisode, but younger than Illinois Episode because they do not have a Sangamon Geosol developed in them (Syverson and Colgan, 2004, 2011). The Hayton Till, which underlies the Athens Subepisode age Plymouth sediments is described in a dozen cores in Calumet, Manitowoc, and Sheboygan Counties, Wisconsin (Carlson et al., 2011; Mickelson and Socha, in press). This till has similar color and texture to the Hemlock Crossing till. Most of the early Wisconsin (MIS 4) age assignments in the Great Lakes were questioned or falsified in the 1980s and 1990s (e.g. Curry, 1989; Szabo, 1992; Clark et al., 1993; Curry and Pavich, 1996), and at this time the only hypothesized MIS 4 advance south of the Great Lakes is based on the Sunnybrook Till in the eastern Great Lakes region (Hicock and Dreimanis, 1989; Karrow et al., 2000; Larson, 2011).

Illinois Episode (MIS 6) tills have been described in Illinois and Wisconsin. In Illinois evidence for four or perhaps five glaciations is present (Curry et al., 2011). The Winnebago Formation (Fig. 11) of northern Illinois is from the latest part of the Illinois Episode (~190–130 ka) based on Sangamon Geosol developed in it and OSL and ^{10}Be ages, and amino acid analyses (Curry et al., 2011; Berg et al., 2013; Grimley and Oches, 2015). The underlying and more extensive Glasford Formation (Fig. 11) is till underlying the type area of the Illinois Episode (in its original definition). Older till units indicate two or three pre-Illinois Episode glaciations, perhaps occurring during MIS 12, MIS 16, and MIS 22 (see fig. 36.2 of Curry et al., 2011).

In northern Wisconsin, the River Falls Formation and the Bakersville member of the Copper Falls Formation are thought to be at least Illinois Episode based their the deep weathering profiles (Syverson and Colgan, 2004, 2011). There are older glacial sediments underlying these, some of which have reverse remnant magnetism indicating they are older than 0.78 Ma. In southeastern Wisconsin, the Capron Till Member of the Zenda Formation and the underlying Walworth Formation are both assigned to the Illinois Episode based on weathering surfaces and preserved paleosols (Syverson and Colgan, 2004, 2011).

Implications for ice-lobe dynamics and history

Kehew et al. (2005) hypothesized that the Saginaw lobe was the dominant and more extensive lobe in Lower Michigan as ice advanced to its late glacial maximum limit and during the early part of the Michigan Subepisode deglaciation. They argued that at its maximum extent the Saginaw lobe reached the eastern shore of Lake Michigan; and then began to down waste leaving stagnant ice filling tunnel valleys. The Lake Michigan lobe then surged over stagnant and down-wasting ice of the Saginaw lobe. A similar sequence of events may have also occurred in earlier glaciations and the Glenn Shores till could be an example of sandy Saginaw lobe till found west of its Michigan Subepisode extent. The finer textured Hemlock Crossing till may represent a subsequent pre-Wisconsin Episode Lake Michigan lobe advance that over ran the area recently deglaciated by the pre-Wisconsin Episode Saginaw lobe.

Summary and conclusions

1. We describe the first complete core to bedrock in southwestern Michigan containing a radiocarbon defined sequence of Michigan Subepisode glacial sediments, Athens Subepisode organic sediments, and two underlying tills presumably of the Illinois or pre-Illinois Episodes.
2. We propose the name Port Sheldon Formation for Athens Subepisode sands and interbedded organic silt underlying Michigan Subepisode tills and overlying older tills. This unit was deposited in lacustrine and palustrine environments that were probably restricted to lowlands during the Athens Subepisode.
3. The Hemlock Crossing core and water-well records in Ottawa County, Michigan suggest that the Port Sheldon Formation and older tills are common and locally laterally continuous. Our new radiocarbon ages supplement and correlate to existing radiocarbon ages (Table 1). These ages suggest that Lower Michigan was ice-free during the Athens Subepisode from ~65 to ~29 ka.
4. Lower (unit 1) and middle (unit 3) tills were most likely deposited during the Illinois or an older Episode, even though we cannot rule out an MIS 4 age. We correlate the lower till (unit 1) with the Glenn Shores till. We propose the name Hemlock Crossing till for a pre-Athens Subepisode till (unit 3) overlying the Glenn Shores till in the Hemlock Crossing core.
5. The upper lacustrine fines and tills were deposited during the Michigan Subepisode and correlate to the Ganges and Saugatuck tills and overlying lacustrine sediments of Glacial Lake Chicago. Glaciolacustrine sediments in this sequence were deposited near the ice margin in proglacial lakes Milwaukee and Chicago.
6. The Hemlock Crossing core and water-well records provide a glimpse of the enigmatic of pre-Michigan Subepisode events in Lower Michigan. A sustained program of rotosonic drilling linked to surface mapping and subsurface stratigraphic studies will be required to unveil this record. New geochronologic methods including cosmogenic radionuclide burial and OSL dating will be required to date the older glacial sequence. We highlight an untapped archive of pre-Michigan Subepisode (Wisconsin Episode) history that exists in Lower Michigan.

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