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Sedimentary architecture of the southern basin of Lake of the Woods, Minnesota and its relation to Lake Agassiz history and Holocene environmental change

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Abstract

Lake of the Woods (LOTW) is a large, complex lake basin once occupied by glacial Lake Agassiz. High-resolution seismic-reflection profiles and cores in the shallow, open southern basin of LOTW reveal a sedimentary architecture comprising four lacustrine units separated by three low-stand unconformities. These units represent several phases of Lake Agassiz and its changing configuration. One unconformity marks the Moorhead low phase and another marks the separation of LOTW from Lake Agassiz, perhaps ~10 cal ka BP, as the level of the latter fell, but before final drainage of Agassiz. Initially, the separate Holocene lake in the southern basin was broad and shallow, sometimes marshy or dry. Shortly after 8 cal ka BP, the southern basin dried up completely, despite the progressive rise of the northern outlet of the lake due to differential isostatic uplift. The resulting hiatus is related to the well-documented mid-Holocene arid interval in central North America. A return to wetter conditions in the late Holocene caused the southern basin of LOTW to refill since about 3800 cal yr BP. Late Holocene sediments have accumulated slightly asymmetrically in the basin, possible due to continued southward transgression of the lake as a result of isostatic tilting.

Key words: Lake of the Woods; Lake Agassiz; Seismic-reflection profiles; Sediment cores; Deglaciation; Mid-Holocene climate

INTRODUCTION

Lake of the Woods (LOTW), on the border of the United States and Canada, potentially contains an important record of late-glacial and Holocene conditions in north-central North America. In its early history, the LOTW basin was occupied by glacial Lake Agassiz, which was intimately involved in deglaciation of the Laurentide Ice Sheet and whose drainage likely played a role in global climate events such as the Younger Dryas interval. The early record of Lake Agassiz, the timing and mechanism of separation of LOTW from Lake Agassiz, and the Holocene limnological evolution of LOTW have important paleoenvironmental implications, especially with respect to the paleolimnology of the basin and postglacial climate changes.

LOTW is a large, irregularly shaped lake (Fig. 1) that can be divided into two physiographic parts. The northern half is a complex of islands and small basins with relatively restricted areas of open water. The southern part of the lake basin is mostly shallow and open, with water depths averaging about 10 m. The Rainy River, located in the southeast section of the drainage basin, is the primary inlet, accounting for ~75% of the total water input into the lake (Yang and Teller, 2005). The outlet complex of the lake, with a sill elevation of 320.7 m, is near the town of Kenora, Ontario, draining into the Winnipeg River and then into Lake Winnipeg, 235 km downstream (Yang and Teller, 2005).

During deglaciation, the Laurentide Ice Sheet, a major component of the global climate system, retreated downslope into the isostatically depressed regions of southern Canada. As it did so, it impounded a vast glacial lake called glacial Lake Agassiz. The history and evolution of Lake Agassiz is complex and has been studied by researchers for more than a century (Upham, 1895; Clayton, 1983; Teller and Clayton, 1983; Teller, 1995; Teller and Leverington, 2004; Lowell et al., 2005; Fisher et al., 2008; Breckenridge, 2015). Particularly contentious has been the timing of changes in Lake Agassiz and their possible role in climate events such as the Younger Dryas cold interval. A full review of these issues is beyond the scope of this paper, but several recent reviews exist (Fisher et al., 2011; Teller, 2013; Breckenridge, 2015). Glacial Lake Agassiz was in contact with the receding ice

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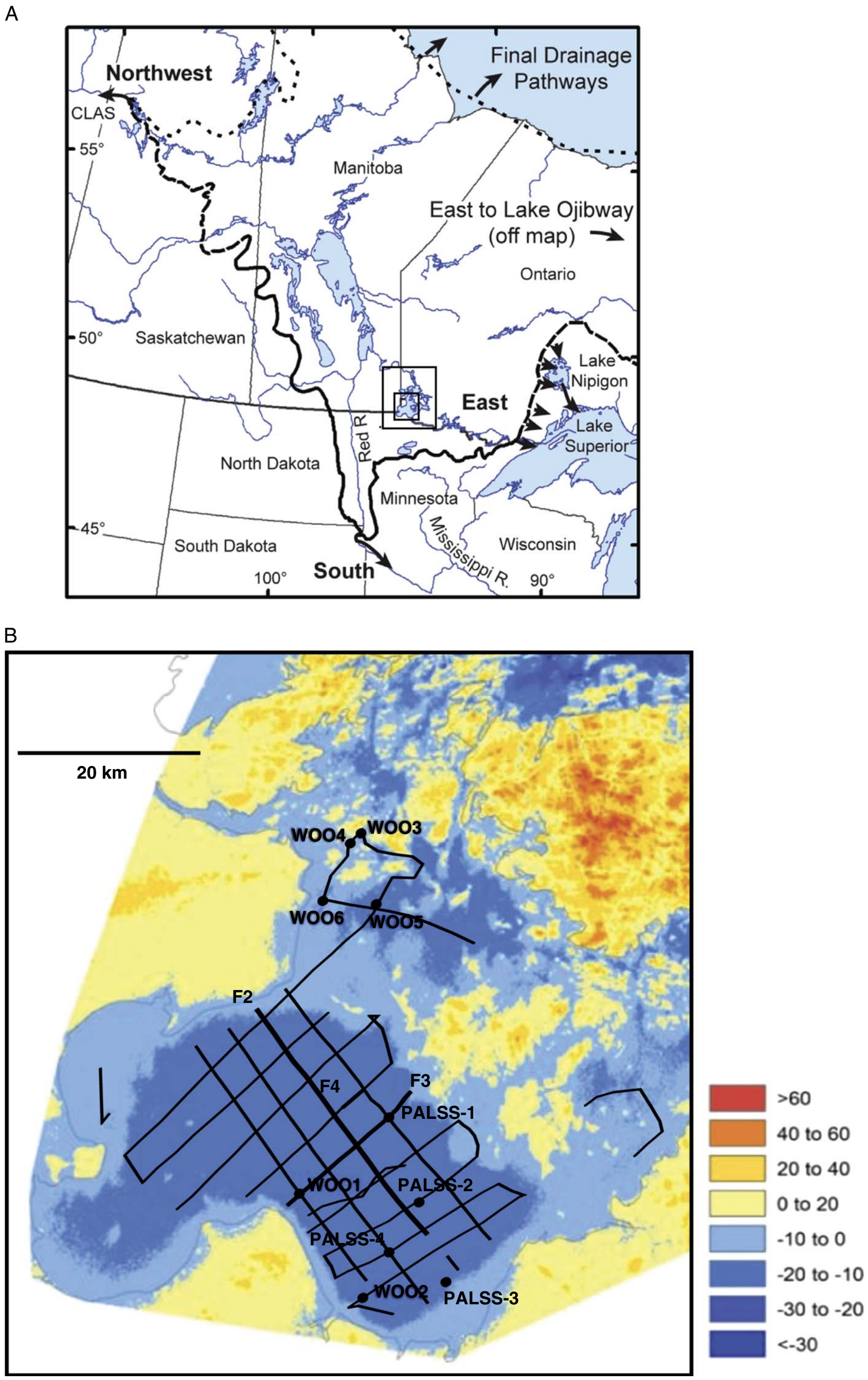

Figure 1. (color online) Location maps. (A) Index map showing maximum extent of Lake Agassiz (west of the glacial Lake Ojibway basin), adapted by Breckenridge (2015) from Teller and Leverington (2004). Maximum levels are dotted where inferred. Overflow routes are shown as arrows, including to the east (Lake Superior basin/Atlantic Ocean), south (Mississippi basin and Gulf of Mexico), and northwest (Mackenzie basin and Arctic Ocean). Two inset rectangles indicate the Lake of the Woods (LOTW) basin and the area shown in Figure 1B, respectively. (B) Map of the southern basin of LOTW showing core sites and seismic profiles. Topography in m relative to modern level of LOTW (after Yang and Teller, 2005). Core locations from Mellors (2010; WOO-) and Hougardy (2013; PALSS-). The locations of seismic profiles shown in Figures 2–4 are indicated by labeled (F2–F4) thick black lines; other profiles collected in this study are indicated by thin black lines.

sheet when the LOTW region was deglaciated, so that the LOTW basin was immediately covered by Lake Agassiz. Thus, the early history of LOTW is intimately entwined with that of Lake Agassiz. The major phases of Lake Agassiz should be recorded in the sediments below LOTW, although LOTW may have been isolated from Lake Agassiz by isostatic uplift

(Yang and Teller, 2005) by the time Lake Agassiz finally drained at about 8.5 cal ka BP (Barber et al., 1999).

Surprisingly little research has been focused on the formation and evolution of LOTW. Yang and Teller (2005) modeled the extent and depth of water over the LOTW basin at various time intervals by using crustal rebound isobases to reconstruct the paleotopography across the LOTW basin. Only one previous significant investigation of the sediments below LOTW has been conducted (Mellors, 2010; Teller et al., 2018), based on cores collected from the upper part of the sedimentary section in several sub-basins from north to south across LOTW. No previous seismic-reflection studies have been done on LOTW, although high-resolution acoustic surveys have been performed on nearby Lake Winnipeg (Todd et al., 1998) and Elk Lake (Colman et al., 2012).

The purpose of this paper is to describe the entire sedimentary section beneath LOTW from a network of seismic-reflection profiles from the southern basin of the lake. Interpretation of the seismic-reflection data is aided by cores we collected at four sites in the southern basin, as well as by the cores collected in a previous study (Mellors, 2010; Teller et al., 2018). The distribution of the seismic-stratigraphic units and their relation to unconformities in the section reveals much new information about the evolution of the LOTW basin. We also explore the extent to which these data reveal new insights into the history of Lake Agassiz.

METHODS

The seismic survey consisted of about 475 km of CHIRP (Compressed High Intensity Radar Pulse) sub-bottom profiles (Fig. 1B), mostly from the southern basin (Minnesota) of LOTW (Hougardy, 2013). The survey was conducted using a single-channel EdgeTech 3100P CHIRP sub-bottom profiler and an EdgeTech SB424 towfish, using 10 ms sound pulses at a swept frequency of 4–24 kHz. Survey speeds were kept between 2 and 4 knots (5–8 km/hr) with the towfish 0.5 m below the water surface throughout the survey. Locations of seismic data were recorded from standard GPS navigation. Penetration of the seismic signals into the sediments was as much as 25 m, reaching bedrock or till in most of the southern basin of the lake. An average sound velocity of 1450 m/s for fresh lake water and unconsolidated sediments was assumed, yielding a vertical resolution of about 10 cm. Data were processed using the standard Kingdom Software Suite (IHS, Houston, Texas), and archived in the Geophysics Laboratory at the Large Lakes Observatory in Duluth, MN.

Four long (3–7 m) piston cores were collected from the southern basin through ice in March 2012, along a roughly north-south oriented transect (Fig. 1B) for the purpose of correlating seismic-stratigraphic units with lithological units. The cores are formally named PALSS-WOO12-xx, where xx includes the site, hole, drive, coring tool, and section designations (Hougardy, 2013); here they will be referred as PALSS- plus the site and hole number (e.g., PALSS-4A). Core site PALSS-2A/2B was selected to capture a particular onlapping sequence identified from the preliminary seismic data. This is the only site where two overlapping cores (2A and 2B, spaced about 1 m apart) were taken. Bolivia and Livingstone-type piston corers were used for sediment recovery (Myrbo and Wright, 2008).

The cores were split, imaged, logged, and archived at the LacCore laboratory at the University of Minnesota. Low-field magnetic susceptibility and gamma-ray density measurements were conducted on lined, whole-core drives using a Geotek Multi-Sensor Core Logger. Sediment cores were described using visual and textural analysis at the Sedimentology Laboratory of the Large Lakes Observatory according to the classification scheme outlined by Schnurrenberger et al. (2003).

Eight samples of wood, seeds, or peat were rinsed with deionized water before being processed and analyzed by accelerator mass spectrometry (AMS) at the Woods Hole Oceanographic Institute's radiocarbon laboratory (NOSAMS). Radiocarbon ages (^{14}C) were converted to calibrated years before present (AD 1950) using Calib v.5.0.1 (Stuiver and Reimer, 1986) and IntCal13 calibration data (Reimer et al. (2013).

RESULTS

Seismic-reflection data

The seismic-reflection data from LOTW have been used to define five individual seismic-stratigraphic units according to their reflection character, reflection configuration, and external geometries, following the criteria of Stoker et al. (1997). Details of the character of the different seismic units are included as Supplementary Table S1. The seismic units, labeled SU- A, B, C, D, and E from oldest to youngest, are shown in two intersecting basin-wide profiles (Fig. 2 and 3). Details of the character and relationships among these units and the unconformities that separate them are shown in Figure 4.

Unit SU-A is the acoustic basement of the seismic stratigraphy. Near the margins of the southern basin, the amplitude of the upper boundary reflection is very high and the reflection is relatively smooth, suggesting that SU-A represents bedrock (Supplementary Table S1; Fig. 2 and 3). In contrast, in the middle of the southern basin, the reflection amplitude at the top of SU-A is lower than at the basin margins, the configuration of the surface of is highly irregular, and in a few places, the seismic signal penetrated into the underlying material and weak internal reflections were observed. In such cases, we infer that that SU-A locally represents till, although it is difficult to consistently delineate from bedrock in the seismic images. The upper units of the seismic stratigraphy (SU-B to SU-E) are all interpreted as lacustrine deposits, whose origin will be discussed in detail. Unit SU-E is the youngest unit, whose upper boundary is the modern lake floor. SU-E is thickest in the southwestern part of the southern basin.

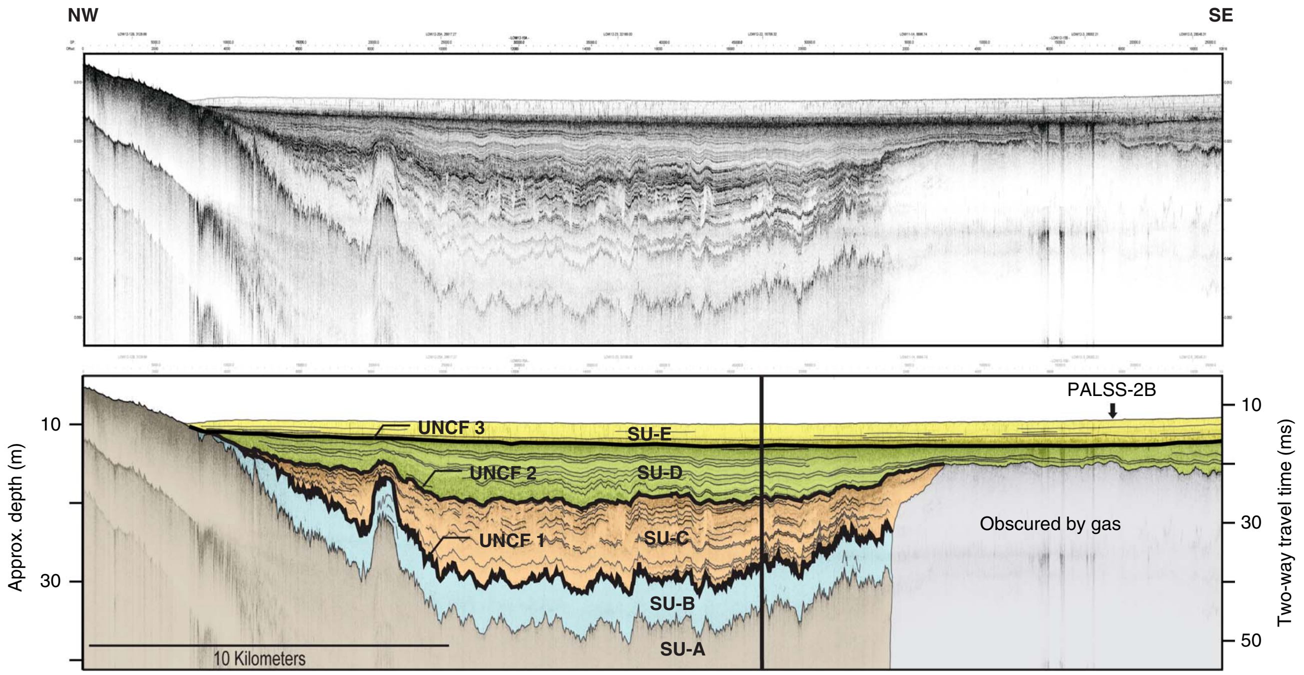

Figure 2. (color online) Seismic line 12-15 (Hougardy, 2013) in the south basin of Lake of the Woods (LOTW), extending from northwest to southeast. Location shown as heavy line labeled F2 in Figure 1B. In the interpreted section (bottom), vertical scales are in two-way travel time (TWTT) and depth, assuming a sound velocity of 1450 m/s. Vertical exaggeration is ~195×. Seismic units (SU-) A through E are shown, along with three major unconformities (UNCF-) 1 through 3. Projection of the location of core PALSS-2B into the seismic line is indicated. The intersection with seismic line 12-22 (Fig. 3) is shown by heavy vertical line.

Unconformities are an integral part of the lacustrine stratigraphy beneath LOTW. They are responsible for distinct reflections, and they define the boundaries between the upper four seismic-stratigraphic units. They are most obvious beneath shallow water areas around the margins of the basin, where they commonly truncate underlying units and are onlapped by younger sediments (Fig. 4). The unconformable horizons commonly become parallel with other reflections

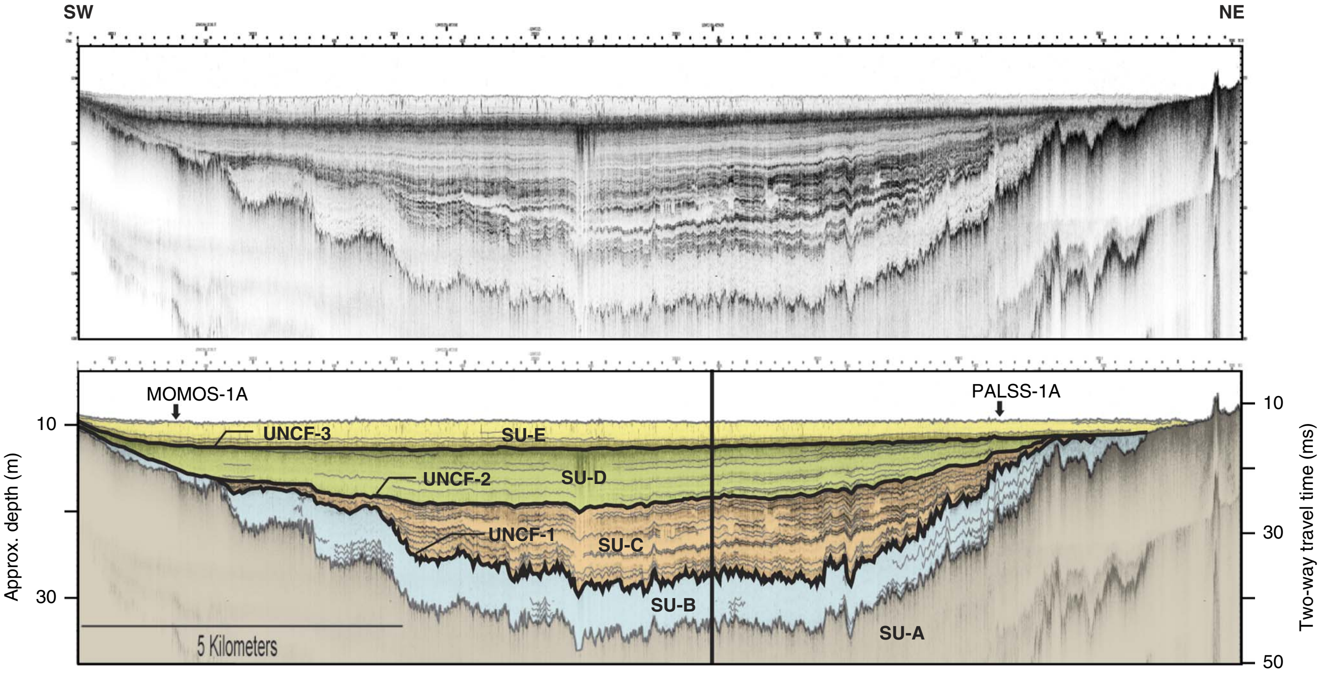

Figure 3. (color online) Seismic line 12-22 (Hougardy, 2013) in the south basin of Lake of the Woods (LOTW), extending from southwest to northeast. Location shown as heavy line labeled F3 in Figure 1B. Scales, units, and core locations as in Figure 2. Vertical exaggeration is ~73×. The intersection with seismic line 12-15 (Fig. 2) is shown by heavy vertical line.

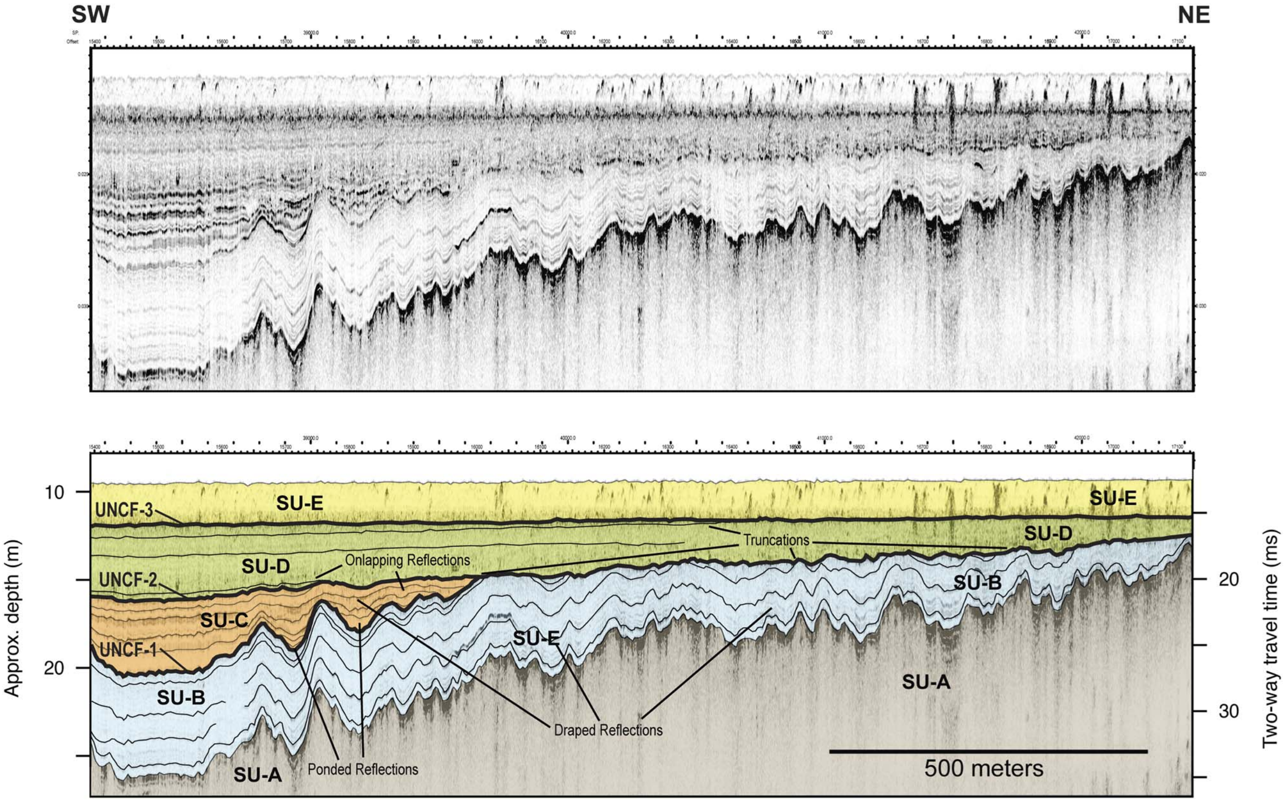

Figure 4. (color online) Enlarged portion of seismic line 12-23 (Hougardy, 2013) near the northeast margin of the southern basin, showing the relationships between seismic units and unconformities. Location shown as heavy line labeled F4 in Figure 1B. Scales and units as in Figure 2. Vertical exaggeration is ~28×.

toward the center of the depositional basin and there may or may not be a time hiatus at the horizons in these areas.

The unconformities are numbered from oldest to youngest. The oldest, Unconformity 1 (UNCF-1), separates sedimentary units SU-B and SU-C (SU-B conformably overlies SU-A). The reflection amplitude of UNCF-1 is high at the margins of the basin but decreases towards the middle. At the basin margins, where reflection amplitudes are highest, the surface is erosional and the surface truncates internal reflections of underlying unit SU-B (Fig. 2–4). In the middle of the basin, the surface is concordant with the internal reflections in the surrounding units. At the margins of the basin, UNCF-1 is always truncated by UNCF-2 or UNCF-3.

UNCF-2 separates unit SU-D from SU-C and SU-B. Like UNCF-1, its reflection amplitude decreases from the margins to the middle of the basin but to a lesser degree than UNCF-1. The related reflection is typically broad and laterally continuous, although occasional discontinuities are observed in the middle of the basin. UNCF-2 truncates internal reflections of underlying units SU-C and SU-B near the margins of the basin, but is concordant with surrounding reflections in the middle of the basin. UNCF-2 also frequently truncates UNCF-1, causing sedimentary unit SU-C to pinch out. The topographic relief of unconformity UNCF-2 is less than that of UNCF-1 (Fig. 2–4) and the horizon is more continuous across the survey area. At the basin margins, UNCF-2 is frequently truncated by UNCF-3.

UNCF-3 separates SU-E from underlying sedimentary units SU-B, SU-C, and SU-D. UNCF-3 is continuous and forms a very high-amplitude reflection across the basin. Underlying seismic units and older unconformities all are truncated by UNCF-3 at the margins of the basin. There is very little variation (<4 m) in topographic relief on UNCF-3, but the thickness of the overlying sediments is not constant, being thickest in the southwestern part of the southern basin (Fig. 5).

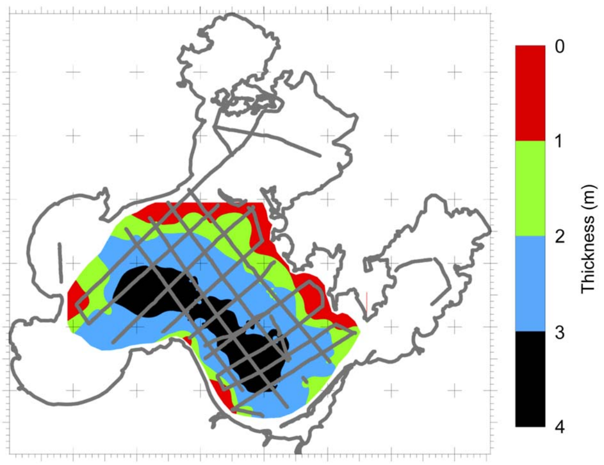

Figure 5. (color online) Isopach map for unit SU-E, the uppermost sedimentary unit in the basin.

Cores

Two major lithologic units are present in the cores obtained in this study. The cores were taken adjacent to seismic-reflection profiles, allowing direct correlation of the lithological units with the seismic-stratigraphic units by depth. In the upper part of the seismic profiles, all of the significant reflections can be traced among the core sites. Because of this correspondence, the two lithological units in the cores clearly correspond to seismic units SU-E and SU-D, and the seismically defined unconformity that separates the two seismic units (UNCF-3) is clearly represented in the cores by a major change in lithology. Because the two types of units, seismic and lithologic, are so clearly equivalent in the upper part of the section, the seismic terminology for the units is used for convenience. In the core logs, the individual seismic-reflection horizons (Supplementary Fig. S6), designated by numbered "Hs" from the top down in the lithologic logs, can be correlated between the seismic profiles and the cores (Supplementary Fig. S6). In this scheme, H4 corresponds to UNCF3 in Fig. 6.

All of our cores primarily contain fine-grained lacustrine sediment: clay and silt, with minor amounts of sand, peat, and other materials. Lithologic logs of the representative core PALSS-2B are shown in Figure 6; logs of the other cores are included in the Supplementary Figures S1–S4. Optical scans of segments of the core from PALSS-2B are shown in Supplementary Figure S5.

The upper lithological unit, corresponding to seismic unit SU-E, is mostly massive to weakly laminated brown silty clay (Fig. 6; Supplementary Fig. S5), extending upward to the modern mud at the lake floor. The unit has relatively low magnetic susceptibility, increasing downward. Its density increases downward, as well, presumably as compaction increases and water content decreases. Few macrofossils suitable for radiocarbon analyses occur in the unit. In cores (WOO5 and WOO6; Fig. 1B) from basins to the north, Teller et al. (2018) described as much as 0.5 m of reworked material (marked by paleosol peds) derived from the unit below in the upper lithologic unit, but we did not observe such material in cores from the central part of the southern basin.

The lower lithological unit, corresponding to seismic unit SU-D, is mostly gray to brown, laminated silts and clays (Fig. 6, Supplementary Fig. S5) with variable amounts of sand and organic material (Fig. 6, Supplementary Fig. S5). It is thinner near the basin margins than in the center of the basin, and the upper part of the unit contains more sand and dry clay there. Fragmented woody peat occurs as distinct layers or in trace amounts throughout the lower unit. Several medium-grained sand beds are present in the unit, some of which contain bivalve fossil shell fragments. The magnetic susceptibility and density of the unit are variable, mostly corresponding to lithologic changes, but the density is mostly higher than that of the upper unit (Fig. 6). We observed relatively dry, blocky clay at the top of unit DU-D, just below UNCF-3, probably corresponding to one of the pedogenic zones described by Teller et al. (2018).

The lithology of unit SU-D is highly variable and difficult to correlate among core sites. Even cores PALSS-2A and -2B, taken a few meters apart, do not match well in their lower sections. The two cores correlate well for the upper lithological unit, both for the unconformity (UNCF-3)

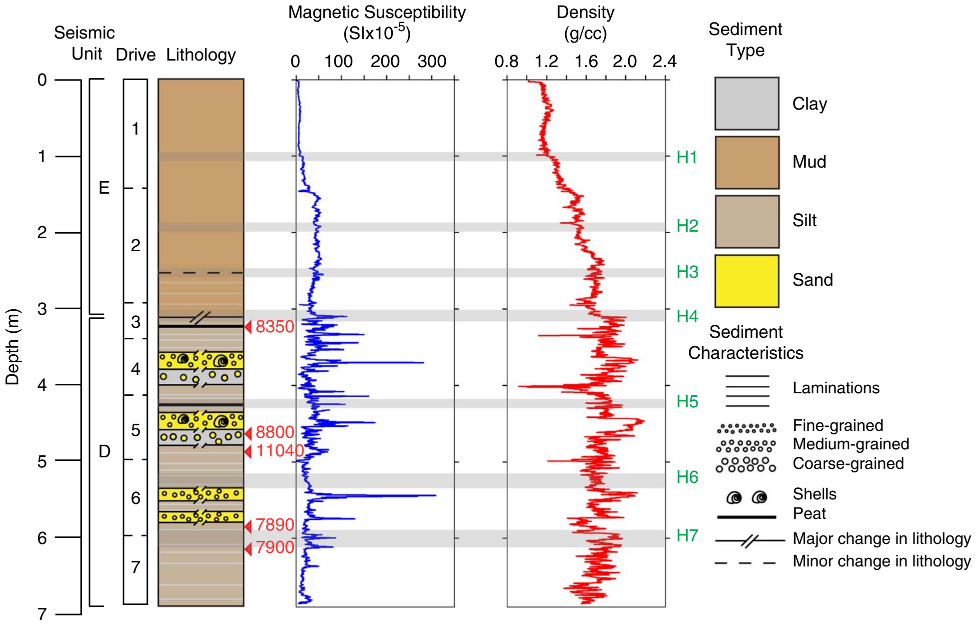

Figure 6. (color online) Stratigraphic data for core PALSS-2B; location shown in Figure 1B. Columns show seismic units, drive length, lithology, magnetic susceptibility, and density data. Gray shaded bars and H labels represent local reflections (contrasts in acoustic impedance) in seismic-reflection profile over the core site (see Supplementary Fig. S6). Triangles and numbers to the right of the lithology column are radiocarbon ages in cal yr BP (Table 1). A major abrupt change in lithology from mud-dominated sediment to clay occurs at a depth of ~3 m (H4) and corresponds to UNCF-3.

separating the two units and the upper part of the lower lithological unit, down to a depth below the lake floor of about 4.3 m. The reason for the lack of similarity below 4.3 m is unknown, but it is likely the result of coring disturbance caused by multiple re-entries of the piston corer into the boreholes.

These lithology of the upper part of the lower unit (SU-D) and the fact that it is truncated in the seismic data by UNCF-3, suggest that this lower lithologic unit was subaerially exposed for an extended period of time, leading to erosion of its upper part around the margins of the basin during the subsequent transgression. The exposure interval and subsequent transgression are now represented by UNCF-3.

Radiocarbon ages

Eight radiocarbon ages were obtained on terrestrial macrofossils (Table 1) from sediment in cores PALSS-2A, -2B, and -4A. Also included in this discussion are four ages (Table 1) from sediment core MOMOS-1A (Mellors, 2010; Teller et al., 2018) in the southern basin of LOTW (Fig. 1B). Radiocarbon ages for lake sediments are commonly difficult to interpret (Colman et al., 1996), in part because endogenic materials are subject to unknown reservoir effects. Because of this, terrestrial macrofossils are commonly sought, but these materials have, by definition, been transported to the site of deposition, and thus are at least slightly older than the sediments in which they are found. In many cases, however, terrestrial macrofossils yield reliable radiocarbon ages. We believe that this is the case for the upper lithologic unit, above UNCF-3, where the two ages from MOMOS-1A and one from PALSS-4A are consistent and in sequence (Fig. 7).

Four ages, two from MOMOS-1A and two from PALSS-2A, were obtained from directly below UNCF-3 and near the top of the lower lithologic unit (sedimentary unit SU-D). They cluster together (Fig. 7) and yield an average of about 8000 cal yr BP. The age 7750 cal yr BP from PALSS-2A (Table 1) is the youngest of the group and probably represents the best estimate for the age of the top of the lower lithologic unit, sedimentary unit SU-D (Table 2). No evidence of significant erosion of the top of unit SU-D in the center of the southern basin was observed in the seismic data, and no reworked material in unit SU-E was observed in cores from the basin, although such material has been described from basins to the north (Teller et al., 2018). Despite the fact that two of these ages are on macrofossils that have been transported to the site, two are on what appears to be in-situ peat, so that, as a group, these ages are interpreted as being approximately accurate.

For the rest of the lower lithologic unit, the radiocarbon ages are difficult to interpret (Fig. 7). One age is >11 cal ka BP, much older than the expected age for this part of the section, as discussed in the next section. We interpret the wood in this sample as being older than the sediments, having been transported to the site of deposition. The other three anomalous ages from the lower part of the cored section are all unexpectedly young, essentially the same age as the top of the unit (SU-D). As discussed previously, there is evidence of coring disturbance in the lower parts of cores PALSS-2A and 2B, and the stratigraphy in the lower part of these two cores does not match. We interpret the three anomalously young ages from deep in these cores as younger materials that were physically displaced downward in the cores. The only other explanation for these ages is that the lower lithological unit was deposited essentially instantaneously, which is unlikely because of the thickness and stratigraphy of the unit and because of the basin-wide continuity of the internal reflections in seismic unit SU-D.

DISCUSSION

Early history of the basin

The timing of the deglaciation of the southern basin of LOTW and the bedrock and till of SU-A is difficult to determine precisely. Deglaciation must be younger than the Big Stone Moraine (crossed by the southern outlet, Fig. 1A) to the southwest, whose age is about 14.0 cal ka BP (Lepper et al., 2007). The Rainy River basin, feeding LOTW, was inferred to have been deglaciated while Lake Agassiz was at the Herman level (Johnston, 1946). The Herman-Norcross shorelines, formed during the earliest (Lockhart phase) history of Lake Agassiz, are all above the level of LOTW, and are dated to 14.6–13.3 cal ka BP (Lepper et al., 2011, 2013). The absence of diamictons or deformed structures in the lacustrine sequence above SU-A in the southern LOTW basin suggests that the Laurentide Ice Sheet did not readvance into the southern basin of LOTW after initial deglaciation of the basin.

The uniform thickness and draped configuration of SU-B, which is 6-m-thick in much of the basin, suggest a period of high lake level following the retreat of the ice margin north of LOTW. The lack of depositional focusing despite deposition in a clearly defined basin suggests that the lake level was higher than the margins of the southern basin and likely extended far beyond the boundary of present-day LOTW. Although no cores or samples of SU-B have been obtained, the largely reflection-free character of SU-B suggests the lithology is relatively fine-grained and uniform in character. Seismic units with similar character and stratigraphic position in Lake Winnipeg contain varved lacustrine sediment (Todd et al., 1998). Varved lacustrine clays are also observed at the bottom of sediment cores from West Hawk Lake, ~65 km northeast of the southern basin of LOTW (Teller et al., 2008), and from the Rainy River basin (Bajc et al., 2000), both of which were interpreted to have been deposited during the Lockhart phase of Lake Agassiz when lake levels were relatively high because the lake was still impounded between the ice and its southern outlet.

Sequence-bounding reflections in seismic-reflection data are generally interpreted as representing low-stand unconformities. We follow this interpretation for the three major unconformities present in the LOTW seismic data. Accordingly, we correlate sedimentary unit SU-B, the lowest

Table 1. Radiocarbon ages from the southern basin of Lake of the Woods (LOTW). Radiocarbon ages converted to calibrated years before present (cal BP; AD 1950) using Calib v.5.0.1 (Stuiver and Reimer, 1986) and IntCal13 calibration data (Reimer et al., 2013). Data for MOMOS cores from Mellors (2010).

Core ID	Lab Number	Depth from top of core (cm)	Dated material	^{14}C age	δ^{13}C	Age range cal BP (2σ)	Probability	Mean age cal BP (1σ)	Probability	Weighted avgerage (1σ)	Years cal BP
PALSS-2A	OS-103426	308–309	Peat	6930 ± 30	–28.2	7830–7690	1	7750	1	7750	7748 ± 40
PALSS-2A	OS-103432	652–658	Wood Macro	7040 ± 35	–27.71	7950–7820	0.96	7910	0.57	7890	7879 ± 41[b]
						7810–7780	0.04	7860	0.43		
PALSS-2B	OS-103427	322–323	Peat	7500 ± 30	–26.06	8390–8290	0.82	8350	1	8350	8340 ± 29
						8260–8210	0.18				
PALSS-2B	OS-103428	458–459	Seeds	7940 ± 40	–23.85	8820–8640	0.55	8740	0.45	8800	8773 ± 108
						8980–8820	0.45	8940	0.24		
PALSS-2B	OS-103429	470	Wood macro	9650 ± 40	–26.85	11,190–11,060	0.52	11120	0.64	11040	11,075 ± 106[a]
						10,970–10,790	0.45	10910	0.36		
PALSS-2B	OS-103430	587	Wood macro	7040 ± 40	–25.94	7950–7790	1	7910	0.55	7890	7878 ± 46[b]
								7860	0.45		
PALSS-2B	OS-103431	617	Wood macro	7080 ± 40	–24.69	7980–7830	1	7880	0.52	7900	7919 ± 38[b]
								7940	0.48		
PALSS-4A	OS-103125	154–155	Wood macro	1800 ± 25	–26.76	1820–1690	0.88	1720	0.57	1750	1724 ± 35
						1650–1630	0.11	1770	0.28		
MOMOS-1A	48250	90–92	Clam	1460 ± 45	–	1420–1290	0.97	1340	1	1340	1345 ± 36
						1480–1460	0.02				
MOMOS-1A	61723	140–145	Seed material	1675 ± 20	–	1620–1530	1	1560	0.55	1570	1564 ± 24
								1590	0.45		
MOMOS-1A	48217	280–282	Seed material	7375 ± 20	–	8220–8160	0.73	8190	0.89	8200	8186 ± 20
						8310–8260	0.23	8270	0.11		
MOMOS-1A	54959	320–323	Seed material	7140 ± 40	–	8020–7930	0.92	7970	1	7970	7961 ± 28
						7900–7870	0.08				

[a] Age interpreted as being invalid due to reworking of older material (see Results).

[b] Age interpreted as being invalid due to younger material falling into bottom of core hole from above (see Results).

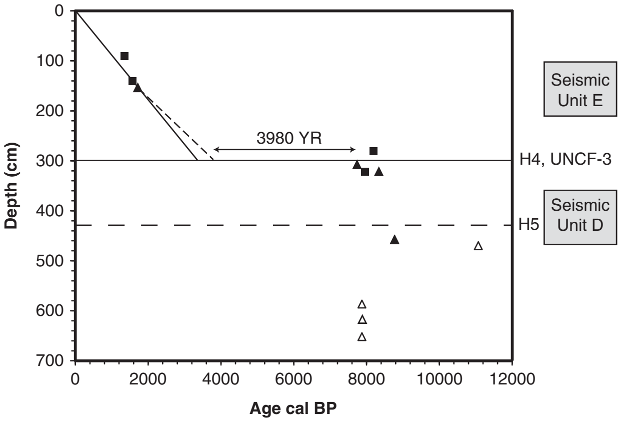

Figure 7. Radiocarbon ages from the southern basin of Lake of the Woods (LOTW). Seismic reflections (H4 and H5) are from Figure 6. Eight radiocarbon ages (cal yr) from this study (triangles) and four from previous studies (squares, Mellors, 2010; Teller et al., 2018) are shown in relation to the depth (cm) to prominent reflections (solid and dashed lines) at core site PALSS-2A/2B. Corresponding interpreted seismic units are labeled on the right. The MOMOS ages are plotted by depth, and one appears to be above UNCF-3 at our sites, even though it is just below the unconformity (280 cm) at its own site. Radiocarbon ages near the top of unit SU-D (solid triangles) agree well with ages from MOMOS-1A and are thought to be accurate. Four of the ages below 430 cm (empty triangles) are likely disturbed younger materials or transported older materials and are discounted (see text). Solid and dashed lines in unit SU-E are extrapolations from the lake floor through the indicated age, assuming a constant sedimentation rate (cm/yr, solid) or a constant mass accumulation rate (g/cm^2/yr, dashed). Calculations summarized in Table 2.

lacustrine unit in the sequence, with the initial high phase (Lockhart Phase) of Lake Agassiz). UNCF-1, forming the upper bound of unit SU-B, is interpreted as representing a low phase of LOTW following the high stand marked by SU-B. Stratigraphically, this sequence strongly suggests that UNCF-1 corresponds to the Moorhead Phase of Lake Agassiz, the first low phase of Lake Agassiz following the Lockhart high phase. The Moorhead phase is almost universally recognized in the geomorphic and stratigraphic sequences in the Lake Agassiz region as a distinct, relatively low phase (Elson, 1967; Fenton et al., 1983; Bajc et al., 2000; Fisher et al., 2008), although its timing and cause are controversial (see recent discussions by Fisher et al. [2011], Teller [2013], and Breckenridge [2015]). Toward the margins of the basin, erosion associated with UNCF-1 appears to have removed as much as 4 m of SU-B, although no subaerial channels were observed. Toward the center of the basin, the reflection associated with UNCF-1 remains moderately strong, but it becomes conformable with its surrounding units. These observations suggest that a small, shallow lake persisted in the southern basin of LOTW during the Moorhead low stand of Lake Agassiz. Although no cores have penetrated UNCF-1 to date, the potential exists to better define and date the Moorhead phase of Lake Agassiz with future coring in LOTW.

The level to which Lake Agassiz fell during the Moorhead phase is a matter of considerable debate (Fisher et al., 2008, 2011; Lowell et al., 2013; Breckenridge, 2015), with recent estimates of more than 50 m and probably as much as 90 m (Breckenridge, 2015). At LOTW, the elevations of the reconstructed Tintah and Campbell shorelines, which bracket the Moorhead low phase in time, allow us to place a constraint on the level of Lake Agassiz during the Moorhead phase (Table 3). The differential uplift of the Moorhead shoreline across the LOTW basin must be between that of Tintah and Campbell shorelines, or between 30 and 44 m (Table 3). However, the current outlet sill of LOTW is only about 30 m above the level of UNCF-1 in the southern basin; therefore, the modern outlet sill must have been below the floor of the southern basin during the Moorhead low phase, and that phase must have been more than 30 m lower than that of the Tintah shoreline. This is not a strong constraint on the actual level of the Moorhead shoreline, but it is consistent with previous estimates of 50 m or more.

If our inference that a small, shallow lake existed in the southern basin of LOTW during the Moorhead phase of Lake Agassiz is correct, then the data in Table 3 indicate that the current outlet sill was not the controlling outlet for this lake.

Table 2. Calculations for the duration of the mid-Holocene hiatus in the southern basin of Lake of the Woods (LOTW; also see Fig. 7).

Datum	Depth (cm)	Age (yr or cal yr BP)	Depth (cm)	Density[a] (g/cm^3)	Cumulative mass (g/cm^2)	Age (yr or cal yr BP)
Lake floor surface	0	0	0	1.15	0	0
Radiocarbon age[b]	155	1750	155	1.45	201.5	1750
Base of Unit SU-E, age extrapolated UNCF-3	300	3390[c]	300	1.75	433.5	3770[d]
Radiocarbon age at top of Unit SU-D[a]	300	7750	300	–	–	7750
Calculated hiatus length (assuming constant rate of sedimentation)		4360		Calculated hiatus length (assuming constant rate of mass accumulation)		3980

[a] From Figure 6.
[b] Wood macrofossil (Table 1).
[c] Calculated assuming constant rate of sedimentation (cm/yr), extrapolated from 0–155 cm.
[d] Calculated assuming constant rate of mass accumulation (g/cm^2/yr), extrapolated from 0–155 cm.

Table 3. Reconstructed elevations at Lake of the Woods (LOTW).

Location	Elevation of Tintah shoreline (m)[a]	Elevation of Campbell shoreline (m)[b]	Modern elevations (m)
Outlet, at isobase 580[c]	430	375	320 (outlet)
Southern basin, at isobase 500[c]	382	345	290 (UNCF-1)[d]
Difference	48	30	30

[a] From equation 4 of Breckenridge (2015).
[b] From equation 3 of Breckenridge (2015).
[c] Isobase distance based on figure 3 in Breckenridge (2015).
[d] Elevation of UNCF-1 based on Figures 2 and 3.

The current outlet would have been below the floor of the southern basin, and a more southerly sill would have impounded the southern basin. In addition, the lake in the southern basin of LOTW briefly would have been separated from Lake Agassiz, until the transgression following the Moorhead low (to the Campbell level) re-flooded much of the LOTW basin.

The lower part of unit SU-C is ponded in topographic lows and it onlaps onto the UNCF-1 surface. The upper part of the unit is broadly continuous across the basin. These relationships suggest that SU-C represents deposition in Lake Agassiz as it rose from its Moorhead low stand and continued into its high-level Emerson Phase. Internal reflections within the middle part of SU-C diverge to the southwest, which we interpret as the result of isostatic tilting of the basin toward the southwest, along with transgression of the southern margin of the lake caused by differential uplift of the northern outlet. This is the only clear evidence of differential isostatic uplift observed in the seismic-reflection data from LOTW, although, as discussed below, the thickness pattern of unit SU-E may be partly due to tilting.

Final separation from Lake Agassiz

The upper boundary of SU-C is formed by UNCF-2, which truncates that unit (and older ones) near the margins of the basin. The reflection associated with UNCF-2 is strong near the basin margins, but becomes conformable and relatively weak toward the center. Comparison of the position of the transition from unconformable to conformable character between UNCF-1 and -2 suggests that the low relative lake level associated with UNCF-2 was not as low as that associated with UNCF-1 (Moorhead phase). Differential uplift of the northern outlet of LOTW evidently limited the level to which LOTW could fall.

We suggest that UNCF-2 records the separation of Lake of the Woods from Lake Agassiz, partly because of the stratigraphic position of the unconformity and the fact that the separation is the most dramatic local limnological event in this general time frame. The major contrast in seismic character between units SU-C and SU-D supports this interpretation, but confirmation and dating of this event await future coring to these depths in the stratigraphic section. Prior to the separation of LOTW, but following the Moorhead low stand of Lake Agassiz represented by UNCF-1, the lake rose and its overflow eventually returned to the higher-elevation southern outlet (Emerson phase). A distinct pinkish bed or lamina was deposited in Lake Agassiz at about this time, estimated to be ~11.3 cal ka BP (Teller and Thorleifson, 1983), probably resulting from a readvance of the Superior lobe of the ice sheet, which caused an influx of sediment derived from the red Paleozoic sandstones in the Lake Superior basin. Although our cores did not reach sediments of this age in the southern basin of LOTW, this pinkish lamina is present in a core from one of the northern basins of LOTW (Teller et al., 2018), presumably correlative with part of our seismic unit SU-C.

Following the Emerson phase, the lake level fell gradually as deglaciation progressively uncovered a series of lower outlets (Breckenridge, 2015; Kelly et al., 2016, and references therein). We infer that the isolation of LOTW was the result of one of these falls in the level of Lake Agassiz. As with all lowstand unconformities, the associated seismic reflection could result from a change in lithology, a hiatus, or both. In this case, in addition to the fall in lake level and the lowstand unconformity, the isolation resulted in a much smaller lake within the basin of the modern LOTW, contributing to the prominence of the reflection associated with UNCF-2 and the change in character from unit SU-C to SU-D.

The age of the separation of LOTW from Lake Agassiz is not well constrained. Regional paleotopographic modeling of isostatic rebound and the configuration of Lake Agassiz (Yang and Teller, 2005) indicate that Lake Agassiz had left the LOTW basin by ~10 cal ka BP, although ostracodes and diatoms from cores in northern LOTW basins indicate that Lake Agassiz could have occupied the area until sometime later (Mellors, 2010; Teller et al., 2018).

In our interpretation, Unit SU-D records the time between the separation of LOTW from Lake Agassiz until slightly less than 8 cal ka BP, the age of the top of Unit SU-D. Accordingly, the final draining of Lake Agassiz at about 8.5 cal ka BP (Barber et al., 1999) is not directly recorded in LOTW, because the two lakes were separated at the time Lake Agassiz drained.

Unit SU-D represents the earliest history of LOTW as a separate lake. The unit has been well sampled by cores in the southern basin of the lake in this study and in LOTW as a whole in the previous coring effort (Mellors, 2010; Teller et al., 2018). Reflections within SU-D are strongly stratified parallel and are generally similar in amplitude, onlapping units below, suggesting a widespread succession of lacustrine sediments. This interpretation matches the lithology (laminated silt and clay) observed in sediment cores (e.g., PALSS-2B; Fig. 6, Supplementary Fig. S5). The cores contain abundant thin in-situ beds of peat and medium sand, however, and the silts and clays contain fragments of reworked peat. This lithology suggests nearly continuous deposition, but in a lake whose levels were relatively shallow, allowing occasional fluctuations from lacustrine to wetland or shoreline environments.

Exposure of the lake floor is suggested by zones of inferred pedogenesis identified by Teller et al. (2018) in their lower core unit (correlative with our Unit SU-D) in the northern part of the lake. The amount of time represented by such pedogenesis is uncertain, however, and we identified indications of subaerial exposure (blocky, desiccated clay) only at the very top of unit SU-D in the southern basin.

Radiocarbon ages from SU-D range from less than 8.0 to more than 11.0 cal ka BP, but some of the ages are out of stratigraphic order, and some are on fragments of wood, suggesting the reworking of older organic materials in the shallow lake and intermittent peat wetlands. However, a cluster of closely spaced, consistent ages have been obtained from near the top of unit SU-D (Table 1; Fig. 7). A composite of these ages, from different cores and locations, averages about 8000 cal yr BP (Fig. 7), and the youngest, 7750 cal yr BP, yields the best estimate for the top of the unit. As discussed in the Results section, four of the ages lower in unit SU-D (Fig. 7) are thought to be anomalous for several reasons.

Paleotopographic modeling (Yang and Teller, 2005; Teller et al., 2018) has suggested that the southern basin of LOTW was above the modern outlet of the lake (the overflow level), during much of the early Holocene, from 10 until about 7 cal ka BP. Because of this, they indicate that the southern basin was dry during this interval. On the other hand, unit SU-D was deposited between the separation of LOTW from Lake Agassiz (exact timing uncertain) and about 8 cal ka BP. As discussed above, evidence of marshy or shallow water during this time period is abundant, and structures interpreted as pedogenic may indicate periods of exposure. Overall, however, the thickness and basin-wide extent of Unit SU-D, including prominent, continuous internal reflections, suggests that the southern basin of LOTW did contain a lake throughout much of the early Holocene, albeit with short intervals of dry or marshy conditions. This interpretation is consistent what Teller et al. (2018) concluded about the presence of water in the northern basins of LOTW from ~10 to 7.6 cal ka BP.

Mid-Holocene drought and sedimentary hiatus

Unit SU-D is truncated throughout the basin by UNCF-3, represented by a strong reflection that truncates reflections in lower units (Fig. 2–4). It becomes conformable with the surrounding units in the center of the basin, but unlike UNCF-1 and -2, it maintains its high-amplitude character across the whole basin. From the seismic data alone, we can infer that the basin was entirely dry. Even so, in the center of the basin, the horizon is conformable, and we observed no evidence of incision or differential subaerial erosion of the basin floor.

All cores taken from the southern basin of LOTW contain a major change in lithology that occurs at the same depths as UNCF-3 in the seismic profiles. The change involves an abrupt transition from desiccated silts and clays, intercalated with sand and peat, to fine grained, uniform silty clay. These observations strongly suggest that a shallow lake in center of the southern basin of LOTW dried up entirely shortly after 8 cal ka BP (7750 yr BP, the age of the top of unit SU-D), and remained dry for a considerable period. Teller et al. (2018) concluded from cores in the northern basins of the LOTW, that from ~7.6 to 4.3 cal ka BP, these basins were closed and water levels were low.

Mid-Holocene drought in central North America is well documented in many paleoclimate records, including several syntheses (COHMAP, 1988; Hu et al., 1999; Dean et al., 2002; Williams et al., 2010; Grimm et al., 2011), all of which indicate dry conditions from roughly 8 to 4 cal ka BP. Especially pertinent are the multidisciplinary studies at nearby Elk Lake, Minnesota (summarized in Bradbury et al., 1993). Seismic data collected with the same system as used in this study document a major mid-Holocene unconformity in Elk Lake, which indicates a 10 m fall in lake level (Colman et al., 2012). A major Holocene unconformity is also represented in seismic-reflection data from Lake Winnipeg (Todd et al., 1998) and from the Laurentian Great Lakes (Lewis et al., 2008). We interpret UNCF-3 in LOTW, the most significant unconformity in the post-glacial record, as resulting from a fall in lake level due to mid-Holocene drought. Paleotopographic modeling indicates that the southern basin of LOTW was below the level of the northern outlet during the middle Holocene (Yang and Teller, 2005), so the basin would have held a lake had climate permitted. Accordingly, and in contrast to other times, mid-Holocene lake level was controlled by climate rather than by the position and isostatic rebound of the lake outlet.

Late Holocene resumption of sedimentation

The uppermost unit, SU-E at LOTW is a relatively uniform lacustrine silty clay that overlies UNCF-3 and whose upper surface is the modern lake floor. The base of the unit is nearly horizontal, but the thickness of the unit is asymmetric, being thickest in the southwestern part of the basin (Fig. 5). This asymmetry may be related to ongoing isostatic tilting of the basin to the southwest and southward transgression of the lake. Macrofossils are rare in SU-E, but two radiocarbon ages from MOMOS-1A are consistent (within depth correlation and age errors) with our age (Table 1) from about the middle of the unit in the southern basin of the lake (Fig. 7). Our age of 3750 cal yr BP at 155 cm in core PALSS-4A yields an average sedimentation rate of about 0.09 cm/yr for the late Holocene. Assuming a constant sedimentation rate, extrapolating to the low-relief mid-Holocene unconformity (UNCF-3) yields an age estimate of 3390 cal yr BP for the base of SU-E (Table 2). The density data (e.g., Fig. 6), however, show significant compaction in the upper sedimentary section (unit SU-E), making a constant rate of sedimentation (cm/yr) unlikely. A better assumption is one of constant mass accumulation. The average mass accumulation rate between 0 and 155 cm is 0.115 g/cm^2/yr (Table 2), and at this rate, the age of the base of Unit E is estimated to be 3765 cal yr BP (Table 2; Fig. 7).

From the best estimates for the top of unit SU-D (7750) and the base of unit SU-E (3770), we estimate that UNCF-3 represents a hiatus of just under 4000 yr in the central southern basin of LOTW. This estimate is in accord with the dry interval interpreted from cores in the northern basins of LOTW (Teller et al., 2018). The magnitude of this hiatus is a testament to the aridity of central North America during the middle Holocene.

CONCLUSIONS

The stratigraphy and architecture of the sediments beneath the southern basin of Lake of the Woods appear to represent a nearly complete record of the basin from the time it was deglaciated until the middle Holocene. Although multiple unconformities exist, only the one marking the mid-Holocene appears to include a significant hiatus in deposition in the center of the basin. Seismic-reflection data indicate four stratigraphic units above bedrock and till, the upper two of which have been sampled in cores. Three major low-stand unconformities separate the upper stratigraphic units.

Immediately after deglaciation, the basin was occupied by glacial Lake Agassiz, which progressively covered a large area of central North America, and sedimentary unit SU-B was deposited in a quiet, deep lake (Lockhart phase of Lake Agassiz). We correlate the oldest unconformity (UNCF-1) in the stratigraphic section, truncating unit SU-B, with the Moorhead low phase of Lake Agassiz, a major lake-level fall. The subsequent transgression and the Emerson high phase of Lake Agassiz resulted in the deposition of unit SU-C, as overflow returned to the south and the Campbell shoreline formed at about 10.5 cal ka BP (Lepper et al., 2013). Then, the lake level progressively fell as lower outlets to the north were re-opened. We infer that one of these lake-level falls separated Lake Agassiz from LOTW, perhaps at about 10 cal ka BP, and created the middle unconformity (UNCF-2) in the southern basin of LOTW. The separation also caused a major change in seismic character between units SU-C and SU-D. We cannot independently date these Moorhead and Emerson phase events of Lake Agassiz in the LOTW basin because cores have not penetrated down to sediments of this age. The seismic-reflection data, however, clearly indicate that the sediments are there and that the sequence of events is represented. Further information about this part of the history of Lake Agassiz awaits deeper coring efforts.

Unit SU-D, a basin-wide unit with continuous internal reflections, records the early history of LOTW as a separate lake. Cores confirm the lacustrine character of SU-D, but the laminated silts and clays are intercalated with thin sandy bed, peat layers, and possibly zones of pedogenesis. These data suggest a persistent shallow lake environment during the early Holocene, interrupted periodically by intervals of marsh or brief subaerial exposure. The upper part of unit SU-D is marked by a pedogenic zone, and the top of the unit is relatively well-dated at slightly less than 8 cal ka BP. Because it was a separate lake at the time, LOTW apparently did not record the final drainage of Lake Agassiz at about 8.5 cal ka BP.

The uppermost two sedimentary units are separated by a major unconformity (UNCF-3), attributed to desiccation associated with mid-Holocene aridity, from about 8 to 4 cal ka BP. The southern basin of LOTW was actually dry, with the hiatus duration estimated to be from 7750 to 3770 cal yr BP. This unconformity is similar to those observed in seismic-reflection data from Elk Lake, Minnesota (Colman et al., 2012), Lake Winnipeg, Manitoba, (Todd et al., 1998), and other areas and is consistent with the conclusions based on cores from the northern basins of LOTW (Teller et al., 2018). The southern basin of LOTW was below the lake's northern outlet at this time, and the dry climate overcame the increasing elevation of the outlet due to differential isostatic rebound that otherwise would have incrementally deepened the lake. The uppermost stratigraphic unit (SU-E) is a relatively uniform silty clay that has accumulated at a nearly constant rate in the shallow southern basin of LOTW for the last 3800 cal yr BP after the amelioration of mid-Holocene aridity. Continued isostatic uplift of the northern outlet is evident in the southward transgression and thickness pattern of the late Holocene sediments.

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SUPPLEMENTARY MATERIAL

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