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Northwest outlet channels of Lake Agassiz, isostatic tilting and a migrating continental drainage divide, Saskatchewan, Canada

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Abstract

Lake cores obtained from the northwest outlet of glacial Lake Agassiz in northwest Saskatchewan, Canada, provide a minimum date for the cessation of the flood from the northwest outlet, and a chronology for abandonment of mid-Holocene channels that presently straddle the Mackenzie and Churchill drainage divide. The stratigraphy of a vibracore taken from Long Lake consists of a lower pebble gravel fining to massive sand, silty-clay and then fibrous peat. Wood fragments from the base of the clay yielded an accelerator mass spectrometry (AMS) date of 9120 BP. Because the lake is scour in origin and is in the head of the spillway, the date is considered to be a minimum estimate for cessation of the flood from the northwest outlet at the beginning of the Emerson Phase. A vibracore taken at Haas Lake in an abandoned channel surrounded by muskeg with no influent streams, consists of 0.8 m of stratified, pebble gravel containing abundant shell and wood fragments, overlain by 1.62 m of gyttja with a sharp, conformable lower contact. AMS dates range from 5590 BP from the topmost gravel to 3080 BP within the gyttja. The gravel is interpreted as fluvial, recording a river draining Wasekamio Lake north into the Clearwater River across the present-day drainage divide. Today, a drop of 2 m occurs from Wasekamio Lake southeast to Lac Ile-a-la-Crosse, along 150 km of lake basins parallel to the Cree Lake Moraine. The dates from Haas Lake suggest that before 5200 BP, the drainage divide was about 100 km further southeast, implying that during the Emerson Phase, lake level was controlled by a sill near Flatstone Lake at about 430 m instead of between Wasekamio Lake and the Clearwater River, as was previously proposed. Holocene differential isostatic uplift caused the flow reversal in the upper Churchill basin. Anastomosed channels at the mouth of rivers flowing north into lakes indicate that uplift is still active in the area today. © 1998 Elsevier Science B.V. All rights reserved.

Keywords: glacial lake; Lake Agassiz; Saskatchewan; isostasy; glaciolacustrine environment

1. Introduction

From about 12,000 to 8000 BP, glacial Lake Agassiz served a pivotal role in controlling the release of cold glacial meltwater from the southern margin of the receding Laurentide Ice Sheet in central North America (Teller, 1990). Ice-marginal fluctuations and isostatic recovery of the crust determined whether the cold lake water drained: (1) south to the Gulf of Mexico by way of the southern outlet and Mississippi River; (2) east to the North Atlantic Ocean through the Great Lakes and St. Lawrence; or

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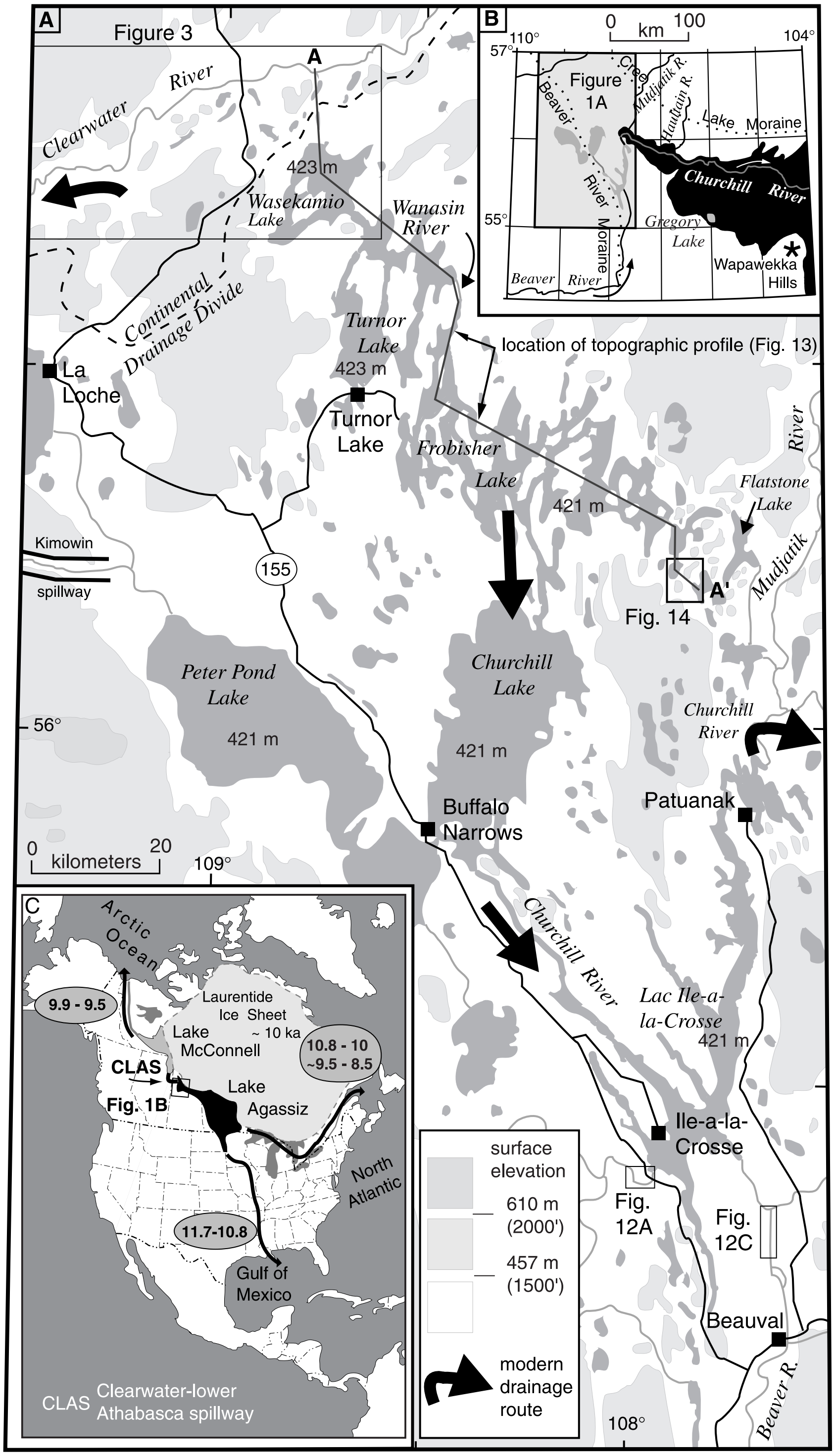

A
Figure 3
A
Clearwater
River
423 m
Wasekamio
Lake
Wanasin
River
Continental
Drainage Divide
Turnor
Lake
423 m
La
Loche
Turnor
Lake
Frobisher
Lake
421 m
location of topographic profile (Fig. 13)
River
Flatstone
Lake
Mudjatik
Kimowin
spillway
155
A'
Fig. 14
Churchill
Lake
Peter Pond
Lake
421 m
421 m
Churchill
River
56°
Patuanak
Buffalo
Narrows
0 kilometers 20
109°
Churchill River
Lac Ile-a-
la-Crosse
421 m
Ile-a-la-
Crosse
Fig.
12A
Fig.
12C
Beauval
Beaver R.
108°
surface
elevation
610 m
(2000')
457 m
(1500')
modern
drainage
route
B
0 km 100
110°
104°
57°
Figure
1A
Cree
Mudjatik R.
Haultain R.
Lake Moraine
Beaver
River
Churchill River
55°
Gregory
Lake
Wapawekka
Hills
Moraine
Beaver River
C
Arctic
Ocean
9.9 - 9.5
Laurentide
Ice Sheet
~ 10 ka
Lake
McConnell
10.8 - 10
~9.5 - 8.5
CLAS
Fig. 1B
Lake
Agassiz
North
Atlantic
11.7-10.8
Gulf of
Mexico
CLAS Clearwater-lower
Athabasca spillway

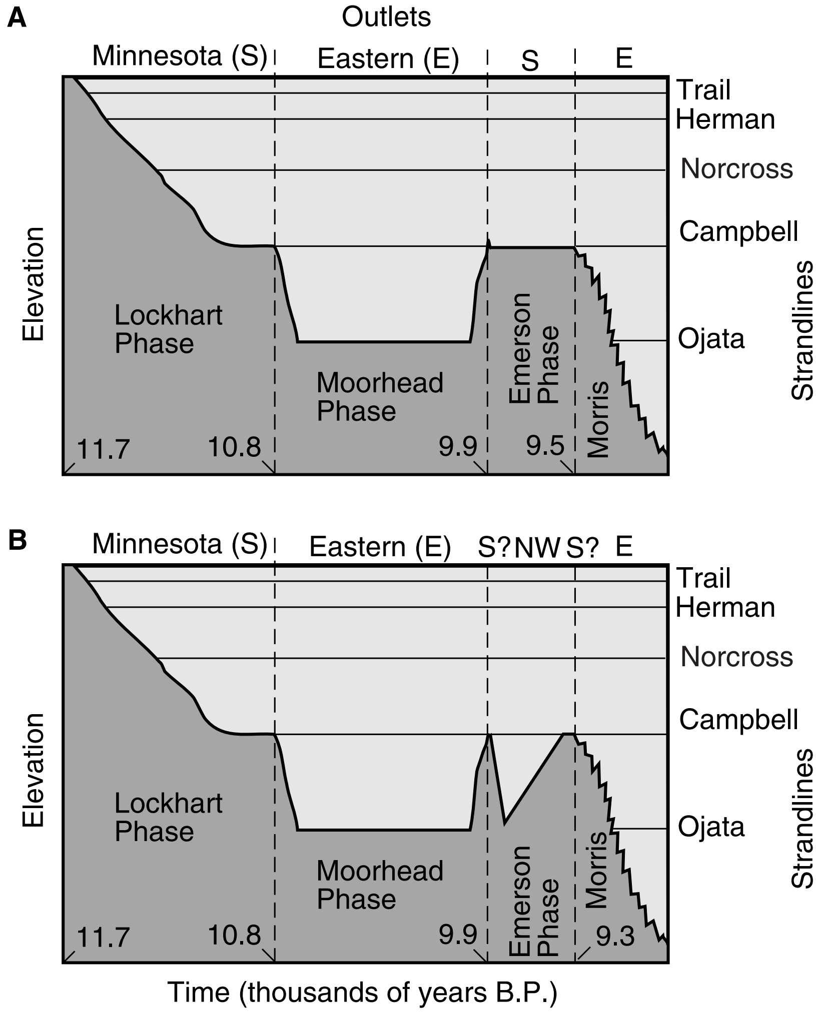


Fig. 2. Schematic representation of the chronology of Lake Agassiz. (A) Based on Fisher and Smith (1994) and data from Risberg et al. (1995). (B) Based on Clayton (1983) and Teller et al. (1983).

(3) northwest to the Arctic Ocean through the Mackenzie River and its tributaries (Fig. 1C). Determining the volume of glacial meltwater that drained south, east, or north is critical to understanding and reconstructing ocean circulation patterns and paleoclimates (Rodrigues and Vilks, 1994; Hu et al., 1997).

The study area in northwest Saskatchewan (Fig. 1) lies along the upper reaches of the Churchill River. This lowland area dividing the Precambrian rock of the Canadian Shield from Paleozoic rock is marked by a series of lakes. During the late Wisconsin glacial episode, the region was covered by the Laurentide Ice Sheet that advanced off the Canadian Shield from the northeast (Dyke and Prest, 1987). As new topographic information became available for the area, Lake Agassiz was mapped into the upper Churchill valley by Elson (1967).

Fig. 1. (A) Study area in the upper Churchill valley. (B) Extent of Lake Agassiz in northwestern Saskatchewan from Teller et al. (1983). (C) Location and timing of the northwest, eastern, and southern Lake Agassiz outlets according to Fisher and Smith (1994). Outlet age is given in thousands of years before present.

By 1983, a chronology sequence for the lake had been developed (Clayton, 1983) with a south and east outlet (Fig. 2A). This sequence, however, was questioned by Smith and Fisher (1993), Fisher (1993a) and Fisher and Smith (1994) who provided evidence for a northwest outlet (Fig. 2B). Such an outlet was originally suggested by Upham (1895) and Elson (1967) (see Elson (1983) for the history of Lake Agassiz research earlier this century). To date, little research has been conducted in the northwest corner of the lake. We review recent work that pertains to the northwest outlet and present chronologic and geomorphic data from scour lakes in the northwest outlet channels to gain a better understanding of the northwest outlet history.

2. History of the northwest outlet and recent work

During the northeasterly recession of the Laurentide Ice Sheet (Dyke and Prest, 1987), the Beaver River (11,000 BP) and Cree Lake Moraines (10,000 BP) were constructed (Fig. 1B). Christiansen (1979) suggested that flow in the Clearwater-lower Athabasca spillway (CLAS) (Figs. 1C and 3) was from west to east when ice was at the Cree Lake Moraine. On the basis of paleocurrents from imbricate clasts and cross-bedding, however, Smith and Fisher (1993), Fisher (1993a), and Fisher and Smith (1994) demonstrated an east to west direction of flow.

Schreiner (1983, 1984) suggested that glacial Lake Meadow, which formed between the Beaver River Moraine ice margin and higher ground to the west (Fig. 1B), drained west and cut the CLAS. This is unlikely for two reasons: the head of the spillway is approximately 50 km further east of the Beaver River Moraine, and the head of the Kimowin spillway (Fig. 1A), mapped by Simpson (1988), starts at the continental drainage divide near the Alberta and Saskatchewan border and extends from the McMurray basin (Fisher and Smith, 1993) into the Meadow basin and cross-cuts Meadow strandlines. This suggests that Lake Meadow in the Churchill basin drained before Lake McMurray in the Mackenzie basin. Strandlines at elevations above this drainage divide were mapped by Fisher (1993a) and presented in Fisher and Smith (1994) (Fig. 6). They were explained by a contiguous Lake Meadow–McMurray which drained sometime between 11,000 and 10,000 BP first to the east and then to the northwest as ice retreated out of the Athabasca valley in Alberta (Fisher, 1993b).

Fisher and Smith (1994) reasoned that once the upper Churchill basin was deglaciated and Meadow Lake had drained, Lake Agassiz transgressed up the Churchill valley between 10,000 and 9900 BP. As the lake overtopped and incised the Beaver Lake Moraine drainage divide, it was lowered by 52 m to initiate the northwest outlet, and form the CLAS. The evidence for this transgression is described by Fisher and Smith (1994) and consists of previously unmapped strandlines above the Campbell level, glaciolacustrine sediment on either side of the Churchill River at elevations above those previously mapped, and glaciolacustrine sediment overlying fluvial terraces. Determining if the transgressing lake in the upper Churchill valley was Lake Agassiz or another previously undescribed lake is problematic. Fisher and Smith (1994) assumed it was Agassiz based on radiocarbon dates on catastrophic flood and deltaic deposits from the CLAS, which coincide with closure of the eastern outlets at the end of the Moorhead Phase. Six radiocarbon dates within catastrophic flood and deltaic deposits downstream of the northwest outlet near the mouth of the CLAS (Smith and Fisher, 1993) provided the dates for the opening of this outlet. Based on these dates that average 9869 BP and range from $10{,}310 \pm 290$ to 9410 ± 240 BP, they concluded that between 9900 to about 9500 BP, the northwestern outlet was routing water to the Arctic Ocean instead of the Gulf of Mexico. In support of this hypothesis is the reworked nannofossil (Marchitto and Wei, 1995) record recovered from cores in the Gulf of Mexico which suggests that the southern outlet was used only once: from 11,300 to 10,700 BP, and not a second time between 9900 and 9500 BP as has been commonly presumed (Clayton, 1983). The oxygen isotope record of white and pink varieties of *Globigennoides ruber* (Broecker et al., 1989) is less persuasive as only the white variety, which lives year-round, records a reduction in $\delta^{18}O$ at approximately the time when the south outlet would have been re-opened (Emerson time). The pink variety, which lives in the summer only, records a meltwater spike during Lockhart time but not during Emerson time. It is only speculative that the

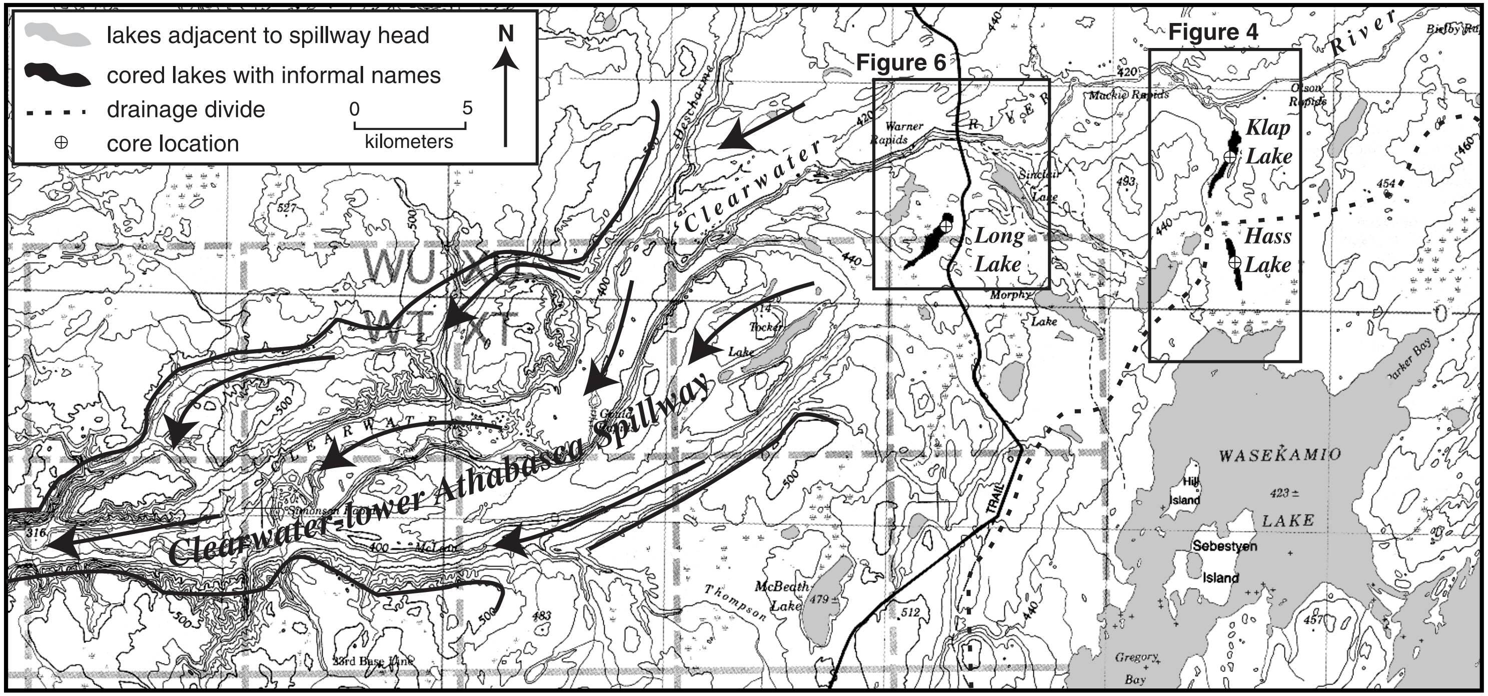


Fig. 3. Location map of cored lakes, continental drainage divide, and topography at the head of the Clearwater-lower Athabasca spillway (CLAS).

younger meltwater spike records meltwater from Lake Agassiz. Recently, Hajic (1997) described 9800–9500 BP flood deposits in the Mississippi valley from a source in the Lake Superior area. A study of fish biogeography by Rempel and Smith (in press) found a 96% similarity between disjunct Mississippi species in the Mackenzie basin (in the upper Clearwater River above an 18.5 m waterfall) and species occupying former Lake Agassiz. This distribution can be explained by a hydrologic link across the Churchill and Mackenzie drainage divides, i.e., the northwest drainage of Lake Agassiz.

Because the northwest outlet was the most recently deglaciated area and would have had the fastest rates of rebound, a mid-Emerson transgression throughout the lake basin during the Emerson Phase would have occurred (Fig. 2B). Recently obtained AMS ages on the Upper Campbell beach (9350 ± 70 BP, TO-5880, Mann et al., 1997; 9380 ± 90 BP, TO-4873, Risberg et al., 1995) support this second transgression, because the Upper Campbell beaches have dates of late Emerson time (9300 BP). Without a second transgression, the Upper Campbell beaches should have older dates. Older dates in these beaches reported by Nielsen et al. (1984) are on reworked bone.

Thorleifson (1996) presents an alternative interpretation, that differential uplift of the eastern outlets during Moorhead time may have caused the northwest outlet to be opened in late Moorhead time and then abandoned. This requires that the lake reached the Norcross level which would explain high elevation clay near the eastern outlets at the Norcross level and the high strandlines of Fisher and Smith (1994) which were interpreted to be at Norcross level at the head of CLAS. However, it also requires that at the beginning of the Moorhead Phase, the southern outlet was at the Norcross level, not at the Campbell level as has traditionally been assumed. If the northwest outlet was opened in late Moorhead time, a readvance across the Churchill River is then needed to separate the northwest basin (upper Churchill valley) from the main Agassiz basin to allow water to again reach the Norcross level at the south outlet. Other than a newly discovered moraine (discussed below) there has not been any field evidence to document this readvance. Thorleifson then suggested that the south outlet was subsequently lowered to the Campbell level during Emerson time (Thorleifson, 1996).

Rayburn (1997) reconstructed isobases from the Campbell strandlines from Dauphin, Manitoba to the northwest outlet based on high precision global positioning surveys. The existing isobases south of Dauphin, Manitoba to the south outlet (Johnston, 1946; Teller et al., 1983) appear to be accurate (Matile and Thorleifson, pers. comm.). Rayburn was unable to trace the Upper Campbell beyond the Wapawekka Hills, and the Lower Campbell northwest of Gregory Lake (Fig. 1B) with any confidence, although he recognized that there are discontinuous strandlines northwest of Gregory Lake to the maximum extent mapped by Teller et al. (1983) (Fig. 1B). Rayburn's new isobases curve further to the west suggesting that there was more post-glacial rebound in the northwest region than previously recognized. To explain this westerly trend, Rayburn (1997) maintains that deglacial events in the upper Churchill were later and that ice did not retreat from the Wapawekka Hills until about 9350 BP at which time Lake Agassiz transgressed into the rapidly deglaciating, and isostatically depressed Churchill valley, to an elevation of 490 m and began incising the CLAS. Rayburn (1997) explains the older radio-

Table 1
Lake specifications

Lake	UTM grid reference	Map[a]	Lake elev. (m)	Water depth (m)[b]	Core length (m)	Compression[c] %
Haas	635650E, 6302250N	74C/15	422	6.01	2.42	326
Klap	635400E, 6306900N	74C/15	421	2.62	4.85	147
Long	622625E, 6303500N	74C/15	423	1.07	2.2	282

[a] Department of Energy, Mines and Resources, Canada, 1:50,000 topographic maps.
[b] Water depth determined by spot depth at core locations.
[c] Compression calculated using [(core barrel length − water depth)/core length retrieved] × 100. Compression greatly reduced when core catcher not used (e.g., Klap Lake). Note, the compression may actually reflect plowing of the core barrel and incomplete recovery.

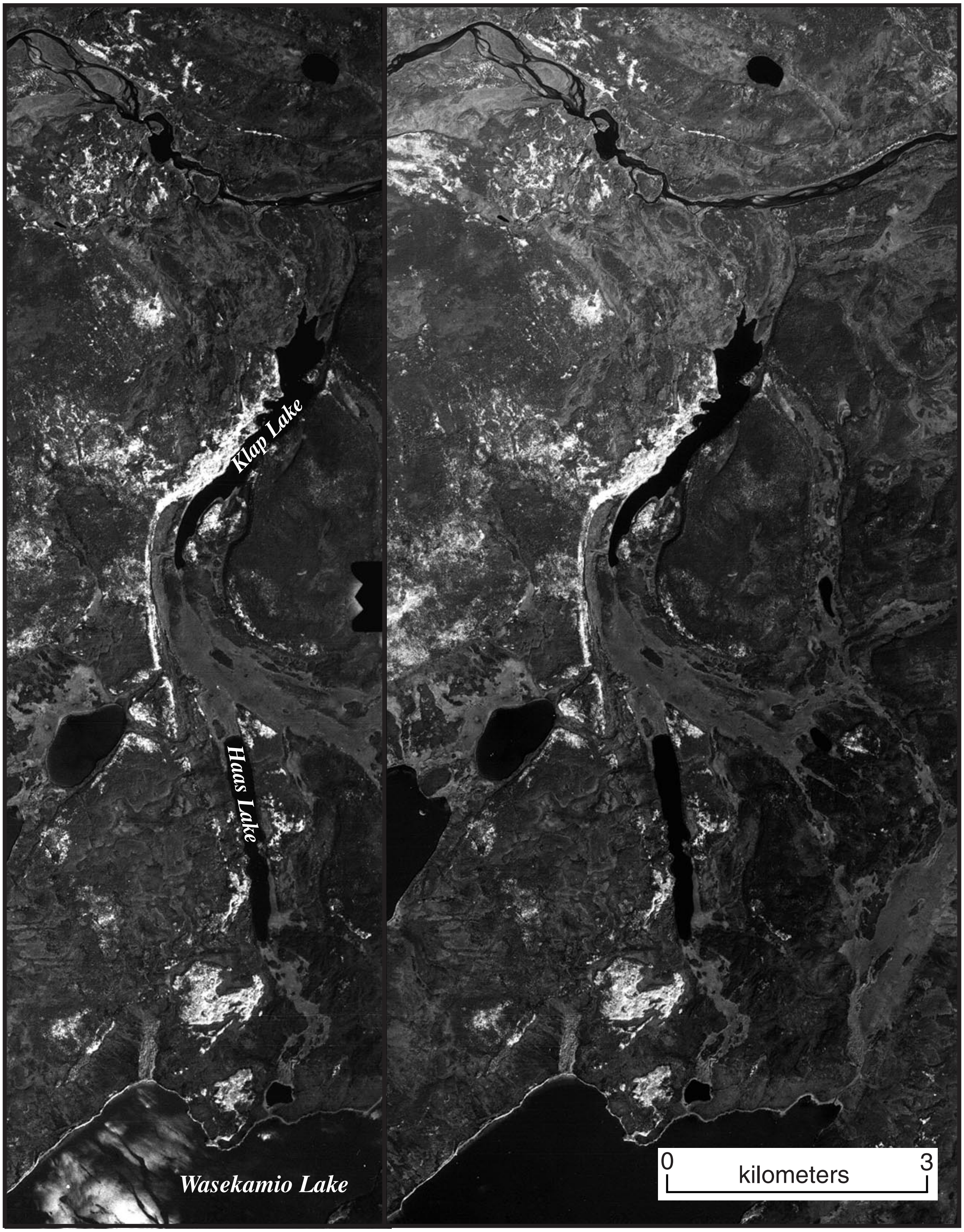


Fig. 4. Stereophoto pair of Haas and Klap Lakes. From Department of Energy, Mines and Resources aerial photographs A25327-118, 119.

carbon dates in CLAS by drainage from Lake Meadow or from other proglacial lakes in the Churchill valley when the head of the spillway was still under ice. When Lake Agassiz transgressed the region at a later date, it cut the head of the spillway that was formerly buried in ice and re-occupied the rest of the spillway. Rayburn (pers. comm., 1997) also presents evidence for a moraine at the north end of the Wapawekka Hills (Fig. 1B) which he interprets as marking a readvance.

Considering the hypotheses of Fisher and Smith (1994), Thorleifson (1996) and Rayburn (1997), detailed strandline investigations, and the moraine at the north end of the Wapawekka Hills, two possible scenarios for the lake in the upper Churchill valley and the timing of the northwest outlet must be considered.

First, if the recently discovered moraine at the north end of the Wapawekka Hills marks the re-advance of the ice sheet (such as was suggested by Thorleifson (1996) to the Wapawekka Hills) then the upper Churchill valley was dammed and separated from the main Lake Agassiz basin. The lake in the upper Churchill valley may have overtopped the Beaver River Moraine (former drainage divide) and opened the northwest outlet rather than glacial Lake Agassiz. The first scenario is based on late Emerson age radiocarbon dates from Upper Campbell beaches in southern Manitoba (9350 ± 70 BP, TO-5880, Mann et al., 1997; 9380 ± 90 BP, TO-4873, Risberg et al., 1995) and the observations that the Upper Campbell beaches are missing west of the Wapawekka Hills. Ice did not retreat from the Wapawekka Hills until late Emerson time at approximately 9300 BP. In this reconstruction, the northwest outlet was not opened until about 9300 BP, which is about 600 years earlier than the average of the radiocarbon dates within the spillway deposits reported by Fisher and Smith (1994). To more fully evaluate this reconstruction, additional evidence in the form of lateral moraines, subglacial landforms and stratigraphic evidence for this ice lobe to re-advance to the Wapawekka Hills, is required.

In the second scenario, the moraine described by Rayburn (pers. comm., 1997) is recessional and formed during general recession of the ice from the Beaver River to the Cree Lake and High Rock Moraines. This is consistent with the transgressive lake being Lake Agassiz, as suggested by Fisher and Smith (1994) and the northwest outlet opened at about 9900 BP. Once Lake Agassiz transgressed to the Upper Campbell strandline in late Emerson time, the southern outlet may have been in use for a short period of time before the eastern outlets were re-occupied. The landforms and sediment interpreted by Fisher and Smith (1994), however, were not directly

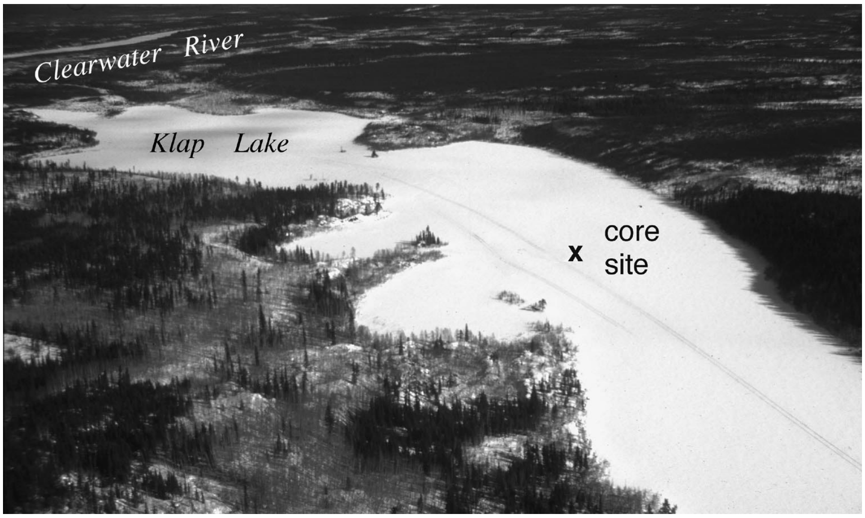


Fig. 5. Oblique aerial photograph of the core location on Klap Lake. Note the Clearwater River in the background. The peninsulas are composed of bedrock and exhibit a smooth stoss side and irregular plucked lee side. When the outlet was active, hydraulic plucking of the bedrock was likely an important agent of erosion here.

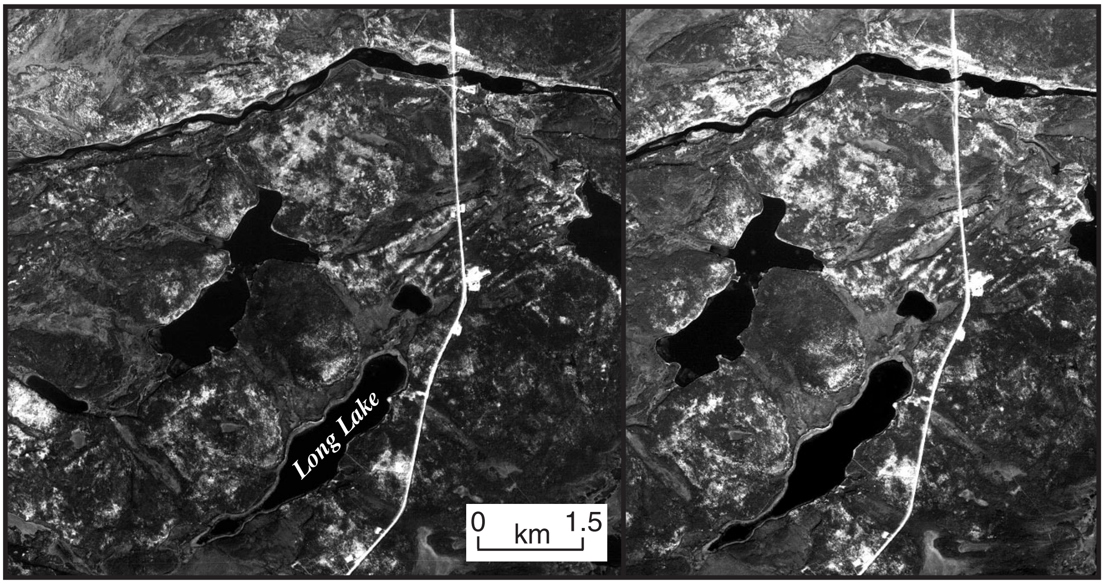


Fig. 6. Stereophoto pair of Long Lake. Note the giant current ripples transverse to flow northeast of Long Lake (Fisher, 1993a). From Department of Energy, Mines and Resources aerial photographs A25327-119, 120.

radiocarbon dated, are not continuously linked to the main Agassiz basin (discontinuous strandlines and patchy areas of glaciolacustrine sediment), and rely upon proxy evidence outside of the Lake Agassiz basin for age constraints. Thus, this scenario also needs additional support.

This paper supplements the proxy data described above with dated sediment cores recovered in March 1997 from scour lakes in the northwest outlet. The objective is to bracket the times when the northwest outlet was last in use, and to suggest that the steady state flow to the northwest from Lake Agassiz was

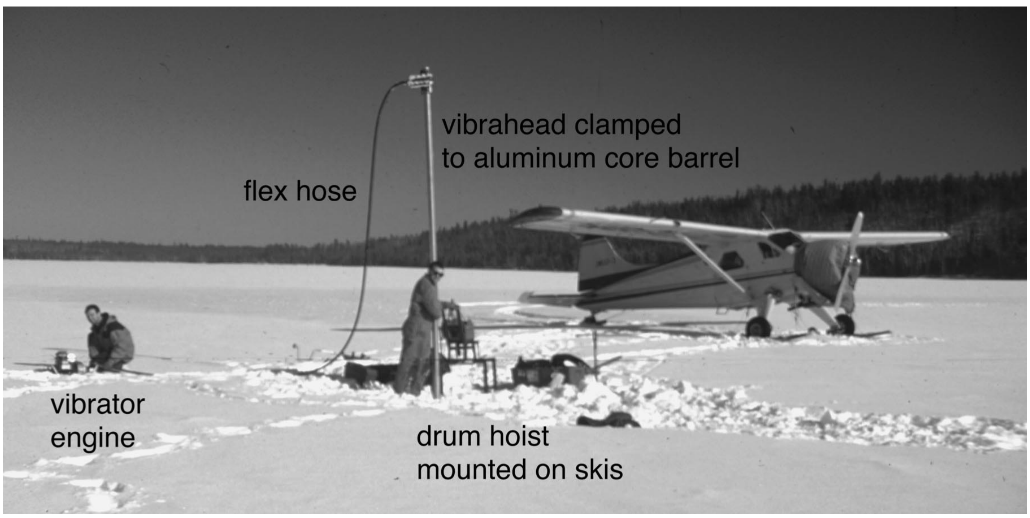


Fig. 7. Vibracoring setup used, shown here on Haas Lake. A 5.5 hp engine powers the vibrahead though a 6 m cable. The drum hoist is mounted on skis and a steel cable runs from it to the lowest core barrel.

controlled by a bedrock sill approximately 100 km further to the southeast of the location originally suggested by Fisher and Smith (1994).

3. Methodology

Three small lakes (Haas, Klap, and Long—all informal names) in scoured outlet channels at the head of the CLAS were selected for the study (Fig. 3; Table 1). Haas and Klap Lakes were chosen because they are within a channel interpreted by Fisher and Smith (1994) to have formed during steady-state flow (438 m water plane) from the northwest outlet (Figs. 3–5). Long Lake lies within the Mackenzie drainage basin and geomorphically occupies a scour lake (traverse trough proximal to residual hills) that records the CLAS flood (Figs. 3 and 6). A bulk radiometric date of 11,100 ± 150 BP (GSC-4807) had been obtained previously on basal lake sediment at this site; however, the date is suspected of being contaminated with older carbon (Anderson and Lewis, 1992).

In March 1997, cores were collected from Long, Haas, and Klap lakes using a vibracorer powered by a 5.5 hp engine (Fig. 7). Aluminum tubes with a 3-in. diameter (7.62 cm) were used with couplers to increase the depth of coring (maximum depth reached 14 m), and a drum hoist rated to 4000 lb was used to

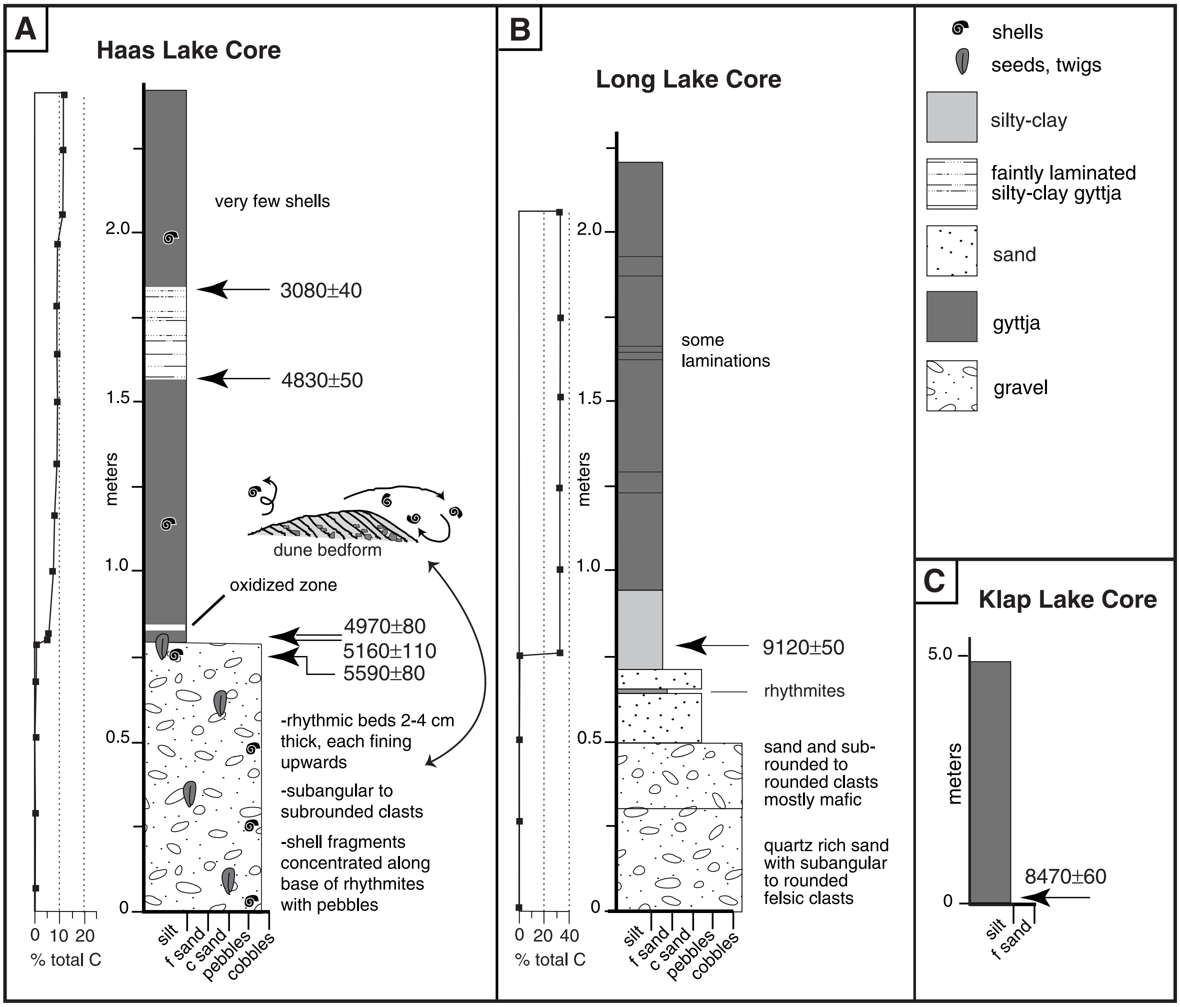


Fig. 8. Core diagrams: (A) Haas Lake; (B) Long Lake; and, (C) Klap Lake.

Table 2
Radiocarbon dates obtained in this study

Lab number	Core	Height (m)[a]	Date (BP)[b]	Material dated
Beta-104544	Long Lk.	0.705–0.73	9120 ± 50	Plant material
Beta-104541	Haas Lk.	0.79	5590 ± 80	seeds
Beta-104542	Haas Lk.	0.805	5160 ± 110	wood fragments
Beta-104543	Haas Lk.	0.81	4970 ± 80	wood fragments
Beta-107690	Haas Lk.	1.58	4830 ± 50	gyttja
Beta-107691	Haas Lk.	1.8	3080 ± 40	gyttja
Beta-107692	Klap Lk.	0–0.003	8470 ± 60	gyttja

[a] Height is measured from the bottom of the core upwards, as some sediment was lost from the top of the core (see Fig. 8).
[b] Not corrected to calendar years. All samples followed standard Beta Analytic acid–alkali–acid treatment; all are AMS dates.

retrieve the core barrels from the lake bottom. Details of the vibracorer and its use in the field are presented by Smith (1992). Access to the lakes was by Beaver airplane equipped with skis. At each site, coring continued until coarser materials underlying the finer lake sediment were encountered or core penetrations ceased.

Upon return to the laboratory, the core barrels were cut with a skill-saw equipped with a masonry blade in a wooden jig. Cores were split using metal guitar strings kept taut between wooden dowels; then scraped clean, photographed, and described while moist, with supplemental information added as they dried. Half of each core was archived. Descriptions were made on each sedimentary unit (depth, contacts, inclusions, grain size, sorting, sedimentary structures, and color) in each core.

For each lake, a master core with the best representation of all the sedimentary units present was selected for more detailed analysis. Core lengths and degrees of sediment compression for these master cores are listed in Table 1. Each of these cores were sub-sampled for analyses of total carbon and total inorganic carbon using a UIC Inc Model 5012 CO2 coulometer. All carbon analyses were performed by CO_2 coulometry (UIC Coulometrics). Total carbon was determined by combustion at 950°C, inorganic carbon was determined by acidification (2 N HCl), and organic carbon was the calculated difference between these two values.

From each of the master cores, macrofossils for AMS radiocarbon dating were obtained from the lowest sedimentary units. Small samples of sediment were removed from the cores and gently disaggregated by washing through a 63 μm sieve with distilled water. Organic fragments were then hand picked under a binocular microscope. Because of the very small amounts of organic material in the lowest sediment, most of the material submitted to be dated consisted of a composite of small fragments of largely unidentified, finely disseminated organic material. All samples were submitted to Beta Analytic and were subjected to standard acid–alkali–acid preparation procedures for AMS dating.

4. Results

Descriptions of Long, Haas, and Klap lake cores are provided in Fig. 8. The radiocarbon dates obtained from the basal sediment are listed in Table 2. Where possible, several dates were obtained in the same core to ensure consistency in stratigraphy and chronology. The dates reported here are presented in ^{14}C years before present.

The stratigraphy of Long Lake consists of a lower pebble gravel, with subrounded to subangular mafic pebbles in excess of 5 cm, fining to sand, silty-clay, and then fibrous peat (Figs. 8B and 9). The lowermost gravel, sand, and silty-clay deposit has very little organic carbon (less than 1%) content. No organic material was found in the lower pebble gravel or sand so it could not be dated. Wood fragments from the base of the clay (integrated over

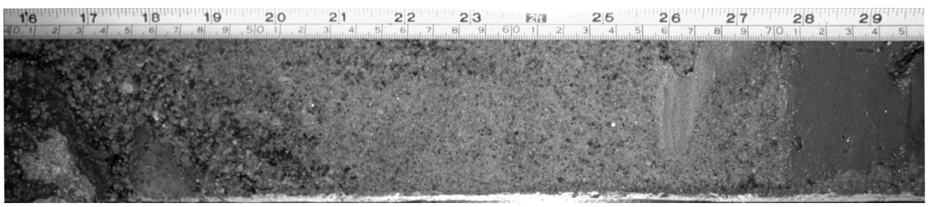


Fig. 9. A segment of core from Long Lake that consists of large pebble gravel fining upwards to coarse sand at 0.655 m. A short sequence of rhythmites up to 0.675 m is truncated by coarse sand (likely by a sediment gravity flow) which sharply returns to silty-clay at 0.705 m.

Fig. 10. Segment of core from Haas Lake. Note the scale in the photo does not correspond to height in Fig. 8A. The contact between gravel and gyttja is oblique at 0.965 m. Note the thin oxidized zone in the gyttja at 0.995 m.

a depth of 2.5 cm) yielded an AMS date of 9120 ± 50 BP (Table 2).

In Haas Lake, the lowermost sediment consists of 0.8 m of stratified, pebble gravel containing abundant shell and wood fragments (Figs. 8A and 10). Within this deposit are distinct beds, 2 to 4 cm in thickness, which fine upwards. Shell fragments are concentrated along the base of the gravel rhythmites along with subangular to subrounded pebbles. Above a sharp, conformable contact this deposit is overlain by 1.6 m of gyttja. This sediment is rich in organic carbon (12% increasing to 25%) and fine grained (silt and clay) with few shells. A thin layer (0.5 cm) of oxidized sediment is found within the gyttja 3.5 cm above its base. AMS dates on seeds and wood fragments from the top-most gravel and from the lower 3 mm, and 6 mm of the gyttja are 5590 ± 80 BP, 5160 ± 110 BP and 4970 ± 80 BP, respectively (Table 2). Bracketing dates on faintly laminated gyttja higher up the core are 4830 ± 50 BP and 3080 ± 40 BP (Fig. 8A; Table 2).

While coring Klap Lake, the expected basal sand and gravel was not encountered because of a thicker accumulation of gyttja. The core consists of 4.86 m of gyttja, and an AMS date from the lowermost 3 mm of gyttja from this core is 8470 ± 60 BP.

5. Discussion

The lower pebble gravel deposits of Long Lake, interpreted to be fluvial sediment, provide evidence of a major flood. The transition from felsic to mafic gravel suggests the greater incorporation of local gnessic rock as the flood waned. The fining up of these deposits records the transition from a fluvial to a lacustrine environment, with the subsequent development of a low-energy depositional environment with deposition of organic material that has persisted through much of the Holocene. Because the lake is in the head of CLAS, and scour in origin (transverse trough upflow of rock knobs, and adjacent to giant current ripples [Fig. 6]), the radiocarbon date of 9120 BP for the deposition of the lowest lake sediment is considered a minimum age for the flood from the northwest outlet at the beginning of the Emerson Phase. This young spillway age is consistent with the history of Lake Agassiz and chronology put forward by Fisher and Smith (1994), although it is about 800 years younger than the average age on wood from the lower spillway and associated delta. This discrepancy may be explained by contamination of younger peat in the sample or a significant time lag between the onset of lake sedimentation and the deposition of the oldest datable organic material. A second sample could not be collected because of the paucity of organic material distinguishable from younger fibrous peat. If the 9120 BP date is accurate, it (1) supports the hypothesis of Rayburn (1997) about a late transgression of Lake Agassiz into the upper Churchill valley, assuming this transgression was responsible for forming the CLAS, and (2) refutes the suggestion of Thorleifson (1996) about the northwest outlet being open in late Moorhead time.

Given the stratigraphy of the deposits in Haas Lake, the series of mid-Holocene radiocarbon dates was initially surprising. These dates do not provide information on the chronology of flow from glacial Lake Agassiz through the northwest outlet channel, however, they do provide important insight into the sill between Wycherley and Leboldus Lakes (see full description below). This sill, in concert with rebound, controlled lake level throughout the basin, provides support for ongoing rebound in the area, and indirectly supports the new isobases of Rayburn (1997). One possible explanation, that is consistent with the stratigraphy and broader-scale geomorphology of this region, is that the basal gravel is interpreted to be fluvial, recording a river draining Wasekamio Lake north into the Clearwater River across the present day drainage divide (Fig. 3). The 5590, 5160 and 4970 dates at the contact of the gravel and gyttja indicate that northward drainage lasted until the mid-Holocene, followed by channel abandonment and infilling (Fig. 11).

Channel abandonment is explained by on-going isostatic uplift which is still active today in the upper Churchill basin. Estimates of modern rates of isostatic rebound during the Holocene from the Birch River delta building into Lake Clair in northeast Alberta, are as high as 1.4 mm/yr (Molnar, 1994). Additional evidence of continuing isostatic rebound are from the Canoe and Beaver Rivers, which enter the south end of Lac Ile-a-La-Cross and anastamose at the mouths (Fig. 12A–C). The anabranching pattern of channels in anastomosing rivers, is explained by very low slopes (Smith and Putnam, 1980; Nadon, 1994). In the example of the Beaver and Canoe Rivers, the low slope may be a result of on-going isostatic adjustment. In this area, rebound is causing the lakes to transgress southwards, flooding the mouths of north-flowing rivers, reducing slopes, and initiating a change in channel morphology from meandering to anastomosing (Fig. 11B).

A topographic profile (Fig. 13), approximately parallel to the axis of the Churchill valley, was constructed to show that minor isostatic adjustments and tilting of the crust can cause significant shifts in the location of continental drainage divides. Elevations used were from the Department of Energy, Mines and Resources, Canada, 1:50,000 topographic maps with 10 m contour elevations and spot elevations for lakes. Referring to Fig. 12, at the modern drainage divide an elevation difference of only 4 m exits between the Clearwater River and Wasekamio Lake. The drainage divide could also be between Klap and Haas Lakes. When the former Wasekamio River flowed, the drainage divide must have been further to the southeast where today a drop of only 2 m occurs from Wasekamio Lake southeast to Lac Ile-a-la-Crosse, along 175 km of lake basins parallel

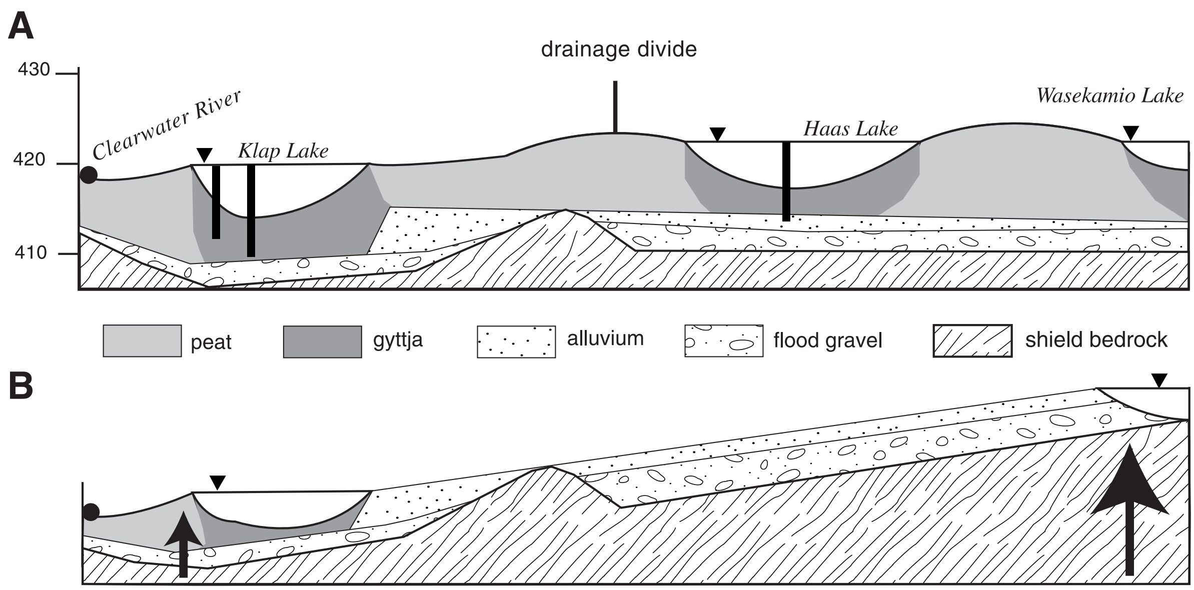


Fig. 11. Schematic cross-section between Wasekamio Lake and the Clearwater River, showing core locations and inferred stratigraphy. (A) Slopes of the modern surface and topography. (B) Paleo-slopes and topography when Lake Wagtufro drained north via the Wasekamio River into Klap Lake, and ultimately into the Clearwater River. Arrows indicate isostatic rebound that had already occurred by 5600 BP, at which point, the Wasekamio River ceased flowing, and Wasekamio Lake emptied into the Churchill River basin.

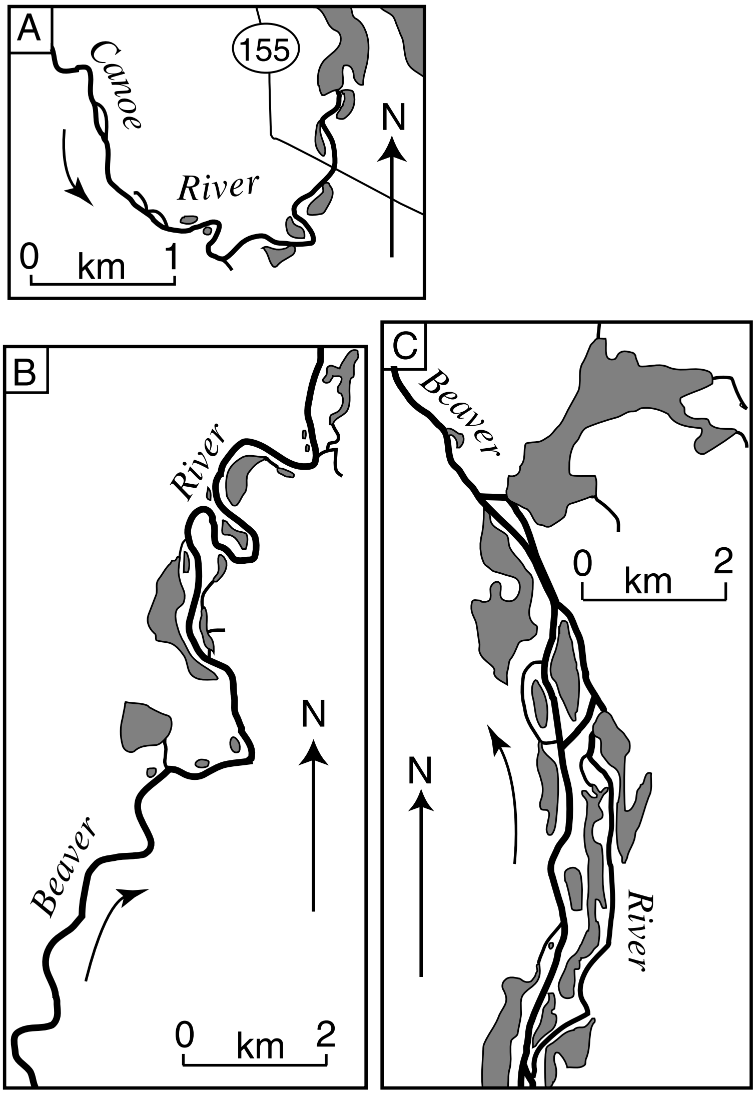


Fig. 12. Examples of anastomosing patterns in rivers entering Lac Ile-a-la Crosse. See Fig. 1A for location of 12A, C; 12B is located south of Beauval just off of Fig. 1A.

to the Cree Lake Moraine (Fig. 1). It is probable that a temporary drainage divide existed at the east edge of Turnor Lake, where today, it is drained by the Wanasin River (Figs. 1A and 13). The land between Wycherley and Flatstone Lakes was likely a part of the drainage divide during the early Holocene. Re-

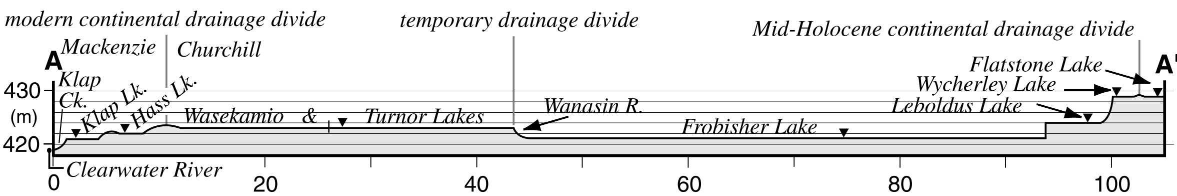
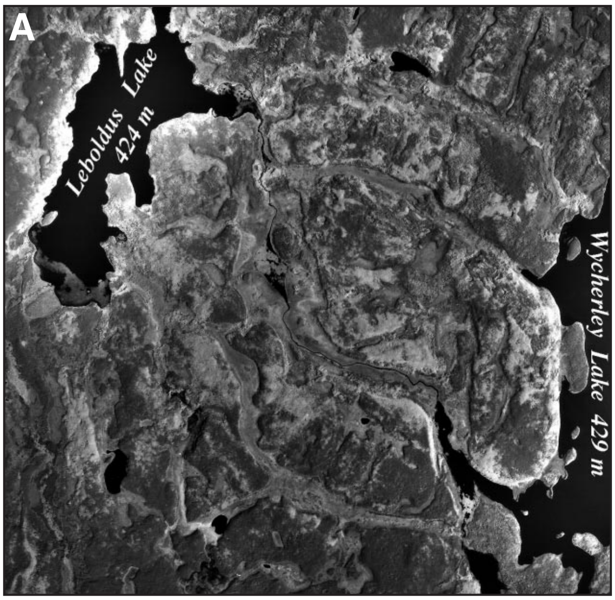


Fig. 13. Topographic profile from the Clearwater River southeast to Flatstone Lake. See Fig. 1A for profile location.

constructing the precise location of past drainage divides in the Flatstone Lake area is uncertain at best: it is complicated by the low resolution of the topographic data, an extremely irregular bedrock and glacial topography, on-going rebound, and thick organic fills in valleys and lowlands.

The mid-Holocene dates from Haas Lake suggest that before 5200 BP, the drainage divide was further southeast in the vicinity of Flatstone Lake (Figs. 1A and 13). By shifting the early Holocene drainage divide further southeast, it is now suggested that during the Emerson Phase, Lake Agassiz was controlled by a sill and series of channels between Wycherley and Leboldus Lakes just west of Flatstone lake at 440 to 430 m (Fig. 14) after the incision of CLAS, instead of between Wasekamio Lake and the Clearwater River as proposed by Fisher and Smith (1994).

The topography around Wycherley Lake is one of glacial erosion superimposed upon contorted Shield rock resulting in a series of ridges and valleys with superimposed drumlins and eskers. Further east, the Mudjatik River (Fig. 1A) has infilled low-lying areas to the eastern edges of Flatstone and Little Flatstone Lakes. Schreiner (1983) used an elevation of 420 m to mark the elevation of deltas building into Lake Agassiz, which was used by Teller et al. (1983) to demarcate the northwestern extent of Lake Agassiz in the Churchill valley. The presence of glaciolacustrine sediment in the Haultain River valley (convolute silt and clay with dropstones) at elevations of up to 465 m (Fig. 9; Fisher and Smith, 1994), indicates that a lake higher than 420 m occupied this area. Topographic maps of the Flatstone Lake area, indicate a plain topography to about 430 m. An esker ridge in the west edge of the map (Fig. 14) has a distinct break of slope at 440 m; it is broader below, and sharper above, and suggests that for a period of time the lake in the area remained at 440 m. Field observations around the Keewatin Ice Divide (Fisher, unpublished field notes), include evidence for eskers forming peninsulas and islands that were weakly, or if at all, modified. As these eskers have been in lakes for at least 25 times as long as the esker in Fig. 14,



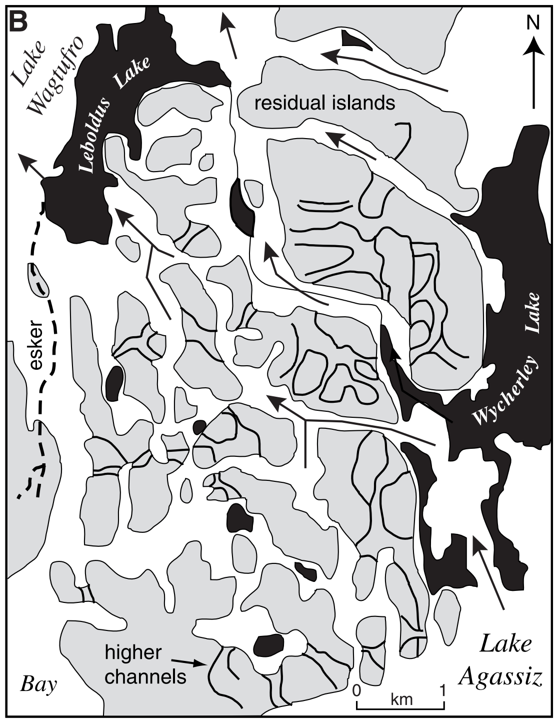


Fig. 14. (A) Aerial Photograph of area shown in B. (B) Geomorphic map of channels between Wycherley and Leboldus Lakes. Figure location is on Fig. 1A.

eskers can be easily preserved in glacial lakes and still provide valuable information on lake level.

Four well-defined channels with upper bank elevations of 440 m, dissect the landscape between Wycherley and Leboldus lake (Fig. 14). Today, Leboldus Lake drops 3 m through a channel into Frobisher Lake. The higher channels above 440 m on the residual islands are presumed incipient channels formed when deeper water flowed over the area and the channel network was forming. As the channels are parallel to isobases, Holocene uplift will not have modified relative gradients, and as Wycherley Lake is higher than Leboldus Lake, the water that cut the channels flowed from southeast to northwest (Fig. 14).

These Wycherley channels are interpreted as marking the maximum northwest extent of Lake Agassiz during Emerson time after the flood which created CLAS and lowered Lake Agassiz to the controlling sills and channels shown in Fig. 14. The channels themselves are the outlets that fed a lake to the northwest 5 m in elevation lower. This lake is referred to as Lake Wagtufro—its remnants being Wasekamio, Turnor and Frobisher Lakes. We suggest that Lake Wagtufro extended to another sill between Wasekamio Lake and the Clearwater River, which was formerly thought to be the controlling outlet for Lake Agassiz (Fisher and Smith, 1994), and is marked by a 438 m strandline (Fig. 4). Upon re-opening of the eastern outlets during the Morris Phase and lowering of Lake Agassiz below the northwest outlet, the channels between Wycherley and Leboldus Lakes were abandoned. The fluvial sediment in the base of the Haas core suggest that the upper Churchill valley drainage was north through the Wasekamio River, Klap Lake, and into the Clearwater River until the mid-Holocene.

The 8470 BP date from the base of the Klap Lake core suggests that Klap Lake has remained a lake throughout the Holocene. And that the Wasekamio River entered Klap Lake from the south and was not a continuous river from Wasekamio Lake to the Clearwater River.

6. Conclusions

The observations are consistent with a major flood in the northwest outlet before 9100 BP. Long Lake was established and organic material had been deposited by 9100 BP and deposition has been continuous since then.

The mid-Holocene Haas Lake radiocarbon ages are younger than expected, and suggest that during the Holocene the continental drainage divide migrated northward in response to isostatic rebound. These dates provide a chronology for abandonment of mid-Holocene channels that presently straddle the Mackenzie and Churchill drainage divide.

The proposed history of the northwest outlet area is: (1) a northwest outlet opened at the beginning of the Emerson Phase as Lake Agassiz transgressed up the isostatically depressed Churchill valley, overtopped the Beaver River Moraine, and incised the Clearwater-lower Athabasca spillway at some time between 9900 and 9100 BP; (2) as the spillway was cut, Lake Agassiz was lowered 52 m (Fisher and Smith, 1994), and the northwest outlet was then controlled by bedrock between Wycherley and Leboldus Lakes; (3) outflow from these lakes entered a lower basin of Lake Agassiz, Lake Wagtufro (a higher stand of present day, Wasekamio, Turnor, and Frobisher Lakes), which led to the formation of the 438 strandline above the western shores of Wasekamio Lake; (4) once the lake had transgressed to the Upper Campbell strandline, the northwest outlet may have been abandoned in favor of the southern outlet for an unknown duration before the eastern outlets were re-occupied at the beginning of the Morris Phase; (5) meanwhile, flow in the upper Churchill valley continued to flow north through a channel into Klap lake and then into the Clearwater River. At this time, the continental drainage divide was somewhere in the vicinity of Flatstone Lake; (6) the present-day drainage divide between Wasekamio Lake and the Clearwater River was established by mid-Holocene time.

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