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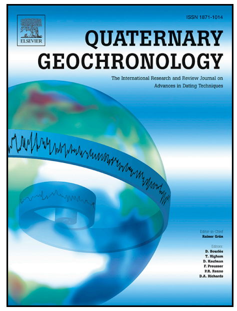
Crann, C. A., Patterson, R. T., Macumber, A. L., Galloway, J. M., Roe, H. M., Blaauw, M., Swindles, G. T., & Falck, H. (2015). Sediment accumulation rates in subarctic lakes: insights into age-depth modeling from 22 dated lake records from the Northwest Territories, Canada. *Quaternary Geochronology*, *27*, 131-144. https://doi.org/10.1016/j.quageo.2015.02.001

Published in:
Quaternary Geochronology

Document Version:
Peer reviewed version



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PII: S1871-1014(15)00014-X

DOI: 10.1016/j.quageo.2015.02.001

Reference: QUAGEO 627

To appear in: *Quaternary Geochronology*

Received Date: 14 May 2014

Revised Date: 3 February 2015

Accepted Date: 4 February 2015

Please cite this article as: Crann, C.A., Patterson, R.T., Macumber, A.L., Galloway, J.M., Roe, H.M., Blaauw, M., Swindles, G.T., Falck, H., Sediment accumulation rates in subarctic lakes: insights into age-depth modeling from 22 dated lake records from the Northwest Territories, Canada, Quaternary Geochronology (2015), doi: 10.1016/j.quageo.2015.02.001.

Sediment accumulation rates in subarctic lakes: insights into age-depth modeling from 22 dated lake records from the Northwest Territories, Canada

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Abstract

Age-depth modeling using Bayesian statistics requires well-informed prior information about the behavior of sediment accumulation. Here we present average sediment accumulation rates (represented as deposition times, DT, in yr/cm) for lakes in an Arctic setting, and we examine the variability across space (intra- and inter-lake) and time (late Holocene). The dataset includes over 100 radiocarbon dates, primarily on bulk sediment, from 22 sediment cores obtained from 18 lakes spanning the boreal to tundra ecotone gradients in subarctic Canada. There are four to twenty-five radiocarbon dates per core, depending on the length and character of the sediment records. Deposition times were calculated at 100-year intervals from age-depth models constructed using the 'classical' age-depth modeling software Clam. Lakes in boreal settings have the most rapid accumulation (mean DT 20 ± 10 years), whereas lakes in tundra settings accumulate at moderate (mean DT 70 ± 10 years) to very slow rates, (>100 yr/cm). Many of the age-depth models demonstrate fluctuations in accumulation that coincide with lake evolution and post-glacial climate change. Ten of our sediment cores yielded sediments as old as c. 9,000 cal BP (BP = years before AD 1950). From between c. 9,000 cal BP and c. 6,000 cal BP, sediment accumulation was relatively rapid (DT of 20 to 60 yr/cm). Accumulation slowed between c. 5,500 and c. 4,000 cal BP as vegetation expanded northward in response to warming. A short period of rapid accumulation occurred near 1,200 cal BP at three lakes. Our research will help inform priors in Bayesian age modeling.

Keywords

Bayesian age-depth modeling, accumulation rate, deposition time, Bacon, Subarctic,

Northwest Territories, paleolimnology

1. Introduction

Lake sediment accumulation rates vary across space and time (Lehman, 1975; Terasmaa, 2011). Characterization of the spatial trends in accumulation rate for a region and within a lake basin is valuable for sample site selection in paleolimnological studies, as it is often favorable to sample lakes with sufficiently high accumulation rates to achieve a desirable temporal resolution in the data. Understanding the temporal variability and timing of major shifts in accumulation rate as well as the causes of major accumulation rate shifts for a region can be extremely valuable for deciding on levels in an age-depth model that would benefit from additional radiocarbon dates. Such changes in accumulation rate can be used to better understand the limnological system of study and the impact of climate change on that system. Moreover, there are many examples where changes in sediment accumulation rate have been linked to climatic change. For example, in the Cathedral Mountains of British Columbia, the highest Holocene levels of sediment yield are coincident with late Holocene (~ 4,000 BP) climate cooling, reduced catchment vegetation and increased terrestrial erosion (Evans and Slaymaker, 2004). Similarly, in a crater lake in equatorial East Africa, Blaauw et al. (2011) found that cooler climate conditions also resulted in reduced vegetation cover and increased terrestrial erosion and allochtonous sediment input into the lake. Knowledge of accumulation rate is also necessary for proxy-based reconstructions of mean fire return interval, rates of vegetation change (Koff et al., 2000; Marlon et al., 2006), and carbon accumulation rate studies (e.g. Charman et al. 2013), for example, that are only as good as the chronologies they are based upon.

The integration of sediment accumulation rate information into Bayesian age-depth models as prior knowledge, or "priors" is particularly important for sections of an age-depth model where the behavior of the model is uncertain (e.g. sparse data, age reversals, age offsets, dates within a radiocarbon plateau). It can be a challenge, however, to estimate the accumulation rate prior. Goring et al. (2012) provided a summary of sediment accumulation rates from 152 lacustrine sites in the northeastern US/southeastern Canada region and found that, in general, sediment accumulated with a DT of around 20 yr/cm. This result is fairly similar to the previous findings of Webb and Webb (1988; 10 yr/cm) for the same region. However, these estimates are too rapid for subarctic and arctic lakes, where a short ice-free season and low availability of organic material relative to more southern sites lead to slow annual sediment accumulation rates (e.g. Saulnier-Talbot et al., 2009).

This paper expands upon the temperate lake research of Goring et al. (2012) and Webb and Webb (1988). We examine Holocene accumulation rate data for 22 lacustrine sites from a latitudinal gradient spanning boreal forest, treeline, and tundra settings in the Northwest Territories, Canada. While this is a much smaller dataset than Webb and Webb (1988) and Goring et al. (2012), it is significant given that it is logistically difficult to obtain sediment records in arctic and subarctic regions due to the lack of infrastructure. Goring et al. (2012) suggest that such regional datasets can provide important prior knowledge to inform Bayesian (and other) age models.

The age-depth models presented in this paper were constructed in support of an interdisciplinary project aimed at better understanding the natural variability of climate along the routed of the Tibbitt to Contowyto Winter Road (TCWR) in the central Northwest Territories (Canada). Increased precision of age-depth models and increased sampling resolution of proxy data from lake sediment cores have permitted higher resolution characterization paleoclimate patterns (e.g., Galloway et al., 2010; Macumber et al., 2012; Upiter et al., 2014).

2. Regional setting

Lakes investigated in this study are located in the central Northwest Territories (Fig. 1) in an area underlain by a portion of the Canadian Shield known as the Slave Craton. This section of Archean crust is characterized by a depositional and volcanic history that has been overprinted by multiple phases of deformation and intruded by granitoid plutons (Bleeker, 2002). Major rock units include basement gneisses and metavolcanics, metasedimentary rocks, and widespread gneissic–granitoid plutons (Padgham and Fyson, 1992; Helmstaedt, 2009). This bedrock geology lacks carbon-rich rocks such as limestones or marl, and is unlikely to be a source of '^{14}C dead' carbon, which can cause radiocarbon dates to appear anomalously old.

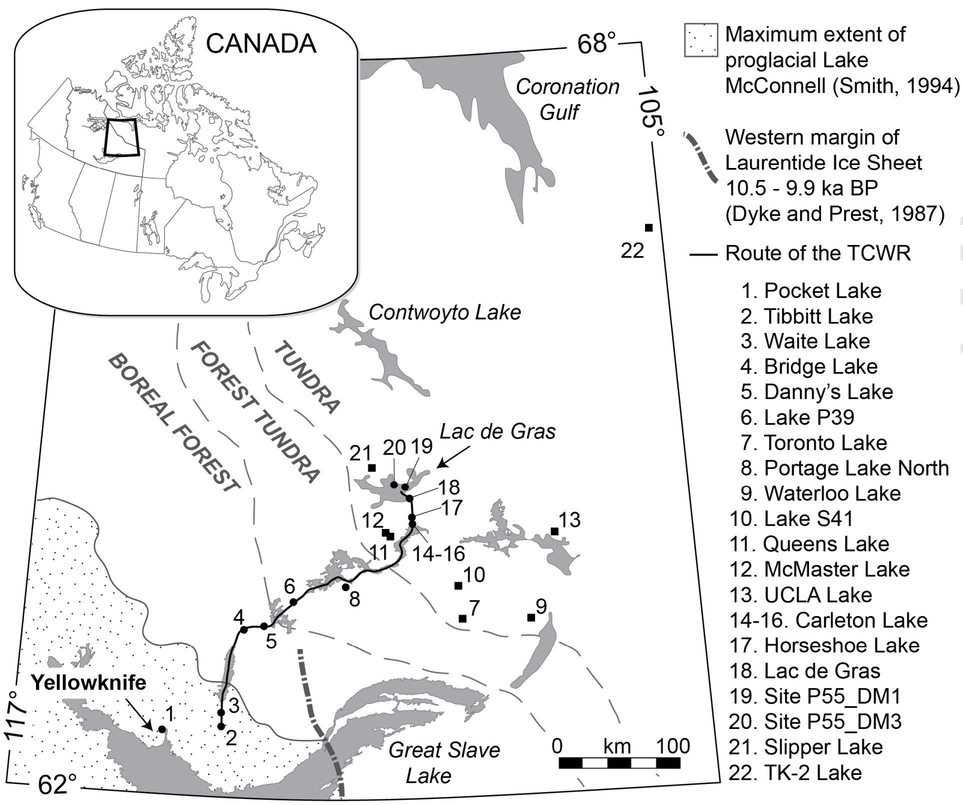


Figure 1. Map of the Northwest Territories showing the locations of core sites. Circles are sites from the TCWR project, squares are sites from previously published work, dashed lines show current boundaries between tundra, forest tundra, and boreal forest ecozones, and the inset shows the location of the study area within Canada. References for the previously published sites are given in Table 1. ***Two column image.***

The Slave Craton has been isostatically uplifting since the retreat of the Laurentide Glacier about 10,000–9,000 years ago (Dyke and Prest, 1987; Dyke et al., 2003). Glacial-erosional processes have shaped the terrain, which is characterized by a gentle relief of only a few tens of meters (Rampton, 2000). Where bedrock is not exposed, it lies beneath deposits of till and glaciofluvial sediment of varying thickness. The action of glacial erosion and subglacial meltwater flow has resulted in a landscape with abundant, often interconnected lakes. Figure 1 shows the approximate western margin of the Laurentide Ice Sheet as it retreated toward the east, sometime between 10,500 and 9900 years ago (Dyke and Prest, 1987) as well as the maximum extent of proglacial Lake McConnell (Smith, 1994). Lake McConnell was the main proglacial lake in the region following the retreat of the Laurentide Ice Sheet.

The present-day treeline runs NW/SE across the study area, roughly reflecting the polar front (Fig. 1). The treeline is marked by the northern limits of the boreal forest (Fig. 2a), where forest stands are open and lichen woodlands merge into areas of shrub tundra (Galloway et al., 2010; Fig. 2b). Soils are poorly developed with discontinuous permafrost south of the treeline, and continuous permafrost north of the treeline (Clayton et al., 1977). Tundra vegetation is composed of lichens, mosses, sedges, grasses, and diverse herbs (MacDonald et al., 2009). The vegetation cover and soils are often affected by polygonal permafrost features (Fig. 2c), and are discontinuous on rocky substrates.

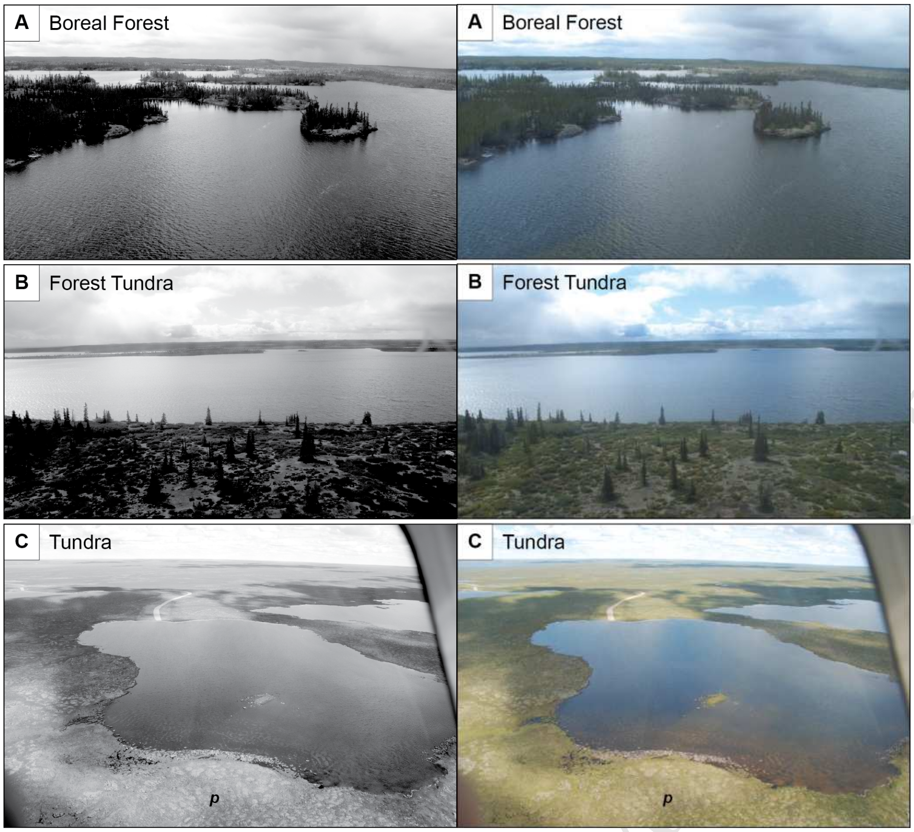


Figure 2. Images of the (a) boreal forest zone at Waite Lake, (b) forest tundra ecotone near Portage Lake North (actually Mackay Lake, not mentioned in this paper), and (c) tundra zone at Carleton Lake, where "p" shows an area with soil polygon development. At Carleton Lake, the path of the TCWR can be seen exiting the lake to the north. ***One column image. Colour version for web only. Black and white for print.***

The climate of the region is subarctic continental, characterized by short summers and long cold winters. Annual precipitation is low (175 – 200 mm) and mean daily January temperatures range from -17.5°C to -27.5°C, while mean daily July temperatures range from 7.5°C to 17.5°C. Lakes in the region are often ice-covered for much of the year, with an average open-water period of only 90 days (Wedel et al., 1990).

Broad-scale patterns of Holocene climate change in the study area have been identified by proxy evidence from lake sediment cores from Toronto Lake (MacDonald et al., 1993; Wolfe et al., 1996; Pienitz et al., 1999), Waterloo Lake (MacDonald et al., 1993), Lake S41 (MacDonald et al., 2009), Queen’s Lake (Moser and MacDonald, 1990; MacDonald et al., 1993; Wolfe et al., 1996; Pienitz et al., 1999), McMaster Lake (Moser and MacDonald 1990; MacDonald et al., 1993), UCLA Lake (Huang et al., 2004), Slipper Lake (Rühland and Smol, 2005), and Lake TK-2 (Paul et al., 2010) (Fig. 1; Table 1). Based on this body of previous work, three main stages of landscape development have been inferred: (1) between deglaciation (c. 9,000 cal BP) and c. 6,000 cal BP, terrestrial erosion decreased as vegetation developed from tundra to *Betula*-dominated shrub tundra, and finally to spruce forest tundra (Huang et al., 2004; Sulphur et al., in prep) and stabilized the landscape; (2) between c. 6,000 and c. 3,500 cal BP the treeline moved north of its present location in response to climate warming (Moser and MacDonald, 1990; MacDonald et al., 1993), likely reflecting a northward retreat of the polar front following the demise of the ice sheet in the middle Holocene (Huang et al., 2004); and (3) between c. 3,000 cal BP to the present, there was a general trend towards climate cooling. This resulted in an increase in birch-dominated shrub tundra in the more northerly sites (UCLA lake; Huang et al., 2004). At the more southern locations, vegetation shifts associated with climate change during the latest Holocene are also documented (change c. 1,000 cal BP at Danny’s Lake; Sulphur et al., in prep.).

Table 1. Coordinates and physical characteristics of the lakes used in this study. Citations: (1) Moser and MacDonald, 1990; (2) MacDonald et al., 1993; (3) Edwards et

al., 1996; (4) Wolfe et al., 1996; (5) Penitz et al., 1999; (6) Huang et al., 2004; (7) Rühland and Smol, 2005; (8) MacDonald et al., 2009; (9) Paul et al., 2010; (10) Galloway et al., 2010; (11) Macumber et al., 2012; (12) Upiter et al., 2014.

*TCWR JV = Tibbitt to Contwoyto Winter Road Joint Venture

Site ID	Site name	TCWR JV* ID	Latitude	Longitude	Surface area (ha)	Depth (m)	Citation
1	Pocket Lake	-	62°30.540	114°22.314	6	3.5	
2	Tibbitt Lake	P0	62°32.800	113°21.530	300	6.72	10, 11
3	Waite Lake	P14-2	62°50.987	113°19.643	100	1.8	10, 11
4	Bridge Lake	P26	63°23.297	112°51.768	119.5	4.5	11
5	Danny's Lake	P34	63°28.547	112°32.250	4.4	4.4	11
6	Lake P39	P39	63°35.105	112°18.436	37.3	1.1	11
7	Toronto Lake	-	63°25.800	109°12.600	10	6.75	2, 4, 5
8	Portage Lake N	P47	63°44.538	111°12.957	194.9	4.85	11
9	Waterloo Lake	-	63°26.400	108°03.600	?	?	2
10	Lake S41	-	63°43.110	109°19.070	<0.3	4.4	8
11	Queens Lake	-	64°07.000	110°34.000	50	4.5	1–5
12	McMaster Lake	-	64°08.000	110°35.000	12	8.0?	1, 2
13	UCLA Lake	-	64°09.000	107°49.000	28	7.7	6
14	Carleton-1A	P49	64°15.571	110°05.878	29.8	15	11
15	Carleton-1B	P49	64°15.571	110°05.878	29.8	1.5	11, 12
16	Carleton-2012	P49	64°15.500	110°05.928	29.8	3.0	
17	Horseshoe Lake	P52	64°17.381	110°03.701	505	4.0	11
18	Lac de Gras	P55	64°25.794	110°08.168	~57 k	4.0	11
19	Lac de Gras_DM1	P55	64°30.393	110°15.255	~57 k	?	
20	Lac de Gras_DM3	P55	64°33.723	110°26.841	~57 k	?	
21	Slipper Lake	-	64°37.000	110°50.000	190	14.0	7
22	Lake TK-2	-	66°20.900	104°56.750	2.8	7.5?	9

3. Materials and methods

3.1 Core collection

The coordinates of each lake, as well as basic lake parameters (surface area, core depth, inlets/outlets) for each site and the relevant references are summarized in Table 1. Data from eight previously published paleolimnological studies located in the area have been incorporated into the dataset to improve perspective on regional trends. The sediment cores from these studies were collected using a modified Livingstone corer (Wright et al., 1984), except the Slipper Lake core, which was collected using a modified KB gravity corer and a mini-Glew gravity corer (Glew, 1991; Glew et al., 2001).

Sampling sites were distributed across the boreal forest, forest-tundra, and tundra ecozones. Coring typically took place during the winter when equipment could be set up directly on the TCWR, thus limiting sites to lakes with winter road access. Water depth was measured in the field using a fish finder (echo sounder). For five lakes, detailed bathymetric profiles were provided by EBA Engineering Consultants Ltd. These profiles were collected during a through-ice bathymetry survey using ground-penetrating radar (GPR) towed behind a vehicle.

The 14 new cores were collected using 1.5-2.0 m long, 10-20 cm wide, freeze corers (hollow, metal-faced corers filled with dry ice; Galloway et al., 2010; Macumber et al., 2012). Freeze corers are ideal for the extraction of cores in unconsolidated and water-saturated sediment as they capture sediment by *in situ* freezing (Lotter et al., 1997; Glew et al., 2001; Kulbe and Niederreiter, 2003; Blass et al., 2007). In 2009, Tibbitt and Waite lakes were cored using a single-sided freeze corer (Galloway et al., 2010). The uppermost sediments from the Waite Lake coring site were unfortunately not recovered as the freeze corer over-penetrated the sediment-water interface during sampling. A Glew core (Glew, 1991) was collected in 2011 in an attempt to capture the missing sediment-water interface. In 2010 a custom designed double-sided freeze corer was deployed in addition to the single-faced corer, to increase the volume of sediment obtained at a given site (Macumber et al., 2012). Freeze cores were sliced at millimeter-scale resolution using a custom designed sledge microtome (Macumber et al., 2011). The highest sampling resolution previously reported previously reported for the region had been half-centimeter intervals from the Slipper Lake (Rühland and Smol, 2005) and Lake S41 cores (MacDonald et al., 2009).

3.2 Chronology

With the exception of one twig date in each of the Waite Lake and Queen's Lake cores, and four twig dates in the Lake TK-2 core, radiocarbon dates were obtained from bulk sediment samples, as macrofossils were not encountered during screening. Samples were pretreated with a standard acid wash to remove carbonate material, and unless otherwise stated in Section 4, analyses were performed using the accelerator mass spectrometer (AMS) at the ^{14}Chrono Dating Laboratory at Queen's University Belfast. Radiocarbon dates reported from previous work employed both conventional and AMS techniques. All radiocarbon ages in were calibrated using either Clam (Blaauw, 2010) or Calib software version 6.1.0 (Stuiver and Reimer, 1993); both programs used the IntCal09 calibration curve (Reimer et al., 2009). Radiocarbon ages younger than AD1950 were calibrated in CALIBomb (Reimer et al., 2004) with the NH_zone1.14c dataset (Hua and Barbetti, 2004). For the Holocene dates used in this study, the differences between the IntCal09 and IntCal13 (Reimer et al., 2013) calibration curves, as well as between the 2004 and 2013 (Hua et al., 2013) postbomb curves are negligible (for our purposes), but we would recommend using the newest curves in future studies. Dates from a ^{210}Pb profile from Slipper Lake were also incorporated into the dataset (Rühland and Smol, 2005). The Pocket Lake core contains a visible tephra layer, which was geochemically confirmed to as part of the White River Ash deposit (Crann et al., in prep). This horizon will be used in future studies to further constrain the age-depth model. The core from nearby Bridge Lake was analyzed for both visible and cryptotephra, but was unsuccessful in finding evidence for deposition of the White River Ash.

3.3 Classical age-depth modeling with Clam

Smooth spline age-depth models were constructed for sediment cores obtained from the TCWR and previously published studies using the 'classical' age-depth modeling software Clam (Blaauw, 2010, R statistical software package) and the IntCal09 calibration curve (Reimer et al., 2009). The year the core was collected was added as the age of the sediment-water interface with an error of ±5 years. The smoothing parameter, which controls how sharply the model will curve toward radiocarbon dates, was increased from the default value of 0.3 to 0.7 for the Danny's Lake model and to 0.5 for the Waite Lake model in order to increase smoothness of the models through the large number of radiocarbon dates. Otherwise, Clam's default smoothing parameter of 0.3 was employed. The core from Lake P39 had only three non-outlying (see next paragraph) dated horizons so the model was constructed using a linear regression. For Slipper Lake, the three uppermost non-interpolated ^{210}Pb dates were included in the model.

For cores with low dating resolution (typically less than five radiocarbon dates or less than one radiocarbon date per thousand years), suspected outliers were removed on an ad hoc basis when a radiocarbon date either created a clear age reversal in the model or an anomalous shift in accumulation rate that could not be supported by sedimentological evidence (visible colour change from grey clay to dark green-brown sediment). We also took into account the regional trends in sediment accumulation rate to aid with outlier identification. For example, many age-depth models show a pronounced decrease in accumulation rate after about 6,000 or 5,000 cal BP.

The Danny's Lake core is 115 cm long and has a few age reversals among the 25-radiocarbon dates. A Bayesian outlier analysis was performed using the general outlier model (Bronk Ramsey, 2009a) on a sequence in OxCal version 4.1 (Bronk Ramsey, 2009b). This model assumes that the dates are ordered chronologically (dates further down having older ages) and that outliers are in the calendar time dimension and distributed according to a Student-*t* distribution with 5 degrees of freedom (Christen, 1994; Bronk Ramsey, 2009a). Each radiocarbon date was assigned a 5% prior probability of being an outlier. The first outlier analysis identified all three dates at the bottom of the core as outliers so we increased the prior probability of UBA-16439 to 10%, as this date created the largest age reversal. A subsequent outlier analysis still identified the two bottommost dates as outliers and it was unclear as to which was more likely to be an outlier. We then examined the age-depth models from other lakes and from previous studies for clues to resolve this problem. As many of the other models support a higher accumulation rate prior to about 6000 cal BP we used this information to increase the prior probability of UBA-17932 being an outlier to 10%. In Section 5, we show how the Bayesian software Bacon produces age models without performing a separate, formal outlier analysis.

3.4 Estimation of deposition time (DT)

An estimate of DT (yr/cm, inverse of accumulation rate) is required as *a priori* information to generate age-depth models using the Bayesian software Bacon (Blaauw and Christen, 2011). This estimate can be based on prior knowledge obtained from previously built age-depth models from lakes in the region (Goring et al., 2012). Here we generate a summary for the region using the age-depth models constructed in Clam to calculate the DT at 100-year intervals for each model. It should be noted that the intention of the summary is to produce initial estimates of DT for age-depth modeling and the data has not undergone a rigorous statistical analysis. The DT between the uppermost non-outlying date and the date used to model the surface age were not included in graphing the accumulation rates because: (1) there is potential uncertainty with the assumption that the age of the sediment-water interface is indeed the year that the core was collected; and (2) high water content in the uppermost sediments can lead to an anomalously rapid DT. Webb and Webb (1988) assumed 50% compaction in sediments below the uppermost 5 to 10 cm of the sediment column based on dry weight/wet weight ratios, yet they found that the accumulation rates were still higher during the historic period. Because dry weight/wet weight data has not been collected for this study, the effect of compaction and dewatering is not taken into account in graphing the DT. P39 and Slipper lake cores lacked sufficient chronological control and were omitted from the DT compilation dataset.

4. Results

The radiocarbon dates from all sites included in this study, along with the results from the outlier analysis, are summarized in Table 2. The age-depth models constructed using

Clam have been grouped into three categories (Fig. 3). The first category, rapid sediment accumulation rate lakes, contains five age-depth models that stand out from the rest. Deposition times in this category do not tend to exceed 50 yr/cm, and the average DT (rounded to the nearest 10 = 20 yr/cm) is on par with lakes in the Great Lakes region (Goring et al., 2012). The other two categories, moderate and slow sediment accumulation rate lakes, are not so easily distinguished. Accumulation rates for age-depth models in both categories fluctuate, but moderate sediment-rate accumulating sites tend to fluctuate at more subtle amplitudes (DT of around 50 yr/cm) and do not often exceed a DT of 100 yr/cm. Sites with overall slow accumulation rates fluctuate with DT amplitudes up to 150 yr/cm, and tend to be in excess of 100 yr/cm.

Detailed results for each category are given in Sections 4.1-4.3. Because these results are intended to yield insight into the spatial and temporal variability in accumulation rates in high latitude lakes and to give estimates of DT that can be used as prior information in Bayesian age-depth modeling with Bacon, DTs are rounded to the nearest 10 yr/cm.

Table 2. Radiocarbon ages from all sites, calibrated with the IntCal09 calibration curve (Reimer et al., 2009) using either Calib software version 6.1.0 (Stuiver and Reimer, 1993) or Clam (Blaauw, 2010). The radiocarbon ages younger than AD1950 (italics) were calibrated in CALIBomb (Reimer et al., 2004) with the NH_zone 1.14c dataset (Hua and Barbetti, 2004). The year the core was collected is included as it was used to model the age of the sediment-water interface in the Clam age-depth models. Dates identified as outliers are shown in bold and radiocarbon dates younger than AD1950 are in italics.

Lake information	Lab ID	Method	Depth (cm)	^{14}C age (BP) ± 1σ	Material dated	Cal BP ± 2σ
Pocket Lake	UBA-20676	AMS	10–10.5	362 ± 27	Bulk	310–414
collected in 2012	UBA-22350	AMS	20–20.5	731 ± 31	Bulk	653–727
Freeze core (2F_F1)	UBA-20679	AMS	52–52.5	1335 ± 25	Bulk	1286–1383
	UBA-22351	AMS	57–57.5	1394 ± 30	Bulk	1279–1348
	UBA-22352	AMS	70–70.5	1725 ± 31	Bulk	1556–1708
	UBA-20677	AMS	90–90.5	2501 ± 30	Bulk	2443–2559
	UBA-22353	**AMS**	**110–110.5**	**1516 ± 35**	**Bulk**	**1333–1518**
	UBA-20678	AMS	128.5–129	2966 ± 26	Bulk	2916–3016
Tibbitt Lake (P0)	UBA-17353	AMS	20–21	67 ± 22	Bulk	(-4)–255
collected in 2009	UBA-17354	AMS	40–41	1409 ± 20	Bulk	1292–1343
Freeze core (1FR)	UBA-17355	AMS	80–81	2046 ± 26	Bulk	1930–2111
	Beta-257687	AMS	138–138.5	2390 ± 40	Bulk	2338–2696
Waite Lake (P14-2)	*UBA-18968*	*AMS*	*17–17.5*	*1.0562 ± 0.003*	*Bulk*	*AD1956–1957*
collected in 2010	UBA-18969	AMS	27–27.5	309 ± 22	Bulk	304–455
Glew core	UBA-18970	AMS	37–37.5	556 ± 26	Bulk	522–637
Waite Lake (P14-2)	UBA-18474	AMS	0	1084 ± 41	Bulk	927–1066
collected in 2009	UBA-16433	AMS	16.9	995 ± 24	Bulk	800–961
Freeze core (1FR)	UBA-16434	AMS	29.1	1129 ± 22	Bulk	965–1076
	UBA-16435	AMS	43.2	1455 ± 23	Bulk	1304–1384
	UBA-16436	AMS	57.8	1519 ± 22	Bulk	1345–1514
	Beta-257686	AMS	66.3	1520 ± 40	Bulk	1333–1520
	UBA-15638	AMS	109.7	2107 ± 29	Twig	1997–2149
	Beta-257688	AMS	154	2580 ± 40	Bulk	2498–2769
	Beta-257689	AMS	185	2920 ± 40	Bulk	2955–3210
	Beta-257690	AMS	205.1	3460 ± 40	Bulk	3633–3838
Bridge Lake (P26-1)	UBA-18964	AMS	6.5–7	28 ± 23	Bulk	(-4)–244
collected in 2010	UBA-22873	AMS	12.5–13	694 ± 26	Bulk	565–683
Freeze core (2F_F2)	UBA-18965	AMS	18–18.5	1883 ± 23	Bulk	1736–1882
	UBA-22874	AMS	24.5–25	3782 ± 30	Bulk	4082–4246
	UBA-22875	AMS	30.5–31	4730 ± 30	Bulk	5326–5583
	UBA-22876	AMS	34.5–35	5487 ± 31	Bulk	6210–6322
	UBA-18966	AMS	41.5–42	5816 ± 42	Bulk	6501–6727
	UBA-22877	AMS	50.5–51	6184 ± 32	Bulk	6977–7172
	UBA-18967	AMS	59.5–60	6762 ± 32	Bulk	7576–7667
	UBA-22878	AMS	64–64.5	7025 ± 34	Bulk	7788–7941
Danny's Lake (P34-2)	UBA-17359	AMS	5.7	693 ± 21	Bulk	567–679
collected in 2010	UBA-17360	AMS	10.2	855 ± 23	Bulk	695–795
Freeze core (2F_F2)	UBA-16543	AMS	15–15.5	1329 ± 23	Bulk	1184–1299
	UBA-17361	AMS	21.9	1617 ± 25	Bulk	1416–1556
	UBA-17431	AMS	27.8	1659 ± 21	Bulk	1521–1615
	UBA-16544	AMS	32.6	1916 ± 25	Bulk	1818–1904
	UBA-20377	AMS	33.5	2071 ± 24	Bulk	1987–2120
	UBA-20378	AMS	34.2	2159 ± 24	Bulk	2061–2305
	UBA-17929	AMS	34.5	2257 ± 26	Bulk	2158–2343

Lake information	Lab ID	Method	Depth (cm)	^{14}C age (BP) ± 1σ	Material dated	Cal BP ± 2σ
	UBA-20376	**AMS**	**35.3**	**2073 ± 28**	**Bulk**	**1986–2124**
	UBA-20375	AMS	36.8	2248 ± 25	Bulk	2158–2339
	UBA-17432	**AMS**	**37.6**	**2659 ± 32**	**Bulk**	**2742–2884**
	UBA-20374	AMS	38.4	2392 ± 25	Bulk	2345–2488
	UBA-20373	AMS	39.3	2448 ± 33	Bulk	2358–2702
	UBA-17930	AMS	40.4	2549 ± 26	Bulk	2503–2748
	UBA-20371	AMS	41.4	2554 ± 28	Bulk	2503–2750
	UBA-20372	**AMS**	**43.3**	**4863 ± 29**	**Bulk**	**5583–5652**
	UBA-16545	AMS	45–45.5	2912 ± 24	Bulk	2964–3157
	UBA-16546	AMS	56.9	3604 ± 25	Bulk	3845–3975
	UBA-16547	AMS	70.1	5039 ± 51	Bulk	5661–5903
	UBA-16548	AMS	85–85.5	5834 ± 29	Bulk	6560–6733
	UBA-17931	AMS	89.5	6231 ± 34	Bulk	7016–7253
	UBA-16439	**AMS**	**95.5**	**8112 ± 32**	**Bulk**	**8997–9125**
	UBA-17932	**AMS**	**99.1**	**7623 ± 38**	**Bulk**	**8370–8518**
	UBA-16440	AMS	113.6	7450 ± 30	Bulk	8191–8346
P39-1A	**UBA-17344**	**AMS**	**10–10.5**	**3597 ± 26**	**Bulk**	**3840–3973**
collected in 2010	UBA-17345	AMS	19–19.5	3701 ± 24	Bulk	3974–4144
Freeze core (2F_F1)	UBA-17346	AMS	29–29.5	5385 ± 35	Bulk	6018–6284
Toronto Lake	Beta-49705	conv.	35–50	1760 ± 90	Bulk	1421–1887
collected in 1987	Beta-53129	conv.	80–85	4200 ± 80	Bulk	4450–4956
Livingstone core	Beta-53130	conv.	125–130	5460 ± 90	Bulk	6001–6408
	Beta-49708	conv.	155–160	7040 ± 120	Bulk	7657–8155
Portage Lake N. (P47-1)	UBA-17933	AMS	6.5–7	772 ± 24	Bulk	673–729
collected in 2010	UBA-17159	AMS	13.5–14	4218 ± 38	Bulk	4626–4854
Freeze core (2F_F2)	**UBA-17160**	**AMS**	**41–41.5**	**4885 ± 37**	**Bulk**	**5584–5710**
	UBA-17161	AMS	63–63.5	5333 ± 35	Bulk	5997–6264
	UBA-17162	AMS	86.5–87	5878 ± 34	Bulk	6637–6783
Waterloo Lake	**TO-3312**	**AMS**	**28–31**	**4030 ± 50**	**Bulk**	**4413–4801**
collected in 1987?	TO-3311	AMS	54–56	4640 ± 50	Bulk	5090–5577
Livingstone core	TO-3310	AMS	61–63.5	5300 ± 50	Bulk	5939–6257
	TO-3313	AMS	75–77	7640 ± 100	Moss	8206–8627
Lake S41	UCI-25833	AMS	7–7.5	375 ± 15	Bulk	331–499
collected in 2005	UCI-25841	AMS	13.4–14	1045 ± 20	Bulk	926–1042
Livingstone core	UCI-25836	AMS	23–23.5	1985 ± 15	Bulk	1892–1987
	UCI-25835	AMS	32.5–33	2765 ± 20	Bulk	2789–2924
Queen's Lake	WAT-1770	conv.	15–20	3820 ± 60	Bulk	4010–4414
collected in 1987?	WAT-1771	conv.	45–50	5600 ± 60	Bulk	6291–6493
Livingstone core	WAT-1772	conv.	60–65	6150 ± 60	Bulk	6888–7241
	WAT-1773	conv.	100–105	7150 ± 70	Bulk	7842–8159
	TO-827	AMS	105	7470 ± 80	Twig	8060–8417
McMaster Lake	**TO-766**	**AMS**	**10–12**	**3690 ± 50**	**Bulk**	**3888–4212**
collected in 1987?	TO-158	AMS	20–22	3680 ± 60	Bulk	3849–4220
Livingstone core	TO-767	AMS	30–32	5120 ± 60	Bulk	5730–5990

Lake information	Lab ID	Method	Depth (cm)	^{14}C age (BP) ± 1σ	Material dated	Cal BP ± 2σ
	TO-156	AMS	40–42	5360 ± 60	Bulk	5998–6279
	TO-154	AMS	60–62	6180 ± 60	Bulk	6943–7248
UCLA Lake	TO-8840	AMS	20–21	2370 ± 50	Bulk	2319–2698
Livingstone core	TO-8842	AMS	35–35.5	4130 ± 50	Bulk	4527–4824
	TO-8844	AMS	45–45.5	5680 ± 70	Bulk	6317–6635
	TO-8845	AMS	50–50.5	6280 ± 70	Bulk	7002–7413
	TO-8846	AMS	55.5–56	7040 ± 70	Bulk	7707–7978
	TO-8847	AMS	64.5–65	7680 ± 70	Bulk	8382–8590
	TO-8848	AMS	69.5–70	7960 ± 80	Bulk	8605–9006
Carleton Lake (P49-1A)	**UBA-19464**	**AMS**	**9.5–10**	**2794 ± 34**	**Bulk**	**2791–2970**
collected in 2010	**UBA-20002**	**AMS**	**15–15.5**	**2778 ± 26**	**Bulk**	**2793–2950**
Freeze core (2F_F2)	UBA-20003	AMS	25–25.5	2716 ± 33	Bulk	2757–2868
	UBA-19465	AMS	32.5–33	3124 ± 41	Bulk	3254–3443
	UBA-19466	AMS	40.5–41	3616 ± 37	Bulk	3835–4075
	UBA-19467	AMS	66.5–67	4927 ± 38	Bulk	5594–5728
Carleton Lake (P49-1B)	*UBA-18472*	*AMS*	*0–0.5*	*1.0264 ± 0.0035*	*Bulk*	*AD1955-1957*
collected in 2010	UBA-17934	AMS	10–10.5	1046 ± 24	Bulk	925–983
Freeze core (1F)	UBA-17347	AMS	19.5–20	1925 ± 25	Bulk	1822–1926
	UBA-17935	AMS	40–40.5	2762 ± 35	Bulk	2780–2946
	UBA-17348	AMS	64.5–65	3675 ± 24	Bulk	3926–4087
	UBA-17936	AMS	80–80.5	4635 ± 32	Bulk	5304–5465
	UBA-17349	AMS	100–100.5	5663 ± 26	Bulk	6399–6497
Carleton Lake (R12-P49)	UBA-20612	AMS	10.0	702 ± 39	Bulk	560–699
collected in 2012	UBA-20613	AMS	36.2	1337 ± 31	Bulk	1181–1305
Freeze core (2F_F2)	UBA-20614	AMS	55.3	1302 ± 46	Bulk	1132–1304
	UBA-20615	AMS	81.5	2132 ± 31	Bulk	2002–2299
	UBA-20616	AMS	117.8	2944 ± 32	Bulk	2989–3216
Horseshoe Lake (P52-1)	UBA-17350	AMS	9–9.5	178 ± 25	Bulk	(-2)–291
collected in 2010	UBA-17163	AMS	18–18.5	1148 ± 42	Bulk	967–1172
Freeze core (2F_F2)	UBA-17351	AMS	28–28.5	2763 ± 22	Bulk	2785–2924
	UBA-17352	AMS	38–38.5	3343 ± 23	Bulk	3481–3639
	UBA-19973	AMS	43.2	3776 ± 36	Bulk	3992–4281
	UBA-17938	AMS	46–46.5	4885 ± 27	Bulk	5589–5653
	UBA-17165	AMS	55–55.5	5916 ± 58	Bulk	6628–6897
	UBA-17937	AMS	68–68.5	6723 ± 29	Bulk	7516–7656
	UBA-17166	AMS	80–80.5	7488 ± 40	Bulk	8199–8383
	UBA-17167	AMS	106–106.5	8011 ± 43	Bulk	8718–9014
Lac de Gras (LDG)	UBA-17939	AMS	12–12.5	1123 ± 23	Bulk	965–1067
collected in 2010	**UBA-17356**	**AMS**	**19–19.5**	**3299 ± 38**	**Bulk**	**3447–3631**
Freeze core (2F_F2)	UBA-17357	AMS	32–32.5	1607 ± 29	Bulk	1412–1551
	UBA-17358	AMS	46–46.5	2144 ± 35	Bulk	2003–2305
Lac de Gras (LDG_DM1)	D-AMS 001550	AMS	10–11	784 ± 23	Bulk	677–732
collected in 2012	D-AMS 001551	AMS	20–21	1797 ± 23	Bulk	1629–1817
Freeze core	D-AMS 001552	AMS	30–31	2636 ± 25	Bulk	2738–2781
	D-AMS 001553	AMS	40–41	3590 ± 27	Bulk	3836–3972
Lac de Gras (LDG_DM3)	D-AMS 001554	AMS	10–11	1719 ± 23	Bulk	1561–1696

Lake information	Lab ID	Method	Depth (cm)	^{14}C age (BP) ± 1σ	Material dated	Cal BP ± 2σ
collected in 2012	D-AMS 001555	AMS	20–21	3459 ± 26	Bulk	3642–3828
Freeze core	D-AMS 001556	AMS	30–31	5509 ± 28	Bulk	6223–6396
	D-AMS 001557	AMS	40–41	7827 ± 31	Bulk	8543–8696
Slipper Lake	^{210}PB Age	n/a	0	n/a	Bulk	(-49)–(-45)
collected in 1997	^{210}PB Age	n/a	2	n/a	Bulk	6–20
KB gravity and mini-Glew	^{210}PB Age	n/a	3	n/a	Bulk	34–94
	TO-9671	AMS	21.5–22.5	3270 ± 80	Bulk	3359–3688
	TO-9672	AMS	43.5–44.5	4760 ± 70	Bulk	5321–5603
Lake TK-2	Beta-167871	AMS	32–34	2480 ± 40	Bulk	2365–2718
collected in 1996	Beta-167872	AMS	60–62	3870 ± 40	Bulk	4157–4416
Livingstone core	Beta-167873	AMS	96–98	5670 ± 40	Bulk	6322–6558
	TO-7871	AMS	132	7370 ± 80	Twigs	8020–8349
	TO-7870	AMS	137	7190 ± 80	Twigs	7860–8178
	TO-7869	AMS	142	7740 ± 90	Twigs	8375–8772
	TO-7868	AMS	174	7780 ± 70	Twigs	8412–8761

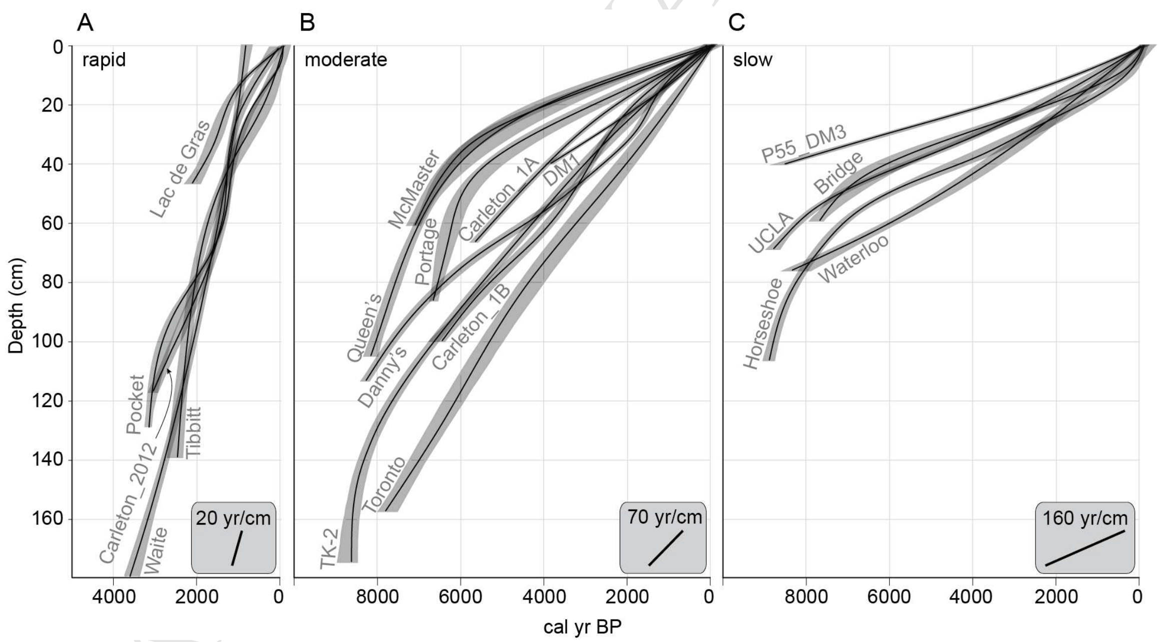


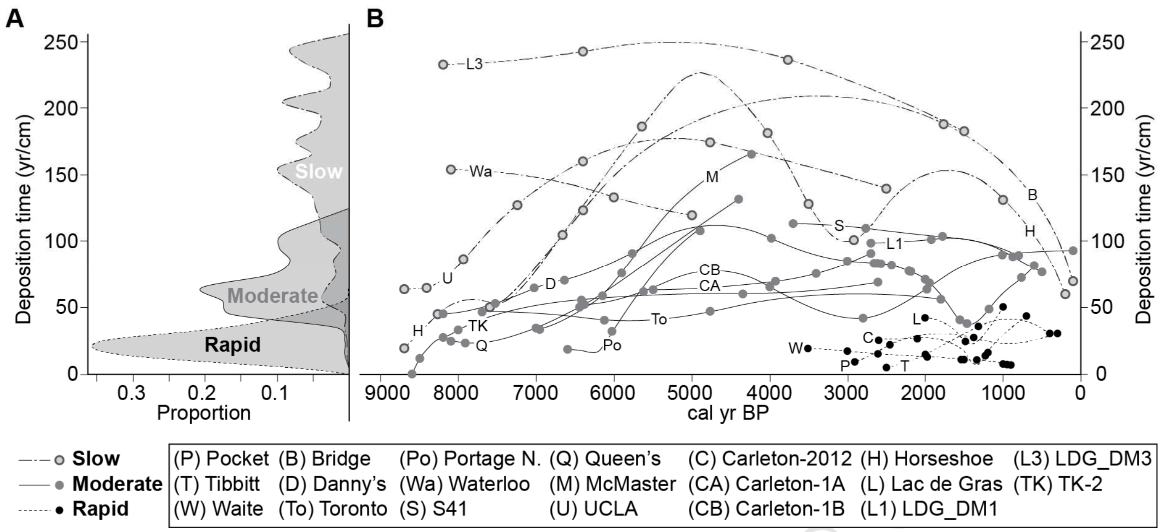
Figure 3. Age-depth models constructed using a smooth spline regression in Clam, grouped into (a) rapid, (b) moderate, and (c) slowly accumulating sites. The 95% confidence interval is light grey. The scale for Waite Lake is to be used as a relative measure only as the freeze corer over-penetrated the sediment-water interface. ***Two***

column image.

4.1 Sites with rapid accumulation rates (DT<50 yr/cm)

Rapid sediment accumulation rates are defined as having the DT for the majority of the core of less than 50 yr/cm. Five distinctive age depth models belonging to this category were produced for cores from Lac de Gras, Pocket, Tibbitt, Waite and Carleton lakes. Due to rapid sediment accumulation rates, these core records tend to span ~3,500 years at most. The cores in this category yielded internally consistent age-depth models, with the exception of one radiocarbon date that is a clear outlier in the Lac de Gras core (Table 2). The average DT (rounded to the nearest 10 = 20 yr/cm) is on par with lakes in the Great Lakes region (Goring et al., 2012).

Deposition times in these lakes vary between c. 10 and 50 yr/cm, with a mean of c. 20±10 yr/cm (1σ) and a unimodal distribution, based on 107 DT measurements at 100-year intervals (Fig. 4a). The accumulation pattern for Tibbitt Lake is different from the others as it increases steadily from a DT of c. 5 yr/cm at c. 2,500 cal BP to c. 50 yr/cm at the top, but the very rapid deposition near the base overlaps the Hallstatt Plateau (c. 2,700-2,300 cal BP; Blockley et al., 2007), which is a flat section in the IntCal09 calibration curve and therefore may be an artifact of calibration.



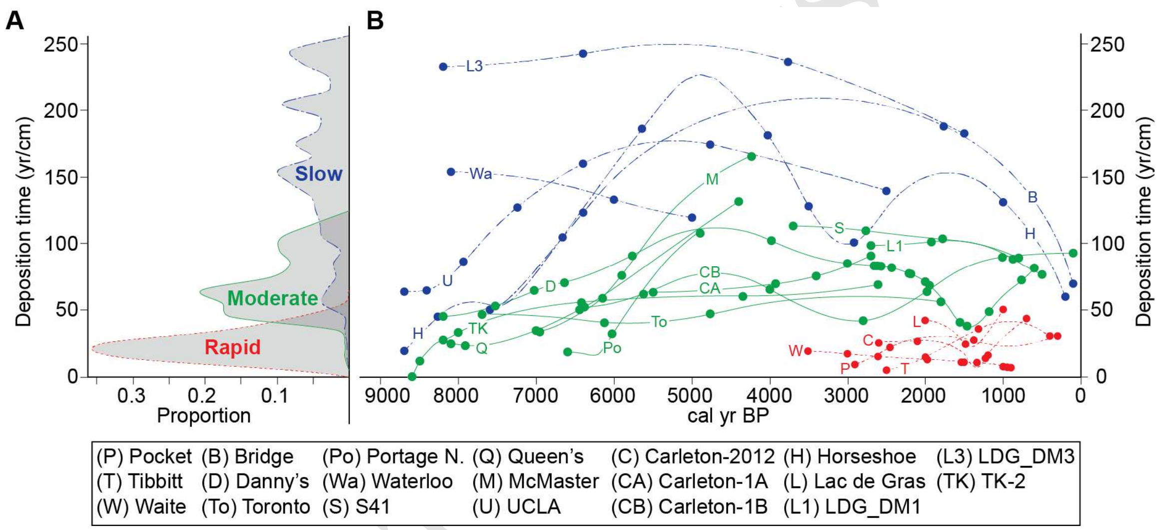


Figure 4. (a) Histogram of DT from rapid, moderate, and slowly accumulating lake site categories, sampled at 100-year intervals from the age-depth models constructed in clam. (b) Accumulation rate profiles for each site showing fluctuation of DT over time and the variability between lake sites. The dots correspond to radiocarbon dates. ***Two column image. Colour version for web only. Black and white for print.***

4.2 Sites with moderate accumulation rates (DT 50 – 100 yr/cm)

The distinguishing characteristics of sites within this category include fluctuations in sediment accumulation rate at relatively subtle amplitudes (DT around 50 yr/cm) and DTs that do not generally exceed 100 yr/cm. The sites in this category are Danny's, Toronto, S41, Carleton-1A, Carleton-1B, LDG_DM1, and TK-2. Three of the cores in the moderate accumulation rate category are characterized by a sedimentary record that extends just beyond 8,000 cal BP. The other four cores in this category have records that extend back between c. 6,000 and c. 4,000 cal BP (Fig. 3).

The outlier analysis performed in OxCal identified five outliers in the Danny's Lake core, which were omitted from the smooth spline age-depth model constructed with Clam. Four of the five outliers were older than the model and the fifth was only slightly younger. For Carleton-1A, the upper three radiocarbon dates, at 9.5, 15 and 25 cm, all overlapped within the age range of c. 2,900 to c. 2,700 cal BP. For this reason the uppermost two dates were omitted from the age-depth model constructed in Clam. The overlap may have been the result of sediment mixing. The core from Lake TK-2 has an age reversal within the bottommost four dates. Because these dates were obtained from twigs (allochthonous origin and lack of heartwood), the reversal is likely due to delayed deposition of older organic material. Clam was able to accept the reversal as the date was within error of the others.

The lakes in this category accumulated with DTs between 50 and 100 yr/cm with a mean of c. 70±20 yr/cm (1σ) based on 343 DT measurements at 100-year intervals (Fig. 4). The histogram shown in figure 4a has a bimodal distribution with a primary mode around 60 yr/cm and a secondary mode around 100 yr/cm. Most of the lakes in this category exhibit fluctuations in accumulation rate over time.

4.3 Sites with slow accumulation rates (DT 100 – 250 yr/cm)

Accumulation rates fluctuate in age-depth models for lakes with moderate and slow rates, producing some overlapping characteristics. Sites with overall slow accumulation rates fluctuate with DT amplitudes up to 150 yr/cm that tend to exceed 100 yr/cm. The sites in the slow accumulation category are Bridge, Waterloo, UCLA, Horseshoe, and LDG_DM3. All five sites in this category extend back to at least c. 8000 cal BP or beyond. The age-models are internally consistent, with only one outlier identified from the Waterloo Lake age-depth model, where the age is older than the model (Fig. 3).

The histogram of DTs (Fig. 4a) is multi-modal, reflecting high variability of sediment accumulation rates for cores within this category. The main pattern occurs between about 8,000 and 5,000 cal BP, where Bridge, UCLA, and Horseshoe lakes are all characterized by a slowing of accumulation rate (increased DT). This rate change is coincident with changes in sedimentation from minerogenic-rich at the base of the core to organic-rich above (Macumber et al., 2012). For Bridge Lake, the accumulation rate slows steadily from a DT of ~50 yr/cm at 7,600 cal BP to c. 200 yr/cm at 4,000 cal BP. This accumulation rate change is linked to a distinct color change at ~4,200 cal BP, from light grey below (Munsell code 5y 3/2) to brown (Munsell code 10yr 2/1) above (Macumber et al., 2012). The DT is constant around 200 yr/cm until c. 2,500 cal BP and steadily increases to c. 160 yr/cm by 100 cal BP.

The accumulation rate profile for Horseshoe Lake displayed the highest variability of any studied profile. Modeled DT is high (c. 20 yr/cm) between 8,700 – 7,500 cal BP and then decrease to c. 225 yr/cm by 5,000 cal BP. The transition around 7,500 cal BP is associated with a shift from minerogenic-rich sediment at the core bottom to organic-rich sediment above. Stratigraphically above ~7,500 cal BP, the accumulation rate gradually increases; DT reaching c. 100 yr/cm by 3,000 cal BP, then decreasing to 150 yr/cm by 2,000 cal BP, and finally increases again to 60 yr/cm at the core top.

4.4 Sites with poor chronological constraint

Some sites do not easily fit into the three recognized categories, either due to lack of dating resolution (P39 and Slipper lakes) or because the accumulation profile is characterized by a dramatic shift in accumulation rate (Portage North, Queens, and McMaster; Fig. 4). P39, Portage North, and McMaster lakes all had one outlier – identified on an ad hoc basis – that fell between 5,000 and 4,000 cal BP (Fig. 3). For P39, the radiocarbon date at the top of the core was determined to be an outlier. Because the core was collected in only 110 cm water depth, upper lake sediments may have been disturbed due to freezing of ice to the sediment-water interface. No further research was undertaken on this core and accumulation rates were not estimated. Slipper Lake lacked sufficient chronological control (based on two ^{14}C dates and a ^{210}Pb profile) and was also omitted from calculations of accumulation rate.

5. Bayesian age-depth modeling with Bacon

The temporal and spatial variations identified above are used as prior information for three Bayesian age-depth models to demonstrate the power and robustness of this approach. The age modeling procedure for Bacon is similar to that outlined in Blaauw and Christen (2005), but more numerous and shorter sections are used to generate a more flexible chronology (Blaauw and Christen, 2011, 2013). Radiocarbon age distributions are modeled using the Student-*t* distribution, which produces calibrated distributions with longer tails than obtained using the Normal model (Christen and Pérez, 2009). Due to the longer tails on radiocarbon dates and a prior assumption of unidirectional sediment accumulation, in most cases excluding outliers is not necessary when using Bayesian age modeling. The cores from Waite, Danny's and Horseshoe lakes all have at least ten non-outlying radiocarbon dates and were deemed suitable for Bayesian modeling with Bacon.

As this is a demonstration of the practical application of Bacon (version 2.2; Blaauw and Christen, 2011, 2013), text in italics denotes the actual code typed in R (statistical computing and graphics software). Bacon version 2.2 uses the currently most recent calibration curve, IntCal13 (Reimer et al., 2013), and has an added feature of plotting accumulation rate data with the *plot.accrate.depth()* and *plot.accrate.age()* functions. In Section 6.3 we show a practical example of the accumulation rate plotting function.

Memory or coherence in accumulation rates along the core is a parameter that is defined based on the degree to which the accumulation rate at each interval depends on the previous interval. For example, the memory for modeling accumulation in peat sediments should be higher than for lacustrine sediments because accumulation of peat in peat bogs is less dynamic over time than the accumulation of sediments in a lake. Here we used the memory properties from the lake example in Blaauw and Christen (2011;

mem.strength=20 and *mem.mean=0.1*).

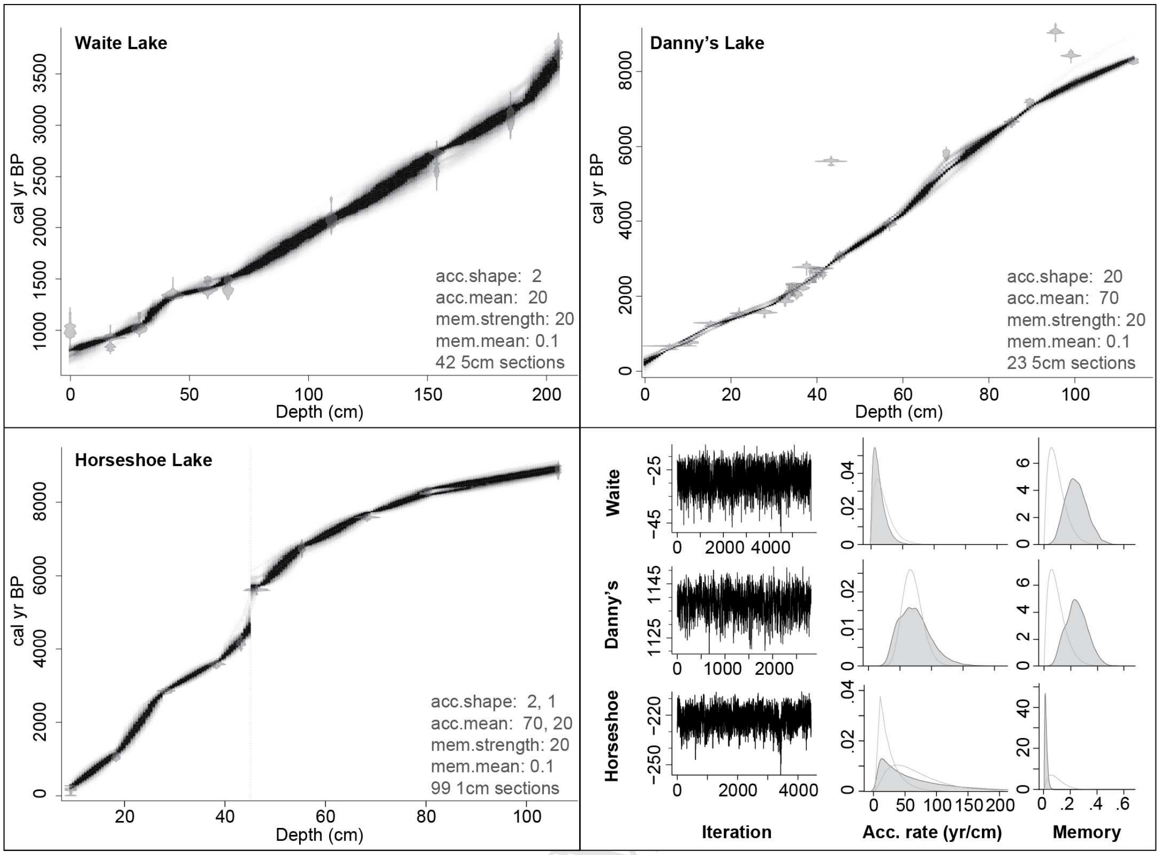
The accumulation rates (*acc.rate=*) for Waite and Danny's lakes were based on the DT estimates from Section 4 (20, and 70, respectively). The accumulation shape (*acc.shape=*) for the Waite Lake cores was set to 2, as suggested by Blaauw and Christen (2011). The accumulation shape controls how much influence the accumulation rate will have on the model. The default value of 2 is fairly low, thus the model has a fair amount of freedom to adapt rates to what the data suggest. For the Danny's lake age model, the accumulation shape was increased to a value of 20 to avoid perturbations in the model caused by known outliers. The step size for Waite Lake was set to 5 cm, which is the default for a lake (Blaauw and Christen, 2011). The Danny's lake age-depth model required more flexibility due to the observed shifts in accumulation rate that are unlikely to be the product of spurious radiocarbon ages (they are sustained changes coherent with known climate events), so the step sizes was lowered to 2 cm.

Horseshoe Lake required the addition of a hiatus (*hiatus.depths=45, hiatus.mean=10*) in order to produce a realistic, stable model. Because the hiatus accounts for the slowest accumulation rates for the age-depth model (>150 yr/cm between c. 6000 – 4000 cal BP), the portion of the model below the hiatus accumulates at moderate rate (*acc.mean=70, acc.shape=2*) and the portion of the model above the hiatus rate (*acc.mean=20, acc.shape=1*). The physical nature of this hiatus is explored in Section 6.2.

The resulting age-depth models are shown in Figure 5, along with plots that describe: (1)

the stability of the model (log objective vs. iteration); (2) the prior (entered by the user) and posterior (resulting) accumulation rate, and; (3) the prior and posterior memory properties. The Bayesian model from Waite Lake shows stable accumulation rates over time, most likely because this core covers the latest Holocene, during which time climate was relatively consistent (Karst-Riddoch *et al.* 2005; Rühland & Smol 2005; Miller *et al.* 2010). Danny's Lake also yielded a stable model, with the consideration that the weight on accumulation rate was set very high. The Horseshoe Lake model ran fairly stable, with a minor perturbation.

The prior and posterior probability diagrams for accumulation rate were fairly similar for Waite and Danny's lakes, and for Horseshoe Lake, the posterior distribution for accumulation rate is a combination of the two assigned rates. Waite and Danny's lakes models both showed memory of around 0.25, which is higher than was assigned (0.1). The Horseshoe Lakes model had far less memory than assigned, but this is because memory falls to 0 across a hiatus.

499 
Waite Lake
cal yr BP
Depth (cm)
acc.shape: 2
acc.mean: 20
mem.strength: 20
mem.mean: 0.1
42 5cm sections
Danny's Lake
acc.shape: 20
acc.mean: 70
mem.strength: 20
mem.mean: 0.1
23 5cm sections
Horseshoe Lake
acc.shape: 2, 1
acc.mean: 70, 20
mem.strength: 20
mem.mean: 0.1
99 1cm sections
Waite
Danny's
Horseshoe
Iteration
Acc. rate (yr/cm)
Memory

500

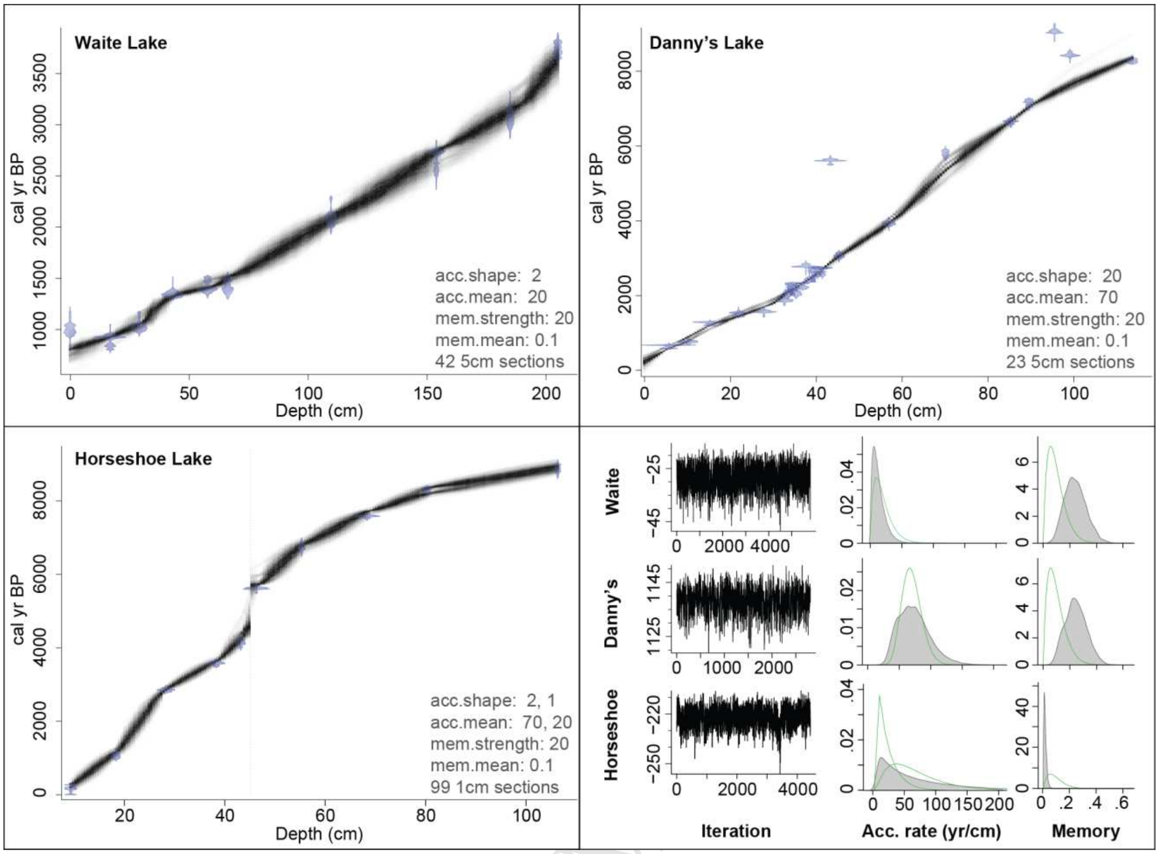


Figure 5. Bayesian age-depth models constructed with the age-depth modeling software Bacon for Waite, Danny's, and Horseshoe lake cores. The grayscale on the model represents the likelihood, where the darker the grey, the more likely the model is of running through that section. The vertical, dashed line on the Horseshoe Lake model denotes a hiatus. The bottom right panel shows three plots for each model: (left) stability of the model; (middle) prior (line) and posterior (filled) distributions of accumulation mean; and (right) prior (line) and posterior (filled) distributions of memory properties.

Double column image. Colour version for web only. Black and white for print.

6. Discussion

6.1 Spatial variability in accumulation rates

The three southernmost boreal forest lakes (Pocket, Tibbitt, and Waite) have the highest accumulation rates, suggesting that the accumulation rate may be can be related to in-lake productivity and in-wash of organic detritus. Sediment accumulation rates at Bridge and Danny's lakes are slower than the more productive boreal lakes; Pocket, Tibbitt, and Waite lakes. The last c. 3,000 years of accumulation at Danny's lake mirrors the pattern of rapidly accumulating sites, but is slower by about a DT of 10-20 yr/cm. This suggests that Danny's lake responded similarly to climate as the southernmost lakes, but may either be slightly less productive due to colder temperatures at its location closer to the polar front, or, judging by the bathymetry (Fig. 6), the coring site itself may receive less sediment than the main basin of the lake, where sediment accumulation is most commonly the greatest (c.f. Lehman, 1975). The accumulation rate at Bridge Lake is extremely slow for the location south of the treeline and again we look at the bathymetry for an explanation (Fig. 6). The coring location for Bridge Lake is nestled into a steep slope, proximal to a deeper sub-basin with a much thicker sediment package. The slope limits the amount of sediment that can accumulate at this site, and similarly to Danny's Lake, much of the material is likely to have drifted toward the deeper basin.

Two of the most rapidly accumulating lakes are located in the tundra (Carleton-2012 and Lac de Gras). Examination of the bathymetry profiles reveals certain basin features that could explain the rapid accumulation rates (Fig. 6). Carleton Lake has a shallow shelf over 500 m long that has a maximum depth of two meters, a slope covering less than 100 m, and a main basin that is about 500 m long at a depth of about 4 m (Fig. 6). The Carleton-2012 freeze core was collected from a site closer to the slope and shelf than the

Carleton-1A and Carleton-1B freeze cores. The shelf, which is situated in two meters water depth, may be susceptible to re-suspension of fine detritus due to surface waves touching bottom generated during windy or stormy conditions. The re-suspended sediments would be transported down into the basin, with the majority being deposited closer to the slope terminus. A similar trend has been noted at two Lakes in Estonia whereby sediments deposited nearshore are thought to have eroded during a regressive period and redeposited elsewhere (Punning et al., 2007a, 2007b; Terasmaa, 2011). Looking at the bathymetry for Lac de Gras, it would be expected that since the coring site is steep, sediment would by-pass and be deposited in the deeper part of the lake. It is unclear, however, if there is a sub-basin at the coring site due to the low resolution of the available bathymetry (Fig. 6). The coring site was characterized by turbid water, steep surrounding landscape, and high minerogenic content of the core sediments (Macumber et al. 2012). Therefore, the rapid accumulation rate at this site is likely due to in-wash of material from the lake catchment. The other two cores from Lac de Gras (DM1 and DM3) are in a completely different sub-basin of the lake. These cores exhibit moderate to very slow accumulation rates, as would be expected on the tundra.

The Horseshoe lake core shows the highest variability in sedimentation rate of all the lakes. The core was extracted from a steep-sided sub-basin of the main lake (Fig. 6). The bathymetric profile is at a lower resolution than Bridge and Danny's lakes so it is not possible to determine exactly how the sediments drape over the bedrock. What is recognizable is that the sub-basin is only connected to the main basin by a shallow (0.5 m deep) passage. The sub-basin therefore would receive little direct sediment input from snowmelt tributaries.

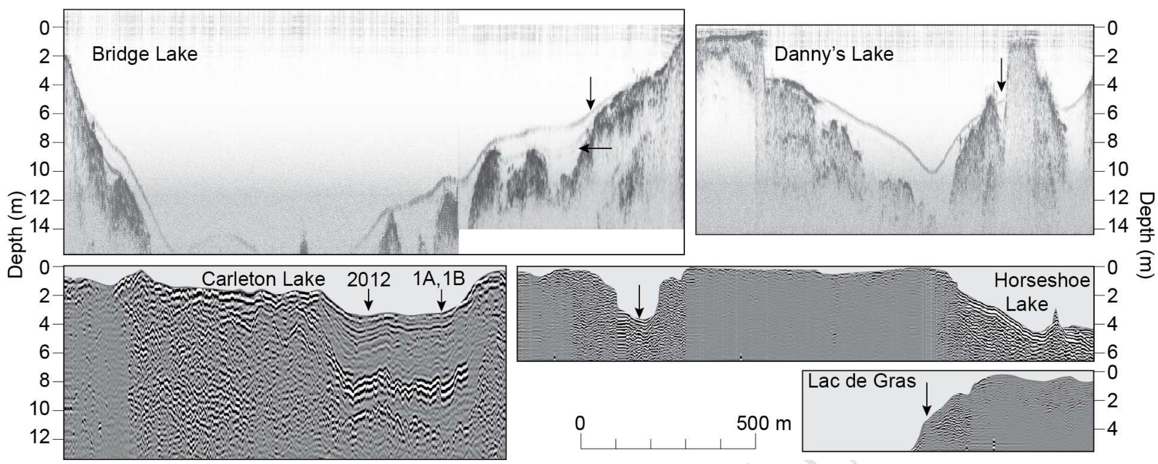


Figure 6. Bathymetry profiles from six lakes with arrows showing coring sites. The horizontal arrow at Bridge Lake is pointing to a weak second reflector that is likely a result of a change in sediment deposition from clay to gyttja, as observed in the core. The coring site for Horseshoe Lake is in a sub-basin that is hydrologically connected to the main basin through a meandering path as is shown in figure 3. ***Double column image.***

6.2 Temporal variability in accumulation rates

It is clear that the lakes in this region respond similarly during certain time periods (Fig. 4). It is also noteworthy that the density of radiocarbon dates has an influence on the observed shifts in accumulation rate. For example, Danny's Lake and Horseshoe Lake are well-dated cores (25 and 10 radiocarbon dates, respectively) and the accumulation profiles are much more dynamic than most of the others. This is an important point because it emphasizes that the first means of improving an age-depth model should always be to add more radiocarbon dates. However, because radiocarbon dates are expensive, it can be helpful to have an idea of when major shifts in accumulation rate for a region are to be expected. That way, a more targeted approach can be employed when refining an age-depth model using additional chronological control. Moreover, having an idea of how the accumulation rate may shift over time for an age-depth model can assist with identification of outliers as shown in section 3.3. Prior to a radiocarbon analysis, major shifts in accumulation rate can be determined either visually (changes in sediment composition) or by relatively inexpensive methods such as loss on ignition, magnetic susceptibility, or palynology.

Seven of the ten cores that extend past about 7,000 cal BP show rapid accumulation rates (DT ~50 yr/cm) at the base of their record and for nearly all these sites this is an above average accumulation rate (Fig. 4). This rapid accumulation rate then steadily decreases until c. 5,000 cal BP when most lakes with well-constrained age-depth models display the slowest accumulation rates. At all seven sites, this occurs just after a transition from minerogenic-rich sediment at the bottom to organic-rich sediment at the top (Fig. 7). This is a common phenomenon in paraglacial environments when sediment availability following glaciation is relatively high as long due to the presence of unstable drift material in fluvial pathways (e.g. Church and Ryder, 1972; Ballantyne, 2002). Sediment availability decreases as it is deposited, but also erosion rates are tempered as vegetation is established (Huang et al., 2004). Results from an exponential exhaustion model by Ballantyne (2002) support a decreasing accumulation rate over time as unstable sediment is deposited. Briner et al. (2010) attribute the transition from minerogenic-rich to organic-rich sediments to be indicative of the catchment for a proglacial lake getting cut off from a nearby glacier. While most cores show a gradual colour change toward the basal sediments, the bottom 1 cm of Bridge Lake is composed of light grey clay that was likely deposited in just such a proglacial setting. We also see evidence for this shift in sediment type at Bridge Lake when looking at the bathymetry profile (Fig. 6), which shows a weak, second reflector near the bottom of the core site. Around the transition from minerogenic-rich sediments to organic-rich sediments, most lakes are characterized by slowest accumulation rates, coeval with a period of treeline advance in the region (Kaufman et al., 2004 and references therein). Similar relationships were noted for a lake in the Cathedral Mountains of British Columbia (Evans and Slaymaker, 2004) and in a crater lake in equatorial East Africa (Blaauw et al. 2011), whereby vegetation cover is thought to slow terrestrial erosion and allochthonous sediment supply to lakes due to physical stabilization of surficial materials. Following treeline advance, the accumulation rates in cores with the highest dating resolution (Danny's, Carleton-1B, and Horseshoe lakes) begin to increase again during late Holocene Cooling.

The accumulation rates for the cores from Lac de Gras, Carleton-2012 Lake, and Danny's Lake increase sharply between 1,500 cal BP and 1,300 cal BP, creating a small dip toward increased accumulation rates (Fig. 4, 7). Anderson et al. (2012) also found an increase in mineral accumulation rates at inland and coastal sites from c. 1,200 to 1,000 cal BP on southwest Greenland. They attribute this shift to regional cooling, increased aridity, and increased delivery of allochthonous material to the lake. At Carleton Lake, a cooling event between c, 1,690 and c. 940 cal BP is inferred based on chironomid proxy data (Upiter et al., 2014) and is temporally correlative with the timing of First Millennial

Cooling, a period of cool climatic conditions in the Northern Hemisphere and documented in records from British Columbia (Reyes et al., 2006), Alaska (Hu et al., 2001; Reyes et al., 2006; Clegg et al., 2010), and the Canadian Arctic Archipelago (Thomas et al., 2011). Increased accumulation rates between c. 1,500 and c. 1,300 cal BP may therefore correspond to cooling in the central NWT that would have resulted in a brief period of reduced vegetation and consequently, increased erosion.

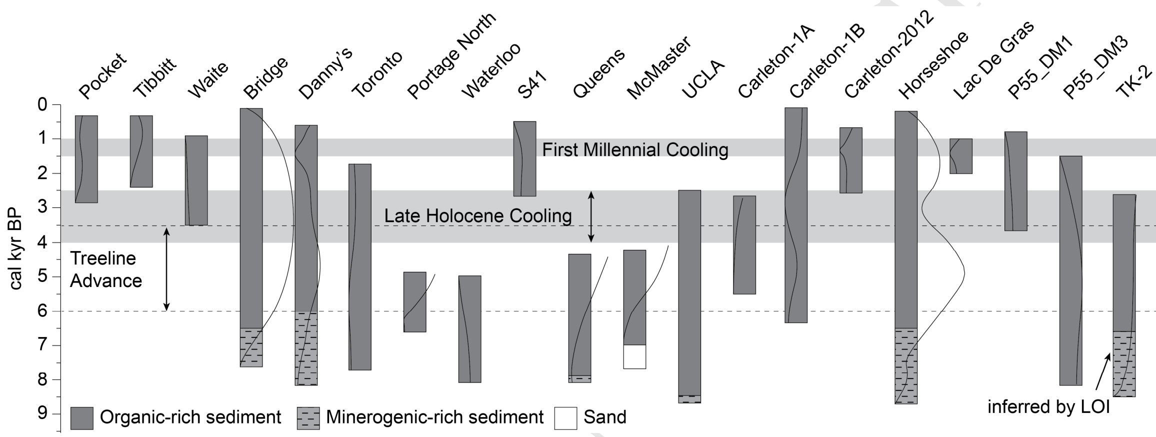


Figure 7. Stratigraphic core logs plotted against cal BP. The top of each core is defined by the uppermost non-outlying radiocarbon date. Curved lines are accumulation profiles from Fig. 4b and are to be interpreted left to right is faster to slower. Time ranges for the treeline advance and Late Holocene Cooling follow Kaufman et al. (2004), and First Millennial Cooling follows Reyes et al. (2006), Hu et al. (2001), Clegg et al. (2010), and Thomas et al. (2011). ***Double column image.***

6.3 Accumulation rate (DT) prior

In Section 6.1 and 6.2, accumulation rates are discussed in terms of the natural environment, which is a critical first step in any modeling study. In this section, we switch gears to discuss the practical application of accumulation rates as prior information for age-depth modeling with Bayesian statistics.

The default DT prior for Bacon version 2.2 is 20 yr/cm based on the estimate from the great lakes region by Goring et al. (2012). Bacon version 2.2 is programmed to suggest an alternative DT based on round values (e.g. 10, 50, 100 yr/cm) if the default of 20 yr/cm is inappropriate for the core. As was shown for Waite Lake, 20 yr/cm is an appropriate estimate for most lakes found in the boreal forest zone, but lakes north of the treeline accumulated at much slower rates. Here we use estimates from a summary of accumulation rate data for the region to construct the age-depth models in section 5. The most striking feature of these age-depth models is how variable the accumulation rate appears to be. Figure 8 (constructed using the *plot.acc.rate()* function in Bacon 2.2) shows a more detailed version of accumulation rate patterns for the three cores from Section 5. Waite Lake only covers the past c. 3,500 years so variability is minimal, but both the longer Danny's and Horseshoe Lake records display highly variable accumulation rates (as discussed in Section 6.2). The estimates for accumulation rate entered *a priori* into the model therefore act as a guide for the age-depth model, but do not control the model entirely.

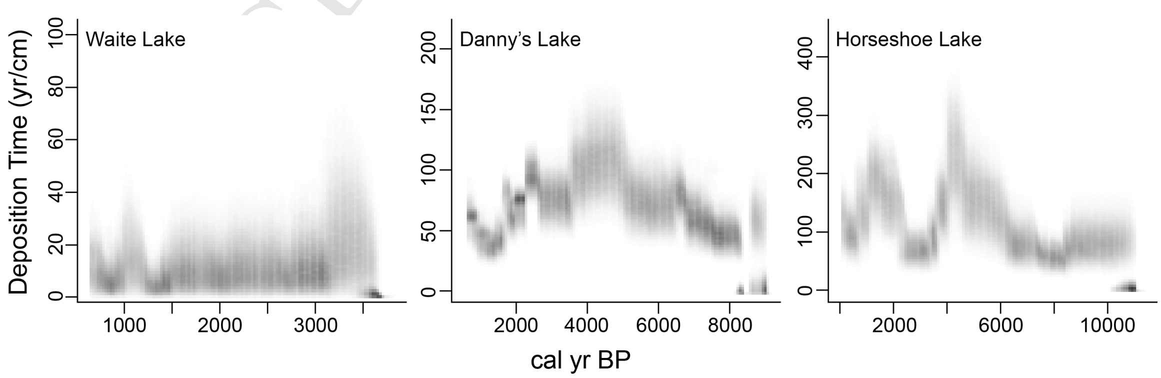


Figure 8. Accumulation profiles plotted with Bacon v2.2. The darker the grey, the

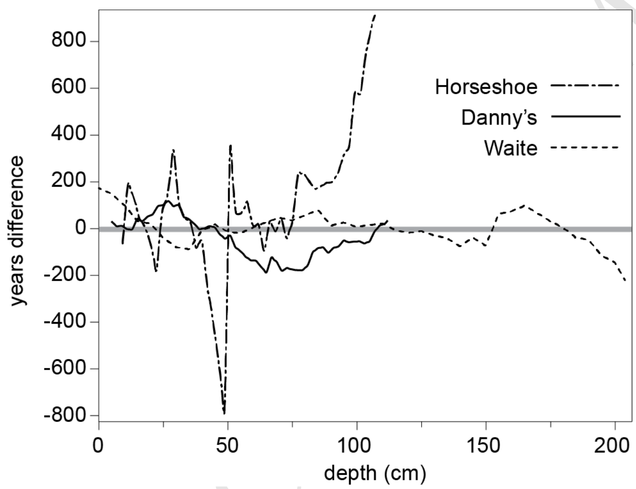
greater the certainty. ***Double column image.***

When an age-depth model is well dated, the dates themselves should guide the accumulation rate. In sections of the core with low dating resolution or age reversals, the Bayesian model can aid by incorporating prior information (Christen, 1994; Buck et al., 1996; Buck and Millard, 2004; Blaauw and Heegaard, 2012). Here we compare the Bayesian models to the Clam models in order to evaluate the effect of incorporating prior information. Because the Clam models were initially constructed with IntCal09, we reconstructed the models with IntCal13 order to ensure consistency (Supplementary Fig. 1). Moreover, a hiatus was added at 45 cm to the Horseshoe Lake model constructed with Clam. Differences between the maximum probability age of the Bayesian model and non-Bayesian model for Waite Lake, Danny’s Lake, and Horseshoe Lake are presented in Figure 9.

Waite Lake has the simplest chronology, with only one distinguishable shift in accumulation rate just before c. 1,500 cal BP. The difference between the Bayesian and non-Bayesian models is 90 years at the most, which is minimal. For Danny’s Lake, the difference between the two models is also fairly minimal (175 years at the most), which happens near the bottom of the model where the greatest uncertainty lies.

The difference between Bayesian and non-Bayesian age depth models for the Horseshoe Lake record does not tend to exceed 200 years, except in the region of the hiatus between c. 6,000 and c. 4,000 cal BP (45 cm), where the difference is 468 years. This is to be expected as the hiatus is handled slightly differently between the two programs and it causes a major disturbance in the model. C/N ratios from Horseshoe Lake suggest that the sub-basin of Horseshoe Lake has undergone fluctuations in water depth (Griffith, 2013). Therefore, it is possible that there is a hiatus in deposition between c. 6,000 and c. 4,000 cal BP. A hiatus would also explain the anomalously slow accumulation rates around this period as shown in figure 4.

Although not shown in Figure 9, the age-depth models constructed with Bacon have wider and more realistic calculated error ranges than for the smooth spline models constructed with Clam.



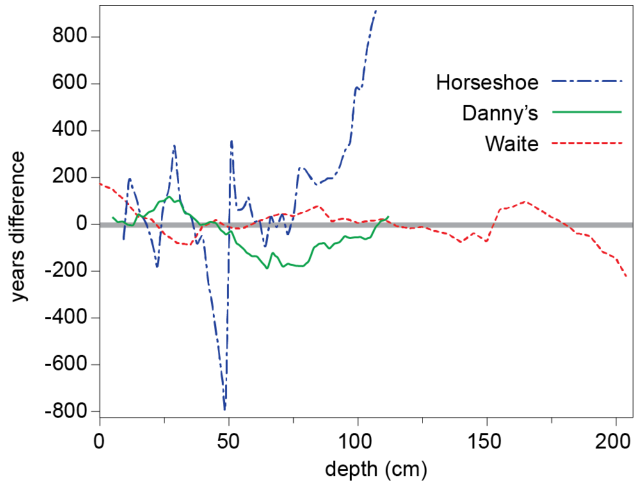


Figure 9. Plot showing the difference (in years) versus depth between the models constructed in Clam and Bacon for the Horseshoe, Danny's and Waite Lake cores.

Single column image. Color for web version only.

7. Conclusions

High resolution sampling and detailed age dating of subarctic lake cores from the Northwest Territories have provided new information about the spatial and temporal variability in lake accumulation rates in this cold, high latitude region. Based on a dataset comprised of 105 radiocarbon dates (64 new and 41 previously published) from 22 sites distributed amongst 18 lakes, we make the following conclusions:

(1) "Rapid" accumulation rates (DT ~20 yr/m) tend to occur in lakes with high productivity (boreal forest zone) or high sediment availability. Sites north of the treeline are characterized by moderate (DT ~70yr/cm) to slow (DT >100 yr/cm) accumulation rates with high spatial variability.

(2) Temporal shifts in accumulation rates coincide with centennial to millennial-scale climate change and the waxing and waning of vegetation cover, which is an important mechanism controlling erosion of material into lakes. Accumulation rates prior to about

7,000 cal BP were rapid, reflecting recently deglaciated conditions characterized by high sediment availability and low vegetation cover. As vegetation became better established during the treeline advance, we observed a shift from minerogenic-rich to organic-rich sediments and a decrease in accumulation rates between 7,000 and 4,000 cal BP. This was followed by a cool period and increasing accumulation rates between 4,000 cal BP and 2,500 cal BP.

(3) Deposition time estimates from this research will be useful as a starting point for building robust age-depth models using Bayesian statistics and state-of-the-art software such as Bacon. Moreover, by elucidating the timing of regional shifts in accumulation rate for the Canadian Subarctic, future radiocarbon dating sampling strategies will be better informed about where to add additional radiocarbon dates to an age-depth model.

Acknowledgements

Funding for this collaborative research project was provided by a Natural Sciences and Engineering Research Council of Canada (NSERC) Strategic Project Grant and Discovery Grant to RTP and an Ontario Graduate Scholarship to CC. Direct and in-kind funding was provided by the Northwest Territories Geoscience Office, Polar Continental Shelf Project, the Department of Aboriginal Affairs and Northern Development Canada (by, in part, a Cumulative Impacts and Monitoring Program award to JMG), the Geological Survey of Canada, the Tibbitt to Contwoyto Winter Road Joint Venture (Erik Madsen and the crew of the Dome, Lockhart, and Lac de Gras maintenance camps), EBA Engineering Consultants Ltd., the North Slave Métis Alliance, IMG Golder, Inuvik, and Golder Associates, Yellowknife.

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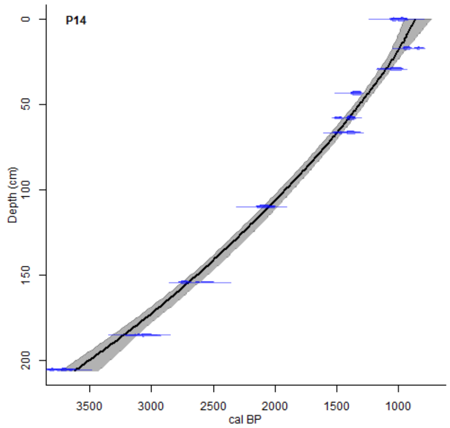
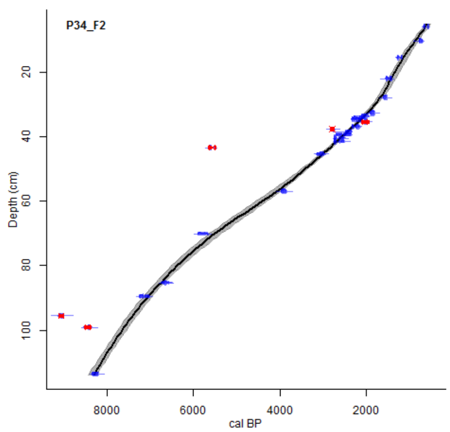
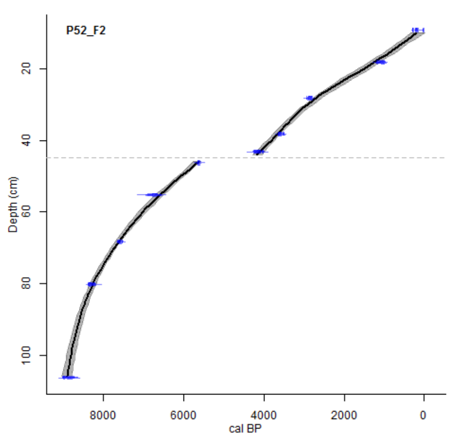
a) Waite Lake



b) Danny’s Lake



c) Horseshoe Lake



Supplementary Figure 1. Smooth spline age-depth model constructed for: a) Waite Lake; b) Danny’s Lake; and c) Horseshoe Lake using the age-depth modeling software Clam and the IntCal13 calibration curve. For Horseshoe Lake, a hiatus is shown with a dashed line at 45 cm