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OSL ages on glaciofluvial sediment in northern Lower Michigan constrain expansion of the Laurentide ice sheet

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Abstract

We report new ages on glaciofluvial (outwash) sediment from a large upland in northern Lower Michigan—the Grayling Fingers. The Fingers are cored with >150 m of outwash, which is often overlain by the (informal) Blue Lake till of marine isotope stage (MIS) 2. They are part of an even larger, interlobate upland comprised of sandy drift, known locally as the High Plains. The ages, determined using optically stimulated luminescence (OSL) methods, indicate that subaerial deposition of this outwash occurred between 25.7 and 29.0 ka, probably associated with a stable MIS 2 ice margin, with mean ages of ca. 27 ka. These dates establish a maximum-limiting age of ca. 27 ka for the MIS 2 (late Wisconsin) advance into central northern Lower Michigan. We suggest that widespread ice sheet stabilization at the margins of the northern Lower Peninsula, during this advance and later during its episodic retreat, partly explains the thick assemblages of coarse-textured drift there. Our work also supports the general assumption of a highly lobate ice margin during the MIS 2 advance in the Great Lakes region, with the Fingers, an interlobate upland, remaining ice-free until ca. 27 ka.

Keywords: Glaciation; Outwash; MIS 2; Great Lakes region; OSL dating; Laurentide ice sheet

Introduction

Grayling Fingers is the name given to a large, upland landform assemblage in northern Lower Michigan, formed mostly by late Pleistocene glacial and glaciofluvial processes (Fig. 1). Limited geomorphic and stratigraphic research has been done in this region; instead, most work has been associated with sites near the edges of the peninsula, by the Great Lakes and the large moraines that dominate there (Blewett, 1991; Blewett et al., 1993; Larson et al., 1994; Lichter, 1995; Schaetzl, 2001; Schaetzl et al., 2002; Fisher and Loope, 2005). The physiography, Quaternary stratigraphy, and soils of the Grayling Fingers (Fig. 1C) primarily reflect late Pleistocene glacial processes (Schaetzl and Weisenborn, 2004). Absolute age assessment of this landform assemblage is important to the regional glacial chronology, because it lies at the intersection of the Lake Michigan and Saginaw lobes, and may have been one of the last parts of Lower Michigan to be glaciated during marine isotope stage 2 (MIS 2; late Wisconsin) (Schaetzl and Weisenborn, 2004). With one exception (Blewett et al., 1993), age assessment in this area has been difficult because of the paucity of buried soils or carbon-rich materials in the dry sands for radiocarbon dating. Initial attempts at optically stimulated luminescence (OSL) dating of outwash sediments from the Fingers by Schaetzl and Weisenborn (2004) provided mixed results and only broad age control of ca. 15 to 30 ka. In this contribution we present ten new OSL ages on shallow channel facies of outwash sediment from the core of the Fingers, using advances in single aliquot regeneration protocols for quartz grains (Murray and Wintle, 2003; Olley et al., 2004). These ages provide new chronologic control on the advancing MIS 2 ice margin in this part of Lower Michigan and refine the understanding of ice-marginal locations and timing for the northern Michigan interlobate zone between the Lake Michigan and Saginaw lobes.

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Study area

The Grayling Fingers area forms the highest part of the sandy uplands of northern Lower Michigan, known locally as Michigan's "High Plains" (Davis, 1935; Figs. 1B, 2). They form a triangular assemblage of uplands that are about 43 km wide and 40 km in N–S extent, with flat-floored valleys (hereafter: Finger valleys) between them. The broad Finger valleys, assumed to be cut by glacial meltwater, are commonly 1.5 to 3.5 km wide and incised between 30 and 60 m below the uplands. The entire sediment assemblage slopes gradually to the south; most uplands in the northern third of the Fingers range in elevation from about 400 to 450 m ASL, whereas in the south the summits are about 365 to 400 m ASL.

The High Plains area is a broad, sandy upland, centered between the Lake Michigan and Saginaw lobes of the Laurentide ice sheet (Leverett and Taylor, 1915; Schaetzl and Weisenborn, 2004). Like the Fingers, the High Plains are dominated by sandy, glaciofluvial and possibly glaciolacustrine sediment, and coarse-textured diamictons (Fig. 1). Rieck and Winters (1993) reported on the great thickness of the drift in northern Lower Michigan, where it is commonly >150 m across the High Plains and approaches 300 m in the Fingers. The High Plains is dominated by the large outwash plain of the Port Huron readvance of the Laurentide ice sheet (Leverett and Taylor 1915; Fig. 1B). The Port Huron ice advanced to its farthest point ca. 15.1 ka (12,610–13,310 ^{14}C yr BP (TX-6151); Blewett, 1991; Blewett et al., 1993)[1]. The Port Huron advance is distinguished by its large head of outwash (morphosequence), associated with a stagnant ice margin (Blewett, 1991; Blewett and Winters, 1995). Its outwash plain has a conspicuous proximal slope that extends several km beyond and to the north of the Fingers. The valleys between the Fingers are generally graded to the Port Huron outwash plain, suggesting that they were occupied by Port Huron meltwater.

Much of the sandy and stratified drift in the Fingers is associated with glaciofluvial processes; sand dominates the High Plains in general and the Fingers in particular. Several m of sandy till, assumed to be associated with the MIS 2 advance over the Fingers and given the informal name Blue Lake till by Schaetzl and Weisenborn (2004), caps the thick outwash core (Fig. 1). A thin (<1 m), discontinuous silt cap on the crests of the flattest Finger uplands is the only major sedimentologic unit in the region that is not sandy, attesting to the dominance of glaciofluvial processes in the recent geologic past (Schaetzl and Weisenborn, 2004).

Methods

Our methods involved sampling of outwash facies in the Fingers for OSL dating. Unfortunately, there exists only three, currently active, borrow pits in the Fingers that are inset into the glacial outwash that forms the core of this landform, and all are near the center of the region (Fig. 1B). These three sites served as the focus of our sampling efforts. The first site, the Oakville cemetery pit, at 381 m elevation, is cut into the bottom-most part of the side slope of the Maple Forest Finger, and is stratigraphically the lowest of the three sampled. The other two sites, at the Waters landfill and the Waters gas station, are both near the top of the Maple Forest Finger, and hence, higher in the sequence of outwash sediment. The Waters gas station site, at 418 m elevation, is a sand and gravel borrow pit located about 3/4 of the way up the western sideslope (backslope) of the Maple Forest Finger. The Waters landfill site, at 415 m ASL, was exposed only for a few days during excavation. Although the landfill site is on the crest of the Maple Forest Finger, we were able to gain access to outwash sediment that had been recently exposed to a depth of approximately 5 m below the original upland surface. The sedimentology of the outwash sands and gravels at each of the sites is generally similar, but spatially and sedimentologically complex. Bed thicknesses range from mm to m, varying in granulometry from very fine sand to boulders.

We collected four samples for OSL analysis, from both the Waters landfill and gas station sites, and two samples from the Oakville cemetery site, using a two-inch black PVC pipe driven directly into freshly cleaned pit faces. Sedimentary sequences at the sampled horizons were represented by well-sorted, medium to fine sand in channel fills <20 cm thick, and with mm-scale horizontal to subhorizontal laminations (Fig. 3). Aliquots of fine to medium (150–250 or 250–355 μm) quartz sand were isolated for OSL dating. The outwash was probably deposited under low-energy flow and low turbidity conditions. The mm-scale bedding indicates bed accretion by ripple migration at depths of 10's of cm or less. This type of sedimentary facies was chosen for OSL sampling because the inferred depositional environment favors exposure of the outwash sediment to light, rendering little to no inherited luminescence (Berger, 1990; Forman, 1990). Indeed, it has been recently demonstrated that the fast component of the OSL signal in quartz is completely solar reset during fluvial deposition (Singarayer et al., 2005). The OSL fast and medium components for quartz grains from the Grayling Fingers accounts for >97% of the total emission and decays to near-background levels in the first 10 s of blue light exposure (e.g., Smith and Rhodes, 1994; Wintle and Murray, 2006). Solar resetting of the dated sediments to a low and consistently definable level is also indicated by Gaussian distribution of equivalent doses (Fig. 4) rather than a skewed distribution (Lepper and Mckeever, 2002).

Optically stimulated luminescence geochronology is based on the time-dependent dosimetric properties of silicate minerals, predominately quartz (Aitken, 1998). Single-aliquot regenerative (SAR) (Murray and Wintle, 2000, 2003; Olley et al., 2004) protocols were used in this study to estimate the equivalent dose of the 150–250 or 250–355 μm quartz fractions (Table 1; Fig. 3). Sands from northern Michigan are often mineralogically mature, consisting of well-sorted medium sand composed of >85% quartz (Mikesell et al., 2004). The quartz fraction was isolated by density separations using the heavy liquid Na polytungstate. A 40-min immersion in HF was applied to etch the outer 10+ microns of grains, which are affected by alpha radiation (Mejdahl

[1] All radiocarbon dates discussed in this paper were converted to calendar years using the radiocarbon calibration curve of Fairbanks et al. (2005), on the website: http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm. The ^{14}C-to-calendar year conversions for two ^{14}C dates that extended slightly beyond the range of this curve were visually estimated.

and Christiansen, 1994). The purity of the quartz extract was evaluated by petrographic inspection and point counting of a representative aliquot. Samples that showed >1% non-quartz minerals were retreated with HF and checked petrographically. Treatments with HF were often needed to obtain an extract with <1% non-quartz minerals.

To further ensure a mineralogically pure quartz emission for dating, samples were exposed to infrared excitation at 125°C to eliminate a feldspar component either from stray grains or inclusions within quartz (Olley et al., 2004). Thus, each aliquot of separated quartz grains was excited initially with infrared light to optically remove feldspathic components, and then exposed to blue light, which excited the remaining quartz component. In the purified quartz extract the quartz signal dominates, with ≥94% of the total emissions (Table 1). Although the corresponding negligible feldspar emissions have no statistically significant effect on ages, this small, potentially contaminating feldspar signal was removed with infrared excitation before determining equivalent dose with blue excitation.

An Automated Risø TL/OSL-DA-15 system (Bøtter-Jensen et al., 2000) was used for SAR analyses. Blue light excitation (470±20 nm) was from an array of 30 light-emitting diodes that deliver ~15 mW/cm^2 to the sample position at 90% power. A Thorn EMI 9235 QA photomultiplier tube coupled with three 3-mm-thick Hoya U-340 detection filters, transmitting between 290 and 370 nm, measured photon emissions. Laboratory irradiations used a calibrated ^{90}Sr/^{90}Y beta source coupled with the Risø reader. All SAR emissions were integrated over the first 0.8 s of stimulation out of 500 s of measurement, with background based on emissions for the last 90- to 100-second interval.

Before the application of SAR protocols, a series of experiments was performed to evaluate the effect of preheating at 180°, 200°, 220°, and 240°C on the regenerative signal (Murray and Wintle, 2000). These experiments showed that preheat temperatures of 220°C yielded the highest and most consistent equivalent doses. Therefore, aliquots were preheated at this temperature for 10 s for the SAR protocols. Tests for dose recovery were also performed and the results showed the last dose coincided well with the initial dose (at one-sigma errors). Up to 40 aliquots of quartz were analysed for each sample; only aliquots that yielded recycling ratios between 0.9 and 1.1 were retained.

A critical analysis for luminescence dating is the dose rate, which is an estimate of the exposure of the sediment to ionizing radiation from U and Th decay series, ^{40}K, and cosmic sources during the burial period (Table 1). The U and Th contents of the dose rate samples, assuming secular equilibrium in the decay series and ^{40}K, were determined by inductively coupled plasma-mass spectrometry (ICP-MS) analysed by Activation Laboratory LTD, Ontario, Canada. The beta and gamma doses were adjusted according to grain diameter to compensate for mass attenuation (Fain et al., 1999). A small cosmic ray component between 0.19 and 0.13±0.01 mGy/yr, depending on depth of sediment, was included in the estimated dose rate (Prescott and Hutton, 1994). A weighted, mean, volumetric soil water content of 15±5% was assumed for the cumulative period of burial. Optical ages are reported in years prior to AD 2000.

Age of outwash sediment in the Grayling Fingers

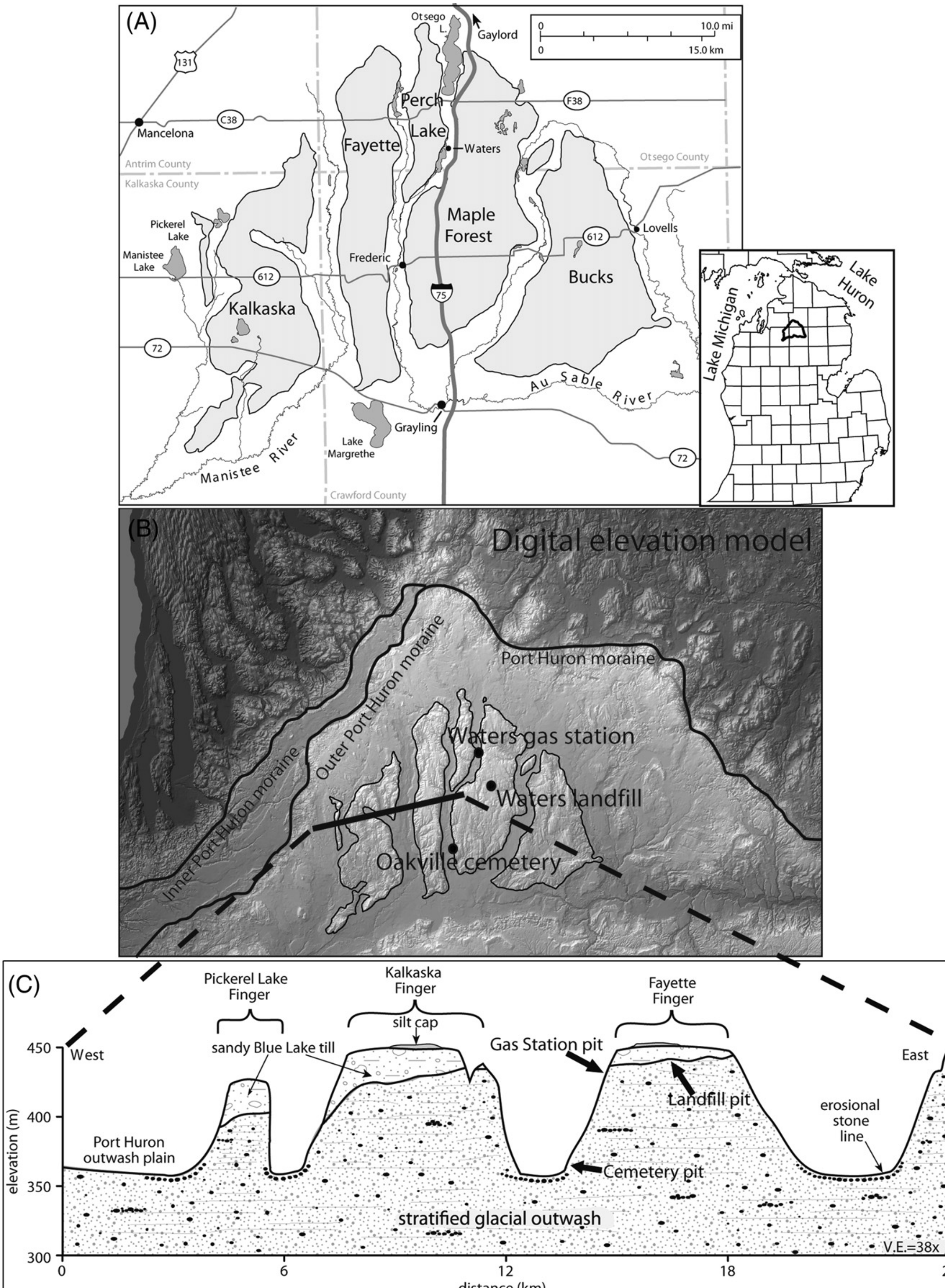
The Waters gas station and Waters landfill sites, which expose outwash near the top of the sequence, are each represented by four OSL ages, whose respective unweighted means and two-sigma errors are 27.27±2.76 ka and 26.75±4.46 ka respectively, (Table 1), suggesting that the ice advance onto the Grayling Fingers probably occurred after ca. 27 ka, and if the two-sigma error terms are used, within a time period spanning 22.3–31.2 ka (Fig. 5). The Oakville cemetery site, associated with outwash that is stratigraphically lower than the preceding two sites, is represented by two OSL ages with two-sigma errors of 27.86±5.32 and 30.98±6.52 ka. These ages overlap the OSL ages from the two Waters sites, but their mean age is slightly older, as would be expected for sediments lower in the stratigraphic column.

The OSL ages on glaciofluvial sediments in the core of the Fingers (Table 1) reflect deposition associated with the advance of the Laurentide ice sheet into northern Michigan, because the outwash sediment is overlain by a till sheet that is several m thick. This till sheet almost certainly was deposited as the ice advanced over its proglacial outwash during MIS 2 (Schaetzl and Weisenborn, 2004). It is unknown how much of the >150-m-thick glaciofluvial sediment package was deposited in the last glacial cycle. Schaetzl and Weisenborn (2004) suggested that at least the upper 37 m (i.e., most of the sedimentary units above the floor of the Finger valleys) can be attributed to the late Wisconsin advance.

Our dates are particularly important to, and useful in the interpretation of, the High Plains region, not only because organic matter is rare or non-existent here, but also because OSL dating provides an age estimate for emplacement of the sediment itself rather than on ancillary events such as tree death, soil burial or pond drainage. We believe that ours are some of the first successful and interpretable OSL dates on glaciofluvial sediment, in an ice-marginal location, in North America. Our work may validate this method—for this application—such that OSL dating may become increasingly valuable as a dating tool in the Great Lakes region, and for this time period, during which there was probably so little forest as to render the likelihood of finding wood in the drift very low (Clayton et al., 2001).

Onset of the MIS 2 (late Wisconsin) ice

Because of its general interlobate position, the Lower Peninsula of Michigan probably was glaciated later than nearby surrounding areas, which were nearer to the major ice lobe axes (Winters et al., 1988). However, direct evidence in support of this assertion is minimal. There exists only limited ^{14}C age control on wood buried beneath late Wisconsin drift in Michigan (Fig. 2). Eschman (1980), Johnson (1986) and Eschman and Mickelson (1986) summarized much of this information, and in Figure 2 we add ages (on wood only) that have been published since these three articles (Winters et al., 1986, 1988;


(A)
Otsego L.
Gaylord
0 10.0 mi
0 15.0 km
131
Perch
Lake
F38
C38
Mancelona
Fayette
Waters
Otsego County
Antrim County
Kalkaska County
Maple
Forest
Pickerel
Lake
612
Lovells
Manistee
Lake
Frederic
612
Bucks
75
Kalkaska
72
Au Sable River
Grayling
Lake
Margrethe
Manistee River
72
Crawford County
Lake Michigan
Lake
Huron
(B)
Digital elevation model
Port Huron moraine
Outer Port Huron moraine
Inner Port Huron moraine
Waters gas station
Waters landfill
Oakville cemetery
(C)
Pickerel Lake
Finger
Kalkaska
Finger
silt cap
Fayette
Finger
sandy Blue Lake till
Gas Station pit
Landfill pit
West
East
Port Huron
outwash plain
erosional
stone
line
Cemetery pit
stratified glacial outwash
elevation (m)
distance (km)
V.E.=38x

Rieck et al., 1991). Five published (but infinite) ^{14}C ages on wood (Crane and Griffin, 1961; Miller, 1973; Eschmann, 1980; Zumberge and Benninghoff, 1970; Benninghoff and Brunett, 1984) were examined during the course of this study but are not shown in Figure 2. We recognize that ^{14}C ages of ca. 35–50 ka may not be finite estimates because ages in this range are near the upper limit of ^{14}C dating (Taylor, 1987).

The ages shown in Figure 2 represent carbonaceous materials that all lie beneath what is presumably glacigenic sediment; all were buried by the advance of late Wisconsin ice. Therefore, they represent maximum-limiting ages for the last major glacial advance that covered southern Michigan. Although these radiocarbon ages were based on composite bulk samples, and the possibility exists of contamination, we nonetheless conclude from Figure 2 that MIS 2 ice did not enter the southern Lower Peninsula before about 30 ka, except perhaps in areas near the Great Lakes. This conclusion is largely supported by ages of 30.6 and 30.1 ka under the MIS 2 glacial drift on the eastern and western sides of Lower Michigan, near the current Lake Huron and Lake Michigan shorelines (Fig. 2). In their review of these data, Eschman and Mickelson (1986, 55) had earlier concluded that "much of the Southern Peninsula of Michigan was ice-free" prior to 24,000 ^{14}C yr BP (28.7 ka). Likewise, based on evidence near Toronto, Ontario, Eyles and Westgate (1987, 537) concluded that, during the "early phase of the Wisconsin glaciation" the Laurentide ice sheet was "thin, highly dynamic, and of insufficient volume to extend fully across the Great Lakes basins." The stratigraphically comparable radiocarbon ages from northern Lower Michigan (Fig. 2), older than ~40 ka, preclude mid-Wisconsin (MIS 3) ice from having covered these sites. However, the sites are not near the Great Lakes' shore, maintaining the possibility that MIS 2 ice had advanced onto the *margins* of the Lower Peninsula by that time, partly based on sedimentological and botanical data from buried sediments in NW Lower Michigan dated ≥40.5 ka (Site A, Fig. 2). Based on botanical evidence, Winters et al. (1986) concluded that the environment there, at that time, was a cold, boreal forest. They present other evidence for "an unusually large amount of glacial deposition" in the NW Lower Peninsula (p. 300), possibly suggestive of a nearby, stagnant or stable glacial margin. Rieck et al. (1991) also suggested that the environment of western Lower Michigan at about 48 ka was an open wetland with scattered spruce and larch, indicative of boreal conditions with a possible ice margin in the area, but their chronology remains untested. Lastly, Dyke et al. (2002) present a schematic diagram of the likely extent of the Laurentide ice sheet at ca. 27–30 ^{14}C yr BP (32.3–35.4 ka), which shows an ice margin in northern Lower Michigan at the northern edge of the Fingers and approximately parallel to the margin of Michigan's High Plains.

Taken collectively, this information suggests that an ice margin existed in or near the surrounding Great Lakes during MIS 3, consistent with an ice margin in the Upper Mississippi Valley and concomitant Roxana silt deposition in the Midwest ca. 35–55 ka (Forman and Pierson, 2002; Leigh and Knox, 1993; Leigh, 1994). These data also point to a generally ice-free northern and central Lower Peninsula as late as 30 ka.

With respect to final deglaciation during MIS 2, Michigan's northern High Plains and Fingers areas were ice-free by 15.1 ka (12,610–13,310 ^{14}C yr BP (TX-6151; Blewett, 1991), based on a ^{14}C age for organic materials in a proglacial pond on the proximal side of the Port Huron moraine. The Port Huron moraine marks a major glacial readvance in this region, and could only have occurred after the retreat of the ice from the Fingers (Blewett et al., 1993). In summary, OSL ages presented here do not contradict with earlier interpretations based on ^{14}C ages, and suggest that initial MIS 2 ice did not cover the Fingers until after about 27 ka and was gone by no later than 15 ka.

Implications for glacial chronology

Sedimentologic data, in conjunction with our OSL ages (Table 1) and the general lack of buried soils in the region, all suggest that much of the coarse-textured drift in northern Lower Michigan's High Plains is late Wisconsin in age (MIS 2) (Winters et al., 1986; Schaetzl and Weisenborn, 2004). We suggest that the ice margin associated with the deposition of outwash in the Fingers was stable at the northern, eastern and western edges of the Fingers for a millennium or more, based on (1) the immense volume of outwash that accumulated here (Blewett and Winters, 1995), (2) the coarseness and abundance of gravels and cobbles in the outwash at marginal locations in the Fingers (Schaetzl and Weisenborn 2004), and (3) the OSL ages of the outwash in the three sampled pits, which suggest continued proglacial deposition for at least 3–4 ka. Sediments there—at the northern, western and eastern edges of the Fingers—may have formed in association with a stable ice margin (Schaetzl and Weisenborn, 2004; Fig. 6). Coincidentally, oxygen isotope data from both the Atlantic and Pacific basins also support this interpretation; they show a relatively stable period of global ice volume and ^{18}O contents from ca. 37–28 ka, followed by a ca. 3–4 ka period of rapid growth (Shackleton and Pisias, 1985; Mix, 1987; Lambeck et al., 2002). GISP2 ice core data from Greenland also show a period of relatively constant ^{18}O content around 29–27 ka (Lowell et al., 1999a). Taken collectively, these data support our conclusion that the MIS 2 ice margin may have been stable in northern Lower Michigan until ca. 27 ka, and advanced over the Fingers shortly thereafter.

The Fingers represent a landform assemblage not unlike the Port Huron moraine in northern Lower Michigan, as the parallel morphology, sedimentology, and location of these two landform regions seem too similar to be coincidental (Fig. 1B). Both are large assemblages of sandy glaciofluvial sediment, reflective of shallow, braided stream conditions, and both are atop

Figure 1. General physiography, cultural features and stratigraphy of the Grayling Fingers. After Schaetzl and Weisenborn (2004). (A) Base map with major place and Finger names, major rivers and highways. (B) Digital elevation model of the region. Also shown are the three sites (two sand and gravel borrow pits and one landfill cell) that were sampled for OSL dating. (C) The internal stratigraphy and physiography of the Grayling Fingers, as exemplified by the three westernmost Fingers, with sample pit locations shown.

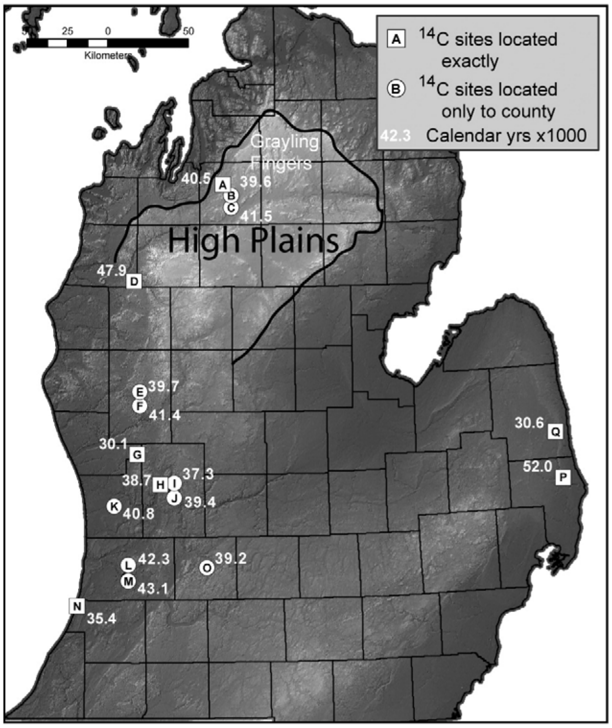


Figure 2. Locations of published dates of radiocarbon-dated materials, mainly wood, underlying drift in southern Michigan. The locations of the High Plains and the Grayling Fingers are also noted.

Key to map	Source	Original ^{14}C age (yr BP)	Calibrated age range[1] (yr BP)	Mean calibrated age shown on map (yr)
A	Winters et al. (1986)	34,200±1320 (BETA-9046) and 36,300±2450 (BETA-9273)	38,269–40,831 and 39,218–43,688	40,500
B[2]	Rieck et al. (1991)	34,200±1320 (BETA-9046)	38,269–40,831	39,600
C[2]	Rieck et al. (1991)	36,300±2450 (BETA-9273)	39,218–43,688	41,500
D	Stuiver et al. (1978)	45,800±700 (QL-963)	Visually estimated from curve	47,900
E[2]	Rieck et al. (1991)	34,340±520 (BETA-31046)	39,172–40,238	39,700
F[2]	Rieck et al. (1991)	36,120±620	40,785–41,939	41,400
G	Holman (1976)	25,050±700 (M-2145)	29,170–30,960	30,100
H	Eschman (1980)	33,300±1800 (I-5078)	36,895–40,425	38,700
I[2]	Rieck et al. (1991)	31,950±2600 (GX-8187)	34,730–39,886	37,300
J[2]	Rieck et al. (1991)	33,840± 1400/-900 (GX-8218)	38,318–40,568	39,400
K[2]	Rieck et al. (1991)	35,520±940 (BETA-21591)	39,927–41,691	40,800
L[2]	Gephart et al. (1982)	37,150±540 (BETA-3311)	41,765–42761	42,300
M[2]	Gephart et al. (1982)	38,130±740 (BETA-3310)	42,444–43766	43,100
N	Eschman (1980)	30,000±800 (W-108)	34,598–36,192	35,400
O	Winters et al. (1988)	33,810±750 (BETA-17891)	38,435–39,937	39,200
P	Eschman (1980)	25,480±700 (W-3667)	29,738–31,460	30,600
Q	Eschman (1980)	48,300±800 (QL-1215)	Visually estimated from curve	>52,000

[1]Conversion to calendar years using the radiocarbon calibration curve of Fairbanks et al. (2005), on this website: http://radiocarbon.ldeo.columbia.edu/research/radcarbcal.htm. The ^{14}C-to-calendar year conversion for two ^{14}C dates that extended slightly beyond the range of this curve was visually estimated.
[2]Additional dates, provided in Rieck et al. (1991) but not specific to location (only to county), are included here, but shown as circles and placed in the county centers because their exact location cannot be readily determined.

Figure 3. The Waters landfill exposure, a portion of which is seen here, provides a typical example of the fine-grained outwash sediment sampled for this study. One of the Waters Landfill OSL samples was taken from sediment like that within which the knife is embedded. Photo by RJS.

the High Plains physiographic region. Thus, we conclude that an ice margin was probably at or adjacent to the northern Lower Michigan locations shown in Figure 6B—at the N, W and E sides of the Fingers—for a significant period of time between ca. 30 and 27 ka, and that the upper parts of the Fingers outwash date to this period. The significance of this finding lies in the fact that, unlike most other morphosequences and areas of ice-marginal stability and/or stagnation in the Great Lakes region, the one associated with the Fingers was associated with the lateral margins of a generally advancing ice sheet, rather than a readvance during a period of regional ice recession (as at the Port Huron moraine). Curry and Yansa (2004) reported another example of ice-marginal stagnation associated with the advancing Lake Michigan lobe, but this event was much later in time, 21–18 ka. Therefore, the Grayling Fingers may represent the first landform/sediment assemblage in Michigan known to have formed mainly by advancing but marginally stable MIS 2 ice.

Northern Lower Michigan is bounded by two over-deepened lake basins (Lakes Michigan and Huron), which diverted the major ice lobes/advances around, and indeed, via their erosion, formed the Lower Peninsula (Fig. 6A). The southern Lower

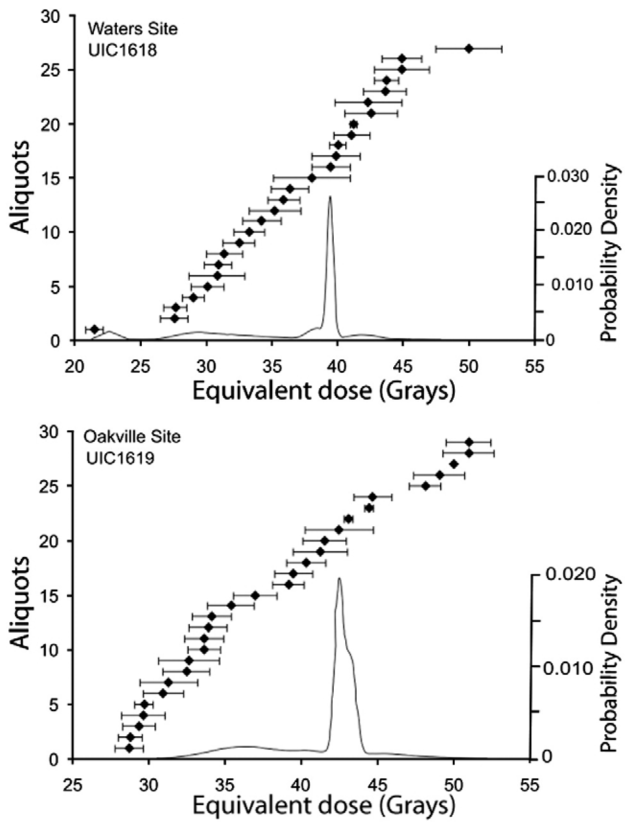


Figure 4. Plot of ranked equivalent dose values for aliquots of purified quartz grains from the Waters gas station and Oakville cemetery sites; the monotonic trend reflects a normal distribution. The curve is the probability density function defined by the equivalent dose data.

Peninsula has largely been influenced by the Saginaw glacial lobe (Rieck and Winters, 1993; Kehew et al., 1999; Fisher et al., 2005), which advanced into the region from the northeast and covered or influenced most of the state south and west of Saginaw Bay. The north-central part of the Lower Peninsula, located between the principal flow streamlines of the Lake Michigan and Saginaw lobes, became a type of glacial "backwater"—a widespread interlobate region where ice-marginal stability or stagnation was favored (Rieck and Winters, 1993; Schaetzl, 2001; Schaetzl and Weisenborn, 2004; Fig. 6A). For this reason, and perhaps others, such as regional bedrock topography, the area probably was glaciated later than areas to the east, west and even south. It stands today as a high, sandy upland, dominated by glaciofluvial and sandy glaciolacustrine sediments—the "High Plains" (Figs. 2, 6A). Whether the High Plains originated because of ice-marginal stagnation/stability, accompanied by large-scale proglacial outwash deposition, or whether ice-marginal stability occurred here because of a preexisting bedrock and/or drift-covered upland with steep marginal slopes, slowing the ice as it climbed out of the lake basins, is as yet unclear. It is possible that the two process scenarios have worked jointly to form this high, sandy upland.

Our data provide a key anchor point for the glacial chronology of the region, especially with regard to the MIS 2 advance. Most of the ^{14}C ages that have been used to refine the glacial chronology in the Great Lakes region are associated with the farthest ice advance, or with glacial readvances near the LGM or later, during the general period of ice retreat. In both cases, the ice buried organic materials provide a maximum-limiting date for the glacial event (Blewett et al., 1993; Kaiser, 1994; Larson et al., 1994; Curry et al., 1999; Lowell et al., 1999a, b). Two sets of radiocarbon dates have traditionally been used to define the outermost extent of the MIS 2 margin in southern Ohio (Lowell et al., 1990) and northern Illinois (Follmer et al., 1979). Both studies reported ages of about 19.7 ^{14}C ka BP for organics buried by the advance. This age calibrates to 23.5 cal ka BP (Fig. 6B). Additionally, Lowell et al. (1999a) reported several additional dates for organic sites in southern Ohio, overrun by the Laurentide ice at or near its southern margin. In this work, the Cincinnati radiocarbon dates reported above were refined to 19.6 ^{14}C ka BP (23.4 cal ka BP), and the means of the other calibrated dates from sites nearby are as follows: Chillicothe at 20.7 cal ka BP, Cuba City at 24.3 cal ka BP, and Todd Fork at 27.8 cal ka BP. It is likely that at least some of these dates represent readvances that postdate the LGM; Lowell et al. (1999a) even concluded that the Todd Fork sites (27.8 cal ka BP) represented, "the first expansion of the Laurentide ice sheet to its maximum extent."

Therefore, if we assume that the margin of the MIS 2 ice was generally anchored at the Fingers until at least ca. 27 ka, and using the dates given above for the LGM and the ice position(s) at that time, regional ice-geography scenarios can be envisioned. First, the ice could have advanced directly south from the Fingers, starting at 27 ka, to the southernmost MIS 2 margin by ca. 20.7 ka, in roughly 6300 yr. Alternatively, the ice margin may have been anchored at the Fingers *and* in southern Ohio at comparable times (27 ka), a scenario that would predicate a greatly expanded Huron–Erie lobe with a dramatic ice-marginal re-entrant in northern Lower Michigan. Given our knowledge of the geomorphology and bedrock geology of the region and based on an understanding of glacial processes, we envision a scenario closer to that latter—an advancing MIS 2 ice margin that was highly lobate, with a large interlobate re-entrant centered on the Fingers that remained open but generally surrounded by ice until at least ca. 27 ka (Fig. 6B). This scenario presupposes that the Lake Michigan, Saginaw and Huron–Erie lobes had advanced well to the south of the latitude of the Fingers by this time. Indeed, in Wisconsin, a subtle upland at roughly the same latitude, albeit a bedrock-cored one (the Wisconsin Arch), flanked by lowlands underlain by weaker rocks on either side (as is the case in Lower Michigan), similarly diverted the ice around and to either side. In Wisconsin, this "interlobate" area never did get closed.

We suggest that when the Fingers area finally did close and became covered with ice at ca. 27 ka, the margins of the Saginaw, Lake Michigan and Saginaw lobes were much farther south. The ice that covered this area effectively ended outwash deposition in the Fingers and deposited several m of sandy, Blue Lake till (Schaetzl and Weisenborn, 2004) across the Fingers. In the ensuing millennia, continuing ice advances, mainly along the axes of the Lake Michigan, Saginaw and Huron–Erie lobes, allowed the outermost MIS 2 ice margin to coalesce across central and southern Ohio, Indiana and Illinois (Fig. 6B; Lowell et al.,

Table 1
Single aliquot regeneration ages for the coarse-grained quartz fraction of glaciofluvial sediments at three sites in the Grayling Fingers of northern Lower Michigan

Laboratory #	Aliquots	Particle size (um)	Equivalent dose (Gy)[1]	U (ppm)[2]	Th (ppm)[2]	K_20 (%)[2]	Cosmic dose (Gy/ka)[3]	Dose rate (Gy/ka)[4]	SAR age (ka)[5]
Waters gas station									
UIC1527	30	250–355	26.36±1.25	0.90±0.1	2.3±0.1	0.78±0.01	0.11±0.011	1.02±0.05	28.57±3.08
UIC1528	30	250–355	33.92±2.50	0.7±0.1	2.3±0.1	1.08±0.01	0.17±0.017	1.26±0.06	26.99±2.89
UIC1620	26	150–250	41.59±1.52	0.6±0.1	1.7±0.1	1.32±0.01	0.17±0.017	1.50±0.07	27.64±2.20
UIC1618	30	150–250	38.58±1.94	0.9±0.1	2.0±0.1	1.23±0.01	0.13±0.013	1.48±0.07	26.09±2.66
								Unweighted mean	27.27±1.38
Waters landfill									
UIC1779	27	150–250	24.82±0.14	0.5±0.1	1.4±0.1	1.00±0.01	0.19±0.019	1.12±0.05	22.06±1.79
UIC1776	30	150–250	42.84±3.15	0.6±0.1	1.4±0.1	1.26±0.01	0.17±0.017	1.43±0.07	29.42±2.39
UIC1777	25	150–250	45.40±2.66	0.4±0.1	1.9±0.1	1.30±0.01	0.19±0.019	1.48±0.07	30.76±3.33
UIC1778	26	150–250	37.64±4.28	0.5±0.1	1.3±0.1	1.39±0.01	0.17±0.017	1.51±0.07	24.85±3.36
								Unweighted mean	26.75±2.23
Oakville cemetery									
UIC1619	30	150–250	42.30±1.84	0.4±0.1	1.3±0.1	1.55±0.01	0.14±0.014	1.52±0.07	27.86±2.66
UIC1617	30	150–250	38.95±2.50	0.5±0.1	1.4±0.1	1.22±0.01	0.11±0.011	1.26±0.06	30.98±3.26
								Unweighted mean	27.33±1.32

[1]Single aliquot regeneration (SAR) protocols determined equivalent dose with an initial infrared wash and subsequent blue light excitation (Murray and Wintle, 2003; Olley et al., 2004).
[2]U, Th and K_20 contents determined by ICP-MS by Activation Laboratory Inc. Ontario, Canada.
[3]Based on Prescott and Hutton (1994).
[4]Includes an assumed, long-term, volumetrically weighted moisture content of 15±5%.
[5]All errors are at 1 sigma.

1999a). The remainder (post-23.5 ka) of the MIS 2 glaciation then represents a period of regional ice-marginal stability or episodic retreat.

Conclusions

Results of the present research improve our understanding of dynamics or geography of the advancing Laurentide ice sheet during MIS 2 within the Great Lakes region and provide a key datum for the advancing ice margin in northern Lower Michigan. Luminescence ages on ten glaciofluvial sediment samples from the Grayling Fingers, ranging in age from 30–25 ka and with a mean age of ca. 27 ka (Table 1; Fig. 5), provide a maximum-limiting age for the MIS 2 advance into northern Lower Michigan. Our OSL ages also support the longstanding but generally untested notion that the advancing ice margin was highly lobate, just as it was during its retreat (Farrand and Eschman, 1974; Fig. 6B).

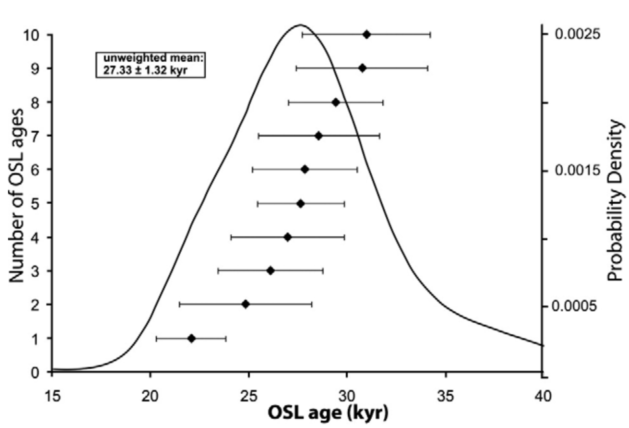


Figure 5. Plot of ranked single aliquot regeneration (SAR) ages for outwash sediments from Grayling Fingers. The curve is the probability density function defined by the ranked SAR ages.

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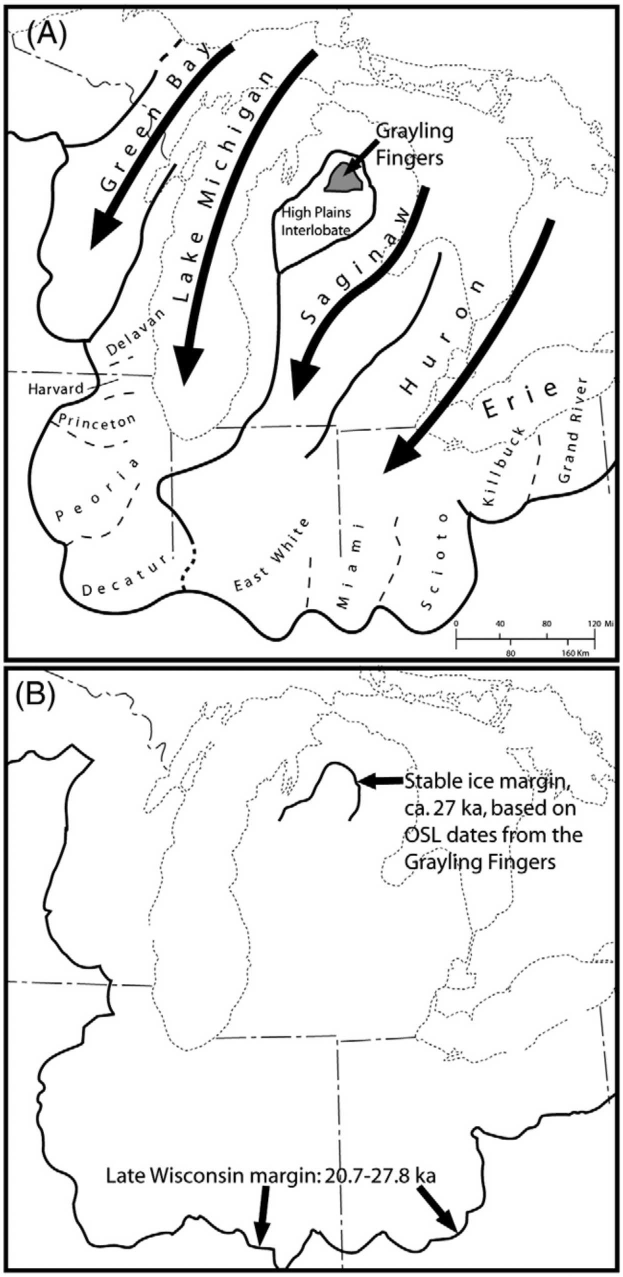

Figure 6. The geography of the glaciation, known and inferred, of Michigan and points to the south. A. The major glacial lobes in the Great Lakes region, as they relate to the Grayling Fingers. Margins of glacial lobes based on maps in Kehew et al. (1999) and Fullerton (1986). B. Likely margin of the advancing Laurentide ice sheet, ca. 27 ka, in the vicinity of the High Plains.

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