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The chronology, climate, and confusion of the Moorhead Phase of glacial Lake Agassiz: new results from the Ojata Beach, North Dakota, USA

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ABSTRACT

Rapid drainage of glacial Lake Agassiz to the North Atlantic Ocean has been implicated as a triggering mechanism for the Younger Dryas (YD) cold event (13–11.6 ka cal). A key component to this hypothesis is the interpretation that the Ojata Beach of Lake Agassiz in North Dakota, USA, formed during a regression of the lake at the beginning of the YD. This paper reviews the chronological data for the low-water Moorhead Phase, presents new radiocarbon and optically stimulated luminescence (OSL) ages for the Ojata Beach, and utilizes plant and insect macrofossils to reconstruct the paleoenvironmental conditions during the Moorhead Phase in eastern North Dakota. The integrated analysis of the geochronologic data emphasizes the need to distinguish between *in situ* and reworked plant macrofossils. New ages obtained stratigraphically below the Ojata Beach sediments, and reinterpreted chronologic data for the Moorhead Phase, suggest that contrary to previous interpretations, the Ojata Beach is a record of transgression of the lake in the later part of the YD, and the oldest, *in situ* minimum age for the Moorhead Phase is 10.47 ± 75 ka ^{14}C BP. Paleoenvironmental analysis indicates that a spruce–sedge parkland was established at the new Ojata Beach site prior to inundation and gave way to a wetland/shoreline setting as glacial Lake Agassiz transgressed. Comparison of this data set with past paleoecological work 130 km to the south in Fargo, North Dakota, suggests that the ecotone between a cooler "spruce parkland" and a more temperate "deciduous parkland" vegetation during the Pleistocene–Holocene transition was somewhere between Grand Forks (47°58′N) and Fargo (46°51′N) at this time.

1. Introduction

Considerable interest exists in understanding the causal mechanism for the Younger Dryas (YD) cold event (13–11.6 ka cal). In 1989 an important paper was published relating the ^{18}O record from the Gulf of Mexico to meltwater diversion history of Lake Agassiz (Broecker et al., 1989). It was proposed that rapid drainage of Lake Agassiz, facilitated by outlet switching, delivered a large outburst of freshwater to the North Atlantic that shut down or slowed the ocean's thermohaline circulation (Johnson and McClure, 1976; Rooth, 1982; Broecker et al., 1989; Carlson et al., 2007). An additional record from the Gulf of Mexico shows a similar signal (Flower et al., 2004). However, this hypothesis is not without its detractors. Others who question the Lake Agassiz-trigger hypothesis cite lack of a meltwater signal in the St. Lawrence at the onset of the YD (Rodrigues and Vilks, 1994; de Vernal et al., 1996), insufficient volumes of meltwater at the right time (Moore, 2005), and a later deglaciation preventing opening of an eastern outlet of Lake Agassiz (Lowell et al., 2005; Teller et al., 2005). A key relationship in this hypothesis is the purported rapid drop of water level in Lake Agassiz at the start of the YD event, which is tested in this paper.

The prior evidence used for the drop from the high-water Lockhart Phase to the low-water Moorhead Phase of Lake Agassiz, is the oldest wood from the Ojata Beach in North Dakota (Fig. 1A and B) yielding a date of 10.96 ± 0.3 ka ^{14}C BP (W-723) (Moran et al., 1973). Elson (1967) tentatively associated this sample with an early low stand before the main Moorhead low-water Phase, while Arndt (1977) used it for the start of the Moorhead Phase. After reviewing the chronological data for the Moorhead

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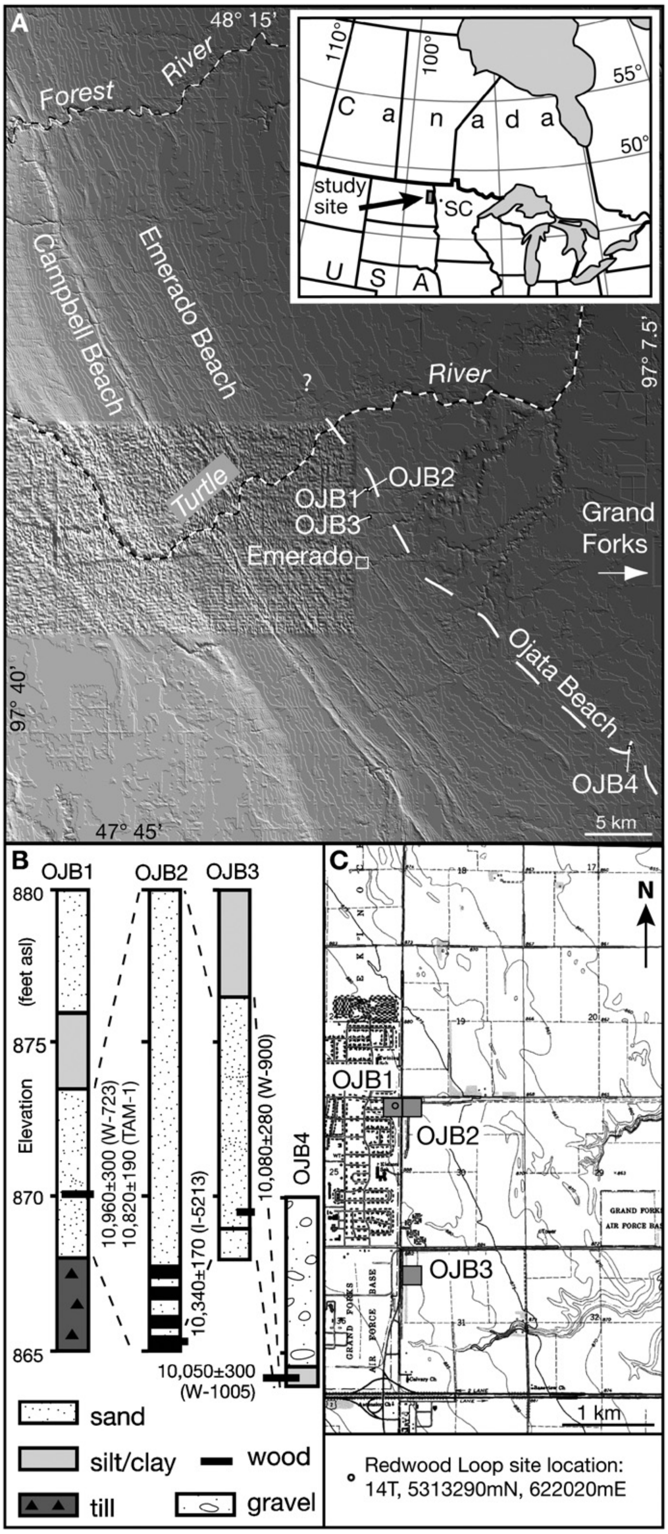

Fig. 1. (A) Digital elevation map showing the suite of strandlines along the western basin of glacial Lake Agassiz in North Dakota. SC on the inset map refers Snake Curve section. (B) Lithostratigraphic logs of four exposures arbitrarily labeled OJB1–4 with radiocarbon dates described in Moran et al. (1973). (C) Emerado 7.5′ topographic quadrangle with the sample sites shown as areas (1/64th mile^2), as reported in Moran et al. (1973). The Redwood Loop site is the circle within the OJB1 symbol square.

Phase, we present new data with which to reexamine the Ojata Beach evidence and suggest that, contrary to previous interpretations, the Ojata Beach is not a record of lake level drop at the beginning of the YD, but instead it is a record of lake level rise at the end of the YD. Paleoecological analysis of sandy laminated peat immediately below the Ojata Beach deposits are used to reconstruct a climate preceding the Moorhead transgression that was only slightly cooler than today. Obtaining a high-resolution chronology of hydrologic events in the southern Lake Agassiz basin during the Moorhead Phase was the primary objective of this research, with a secondary goal of reconstructing the local paleoenvironment.

1.1. Moorhead Phase chronology

The Moorhead Phase is defined as the phase when Lake Agassiz dropped, abandoning the southern outlet (cf Clayton, 1983; Fenton et al., 1983), and fluvial deposits of the Poplar River Formation were deposited on the newly exposed lake plain (Arndt, 1977). A recent examination of the radiocarbon dates associated with the Moorhead Phase differentiated between *in situ* and non *in situ* radiocarbon dates from wood (Fisher and Lowell, 2006). The age of the *in situ* wood samples from peat or small terrestrial macrofossils, along with the sample elevation, can constrain maximum limiting water-plane elevations. Table 1 lists the 60 Moorhead Phase ages that we are aware of, with the samples considered *in situ* italicized. Unfortunately, the non *in situ* samples comprise the majority of the samples usually found within beach and alluvial deposits, and often cannot be associated with a specific water level due to their transportation history. Organic samples from beach deposits are considered maximum ages for that strandline; thus the youngest maximum age is the best age estimate for the strandline. Where wood is found within fine-grained lacustrine deposits, such as the case for an abraded stump (#8 and 9, Table 1), the sample history is more complex, but erosion from a littoral environment followed by sinking offshore is a reasonable explanation (Moran et al., 1973), with such samples recording a water plane at a higher elevation for that time. To put these relationships into a graphical context, all relevant Moorhead-aged dates listed in Table 1 are plotted in Fig. 2. The initiation of glacial Lake Agassiz (Lepper et al., 2007) and closure of the southern outlet sometime after 10.675 ka ^{14}C BP (Fisher and Lowell, 2006) are also indicated in Fig. 2. The young age for closing the southern outlet is based on the maximum radiocarbon age of 10.675 ka ^{14}C BP from a gravel unit overlying bedrock and underlying lacustrine mud in the base of a core from the southern outlet spillway (Fisher, 2003), implying that the spillway was active (i.e., the gravel) after the death of the tree as recorded by the wood date. The rate of the subsequent regression and lowest level reached during the Moorhead Phase are both unknown, and wood ages older than closure of the southern outlet (plotted as black squares, Fig. 2) must have been transported into the basin, likely by rivers. One younger age from the Mirror Pool site (#16, Table 1) is included to record the subsequent drop in lake level from the Upper Campbell Beach (McAndrews, 1967). Eight of the reviewed 60 radiocarbon ages are considered to be *in situ* (italicized in Table 1) some of which are used to constrain a possible lake level curve (dashed line) with question marks indicating significant uncertainties. One of these uncertainties is the rise to just above the Campbell level, as originally suggested by Moran et al. (1971) from the Snake Curve section (Fig. 1A), which shows up on lake level diagrams (e.g., Clayton, 1983). This rise in lake level has historically been used to separate the Moorhead from the subsequent Emerson Phase of glacial Lake Agassiz at 9.9 ka ^{14}C BP. The numerous dates younger than 9.9 ka ^{14}C BP for the Campbell Beach indicate that lake level was lower, implying that the Moorhead Phase transgression to the southern outlet did not end until about 9.3–9.4 ka ^{14}C BP (cf Fisher, 2005,

Table 1
Radiocarbon ages for the Moorhead Phase and Campbell Beach from previous studies

#	Elevation (m a.s.l.)	Lab. ID	^{14}C Age (^{14}C yr BP)	Material	Comments	Reference
Northeast North Dakota						
1	265	W-723	10,960±300	Wood	Underlain by till, sampled within cross-bedded sand, overlain by 2.5 ft of clayey silt with a few pebbles, followed by 4 ft of massive sand	Moran et al. (1973)
2	265	TAM-1	10,820±190	Wood	Replicate date of W-723	Moran et al. (1973)
3	264	I-5213	10,340±170	Needles, twigs, cones	From numerous beds in 15 ft of sand	Moran et al. (1973)
4	265	W-900	10,080±280	7.6 cm diameter wood	From base of 7.5-ft-thick cross-bedded sand with few pebbles and overlain by 3.5 ft of sandy clay	Moran et al. (1973)
5	263	W-1005	10,050±300	Abraded wood	Organic trash in gray clay below 5.5 ft of sand and gravel	Moran et al. (1973)
6	300	I-3880	9940±160	Wood	In fine sand directly over peat, all ≈5 m below upper Campbell Beach	Ashworth et al. (1972)
7	282	W-1360	9810±300	Branches, twigs, fine-grain carbon. material	Wood is waterworn in sand and gravel	Moran et al. (1973)
8	≈296	W-1361	9820±300	Sticks, org. material	Waterworn wood in sand and gravel overlying silt and clay	Moran et al. (1973)
9	248	I-5123	9650±150	Stump with roots	Driftwood interbedded in laminated silty clay	Moran et al. (1973)
10	248	I-5123C	9730±160	Stump with roots	Replicate independent date of I-5123	Moran et al. (1973)
Fargo/Sheyenne, North Dakota						
11	260	Beta-121851	10,230±80	*Populus* sp. wood	In rhythmite deltaic sediments unconformably above clay	Yansa and Ashworth (2005)
12[a]	*261*	*AA-34344*	*10,040±120*	*Populus sp. leaves and wood*	*In rhythmite deltaic sediments*	Yansa and Ashworth (2005)
13	262	AA-34343	9920±60	*Populus* sp. wood	Top of rhythmite deltaic sediments overlain by 1.2 m cross-bedded fine sand, and 3.4 m of lacustrine sediment	Yansa and Ashworth (2005)
14	*263*	*W-993*	*9,900±400*	*Wood*	*In 15-cm-thick peat overlain by 28 ft of laminated silt and clay, and underlain by silt and clay*	McAndrews (1967)
15	*~262*	*W-388*	*9,930±280*	*Wood*	*Wood in same peat as W-993*	McAndrews (1967)
16	*299*	*I-1982*	*9130±150*	*Wood*	*Wood in 0.8 m peat above clay, and buried by eolian sand; Mirror Pool site*	McAndrews (1967)
Assiniboine Delta, Manitoba						
17	302	GSC-902	10,600±150	Plant detritus	In flood plain deposits 60 ft below upper Campbell terrace	Klassen (1969)
18	320	Y-411	10,550±220	Wood	From valley fill	Elson (1957)
19	327	Beta-193587	10,060±60	*Picea* needles	At base of an organic (peaty) unit/A horizon in Rossendale Gully	Boyd (2007)
20	327	TO-11762	9910±90	Wood	As Beta-193587	Boyd (2007)
21	312	GSC-870	10,000±150	Wood	Flood plain deposits 25 ft below upper Campbell terrace	Klassen (1969)
22	316	GSC-797	9700±140	Wood	Flood plain deposits 15 ft below upper Campbell terrace	Klassen (1969)
23	320	TO-534	9600±70	Wood fragments	In fossilferous sandy silty clay and overlain by 4 m of marl, clay, silt and sand in a lagoon behind the Campbell Beach	Teller (1989)
24	320	GSC-4490	9510±90	Wood fragments	as TO-534	Teller (1989)
Wampum, Manitoba						
25	332	TO-4870	12,240±80	Wood fragment	At contact of silty sand and gyttja, interpreted to be reworked	Teller et al. (2000)
26	*336*	*TO-4285*	*10,340±100*	*Peat*	*Base of 7-cm-thick peat*	Teller et al. (2000)
27	*336*	*TO-4284*	*9460±90*	*Peat*	*Top of same 7-cm-thick peat (TO-4285)*	Teller et al. (2000)
28	337	TO-4874	9950±90	Wood fragment	From peat at base of 7 cm peat, overlain by gyttja, sand and peat	Teller et al. (2000)
29	329	TO-4286	10,000±110	Wood	In silty sand below 9.77 m of Upper Campbell Beach sand	Teller et al. (2000)
30	331	TO-4855	9340±90	Wood fragment	In sand of Upper Campbell Beach above TO-4854	Teller et al. (2000)
31	332	TO-4854	9760±80	Wood fragment	In sand of Upper Campbell Beach below TO-4855	Teller et al. (2000)
32	331	TO-4869	9690±70	Wood fragment	Pebbly sand with shells and wood fragments over 24 cm laminated silty clay and diamicton, and below peat just behind Upper Campbell Beach	Teller et al. (2000)
33	333	TO-4873	9380±90	Wood fragment	In laminated silty clay and clayey–sandy silt, overlain by 6.9 m pebbly sand of Upper Campbell Beach	Teller et al. (2000)
34	332	TO-4856	9330±80	Charcoal fragment	From 3-cm-thick peat in 44-cm-thick sand unit over lacustrine sediment and overlain by >7 m of gyttja, marl and peat in lagoon behind Upper Campbell Beach	Teller et al. (2000)
Rainy River Lowland, Ontario/southern Manitoba						
35	330	TO-1504	10,810±240	Wood	From very fine sand in a core	Bajc et al. (2000)
36	351	WAT-1910	10,700±140	Peat	From a restricted pond	Bajc et al. (2000)
37	333	WAT-1760	10,500±200	Wood	Beach and or foreshore	Bajc et al. (2000)
38	338	WAT-1749	10,400±160	Wood	Alluvial and or fluvial	Bajc et al. (2000)
39	322	GSC-5430	10,200±110	Abraded wood (*Picea*)	Reworked Moorhead aged wood in Emerson sediment	McNeely and Nielsen (2000)
40	338	WAT-1689	10,100±200	Wood	In alluvial or fluvial sediment	Bajc et al. (2000)
41	341	WAT-1936	10,100±180	Charcoal fragments	Disseminated in clay	Bajc et al. (2000)
42	311	GSC-5710	10,100±140	Unidentifiable wood	In sand, reworked Moorhead aged sediment	McNeely and Nielsen (2000)

Table 1 (*continued*)

#	Elevation (m a.s.l.)	Lab. ID	^{14}C Age (^{14}C yr BP)	Material	Comments	Reference
43	311	GSC-5357	10,100±90	Wood (*Picea*)	Reworked sand of the Upper Campbell Beach	McNeely and Nielsen (2000)
44	332	BGS-1302	10,080±160	Wood	Alluvial and or fluvial	Bajc et al. (2000)
45	335	WAT-1935	10,050±180	Wood	Alluvial or deltaic	Bajc et al. (2000)
46	*338*	*WIS-1325*	*10,050±100*	*Wood and peat*	*At base of 38-cm-thick peat above 7 cm gyttja and organic silt*	Björck and Keister (1983)
47	335	BGS-1303	10,020±120	Wood	Wood fragments dispersed in very fine sand (fluvial or alluvial)	Bajc et al. (2000)
48	300	GSC-5296	10,000±90	Wood (*Picea*)	Base of organic bed, drown river channel	McNeely and Nielsen (2000)
49	323	GSC-391	9990±160	Wood	Trash layer of wood, bark, shells in sand 0.6-m-thick overlying laminated clay and till, underlying silt, sand laminae, and gravel of the Lower Campbell Beach	McNeely and Nielsen (2000)
50	303	GSC-5731	9960±190	Wood (*Picea*)	Presumed reworked from same bed as GSC-5296	McNeely and Nielsen (2000)
51	335	BGS-1305	9920±110	Fine plant detritus	Soil buried by an offshore bar or spit	Bajc et al. (2000)
52	322	GSC-5330	9940±90	Wood (*Picea*)	From sand in a "drowned" beach berm	McNeely and Nielsen (2000)
53	328	GSC-4732	9940±80	Wood (*Picea*)	Wood in organic layer and sand of Lower Campbell Beach	McNeely and Nielsen (2000)
54	330	BGS-1408	9770±110	Wood	From saturated silty sand alluvial sediment that may be contemporaneous with the Lower Campbell Beach	McNeely and Nielsen (2000)
55	333	BGS-1304	9750±170	Wood	Beach and or foreshore	Bajc et al. (2000)
56	352	WAT-1934	9530±140	Wood	Beach and or foreshore	Bajc et al. (2000)
57	*338*	*WIS-1324*	*9350±100*	*Wood and peat*	*Sample from top of peat (30 cm above WIS-1325)*	Björck and Keister (1983)
Snake Curve section, Minnesota						
58	285	I-4853	9890±150	Wood	4 in. log from within sandy gravel with shells	Moran et al. (1971)
59	300	AA-50801	9530±70	Wood fragment	In silty, sandy, clayey and organically laminated sediment (estuarine?) 3 m below Upper Campbell Beach gravel	This study
60	298	AA-50803	9490±70	Wood fragment	As previous date, but 5 m below Upper Campbell Beach gravel	This study

[a] Samples in italics are considered *in situ*.

2007), and is further discussed below. In summary, many Moorhead-aged dates exist, but do not constrain the water-plane elevations. Wood macrofossils *in situ* and overlain by lacustrine or littoral deposits are required to constrain water levels during the Moorhead Phase.

1.2. Study area

The new Redwood Loop site (97.365°W, 47.961°N, 269 m elevation) was a temporary excavation for a house on the Grand Forks Airforce Base (GFAFB) on 19 June 2006 within the area of OJB1 (Fig. 1C). The site is named for its location on Redwood Loop Street, and is located 24 km west of the modern course of the Red River of the North, which lies along the central axis of what was once the southern basin of glacial Lake Agassiz. The local climate is sub-humid continental, and soils in the area are clay-rich. Prior to Euro-American settlement, the vegetation in the area consisted of riparian deciduous forest within a predominantly tall-grass prairie (Anderson, 1982).

1.3. Materials and methods

The reported radiocarbon ages are first discussed in their respective time scales, and because multiple samples come from the same stratigraphic context they are plotted as summed probabilities (Lowell, 1995) before being converted individually and as summed probabilities to calendar years using Calib V5.0.1 (Stuiver and Reimer, 1993) with the IntCal04 calibration data (Reimer et al., 2004). OSL ages were determined using the methodology outlined in Lepper et al. (2007).

The 10-cm-thick sandy laminated peat (C4) was sampled in 2-cm-thick slices (100 cm^3 each) for plant macrofossil analysis. Plant macrofossil samples were sieved using tap water, counted and identified under 20× magnification, and stored following Birks (2001). Species identifications were confirmed by comparison with a reference collection housed in the Paleoecology Laboratory of the Department of Geography, Michigan State University. This collection contains seeds, fruits, cones, buds, and leaves of extant plants (>1500 species) that have Arctic, boreal forest, temperate forest, aspen parkland and grassland affiliations. Taxonomy and modern habitat information for the plants are based on the Great Plains Flora Association (1986) and Looman and Best (1987). *Picea mariana* (black spruce) needle identification was confirmed by resin duct morphology in cross-section, following procedures in Jackson and Weng (1999). Insect fossils were isolated from a 10 kg sample of sandy laminated peat following methods outlined in Ashworth (1979). These fossils were identified by comparison with identified modern and fossil specimens in the reference collections of the Quaternary Entomology Laboratory at North Dakota State University.

2. Results

2.1. Stratigraphy

The Ojata Beach is weakly expressed in North Dakota along the northeastern edge of the GFAFB, consisting of a flat surface at

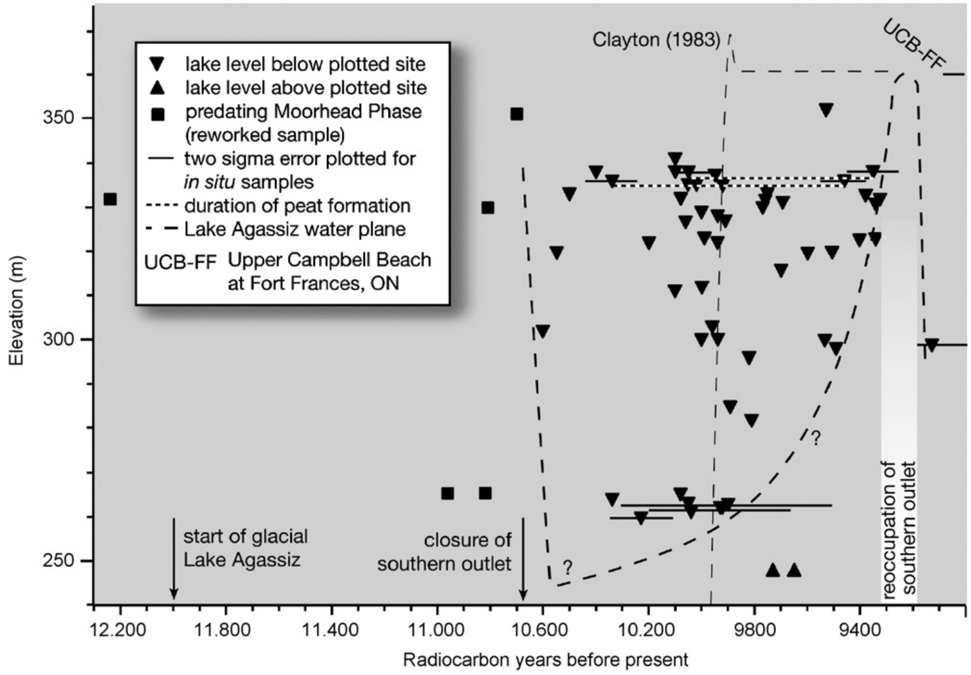

Fig. 2. Plot of Moorhead Phase radiocarbon ages not corrected for differential isostatic rebound. Downward pointing triangles record maximum elevations for lake level at that time, whereas upward pointing triangles record minimum elevations. Squares represent older wood introduced to the basin, likely from rivers. Triangles with solid horizontal bars are *in situ* organic material (italicized samples in Table 1). Dashed horizontal bars represent duration of peat formation where an upper and lower date from an *in situ* peat deposit is available. By definition, Lake Agassiz must have been at a lower elevation during that time. Elevation data for each site are from the cited source or personal communication with the authors. Thick dashed line is our best estimate of the lake level history through time versus an earlier estimate by Clayton (1983). Data for the start of Lake Agassiz are from Lepper et al. (2007), closure of the southern outlet from Fisher (2003) and Fisher and Lowell (2006), and reoccupation of the southern outlet from Fisher (2003, 2007). Plotted data are listed in Table 1.

269 m with a low-relief scarp facing east. A narrow beach ridge about 1.6 km east of the Ojata Beach (Fig. 1C) with a ~1 m cap of silty loam is slightly lower and presumably older than the Ojata Beach as described by Moran et al. (1973). The stratigraphy of the Ojata Beach and first radiocarbon dates from excavations in the area are reported in Moran et al. (1973). For reference here, the four sites are arbitrarily labeled OJB1-4 (Fig. 1A and C) and stratigraphic logs in Fig. 1B summarize this information, with units tentatively correlated. The recorded stratigraphy of the Redwood Loop site (Fig. 3A) is similar to that of site OJB1 of Moran et al. (1973) (Fig. 1B). The exposed section consists of a basal, gray diamicton overlain by pebbly laminated sand, discontinuous laminated sandy peat, and cross-bedded, cross-laminated, plane-bedded, and structureless sand capped with silty loam (22% clay, 50% silt, 23% sand). Similar organic sediment was also described from the base of the OJB2 site (Fig. 1B), a few hundred meters east (Moran et al., 1973).

The diamicton was not extensively studied, but assumed to be till of the Falconer Formation (Arndt, 1977). The overlying units of sand are interpreted as littoral deposits, making up the Ojata Beach or level (both terms are used in Moran et al., 1973). The overlying silty loam records the drowning of the site during the transgressive phase. Because the peat unit contains *Drepanocladus* sp. (a calcareous fen moss) remains and herb macrofossils along with laminated fine sand, woody debris, conifer needles, and insect fossils, we suggest that the paleoenvironment was a shallow wetland, which was subsequently buried by a nearshore sand bar or spit platform. The presence of boulders (Fig. 3A) is not uncommon on beaches underlain by till, as observed along the modern Great Lakes, and where wind-driven shore-ice events transport boulders (Gilbert and Glew, 1986). The sand units above the cross-bedded sand closely mimic those observed in modern beaches at the southern end of Lake Michigan (Fraser et al., 1991; Thompson and Baedke, 1997). Rippled sand occurs in the near shore, pebble lags are found at the plunge point of waves, plane-bedded sand represents the swash zone on the berm, and the structureless sand corresponds to eolian sediments or washover events. While this littoral stratigraphy may be preserved in beach ridges following short-lived regressions, as reported in Indiana (Thompson and Baedke, 1997), they are generally the result of deposition during transgressive events. The silty loam was previously interpreted to be deep-water deposits of the Sherack Formation (cf Arndt, 1977), but they also could record quiet shallow water, thus it is difficult to assign a water depth to the silty loam, and it has not been definitely proved to be waterlain.

2.2. Chronology

The chronology of the Redwood Loop site is documented with 2 OSL ages obtained from the middle littoral sands (Fig. 3A) and 19 AMS radiocarbon ages on woody material, spruce needles and sedge seeds from the base of the exposure (Table 2; Fig. 3). At the one sigma level the OSL ages cannot be distinguished from one another, with deposition of the littoral sand at about 11 ka cal (Tables 3 and 4).

From the base of the littoral sediment, a stump (sample C1; Table 2; Fig. 3A) was disturbed during excavation. Roots (C2), encased by sand and assumed to penetrate the diamicton, were broken off below the water table in the base of the pit. The contact between the till and laminated pebbly sand is rich in littoral wood. Six pieces of *Populus* sp. (poplar/aspen) wood were dated (C3), two showing strong evidence of abrasion, two still with bark attached, and two selected at random from 25 other pieces. There was no correlation between condition of the wood and the analyzed age. Deliberately chosen (#13, 14 in Table 2) and randomly chosen (#15, 16) samples of abraded wood were the

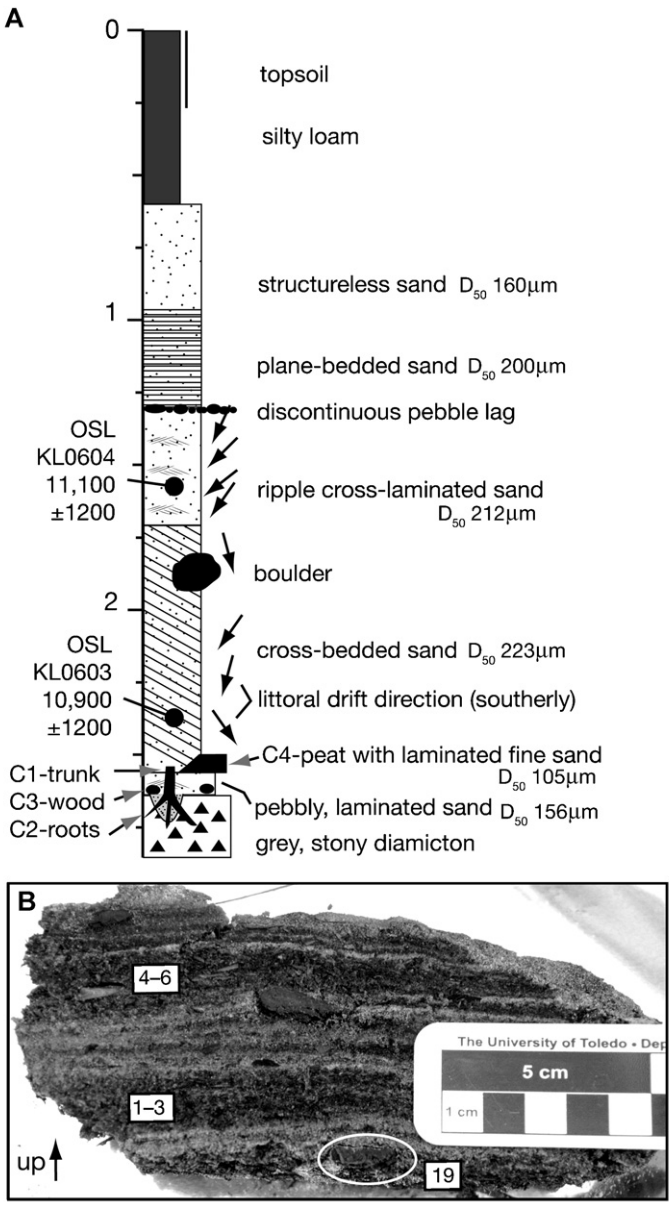

Fig. 3. (A) Lithostratigraphic log with descriptions of units exposed at the Redwood Loop site. (B) Vertical cut through the C4 laminated sandy peat. Note that the photograph is from a different block of C4 material than the one processed for macrofossils. Numbers in figure refer to radiocarbon dates numbered in Table 2.

oldest (#16) and youngest (#15) in the group. Seven ages come from the laminated sandy peat (C4): one date was from an abraded wood fragment shown in Fig. 3B as #19, while the others consisted of three samples from the base of the peat unit (0–2 cm) and three samples from the top layer of the peat (8–10 cm). From the base and top layer we dated *P. mariana* (black spruce) needles, *Carex* cf *C. rostrata* (beaked sedge) seeds, and *Populus* sp. (poplar, aspen) wood fragments. The *Picea* needles and especially the *Carex* seeds were in remarkably good condition (Fig. 4), whereas the *Populus* wood samples were water worn. For the seven ^{14}C ages obtained from the 10-cm-thick laminated sandy peat (C4) there was a spread of 440 radiocarbon years, and the younger ages are not always stratigraphically higher (Table 2). A 360-radiocarbon year spread exists for the *Carex* seed and *Picea* needle samples between the base and top of the laminated sandy peat; stratigraphically reversed in the unit. Therefore, the dated C4 seeds and needles are not considered *in situ*, *senso stricto*, but due to the excellent preservation of most of the seeds and fragile nature of the needles (Fig. 4), they could not have been transported far within the shallow wetland, and on that basis are considered to represent the age of deposition.

The radiocarbon age results are also plotted as the summed probabilities of stratigraphically similar samples: i.e., groups C1–C4 (Table 2; Fig. 5). The summed probability of the trunk ages (C1) is plotted as a separate population from the roots (C2), indicating they are not from the same organism. The other samples from groups C3 and C4 plot within the range of the roots and trunk. The one old root age (#10; Table 2) with the heaviest ^{13}C value appears to be anomalously old; 240 radiocarbon years older than the nearest root in stratigraphic context, nearly 200 radiocarbon years older than the oldest piece of wood, older than the maximum age for closing the southern outlet (Fisher, 2003; Fisher and Lowell, 2006), and thus is rejected. Roots of *Populus* spp. can potentially be older than wood of the same tree, because aspen (poplar) trees today are well known for root suckering, regrowth after trunks are damaged by fire or flooding (Frey et al., 2003), but here we do not suggest any of the roots are from the trunk (C1).

The radiocarbon ages fall within the "radiocarbon plateau", complicating their conversion to calendar ages (Stuiver et al., 1998), and which may explain the dated inverted stratigraphy of the *in situ* C4 macrofossils. The age probabilities of combined samples from each stratigraphic level (C1–4) are plotted in Fig. 6. The age distributions of the roots and wood from the sandy laminated peat support an interpretation that trees were established on the regional landscape beginning at about 12.6 ka cal (10.47$\pm$75 ka ^{14}C BP). The youngest wood is from the trunk with its death at, or shortly after, 11.4 ka cal (10.01 ka ^{14}C BP), most likely caused by drowning because the trunk and littoral wood are overlain by beach sand. The two OSL ages from the beach sand are sequentially younger than the trunk ages but overlap at the 1 sigma level (Table 3).

One final radiocarbon age is from the original drainage ditch exposure (OJB1; Fig. 1) where the W-723 sample was collected (Bluemle, 2000, p. 70). This last sample (#20; Table 2) is from the outer rings of a *Populus* sp. log collected by John Bluemle that was dried, then stored in his garage for over 40 years, and which yielded an age of 39.44$\pm$0.75 ka ^{14}C BP.

2.3. Paleoecology

Typically plant macrofossils are not transported far from the plant (<1 m), making them excellent proxies for reconstructing local paleoenvironments (Birks, 2001). The lack of obvious trends in macrofossil abundances with depth (Fig. 7) and the laminated nature of sand and wood fragments together suggest rapid deposition and introduction of allochthonous material. The superb conditions of the *P. mariana* needles, many of which are intact, and preservation of delicate perigynia (papery sheaths) surrounding several *Carex* cf *C. rostrata* (beaked sedge) seeds indicate the *in situ* nature of some of these deposits (Fig. 4). The range of ages in the same sample set (Table 2), and the abraded wood fragments support the interpretation of episodic input of material into a wetland site where autochthonous organics also accumulated.

The fossil flora of the Redwood Loop site shares taxonomic affinities with the southern boreal forest of today. The macrofossil assemblage is dominated by needles and seeds (which confirm species identification) of *P. mariana* (black spruce), *Abies balsamea* (balsam fir), and *Larix laricina* (tamarack, larch) (Figs. 4 and 7). Currently, these species inhabit lowland moist soils in the boreal forest (for further information, see MacDonald, 2002). Only a few seeds and needles of *Picea glauca* (white spruce), an upland taxon,

Table 2
New radiocarbon results from the Redwood Loop site

#	Sample group	Lab no.	Age and error	∂13C	Material	Calibrated age range (2σ)	Probability	Calibrated age (1σ) mean	Probability
1	C4b	ETH-32665	10,150±75	−28.8±1.2	*Carex* cf *C. rostrata* seeds	12,070–11,590 BP	0.88	11,840	0.89
						11,580–11,400 BP	0.12		
2	C4b	ETH-32666	10,080±75	−31.3±1.2	*Picea mariana* needles	11,980–11,330 BP	1.0	11,510	0.25
								11,702	0.62
3	C4a	ETH-32667	10,520±70	−22.3±1.2	*Populus* sp. wood fragment abraded	12,770–12,340 BP	0.91	12,530	1.0
4	C4b	ETH-32668	10,260±80	−27.7±1.2	*Carex* cf *C. rostrata* seeds	12,390–11,710 BP	0.99	11,990	1.0
5	C4b	ETH-32669	10,440±80	−23.5±1.2	*Picea mariana* needles	12,670–12,080 BP	1.0	12,320	0.5
								12,530	0.38
6	C4a	ETH-32670	10,330±75	−24.9±1.2	*Populus* sp. wood fragment abraded	12,400–11,950 BP	0.89	12,140	0.70
								12,320	0.30
7	C2	ETH-32671	10,470±75	−21.9±1.2	Root (cf *Populus*)	12,690–12,110 BP	1.0	12,500	0.87
8	C2	ETH-32672	10,390±75	−25.3±1.2	Root (cf *Populus*)	12,420–12,030 BP	0.79	12,240	1.0
						12,630–12,440 BP	0.21		
9	C2	ETH-32673	10,370±75	−24.7±1.2	Root (cf *Populus*)	12,410–11,980 BP	0.85	12,230	1.0
						12,620–12,450 BP	0.15		
10	C2	ETH-32674	10,710±75	−19.3±1.2	Root	12,870–12,610 BP	0.98	12,770	1.0
11	C1	ETH-32675	10,160±70	−19.5±1.2	*Populus* sp. trunk	12,080–11,600 BP	0.93	11,850	0.96
12	C1	ETH-32676	10,010±70	−19.4±1.2	*Populus* sp. trunk	11,770–11,250 BP	0.99	11,470	0.97
13	C3	ETH-32677	10,260±75	−21.4±1.2	Partially abraded wood[a]	12,250–11,750 BP	0.90	11,880	0.3
								12,045	0.7
14	C3	ETH-32678	10,030±70	−25.5±1.2	Not abraded wood (bark on)[a]	11,820–11,260 BP	0.99	11,520	0.83
								11,680	0.12
15	C3	ETH-32679	10,000±70	−28.8±1.2	Highly abraded wood	11,770–11,250 BP	1.0		
16	C3	ETH-32680	10,340±75	−28.7±1.2	Highly abraded wood	12,400–11,960 BP	0.89	12,150	0.67
						12,600–12,460 BP	0.08	12,320	0.33
17	C3	ETH-32681	10,190±70	−27.1±1.2	Not abraded wood (bark on)	12,150–11,600 BP	0.98	11,900	1.0
18	C3	ETH-32682	10,210±70	−27.6±1.2	Partially abraded wood	12,170–11,610 BP	0.99	11,930	0.94
19	C4a	Beta-218508	10,170±40	−26.1	*Populus* sp. wood fragment, abraded	12,040–11,710 BP	0.99	11,800	0.39
								11,910	0.61
20		ETH-32683	39,440±750	−28.3	*Populus* log				

[a] Selected at random from 25 samples.

Table 3
OSL results, Redwood Loop site

Sample ID	*N*	M/m ratio	Analysis details	Grain size range (μm)	Representative dose (Gy)	Dose rate (Gy/ka)	Age (ka)
KL0603	104/106	1.05	D(le) mean–S.D.; data	150–250	16.624±0.592	1.511±0.127	11.0±1.2
KL0603	106/106	1.11	D(le) 1 population fit	150–250	16.324±0.612	1.511±0.127	10.8±1.2
KL0603	106/106	1.11	D(le) 2 population fit	150–250	16.410±0.587	1.511±0.127	10.9±1.2
						Average sample age	10.9±1.2
KL0604	94/96	1.05	D(le) mean–S.D.; data	150–250	15.123±0.799	1.420±0.106	10.7±1.2
KL0604	96/96	1.07	D(le) 1 population fit	150–250	15.924±0.748	1.420±0.106	11.2±1.2
KL0604	96/96	1.07	D(le) 2 population fit	150–250	16.059±0.718	1.420±0.106	11.3±1.2
						Average sample age	11.1±1.2
						Average age and S.D. of beach deposits	11.0±0.3

Table 4
OSL dosimetric data, Redwood Loop site

Sample ID	Depth (cm)	H_2O content (%)	K concentration (ppm)	Rb concentration (ppm)	Th concentration (ppm)	U concentration (ppm)
KL0603	247	30±3	11,106±1585	17.89±9.40	6.60±0.52	1.47±0.23
KL0603			10,432±1526	27.36±6.87	7.40±0.56	1.68±0.21
KL0603 average			10,769±1556	22.63±8.14	7.00±0.54	1.57±0.22
KL0604	188	18±3	12,243±1544	30.85±4.66	3.10±0.24	1.34±0.15
KL0604			9550±777	39.19±10.65	2.39±0.22	1.39±0.17
KL0604 average			10,897±1161	35.02±7.66	2.74±0.23	1.37±0.16

Elemental analysis by instrumental neutron activation (INAA) performed at the Ohio State University Research Reactor.

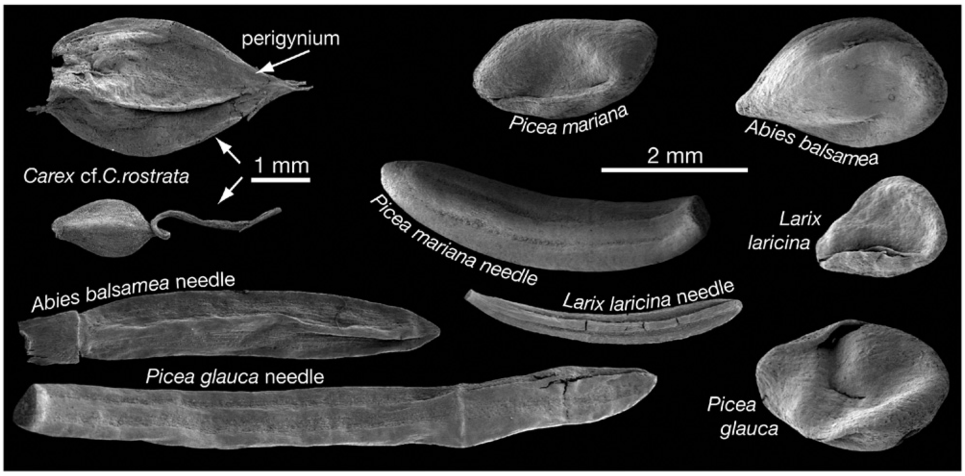

Fig. 4. SEM images of selected terrestrial macrofossil needles and seeds from the laminated sandy peat (C4). Note that the fossils are extremely well preserved and are unabraded.

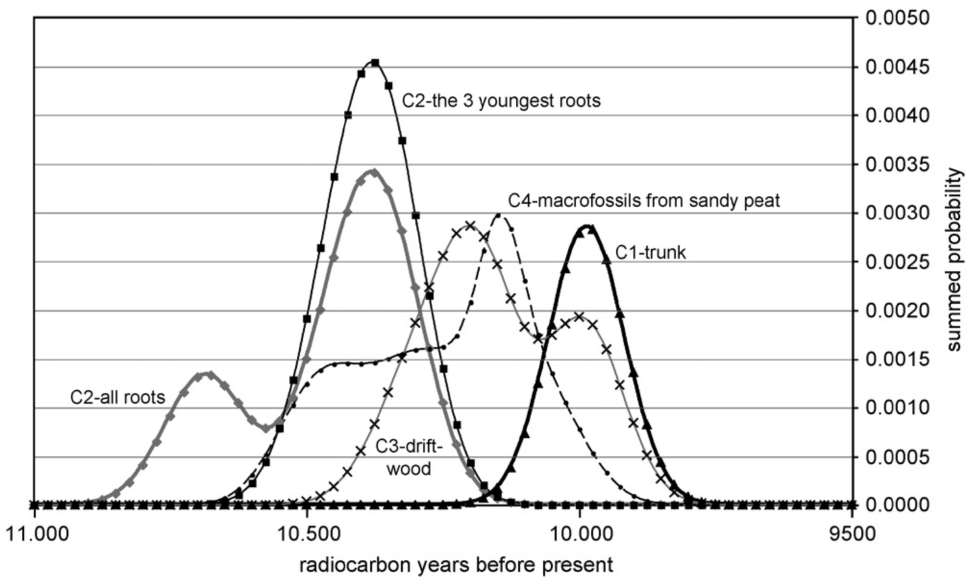

Fig. 5. Summed probability plot of the 19 radiocarbon ages at the Redwood Loop site. C1–4 refer to groups of ages in a similar stratigraphic context (Fig. 3; Table 2).

were recovered (Fig. 4). Low macrofossil counts of *Populus tremuloides* (aspen poplar/trembling aspen) and species of *Betula* (birch) suggest that these deciduous trees existed as subdominates in this vegetation. Emergent plants also occupied shallow water (<0.3 m) or saturated soils of this lowland site, including *Juncus* sp. (rush) and at least four species of *Carex* (sedge), at numbers greater than in comparable modern environments.

The vegetation reconstructed is a spruce–sedge parkland/wetland, rather than a true boreal forest, for two reasons. First, the tremendous abundance of *Carex* and *Juncus* (rush) is unlike that seen today in lowlands of the boreal forest and, second, *Pinus banksiana* (jack pine) and several other constituents of the modern boreal forest are absent. This anomalous spruce–sedge parkland has been reported elsewhere in the Northern Plains and eastern North America during the late-glacial (e.g., Webb et al., 2004; Yansa, 2006).

The dominance of *Carex* and *Juncus* in the macrofossil record of the Redwood Loop site is unlike that of other coeval wetland sites in the area. The few seeds of *Typha latifolia* (cat-tail) recovered and the absence of *Scirpus* spp. (bulrush) seeds is not indicative of a shallow marsh, as has been reconstructed for the Wendel site 200 km to the southwest (Yansa et al., 2007). Macrofossil counts of mudflat herbs (Fig. 7) are also less than reported for a deltaic environment (Yansa and Ashworth, 2005), but are consistent with our interpretation of a shoreline setting. So, we interpret the remarkably high macrofossil abundance of *Carex* spp., *Juncus* sp., and to a lesser extent *Sparganium* sp. (bur-weed) at the Redwood Loop site as indicating emergent plants having occupied saturated clay soils, sometimes flooded by shallow water (<0.3 m), in a wide belt along the shoreline of a lake. Seeds from these plants as well as the seeds, needles and bracts of the trees were transported a short distance, along with sand, to the depositional site. Possibly the ancestral Turtle or Forest River (Fig. 1A) delivered some of the plant remains to the site.

Chitinous fragments of insects and arachnids are abundant in the laminated peat and fine sand bed. They represent beetles, hemipteran bugs, dragonflies, ants, midges, oribatid mites and spiders. The most abundant remains are those of Coleoptera (beetles) and the taxa identified are found today in the sedimentary facies identified in the stratigraphic study. Moreover, the species are associated today with the vegetation identified in the study of plant macroscopic remains. The taxa represent the margins of a eutrophic lake. Aquatic water beetles are represented by predaceous dytiscids and herbivorous hydrophilids. The saturated peaty and mossy soils and dense emergent vegetation was inhabited by several omaliine staphylinids, including *Olophrum rotundicolle* (C.R. Sahlberg), *Olophrum consimile* (Gyllenhal) (Campbell, 1983), and a species of *Arpedium. Carex* spp., *Juncus* sp. and other plants of the emergent vegetation provided habitat for helodids and the iridescent chrysomelids *Plateumaris.* The wet clay soils on the margins of the lake were inhabited by scavenging carabid (ground beetles); at progressively further distances from the water's edge were the species *Agonum consimile* (Gyllenhal), *Elaphrus clairvillei* Kirby and *Bembidion sordidum* (Kirby) (Goulet, 1983; Larochelle and Larivière, 2003). The better drained and less vegetated sandy beach ridge provided habitat for the carabid *Notiophilus*.

3. Discussion

Our interpretation of spruce–sedge parkland/wetland vegetation and shoreline setting for the Redwood Loop site in the Grand Forks, North Dakota area, is similar to the Rainy River area of northwestern Ontario for this time interval (Bajc et al., 2000). Also, coeval vegetation in northwestern Minnesota has been interpreted as a spruce forest or parkland (Ashworth et al., 1972; Whitlock et al., 1993; Hu et al., 1997). Therefore, after regression of glacial Lake Agassiz during the Moorhead Phase, with lake level lowering below the southern outlet sill, a swampy conifer-deciduous parkland colonized the northern part of the exposed Lake Agassiz basin in North Dakota. Based on the plant and insect fossils identified, we estimate that July temperatures were 1–2 °C cooler than at the site today.

Interestingly, the vegetation in the Fargo area (130 km south of the Redwood Loop site) was a deciduous parkland known from organics in an interpreted deltaic sequence, in existence from 10.23 to 9.9 ka ^{14}C BP before burial presumably by transgressing Lake Agassiz (Yansa and Ashworth, 2005). This suggests that an ecotonal boundary between a cooler "spruce parkland" and a more temperate "deciduous parkland" vegetation existed somewhere between Grand Forks (47°58′N) and Fargo (46°51′N) at this time.

The lowest elevation reached by the regression at the beginning of the Moorhead Phase is unknown. Fenton et al. (1983) proposed, based on stratigraphic interpretations, that the southern Agassiz basin went dry in North Dakota and only a few meters of lake water stood over Winnipeg, Manitoba, at that time. Teller and Thorleifson (1983) and Warman (1991), argued that during the Moorhead Phase, lake level could not have dropped below the delta at Fargo, North Dakota, based on strandline projections and continuous varve records in Dryden, Ontario, respectively. Alternatively, Thorleifson (1996) suggested that during the early Moorhead Phase the lowest level was lower, with the shoreline just north of Grand Forks, North Dakota, approximately 24 m lower than the Ojata Beach. Detailed excavations at successively lower elevation beaches than the Ojata Beach are necessary to generate chronological and stratigraphic data to determine how low Lake Agassiz dropped during the Moorhead Phase, and if the beaches preserved on the modern landscape formed during the Moorhead or younger phases.

Our data from the Redwood Loop site provide information for only one level of the lake but can be used to bracket the lake level fall and rise during the Moorhead Phase. The oldest accepted root age of 10.47 ka ^{14}C BP (#7; Table 2) is the oldest minimum age for constraining when Lake Agassiz fell below the elevation of the Redwood Loop site. This age assignment is $\approx$130 radiocarbon years older than the previous oldest minimum onset age of 10.34 $\pm$ 0.1 ka ^{14}C BP (#26; Table 1) from peat at the Wampum site in Manitoba, Canada (Teller et al., 2000), as discussed by Fisher

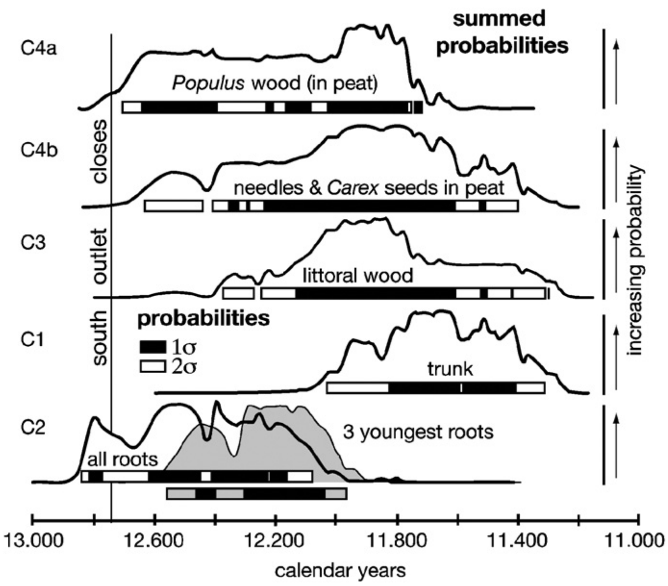

Fig. 6. Summed probability distributions plotted in calibrated calendar years of the grouped radiocarbon dates shown in Fig. 5. Note that there are two plots for the C4 peat; distinguishing between transported *Populus* sp. wood (C4a) and *in situ Carex* cf *C. rostrata* seeds and *Picea mariana* needles (C4b).

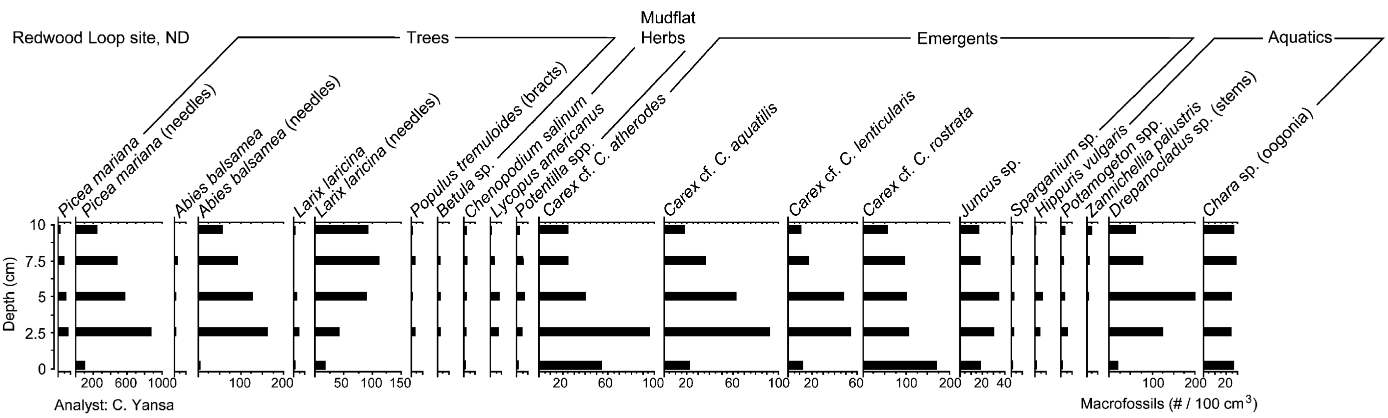

Fig. 7. Plant macrofossil abundance diagram of the sandy laminated peat (C4). All are seeds (or fruits) unless otherwise noted. Note that there is no obvious trend with depth.

and Lowell (2006). The youngest *in situ* organic samples from the Redwood Loop site are considered maximum ages for the rise of Lake Agassiz leading to the development of the Ojata Beach. These ages are from the black spruce needles and youngest trunk age of 10.08±0.075 ka ^{14}C BP and 10.01±0.07 ka ^{14}C BP, respectively (#2, 12; Table 2), similar to the youngest piece of driftwood at the base of the beach sediment (10±0.07 ka ^{14}C BP, #15; Table 2). Thus the minimum time period for the Redwood Loop site being aerially exposed is ≈500 radiocarbon years, having started sometime before 10.47±0.075 ka ^{14}C BP and ending by 10±0.070 ka ^{14}C BP. If the transgression at the study site is considered to have been at 10 ka ^{14}C BP (11.77–11.25 ka cal), the radiocarbon chronology is consistent with the OSL age assessment of 11.0±0.3 ka for the overlying littoral deposits (Table 3).

From our analysis of the Moorhead dates collected throughout the basin, and from the Redwood Loop site, it is clear that distinguishing between *in situ* and reworked material is critical for reconstructing water levels through time (cf Fisher and Lowell, 2006). The vast majority of ages documenting the Moorhead Phase are from reworked material either of autochthonous or allochthonous origin, transported, and then deposited in littoral environments, or deposited in deeper water. The old age of 12.24±0.08 ka ^{14}C BP from wood fragments from Wampum, Manitoba, below the Upper Campbell Beach, and the log dated at 39.44±0.75 ka ^{14}C BP from the OJB1 site (Table 2) are good examples of reworked older material in littoral environments. The new radiocarbon ages that stratigraphically underlie the Ojata beach littoral deposits document that the Ojata Beach is younger than previously interpreted; approximately 900 years younger than the W-723 (and TAM-1) and I-5213 ages (OJB1, 2; Fig. 1B). Two of the original ages (10.08±0.28 ka ^{14}C BP, W-900) and (10.05±0.3 ka ^{14}C BP, W-1005) are similar and consistent with the youngest data from the Redwood Loop site for the age of the beach.

Assuming that neither the Moorhead Phase regression nor transgression was instantaneous, land at elevations between the Redwood Loop site and the Upper Campbell Beach should have been exposed longer, and likewise, for shorter periods at lower elevations. Only by sampling more beaches at different elevations, can these lake level fluctuations and rates of lake level change be better constrained.

The new Redwood Loop data, and data from Fig. 2 are replotted in Fig. 8 with the elevation of each sample corrected for differential isostatic rebound by subtracting the difference in elevation between the closest Upper Campbell Beach (UCB) elevation (on the same isobase) and the elevation of the UCB at the head of the southern outlet spillway. Isobases were taken from Johnston (1946) and Brevik (1994). In all cases the sample sites are at or below the UCB, thus the elevation of samples deposited and buried early in the Moorhead Phase, and during the beginning of the Moorhead transgression, have not been fully corrected for rebound.

A rise in lake level to above the UCB level was proposed in the 1970s (Moran et al., 1971) and depicted in lake level curves (e.g., Clayton, 1983), and is shown in Fig. 8. The presence and elevation of continuous peat deposition at lower elevations from the Swift site in northern Minnesota (Björck and Keister, 1983) and the Wampum site in southern Manitoba (Teller et al., 2000), negates a high lake level at this time. Listed in Table 1 are two more radiocarbon dates (#59, 60; Table 1), from the Snake Curve section in Minnesota (52 km due east of Grand Forks; Fig. 1A inset) predating the UCB, that were sampled from estuarine sediment just below cross-bedded gravel of the UCB. These dates are interpreted as recording the rise to the UCB, and backfilling of an estuary. The peat deposits and additional dates from the Snake Curve section support a later (≈9.4 ka ^{14}C BP), rather than earlier (≈9.9 ka ^{14}C BP) rise to the UCB. We propose here formally that the end of the Moorhead Phase was short-lived at 9.4–9.3 ka ^{14}C BP, coincident with reopening of the southern outlet (cf Fisher, 2003, 2007).

Not discussed here has been the cause of the drop to the low-level Moorhead Phase of glacial Lake Agassiz, and what the controls might have been. Commonly, deglaciation and the associated opening of eastern outlets is invoked to cause the drawdown (e.g., Upham, 1895; Elson, 1967; Teller and Thorleifson, 1983; Teller, 2001) or opening the northwestern outlet (Teller and Leverington, 2004), but dated ice margins allowing for such drainage routing, and dated spillways or flood deposits of the necessary age have not been presented, hence the confusion for why the lake dropped to the Moorhead Phase low level. Here, our data only record the drop in lake level, estimating the duration of the low lake level at or below one particular elevation, and not the reason for the drop in the level of Lake Agassiz or the cause of the Younger Dryas episode. In the past, the oldest age from the Ojata Beach of 12.87±320 ka cal (10.96±0.3 ka ^{14}C BP W-723) was used to assign an age to abandonment of the southern outlet. Now with

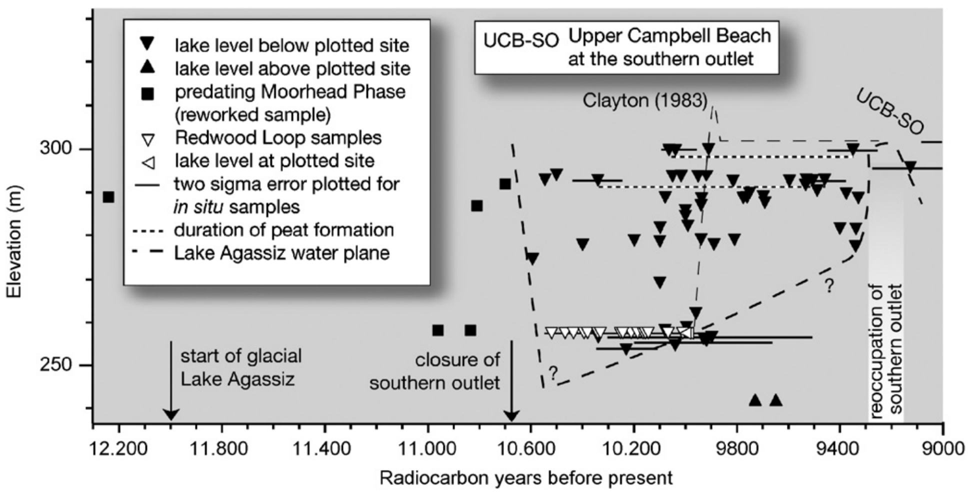

Fig. 8. Plot of Moorhead Phase radiocarbon ages after partial correction for differential isostatic rebound using the elevation of the Upper Campbell Beach. Symbols are the same as in Fig. 2, but also include left pointing triangles representing transgression of the lake at the site, and open triangles for the Redwood Loop site data. Additional sites with buried *in situ* terrestrial macrofossils at elevations below and above the Redwood Loop site are required to constrain the transgression rates and to determine if the rates varied through time. Data are within Tables 1 and 2.

the age of the Ojata Beach nearly 1.4 ka cal years younger and no longer relevant to constraining abandonment of the southern outlet, we instead bracket the age of abandonment, with: (1) the maximum age of 12.755 ka cal based on the 1 sigma mean age of wood in gravel from the bottom of the southern outlet spillway (Fisher, 2003; Fisher and Lowell, 2006) recording abandonment, and (2) the minimum age of 12.5 ka cal (1 sigma mean age) from the oldest *in situ* organics beneath the Ojata Beach from the Redwood Loop site. We also note that the shift to heavier isotopes from 13.4 to 12.9 ka cal in core EN32-PC6 in the Gulf of Mexico (Flower et al., 2004) started before abandonment of the southern outlet, predating closure of the southern outlet by a minimum of $\approx$650–150 years. While the low-water Moorhead Phase was concurrent with the Younger Dryas, its beginning postdates the beginning of the Younger Dryas.

4. Conclusions

The *in situ* terrestrial plant and insect macrofossils at the Redwood Loop site west of Grand Forks, North Dakota, brackets a time of nearly 500 radiocarbon, or 1000 calendar years, for subaerial exposure during the Moorhead Phase of glacial Lake Agassiz. The oldest *in situ* minimum radiocarbon age is now 10.47 ± 0.07 ka ^{14}C BP, close to the maximum age estimate of 10.675 ± 0.06 ka ^{14}C BP for the beginning of the Moorhead Phase (Fisher and Lowell, 2006), and 130 radiocarbon years older than peat described from Wampum, Manitoba (Teller et al., 2000). Additional sites higher on the landscape are required to more closely bracket the age of the regression/transgression cycle. Even though new and reanalyzed data are emerging from the Agassiz basin to constrain the lake's paleogeography and meltwater routing history (Fisher, 2003, 2007; Lowell et al., 2005; Teller et al., 2005; Lepper et al., 2007; this study), much remains to be documented for understanding ice margin retreat, lake levels, and outlet histories of perhaps the largest proglacial lake that ever existed.

The paleoecological results from the Redwood Loop site demonstrate that the Younger Dryas was not especially cold during the Moorhead Phase in the southern Lake Agassiz basin (cf Yansa and Ashworth, 2005; Yansa and Fisher, 2007). Instead, our analysis of plant and insect macrofossils at the Redwood Loop site reconstructs a spruce–sedge parkland/wetland, a vegetation comparable in species composition and structure to that of other areas of the Upper Midwest during this time (e.g., Whitlock et al., 1993; Bajc et al., 2000). An ecotone did exist between this vegetation in Grand Forks and a deciduous parkland found 130 km to the south in Fargo, but this is attributed to a slight north–south temperature gradient of 1–2 °C, as reported for other parts of eastern North America during this time (e.g., Grimm and Jackson, 2004; Webb et al., 2004). The results of this research provide stratigraphic data for the Moorhead Phase of glacial Lake Agassiz beginning after the start of the Younger Dryas episode, supporting the recent results for later deglaciation in the eastern outlet region (Lowell et al., 2005; Teller et al., 2005).

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References

Anderson, R.C., 1982. The eastern prairie–forest transition—an overview. In: Brewer, R. (Ed.), Proceedings of the 8th North American Prairie Conference. Western Michigan University, Kalamazoo, pp. 86–92.

Arndt, B.M., 1977. Stratigraphy of offshore sediment of Lake Agassiz. North Dakota Geological Survey Report of Investigations, 60, pp. 1–58.

Ashworth, A.C., 1979. Quaternary Coleoptera studies in North America: past and present. In: Erwin, T.L., Ball, G.E., Whitehand, D.R., Halpern, A. (Eds.), Carabid Beetles, Their Evolution, Natural History and Classification. W. Junk, The Hague, pp. 395–405.

Ashworth, A.C., Clayton, L., Bickley, W.B., 1972. The Mosbeck site: a paleoenvironmental interpreation of the Late Quaternary history of Lake Agassiz based on fossil insect and mollusk remains. Quaternary Research 2, 176–188.

Bajc, A.F., Schwert, D.P., Warner, B.G., Williams, N.E., 2000. A reconstruction of Moorhead and Emerson phase environments along the eastern margin of glacial Lake Agassiz, Rainy River basin, northwestern Ontario. Canadian Journal of Earth Sciences 37, 1335–1353.

Birks, H.H., 2001. Plant macrofossils. In: Smol, J.P., Birks, H.J.B., Last, W.M. (Eds.), Tracking Environmental Change Using Lake Sediments, III Terrestrial, Algal, and Siliceous Indicators. Kluwer Academic Press, Dordrecht (Chapter 4).

Björck, B., Keister, C.M., 1983. The Emerson Phase of Lake Agassiz, independently registered in northwestern Minnesota and northwestern Ontario. Canadian Journal of Earth Science 20, 1536–1542.

Bluemle, J.P., 2000. The face of North Dakota. North Dakota Geological Survey, 205pp.

Boyd, M., 2007. Early postglacial history of the southeastern Assiniboine delta, glacial Lake Agassiz basin. Journal of Paleolimnology 37, 313–329.

Brevik, E.C., 1994. Isostatic Rebound in the Lake Agassiz Basin Since the Late Wisconsinan. University of North Dakota.

Broecker, W.S., Kennett, J., Flower, B., Teller, J., Trumbore, S., Bonani, G., Wolfli, W., 1989. Routing of meltwater from the Laurentide Ice Sheet during the Younger Dryas cold episode. Nature 341, 318–321.

Campbell, J.M., 1983. A revision of the North American Omaliinae (Coleoptera: Staphylinidae). The genus Olophrum Erichson. The Canadian Entomologist 115, 577–622.

Carlson, A.E., Clark, P.U., Haley, B.A., Klinkhammer, G.P., Simmons, K., Brook, E.J., Meissner, K.J., 2007. Geochemical proxies of North American freshwater routing during the Younger Dryas cold event. Proceedings of the National Academy of Science 104, 6556–6561.

Clayton, L., 1983. Chronology of Lake Agassiz drainage to Lake Superior. In: Teller, J.T., Clayton, L. (Eds.), Glacial Lake Agassiz, Geological Association of Canada, Special Paper 26, pp. 291–307.

de Vernal, A., Hillaire-Marcel, C., Bilodeau, G., 1996. Reduced meltwater outflow from the Laurentide ice margin during the Younger Dryas. Nature 381, 774–777.

Elson, J.A., 1957. Lake Agassiz and the Mankato–Valders problem. Science 126, 999–1002.

Elson, J.A., 1967. Geology of Glacial Lake Agassiz. In: Mayer-Oakes, W.J. (Ed.), Life, Land and Water. University of Manitoba Press, Winnipeg, pp. 37–96.

Fenton, M.M., Moran, S.R., Teller, J.T., Clayton, L., 1983. Quaternary stratigraphy and history in the southern part of the Lake Agassiz Basin. In: Teller, J.T., Clayton, L. (Eds.), Glacial Lake Agassiz, Geological Association of Canada, St. John's, Special Paper 26, pp. 49–74.

Fisher, T.G., 2003. Chronology of glacial Lake Agassiz meltwater routed to the Gulf of Mexico. Quaternary Research 59, 271–276.

Fisher, T.G., 2005. Strandline analysis in the southern basin of glacial Lake Agassiz, Minnesota and North and South Dakota, USA. Geological Society of America Bulletin 117, 1481–1496.

Fisher, T.G., 2007. Abandonment chronology of glacial Lake Agassiz's northwestern outlet. Palaeogeography, Palaeoclimatology, Palaeoecology 246, 31–44.

Fisher, T.G., Lowell, T.V., 2006. Questioning the age of the Moorhead Phase in the glacial Lake Agassiz basin. Quaternary Science Reviews 25, 2688–2691.

Flower, B.P., Hastings, D.W., Hill, H.W., Quinn, T.M., 2004. Phasing of deglacial warming and Laurentide Ice Sheet meltwater in the Gulf of Mexico. Geology 32, 597–600.

Fraser, G.S., Thompson, T.A., Kvale, E.P., Carlson, C.P., Fishbaugh, D.A., Gruver, B.L., Holbrook, J., Kairo, S., Kohler, C.S., Malone, A.E., Moore, C.H., Rachmanto, B., Rhoades, L., 1991. Sediments and sedimentary structures of a barred, nontidal coastline, southern shore of lake Michigan. Journal of Coastal Research 7, 1113–1124.

Frey, B.R., Lieffers, V.J., Landhäusser, S.M., Comeau, P.G., Greenway, K.J., 2003. An analysis of sucker regeneration of trembling aspen. Canadian Journal of Forest Research 33, 1169–1179.

Gilbert, R., Glew, J.R., 1986. A wind-driven ice-push event in Eastern Lake Ontario. Journal of Great Lakes Research 12, 326–331.

Goulet, H., 1983. The genera of holarctic Elaphrini and species of Elaphrus Fabricius (Coleoptera: Carabidae): classification, phylogeny, and zoogeography. Questiones Entomologicae 19, 219–482.

Great Plains Flora Association, 1986. Flora of the Great Plains. University of Kansas Press.

Grimm, E.C., Jackson, G.L.J., 2004. Late-Quaternary vegetation history of the eastern United States. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), The Quaternary Period in the United States. Elsevier, Amsterdam, the Netherlands, pp. 381–402.

Hu, F.S., Wright, H.E.J., Ito, E., Lease, K., 1997. Climatic effects of glacial Lake Agassiz in the midwestern United States during the last deglaciation. Geology 25, 207–210.

Jackson, S.T., Weng, C., 1999. Late Quaternary extinction of a tree species in eastern North America. Proceedings of the National Academy of Science 96, 13847–13852.

Johnson, R.G., McClure, B.T., 1976. A model for northern hemisphere continental ice sheet variation. Quaternary Research 6, 325–353.

Johnston, W.A., 1946. Glacial Lake Agassiz, with special reference to the mode of deformation of the beaches. Geological Survey of Canada Bulletin 7, 20.

Klassen, R.W., 1969. Quaternary stratigraphy and radiocarbon chronology in southwestern Manitoba. Geological Survey of Canada, Paper 69-27, pp. 1–19.

Larochelle, A., Larivie´re, M.C., 2003. A Natural History of the Ground Beetles (Coleoptera: Carabidae) of America North of Mexico. Pensoft, Sofia–Moscow, 583pp.

Lepper, K., Fisher, T.G., Hajdas, I., Lowell, T.V., 2007. Ages for the Big Stone moraine and the oldest beaches of glacial Lake Agassiz: implications for deglaciation chronology. Geology 35, 667–670.

Looman, J., Best, K.F., 1987. Budd's Flora of the Canadian Prairie Provinces. Agriculture Canada, Research Branch, Publication No. 1662.

Lowell, T.V., 1995. The application of radiocarbon age estimates to the dating of glacial sequences: an example from the Miami sublobe, Ohio, USA. Quaternary Science Reviews 14, 85–99.

Lowell, T.V., Fisher, T.G., Comer, G.C., Hajdas, I., Waterson, N., Glover, K., Loope, H.M., Schaefer, J.M., Rinterknecht, V., Broecker, W.S., Denton, G.H., Teller, J.T., 2005. Testing the Lake Agassiz meltwater trigger for the Younger Dryas. EOS Transactions 86, 365,372.

MacDonald, G.M., 2002. The boreal forest. In: Orme, A.R. (Ed.), The Physical Geography of North America. Oxford University Press, New York.

McAndrews, J.H., 1967. Paleoecology of the Seminary and Mirror Pool peat deposits. In: Elson, J.A. (Ed.), Life, Land and Water. University of Manitoba Press, Winnipeg, pp. 253–269.

McNeely, R., Nielsen, E., 2000. Manitoba radiocarbon dates: geological radiocarbon dates (Section 1). Manitoba Industry, Trade and Mines Geological Survey Open File Report OF2000-1.

Moore, T.C.J., 2005. The Younger Dryas: from whence the fresh water? Paleoceanography 20.

Moran, S.R., Clayton, L., Cvancara, A.M., 1971. New sedimentological and paleontological evidence for history of Lake Agassiz: Snake Curve section, Red Lake County, Minnesota. Proceedings of the North Dakota Academy of Science 24, 61–73.

Moran, S.R., Clayton, L., Scott, M.W., Brophy, J.A., 1973. Catalog of North Dakota radiocarbon dates. North Dakota Geological Survey Miscellaneous Series 53, 51.

Reimer, P.J., Baillie, M.G.L., Bard, E., Bayliss, A., Beck, J.W., Bertrand, C.J.H., Blackwell, P.G., Buck, C.E., Burr, G.S., Cutler, K.B., Damon, P.E., Edwards, R.L., Fairbanks, R.G., Friedrich, M., Guilderson, T.P., Hogg, A.G., Hughen, K.A., Kromer, B., McCormac, F.G., Manning, S.W., Ramsey, C.B., Reimer, R.W., Remmele, S., Southon, J.R., Stuiver, M., Talamo, S., Taylor, F.W., van der Plicht, J., Weyhenmeyer, C.E., 2004. IntCal04 Terrestrial radiocarbon age calibration, 26–0 ka BP. Radiocarbon 46, 1029–1058.

Rodrigues, C.G., Vilks, G., 1994. The impact of glacial lake runoff on the Goldthwait and Champlain Seas: the relationship between glacial Lake Agassiz runoff and the Younger Dryas. Quaternary Science Reviews 13, 923–944.

Rooth, C., 1982. Hydrology of ocean circulation. Progress in Oceanography 11, 131–149.

Stuiver, M., Reimer, P.J., 1993. Extended ^{14}C data base and revised CALIB 3.0 ^{14}C age calibration program. Radiocarbon 35, 215–230.

Stuiver, M., Reimer, P.J., Bard, E., Beck, J.W., Burr, G.S., Hughen, K.A., Kromer, B., McCormac, G., van der Plicht, J., Spurk, M., 1998. INTCAL98 radiocarbon age calibration, 24,000–0 cal BP. Radiocarbon 40, 1041–1083.

Teller, J.T., 1989. Importance of the Rossendale site in establishing a deglacial chronology along the southwestern margin of the Laurentide Ice Sheet. Quaternary Research 32, 12–23.

Teller, J.T., 2001. Formation of large beaches in an area of rapid differential isostatic rebound: the three-outlet control of Lake Agassiz. Quaternary Science Reviews 20, 1649–1659.

Teller, J.T., Leverington, D.W., 2004. Glacial Lake Agassiz: a 5000 yr history of change and its relationship to the ∂18O record of Greenland. Geological Society of America Bulletin 116, 729–742.

Teller, J.T., Thorleifson, L.H., 1983. The Lake Agassiz–Lake Superior connection. In: Teller, J.T., Clayton, L. (Eds.), Glacial Lake Agassiz, The Geological Association of Canada, Special Paper 26, pp. 261–290.

Teller, J.T., Risberg, J., Matile, G., Zoltai, S., 2000. Postglacial history and paleoecology of Wampum, Manitoba, a former lagoon in the Lake Agassiz basin. Geological Society of America Bulletin 112, 943–958.

Teller, J.T., Boyd, M., Yang, Z., Kor, P.S.G., Mokhtari Fard, A., 2005. Alternative routing of Lake Agassiz overflow during the Younger Dryas: new dates, paleotopography, and a reevaluation. Quaternary Science Reviews 24, 1890–1905.

Thompson, T.A., Baedke, S.J., 1997. Strand-plain evidence for late Holocene lake-level variations in Lake Michigan. Geological Society of America Bulletin 109, 666–682.

Thorleifson, L.H., 1996. Review of Lake Agassiz history. In: Teller, J.T., Thorleifson, L.H., Matile, G., Brisbin, W.C. (Eds.), Sedimentology, Geomorphology and History of the Central Lake Agassiz Basin, Field Trip B2. Geological Association of Canada Field Trip Guidebook for GAC/MAC Joint Annual Meeting, pp. 55–84.

Upham, W., 1895. The Glacial Lake Agassiz. United States Geological Survey Monograph 25, 685.

Warman, T.A., 1991. Sedimentology and history of deglaciation in the Dryden, Ontario area, and their bearing on the history of Lake Agassiz. Unpublished M.S. Thesis. University of Manitoba.

Webb III, T., Shuman, B., Williams, J.W., 2004. Climatically forced vegetation dynamics in eastern North America during the late Quaternary Period. In: Gillespie, A.R., Porter, S.C., Atwater, B.F. (Eds.), The Quaternary Period in the United States. Elsevier, the Netherlands, pp. 459–478.

Whitlock, C.W., Bartlein, P., Watts, W.A., 1993. Vegetation history of Elk Lake. In: Bradbury, J.P., Dean, W.E. (Eds.), Elk Lake Minnesota: Evidence for Rapid Climate Change in the Northcentral United States, Geological Society of America, Boulder, CO, Special Paper 276, pp. 251–274.

Yansa, C.H., 2006. The timing and nature of late Quaternary vegetation changes in the northern Great Plains, USA and Canada: a re-assessment of the spruce phase. Quaternary Science Reviews 25, 263–281.

Yansa, C.H., Ashworth, A.C., 2005. Late Pleistocene palaeoenvironment of the southern Lake Agassiz Basin, USA. Journal of Quaternary Science 20, 255–267.

Yansa, C.H., Fisher, T.G., 2007. Absence of a Younger Dryas signal along the southern shoreline of glacial Lake Agassiz in North Dakota during the Moorhead Phase (12,600–11,200 CALYBP). Current Research in the Pleistocene 24, 24–28.

Yansa, C.H., Dean, W.E., Murphy, E.C., 2007. Late Quaternary paleoenvironments of an ephemeral wetland in North Dakota, USA: relative interactions of groundwater hydrology and climate change. Journal of Paleolimnology 38, 441–457.