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Numeric control on the late-glacial chronology of the southern Laurentide Ice Sheet derived from ice-proximal lacustrine deposits

Eric C. Carson [a,*], Paul R. Hanson [b], John W. Attig [a], Aaron R. Young [b]

[a] University of Wisconsin-Extension, Wisconsin Geological & Natural History Survey, 3817 Mineral Point Road, Madison, WI 53705, USA
[b] University of Nebraska-Lincoln, School of Natural Resources, 3310 Holdrege Street, Lincoln, NE 68583, USA

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ABSTRACT

We used a combination of radiocarbon and OSL dating in ice-proximal lacustrine silt and clay and outwash sand to estimate when ice of the Green Bay Lobe of the Laurentide Ice Sheet began retreating from its maximum position in south-central Wisconsin. The radiocarbon ages indicate that lakes had formed in the two tributary valleys by ~17.2 and 20.1 ka, respectively. The OSL ages indicate that the Green Bay Lobe was at its maximum position from about 26.4 ± 5.1 ka to 21.4 ± 3.3 ka. These data provide entirely new chronologic control on late Wisconsin (Marine Isotope Stage 2) glacial event in the upper Midwest, as well as the opportunity to directly compare radiocarbon and OSL ages in this setting.

Introduction

Establishing a detailed chronologic record of ice margin fluctuations for the southern margin of the Laurentide Ice Sheet has historically proven to be an elusive goal. Despite concentrated efforts over the past several decades, no well-constrained numerical chronology exists for fluctuations of lobes of the Laurentide Ice Sheet during the middle and late Wisconsin (see Mickelson et al., 1983; Attig et al., 1985). Much of our understanding of the Midwest glacial record rests on studies of key stratigraphic sections and sites (e.g., Maher, 1982; Leigh and Knox, 1994; Maher and Mickelson, 1996; Lowell et al., 1999). While understanding the stratigraphy, sedimentology, and chronology at a specific site is valuable, it fails to provide the broader insight provided by a regional perspective. The numerical data that form our regional understanding of the glacial chronology in the midcontinent relies primarily on a relatively small number of radiocarbon and, more recently, cosmogenic exposure dates (e.g., Colgan et al., 2002; Ullman et al., 2011).

The struggles to develop a radiocarbon-based chronology for the southern Laurentide Ice Sheet have been driven by several factors. Permafrost conditions existed in Wisconsin and elsewhere in the midcontinent during and following the late Wisconsin maximum based on the presence of ice-wedge casts, ice-wedge polygons, and other permafrost-related features that are preserved in sediments deposited during the late Wisconsin maximum (Clayton et al., 2001). The existence of permafrost likely plays a critical role in the absence of closely limiting radiocarbon ages in the midcontinent during the critical time period of 32 to 16 ka (Syverson and Colgan, 2011). The radiocarbon dates that do exist from glacial environments are often difficult to interpret and correlate with discrete events. Glacial sediments and landforms can be unstable for a significant time following deposition, directly limiting the ability to relate the age of organic growth relative to glacial events (e.g., Lowell, 1995; Grimm et al., 2009). For example, basal dates from kettles reflect the timing of stagnant blocks melting to form the kettles rather than retreat of the ice sheet; a lag of centuries to millennia can occur between the glacial retreat and kettle formation (Porter and Carson, 1971; Mickelson and Borns, 1972). Radiocarbon data can limit the timing of glacial advances and retreats but rarely constrain an ice margin in place and time. The Two Creeks forest bed in east-central Wisconsin is such an example (Broecker and Farrand, 1963; Hooyer, 2007). The numerous dates from this site document the timing of ice retreat that allowed the spruce forest to grow and the timing of ice advance that overran the forest, but the dates provide no insight into the ice margin position at the ends of the retreat and advance.

Due to the pervasive lack of easily interpretable organic material dating to the late Wisconsin maximum, alternative dating methods have been employed, including OSL dating. Over the past several decades, OSL dating has been successfully applied to a range of geomorphic settings (see Rittenour, 2008; Wintle, 2008). In recent years, OSL dating has been applied in a number of settings in the upper Midwest in an attempt to refine the chronology of late glacial events by directly dating sediment from ice-marginal lakes (e.g., Hooyer, 2007; Lepper et al., 2007; Fisher et al., 2008). However, these studies were conducted in large lakes with complex histories where lake levels may not be easily associated with moraine positions, and may have been hampered

* Corresponding author. Fax: +1 608 262 8086.
E-mail address: eccarson@wisc.edu (E.C. Carson).

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by problems with the use of OSL in lacustrine settings that include partial bleaching (Fuchs and Owen, 2008), low luminescence signals in quartz grains (Lukas et al., 2007), and uncertainties in estimating environmental dose-rate values.

Recently, Attig et al. (2011) applied OSL dating to lacustrine sediments deposited in small ice-dammed lakes high in the Baraboo Hills in south-central Wisconsin. The lakes' landscape positions clearly show that they drained as soon as ice began to retreat from its maximum position; OSL ages indicate that this occurred at ~18.5 ka. These promising results suggest that OSL can be applied to ice-proximal lacustrine sediments for constraining the local glacial history; however, the lakes from this study did not contain datable carbon and therefore the OSL age estimates are not supported by ages obtained using other dating methods.

In the Baraboo Hills and lower Wisconsin River valley, many small ice-proximal lakes existed. Regional geologic studies (Clayton and Attig, 1989, 1990, 1997) indicate that these lakes' histories can be confidently correlated to discrete events of the Green Bay Lobe. Initial coring at two sites, Marsh Valley and Swamplovers Valley (Fig. 1), has suggested a direct relationship between the lakes' histories and the Green Bay Lobe's late Wisconsin advance and retreat, and has also revealed a unexpected wealth of organic matter to provide radiocarbon control from the end of the late Wisconsin maximum (Carson et al., 2011). These data represent new numeric control on the onset of retreat from the late Wisconsin maximum. They also provide the opportunity to directly compare radiocarbon and OSL age estimates derived from ice-proximal lake sediments. In this paper, we describe the evolving methodology and application of OSL dating in ice-proximal lacustrine settings combined with radiocarbon control to both evaluate the utility of OSL dating in this environment and to provide new, precise numeric control on the timing of the late Wisconsin maximum for the Green Bay Lobe.

Setting

The juxtaposition of the well-integrated drainage system of in the Driftless Area of southwestern Wisconsin, the resistant quartzite uplands of the Baraboo Hills, and the late Wisconsin ice margin create a setting where many ice-proximal lakes formed in a variety of distinct geomorphic settings at different times relative to glacial advances and retreats (Fig. 1). Several moraines are found in close proximity to the Wisconsin ice margin: the Johnstown moraine (late Wisconsin maximum) and the Elderon and Milton moraines (recessional moraines post-dating the Johnstown moraine). Previous 1:100,000-scale geomorphic mapping and other research (see Clayton and Attig, 1989, 1990, 1997) has identified former ice- and outwash-dammed lakes that existed at various times and can be correlated to the different ice margin positions.

Two tributary valleys, Marsh Valley and an unnamed tributary informally referred to here as Swamplovers Valley, are located in a precise landscape position such that Johnstown-age ice advanced only roughly 2 to 3 km into their headwaters at the time of maximum ice extent. Outwash prograded down these valleys only when ice was at its maximum position; prior to and following the late Wisconsin maximum, lakes existed in these tributaries (Fig. 2). Radiocarbon and OSL dates from near the base and top of the outwash in the tributary valleys can therefore be interpreted to reflect the timing of advance to, and retreat from, the Johnstown position.

Methods

Field

Coring at Marsh Valley and Swamplovers Valley was conducted with Geoprobe direct-push coring which collected 5-cm diameter cores. At both sites, Geoprobe cores retrieved samples entirely through the

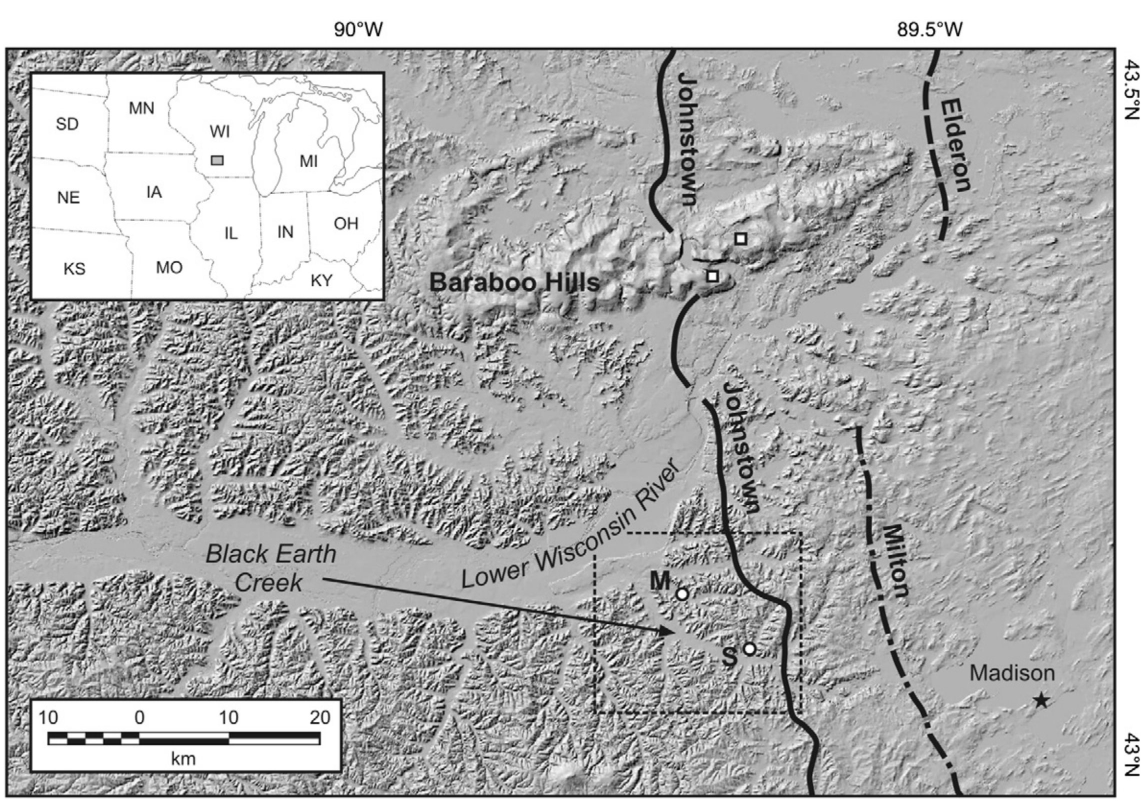

Figure 1. Topography of south-central Wisconsin showing Baraboo Hills and lower Wisconsin River valley in relation to Johnstown, Milton, and Elderon moraines. White circles identify locations of Swamplovers Valley ('S') and Marsh Valley ('M') coring sites; white squares identify study sites of Attig et al. (2011). Inset map shows location of study area as gray box. Area of Fig. 2 identified by dashed box.

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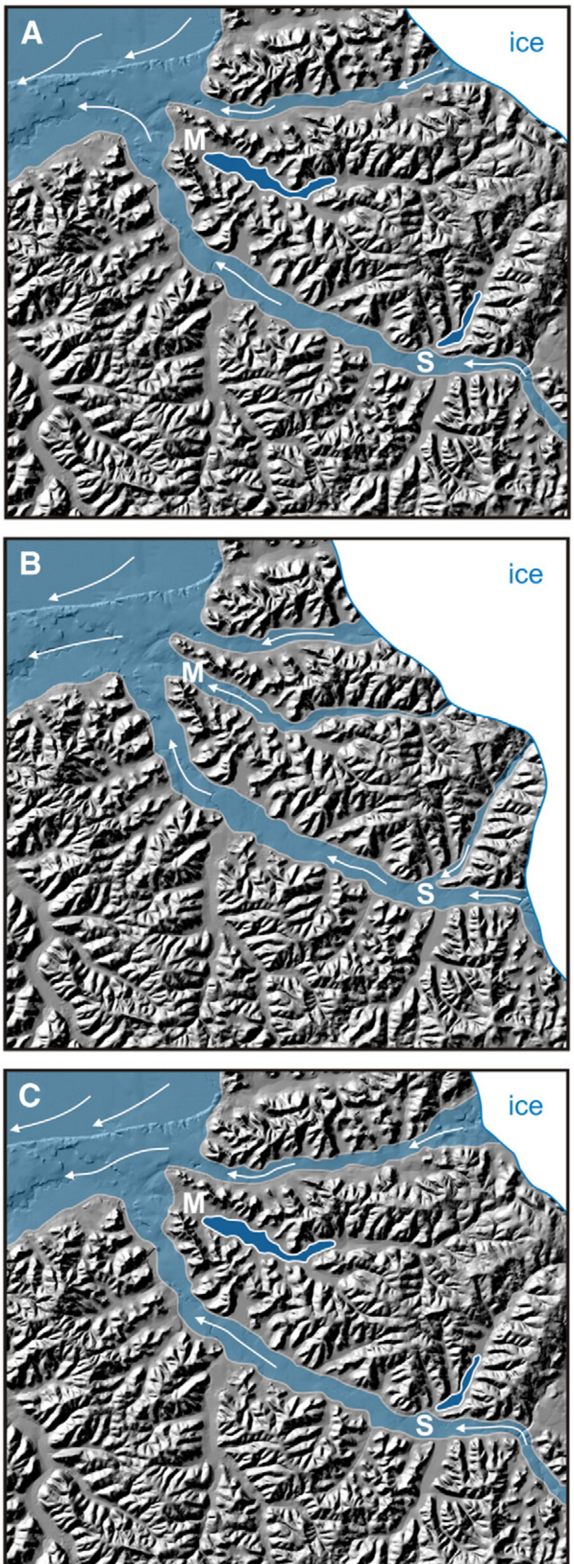
post-glacial lake section and Johnstown phase outwash, and into laminated silt and clay interpreted to be pre-Johnstown lake sediment. Two cores were collected at Marsh Valley and seven cores were collected at Swamplovers Valley to ensure collection of ample material for laboratory analyses, including AMS radiocarbon dating. At each site, the multiple cores were tightly spaced (all within 2 m of each other). Cores were split and described; key sections suitable for OSL dating were then resampled using black-coated Geoprobe core liners and transported to the Luminescence Geochronology Laboratory at the University of Nebraska-Lincoln for analysis.



Laboratory

We used similar OSL dating procedures to those used by Attig et al. (2011) on samples of lacustrine sediment from the Baraboo Hills (see Fig. 1). Quartz grains were isolated by sieving, floatation in heavy liquid and treatments in hydrofluoric and finally hydrochloric acid to etch quartz grains and remove feldspars. OSL measurements were made on a Risø model DA 20 TL/OSL reader equipped with a $^{90}Sr/^{90}Y$ beta source. D_e values were determined through the use of the SAR method (Murray and Wintle, 2000), which was run using six beta doses that included a zero dose and one repeated dose. OSL signals were measured for 40 s at 125°C. Each aliquot contained approximately 150 to 250 grains, 90–150 μm diameter, that were mounted to the inner 2 mm of the 1-cm disk. This 'small aliquot' procedure was done to limit the potential impact of partial bleaching on our samples. A preheat temperature of 220°C was determined using a preheat plateau test (Wintle and Murray, 2006) and a cut heat temperature of 160°C was used for test doses. OSL signals for natural, regenerative doses, and test doses were integrated using the first four channels of the shinedown after subtracting the background signal calculated from averaging the last 31 channels measured. Individual aliquots were rejected if they had measurable signals when exposed to IR diodes, recycling ratios that were $>\pm 10\%$, or if they had D_e values that were greater than the highest regenerative dose. Final age estimates were based on at least 32 accepted aliquots. Environmental dose-rate estimates were determined using the concentrations of K, U, and Th as determined by high-resolution gamma spectrometry. The cosmogenic component of the dose rate was calculated using equations from Prescott and Hutton (1994), and the final dose-rate values calculated following equations from Aitken (1998).

Results and discussion

Geoprobe coring at the Swamplovers and Marsh Valley sites (Fig. 3) confirmed the presence at these locations of sediment consistent with the depositional model described in Figure 2. At Swamplovers Valley, approximately 2.2 m of silty clay with abundant riparian plant macrofossils and dispersed organics (swamp) overlie 3.7 m of dark gray to black laminated silt (lacustrine); this in turn rests on 6.0 m of medium to coarse sand and gravel (outwash). Beneath the sand and gravel, an additional 3.4 m of weakly laminated silt (lacustrine) was collected. No samples were retrieved below that depth, although solid-stem core was advanced to the bedrock surface at 28.5 m depth. A similar stratigraphy was encountered at Marsh Valley. Including the surface tilled horizon, approximately 13.4 m of dark gray to black laminated silt (lacustrine) overlies medium to coarse sand and gravel (outwash). A total of 7.4 m of sand and gravel was retrieved; bedrock was encountered at 34.5 m depth.

At both Swamplovers and Marsh valleys, the laminated silty clay overlying the sand and gravel contained a surprising abundance organic material; recognizable leaves, twigs, and gastropod shells were found in

Figure 2. Depositional model for Swamplovers Valley ('S') and Marsh Valley ('M'), depicting extent of ice in white, outwash flow paths in blue shading with white arrows, and ice-proximal lakes in darker blue. (A) During advance to late Wisconsin maximum, outwash aggrading in the valleys of Black Earth Creek and the Wisconsin River dammed the mouths of tributary valleys, causing lakes to form in Swamplovers and Marsh valleys, as well as other similar valleys in the area. (B) At the late Wisconsin maximum, ice in the headwaters of Swamplovers and Marsh valleys allowed outwash to prograde down the valleys and cover the pre-maximum lake deposits. (C) As ice began to retreat, outwash deposition ceased in Swamplovers and Marsh valleys. However, outwash continued to aggrade for some time in the valleys of Black Earth Creek and the Wisconsin River, once again damming tributary valleys and re-establishing lakes in Swamplovers and Marsh valleys.

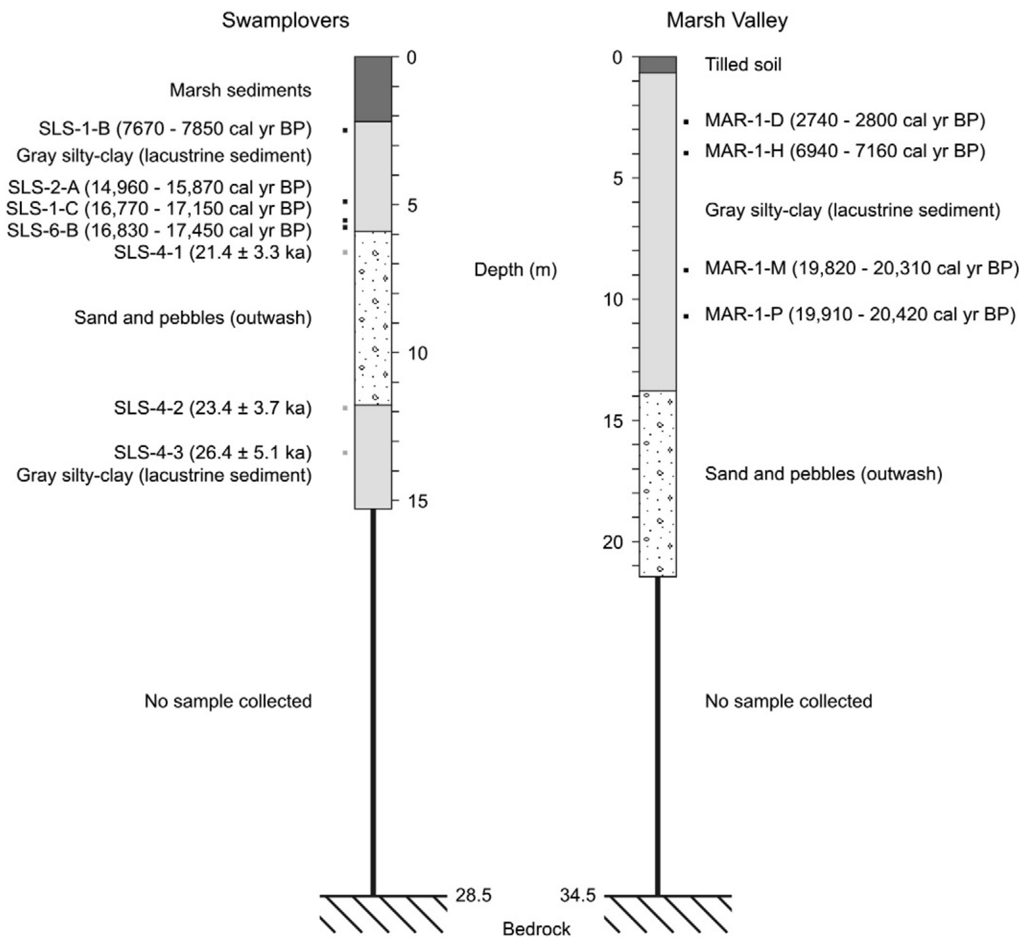


Figure 3. Stratigraphy as described from Geoprobe cores from Swamplovers and Marsh valleys. Radiocarbon dates from both cores are identified by black squares with sample numbers and ages (Table 1); OSL ages from Swamplovers Valley are identified by gray squares with sample numbers and ages (Table 2).

the core sediment. For this study, AMS radiocarbon dates were retrieved solely from individual riparian leaves. The unparalleled wealth of organic material from the two sites allows precise radiocarbon control dating to the end of the late Wisconsin maximum.

At Swamplovers Valley, a basal date from 5.9 m depth identifies the transition from outwash deposition to lacustrine silt deposition to approximately 17.2 ka, and a date from 2.5 m depth constrains the transition from lacustrine to swamp setting at just after 7.7 ka. At Marsh Valley, a date from 10.7 m depth (roughly 3 m above the transition from outwash to lacustrine sediment) indicates that the lake had been established by approximately 20.1 ka. A date from 2.7 m depth in lacustrine sediment indicates that the site remained a lake until at least 2.8 ka (Fig. 3, Table 1). It should be noted that these data indicate that the lakes represent a sedimentary archive of perhaps 17,000 years immediately following the late Wisconsin maximum; further research will address the paleo-environmental record preserved at these sites.

Table 1
Radiocarbon dates from Swamplovers and Marsh valleys.

Site name	Sample ID	Lab ID	Depth (m)	Radiocarbon yr BP	Calibrated yr BP (2 σ) [a]
Swamplover	SLS-1-B	Beta-290399	2.5	6930 ± 40	7670–7850
Swamplover	SLS-2-A	Beta-290400	5.5	12,840 ± 60	14,960–15,870
Swamplover	SLS-1-C	Beta-296948	5.7	13,870 ± 60	16,770–17,150
Swamplover	SLS-6-B	Beta-304604	5.9	14,020 ± 90	16,830–17,450
Marsh Valley	MAR-1-D	Beta-304591	2.7	2650 ± 30	2740–2800
Marsh Valley	MAR-1-H	Beta-304594	4.0	6150 ± 40	6940–7160
Marsh Valley	MAR-1-M	Beta-304598	8.8	16,860 ± 60	19,820–20,310
Marsh Valley	MAR-1-P	Beta-304600	10.7	17,020 ± 70	19,910–20,420

[a] Calibrated using Calib 6.0 (Stuiver and Reimer, 1993).

In light of the general lack of datable organic material that has been found associated with glacial sediments in the North America midcontinent, the occurrence of abundant plant macrofossils was entirely unexpected. We suggest that this reflects extremely localized conditions. Specifically, the occurrence of long-lived lakes on the landscape would have thawed the permafrost to several tens of meters depth beneath and immediately adjacent to the lakes (French, 2007). This would have allowed vegetation to grow in greater abundance at the lake shores than at other places on the landscape. Thus, our discovery of datable organic material from sediment deposited at the late Wisconsin ice margin relates directly to the specific geomorphic setting we are studying. Samples from near the base and near the top of the outwash were also collected at Swamplovers site for OSL dating. A sample collected from the top of the outwash at 6.7 m depth returned an age estimate of 21.4 ± 3.3 ka. Two samples collected from the lacustrine sediment immediately underlying the outwash at 11.9 and 13.4 m depth returned age estimates of 23.4 ± 3.7 ka and 26.4 ± 5.1 ka, respectively (Fig. 3, Table 2). The radiocarbon dates are in proper stratigraphic order and are statistically distinct from one another. The combined radiocarbon and OSL dates from Swamplovers Valley are in proper stratigraphic order, although the larger errors associated with the OSL dates preclude recognizing them as distinct from one another.

The depositional model presented in Figure 2 suggests that the onset of retreat of the Green Bay Lobe should be reflected by a

Table 2
Equivalent dose, dose rate data, and OSL age estimates for Swamplovers Valley samples. OSL ages are calculated for both the mean and median d_e values. The preferred age based on the mean d_e is in bold.

Field #	Aliquot size	UNL lab #	Depth (m)	U (ppm)	Th (ppm)	K_20 (wt.%)	In situ H_20 (%)[a]	Dose rate (Gy/ka)	Aliquots (n)[b]	D_e (Gy) ± 1 std. err.	Optical age ± 1σ	Mean/median ratio
SLS4-1	2 mm	UNL-3156	6.7	0.5	1.6	1.0	16.6	0.93 ± 0.13	32/46	19.8 ± 1.1[c] 18.0 ± 1.1[d]	**21.4 ± 3.3** 19.5 ± 3.3	1.10
SLS4-2	2 mm	UNL-3157	11.9	0.5	1.5	0.8	17.2	0.77 ± 0.11	32/40	17.9 ± 0.8[c] 17.7 ± 0.8[d]	**23.4 ± 3.7** 23.1 ± 3.7	1.01
SLS4-3	2 mm	UNL-3158	13.4	0.4	1.7	1.2	20.9	0.96 ± 0.17	35/40	25.3 ± 1.3[c] 25.3 ± 1.3[d]	**26.4 ± 5.1** 26.4 ± 5.1	1.00

[a] Dose rate calculation assumes 100% error in measured value.
[b] Accepted disks/all disks.
[c] Mean d_e value.
[d] Median d_e value.

transition from sand and gravel (outwash) deposition to laminated silt (lacustrine) in Swamplovers and Marsh valleys. The stratigraphy of the cores confirms the general validity of the depositional model, and the radiocarbon data provide new and valuable insight into the timing of retreat. However, discrepancy does exist between the dates from the two lakes, as the basal date from Swamplovers Valley is approximately 17.2 ka and the lowest date from Marsh Valley (2.7 m above the transition) is approximately 20.1 ka. There are several possible explanations for this difference in radiocarbon dates. Swamplovers Valley is a tributary of Black Earth Creek, which drains a relatively small portion of the Green Bay Lobe margin. It is possible that a time lag existed between the onset of retreat and when sufficient outwash had aggraded in Black Earth Creek to dam Swamplovers Valley; if this was the case, than the basal radiocarbon date from Swamplovers Valley would be somewhat younger than the onset of ice retreat. In contrast, Marsh Valley is a tributary of the Wisconsin River, which drains a much larger portion of the Green Bay Lobe. It is possible that aggradation in the Wisconsin River valley was rapid enough that ponded water existed in Marsh Valley prior to the onset of retreat of the Green Bay Lobe; if this was the case, then the lowest radiocarbon date from Marsh Valley would be somewhat older than the onset of ice retreat. Thus, it is possible that neither age precisely dates the onset of glacial retreat but, in combination, provides new control on the timing of that event. The OSL ages of 21.4 ± 3.3 ka from the top of the outwash and 23.4 ± 3.7 and 26.4 ± 5.1 ka from immediately below the outwash provide additional chronologic control on the time that ice was at its maximum position in the headwaters of Swamplovers Valley. The two lower OSL ages were retrieved from silty lacustrine sediment immediately underlying the outwash, interpreted to be sediment deposited in standing water while outwash was prograding down Swamplovers Valley; those ages therefore suggest that ice was at its maximum position for only a few thousand years.

The exact timing of when the Green Bay Lobe reached and receded from its maximum extent is not well identified (Mickelson et al., 1983; Syverson and Colgan, 2011). The results of Attig et al. (2011), which suggested that ice began thinning and retreating from the Baraboo Hills about 18.5 ka, represent a new research direction: applying OSL dating to ice-proximal lacustrine sediments in order to numerically constrain the timing of late Wisconsin fluctuations of the southern Laurentide Ice Sheet. The application of OSL dating in this geomorphic setting circumvents the all too pervasive lack of organic material for radiocarbon dating in late Wisconsin glacial sediments, as well as the common uncertainty of confidently correlating numeric dates retrieved from glacial sediment to discrete glacial events. The results of Attig et al. (2011) suggest that OSL applied to lacustrine sediment can be a viable and valuable tool for determining the timing of events that control the occurrence of lakes near former glacial margins. Clayton et al. (2001) have documented a 'gap' in the radiocarbon record for the upper Midwest caused by the presence of ice and permafrost that persisted prior to and following the last glacial maximum. The estimate for the onset of ice retreat from the Baraboo Hills provided by Attig et al. (2011) falls within this gap period (Fig. 4), suggesting the potential for this application of OSL dating to continue to refine our understanding of the chronology of glacial fluctuations in the upper Midwest. However, the OSL ages from that study are uncorroborated by an independent dating method because the small ice-marginal lakes in the Baraboo Hills that were the basis of that study did not contain datable carbon.

The data presented here provide both empirical limits on glacial fluctuations during the 'gap' period (Fig. 4) and two independent dating methods that can be directly compared. While partial bleaching can yield OSL age estimates that are too old, our results suggest that this potential problem is not adversely affecting our age estimates. This conclusion stems in part from our use of 2-mm aliquots to limit the impact of poorly bleached grains in our samples. In addition, we monitored the ratios between the mean to median D_e values as suggested by Rowland et al. (2005). Mean-to-median ratios of the D_e values for samples UNL-3157 and UNL-3158 were near unity, but the ratio for sample UNL-3156 was 1.10 (Table 1) suggesting that partially bleached grains may be present in this sample. However, all of our ages calculated using the median D_e values fall within 1σ errors of the ages calculated using the mean D_e values (Table 1), suggesting that this factor is not significantly affecting our final age estimates. Finally, good correspondence between our OSL and radiocarbon

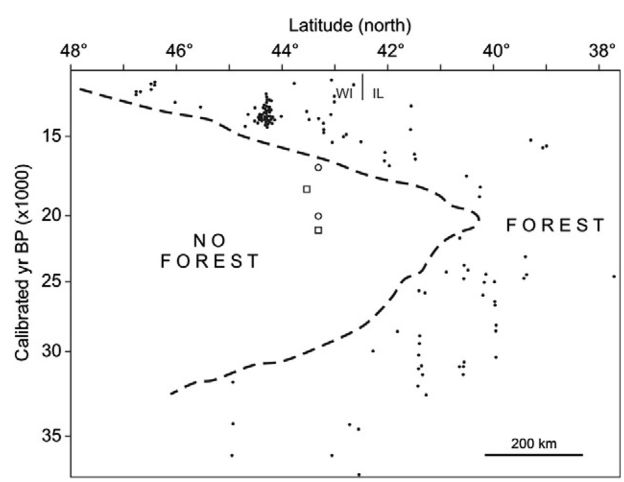


Figure 4. Distribution of radiocarbon–carbon dated wood (black circles) with latitude in Wisconsin and Illinois. Dates from large woody material are absent in the central and left portion of the diagram presumably because of the presence of late Wisconsin ice and persistent permafrost, which would have prevented the growth of large trees. Modified from Clayton et al. (2001). Open circles represent basal radiocarbon ages retrieved from Swamplovers site and Marsh Valley for this study. Open squares represent OSL ages from Swamplovers site (this study) and the Baraboo Hills (Attig et al., 2011); these dates represent closely limiting age control for late Wisconsin ice margin fluctuations not previously provided by radiocarbon dating.

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dating results suggest that our OSL ages are not adversely affected by this potential problem.

The suite of OSL and radiocarbon ages suggests that the Green Bay Lobe was at its maximum extent at Swamplovers Valley between 26.4 ± 5.1 and 21.4 ± 3.3 ka (based on OSL ages), and that lakes had been re-established in Marsh Valley and Swamplovers Valley following onset of ice retreat by about 20.1 and 17.2 cal ka BP (based on radiocarbon dates), respectively. These age estimates are suitably internally consistent, in that the older OSL ages are estimating the time that late Wisconsin ice was at its maximum extent and outwash was aggrading down Marsh Valley and Swamplovers Valley, whereas the younger radiocarbon dates are limiting the reestablishment of lakes in those valleys after ice had retreated from the headwaters and sufficient outwash had continued to aggrade in the Wisconsin River and Black Earth Creek to dam those tributaries. Furthermore, the OSL age of 21.4 ± 3.3 ka collected from the top of the outwash in Swamplovers Valley, and 23.4 ± 3.7 ka and 26.4 ± 5.1 ka from lacustrine sediment immediately underlying the outwash provide an estimate for when ice was at its maximum extent at the site. This is broadly consistent with the estimate of 18.5 ka from the Baraboo Hills by Attig et al. (2011) as the time when ice had begun thinning and retreating.

Standing alone, the radiocarbon data represent entirely new numeric control on the timing of retreat of the Green Bay Lobe in south-central Wisconsin. The data collected for this study provide further methodological advancement over those of Attig et al. (2011) by being able to combine and compare radiocarbon and OSL dates. The internal consistency of the radiocarbon and OSL ages would suggest that the OSL ages retrieved from ice-proximal lacustrine sediment provide reasonable estimates for the local timing of the late Wisconsin maximum; further analyses will be needed to more carefully evaluate the use of OSL dating in this geomorphic setting. The radiocarbon dates further provide minimum limiting ages for the timing of lakes forming in the two valleys following retreat of ice from the headwaters. Because the formation of the lakes was intimately associated with glacial fluctuations and outwash supply, these dates also provide insight into the timing of the onset of retreat of the Green Bay Lobe.

The data presented here provide site-specific, field-based information about the timing of the Green Bay Lobe fluctuations that can be added to the cumulative understanding of global patterns of ice fluctuations at the end of the last glaciation. Clark et al. (2009) identified the global last glacial maximum as lasting from 26.5 ka to 20–19 ka. The OSL ages from Swamplovers Valley at 26.4 ± 5.1 to 21.4 ± 3.3 ka relate directly to outwash being deposited in that valley while ice was at its maximum extent. The basal radiocarbon age of 17.2 cal ka BP from Swamplovers Valley and the oldest radiocarbon age of 20.1 cal ka BP from Marsh Valley relate directly to the establishment of lakes in those valleys near or following the onset of the Green Bay Lobe's retreat from its maximum position. The general agreement between these suites of ages both provides confidence in the results of this study and suggests that further work with ice-proximal lacustrine sediments can continue to refine our understanding of the chronology of events at the end of the last glaciation.

Conclusions

Ice-proximal lakes that existed along the southern margin of the Green Bay Lobe in south-central Wisconsin during and following the late Wisconsin (MIS 2) glaciation provided the opportunity to directly date fluctuations of the Green Bay Lobe. OSL dating of outwash sediment underlying lacustrine deposits in one tributary valley indicate that the Green Bay Lobe was at its maximum from about 26 to at least 21 ka. Lakes were established in this and one other nearby tributary valley once ice began to retreat from the maximum position; radiocarbon dates from basal organic material collected from the lacustrine sediments indicate that the two lakes had formed by 20.1 and 17.2 cal ka BP. These data are significant for several reasons:

1 Because the various sediments deposited at these sites are so closely and clearly related to discrete glacial events, the absolute ages can be correlated to ice-margin fluctuations with a confidence atypical to most glacial depositional environments.
2 The radiocarbon dates fall into a time period from which no other datable organic material has been found in the upper Midwest. Persistent permafrost conditions that existed in Wisconsin and other parts of the upper Midwest and retarded significant plant growth prior to and following the last glacial maximum were apparently countered by the local effects of these long-lived lakes.
3 The internal consistency of the radiocarbon and OSL dates lends additional credence the application of OSL dating to ice-proximal lacustrine sediments, which represents a methodological improvement over previous studies that have applied OSL dating in this geomorphic setting (e.g., Attig et al., 2011).
4 The reasonably close agreement between the OSL ages from this study and the estimate by Attig et al. (2011) for the onset of thinning and retreat of Green Bay Lobe ice from the Baraboo Hills further supports the application of OSL dating to ice-proximal sediments and suggests that continued research along these lines will further refine the late Wisconsin glacial chronology in the upper Midwest and, eventually, the North American midcontinent.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at http://dx.doi.org/10.1016/j.yqres.2012.08.005.

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