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Short Paper

Early Holocene dune activity linked with final destruction of Glacial Lake Minong, eastern Upper Michigan, USA

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ABSTRACT

The early Holocene final drainage of glacial Lake Minong is documented by 21 OSL ages on quartz sand from parabolic dunes and littoral terraces and one radiocarbon age from a lake sediment core adjacent to mapped paleoshorelines in interior eastern Upper Michigan. We employ a simple model wherein lake-level decline exposes unvegetated littoral sediment to deflation, resulting in dune building. Dunes formed subsequent to lake-level decline prior to stabilization by vegetation and provide minimum ages for lake-level decline. Optical ages range from 10.3 to 7.7 ka; 15 ages on dunes adjacent to the lowest Lake Minong shoreline suggest final water-level decline ~9.1 ka. The clustering of optical ages from vertically separated dunes on both sides of the Nadoway–Gros Cap Barrier around 8.8 ka and a basal radiocarbon date behind the barrier (8120 ± 40 ^{14}C yr BP [9.1 cal ka BP]) support the hypothesis that the barrier was breached and the final lake-level drop to the Houghton Low occurred coincident with (1) high meltwater flux into the Superior basin and (2) an abrupt, negative shift in oxygen isotope values in Lake Huron.

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Introduction

Lake Superior basin lake-level history

Late Quaternary water-plane variation in the Upper Great Lakes basin has been studied for over 100 yr (Leverett and Taylor, 1915). Today, our understanding of the final retreat of the Laurentide ice sheet (LIS) from the Superior basin and the history of Lake Minong, its last resident glacial lake, remains incomplete. An improved picture of late Pleistocene and early Holocene lake-level change is needed to assess potential linkage of meltwater release from/through the Great Lakes to the ocean with abrupt climate change (Broecker et al., 1989; Teller, 1990; Clark et al., 2001; Breckenridge and Johnson, 2009) and to gage lake response to past non-analogous climate (Booth et al., 2002; Lewis et al., 2007a,b).

The sequence of late Pleistocene and early Holocene lake-level change in the Superior basin is fairly well established (Farrand, 1969; Saarnisto, 1975; Farrand and Drexler, 1985; Fisher and Whitman, 1999), but the timing and causes of lake-level change are not fully understood. This is especially true for the early Holocene sequence of lake-level changes associated with glacial Lake Minong, the final glacial lake to occupy the Superior basin during the retreat of the LIS from the basin, from 10,700 to 8900 cal yr BP (Breckenridge et al., 2004; Breckenridge, 2007). Lake Minong was first described by Stanley (1932) from shorelines along the west side of Isle Royale in western Lake Superior. Its history is best conceptualized through reference to its immediate predecessor, glacial Lake Algonquin (Larsen, 1987). Lake Algonquin filled the isostatically depressed Lake Huron and Lake Michigan basins >13,000 cal yr BP, thereby inundating much of present northern Michigan (Futyma, 1981). By ~12,300 cal yr BP, LIS retreat had reached North Bay, Ontario, permitting northeastward drainage of Lake Algonquin to the North Atlantic via the isostatically depressed Ottawa River Valley (Karrow et al., 1975). This led to significant lowering of lakes in the Michigan and Huron basins (to Lakes Chippewa and Stanley) by ~11,400 cal yr BP (Larsen, 1987).

Nearly concurrently, the Superior Lobe of the LIS briefly re-advanced to the southern rim of the Superior basin (Marquette Stadial; Lowell et al., 1999; Derouin et al., 2007), confining a new lake, Lake Minong, in the basin's southeastern corner (Farrand and Drexler, 1985). Upon retreat of the LIS to the northeast, Lake Minong expanded to fill the entire Superior basin, retained by bedrock (Cambro-Ordovician escarpment and the Canadian Shield) and glacial sediment on the south, by the Canadian Shield on the east and by a broad, sandy

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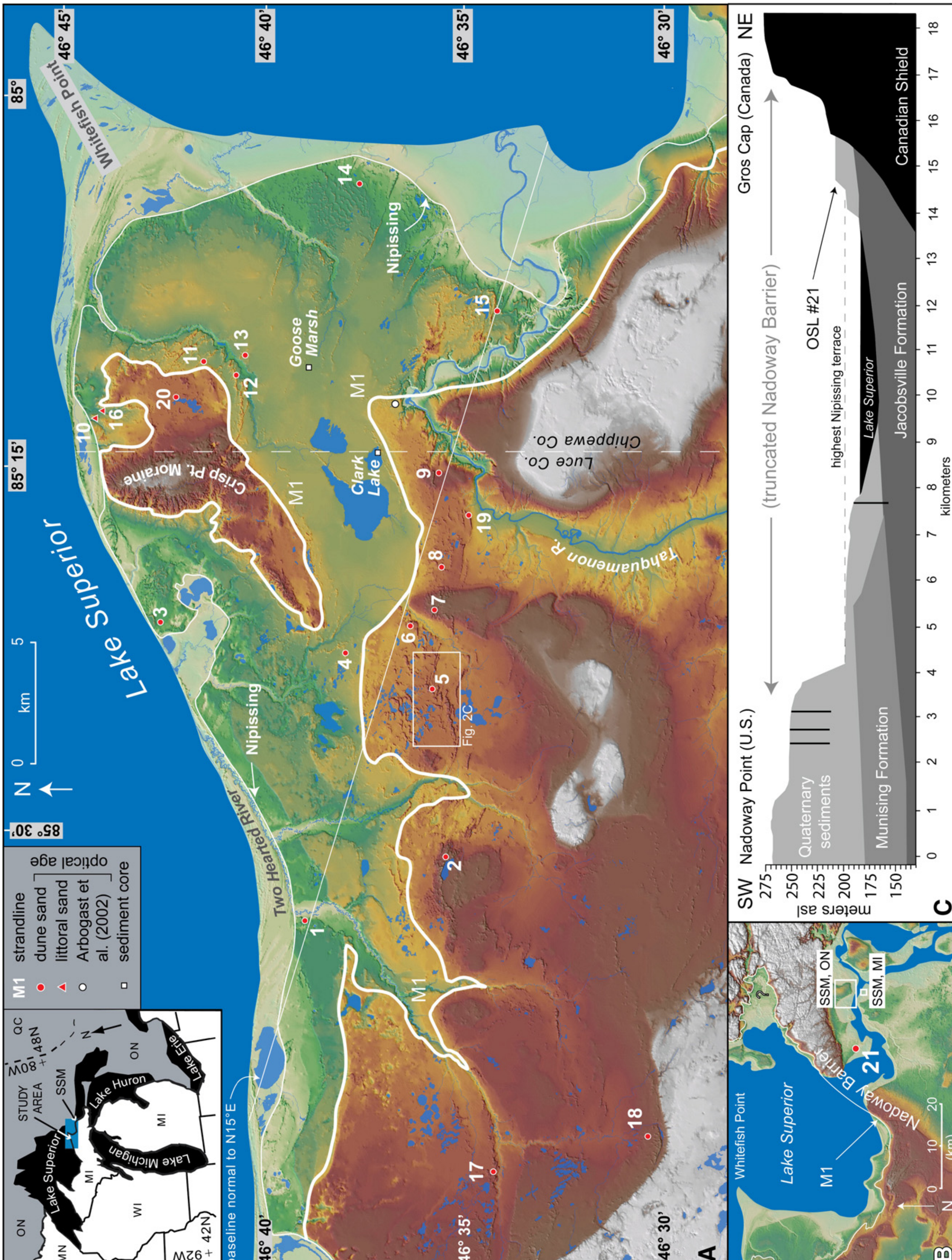
Lake Superior
Whitefish Point
Crisp Pt. Moraine
Clark Lake
Goose Marsh
Nipissing
Two Hearted River
Tahquamenon R.
Luce Co.
Chippewa Co.
baseline normal to N15°E
M1 strandline
dune sand
littoral sand
Arbogast et al. (2002)
optical age
sediment core
STUDY AREA
SSM
Lake Huron
Lake Michigan
Lake Erie
85° 30'
85° 15'
85°
46° 45'
46° 40'
46° 35'
46° 30'
km
Fig. 2C
SSM, ON
SSM, MI
Nadoway Barrier
SW Nadoway Point (U.S.)
Gros Cap (Canada) NE
(truncated Nadoway Barrier)
OSL #21
highest Nipissing terrace
Quaternary sediments
Munising Formation
Jacobsville Formation
Canadian Shield
meters asl
kilometers
A
B
C

berm, the Nadoway–Gros Cap Barrier (hereafter, Nadoway Barrier), on the southeast at the presumed lake outlet (Figs. 1B, C; Saarnisto, 1974; Farrand and Drexler, 1985). It is hypothesized that Lake Minong was destroyed as the Nadoway Barrier was incrementally breached during large releases of meltwater to the Superior basin (Farrand and Drexler, 1985).

The early Holocene sequence of lake-level change is complex due to the combined effects of LIS meltwater, possible inflow from glacial Lake Agassiz, fluctuating ice-margin position, changing outlet location, differential isostatic rebound, and early Holocene climate. Multiple levels of Lake Minong have been inferred from subaerial raised shorelines in the Superior basin (e.g., Minong I–III and post Minong I–IV; Farrand, 1960; Farrand and Drexler, 1985; Bajc et al., 1997; Morris, 2001; Slattery et al., 2007), but the ages of these shorelines are not well constrained. Correlation of lake levels and associated shorelines across the basin is difficult due to the large number of closely spaced shorelines and uncertainties as to the rate and azimuth of isostatic rebound. Saarnisto (1974, 1975) provides the best constraint on the timing of drops in the level of Lake Minong through his radiocarbon dating bulk organic matter (gyttja) from basal sediments in small, sequentially emergent lakes adjacent to the northeastern shore of Lake Superior. Other studies established site by site snapshots of shoreline chronology (e.g., Zoltai, 1965; Teller and Mahnic, 1988; Julig et al., 1990; Bajc et al., 1997) and extent (Phillips and Fralick, 1994; Morris, 2001; Slattery et al., 2007).

Purpose and approach

In an attempt to refine the chronology of Lake Minong lake-level change in eastern Upper Michigan (EUM), we obtained OSL ages from littoral and eolian sediments and ^{14}C ages from lake and marsh cores adjacent to mapped paleoshorelines of Lake Minong. Optical dating of presently forested non-coastal parabolic dunes, common along the southeastern edge of the Superior basin in interior EUM (Figs. 1A and 2A), provides an opportunity for improving the absolute chronology for the fall of Lake Minong. In this study, we provide minimum ages for lake-level fluctuation and fall by linking OSL chronology with glacial lake shorelines. We depend upon a simple conceptual model of shoreline behavior predicting sand supply to dunes along receding shores (Bergquist, 1936; Grigal et al., 1976; Hesp, 2002). Lake-level fall exposes unprotected/unvegetated littoral sand to deflation, and dunes form subsequent to lake-level fall and prior to stabilization by vegetation (Olson, 1958; Lichter, 1998). Thus, these dunes potentially contribute temporal and spatial signals of lake-level change. Optical dating has proven effective in studies in varied eolian and littoral settings near the Great Lakes where organic material for radiocarbon dating is rare (Arbogast et al., 2002; Arbogast and Packman, 2004; Loope et al., 2004; Argyilan et al., 2005).

Methods

To contribute to an absolute chronology for the decline of glacial Lake Minong and to test the hypothesis that parabolic dunes of interior eastern Upper Michigan contain signals of such decline, we used three means:

1) We mapped glacial lake shorelines (Lakes Algonquin and Minong) using a 10-m DEM (National Elevation Dataset; http://seamless.usgs.gov) with the aid of GIS-based reconstructions of reported pre-Minong (Algonquin) shorelines interpreted from earlier field mapping (Fig. 2A; Futyma, 1981; see Supplemental Information) and through our own field reconnaissance. Using the same base DEM and digital orthophotos, we mapped dunes (dune crests), most of which were located below the traces of Lake Algonquin (higher in elevation and older in age) and above the traces of Lake Nipissing (lower in elevation and younger in age)[Fig. 2A].
2) We obtained optical ages (Aitken, 1998) on samples of quartz sand 1 m beneath crests of 18 eolian dunes and two littoral terraces in interior EUM (Fig. 1A) and from one eolian dune southwest of Sault Sainte Marie, Ontario, Canada (Fig. 1B). The 18 eolian samples southwest of Whitefish Point were selected to represent typical parabolic dunes within several distinct fields spread across the study area (Figs. 1A and 2A; sites 1–9, 11–15, 17–20). Sample 21 was collected ~1 km north of the Sault Sainte Marie, Ontario airport, southeast of the presumed breach of the Nadoway Barrier and above the Nipissing bluff (Cowan, 1985; Figs. 1B, C). Samples of sand from the two littoral terraces were recovered northeast of the Crisp Point Moraine (Fig. 1A; sites 10, 16). The elevations of inferred sand source (windward of each dune sample collection site) were recorded and adjusted for differential isostatic rebound at 0.37 m/km normal to N15°E (Farrand, 1960; Futyma, 1981; Schaetzl et al., 2002; Fig. 3; Table 1). Optical ages were determined on 90–150 μm quartz grains using the single aliquot regenerative (SAR) protocol (Murray and Wintle, 2000) for determination of the equivalent dose. Laboratory procedures and additional OSL data are found in the Supplementary Information. Optical ages are reported in thousands of years before 2004.
3) To investigate lake-level chronology independent of optical dating, we recovered a vibracore from the southeastern corner of Clark Lake (Figs. 1A and 4; see Fisher, 2004 for details of vibracoring) and a hand-driven core of wetland sediments from Goose Marsh (Figs. 1A and 4) within the former confines of Lake Minong (Farrand and Drexler, 1985). Radiocarbon ages on wood and charcoal from these cores are reported as calibrated ^{14}C yr before present (cal yr BP; Stuiver and Reimer, 1993; Reimer et al., 2004).

Results

Multiple dune fields were mapped and a single prominent shoreline above the Nipissing and below the lowest Algonquin shoreline was identified at ~220 m asl (M1, Figs. 2A, B).

Parabolic morphology (arms open to the northwest) and northwest-southeast orientation of dunes suggest northwesterly effective winds during dune building (Figs. 2A, C). The prominent Minong strandline, M1, can be traced throughout the study area and extends westward and grades to glaciofluvial terraces south and west of Grand Marais, Michigan (Drexler et al., 1983; Blewett, 1994; Loope et al., 2004). Optical ages from 19 eolian dunes range from 10.3 to 7.7 ka (Fig. 3, Table 1, sites 1–9, 11–15, 17–21). Optical ages from the two littoral samples both yielded ages of 9.9 ka (Fig. 3, Table 1, sites 10 and 16). Lake and wetland sediment cores yielded stratigraphic information (Fig. 4) and three ^{14}C ages on wood and charcoal. Radiocarbon ages range from 5900 ± 260 to 8120 ± 40 ^{14}C yr BP (Table 2). Fig. 5 compares optical and radiocarbon ages from this study with timing of events associated with Lake Minong from previous studies within and adjacent to the Superior basin.

Figure 1. (A) 10-m hillshade digital elevation model (National Elevation Dataset [NED]; http://seamless.usgs.gov) of the study area in eastern Upper Michigan with locations of OSL sample sites (numbered red-filled white circles and triangles), identified strandlines (M1 = Minong, N = Nipissing), sediment core sites (black-rimmed white squares), and a baseline normal to N15°E (N15°E is azimuth of maximum isostatic uplift rate based on Futyma, 1981). Black-rimmed, white-centered circle southeast of Clark Lake shows location of the 'Rainbow Lodge Quarry' site of Arbogast et al. (2002). White rectangle enclosing site 5 shows location of digital orthophotograph in Fig. 2C. (B) Digital elevation model of part of eastern Upper Michigan and Ontario centered around Sault Sainte Marie (SSM), Michigan and Ontario. M1 is the main Minong strandline and the lake was held at ~220 m behind the Nadoway–Gros Cap Barrier (Farrand and Drexler, 1985) prior to incision of the barrier. (C) Geologic cross section parallel to the former Nadoway Barrier from Nadoway Point, Michigan to Gros Cap, Ontario inferred from well logs. Sample site 21 and the highest Nipissing scarp are shown in relation to the former Nadoway Barrier.

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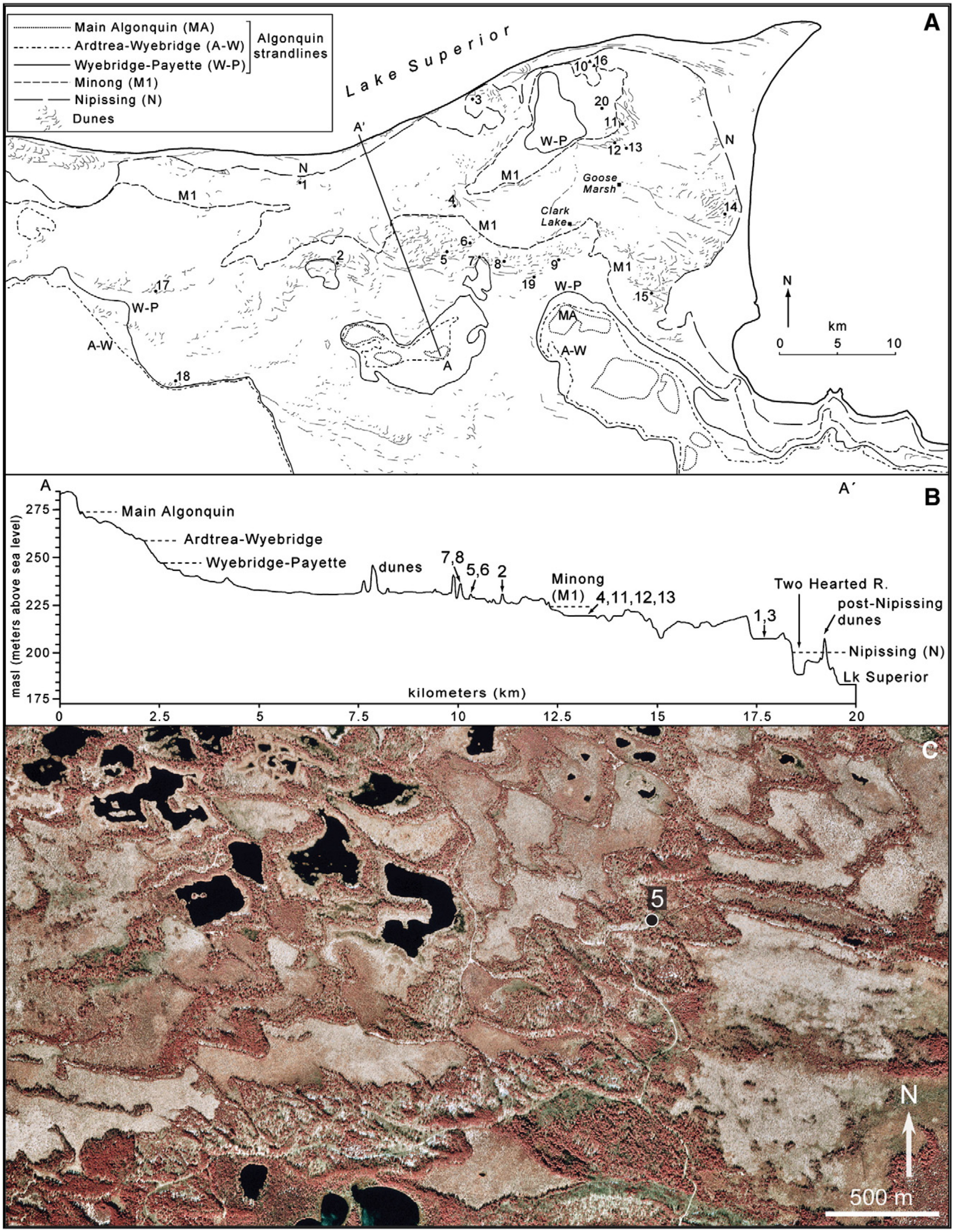

Figure 2. (A) Mapped distribution of dunes and shorelines in the study area. Dune crests and strandlines were traced from a 10-m DEM and digital orthophotos. Samples sites 1–20 and core locations are shown. Identification and location of Lake Algonquin strandlines were aided by a GIS reconstruction of Algonquin strandlines based on data of Futyma (1981). Details of the GIS methodology are found in the Supplementary Information. We chose to adopt the Algonquin strandline names (Main, Ardtrea, Wyebridge, Payette) of Schaetzl et al. (2002) but only identified three Algonquin strandlines. Therefore, the lower two strandline names reflect uncertainty in correlation between our mapping and Schaetzl et al. (2002). Further work is needed to correlate Algonquin strandlines in the study area to those in Schaetzl et al. (2002). (B) Topographic cross section (A–A′ in Fig. 2A) with strandlines and selected OSL sample sites. (C) False-color infrared aerial photograph with forested parabolic dunes and intervening wetlands and lakes in the area surrounding site 5 (UNL662). See Fig. 1A for location.

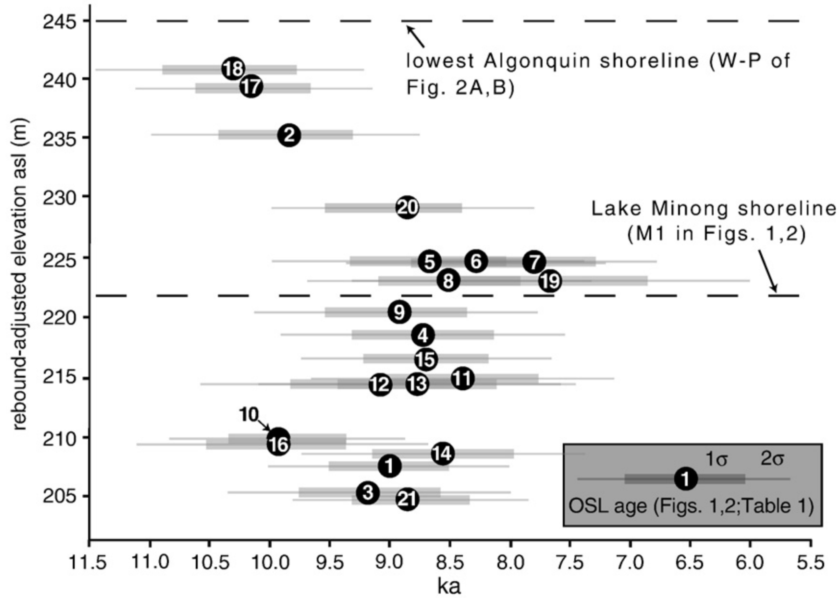

Figure 3. Optical ages with one and two sigma error bars on quartz sand from dunes (sites 1–9, 11–15, 17–21) and littoral sediments (sites 10, 16) plotted against rebound-adjusted elevation of inferred sand source (Table 1). The elevation of the lowest Algonquin shoreline [~245 m] (W-P of Figs. 2A, B) and Lake Minong shoreline [~220 m] (M1 in Figs. 1 and 2) are shown as dashed lines.

Discussion

Final drainage of Lake Minong

The peak in the summed probability distribution of optical ages near 8.8 ka (M in Fig. 5) and a single radiocarbon age (8120 ± 40 ^{14}C yr BP [9.1 cal ka BP]) from Clark Lake (L^1 of Fig. 5), taken together, constitute a strong signature of lake-level decline near 9.0 ka. Sand source elevation for 15 optical ages on dunes, 9.2–8.3 ka (Table 1; Fig. 3, sites 1, 3–6, 8–9, 11–15, 20–21), lie near or below the strongly expressed M1 shoreline, consistent with dune building by lake bed deflation after lake-level fall. The spatial location of these samples

Table 1
Optical ages and associated data of 21 samples of quartz sand collected in Luce and Chippewa Counties in eastern Upper Michigan, USA (sites 1–20) and adjacent Ontario, Canada (site 21) (Figs. 1A, B). Coordinates of sample sites are provided in Table 1 of the Supplementary Information.

Sample[a]	Site no. (Fig. 1)	H_2O[b] (wt%)	K_2O (wt%)	U (ppm)	Th (ppm)	D_{cosmic} (Gy/ka)[c]	D_{total} (Gy/ka)	D_e (Gy)[d]	Age (ka)[e]	Aliquots (n)	Sample elevation (m)[f]	Source elevation (m)[f]
UNL819	1	4.9	2.05	0.4	2.0	0.19	2.01 ± 0.08	18.1 ± 0.5	9.0 ± 0.5	20	214	208
UNL696	2	1.9	2.67	0.7	2.9	0.19	2.71 ± 0.11	26.5 ± 0.5	9.8 ± 0.5	30	256	236
UNL659	3	3.1	1.23	0.5	1.85	0.19	1.37 ± 0.04	12.6 ± 0.3	9.2 ± 0.6	32	208	205
UNL666	4	4.8	1.64	0.5	2.3	0.19	1.68 ± 0.04	14.7 ± 0.5	8.7 ± 0.6	31	220	218
UNL662	5	2.7	2.20	0.5	2.0	0.19	2.14 ± 0.05	18.5 ± 0.9	8.7 ± 0.7	32	231	224
UNL660	6	4.4	2.57	0.7	2.9	0.19	2.48 ± 0.05	20.7 ± 0.6	8.4 ± 0.5	29	229	224
UNL661	7	4.7	3.20	0.67	2.87	0.19	2.95 ± 0.06	22.9 ± 0.6	7.8 ± 0.5	30	257	224
UNL695	8	4.0	1.92	0.6	2.3	0.19	1.98 ± 0.08	16.9 ± 0.7	8.5 ± 0.6	28	232	222
UNL877	9	4.4	2.96	0.6	2.5	0.19	2.84 ± 0.11	25.1 ± 1.1	8.9 ± 0.6	30	250	221
UNL580[g]	10	8.4	3.23	0.9	3.1	0.19	2.99 ± 0.13	29.5 ± 0.5	9.9 ± 0.6	53	210	210
UNL575	11	4.4	2.40	0.5	1.9	0.19	2.30 ± 0.10	19.2 ± 0.5	8.3 ± 0.5	20	223	215
UNL578	12	1.8	2.92	0.5	2.2	0.19	2.81 ± 0.12	23.7 ± 1.1	9.1 ± 0.6	21	218	215
UNL577	13	0.4	2.37	0.5	2.4	0.19	2.43 ± 0.10	21.3 ± 0.7	8.8 ± 0.5	30	220	215
UNL665	14	3.9	2.26	0.6	2.6	0.19	2.22 ± 0.05	18.9 ± 0.7	8.5 ± 0.6	27	211	207
UNL697	15	5.1	2.84	0.6	2.6	0.19	2.70 ± 0.11	23.5 ± 0.7	8.7 ± 0.5	48	220	216
UNL579[g]	16	11.9	3.69	1.1	4.3	0.19	3.33 ± 0.15	33.0 ± 0.9	9.9 ± 0.6	30	210	210
UNL876	17	4.6	1.49	0.4	1.7	0.19	1.57 ± 0.06	15.9 ± 1.0	10.2 ± 0.8	30	244	238
UNL875	18	4.5	1.52	0.5	2.3	0.19	1.65 ± 0.07	17.0 ± 0.8	10.3 ± 0.7	47	245	240
UNL825	19	4.6	3.11	0.5	2.0	0.19	2.89 ± 0.11	22.2 ± 1.7	7.7 ± 0.7	17	242	222
UNL1700	20	4.9	1.96	0.6	2.1	0.19	1.99 ± 0.08	17.4 ± 0.8	8.8 ± 0.6	22	232	228
UNL1215	21	1.9	1.34	0.6	2.3	0.19	1.58 ± 0.06	13.8 ± 0.2	8.8 ± 0.5	40	207	205

[a] All samples taken 1 meter below ground surface.
[b] In situ moisture content; assumption of 30% error.
[c] Calculated using Prescott and Hutton (1994).
[d] ± 1 standard error; mean of D_e distribution; 5-mm disks (~1000 grains) used for all samples.
[e] ± 1 standard deviation; years before 2004.
[f] Meters above sea level; adjusted for differential isostatic rebound at 0.37 m/km normal to N15°E (Farrand, 1960; Futyma, 1981; Schaetzl et al., 2002) [Fig. 1A]; source elevation refers to sediment source elevation (plotted in Fig. 3).
[g] Littoral sediment sample.

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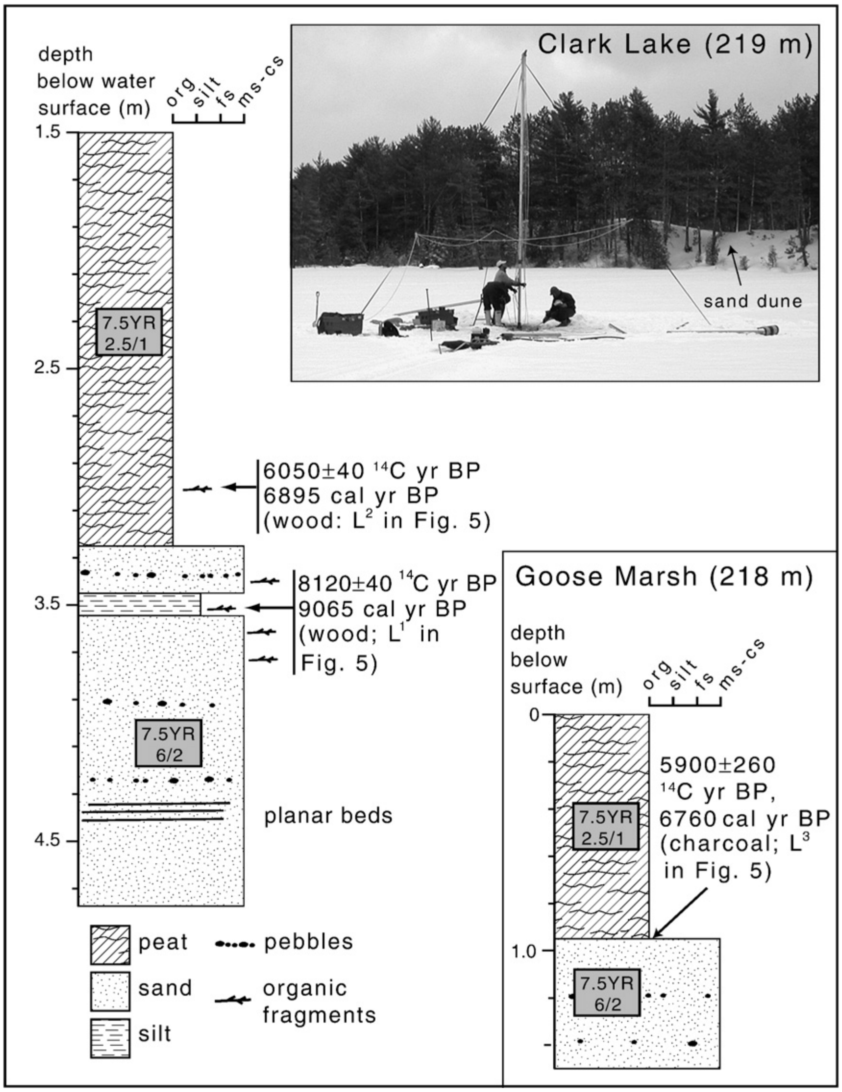

Figure 4. Stratigraphy and ^{14}C ages from Clark Lake and Goose Marsh. Note that both core sites lie below M1 (main Lake Minong shoreline). Table 2 contains additional data regarding the ^{14}C ages. In the stratigraphic log, org = organic, fs = fine sand, ms-cs = medium to coarse sand. Munsell colors of sediment are superimposed on the columns. Locations of core sites are shown in Figs. 1A and 2A and coordinates are found in Table 1 of the Supplementary Information.

near the M1 shoreline is consistent with a rapid drop of Lake Minong at that time. Dune building occurred concurrent with or just after massive receipt of meltwater in the Superior basin (A in Fig. 5; Breckenridge et al., 2004). Breach of the Nadoway Barrier near 9.0 ka (Farrand and Drexler, 1985; Breckenridge, 2007) is suggested by the optical age at site 21 (8.8 ka) collected ~17 m below the M1 shoreline, 1–2 km east of the location of the Nadoway Barrier near Sault Sainte Marie, Ontario (Figs. 1B, C). Light oxygen isotope values from ostracodes recovered in cores from northern Lake Huron (Rea et al., 1994; Moore et al., 2000) are consistent with large-scale passage of

Table 2

Radiocarbon ages from sediment cores near the Crisp Point Moraine, Luce, and Chippewa Counties, MI (Fig. 1A). Core stratigraphy and sedimentology is shown in Fig. 4. Coordinates of cores sites are provided in the Supplementary Information.

Lab no. (Beta)	Site	Elevation (m asl)[a]	Material	^{14}C age[b]	δ^{13}C (‰)	Calibrated age range (BP)[c,d]	Probability distribution[e]	Calibrated age (BP)[f]
191299	Clark Lake	215.8	Wood	6050 ± 40	−27.0	7004–6786	1	6895
191300	Clark Lake	215.3	Wood	8120 ± 40	−25.1	9137–8992	0.95	9065
						9205–9175	0.03	
						9244–9219	0.02	
185637	Goose Marsh	216	Charcoal	5900 ± 260	*	7326–6196	1	6761

*Sample too small for δ^{13}C analysis.
[a] Elevation of dated material.
[b] 1σ error; ^{14}C yr BP (1950).
[c] 2σ range.
[d] Calibrated with CALIB 5.0 using IntCal04 (Stuiver and Reimer, 1993; Reimer et al., 2004).
[e] Probability distributions less than 1% are not reported.
[f] Mean of greatest probability distribution.

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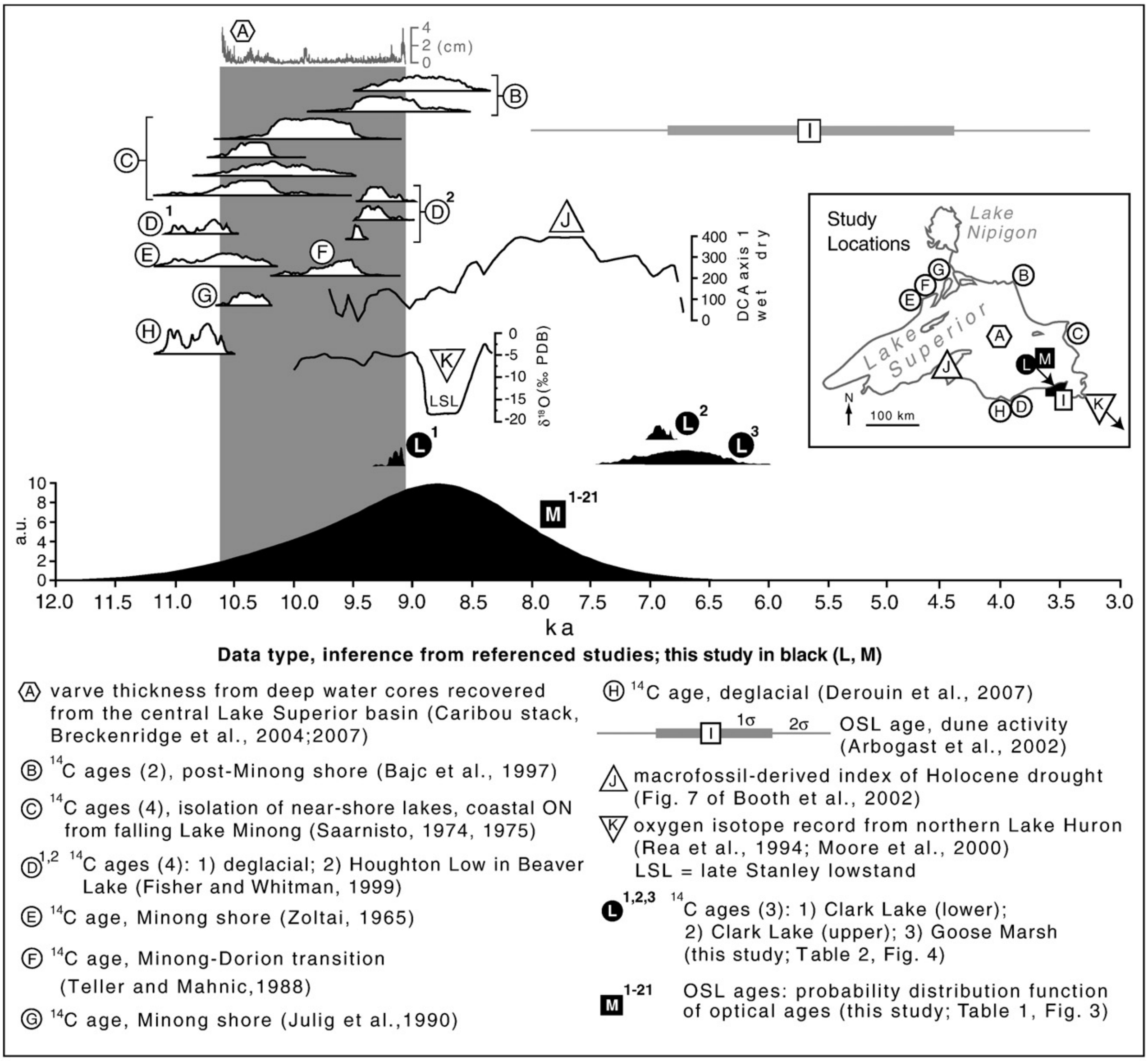

Figure 5. Chronologic comparison of geologic events within and adjacent to the Superior basin during the early and middle Holocene. Data type and inference for eleven previous studies (ten within the Lake Superior basin [A–J] and one within the Lake Huron basin [K]) are shown with white fill. Data type and inference for this study (L, M) is shown with black fill. For previous studies and our study, individual probability distribution functions of calibrated ^{14}C ages (Stuiver and Reimer, 1993; Reimer et al., 2004) are shown and were adjusted from cal yr BP to ka by shifting the probability distribution by 50 yr. Grey bar extending from ~10.6 to 9.1 ka is the temporal existence of Lake Minong (Breckenridge et al., 2004; Breckenridge, 2007). The vertical axis for M (probability distribution function of 21 optical ages from this study) represents arbitrary units (a.u.).

glacial meltwater from the Superior to the Huron Basin just after 9.0 ka (K of Fig. 5).

Prior fluctuation in levels of Lake Minong

Five of 21 optical ages (sites 2, 10, 16–18) are ~1 ka older than the larger group of ages linked to the final drainage of Lake Minong (Table 1, Fig. 3). The older ages on dunes (sites 2, 17, 18) may be related to fluctuations of Lake Minong prior to its final drainage. These dunes lie widely spaced, derived from sand sources lying between ~235 and ~245 m. The fact that sand sources for two dune samples (Table 1, Fig. 3, sites 17–18) lie just below the lowest mapped Algonquin shoreline (W–P in Fig. 2A) suggests the possibility that levels of Lake Minong could have risen several meters before falling back below M1. Sites of the two littoral samples (sites 10 and 16) lie ~30 m lower, below the M1 shoreline at ~210 m (Fig. 3). Interlaminated and interbedded fine sand and silt at those sites may have accumulated in shallow water as the lake stood near ~220 m after this rapid drop. The lack of a clearly defined shoreline connecting these sites hinders a more precise interpretation. Additionally, the older five ages (sites 2, 10, 16–18) overlap at two sigma error with the larger group of ages related to the final drainage of Lake Minong.

On the other hand, fluctuation/fall of Lake Minong near 10.5–10.3 ka is consistent with data presented by Saarnisto (1974, 1975; C of Fig. 5) and Zoltai (1965; E of Fig. 5). Julig et al. (1990) reported a similar radiocarbon age from wood recovered from a lagoon behind a Minong beach (G of Fig. 5) while Teller and Mahnic (1988) report a slightly younger beach date on unspecified organic matter (F of Fig. 5). Additionally, varve thickness data from Breckenridge et al. (2004) suggests an increase in meltwater flux into Lake Minong just prior to 10.5 and ~10.3 ka (Fig. 5A). Further quantification of fluctuations of Lake Minong prior to its final decline below ~220 m (M1) at ~9.0 ka is required before strict interpretations can be made.

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Possible climatic signals

Suggesting an explanation for the youngest pair of optical ages on dunes, 7.7 ka (site 19) and 7.8 ka (site 7) (Figs. 1 and 3; Table 1) requires some speculation with regard to sand source. An expanded temporal window of sand supply after lake-level drop near 9.0 ka may reflect prolonged drought and reduction in ground cover to allow saltation of sand and formation of dunes. Early Holocene drought within and adjacent to the Superior basin is suggested by paleoecological studies (Booth et al., 2002 [J of Fig. 5]; Delcourt et al., 2002; Lytle, 2005) and lake-level reconstructions [within the Huron basin] (Lewis et al., 2007a,b). Drought (Booth et al., 2002) and fire (Filion, 1984; Lytle, 2005) may have played a role in reducing ground cover and increasing sand availability and potential for transport. While early Holocene drought cannot be discounted, the close spatial association of dunes with the Minong strandline [M1] (Fig. 2A) coupled with age constraints on dunes and lake drainage within the study area suggest a mechanism for sand supply related to lake-level fall. Additionally, both age estimates (site 7 and 19) overlap at 1 sigma error with the main cluster of dates from 9.2 to 8.3 ka (Fig. 3).

Optical ages obtained by Arbogast et al. (2002) surrounding and within the study area (Fig. 1A, I of Fig. 5) range from 6.8 to 5.1 ka and are difficult to explain given the ages obtained in this study. The 'Rainbow Lodge Quarry' site (Fig. 1A) of Arbogast et al. (2002) sits <5 km from several OSL sites (e.g., sites 9 and 15) and the Clark Lake core site, all of which indicate dune activity subsequent to lake drainage at ~9.1 ka. Multiple episodes of eolian activity are possible, but no buried soils were found during field reconnaissance or sampling. Additionally, we postulate that the younger ^{14}C ages from Clark Lake (6895 cal yr BP) and Goose Marsh (6760 cal yr BP) represent a shift to higher effective moisture and paludification during the Nipissing transgression after ~7000 cal yr BP (Davis et al., 2000; Booth et al., 2002), prior to dune activity inferred from Arbogast et al. (2002). These conflicting results require additional chronological constraint on eolian activity in eastern Upper Michigan.

History of the Nadoway–Gros Cap Barrier and meltwater routing

The mechanism that drove possible fluctuation and/or decline of Lake Minong near 10.3 ka is unknown. Farrand and Drexler (1985) speculated that variable receipt of glacial meltwater into the Superior basin (Lake Minong) may have caused lake-level fluctuation and episodic breakdown of the Nadoway Barrier. Multiple peaks in meltwater receipt have now been documented (Breckenridge et al., 2004), but well logs from both sides of the barrier's remnants are dominated by unconsolidated sand and suggest no high standing bedrock or durable till (Fig. 1C). Given its apparent composition, once overtopped or sapped through, the Nadoway Barrier would have failed completely (cf. Costa and Schuster, 1988) and the level of Lake Minong would have dropped rapidly to the Houghton Low. Since only one distinct drop in the level of Minong near 9.0 ka is indicated by our data, we suggest earlier 'partial breaching' is unlikely.

Conclusions

Fourteen optical ages on quartz sand from dunes and a radiocarbon age on wood from an inland lake vibracore in eastern Upper Michigan and adjacent Ontario confirm the terminal decline of glacial Lake Minong at ~9.1 ka. Dune activity on both sides of the Nadoway Barrier occurred adjacent to a well-defined Minong shoreline at ~220 m after lake-level fall. Three optical ages from dunes and two ages from littoral sediments also suggest a previous, more poorly constrained, fluctuation and/or decline in the level of Lake Minong ~10.3–9.9 ka. The final decline of Lake Minong occurred concurrent with a large flux of meltwater into the Superior Basin (Breckenridge et al., 2004; A of Fig. 5), isolation of Clark Lake (L^1 of Fig. 5), and a large negative excursion of the Lake Huron oxygen isotope record (Rea et al., 1994; Moore et al., 2000; K of Fig. 5). A conceptual reconstruction of the Nadoway Barrier, inferred from well logs from its remnants within the study area, suggests that the barrier's prior episodic failure is unlikely. Complete failure of the barrier, rather, likely occurred abruptly at ~9.1 ka. While early Holocene aridity (e.g., Lewis et al., 2007b) may have contributed to or prolonged periods of eolian activity, the close spatial association of dunes with the main Minong strandline [M1] (Figs. 2A and 3) coupled with age constraints on dunes and lake drainage within the study area constitute strong evidence for a mechanism for sand supply related primarily to lake-level fall.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.yqres.2010.03.006.

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